Government
Office for Science

FORENSIC SCIENCE AND BEYOND: AUTHENTICITY, PROVENANCE AND ASSURANCE

EVIDENCE AND CASE STUDIES

Annual Report of the Government Chief Scientific Adviser 2015
Forensic Science and Beyond: Authenticity, Provenance and Assurance
Evidence and Case Studies

This volume comprises chapters which form the evidence for the Government Chief Scientific Adviser's Annual Report 2015, together with illustrative case studies. It should be cited as:
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The Government Office for Science would like to thank the authors who contributed evidence chapters, case studies and their time towards this report and gave it freely.

This report is intended for:
Policymakers, legislators, and a wide range of business people, professionals, researchers and other individuals whose interests include the use of forensic analysis within the Criminal Justice System through to authenticity, provenance and assurance in the provision of goods and services.

The report project team was Martin Glasspool, Richard Meadows, Lindsay Taylor, Adam Trigg and Jenny Wooldridge.

This report consists of contributions received from academia and industry and others outside of government. The views expressed do not represent policy of any government or organisation.

This report is presented in two parts. The first is the summary report of the Government Chief Scientific Adviser. This was developed as a result of seminars and the advice of the experts who provided the source of the evidence. The second part, the evidence, has been gathered from and written by a distinguished group of experts. The evidence takes two forms: chapters that consider a major aspect of the forensic landscape; and individual case studies that illuminate points of detail and principle. The evidence section provides the views of the experts themselves, who met on several occasions during the preparation of the report and had the opportunity to help to develop the narrative and to comment on each other's contributions. The Government Chief Scientific Adviser is responsible and accountable for the summary report, and the experts for their individual contributions to the evidence papers and case studies. Neither should be blamed for the sins and omissions of the other!

FOREWORD

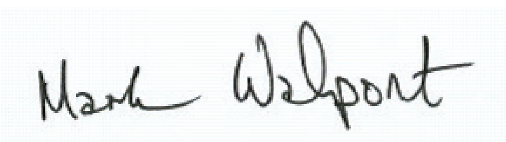
My second annual report explores new and emerging forensic techniques so that policy makers can ensure they are developed and used for the benefit of the UK.

It covers four main areas:

- An overview of the UK's forensic science landscape from the perspective of its users
- The changing nature of crime (including cybercrime), examining how forensic science can predict, deter and overtake it
- The forensic application of analytical science beyond the court system
- The steps required to secure the UK's forensic science sector for the long term, with particular attention to innovation and new market opportunities.

In producing the report, I have drawn on the knowledge of a range of experts and academics. They have provided a clear evidence base for each of these four areas. This volume presents that body of evidence, as well as illustrative case studies.

The chapters and case studies herein represent the authors' personal views rather than those of the Government Office for Science, but their insights – for which I am greatly indebted – have fundamentally informed the messages and questions raised in my report.



Sir Mark Walport
Government Chief Scientific Adviser
December 2015

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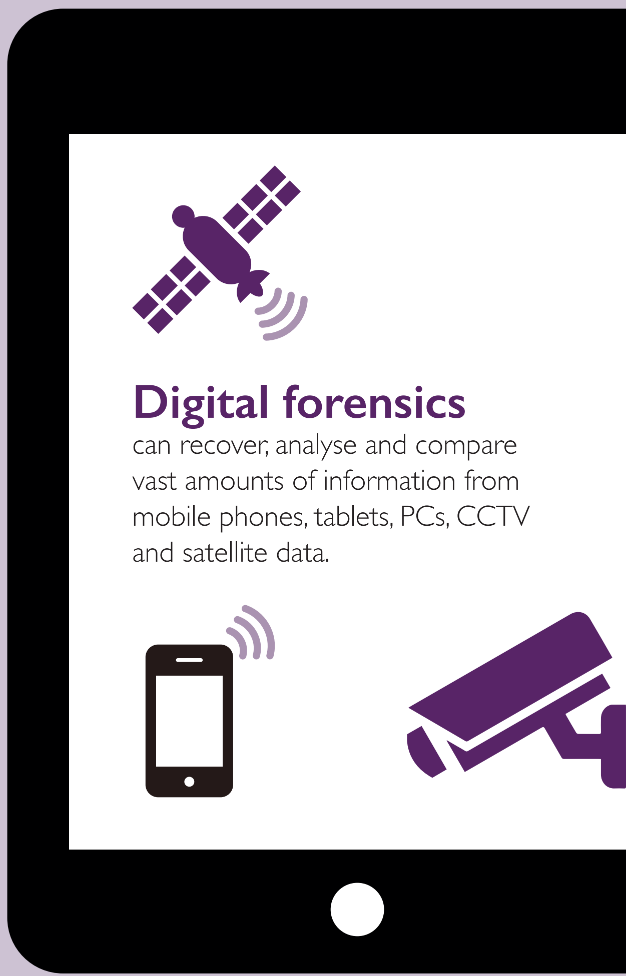
SECTION 1:

THE FORENSIC SCIENCE LANDSCAPE

THE FORENSIC SCIENCE LANDSCAPE

The interaction between criminal investigation, justice and science is complex, but offers one of the strongest safeguards against false allegation and wrongful conviction.

Traditional types of forensics



In the UK we identify approximately **50,000 offenders** from crime scenes using fingerprints each year

There are **25,000 DNA matches** between crime scenes and offenders **each year**

The National DNA Database produces over **2,000 DNA matches a month** and has a match rate of **over 60%** with a DNA profiles obtained from samples taken from a crime scene or victim

Cognitive and human factors underpin many aspects of forensic work, from the initial collection and evaluation of data at the crime scene, throughout work in the laboratory where evidence is interpreted, to presentation in court.

The complexity of forensic science is increasing rapidly. Policymakers and practitioners need to work towards consistency, collaboration, clarity and common standards.

FORENSIC SCIENCE IN CONTEXT

ANGELA GALLOP, *Axiom International Ltd*, KAREN SQUIBB-WILLIAMS, *Acorn Chambers*

The privatisation of forensic science services in England and Wales has been a resounding success, in some ways: it has saved costs, reduced case turnaround times, maintained quality and, to some extent, inspired innovation. But the way services are procured has become increasingly fragmented, threatening future innovation and potentially undermining public confidence in the criminal justice process. The UK urgently needs a national strategy covering all aspects of forensic science that takes account of all stakeholders, not just the police.

In reality there may be no such thing as 'Forensic Science'. Perhaps instead, a multiplicity of sciences and scientific methodologies, old and new, when applied to legal questions, become the discipline of forensic science. These questions are usually associated with the prosecution of crime, but they also cover consumer and environmental protection, health and safety, and civil proceedings such as breach of contract and negligence. The sheer variety of scientific disciplines involved in forensic science can potentially distract focus from the formation of a coherent strategy for their use within the justice system.

Forensic science is a term that has come to be used over the past century and a half to describe an increasing number of practices. These began with the observations that fingertips feature different patterns, and that people write in different, distinguishable ways; that chemistry could help to identify poisons; that the blood shed from different types of injury formed distinctive patterns; and that different chemical groups could be used to distinguish blood from different people. All these were used to clear up mysteries and help get to the bottom of matters in dispute.

As analytical techniques and methodologies developed and experience broadened, it became possible to determine the composition of everyday items such as plastic bags and tracksuit trousers; the trajectory of a knife or a bullet; the precise nature of arson and ballistics residues; the meaning of bone damage; how old a bruise might be; narcotic traces on bank notes; individual characteristics of hair, nails, and teeth and bite marks; the interpretation of simple binary data; tread patterns on shoes and feet marks inside them; differences between voices; paint and glass fragments on tools; the life cycle of flies; and assemblages of pollen grains.

Most recently, forensic science has been further transformed by our ability to detect and analyse tiny amounts of DNA, found to varying extents in every part of the human body and in animals and plants too (see case study p17). And it can now recover, analyse and compare vast amounts of information stored on mobile phones, tablets and PCs, in CCTV footage and other imagery, as well as incalculable quantities of satellite data. This seemingly endless list of capabilities also includes the statistical analysis of the likelihood of a probability, which can generate confusion that potentially weakens the contribution of scientific evidence (see Chapter 4).

Nevertheless, forensic science has led to a much more reliable understanding – and indeed hard physical evidence of – where, when, how and by whom crimes have been committed. It can uncover the nature and likely origin of a wide range of objects and substances; which of two competing accounts is more likely to be right; the extent of an individual's criminality; as well as the nature of drugs and firearms supply chains, and who is involved in them. Increasingly, forensic science is also being used to predict when crimes are likely to be committed so they can be pre-empted and disrupted, and it answers innumerable other questions across endeavours in all sections of society. To this extent, it makes an invaluable contribution to our justice and security systems and thereby to our economic and social stability.

THE IMPACTS OF FORENSIC SCIENCE

Forensic science impacts on government, law enforcement, academia, lawyers, judges, scientists and technicians, insurers, regulators, journalists and the public. All of these different sections of society, as well as different specialists within forensic science, will have different perspectives and interpretations about what forensic science is, and what it can and cannot do. These perspectives go to the heart of our justice system. For instance, prosecution lawyers are statutorily obliged to exercise their own view of the strengths and weaknesses of the scientific evidence before deciding whether an investigation can progress to the prosecution process – this 'gatekeeping' decision takes place long before a judge is involved in the matter. Legal defence teams need to know whether any specific aspects of scientific evidence might usefully be subjected to challenge. How are any of them to make such assessments without a reasonable grasp of the science and scientific methodology? It follows that where discussion and formulation of policy regarding the social utility of the sciences takes place, a very clear common language is necessary; this remains an essential, yet arguably elusive, aim.

How then are forensic science providers and those who use their services and products, particularly law enforcement personnel and lawyers, best able to understand and maximise the opportunities available to them? Scientific excellence, commercial success and just outcomes depend on the consistent understanding, integration and utility of high-quality scientific processes and practices, grounded in a fertile, confident environment that is supported by a consistent government strategy which includes sufficient funding and open, defragmented communication (see case study p20).

While this is a relatively straightforward concept, the reality is far more complex. There are many different forensic science providers, reflecting the sheer scope and scale of forensic activity. They range from organisations that specialise in forensic science to the exclusion of everything else, to those who do it as a side line; from large-scale operations to niche suppliers of specialist services; from those who are both customers and providers of forensic services;

FORENSIC SCIENCE HAS LED TO A MUCH MORE RELIABLE UNDERSTANDING – AND INDEED HARD PHYSICAL EVIDENCE OF – WHERE, WHEN, HOW AND BY WHOM CRIMES HAVE BEEN COMMITTED

and from those whose focus is solely in the UK to those who also operate internationally. Indeed, some UK forensic providers are foreign owned. They include private companies, public organisations, academic institutions, and commercial and industrial operations.

Their customers are just as varied. The 43 police services in England and Wales, and associated investigative and law enforcement bodies (e.g. the National Crime Agency), are the largest cohort of customers, and much of what follows in this chapter will inevitably focus on this area. Prosecution lawyers throughout the UK also represent a large body of users, despite rarely having any contractual or direct contact with the scientists. But there are many other organisations that also use forensic science including, for example, lawyers representing people accused of crime or acting for one side or the other in civil matters; regulatory bodies; manufacturers whose products are alleged to be faulty, contaminated or fraudulent; private individuals and their professional bodies conducting investigations of their own; and insurers (and their loss adjusters) challenging claims. Rightly, of course, there is no limit globally on how the sciences are used, or by whom; consequently, those with criminal intent and terrorists also make full use of scientific opportunity. In response, the UK must have the capability to monitor and analyse such use overtly and, where appropriate, covertly.

A STRATEGY FOR FORENSIC SCIENCE

As we write this chapter, the government is currently in the process of developing a national strategy for forensic science. It is clearly critical that the true views and experiences of forensic suppliers are captured during this process. This is not always easy, owing to significant sensitivities

AS THE MOTHER OF INVENTION, ADVERSITY HAS INSPIRED SOME IMAGINATIVE PARTNERSHIPS BETWEEN DIFFERENT TYPES OF ORGANISATION

about investigative customer perceptions of individual firms, which often limit what these firms are prepared to say openly.

There are different ways in which forensic providers interact with their customers, ranging from contracts covering routine testing, to one-off investigations requiring specific strategies which need continual refinement as work progresses. The greatest change in recent times has been in relation to work commissioned by the police (see Chapter 2). This reflected the shift from public to private providers on cost and effectiveness grounds, and the desire by police services to be able to compare products and services of one provider with another on an 'apples with apples' basis. To assist with this, a system was devised which effectively broke down forensic services into their smallest component parts, which could then be bought and sold as commodities through a national streamlined procurement process. At the same time, and in an effort to further control and reduce costs, police services started in-sourcing increasing amounts of the work themselves, mainly in connection with the initial examination of items for evidential traces. Such traces – often on swabs, in scrapings, or on snippets of fabric – are then submitted for more detailed analysis to one or more external forensic science laboratories.

The leading forensic suppliers complain consistently about the difficulties of continuing to provide services to the various standards required while remaining competitive. They do this in private for fear of creating concern amongst their customers about their resilience and ability to cope with new procurement awards. This inevitably means that funding for activities such as research and development suffers, and projects tend to be skewed towards those more directly related to saving operational costs.

It is in the very nature of science that new technologies and methodologies constantly emerge from the wider scientific community. It is clearly critical that those with potentially important forensic application are tested, and where appropriate, validated and incorporated into operational use as quickly and effectively as possible. But identifying which these might be, and conducting the necessary tests for relevance, reliability and robustness is a costly and time-consuming business (see Chapter 3).

Gone are the days when providers might expect to earn sufficient profits from their work to fund all of this R&D themselves. It is difficult for them to compete effectively for external funding from research councils and other funding institutions because historically this has not been a core skill, and besides, there are few such funds with a forensic science focus – most are targeted towards the 'pure' sciences (see Chapter 16). Gone too is the Forensic Science Service (FSS), which benefitted from additional direct support from government for this purpose. Recognising these difficulties, the House of Commons Science and Technology Committee commented in its 2011 report[1]: "Forensic R&D in the UK is not healthy, and we call on the Home Office and Research Councils to develop a new national research budget for forensic science". In its 2013 report[2], the committee wrote that "it remains as difficult as ever for forensic researchers to obtain funding". While some funds are available from the government's Innovate UK agency, which works closely with the Home Office's Centre for Applied Science and Technology (CAST) and other bodies in administering them, the process is fairly opaque and we know from experience that providers' access to such funds remains very problematic.

As the mother of invention, adversity has inspired some imaginative partnerships between different types of organisation – most notably police services, forensic suppliers and academic institutions, which have added to the richness of projects. But a properly developed national strategy with universal buy-in is required to provide focus and impetus for research, along withthe necessary funds to ensure the timeliness, safety and reliability of emerging forensic technologies.

In formulating such a strategy, we need to look deeper into the way we deploy forensic science. A good place to start would be with the attrition rate in criminal cases in England and Wales: specifically, those cases where forensic evidence was sought during the initial investigation, then passed to the Crown Prosecution Service (CPS), but which fail to continue to court. Since the early 2000s, the authors have been told by a number of Chief Constables and other investigators that only around 10% of cases involving forensic science evidence ever reach a courtroom. Is there really a 90% attrition rate? And if there is, what are the reasons for it? Is this acceptable, for instance through a case ending satisfactorily before reaching court, or does it potentially represent a waste of public funds? And why does our experience suggest that public policymakers do not always seem to be fully aware of these operational issues? Answering these questions would offer valuable information for strategic forward planning. In the interests of justice and in the public interest, therefore, it is worth considering a different approach to investigating crimes using forensic evidence (and necessarily expert evidence) and preparing cases specifically for the CPS (rather than the perpetual focus of preparation for the court room).

HOW USEFUL IS FORENSIC SCIENCE?

It is notable that academic, investigative, political and media attention on forensic science has focused almost exclusively on crime scene investigative input and prosecution process outcomes in the courtroom (i.e. reported cases). But this only addresses the outcomes of about 10% of investigative activity, potentially significantly skewing any analysis. Indeed, if the effectiveness of police investigations, and the utility of forensic evidence, are to be measured by way of appearances in the courtroom this may lead to ignoring the 90% of investigations that, hidden from view in the manner hypothesised above, fall by the wayside post-investigation and pre-trial. Such a lack of reliable, evidence-based information about what has occurred in the significant majority of cases could suggest that what is 'known' about police investigative and forensic practice is just the tip of an iceberg, and any conclusions based upon such limited knowledge thus remain conjecture. No scientific methodology would recommend extrapolating findings from just 10% of their experiments; and yet, if this attrition rate is in any way accurate, police officers, criminologists, forensic scientists, lawyers and judges have been at risk of doing just that. It may be shown in the future that this is not the definitive percentage, but the figure is less important than the need to explore more rigorously what the value of forensic science and forensic analysis is to the criminal justice system as a whole.

The cost of obtaining forensic evidence and using expert witnesses is loosely said among senior police to be second only to salary costs within some law enforcement agencies (there is no reliable and comprehensive data). Consequently, exploring and seeking to reduce this significant and potentially unjust attrition rate should now be placed alongside all the other key considerations of forensic science and related strategic policy making.

Effective public policy can only be achieved through identifying and understanding the real challenges of involving forensic science and scientific methodologies in the criminal justice landscape. In this regard, perhaps much is to be learnt by moving the focus away from the intense, 'sexy' work of police, crime scene investigators (CSIs) and forensic scientists, or the dramatic and charismatic nature of the courtroom; and instead shift it to the 'backroom' dynamics and comparatively dry mechanics of the prosecution process. This is the critical decision-making point where cases either proceed to court, or are filed away with numbers of others that have reached the end of the criminal justice road.

Although a body of research exists into attrition rates of particular crime types, especially domestic violence and rape cases[3], there is a dearth of research in relation to attrition rates associated with particular scientific evidence types (save perhaps for the US National Academy of Sciences Report on Forensic Sciences – see below). While the UK has seen myriad reports on police investigations, and the use of forensic science, these have almost always based their conclusions upon those rarefied cases that end up in court, which are then available for academic and public scrutiny and comment. Even when directly informed by operational police or forensic scientists, these commentators are sometimes at risk of commenting from behind a veil of ignorance of why cases have been 'dropped' by the CPS.

So why might the attrition rate be so high? Law enforcement investigation files are subjected to a seven-stage filtering process, defined by the statutory function of the CPS as cases leave the investigative field and enter into the gateway of the prosecution process. The application of these filters appears to have the effect of reducing the strength of the forensic evidence, particularly when subjected to the "evidential stage" of the Test set out in the Code for Crown Prosecutors (7th Edition), which Crown Prosecutors are statutorily obliged to apply in order to determine whether a case proceeds into the prosecution process. These seven filters can be broadly defined as follows:

1 Applicable statute and case law in the jurisdiction of England & Wales
2 The Code for Crown Prosecutors, 7th Edition
3 The CPS Core Quality Standards
4 The Criminal Procedure Rules
5 The Criminal Procedure and Investigations Act, 1996
6 The more contemporary[4] principles of streamlining Forensic Case Management and proportionate prosecutions
7 The absence of a contractual relationship between forensic science providers and end-users, namely the CPS and the court

The second stage of this filtration process, in particular, calls for attention because it deals with the status of evidence itself – a question which probes the core of the place of science within the development of the modern nation state, and one taken up in the work of major philosophers of science Karl Popper, Thomas Kuhn, and Paul Feyerabend[5]. According to the description of the evidential stage in the CPS's Code for Crown Prosecutors, for evidence to be used in court, the prosecutor must be satisfied that it is reliable, credible, and admissible. It could be that it is in the face of these questions that the findings and methodologies of forensic science encounter significant resistance.

Importantly, it may also help to consider whether the ability of the 43 police services of England and Wales to individually source their forensic science needs – rather than acting together as a nationwide 'super user' – may have fed a tendency for each police service to use their scientific and technological capability in a 'siloed' manner to excel in achieving individual police service performance indicator targets. Such targets are potentially counter-productive to a national cohesive knowledge sharing approach. Looking wider than forensic science, the Soham murders are perhaps an example of the price paid by the public interest for the past lack of unified action and communication by some police services. The Bichard Report on the murders found that if processes to share information between between forces were followed and adequate checks were conducted by the school and the police then Ian Huntley would not have been able to gain employment as a school caretaker.

In addition, law enforcement agencies – and the politicians responsible for them – rely heavily on the positive public perception of their role to achieve co-operation ('policing by consent'). This requires favourable media coverage, and they are potentially drawn into a public-relations approach which accentuates 'success' at tackling crime, and detecting and convicting offenders.

The increase in forensic laboratories and the diversification of forensic techniques over the past thirty years, propelled especially by DNA testing, has occurred without a corresponding efflorescence of published research on the efficacy of such techniques on solving crime and actually convicting criminals[6]. Studies[7, 8] have shown that forensic evidence did impact on prosecution rates, though not uniformly – for example, by increasing sentences and incarceration, though not actually affecting whether or not a defendant was convicted in the first place.

Joseph Peterson and Ira Sommers have shown that the impact of forensic evidence varied between different kinds of cases. Forensic evidence has a strong impact on the rate of arrest, charging, and conviction for aggravated assault, burglary and robbery, and rape, in particular[6]. The same study found that in only "~2% of all cases, 6% of cases with crime scene evidence, and 12% of cases with examined evidence" did forensic evidence link a suspect to a crime scene or a victim. However, it should be acknowledged that this conclusion may, to some extent, depend on the particular methodology used, as with all research.

Kelly Pyrek has represented forensic science as a mêlée in which "the numerous stakeholders in the criminal justice system extract from forensic science what they need to perpetuate their positions"[9]. Further recent research has highlighted the conflicted agendas in which forensic science is caught. According to Kevin Strom and Matthew Hickman, "compared with reducing crime rates, maximizing case solution, conviction, and sentencing rates may not command the same attention"[10]. Though

CASE STUDY

DNA ANALYSIS

SUSAN POPE, *Director of DNA Principal Forensics Ltd*

Different types of DNA test can produce profiles that provide important investigative leads in unsolved cases. Imagine a case where the body of a person has been found with multiple stab wounds. There are no witnesses to the incident, but a knife and a tissue were found beside the body. Investigators swab the handle of the knife and take samples from the tissue, in order to recover DNA from skin cells deposited by people who have touched them.

Standard DNA tests analyse genetic markers in areas of DNA called short tandem repeats (STRs) that vary greatly between people. By testing cells on the tissue, investigators produce a full DNA profile that appears to be from a single person. This result can be searched against the profiles of (a) people and (b) other crimes held on the National DNA Database. Police are notified if the profile matches a named person, who can then be interviewed. Intelligence information can be obtained if the profile matches samples from other crimes. At the same time, individuals that do not match the profile are eliminated from enquiries.

If no matches are obtained in the UK, the police may consider searching international DNA databases. The standard test contains all of the DNA markers needed for searches of European DNA databases, for example. DNA tests are currently available that analyse more than 24 STR areas of DNA, including all of those present in both the European Standard Set and the US CODIS system, enabling wider international searches. These are not performed routinely in England and Wales or Northern Ireland, but are used in Scotland.

If no matches to named individuals are obtained then familial searches for relatives such as parent, child or sibling can be performed for intelligence purposes. Familial leads for male samples can be followed up by testing markers (called Y STRs) on the Y chromosome, which is inherited through the male line. This means that one person's Y profile can be used to include or exclude all of the male blood relatives of the person tested, so the number of people profiled can be limited. Mitochondrial DNA, inherited through the female line, can provide further familial leads.

If the profile obtained from cells on the knife handle shows a mixture of DNA from multiple donors, then the direct DNA database searches for that result may be more limited and its intelligence value is decreased. However, once a named individual is compared with the mixture then standard methods for evaluating the significance can be performed on many mixtures, with an increasing range of specialist statistical analysis available for complex mixtures.

Specialist investigative tests analyse markers for physical appearance including eye, hair and skin colour. These may provide intelligence leads about the general appearance of the offender in cases where a DNA profile from a crime stain has not produced any matches on DNA database searches and there is no eyewitness evidence to describe the offender.

In the short term, the police are testing rapid DNA devices that can analyse reference and crime samples in two hours, producing profiles suitable for DNA database searches. This would provide reference and crime profiles and allow a suspect to be included or eliminated from an investigation within custody time limits.

Longer-term research is currently directed towards Next Generation Sequencing (NGS) systems, which combine and extend all of the applications listed so far. A single test will not only analyse many more STRs, but it will do so at a greater level of discrimination. It will also include Y chromosome markers, physical markers and ancestry informative tests. These are already being used for medical applications, and similar systems useful for forensic work are being evaluated for future implementation, once suitable DNA databases and methods have been produced, evaluated and validated.

they may be important from a justice system perspective, they may command less attention from the police executive which has more influence over funding.

The authors of a 2005 UK Home Office research study on attrition in volume crime presented an optimistic picture about the contribution of forensic science in ensuring conviction in such crimes[11]. They cited the science's ability to create strong "first links" between suspects and offences, as well as the "principal information needed to make a case against a suspect", and that this had changed from a previous situation in which forensic evidence was merely used for corroboration. Most importantly, though, they found that forensic science did not improve the generally high attrition rate within volume crime. This is because forensic evidence was either not collected in efficient ways – in household burglary cases, for example, it may be collected as a way to reassure the victim, rather than because of its likely efficacy – or that it was not collected at all from those crime scenes (such as vehicle crimes) where it would be more likely to prevent attrition[11].

From recent literature on forensic science, attrition, and the Criminal Justice System, it may be suggested that while the growth of forensic science methods and applications has given cause for optimism, significant discrepancies exist in the effective management of the science and its resources. Though the findings of the studies cited here have served to circumscribe this problem, none of them have dealt with it to the extent of offering detailed remedial policy recommendations. The following chapters of this report will help to set out the foundations upon which future government strategy can be built by the integration of well-informed, cohesive and collaborative policy making.

In addition, Northumbria University is now funding a research project to explore precisely the areas of potentially significant attrition described in this chapter. The programme, led by Karen Squibb-Williams, will explicitly concern itself with the passage of cases involving forensic science and scientific methodologies, from the criminal investigation phase through to the prosecution process, as well as 'case management' (which means different things to different organisations). A key aim is to establish whether there is any evidential basis for the anecdotal 90% attrition rate, and if so to set out the cause and effect landscape with the clear aim of supporting future strategic forensic policy in the justice system.

THE CHANGING LANDSCAPE OF FORENSIC SCIENCE

The ethical status of forensic science has seen dramatic changes over recent years. We have come a long way from the miscarriages of justice of the 1970s and 1980s (John Preece, and the Birmingham Six, for example) which highlighted shortcomings in laboratory systems and processes and heralded the introduction of formal quality management. These days there is a requirement for internationally-accredited quality systems in most forensic laboratories (see Chapter 3), except in the newer disciplines such as digital forensics (see Chapter 7), and fingerprints (with its very different origin in the police service), where these are still being developed. A Forensic Regulator (currently non-statutory) has been introduced to develop and oversee standards and codes of conduct and practice; although it should be noted that this superintendence only applies to forensic providers to the prosecution. Scientists have also been required to interpret the significance of their findings in a more 'scientific' way, using statistical approaches to support their otherwise almost entirely subjective assessments, and to set out the basis of their opinion in their witness statements so that this can be more effectively assessed by others (see Chapter 4).

One interesting development is the increase in forensic work being conducted within police services. Many police services have established or extended their own forensic screening units which undertake initial examinations of items to varying extents. As a consequence of this, external suppliers receive significantly fewer items for examination or review, and sometimes receive only samples taken from such items. This equates to a substantial shift in some of the work from external to in-house police facilities. At the extreme end of the scale is the Metropolitan Police Laboratory, re-created after the closure of the FSS. This now provides the vast majority of forensic laboratory services for what is by far the largest police service in England and Wales. Use of digital forensics is rising rapidly, reflecting trends in modern life, and much of this work is also being provided from within police services themselves.

This development puts police services in a position of both hunting criminals, and being responsible for directing and presenting impartial scientific evidence to the prosecution process and courts of law. The very act of selecting which items should be examined for what – irrespective of who actually does the testing – can have an impact on the outcome of an investigation. (See Chapter 4 for a discussion on the range of other factors). Of course, there may be nothing wrong with any of this, but it certainly seems to be something worthy of public awareness and debate before it becomes an accepted norm.

Forensic input is also now sensibly commissioned in stages to avoid any unnecessary work. Individual tests are selected in the order in which they are most likely to yield information of use to an investigation (though it should be noted that prosecuting lawyers are very rarely involved in this selection process). Where this prompts a guilty plea, no further work needs to be undertaken. Wherever possible, the results of such tests are reported by way of Streamlined Forensic Reports (SFRs) that merely contain the facts of a test; as opposed to an expert witness statement, which considers the results in the context of the case and includes a scientist's full expert opinion of what they are likely to mean. At the lowest level, for example, SFRs that report a 'hit' on the National DNA Database are prepared by police officers. At the next level up – for instance, if a reference sample profile is compared with a crime stain profile – a scientist will be involved,although the output will still be a purely factual SFR.

It is obvious to many practitioners in the field that these changes have been successful in dramatically reducing police spending on external forensics. But they have also had a number of unintended consequences that pose a risk of miscarriage of justice. These were highlighted in the 2014 report of the Independent Police Commission[12], and Angela Gallop and Jennifer Brown in their 2014 paper entitled 'The Market Future for Forensic Science Services in England and Wales'[13]. They include, for instance:

- Dangers from the mere selection of which items are to be examined, and for which types of evidential traces. To minimise costs, it is clearly critical to test as few items as is necessary. But it is equally critical that items should not be restricted to just those likely to support the prosecution's case, as this may limit and bias interpretations of what the evidence is likely to mean
- Work on the same case may be fragmented between different organisations. For example, a police screening unit may examine the items, before one or more external laboratories analyse different samples selected from them. This means that no one person is likely to have a full picture of the evidence, which is vital to interpret its likely significance in the wider context of the case. (See chapter 4 for a discussion on how separation of parts of the forensic process can help to counter cognitive bias). This can also lead to the application of the Code for Crown Prosecutors and subsequent presentation of the evidence at court becoming far more complex than it could be
- Reducing the scope of scientific input to a series of tests chosen by others, with no time or opportunity for scientists to advise on the testing strategy, risks narrowing their skill and knowledge base
- Focusing on increasingly fewer types of test – such as DNA, fingerprints and digital forensics – may be inevitable to some extent; but it is also effectively de-skilling scientists. This risks the prospect that critical knowledge and practical skills will diminish, and not be there when they are needed

THE ETHICAL STATUS OF FORENSIC SCIENCE HAS SEEN DRAMATIC CHANGES OVER RECENT YEARS. WE HAVE COME A LONG WAY FROM THE MISCARRIAGES OF JUSTICE OF THE 1970s AND 1980s

Additionally, in the authors' experience there is an extended use of factual SFRs as evidence in contested cases, rather than their originally-intended purpose as the staged form of evidence or advisory documents (as per the Criminal Procedure Rules).

As we engage with these challenges, a reduction in funding for legal defence teams

CASE STUDY

A PARADIGM SHIFT IN UK FORENSIC SCIENCE

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In 2009, the US National Academy of Sciences produced a report – 'Strengthening Forensic Science in the United States: A Path Forward'[1] – that provided a robust critique of many of the techniques used within forensic science. The NAS report (as it has become known) essentially exposed the stark reality that much of the forensic evidence currently presented in our courts had little, if any, scientific underpinning.

To catalyse a long overdue disruption to the forensic science ecosystem, Sue Black and Niamh Nic Daeid from the University of Dundee secured funds from the Royal Society to host a 4-day international event in February 2015. The first 2 days were an open scientific conference[2] where expert forensic scientists from around the world and senior members of the judiciary discussed the current health of the community and why the warnings of the NAS report appeared to have been largely ignored. The output from this event was an anniversary edition of the Philosophical Transactions of the Royal Society B[3]. The meeting was attended by representatives of one-third of all police forces in the UK, the UK forensic science providers, government agencies, professional bodies, 45 universities and a range of industrial partners.

A further 2-day closed event[4] then followed for selected participants and invited guests. This was an extraordinary meeting, facilitated through a business modeling approach that generated a 'strategic conversation'. In our experience, research scientists, forensic practitioners and the most senior judiciary had never before spoken so freely and openly about the type and nature of scientific evidence being used in courts and their shared concerns about the scientific frailty of some of that evidence. What followed was a crumbling of the barriers across the discipline-specific silos within the forensic science ecosystem – a genuine effort to see things from the perspective of others, and to derive a common understanding and direction.

There were two principal outcomes from the second Royal Society event. The first was borne out of a drive initiated by the Lord Chief Justice of England and Wales, supported by the senior judiciary from across the UK, that the scientific community should engage more effectively and efficiently in the communication of science to the judiciary and the public (who form the jury). This project is now under active discussion in a partnership between Niamh Nic Daeid and Sue Black, the Royal Society, the Royal Society of Edinburgh, the Lord Chief Justice of England and Wales and other partners, with the objective to develop scientific primers for use within the courtroom.

The second outcome from the Royal Society event was the unanimous agreement to source an urgent solution to halt the decline in confidence attributed to the poor or inadequate scientific foundations of some forensic science. Participants identified different types of forensic evidence, in current use in the court, which caused them concern regarding the robustness of the underpinning science. This resulted in a list of 40 evidence types ranging from interpretation of complex DNA profiles through to gait analysis. Participants ranked these in order according to value to the court, and used a novel Research Gap Analysis Tool (RGAT) to further interrogate the top 10 evidence types according to five pillars of assessment: detection, recognition, comparison, interpretation/evaluation and communication. This highlighted that in almost every case, deficiencies were most evident in the comparison, interpretation/evaluation and communication aspects of evidence delivery. This has provided an agreed launch pad for the development of a novel, disruptive and visionary pathway for forensic science research requiring strong research leadership to ensure delivery and sustainability.

to commission checks of the prosecution's scientific evidence means that the safety net of proper independent peer review risks growing increasingly thin.

Adding to the risks is the fact that there is currently no requirement for forensic scientists to be individually accredited. It is still perfectly possible for a scientist with an impressive academic or industrial pedigree to present themselves as an expert without a proper understanding of operational facts of life, and how context can turn scientific findings on their head. An attempt to establish such an accreditation body – the Council for the Registration of Forensic Practitioners (CRFP) – was abandoned when it became apparent that it was unlikely ever to be self-funding. Other countries (e.g. the Netherlands) have accepted that such funding is a state responsibility. But the UK relies instead on aspects of the quality systems in place in some laboratories, and voluntary adherence to codes of conduct and practice. This is unlikely to be sufficient to allay concerns about scientists caught up in the prosecution 'machine', and experts 'for hire' by the defence.

Much has been learned in recent years particularly from the work of Itiel Dror about the consequences of a range of cognitive biases, or the risk of confirmatory interpretation of scientific evidence (see Chapter 4). Important experiments have been conducted with both fingerprint and more recently DNA experts, which show that their conclusions can be influenced by the information with which they were initially supplied. We need to work hard on developing a better understanding of this risk, and finding cost-efficient ways to ensure any potential bias is filtered out – in relation to experts for both the prosecution and defence.

CONCLUSIONS

The UK has a proud and illustrious history in forensic science. It has shown that it can take bold and imaginative steps and make them work. It is still the only country (in England and Wales at least) to have privatised all of its forensic science services for the Criminal Justice System (apart from fingerprints, for historical reasons, and the recent trend towards law enforcement in-sourcing). Privatisation has been a resounding success, in terms of driving down the cost of services, reducing case turnaround times, maintaining quality and inspiring innovation, through market competition and professional variety. Without this, police spend on forensics would have been much higher, and it is arguable whether some of the most complex, high-profile cases would have been solved (including, for example, those of Damilola Taylor, Rachel Nickell and Stephen Lawrence). But the market remains fragile in areas (see Chapter 2 case study p29). Providers are engaged in what some of them privately describe as 'a race to the bottom' commercially (i.e. that the market is becoming overly competitive, with the dangers that standards will slip or that firms will withdraw from the market). And the provision of forensic science to the criminal justice process is increasingly fragmented, having been allowed to evolve with insufficient strategic focus or direction, and without effective consultation of all relevant stakeholders.

The closure of the FSS in 2012 could be regarded as an early example of, amongst other things, the harshness of the forensic science market. The House of Commons Science and Technology Committee report[1] on the Forensic Science Service in 2011 concluded that its "dire financial position appears to have arisen from a complex combination of factors, principally the shrinking forensics market, driven by increasing police in-sourcing of forensic science services, and a forensic procurement framework that has driven down prices and does not adequately recognise the value of complex forensic services". When the FSS closed, there was apparently little that could be 'saved' of the organisation which had hitherto been servicing approximately 60% of the external forensic requirement. We are aware of other casualties in the market, and of concern about the wisdom of investing in it at the current time – as predicted by the 2013 report on forensic science by the House of Commons Science and Technology Committee, in which it commented that "there is great concern about the future of the forensics market and that forensic science providers may not be willing to invest further in a shrinking market"[2].

In our view, the UK urgently needs a national strategy covering all aspects of forensic science to ensure that it is:

- Reliable and unbiased
- Used in the most efficient and cost effective way
- Makes the most of new developments in techniques and methodology
- Reflective of the needs and purposes of all stakeholders
- Properly funded for the job it has to do

Unity will be a key element in building the best environment for the continuing success and value of science and scientific methodology, namely via the following qualities across all the relevant sectors of forensic science:

- Communication
- Consistency
- Collaboration
- Clarity
- Common standards

The factors that work against achieving this unity include: the different investigative techniques used across 43 police services; the different applications of the law (prosecutors, Counsel and Judges); the very wide range of understanding of forensic science among ministers and their advisers; and the media's role in explaining forensic science and its implications to the public.

One approach could be to defragment the forensic science community itself. This would enable more cost-effective training mechanisms for all applicable agencies, particularly for law enforcement officers and prosecution lawyers; more commercially effective business planning (within a free-market model); and, most significantly, it could lead to a coherent streamlined UK-wide strategy for research and development to future-proof the use of forensic science. This would support the continuation of three vital objectives:

- Re-positioning the UK at the forefront of (forensic) scientific development
- Enabling the best use of scientific innovation and scientific methodologies in the future
- Preserving confidence in the legal system and the Rule of Law.

To achieve this, we must learn the lessons from the past, from other people who have considered the same issues at length. Perhaps one of the most important here is the US National Academy of Sciences (NAS) whose 2009 report commented on precisely the same sorts of concerns that we have described here[14]. The report made 13 recommendations, which can usefully be summarised as follows:

1. Create a national institute for forensic sciences
2. Standardise terminology and reporting practices
3. Expand research on the accuracy, reliability, and validity of forensic sciences
4. Remove forensic science from administrative control by police or prosecution
5. Support forensic research on human observer bias and sources of human error
6. Develop tools for advancing measurement, validation, reliability, information sharing, and proficiency testing, and establish protocols for examinations, methods and practices
7. Require mandatory accreditation of all forensic laboratories and certification of all forensic practitioners
8. Laboratories should establish routine quality assurance and quality control procedures
9. Establish a national code of ethics with a mechanism for enforcement
10. Support higher education in forensic graduate programs to include scholarships and fellowships
11. Improve the medico-legal death-investigation system
12. Support Automated Fingerprint Identification System (AFIS) interoperability through development of standards
13. Support the use of forensic science in homeland security

The impact of science on society is profound: transport, communications, nutrition, housing, energy and security could not be what they are without generations of dedicated scientists and support from those who believed in, and funded, their innovations.

The diversity, utility and powerful impact on society that forensic science now offers must come with a corollary duty to ensure that it is properly used, properly understood and properly funded well into the future. At the very least, a just society depends on good science being used for the benefit of all.

FORENSIC SCIENCE IN PRACTICE

GARY PUGH, *Director of Forensic Services at the Metropolitan Police Service*

Forensic science is highly successful at solving crimes, eliminating the innocent from investigations, and bringing offenders to justice. But there is a growing need for 'real-time forensics', providing accurate and reliable evidence in minutes rather than days. The underlying technology is already emerging, but bringing that vision to fruition will require better coordination between research organisations, forensic service providers, law enforcement officials and the Criminal Justice System, underpinned by a robust and deliverable forensic science strategy.

Forensic science is one of the most widely known and least understood areas of scientific endeavour. The interaction between criminal investigation, justice and science is a complex dynamic with its own unique set of challenges, but it offers one of the strongest safeguards in the Criminal Justice System against false allegation and wrongful conviction. Although the end user of forensic science in the Criminal Justice System is ultimately the courts – or indeed the jury – the vast majority of forensic science activity takes place much earlier in the criminal investigation process.

From the initial report or allegation of a crime, forensic practitioners are engaged in gathering evidence and establishing whether a crime has been committed. Throughout an investigation, forensic science will be used to establish the sequence of events, validate the accounts of witnesses and victims, eliminate and identify potential suspects and provide the basis for a criminal charge. Once an individual has been charged with a criminal offence, the forensic practitioner will consider alternative scenarios, and will also be the subject of close scrutiny and challenge within our adversarial criminal justice system. There are, of course, a large number of crimes in which forensic science does not feature (such as minor theft). But crimes where there is a significant physical interaction between the suspect and the crime scene or victim can provide the greatest opportunity for forensic science to solve the crime, eliminate the innocent from investigations, and bring offenders to justice.

In cases involving serious violence, sexually-motivated crimes, and acquisitive crime such as burglary or vehicle crime, forensic science has made a long-standing and significant contribution. The introduction of forensic databases of fingerprints and DNA profiles has enhanced this contribution, allowing forensic science to play a significant role in identifying potential suspects where there are no investigative leads has a match rate of over 60% with DNA profiles obtained from samples taken from a crime scene or victim[1]. With a shift to cybercrime and the dramatic proliferation of digital devices, the relatively new area of digital forensics is now becoming an integral part of many investigations and prosecutions (see Chapter 7). However, the core forensic process of assessment, retrieval, analysis, interpretation and presentation of expert evidence is essentially the same for digital forensics as it is for traditional forensics. If there is one constant in the practice of forensic science, it is that it is changing and evolving in response to different challenges and opportunities. These are examined in more detail in three case studies in this chapter, which outline the different perspectives of commercial forensic service providers (see p29), academia (see p30) and policymakers (see p27).

CHALLENGES IN FORENSIC SCIENCE

Some branches of forensic science – such as the identification of illegal drugs or the classification of a firearm – are obligatory, and limited law enforcement activity could occur without them. Moreover, the information gathered from identifying illegal firearms and drugs has an important role in informing our understanding of this criminality, helping to frame legislation aimed at deterring or reducing crime and minimising its impact on society. The challenge for law enforcement is to ensure that forensic science is focused on those crimes and opportunities for detection that will provide a useful outcome, given the current climate of limited and reducing funding. As powerful as DNA profiling has become in its sensitivity and power to discriminate individuals, the major challenge today is to identify the DNA of the criminal against a background of DNA from the victim, or a range of other individuals who may have visited the location of the crime. If the DNA cannot be associated with a particular body fluid or cell type, or cannot be related to a particular activity, then the best DNA science in the world will have little relevance to the investigation of a crime by law enforcement agencies.

As well as providing a useful outcome for law enforcement, the challenge for forensic science practitioners is to produce results in minutes and hours, rather than days or weeks. The sooner an offender is identified and apprehended, the less opportunity they have to commit more crime; earlier intervention may also reduce future offending or divert individuals from a career of crime. The most recent advances in Automated Fingerprint Identification Systems (AFIS), rapid DNA profiling devices, drugs analysers and digital-device data-recovery kiosks provide the prospect of 'real-time forensics' that will change not only the forensic operating model but the policing and investigative models.

COMMERCIAL CONSIDERATIONS

The UK is the only country in the world to have introduced the commercial provision of forensic science. This can be traced back to April 1991, when two keys changes were made: the formation of the Forensic Science Service as an executive agency of the Home Office, combining the six Home Office Forensic Science Laboratories and a Home Office Central Research Establishment into one organisation; and the introduction of direct charging for forensic science services.

The advent of direct charging followed a period of crisis in the late 1980s where staff shortages and backlogs led to forensic examinations taking many months to complete. Prior to being given agency status, forensic science was funded on the basis of capitation i.e. the number of police officers or establishment. The move to direct charging was not to introduce a market, but to change the basis of funding so that police forces would be free to spend more on forensic science, allowing for capacity to increase.

So the commercialisation of forensic science was by accident rather than design, and the formation of a stable and sustainable commercial forensic provision is not an end in itself. While commercial companies will have an important role to play in forensic science delivery and improvement, there needs to be a clear purpose for the commercial

IF THERE IS ONE CONSTANT IN THE PRACTICE OF FORENSIC SCIENCE, IT IS THAT IT IS CHANGING AND EVOLVING IN RESPONSE TO DIFFERENT CHALLENGES AND OPPORTUNITIES.

provision of forensic science within a wider strategy. This is needed not only to manage risk, but to exploit the agility and access to innovation that is available from the private sector. However, the commercial relationships between police forces and commercial providers are not mature, and are based on transaction rather than partnership. This is the result of a procurement framework based on standardised products that do not allow for innovation or integration between public and private providers. To ensure a sustainable forensic science provision, it is important that commercial providers are viable and successful businesses: consequently, the commercial sector needs to have long-term clarity about the demand and capabilities required by the police service and Criminal Justice System in order to make investment decisions.

Real-time forensics will require close collaboration with commercial companies and relationships that are based on long-term partnerships. The current provider base will need to change fundamentally, reducing its reliance on conventional DNA profiling as a revenue stream in favour of a different business model based on service integration and on-site or remote testing and analysis. This change will need to be managed with the commercial sector as partners, but with a clearly-defined role and purpose that allows for major structural change within forensic science to realise the benefits and reduce costs.

EXPERT EVIDENCE

There has been keen interest from senior judges in the progress of forensic science, not least from the Lord Chief Justice; the admissibility of expert evidence was the subject of a very thorough and detailed review by the Law Commission[2]. The judiciary and forensic practitioners have a common purpose in delivering accurate and reliable expert evidence, with quality being non-negotiable. The establishment of an independent Forensic Science Regulator in the UK – the first in the world – is a

THE JUDICIARY AND FORENSIC PRACTITIONERS HAVE A COMMON PURPOSE IN DELIVERING ACCURATE AND RELIABLE EXPERT EVIDENCE, WITH QUALITY BEING NON-NEGOTIABLE.

strong signal of commitment to ensure the accuracy and reliability of expert forensic evidence. The Forensic Science Regulator has developed the Codes of Practice and Conduct[3], which provide the quality-standards framework for the delivery of forensic services to the Criminal Justice System – these apply to all individuals and organisations who undertake forensic examinations. The regulatory framework is important because it puts responsibilities on organisations as well as individuals. This is a significant and far-reaching change because it introduces accountability on senior leaders (Directors and Chief Officers) to ensure that accurate and reliable expert forensic evidence is put before the courts.

Alongside the development of the forensic regulatory framework, the criminal justice system has defined the duty of an expert witness and how expert evidence should be provided to the courts as set out in Rule 19 of the Criminal Procedure Rules[3]. An expert must help the court to achieve the overriding objective of justice by giving an opinion that is objective and unbiased. Justice includes acquitting the innocent and convicting the guilty: it is not the role of forensic staff to support the prosecution or the defence. Rule 19 has been further supported and enhanced by the Criminal Practice Direction[5], published in July 2014, which incorporates many of the recommendations of the Law Commission review on the admissibility of expert evidence in criminal proceedings.

While considerable thought and effort has gone into developing the forensic regulatory framework and the provision of expert evidence, these two important frameworks for ensuring the accuracy and reliability of forensic evidence have been developed in isolation of each other. There needs to be some acknowledgement within the Criminal Procedure Rules of the forensic regulatory framework; of organisational responsibilities; and of the need to achieve accreditation. Accreditation demonstrates a level of control, commitment and rigour in the provision of forensic expert evidence. Organisations cannot give evidence, but they do provide the framework within which expert evidence is delivered in most areas of forensic science.

COMMUNICATING FORENSIC RESULTS

Despite these frameworks, there still remains the challenge of evaluating and communicating the significance of forensic results, particularly where they are the product of statistical or probabilistic interpretation (see Chapter 4 case study p50). Over the past twenty years, much thought has been given to the evaluation of forensic evidence, drawing on the Bayesian inference (see Annexe 1) and seeking to ensure that expert opinion is robust, logical, objective and based on sound reasoning. The introduction of a probabilistic approach to DNA expert evidence, using match probabilities such as '1 in a billion', has caused some difficulty in the courts. In a landmark ruling in 1997 in Regina v Doheny & Adams the judge stated[6]:

"… to introduce Bayes' Theorem, or any similar method, into a criminal trial plunges the jury into inappropriate and unnecessary realms of theory and complexity deflecting them from their proper task"

Forensic practitioners and lawyers have a long way to go to reach a common understanding and a unified approach to the evaluation of forensic evidence. After all, what does the average jury member understand by the difference between 1 in a million and 1 in a billion?

The UK was at the forefront of developing a framework for evaluative reporting of the results of forensic examination, analysis and interpretation. This is based on the principles of balance, logic, robustness and transparency, as set out in the recently published European Network of Forensic Science Institutes (ENFSI) Guideline for Evaluative Reporting in Forensic Science[7]. This framework is based on identifying at least two competing propositions, representing the prosecution and defence positions. The forensic practitioner evaluates the forensic results at source and activity level.

- **Source level** would apply to the results of DNA profiling or a fingerprint comparison, and relate to propositions such as the claim that a person was not inside a premises. The competing propositions could be that "the bloodstain came

CASE STUDY

THE POLICYMAKER'S PERSPECTIVE

AMANDA COOPER, *SRO Digital Policing and Science, Home Office*

The Home Office is responsible for policymaking and legislation for the use of forensic science in law enforcement. We advise ministers of the risks and opportunities in this area, as well as running the national DNA and fingerprint databases. In that context, we see our role as setting the strategic direction rather than influencing operational policing directly.

For example, we support and encourage police to make the most of the opportunities offered by the Police Innovation Fund (PIF). Worth £70 million for 2015/16, the PIF is designed to incentivise collaboration, support improved police ICT and digital working and enable Police and Crime Commissioners to invest in other innovative delivery approaches with the potential to improve policing and deliver further efficiency in the future.

All bids are subject to a robust and objective assessment against the published criteria. This involves an initial panel assessment, followed by further consideration by a senior oversight group that provides advice to ministers. All of the successful bids have the potential to improve efficiency and contribute to improved value for money for the taxpayer.

For example, Lancashire Constabulary was successful in its bid for innovation funding to pilot RapidHIT® DNA profiling. This technology can deliver a DNA profile within 2 hours, which is then speculatively searched against the National DNA Database. If a match is obtained, it is verified by conventional DNA profiling of a duplicate sample.

Lancashire Constabulary is currently in year 2 of their pilot and is using it to process blood stains from crime scenes in cases such as burglary and vehicle crime. There have been a number of successful outcomes using this technology. For example, RapidHIT® played a pivotal role in the case of a recent residential burglary. The resident had been asleep but was awoken by the sound of breaking glass. A kitchen window and an internal glass door had been broken and computer equipment and phones stolen, along with the keys to the family car. When a crime scene investigator (CSI) attended the scene they identified that the offender had cut themselves and left blood on the internal door.

The blood from the internal door was deemed suitable for processing using RapidHIT® and a result was obtained from a speculative search of the DNA Database within a few hours. The search matched with a suspect already being held in custody, but who was denying any involvement in the crime. Once the potential forensic evidence obtained from RapidHIT® was put to the suspect he admitted to the burglary. As a result of this, the police were able to recover the majority of the stolen property and return it to the rightful owner.

The rapid result enabled the offender to be charged and remanded to court the next day, therefore reducing the officer's investigative time and costs, and avoiding the costs of any bail. Overall, the time from a CSI attending the scene to charging an individual was approximately 48 hours.

Alongside ensuring that a new piece of technology can be effectively used in the investigation of crimes, the role for policy is to ensure the wider consideration of areas such as legislation, market impact, regulation, and Criminal Justice System (CJS) efficiency and reforms. All of these areas need appropriate handling, and any changes to methodologies across the supply chain of investigations must be considered in the context of systems thinking.

Addressing how aspects of forensic science in the CJS are governed and organised is a core element of current work on the Home Office Forensic Strategy, particularly the regulation of activities, the early support on experimentation and the introduction of new technologies and applications. Achieving this in a way that keeps pace with technology development and with changing crime types and crime modus operandi is a key objective.

from the defendant" or "the blood stain came from an unrelated individual".

- At **activity level,** the forensic practitioner addresses more complex interpretative issues about the actions of individuals in committing or being the victim of a crime. This will require knowledge and understanding of persistence, transfer and background levels of forensic contact traces such as body fluids or gun shot residues. This knowledge can be used to evaluate the evidence, by assigning probabilities to the findings (given each of the competing propositions) to produce a Likelihood Ratio. This is of greater value to the courts, but the forensic practitioner needs to have a full understanding of the context of the case, and what is alleged by the parties involved. To bring some consistency to the evaluation and expression of the value or weight of the forensic evidence, forensic experts can use a verbal scale that is based on a Likelihood Ratios and ranges from "no support", to "moderate support" through to "extremely strong support" for one proposition over the alternative. It will take some time for the courts to fully embrace this approach but in my experience there is wide acceptance and support for this across the forensic profession.

CONCLUSION

Forensic science constitutes a relatively small part of the overall scientific effort in the UK. As such, it has never sustained a substantial academic research base, instead relying on innovation in other fields (e.g. medical, pharmaceutical or semiconductor sectors) and then adopting new technologies as they emerge. However, this situation has reached a low point in the last five years, with a small and fragmented research base in forensic science that does not allow for the effective development and implementation of large-scale innovation and the application of new science[8]. There is no central government organisation that has a track record in delivering innovation in forensic science and expert evidence to the Criminal Justice System.

Given the range of scientific and technical developments in other fields, the focus for innovation in forensic science should be to take advantage of science and technology that already exists or to develop science that is well advanced (see Chapters 16 and 17). What is lacking is an organisation or structure that will translate this to forensic science and bring about the transformational change in operational and business models that is needed to deliver significant improvements.

There have been major technical advances in fingerprint search algorithms, next-generation sequencing, facial identification and digital forensics. To harness and coordinate research and development of these technologies, and to develop the real-time forensics capability, there needs to be an academic effort that draws together and coordinates universities and research organisations. We could also look to international collaboration: for example, the EU 2020 Horizon programme offers the opportunity to work with European forensic agencies.

For policymakers in government, the goal must be to come forward with a coherent strategy – or at least a strategic framework – for the development of forensic science in the UK, recognising all of its complexities and challenges. Central to this is the next generation of science and technology that will deliver rapid results and offer a wealth of information about criminals from the contact traces they leave on the victim or at the crime scene. This will also bring to the fore the importance of ethical and human rights considerations to the forensic arena (see Chapter 9 case study p100). The growth of cybercrime will also see radical changes in the role of forensic science and the need to develop new tools and technologies to apply the traditional forensic process to the virtual environment (see Chapter 7).

The common theme for policymakers who are developing a strategy for forensic science is the need for a consistent and corporate approach to delivery, development and governance across the forensic science sector. This does not necessarily mean a single organisation, but it does argue strongly for a means of engaging all of the partners within a governance and strategic framework that allows for the delivery and development of forensic science in a way that sustains the current capability, improves performance and knowledge sharing, and reduces cost. This will require a much greater degree of government coordination and collaboration between professions to deliver stability, innovation and change. The benefits are substantial and achievable – but the risks of failure, resulting in the degradation of forensic capability in England and Wales, are equally substantial and will be much more costly.

CASE STUDY

THE COMMERCIAL PROVIDERS' PERSPECTIVE

ROGER ROBSON, *Managing Director of Forensic Access*

It is difficult to accurately determine the revenue generated by the UK commercial forensic services industry. As awareness of the relevance of forensic skills in other industries increases, and technology develops, there is undoubtedly a broader range of customers. This might be expected to result in an increasingly buoyant UK commercial forensic market.

In some areas that is certainly the case. However, the largest influence on the market is inevitably exerted by its largest customer: the police service. Following the closure of the Forensic Science Service in 2012, the police rapidly accelerated its in-sourced forensics capability and reduced its out-sourced capability[1], and it seems likely that this trend will continue.

This decision, together with a reduction in recorded crime and further cuts in forensic spending, has contributed to an increasingly fragile commercial market. In 2013, this was recognised as a significant risk by the House of Commons Science & Technology Committee[2], and in my view nothing has happened to change this since then. While venture capitalists consider their options as the UK commercial market continues to decline, those remaining companies in the UK market are now chasing overseas business to remain profitable. Indeed, the Science and Technology Committee[2] and commercial forensic-service providers are asking questions about whether the UK market will survive.

The reduction in market size[2] has been accompanied by a shift in emphasis between different forensic disciplines. Traditional areas such fires, firearms and trace evidence (such as paint, glass and textile fibres) have dramatically decreased in favour of DNA and fingerprints, and the exponential growth of digital forensics. Consequently, not only is the market much less attractive to potential investors, but it may be more difficult to put together the elegant scientific investigation strategies that helped to solve some of the UK's most high profile cases. It also raises significant concerns about a growth of unsolved cases in the future.

There are also growing questions about how much responsibility the police should have for providing independent, unbiased and objective scientific evidence. The US National Academy of Sciences' report 'Strengthening Forensic Science in the United States: A Path Forward'[3] recognised this as a problem back in 2009. As I write this case study, the UK government is currently drawing up a much-needed strategy for forensic science provision over the next 5 years.

Meanwhile, the profession remains determined to overcome the current difficulties. The financial cuts have prompted a sense of urgency for research and implementation of new technologies. It remains extremely difficult to get funding for basic research into forensic science projects, but this has encouraged collaboration between commercial providers, industrial and academic partners. Apart from improving services through competition, the commercial providers have also formed associations such as the Association of Forensic Science Providers and now work in unison on certain projects.

Markets inevitably change over time, with provision of services dictated largely by customer demands. Commercial providers have to respond increasingly quickly to meet the changing trends in crime and counteract new tools used by the criminal fraternity. At a time when we have so much new technology to bring to forensic science, we need to remember the importance of a holistic approach that helps to ensure that we use the right techniques at the right time in the right sequence to ensure reliability, robustness and value for money from forensics. If these are lost, it would damage our Criminal Justice System and public confidence in it.

CASE STUDY

FORENSIC SCIENCE IN HIGHER EDUCATION

GERALDINE FAHY, *University of Kent*

The Quality Assurance Agency for Higher Education (QAA) defines forensic science as "the application of science to serve the purposes of the law"[1]. Rapid changes in forensic science – stemming from policy responses, increased commercialisation and the advancement of scientific techniques[2] – have led to an increase in undergraduate and graduate courses in forensic science at UK universities. But these courses suffer from a mismatch between what is taught and what the industry actually requires, which urgently needs to be addressed. Given that tomorrow's forensic scientists are those we train today, it is paramount that we get these academic courses right.

Universities are businesses, and often use a degree in forensic science as a selling point to help feed the constant demand to increase student numbers. Courses with a 'forensic' prefix appear more attractive and are often easier to market than chemistry or biology courses. At undergraduate level, these courses offer an overview of a wide range of laboratory and field techniques such as microscopy, analytical chemistry, DNA analysis, ballistics, fire and explosives, trace evidence, incident investigation and expert witness training. Some undergraduate courses, and many postgraduate courses, also provide an opportunity to learn more specialised disciplines such as forensic anthropology, archaeology, botany, entomology, odontology, podiatry, digital forensics, and so on.

Yet there are currently no requirements for both A-level biology and chemistry for the majority of UK forensic science undergraduate courses. Consequently, a large amount of the first year at university is spent training students in basic laboratory skills. QAA benchmark standards for forensic science education at undergraduate and graduate levels essentially consist of two groups: generic standards and area-specific standards[3]. The problem is that myriad disciplines can combine with the term 'forensic', making it extremely difficult to teach 'forensic science' in a university setting. In reality, there is no single subject called 'forensic science', and attempting to educate students under this umbrella term produces a lot of people with overview knowledge of different subjects, but with insufficient detailed practical experience in any of them.

For example, the only career path that utilises the majority of focus areas covered in an undergraduate forensic science course is that of a Scene of Crime Officer (SOCO). However, even this job requires further training that is specific to the police force you work for, and in some cases a degree may not be necessary to get a SOCO position. As a result, most universities try to ensure that their graduates have learned transferable skills that increase their chances of gaining employment, often outside forensic science.

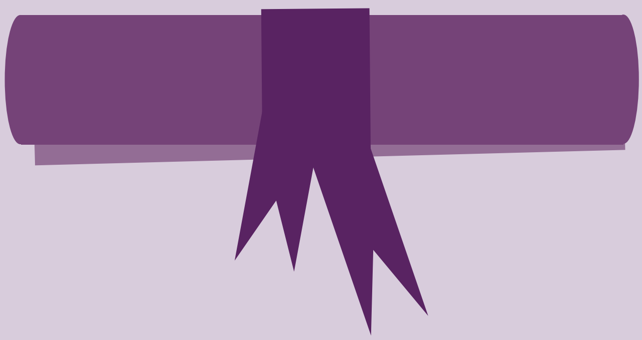
The rapid rise in forensic science undergraduate courses across the UK means that increased learning and teaching quality is vital, particularly at a time when so much attention is paid to accountability in teaching across UK universities[3]. Courses already need to be accredited by The Chartered Society of Forensic Sciences (CSFS), using standards that cover the main aspects of incident investigation and digital forensics[4]. However, the applicability of these standards and their correspondence with the QAA forensic science benchmark criteria are not always clear-cut. For example, while digital forensics is an area that has grown rapidly in recent years, and is itself an area of accreditation under the CSFS, it is only touched upon briefly in the QAA guidelines and remains a small part of most general forensic science undergraduate

COURSES SUFFER FROM A MISMATCH BETWEEN WHAT IS TAUGHT AND WHAT THE INDUSTRY ACTUALLY REQUIRES, WHICH URGENTLY NEEDS TO BE ADDRESSED. GIVEN THAT TOMORROW'S FORENSIC SCIENTISTS ARE THOSE WE TRAIN TODAY, IT IS PARAMOUNT THAT WE GET THESE ACADEMIC COURSES RIGHT.

courses. That makes it virtually impossible for an undergraduate student on a forensic science course to fully grasp this technologically complex sub-discipline without completing a specific digital forensics course.

At the heart of the problem with forensic science courses is a distinct lack of understanding between educators and course developers, and the forensic science industry. While more and more universities and programme convenors have links to industry, and ask for input towards course design, many develop courses based on programme outlines of similar courses in other universities, or using the QAA Forensic Science benchmark standards, none of which address real-life needs of forensic science providers. Additionally, resources and course learning outcomes required by universities can sometimes limit the amount of practical training that undergraduates receive. The ethos of forensic science is that no two scenes or incidents are the same and should be viewed without preconception. However, many forensic science role-play activities in universities concern standard 'common' scenes and incidents.

There are two ways forward. Firstly, if the content of forensic science undergraduate courses remains the same then a year in professional practice must be included as a standard component. However, given the distinct lack of job opportunities (even unpaid) and the associated high cost to either a student or a university, this is unlikely to be feasible. The second option is to do away with courses with the generic title 'forensic science' and focus more on subject-specific forensics at undergraduate level: forensic DNA analysis, forensic anthropology, forensic toxicology, and so on. Retaining the 'forensic' prefix should ensure that courses remain attractive, but offer a much greater depth of training and experience.



ASSURANCE – STANDARDS, VALIDATION AND ACCREDITATION

JOSEPHINE BUNCH, *National Physical Laboratory*

Quality assurance (QA) demonstrates that methods are fit for purpose before they are implemented, and ensures that they remain so during use. This is underpinned by an increasingly well-defined quality system, overseen by the Forensic Science Regulator (FSR). Additional confidence could be realised by awarding statutory powers to the FSR, as well as implementing further regulation to assure the skills of practitioners and providers.

Quality assurance (QA) refers to the range of practices employed to ensure that measurements and evidence are reliable, including internal and external quality control. QA demonstrates that analytical methods are fit for purpose before they are implemented – this involves an assessment of the equipment, standard operating procedures and the provision of trained staff who make judgements about their findings. QA also provides ongoing evidence that the methods remain fit for purpose.

For all laboratory-based methods, assurance procedures should be based on a system of standards, validation and accreditation. Where required, measurement traceability ensures that all steps in a procedure can be queried and validated by reference to documented results, calibrations and standards, through an unbroken chain of comparisons that all have stated measurement uncertainties. Forensic science laboratories or providers have a significant role in providing reliable and credible evidence that may be presented as part of a criminal investigation or a trial.

Forensic science providers may be private companies, government agencies, public organisations, academic research departments and law enforcement agencies, based in the UK or internationally. The majority of expert witnesses for forensic science are engaged by the police at the investigative stage of a criminal case. However guidance from the Crown Prosecution Service (CPS) also provides prosecutors with practical guidelines on issues relating to the selection, instruction and use of experts. Recent updates to the criminal justice procedure rules provide guidance around the validation of methods used by witnesses[1].

The importance of quality assurance procedures in forensic science is now well recognised, and confidence in forensic science and forensic science providers is underpinned via an increasingly well-defined quality system, overseen by the Forensic Science Regulator (FSR). Forensic quality standards in the UK comprise two international standards (ISO17025 for accreditation of laboratory activities[2] and ISO17020 for scene of crime analysis[3]) and the FSR Codes of Practice and Conduct, which detail the requirements of forensic service providers at organisational, technical and practitioner levels. Expert witnesses are bound by the Criminal Procedure Rules and Criminal Practice Directions[4], which work alongside the FSR Codes of Practice and Conduct to increase the overall assurance of forensic science quality. This framework provides a mechanism to objectively demonstrate the reliability, accuracy and limitations of methods, and the competence of the organisations supplying forensic science.

THE FORENSIC SCIENCE REGULATOR

The post of FSR was established in 2007 and is currently held by Dr Gillian Tully. The Regulator is a public appointee, sponsored by the Home Office, who ensures that the provision of forensic science services across the Criminal Justice System (CJS) is subject to an appropriate regime of scientific quality standards. The

Regulator has jurisdiction throughout England and Wales; the Scottish and Northern Irish authorities follow the Regulator's standards on a voluntary basis[5]. The Regulator does not have statutory powers to enforce compliance, and the government has undertaken a consultation on whether this should be the case[6].

The Regulator's priorities and aims[5] are to see that forensic science services are delivered to appropriate standards and that they are tailored to meet the needs of the CJS. To achieve this, the FSR recommends certain aspects of quality and working practice, typically by requiring providers to work in accordance with internationally recognised quality standards. Forensic service providers are then subject to independent assessments to ensure that these requirements are met. The FSR collaborates with the authorities in Scotland and Northern Ireland to achieve UK-wide quality standards. An important role of the FSR is to represent the UK in European and international quality initiatives. The Forensic Science Advisory Council (FSAC)[7] advises and supports the regulator, giving advice on many issues, including monitoring compliance with laboratory quality standards, standards relating to national databases, and validation of new technologies.

The Regulator requires that forensic science providers (FSPs), whether in the private sector or within policing, academia or public sector, operate under accreditation to a suitable international standard; and that their laboratory activities comply with the Regulator's Codes of Practice and Conduct by October 2017. The 'Codes of Practice and Conduct for forensic science providers and practitioners in the Criminal Justice System'[8] outlines the quality requirements for providers of forensic science services into the CJS. It is a firm requirement within the codes that all providers of accredited services shall be compliant with ISO/IEC 17025:2005 (ref. 2), and for scene work to ISO/IEC 17020:2012 (ref. 3). However, accreditation rules are not consistent across all areas of forensic science. Some disciplines have stand-alone codes of practice, and pathologists, for example, are regulated through a different system.

Accreditation is also approached on a voluntary basis with respect to EU regulations[9]. The EU Framework Decision on the accreditation of forensic service providers carrying out laboratory activities mandated that FSPs hold ISO 17025 accreditation with respect to all DNA profiling and fingerprint enhancement work. The UK opted out of these EU criminal justice measures, removing the legal obligation to comply with the ISO standards. However, national policing leads have independently agreed that all police facilities undertaking these services would, in fact, comply with the stated requirements on a voluntary basis.

CONFIDENCE IN FORENSIC SCIENCE AND FORENSIC SCIENCE PROVIDERS IS UNDERPINNED VIA AN INCREASINGLY WELL-DEFINED QUALITY SYSTEM.

ISO STANDARDS AND FORENSIC SCIENCE

ISO is the world's largest developer of voluntary international standards, providing specifications for products, services and good practice, with the aim of helping to make industry more efficient and effective[10]. ISO standards are developed through an international consensus and can be can be normative (specifying what must be done e.g. a particular test method) or informative (providing information). Standards help to ensure that technology and methods are developed and made available for use by practitioners in an open and robust manner.

The ISO/IEC 17025:2005 standard[2] specifies general requirements for the competence of testing and calibration laboratories. The ISO accreditation document covers the provision of opinions and interpretation of evidence, while the UK Accreditation Service (UKAS) provides additional guidance on the assessment of evidence[11].

ISO/IEC 17025 is most easily applied to objective tests: for example, the determination of drug concentration or blood alcohol level. In these cases, the measurement method employed is documented and validated such that all appropriately trained staff will obtain results with the same stated uncertainties within defined, numerical limits. Equipment used to make the measurements must be maintained and calibrated. Visual inspection, qualitative

CASE STUDY

UKAS ACCREDITATION: PROVIDING CONFIDENCE IN FORENSIC SCIENCE

MALCOLM HYND, *External Affairs Manager, UK Accreditation Service*

Forensic science plays an essential role in the effectiveness of the Criminal Justice System (CJS). To sustain confidence in that forensic information, it is important to consider how it is produced: not only in terms of its scientific accuracy, but also to show that samples are handled appropriately to avoid contamination, and to demonstrate the impartiality and integrity of the staff undertaking the work. This assessment of organisations offering forensic science services is known as accreditation.

However, the term 'forensic science' covers a multitude of different fields, ranging from the conventional analytical techniques used in the identification of drugs through to more interpretive examinations of handwriting or blood pattern analysis. It also covers new and constantly developing areas such as digital forensics and cybercrime. The challenge for those involved in accreditation is to define the expectations that must be met by such diverse and evolving areas, while offering the same confidence in the delivered outcome.

As the UK's sole national accreditation body, the UK Accreditation Service (UKAS) visits organisations that undertake forensic work to assess and evaluate their compliance against the internationally recognised standards ISO/SO/IEC 17025 for laboratories[1], and ISO/IEC 17020 for scene of crime[2]. These standards include requirements to implement an appropriate management system, including policies and procedures for internal auditing, control of documents, management of complaints and the definition of key roles and responsibilities. They also include technical requirements relating to the competence of staff, the validity of the techniques used, the suitability of the equipment and the appropriateness of the environment where examinations are performed.

These standards are not used exclusively for forensic science, so UKAS uses an additional guidance document[3] (ILAC G19) that details further expectations in the forensics area. If the organisation demonstrates that it meets all the relevant criteria then it will be granted accreditation for specific activities. However, accreditation is an on-going process that requires annual surveillance visits and a full reassessment every four years.

UKAS is a signatory to international mutual recognition agreements with accreditation bodies in other countries, so there is assurance that the forensic science services delivered by UK-accredited organisations would also be recognised overseas. In the same way, accreditation bodies in other economies use the same standards and guidance documents, so the results provided by laboratories accredited by them can be equally well-trusted here. This becomes ever more important as crime, particularly cybercrime, transcends international boundaries.

Indeed, the fast-moving developments in cybercrime present particular challenges for forensic laboratories and accreditation. For the laboratories, data that can be stored anywhere in the world is increasingly difficult to identify and access, and ever more complex encryption methods need to be circumvented. Accreditation assessments similarly need to keep up with technological developments, and suitable technical expertise secured, to ensure that assessments can be carried out from a position of knowledge.

In the UK, a mixture of private and public sector organisations provide forensic science services. As such, the government appointed a Forensic Science Regulator (FSR) to ensure that all these services were subject to an appropriate regime of quality standards. The FSR has, through their Codes of Practice and Conduct[4], identified accreditation as a mechanism to demonstrate the application of appropriate quality standards and has defined clear expectations with respect to accreditation for all organisations providing forensic services to the Criminal Justice System. These expectations include deadlines for gaining accreditation against the core forensic disciplines, including body fluid recovery, fingerprint enhancement, digital forensics, fingerprint comparison, and crime scene examination.

Accreditation provides an effective framework for providers of forensic science services to develop and improve their systems – this results in greater consistency, both internally and with their peers. The ongoing assessment by UKAS provides independent confirmation of continued compliance, and has also promoted greater transparency by encouraging organisations to report any quality issues. This prompts demonstrable and appropriate actions to deliver further improvements in their services.

STANDARDS HELP TO ENSURE THAT TECHNOLOGY AND METHODS ARE DEVELOPED AND MADE AVAILABLE FOR USE BY PRACTITIONERS IN AN OPEN AND ROBUST MANNER.

examinations and computer simulations are included in the definition of an objective test[12]. However the standard may also be employed in more subjective analyses, such as the verification of practitioner skill in fingerprint or footwear mark comparison. These activities, while largely subjective in nature, can (with the right training and assessment) produce consistent outcomes between different forensic practitioners. Guidance on evaluative interpretation of scientific evidence is also in preparation by the FSR.

The FSR's supplementary information in the Codes of Practice and Conduct provides additional relevance and significantly extends the usefulness and scope of ISO standards for use in forensic sciences. Nonetheless, the standard covers many important aspects of assurance, including validating the method is fit for purpose; evaluating the qualifications, training and experience of the staff; maintenance and calibration of equipment; sampling practices; testing procedures; traceability of measurements; and accurate reporting. As such, it is clearly an important quality standard for many forensic assessments.

A traceable calibration is an unbroken chain of calibration back to a national measurement lab and the International System of Units (SI units) of measurement. Through reference to the internationally-agreed definition of an SI unit, traceable measurements establish confidence in measurement data by ensuring consistency of measurements. They also enable meaningful comparison with other instruments or measurement methods, and are essential requirements of quality assurance procedures for the highest-level assurance of methods within the ISO/IEC 17025:2005 standard.

While traceable calibration is important for a range of analytical methods (e.g. analysis of drugs, measurement of sample toxicity and DNA analysis), many forensic science activities rely on reference data produced internally to the forensic laboratory or within the forensic community. These may include comparison against reference samples, or determination of inherent physical properties, for example. The validation and traceability of data contained within these databases is of critical importance if they are to be used successfully by experts within a court of law in assessing the significance of forensic evidence. To this end, more could be done to promote open data policies, increase data transparency between organisations, and enable knowledge sharing. In promoting this activity, it is important to develop and enforce clear standards for the format of data within forensic databases, including definitions of measured quantities, declaration of measurement units, and standardisation of any required metadata (i.e. those data describing the conditions of measurement).

ISO/IEC17025:2005 requires that "testing laboratories shall have and apply procedures for estimating uncertainty of measurement" when carrying out analytical measurements. The UKAS publication M3003 (2012)[13] recognises "the present state of development and application of uncertainties in testing activities is not as comprehensive as in the calibration fields". However, it states that the "laboratory should use documented procedures for the evaluation, treatment and reporting of the uncertainty". Additional commentary on the uncertainty of measurement is provided within guidance from the FSR (Laboratory accreditation (FSR-G-201 Guidance: Validation (2014)[14]).

Assessing measurement uncertainty is an integral part of laboratory quality valuation because every measurement is subject to some uncertainty, which should be expressed as the quantified doubt about the result of a measurement. There are many possible sources of uncertainty, including the measuring instrument (e.g. bias, drift, noise), 'imported' uncertainties (e.g. calibration uncertainty, operator skill, sampling issues) and the laboratory environment (e.g. temperature and air pressure). Methods for evaluating uncertainty from individual components include uncertainty estimates using statistics (usually from repeated readings), and uncertainty estimates from any other information (e.g. from past experience of the measurements, from calibration certificates, manufacturer's specifications, from calculations or from published information).

When it is not possible to fully quantify measurement uncertainty, ISO17025 allows for the identification of sources of uncertainty, while requiring efforts to minimise these effects. The resulting limitations of measurement must then be disclosed to the customer; effective communication within this matter is crucial to promote good public understanding of the probabilities and uncertainties of forensic measurement, and how the presented measurements translate into a reliable verdict when considered with all other evidence.

The majority of international accreditation bodies have now adopted ISO/IEC 17025 as the basis for accrediting testing and calibration laboratories. This international adoption allows countries to establish agreements among themselves. These Mutual Recognition Arrangements (MRAs) are crucial in enabling test data to be accepted between these countries and vital to transnational working within an accredited framework. Of particular importance is a multi-lateral mutual recognition arrangement called the International Laboratory Accreditation Cooperation (ILAC) Arrangement. ILAC is the primary international authority on laboratory accreditation and has produced comprehensive guidelines for forensic science laboratories[15]. In recognition of the interdependence of accreditation and metrology, and a need to coordinate the actions of the Bureau International des Poids et Mesures (BIPM) and ILAC in tasks relating to national and international measurement infrastructure, the International Committee for Weights and Measures (CIPM) and ILAC signed a Memorandum of Understanding (MoU) in November 2001 (reaffirmed in 2012)[16]. A Joint CIPM/ILAC[17] Working Group consisting of BIPM and ILAC members was established in view of the CIPM-ILAC MoU.

ISO/IEC 17020:2012 (ref. 3), the international standard relating to crime scene examinations, should be read in conjunction with 'IAF/ILAC-A4:2004 Guidance on the Application of ISO/IEC 17020' (ref. 15) and 'EA-5/03 Guidance for the Implementation of ISO/IEC 17020 in the field of crime scene investigation'[18]. Several other ISO documents contain relevant guidance for aspects of digital forensics, such as ISO/IEC 27037:2012 (ref. 19), which provides guidelines for specific activities in the identification, collection, acquisition and preservation of potential digital evidence. It should be noted that this is only a guidance document and not an accreditation standard. A Digital Forensics Validation Guidance document is in preparation by the FSR, due for release this year.

VALIDATION AND REQUIREMENTS OF THE CROWN PROSECUTION SERVICE

The FSR requires FSPs to ensure that all methods routinely employed within the Criminal Justice System, whether for intelligence or evidential use, will be validated prior to each use on live casework material. Validation is a critical aspect of quality assurance, and is defined by the FSR as "confirmation, through the assessment of existing objective evidence or through experiment that a method, process or device is fit (or remains fit) for the specific purpose intended. The provider must demonstrate the reliability of the procedure in-house against any documented performance characteristics of that procedure". Establishing the intended use and limitations of a developed method are important aspects of validation. A validation exercise should establish key performance indicators such as accuracy, precision and limitation (see Figure 1).

The responsibility for validation rests with the forensic science provider, not the FSR, and will be reviewed as part of any accreditation assessment by the accreditation body, normally UKAS[24] (see case study p34). The Regulator should only be informed of the intention to implement a new method if the introduction of a scientific method has not previously been employed within forensic science in the UK, or where analysis of the impact to the Criminal Justice System suggests a significant change in capabilities.

Additional quality assurance is provided by the CPS, which requires compliance with the FSR's Codes of Practice and with international standards. The CPS has provided a paper outlining the core foundation principles that must inform any providers of forensic science analysis for use in the Criminal Justice System[25].

The five key requirements are:

1. To comply with the Codes of Conduct and Practice set down by the independent Forensic Science Regulator
2. To ensure that Quality Standards and Assurance processes are applied, which are nationally consistent and compliant with appropriate ISO standards, UKAS accreditation, EU directives and clear development and validation processes
3. To provide clear communication and interpretation of scientific processes, procedures, strengths, weaknesses and meaning
4. To engage with Streamlined Forensic Reporting (SFR) process associated with proportionate prosecution requirements
5. To be fully aware and compliant with Criminal Procedure and Investigations Act Disclosure and Expert Witness obligations, including the disclosure of details or algorithms and statistical analysis.

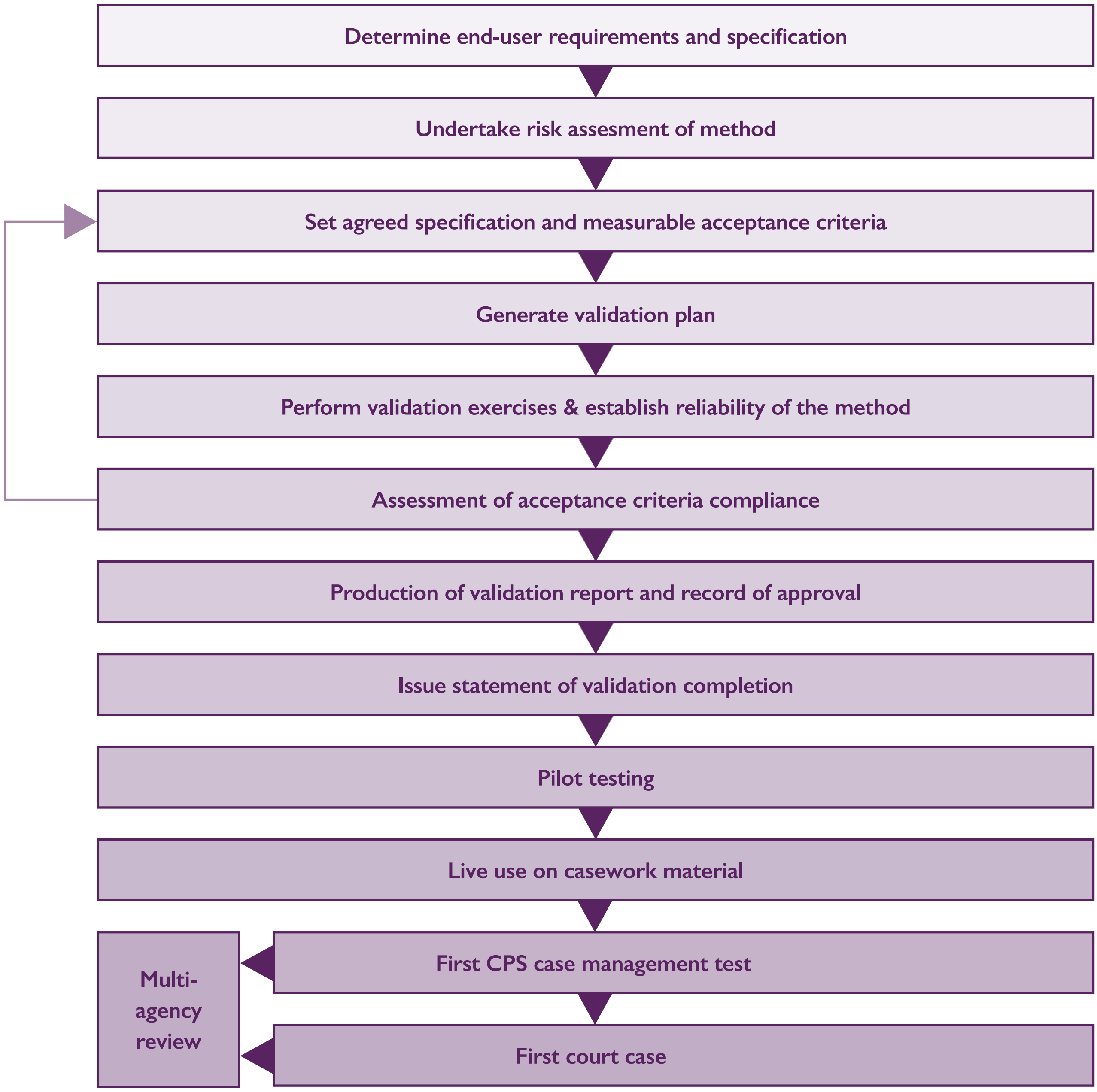
ASSURANCE IN R&D AND INNOVATION IN FORENSIC SCIENCE

Future progress in academic and commercial research, and the development of new methods for forensic science applications, will require new standards to be developed. It is the FSR's role to assist with these activities. The typical development of new ISO standards involves:

1. Research leading to peer reviewed publication
2. Experimental validation via international inter-laboratory studies to establish (i) Repeatability of measurements made by the same method, by the same laboratory, by the same operator, on the same equipment within a short period using identical test material and (ii) Reproducibility of measurements made by the same method, but carried out by different laboratories, different operators and different equipment, using identical test material. Inter-laboratory studies are used to develop a protocol, which forms the basis of the new standard
3. Submission of new work item proposal to ISO
4. Various ballots in ISO, development of an international consensus and progression of draft to published standard

Accreditation of new methodologies can be a long and expensive process. The

Figure 1: Outline of the validation process for forensic science methods



2011 Home Office 'Report on Research and Development in Forensic Science'[20] identified the forensic research landscape as fragmented, and recommended increases in linkage and communication between forensics R&D stakeholders, in order to drive forward innovation more effectively. The Forensic Science Special Interest Group (SiG) at Innovate UK has identified a series of sector challenges, and has set up a Forensic Science UK Innovation Database[21] to encourage "collaboration to overcome these challenges by bringing together those with potential solutions and those who have identified the challenges". In setting up formal collaborative activity, the SiG is helping address traditional innovation challenges such as ownership of intellectual property.

Changes to existing governance processes in forensic service procurement might also help to standardise the approaches undertaken by different FSPs, and bring new techniques to market. The Forensic Market Management

Team (FMMT) within the Home Office runs the National Forensics Framework, which allows the police to purchase forensic services from private sector suppliers[22]. Forensic services are categorised into 13 product types (e.g. DNA, drugs, footwear, and toxicology) and sold with details on the precise nature and level of service required, timescales for delivery, and the quality and reporting standards to be met. The introduction of the FMMT procurement process resulted in substantial reductions in the price of services[23].

In addition, due to the non-statutory nature of the Regulator, in-house forensic services within individual police services do not have to follow the same procurement framework as private-sector FSPs. Private sector FSPs have raised a concern that this may result in some in-house laboratories being able to offer cheaper services by delaying the significant investments required to meet and maintain the relevant ISO standards, as it is seen as a cost burden to comply[22]. If found to be the case, the net result would be market distortion unfavourable to the private-sector FSPs, who would have to squeeze margins to compete on price terms, resulting in a loss of profit available to channel back into research and development.

Research and development is a necessarily risky endeavour; the presence of large fixed costs around accreditation of new technologies can therefore be a barrier to innovation. Forensic science has parallels to other sectors, such as aerospace and pharmaceutical development, where simple deregulation is not an option due to safety concerns. In an increasingly litigious and risk-averse society, the regulations in these areas tend to become more stringent. At the same time, this must be balanced by need to drive technological change for better social outcomes in these sectors, which requires streamlining of regulation. In forensic science, it is the goal of ensuring that justice is served, rather than maintaining physical safety, that drives the need for accurate and fail-safe process.

Regardless, there may be significant opportunities for the forensic science community in looking to other sectors that have similar high-cost-of-failure markets, to analyse their approach to quality and assurance in order to share best practice. For instance, accreditation need not necessarily be a binary factor: one could envisage an operating spectrum of assurance with varying degrees of conformity depending on the requirements of the end user (the CJS at one end, and perhaps consumer protection at the other).

CONCLUSION

The five requirements from the CPS, together with the FSR's Codes of Practice and insistence that providers adhere to internationally recognised standards, form the basis of an increasingly well-developed forensic quality system in the UK. International mutual recognition agreements between international bodies of accreditation and measurement committees help to ensure that this quality infrastructure is fit for purpose on a global scale.

The forensics landscape is clearly challenging from the perspective of assurance, requiring guidance for objective and subjective assessments, delivered to wide ranging end-users. An additional layer of confidence in this framework will likely be realised through the award of statutory powers to the FSR, essential if the FSR is to effectively force providers to comply with expected quality standards.

Further regulation is also required to improve the assurance of the quality of skills of practitioners and providers. The UK and Ireland Association of Forensic Toxicologists (UKIAFT) recommends roles and responsibilities that should be covered by personnel within a forensic science laboratory, and provides some suggested guideline about the qualifications and experience they would expect for staff at different levels, but minimum requirements should also be demanded by the FSR. Several organisations offer staff development opportunities: a series of qualifications, as well as other continuing professional development (CPD) opportunities, are provided regularly by The Chartered Society of Forensic Sciences, and The Forensic Science Society has recently developed a number of Certificates of Competence[26].

These provide a mechanism by which individuals can demonstrate their competency, but to date these have not been widely adopted or required by the regulator. Transparent recommendation from the FSR of the minimum expected formal qualifications, training and experience of staff within FSPs, and accredited programmes of training and development, will help further improve the quality of forensic sciences in the UK.

COGNITIVE AND HUMAN FACTORS

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Even with major advances in forensic science, the human examiner will continue to play an important role in most forensic decision-making. Forensic work often involves interpretation and subjectivity, and hence cognitive and human factors are important to ensure high-quality forensic decisions. To maximise objectivity and decision quality, forensic examiners should receive cognitive bias training and should evaluate only contextually relevant information.

The human examiner plays a critical role in many forensic domains (often it is the human examiner who is the 'instrument of analysis'). Forensic work often involves human perception, interpretation, evaluation, judgment and decision-making. Therefore forensic work is shaped by, and depends on, cognitive and human factors. These underpin most aspects of forensic work: from the initial collection and evaluation of data (e.g. at the crime scene, in determining where and what to look for, and whether the data is of sufficient value to send to the laboratory); throughout the work in the forensic laboratory, where evidence is interpreted and conclusions are reached; to the presentation in court and to other end users who are the customers of forensic work (e.g. how they understand and integrate the information). Maximising the use and benefit of forensic science, while minimising cognitive bias within forensic work, requires educating practitioners and implementing cognitive best practices.

HUMAN COGNITION

The cognitive system underpins much of what we do. How information is perceived, mentally represented, compared, evaluated, and how we reach decisions are just a few of the cognitive operations carried out in the brain. One of the fundamentals in human cognition is that our brain and cognitive system has limited resources. In simple terms, the amount of information input for processing exceeds the computational recourses of the brain.

The brain and cognitive system have adapted to this challenge by developing a variety of mechanisms, including:

- Selective attention is a fundamental cognitive mechanism that allows the brain to focus on some information while ignoring the rest
- Chunking information together reduces the cognitive load by changing how information is encoded and represented
- The brain is active in processing information: it is not only driven by the data, but uses conceptually-driven information processing. In cognitive terms, 'bottom up' information (what comes in from the world) is driven by 'top down' information (what is already in the brain). Top-down information, such as past experience and expectations, governs what information is processed and how it is processed.

These, and many other cognitive processes[1,2,] enable the brain to function efficiently and effectively even though it has limited resources. The use of such cognitive processes is a characteristic of human intelligence and develops with experience and expertise.

The implications of how the brain processes information are far reaching. We do not 'see' the world as it is (naïve realism): instead, it is mediated by how the brain processes it, which is a function of complex cognitive architecture. Take, for example, Figure 1 – count how many 'F's are in the box (try it).

This illustrates that the human mind is not a camera: it does not passively process information, it uses past experiences and expectations to guide information processing. In other words, it is intelligent. As we learn more and have more experience – as we become experts – we develop, use and rely more and more on such processes[4] (e.g. selective

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Figure 1: Count how many 'F's are in the box above (please try before continuing). Most people see 3 or 4, some 5, but people rarely see all of the Fs: there are actually 6 of them. The reason that many people miss some of the Fs is because we are experts in reading. Our base-rate experience tells us (via our unconscious brain) that words such as 'of', 'the', and 'a' do not carry much meaning and weight, and therefore, based on our expectation, we tend to automatically ignore them[3].

attention, chunking information and reliance on top-down information). It is important to note that these processes occur without awareness: it is a cognitive bias, not an intentional bias.

Although such cognitive processes are effective and efficient, they also can lead us astray. By relying on shortcuts, such as using our expectations and past experiences to selectively attend to some information while ignoring the rest, we are cognitively biased[5]. These biases are widespread and have many forms[5], and only increase with expertise[4]: as we have more experience, we are more driven by top-down, conceptually-driven cognitive processes. These processes and biases are especially powerful when subjective decisions are involved or when the data is low quality, ambiguous, and difficult to determine (as is often the case in forensic evidence).

Another example of bias is base-rate expectation. When experience provides a clear expectation of the outcome, then that base-rate expectancy drives our conclusion, even in the face of contradictory data. If X-ray security screeners in airports do not encounter bombs, then they develop an expectation to not find bombs, and are therefore more likely not to find a bomb even when it is present in the X-ray. Similarly, when medical monitors in intensive care units (ICU) sound false alarms very often, then the medical staff are likely to ignore them[6]. The reason for these biases is that, with experience, the brain has picked up regularities in the information it receives and then uses them to guide future information processing. This is effective, but it biases how new information is processed.

FORENSIC SCIENCE

Forensic science consists of many different domains that utilise different types of evidence. However, in many forensic domains it is the human examiner that is central to the forensic work (this is true in the UK, the US, as well as anywhere else that forensic work is carried out). The main reason for this is that there are many subjective judgements that underpin forensic work.

During initial evidence gathering at the crime scene, the crime scene investigation (CSI) examiner is required to make many decisions, most of which are subjective. First, they need to decide where to look for evidence, and what kind of evidence they will look for. The CSI is guided by their experience and expectation. Second, as they look for evidence, they need to determine whether what they have found is actual data (a 'signal' such as blood) or just an artefact ('noise' such as dirt). Third, if what they find is actual data, then they need to subjectively assess the quality and quantity of the evidence to determine if there is sufficient information to warrant its collection and sending it to the forensic laboratory (e.g. shoe prints found at the crime scene can be of such low quality and quantity of information that they do not merit collection, documentation, and having the forensic laboratory examine them further). Such decisions are critical, as evidence not collected and sent to the forensic laboratory is often lost forever.

Once evidence is received in the forensic laboratory, then examiners have to analyse it. Often that process is subjective. Fingerprints, for example, are defined mainly by their minutia – the characteristics in the flow of the friction ridge (see Figure 2).

Figure 2: Different characteristics (minutia) present in the friction ridge of fingerprints (e.g. when a ridge divides or ends).

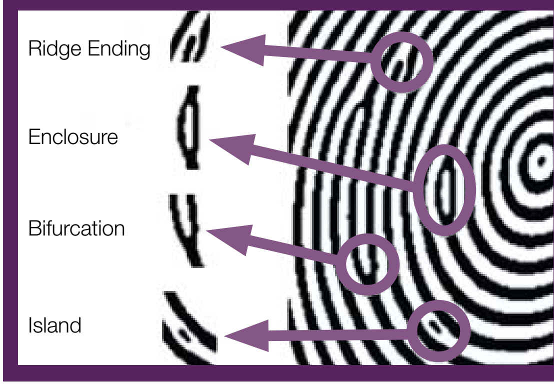


Table 1: The inter-reliability of fingerprinting. Different latent fingerprint examiners looking at the same fingerprints (A to J) lack consistency in the number of minutia they observe[7].

	Latent Fingerprint									
	A	B	C	D	E	F	G	H	I	J
Examiner 1	22	9	15	8	9	3	22	11	7	10
Examiner 2	21	11	25	7	10	9	9	10	6	5
Examiner 3	19	9	18	10	7	9	15	19	6	6
Examiner 4	21	21	29	14	12	9	8	9	4	8
Examiner 5	17	16	15	11	16	9	7	12	5	5
Examiner 6	20	14	22	9	10	7	13	18	7	9
Examiner 7	22	17	15	10	10	8	11	24	8	11
Examiner 8	9	9	19	6	9	8	18	16	9	10
Examiner 9	30	15	25	10	12	12	19	22	12	17
Examiner 10	25	13	18	13	12	10	13	15	7	10
MIN	9	9	15	6	7	3	7	9	4	5
MAX	30	21	29	14	16	12	19	24	12	17
SD	5.49	4.01	4.93	2.49	2.45	2.32	4.25	5.15	2.23	3.54
range	21	12	14	8	9	9	12	15	8	12

These minutiae play a critical role in forensic fingerprinting. However, their presence is subjectively determined. This is evident by the lack of reliability and consistency among fingerprint examiners (see Table 1)[7].

The subjectivity in determining the fingerprint characteristic is further apparent when examining the lack of consistency of expert's judgements with themselves, i.e. their intra-reliability. Not only are examiners not consistent with one another, but the same forensic fingerprint examiner looking at the same print is not always consistent with their own judgment (see Table 2)[7].

The subjectivity underpinning forensic work is not limited to the perception of the evidence, but also to the actual forensic conclusions. In many forensic domains, forensic examiners need to decide whether two patterns are 'sufficiently similar' to conclude that they originate from the same source[8]: for example, whether two handwriting patterns are 'sufficiently similar' to conclude that they were written by the same person, or whether two bullet cartridges are 'sufficiently similar' to conclude that they were fired from the same gun, or whether two fingerprints are 'sufficiently similar' to conclude that they are from the same person, etc. The subjective nature of such forensic decisions arises from the lack of criteria or definition of what constitutes 'sufficiently similar'.

With such subjective decision-making, it is not surprising that different forensic examiners can reach different conclusions. This pertains to many forensic domains, including mixture DNA (even when identical procedures are used)[9], and even when statistical tools are used[10]. In fact, in about 10% of the time, the same fingerprint expert, examining the same pair of fingerprints, will reach different conclusions[11].

Subjective decisions do not only underpin the comparative forensic domains (where evidence from the crime scene is compared to a suspect), but also include many forensic domains, such as blood spatter analysis, forensic anthropology and fire investigations. The subjective decision-making even sometimes pertains to domains such as drug analysis (when one needs to determine if a new designer drug is 'sufficiently similar' to an established illegal drug).

A PROBLEMATIC CONCOCTION

Taken together, the natures of human cognition and of forensic work produce a problematic concoction. Humans are prone to cognitive bias, and that is especially pronounced when information is of low quality and open to different interpretations (as is often the case in forensic evidence) and even more so when subjectivity is involved. That makes cognitive bias a real issue in forensic science, as outlined in a recent briefing to the Houses of Parliament[12]. It is important to note that this relates to cognitive biases that occur without intention or awareness, and that these issues pertain to most aspects involved in forensic work[13]. Below I discuss the potential of biases to affect different aspects and stages of forensic work.

1. At the crime scene

Before the CSI even arrives at the crime scene, before they actually see any evidence, they are briefed. This biases their examination and decisions at the crime scene. Take, for example, a CSI who arrives at a crime scene and has to determine the source of a blood pattern, a highly complex and subjective cognitive process. A briefing that it was caused by a gunshot, or a briefing that it was caused by a knife stabbing, influences how they perceive and evaluate the blood spatter. Similarly, if they come to a crime scene expecting it to be a real burglary, or expecting it to be an attempt at insurance fraud, also affects what evidence is collected and how.

2. At the forensic laboratory

The human examiner at the forensic laboratory, making subjective evaluations and decisions, is often aware of potentially biasing contextual irrelevant information (such as whether the suspect confessed to the crime, if eyewitnesses identified the suspect, whether the detective believes the suspect is guilty etc). Such information is irrelevant to the actual forensic work, but it is nevertheless highly biasing.

The cognitive biases at the forensic laboratory also arise in many forensic procedures, such as verification. Often forensic conclusions are verified, but they suffer from a number of cognitive weaknesses. First, the verifications are not blind: the verifier often knows who did the initial examination, what

Table 2: The intra-reliability of fingerprinting. The table presents the difference between the number of minutia that each expert observes while examining the same fingerprint (A to J) on two separate occasions, i.e. zero indicates consistency[7].

	Latent Fingerprint									
	A	B	C	D	E	F	G	H	I	J
Examiner 1	1	1	4	1	1	2	3	2	0	1
Examiner 2	8	3	5	1	1	2	2	5	2	2
Examiner 3	1	3	3	3	6	4	9	9	1	2
Examiner 4	2	3	2	5	0	1	1	0	0	1
Examiner 5	6	2	2	3	4	1	3	3	0	3
Examiner 6	9	4	2	1	4	6	0	5	1	1
Examiner 7	0	4	5	2	4	3	3	7	0	0
Examiner 8	3	1	4	0	6	2	1	4	2	0
Examiner 9	4	3	9	0	4	4	3	1	1	3
Examiner 10	1	0	0	1	4	1	4	1	0	0
Mean	3.5	2.4	3.6	1.7	3.4	2.6	2.9	3.7	0.7	1.3

TAKEN TOGETHER, THE NATURES OF HUMAN COGNITION AND OF FORENSIC WORK PRODUCE A PROBLEMATIC CONCOCTION.

they decided and why. Second, identification decisions are almost always verified, and hence introduce a base-rate bias (see above).

3. At court

The presentation of evidence in an adversarial legal system is inherently problematic. Although the court wants to rely on and use science, science is often misused and abused in the court. Science within the adversarial system is used by the prosecution to make a case that the suspect is guilty, and by the defence to make the case that the suspect is innocent. Although prosecutors' duty is to do justice, not merely to obtain a conviction (see, for example, the US Supreme Court)[14], "There is reason to doubt that prosecutors comply with these obligations fully" (this statement was made by a US federal appellate judge on the Ninth Circuit[15]). The forensic examiners are often recruited to help make these cases, and that biases the presentation of the evidence.[16,17]

The implications for court and the criminal justice system (regardless if it is in the UK, US, or any other country) are that the forensic evidence may be overstated, and its uncertainties and limitations concealed. Although this should come out in cross-examination, in my view that rarely occurs. First, both sides are rarely equal, because the prosecution often has far more resources than the defence, as well as has better access to the investigative team. Second, many cases enter a plea-bargain or a situation whereby suspects confess to the crime and enter an early guilty plea, and hence the forensic (and other) evidence is never really questioned.

The implications of this bias are corrosive and affect prosecution decisions, plea-bargaining, the actual trial, as well as subsequent appeals[18]. Furthermore, at court, there are cognitive issues that affect how the juries understand the forensic evidence, and how they integrate it within other lines of evidence (see case study, p50).

RESEARCH ABOUT COGNITIVE BIAS IN FORENSIC SCIENCE

Until about a decade ago, there was very little research into the performance of human forensic examiners. The issue of whether they can be biased by irrelevant context, as well as their inter – and intra-reliability, had basically not been studied in any depth. However, in the past few years we have seen a big increase in researching this area (both within forensic science as well as in other scientific domains[19]).

The growing literature includes meta-analytically quantifying the reliability and biasability of forensic experts[20], as well as specific research studies showing that irrelevant contextual information can bias forensic examination most often. This research includes areas such as face comparisons[21], forensic anthropology[22], bite-marks[23], shoe prints[24], firearms[25], fingerprinting[26], DNA[9], blood spatter analysis[27], and fire investigations[28]. There has even been research into forensic bias in the courtroom, showing an 'allegiance effect' whereby forensic experts' conclusions depend on which side hired them[29].

It is worth noting that the research on cognitive bias is complex. First, when participants in the studies are aware that they are taking part in research and that this is not real casework, then the contrived contextual information is not as powerful as when they really believe it. Second, when participating forensic experts think it is real casework, then it is not practically possible to run many examiners on a fully-controlled study with all conditions counterbalanced and good control groups. Third, fully-controlled studies are possible, but then they are mostly done with students. Fourth, contextual information affects perception and cognitive processing, but it does not necessarily determine the decision outcome. This is dependent on the difficulty of the decision (i.e. how close it is to the decision threshold), and the strength and direction of the bias. Only when the decision is within the 'bias danger zone'[3] can bias shift the decision across the threshold and actually determine the decision outcome. Fifth, a null finding that no bias was found does not mean that bias was not there – it could have been there but was not detected, or it may have been absent because of ineffective experimental bias manipulations.

Therefore, although the research literature most often finds biasing effects in studies across the different forensic domains, the effects are not always straightforward and present in terms of decision outcomes. It is not an easy area to study, and there are a number of inherent obstacles in researching it.

Research in this area has also investigated the effects of using technology in forensic science. It has shown that technology does not necessarily solve bias, and may even introduce new forms of biases. For example, the use of computerised fingerprint databases has introduced clear base-rate expectations about a match[30]. This base-rate biasing expectation affects forensic examiners in a number of ways. First, they tend to spend less time comparing suspects that they do not expect to match. Second, they are more likely to make false-positive decisions (i.e. erroneous identifications) when they expect a suspect to match. And third, they are more likely to make false-negative decisions (i.e. not make correct identifications) when they expect a suspect not to match[31].

COGNITIVE BIAS IN FORENSIC CASEWORK

Do these theoretical analyses and research findings apply to actual forensic casework? The answer is clearly yes, as revealed by cases with erroneous forensic identifications and miscarriages of justice. For example, in the US Brandon Mayfield was linked with the 2004 Madrid train bombings after being misidentified by a number of independent forensic examiners, who all concluded with 100% certainty that he was the match. However, because of unusual circumstances the erroneous identification was revealed and prompted an investigation that concluded that confirmation bias was a factor in the mistake[32].

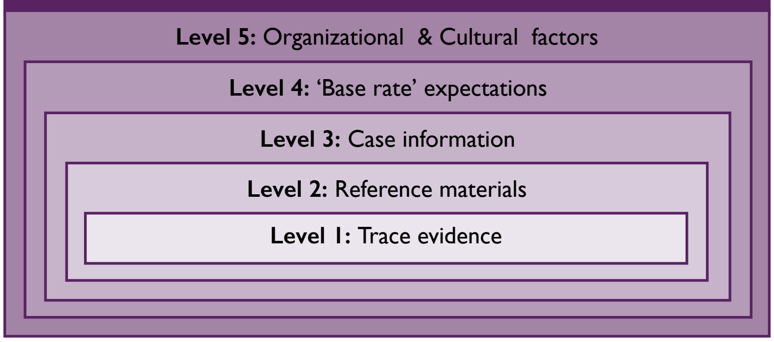
The biasing effects on forensic casework were also revealed in the UK by the public judicial inquiry by the Rt Hon Sir Anthony Campbell, who examined the Shirely McKie case[33]. Other cases include the UK High Court of Justice Court of Appeal (Criminal Division) quashing a conviction that was based on biasing forensic work[34]. In this case, the forensic expert initially examining the evidence "concluded that there was insufficient detail to be able to make a meaningful comparison", but after a suspect had been charged the expert made a comparison and an identification. This type of bias is derived from backward and circular reasoning, whereby the forensic expert is biased by the known reference material (i.e. the suspect who is the target for comparison). Working backwards from the suspect to the evidence in this way is a problem that can be addresses by the Linear Sequential Unmasking method (see below).

We must remember that forensic evidence is not always challenged in court because of the limited resources of the defence as well as the prevalent use of plea-bargaining and early guilty pleas. Furthermore, because we never know the ground truth in casework, it is hard to determine the extent of forensic error. Nevertheless, there is sufficient data to show that forensic bias and error do occur within the criminal justice system. From known miscarriages of justice in the US, 60% included flawed forensic evidence[35].

SOURCES OF CONTEXTUAL BIASING INFORMATION

Bias comes in many forms and guises[5], and it can derive from very different sources. It is important to classify the different sources of contextual biasing information, as this will enable a better understanding of bias in forensic work as well as help to

Figure 3: A taxonomy of the different levels at which task-irrelevant and potentially biasing contextual information may reach a forensic scientist[13, 36].



THE SOLUTIONS ALL SHARE A COMMON GOAL: TO INCREASE THE INDEPENDENCE OF MIND OF THE FORENSIC EXAMINERS, SO THAT THEY CAN ACHIEVE THE HIGHEST POSSIBLE QUALITY DECISIONS.

devise solutions. Clearly, some context and information is needed for forensic examiners to do their job, but other contextual information is extraneous and irrelevant to their forensic work.

I organise the different sources into a 5-level taxonomy[13, 36] (see Figure 3). First is the actual evidence, which may include irrelevant biasing context. For example, handwriting analysis may involve text that includes irrelevant biasing information, voice recognition may include tone and content that includes irrelevant biasing information, and bite-marks may reveal irrelevant information about the nature of the crime.

The second level is the reference material, the known 'target' that the evidence from the crime scene is compared against. This information is relevant and essential: the forensic examiners cannot do their work without it. However, it may cause backward and circular reasoning that can bias the perception and evaluation of the actual evidence. This often occurs when the forensic examiner works from the target suspect to the evidence, rather than from the evidence to the suspect. When examining and analysing the evidence from the crime scene, the target suspect is irrelevant.

The third level is the case information. There is a whole array of case information that is not relevant to the forensic examination in question, but can bias perception, interpretation, judgement and decision-making. Knowing whether eyewitnesses identified the suspect, whether the suspect has previous convictions, and whether the detective believes the suspect is guilty, are all examples of case information that is irrelevant to any forensic examination.

Level four pertains to the base-rate expectations derived from previous work. The forensic examiner has an expectation of what they will find and what they will conclude before they even see or examine the actual evidence – a clear source of bias. Finally, the fifth level relates to larger contextual sources of bias: the organisational and cultural factors, such as the adversarial legal system and being part of the police service (see the allegiance effect discussed earlier).

SOLUTIONS

Many of the solutions to the problems raised in this chapter do not require additional funds and are practical. In fact, some solutions will enhance forensic decision quality and increase efficiency at the same time. This is because the solutions are derived from understanding human cognition as it applies to forensic work. These solutions are detailed in a number of publications[3, 36-38], and many are included in the Forensic Regulator Codes of Practice and Conduct guidance on "Cognitive bias effects relevant to forensic science examinations"[39].

The solutions all share a common goal: to increase the independence of mind of the forensic examiners, so that they can do their work without interference and bias, and thus achieve the highest possible quality decisions.

1. Context management

Many of the solutions focus on how to manage context, providing what I often call the "Context Management Toolbox"[36]. These tools and procedures consider what the forensic examiner needs and when.

The first and most basic step is **masking irrelevant information** from the forensic examiners. Hence, information that they do not need and that is extraneous to their work should be masked from them (see the Linear Sequential Unmasking method below). This will not only make sure they focus on the information relevant to their forensic expertise, but will also increase efficiency because they will not waste time on irrelevant information.

In some cases, regardless of the forensic domain, it is easy to determine that some case information (see level 3 in Figure 3) is not relevant (e.g. whether the suspect confessed to the crime). At other times it is not so clear cut: for example, the location of where a gun is found may be relevant if it was hidden for a long time in a wet gutter, because that may impact the patterns of bullet cartridges fired from it.

Sometimes irrelevant biasing information is not easily masked, such as those originating from within the evidence itself (see level 1 in Figure 3). In such cases (e.g. handwriting and voice analysis) the context is engrained within the actual evidence and cannot be (easily) removed. However, in other cases (e.g. fingerprints) much of the context is irrelevant, so the forensic examiner must focus their decision on the actual fingerprint patterns. Although some contextual information is still needed – such as the material from which the prints were lifted, or the method used to develop the print off the surface – such information is mostly not biasing.

The second step is **sequencing the information**. In cases where biasing information is necessary to conduct the forensic examination, it is recommended that such information will be provided to the forensic examiner only when it is needed. For example, the 'target' reference material (see level 2 in Figure 3) should only be provided after the analysis of the evidence from the crime scene, hence ensuring that the forensic examiner works from the evidence to the 'target' suspect, rather than from the suspect to the evidence. The US Federal Bureau of Investigation (FBI) recognised that backward and circular reasoning from the evidence is a source of bias and have implemented a sequencing of information approach[36]. (It is not clear to what extent this, and other anti-biasing procedures, are currently in use in the UK.)

The Linear Sequential Unmasking (LSU) approach specifies that an examination of the actual evidence takes place first; that this analysis is documented; and only then is the forensic examiner exposed to the suspect. It further restricts changes that can be made to the evidence post-exposure to the reference materials[36]. For example, in DNA analysis, the forensic examiners must first characterise the profile from the biological material found at the crime scene before seeing the DNA profile of the suspect.

Some aspects of applying LSU are simple and straightforward across forensic domains. For example, requiring forensic examiners to first examine the actual evidence from the crime scene without being exposed to the 'target' suspect is very easy to implement without cost or effort, and will enhance forensic decision making by minimising backward and circular reasoning.

Other aspects of applying LSU are dependent on the specific forensic domain. For example, the analysis and documentation of the evidence is different in DNA analysis (e.g. peaks) than in fingerprinting (e.g. minutiae). The complexity and effort in documenting the analysis will therefore also vary. Some forensic domains and certain aspects may be very easy to document, whereas other may be more challenging.

The final aspect of LSU that needs to be considered before implementation is the restriction on changes to the evidence post-exposure to the target suspect. LSU suggests a number of approaches to achieve a balance between not allowing any such changes versus permitting unrestricted changes. For example, changes may be allowed as a function of confidence during the initial analysis, so that things which were clear during the initial analysis cannot be changed later, whereas things that were ambiguous can be changed (but these changes should be documented). Each forensic domain can determine how and to what extent such changes are permitted.

The LSU involves (sometimes temporary) **blinding** to information in the forensic comparative process, but other types of forensic work should also involve blinding of

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information. For example, when one forensic examiner verifies a forensic conclusion of another examiner, the verifying examiner should be blind to various aspects of the first examiner's decision (e.g. what they decided, why, who made the first decision, etc).

Who will do the masking and sequencing of information? Often, one must know a lot of context in order to determine what forensic tests need to be done, what information is relevant, etc. This could be carried out by a **Case Manager**[3], who will initially communicate with the investigative detective, and know all of the available information about the case. The case manager will then determine what tests to run, and what forensic work needs to be done. They will assign those forensic tasks to other examiners who will only be provided with the relevant information they need for those tasks, thus masking the irrelevant information.

Furthermore, the case manager will also communicate with the police and provide them with the forensic results, explaining what they mean and how they may bear on the case. The forensic examiners doing the actual forensic tests and comparisons will not be part of those communications, and will focus on their specific forensic analysis. Since the case manager role is most interesting, it may be a rotating role among the examiners.

2. Triage

Another set of solutions involves matching resources and effort to the complexity of the forensic work, and depending on whether it is within the 'bias danger zone'[3]. For example, some forensic decisions are complex and hence more prone to errors than others. In such cases one may go to the trouble of fully blinding the verifier to all potentially biasing information, whereas one may not need to use such blind-verifying procedures for simple, self-evident forensic decisions[3].

Similarly, some cases involve highly-emotionally biasing information and a variety of pressures that may influence the forensic examiner, whereas other cases may have very limited (if any) biasing information. The need to have a case manager and to blind case information (level 3 in Figure 3) may depend on the existence of biasing information. Hence, a triage approach can determine if and what measures are appropriate[3]. The triage approach makes implementing the bias countermeasures much simpler and cost-effective.

3. Countering base-rate expectations

This is quite easy to achieve by introducing a few examples that change the base rate. In airport security, for example, this may involve introducing fake bombs into the X-ray screening procedure, a tactic known as Threat Image Projection (TIP). In the forensic domain such measures can be implemented in a variety of processes. For example, the base rate for verifying identifications is very high, and this can be countered by including a few 'similar non-matches' as identifications within the verification stream[3].

Another example is countering the technology base-rate expectation, by including matches in locations that they rarely appear, or by randomising the positions so that there are no regularities of where the technology presents the most likely match[3, 30, 31]. All of these measures aim to make sure that the forensic examiner is cognitively engaged and bases their decision on the actual evidence rather than base-rate expectations.

IN MOST FORENSIC DOMAINS IT IS THE HUMAN EXAMINER WHO PERCEIVES INFORMATION, INTERPRETS IT, MAKES JUDGMENTS AND REACHES A DECISION. OFTEN IT IS THE HUMAN EXAMINER WHO IS THE 'INSTRUMENT OF ANALYSIS.

4. Training

The best procedures and forensic practices will not help if the forensic examiners do not accept the need to have them and understand their utility. Since cognitive bias in forensic science is a relatively new topic, most forensic examiners have never received training in this area and have very little (if any) understanding of the underlying cognitive issues. Even the forensic trainers themselves – those who instruct and teach the forensic examiners

HOPEFULLY WE WILL WITNESS THE INCREASED POWER OF FORENSIC SCIENCE TO CONTRIBUTE TO THE CRIMINAL JUSTICE SYSTEM AND TO SOCIETY AT LARGE.

about these issues – are predominately forensic scientists, not cognitive scientists, and therefore have little-to-no understanding of the human cognitive system to address the issues of cognitive bias (e.g. they often mistake them as ethical issues).

Therefore, it is paramount that all forensic and CSI examiners receive proper training on the bias and cognitive factors involved in making forensic decisions. This has started to take place: for example, Hertfordshire, Bedfordshire and Cambridgeshire Police are providing such training to their CSI and forensic examiners. Such training has already had a practical impact on the way they carry out forensic work: by removing possible irrelevant contextual information, for example, thereby ensuring that forensic decisions are based on the relevant forensic evidence and are not contaminated and biased by extraneous information (an aspect of the LSU method). Such higher-quality forensic decisions benefit the Criminal Justice System and save costs in the long run.

It is also important to provide training to judges, lawyers and jurors, so that they understand the strengths of forensic evidence, but also its limitations and vulnerabilities to cognitive bias. Such training should include the Forensic Regulator Codes of Practice and Conduct guidance on "Cognitive bias effects relevant to forensic science examinations"[39].

With education in this area, along with cognitive best practices, forensic science can increase its contribution to the Criminal Justice System and beyond. However, without acknowledging these issues and implementing training and solutions, forensic work may suffer from a variety of biases. A number of police forces in a variety of countries are undergoing such training (e.g. in the United States, the FBI and Police Departments including those in New York City, Los Angeles, San Francisco, and Kansas), have all provided cognitive training to their forensic/CSI examiners. It is suggested that such training also be provided to a variety of police forces in the United Kingdom.

CONCLUSIONS

In most forensic domains – from the work at the crime scene to forensic comparisons at the laboratory – it is the human examiner who perceives information, interprets it, makes judgments and reaches a decision. Often it is the human examiner who is the 'instrument of analysis'. However, until recently the role of the human examiner has been relatively neglected.

For forensic science to increase its positive impact on the Criminal Justice System and beyond, it must ensure that cognitive bias in forensic work is minimised. Understanding human cognition helps to identify the weak points and vulnerabilities inherent in forensic science, and also to develop and implement biasing countermeasures. Without such measures, forensic examiners and CSIs will be cognitively contaminated and biased in their work. These biases affect others and ultimately create a 'bias snowball effect'[37, 38].

Taking on board the cognitive and human factors involved in forensic science is long overdue, but recent years have seen very fruitful progress in advancing these issues within forensic science. Hopefully this trend will continue and increase, and we will witness the increased power of forensic science to contribute to the Criminal Justice System and to society at large.

CASE STUDY

STATISTICS IN COURT

DAVID LAGNADO, *University College London, with contributions from* COLIN AITKEN, *University of Edinburgh*

Imagine you are a juror in a criminal trial, in which the defendant is charged with assault. A key piece of evidence is that the defendant's footprint matches a print found at the crime scene. The prosecution calls a forensic expert, who testifies that the probability of seeing such a match if the defendant was not the source of the footprint is 1 in 1,000. Based on this information alone, what is your estimate of the probability that the defendant left the print?

Many people would be tempted to give a high probability, perhaps even quantifying it as 999 in 1,000. But this line of reasoning is logically flawed – it is an example of the notorious 'prosecutor's fallacy', so called because it usually overstates the prosecution's case.

The prosecutor's fallacy is not just a reasoning error made by lay people. Legal experts such as prosecutors, judges, barristers, and forensic scientists are also susceptible, and the error often crops up in media coverage of legal cases. The fallacy has figured in several high profile cases, with convictions being quashed due to the misrepresentation of the evidence. The seriousness of the error has been recognised by courts, and instructions have been formulated to avoid the mistake. Nevertheless it still seems to be a pernicious problem, and it arises in many other areas with probabilistic evidence, such as medical diagnosis and psychological testing.

WHY IS THIS A FALLACY?

The expert has told you the probability that the footprints would match, based on the hypothesis that someone else left the footprint. This is calculated from an estimate of how rare the footprint is in some relevant population.

But this is entirely different to the probability that someone else left the footprint, based on the evidence that the footprints match.

The former is a statement about the probability of the evidence, whereas the latter is about the probability of the hypothesis of interest.

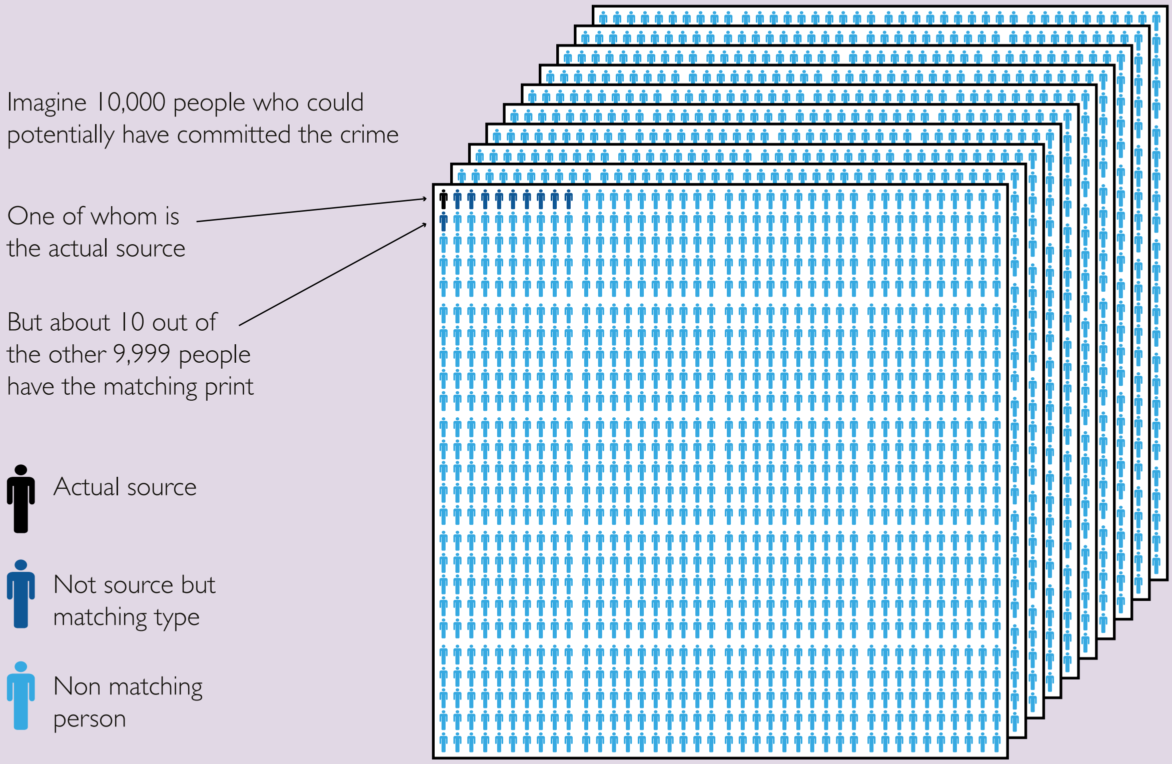
The logically correct method for incorporating the expert's evidence into a judgment about the probability of the hypothesis is to use Bayes' theorem, an approach that depends on an estimate of the probability of the hypothesis before considering the footprint evidence – a concept called 'prior probability'.

An intuitive way to understand the problem is by casting it in terms of frequencies. Suppose that in the absence of the footprint evidence there are 10,000 men, including the defendant, in the local area that could have committed the crime. Given the expert's statement that the match probability is 1 in 1,000, we would expect about 10 of these men to match the print. So the footprint evidence has narrowed the number of possible suspects from 10,000 to about 11 (10 plus the defendant); this increases the probability that the defendant left the print from 1 in 10,000 to about 1 in 11 (see Figure 1).

This is a substantial increase, but it is still relatively unlikely that the defendant left the print, given that about 10 other men would also be expected to match. The prosecutor's fallacy implies that the probability the defendant left the print is 999 in 1,000, whereas the correct calculation, incorporating the prior probability, gives a figure closer to 1 in 11.

Note that footprints are used here for illustrative purposes, and are rarely used in forensic investigations. However, exactly the same logic applies to DNA profiles, fingerprints, and other kinds of trace evidence that are routinely used in court. Also, in the forensic context a 'match' often amounts to the claim of a correspondence between two items (to within a specified tolerance), but not to a claim that they are identical. Indeed, even two footprints from the same individual will not be identical.

Figure 1. Visual depiction of the suspect population (adapted from ref. 1).



WHY IS THE FALLACY HARD TO AVOID?

Forensic experts can only tell us how well the evidence supports a hypothesis. This leaves us with the task of using that information to reach a judgment about the probability of the hypotheses – something that is difficult if left to commonsense and intuition alone.

Extensive psychological research[2,3] reveals that when people face difficult probability problems they use 'cognitive heuristics' – shortcut solutions that can lead to systematic biases. The prosecutor's fallacy is especially tempting because it incorporates several interrelated heuristics and biases.

Attribute substitution: Faced with a difficult question, people often respond with a readily available but incorrect answer. Thus the expert's statement – the probability that the footprint evidence would match if someone other than the defendant had left the print (1 in 1,000) – is readily taken as the answer to the ultimate question of interest i.e. the probability that someone else left the print, given the evidence that the footprints match.

Base rate neglect: When updating their beliefs, people often ignore information about how common something is in the general population – known as base-rate information – and give too much weight to case-specific evidence. In our case, this is tantamount to ignoring the prior probability that the defendant left the print, and focusing just on the match evidence.

Belief bias: People are more likely to accept a fallacious argument if its conclusion fits with what else they know or assume. This means that the prosecutor's fallacy can seem more acceptable when there are other reasons to believe the defendant is guilty.

Defaults: People often use default values to simplify their reasoning. In the legal case, people often assume a 50/50 prior probability, but this assumption is usually unjustified and prejudicial.

Explanatory scenarios: People usually reason in terms of scenarios and stories rather than probabilities, and often prefer scenarios that best explain the evidence, even if these are not the most likely explanations. Thus the fallacy is promoted because the hypothesis that the defendant left the print is clearly the best explanation for the match, and yields a more satisfying story.

WHAT CAN WE DO TO ALLEVIATE THIS FALLACY?

Ideally, everyone involved in a trial should receive proper training in the probabilistic evaluation of evidence. But psychological studies have highlighted various approaches that can also help people to reach better judgments and avoid errors like the prosecutor's fallacy.

Frequency formats: Framing the problem in terms of frequencies (as we did in the example above) helps people reach more accurate judgments and avoid the fallacy.

Exemplar cueing: Framing the evidence in terms of how many other matches are expected, rather than just giving a match probability, makes people evaluate the evidence more accurately.

Visual aids: Using diagrams to represent the relevant populations and show the expected numbers of matches (as in Figure 1) also improves reasoning.

Verbal scales: We can calculate a likelihood ratio (LR), which compares the probability of the evidence under the prosecution and defence hypotheses (see Annexe pg 207). These LR values can then be converted into a verbal scale[4]. For example, an LR of 100–1,000 can be expressed as providing "moderately strong support" for the prosecution rather than the defence hypothesis; an LR of 10,000–1,000,000 as providing "very strong support"; and so on. This enables evidential interpretation to satisfy the key characteristics of balance, logic, transparency and robustness.

THE INCREASING USE OF FORENSIC EVIDENCE AND QUANTITATIVE PROBABILISTIC ANALYSES MAKES IT ESSENTIAL THAT PROFESSIONAL USERS OF EVIDENCE UNDERSTAND HOW TO INTERPRET AND PRESENT THIS INFORMATION.

However, these approaches are harder to scale-up to more complex problems, especially those with multiple pieces of evidence and issues of evidence reliability. One promising solution is to use Bayesian networks[5], which build on likelihood ratios and Bayesian reasoning. These networks provide a graphical representation of the interrelations between hypotheses and evidence, and can capture issues of evidence reliability and credibility.[6]

A key question is whether non-experts need to engage with Bayesian computations from first principles, or whether they can be trained on simpler examples and then learn to trust and understand an expert's explanations in more complicated cases.

What is clear is that the increasing use of forensic evidence and quantitative probabilistic analyses makes it essential that professional users of evidence understand how to interpret and present this information.

SECTION 2:

THE CHANGING NATURE OF CRIME

THE CHANGING NATURE OF CRIME

Forensic science has a tendency towards being reactive; the future for crime reduction is in **proactive** strategies and policies.

Foreign legal systems provide the UK with evidence about crimes, accidents and natural disasters involving Britons, while the UK is obliged to help investigate crimes committed by British citizens abroad.

Crime no longer has national boundaries, so international law enforcement conventions have been adopted to respond to the changing nature of crime.

The global cost of cybercrime is currently more than

$400 billion per year

In a recent report the cost to the UK of cybercrime was estimated to be

£27 billion per year

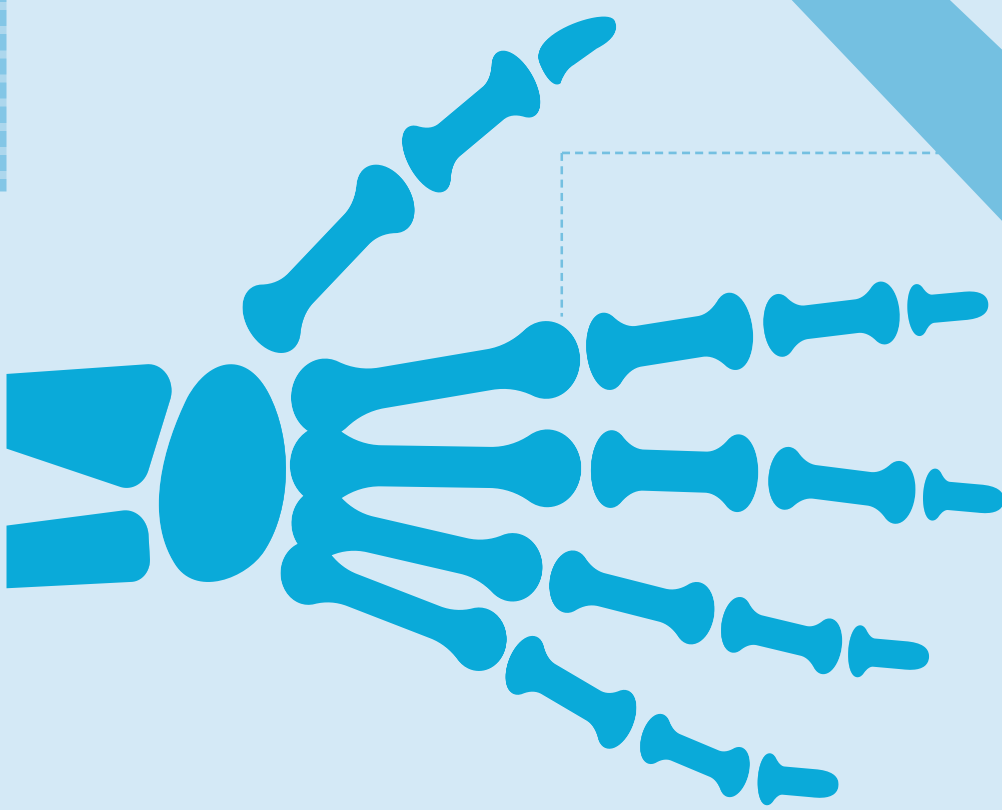
The international exchange of DNA data and fingerprints can identify trends and spatial features in cross-border crime and offending. Forensic science data can be used to inform **crime prevention** strategies.

With a 5% rise between 2013 and 2014, more than 40% of all criminal cases of fraud relate to misappropriation of identity. Its cost to the UK economy runs close to

£3.3 billion a year

UK forensic science makes important contributions to international resilience, demonstrated during the MH17 disaster victim identification process.

As the complexity of cyberattacks grows, so does the volume of evidence that can be collected in relation to a crime.



The International Commission on Missing Persons and Bode Cellmark Forensics have tested

50,000

bone samples and

30,000

unidentified human remains from MH17 to date

THE CHANGING NATURE OF CRIME

PETE MERRILL,
Head of Science & Innovation, National Crime Agency

National and international law enforcement agencies routinely collaborate in tackling cybercrime. Forensic science, in contrast, has failed to keep pace. If we are to combat the changing nature of crime, we must work together to develop global science toolkits.

We live in a world where global crime threats affect everyone, whether they live in a country of supply, trafficking or demand. International criminal markets crisscross the planet, transcending cultural, social, linguistic and geographical borders. These markets are dynamic, sophisticated, highly profitable and able to adapt more quickly than legal counterparts.

Crime no longer has national boundaries and an offender in one country can simultaneously commit offences against victims in other states, meaning that national intervention activity often requires investigators to look beyond their own borders to protect their sovereignties and citizens from harm.

Acting alone to counter crime has become unworkable and, in response, international law enforcement conventions have been adopted to collectively respond to the changing nature of crime, to strengthen security and the rule of law, disrupt criminal markets and to strengthen integrity and anti-corruption activities.

Meanwhile, criminals have diversified and use new ways to carry out the same crimes, with technology playing a key role. Traditionally, global crime was physical: it came in the form of trafficking, starting in one continent and ending in another, but routed through others to disguise its true source. Criminals have always chosen the safest method of operating, by identifying new crime sources, transit hubs and destinations, exploiting free trade zones and vulnerabilities in law enforcement capabilities across different jurisdictions. Now, the greatest threat is non-physical: criminals exploit the internet for economic, cybercrime and sexual exploitation purposes. They co-opt legitimate activities for criminal purposes, using corruption, coercion and white-collar collaborators and enablers in the private and public sectors to commit crimes. Their activities threaten national infrastructures, security and our identities.

Law enforcement is not as agile in adapting its operational response to combat these threats, and forensic science capabilities often lag behind both the investigators' operational tempo and public expectations, which impacts confidence and social wellbeing. Although national and international law enforcement agencies routinely collaborate in tackling the growing phenomenon of cybercrime, forensic science has failed to keep pace: it has not embraced the same collective responsibility, giving rise to missed opportunities. If we are to combat the changing nature of crime, we have no choice but to work together to develop global science toolkits.

While law enforcement is striving to adapt its efforts and capacities to these new challenges, forensic science also needs to transform to keep up with the changing nature of crime. It should do so by maintaining and developing its core business, as well as supporting and embracing new ways of working.

NATIONALLY-COORDINATED FORENSIC SCIENCE WOULD BE MORE PROACTIVE IN TACKLING EMERGING CRIME THREATS, AND ABLE TO PROVIDE A MORE DYNAMIC RESPONSE TO LOCAL, NATIONAL AND INTERNATIONAL THREATS, SUCH AS CRIME IN ACTION.

CRIME MOVES FROM THE PUBLIC SPACE TO THE HOME

The new environment in which criminals now operate – cyberspace – is without borders. The principle that 'every contact leaves a trace' still applies within the digital and online cyber world, but the technologies used to commit, enable and detect crime are not easily transferable within the traditional forensic sciences.

The increased mobility and adoption of technology globally, driven by its wider availability and falling costs, means that the number of potential victims of cybercrime can only increase. For example, a criminal anywhere in the world with internet access can pay to watch and direct child abuse via the internet in live-time. This demonstrates that law enforcement agencies must collectively investigate 'crime in action' across geographical and legal territories. The need for collective responsibility for the forensic analysis of technologies and networks is also imperative.

Victim vulnerability, despite enhanced cybersecurity features and applications, is still a real threat. Increased web interconnectivity, greater dependency on technology by the public and business, the perception that the home is a safe environment and that security applications will always work – these all aid the criminals.

The 'Dark Web' provides a resource where criminals can access web-based tutorials, where they can buy instructions, watch tutorials and purchase the necessary tools to hack computers and commit crime, in virtual anonymity. This cyberspace can create a mental disconnect between the criminal, the crime and the real world, because the victims are faceless and no direct violence is used. You no longer need a gang, guns and a get-away car to rob a bank; an individual can commit the crime from their bedroom with nothing more than a laptop.

Forensic science faces a considerable challenge in supporting investigations into technology-enabled crimes in dealing with the evidential material within cyberspace: the physical devices, networks, and embedded digital systems. Collection, analysing and presenting this evidence is difficult enough, but it is exacerbated by the technology

THE INCREASED MOBILITY AND ADOPTION OF TECHNOLOGY GLOBALLY, DRIVEN BY ITS WIDER AVAILABILITY AND FALLING COSTS, MEANS THAT THE NUMBER OF POTENTIAL VICTIMS OF CYBERCRIME CAN ONLY INCREASE.

expectations of investigators and the public. We live in a digital age, in which technologies and applications change almost daily. Investigators expect to have the same level of mobile technology available to them in their professional life as they do in their private lives, and are frustrated when they do not. The public can also experience this frustration when viewing forensic evidence presented in court.

Law enforcement alone will not be able to tackle the problem. Corporations, agencies, government departments, industries and academics – who all have digital and cyber expertise but are not necessarily engaged in criminal prosecutions – have a significant role to play in keeping the public safe.

WHAT NEW THREATS DOES THE CRIMINAL JUSTICE SYSTEM FACE?

Forensic science faces additional challenges in digital and cybercrime investigations. Exhibits could have been deliberately damaged in an attempt to destroy evidence. They are often security-locked, and data can be obfuscated legitimately for security reasons by manufacturers or by individuals using 'off the shelf' privacy protection and disk cleaning tools. Criminals can also remotely counter law enforcement activity by deleting or creating false data logs. If done effectively, it is sometimes impossible to recover any evidence of illegal activity. Even when it is possible, it requires a difficult and lengthy process which increases the time between an offence being committed and it being resolved in a criminal court.

Moore's law states that, over time, computing power grows at an exponential rate. Yet, while the manufacturers of goods and services exploit these technological advances, the forensic tools

Table 1: Technology Readiness Levels (TRLs) are a technology management tool that provides a measurement to assess the maturity of evolving technology.

TRL 1	Basic principles observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 4	Technology basic validation in a laboratory environment.
TRL 5	Technology basic validation in a relevant environment.
TRL 6	Technology model or prototype demonstration in a relevant environment.
TRL 7	Technology prototype demonstration in an operational environment.
TRL 8	Actual Technology completed and qualified through test and demonstration.
TRL 9	Actual Technology qualified through successful mission operations.

required to investigate their misuse are not being developed in concert. Meanwhile, the forensic professional's ability to act as an expert witness is being narrowed down to specific fields of activity, which are so complex that judges and jurors have little or no concept of the subject matter.

HOW CAN SCIENCE KEEP PACE WITH THE CHANGES IN CRIME AND TECHNOLOGY?

The accelerating rate of change of forensic technology stands in stark contrast to the pace of the traditional forensic sciences. New products and services to support forensic science capability go through lengthy end-to-end quality and validation processes before being used within the Criminal Justice System. But this process is not agile enough to match the speed at which new forensic technologies are needed.

This is most keenly felt at the basic research or proof-of-concept stages. Even at these preliminary stages, funded projects are often mandated with judicial end-user requirements that include accredited laboratories, along with training and application by competent staff – in other words, that these technologies should be 'fit for court'. But mandating these complex and costly end-user requirements at such an early stage of technology development can deter innovators. This narrows the field of available expertise, creates perceived boundaries and stifles engagement.

Although the developers of these tools need to be cognisant of the requirements of the Criminal Procedure Rules that their technologies would eventually have to meet in the criminal justice system, innovators working at the lower Technology Readiness Levels (TRLs) 1–5 (see Table 1) should be allowed to focus on the technical requirements of their systems. Mandating costly base requirements (such as accredited laboratories) does not incentivise the science and technology community to provide rapid solutions for development. Instead, it should be sufficient for them to disclose their basic validation processes before a new method is deemed ready for demonstration and operational evaluation for use within the Criminal Justice System.

To keep pace with the changing criminal threat, we need a nationally-coordinated governance framework across the forensic science community. It should lead an innovation centre, a knowledge exchange network, and undertake horizon scanning. It should manage the relationship with funding bodies, Innovate UK, higher education, research councils, users and service providers to ensure that they adopt a holistic approach to forensic science.

Nationally-coordinated forensic science would be more proactive in tackling emerging crime threats, and able to provide a more dynamic response to local, national and international threats, such as crime in action. It would make better use of available technologies, develop specialist solutions that meet the standards of the Criminal Justice System, recruit specialist expertise for national use, and support the development and training of national capabilities.

The UK also needs to be better positioned within global forensics. This is a considerable challenge, because UK forensic science is principally focused on the requirements of the UK's threats, its control strategies, and local policing plans. European crime and global threats are not seen as a key driver for UK forensic science – as a result, the benefits of influence, collaboration and access to funding are not realised.

Understanding the forensic science challenges requires both a dynamic short-term approach to tackle current and emerging threats, along with a more agile approach to long-term research initiatives. This will only be achieved through a single forensic science gateway that can connect practitioners from the diverse forensic science disciplines and facilitate their collaboration to ensure corporate engagement.

COULD FORENSIC SCIENCE BE BETTER APPLIED TO TACKLING THE FACTORS THAT CAUSE CRIME?

Forensic science is designed to support the Criminal Justice System, and to deal with specific offences committed by specific people. It does not tackle the factors that cause crime, an important distinction. This means that although law enforcement investigate and prosecute offenders, which can lead to

UNDERSTANDING THE FORENSIC SCIENCE CHALLENGES REQUIRES BOTH A DYNAMIC SHORT-TERM APPROACH TO TACKLE CURRENT AND EMERGING THREATS, ALONG WITH A MORE AGILE APPROACH TO LONG-TERM RESEARCH INITIATIVES.

convictions, it may not reduce the supply of illegal commodities, the number of trafficking victims, or curb online exploitation.

Criminals may come and go, but the criminal markets and the factors that cause crimes remain. A disruption-only crime-fighting model will not solve the crime problem. Instead, understanding the crime landscape will help agencies to focus on the activities of significant impact, especially where they span multiple threat areas where intervention will have a more sustainable impact.

Calls for research in forensic science often focus on the natural sciences, rather than on studies of the social and behavioural drivers of crime. These social science questions – which seek to understand crime markets, entities, structures and how they operate – are not seen as a high priority. Likewise, the effectiveness of forensic activity on public confidence, their understanding of the topic, and their expectations are vital issues that we need to understand in order to be more effective (see: The big questions in crime research, overleaf).

The current system of funding forensic science research is clearly biased towards the natural sciences. To be successful in a funding bid, applications must be driven by an expected output of results and benefits. Projects are therefore risk adverse, with little or no flexibility to extend or change their scope. Proof-of-concept bids and social or knowledge-building initiatives are rarely funded. Funding is often for too short a period; bidding formats differ across government departments; and there is a mismatch between the academic and the funding and commissioning cycles.

If, as a society, we want to identify and understand the causes of crime, we must have a

THE BIG QUESTIONS IN CRIME SEARCH

UNDERSTANDING ORGANISED CRIME MARKETS, ENTITIES, STRUCTURES, VALUE AND HOW THEY OPERATE

- What are serious organised crime activities?
- Where are they located?
- Where is their marketplace?
- Do they actually cross borders?
- What are their connections?
- What are their pathways, driveways, motivators and modus operandi?
- How do they interact with the grey market and other legitimate networks?
- Are they demand driven?
- Are there a diverse number of ethnically heterogeneous actors?
- Do they have an organisational structure or a party base?
- Do they follow traditional or media concepts?
- Do we understand what we are up against?
- Does offender management work?
- Are criminals more agile than law enforcement?
- What are the enabling tools and trappings that go with the crime types?
- Does each crime type have a different network?
- What value is given to an individual's reputation?
- Is the nature of violence in serious organised crime changing?
- What are the new patterns and crime types?

PUBLIC CONFIDENCE AND EXPECTATIONS

- How do we measure success within an environment where public confidence and perception has such a varied range?
- How do we measure confidence, visibility, satisfaction, credibility and reputation?
- What is the definition of public confidence?
- What are the unspoken expectations?
- Where are the boundaries of public acceptance for forensic science techniques?
- What is the effect following a disruption on different communities?
- Can we define the types of real and virtual communities?
- How can we actively engage with community experiments?
- How do you change lifestyle and culture?
- Can we 'future proof' the public against crime?
- What does civil engagement look like?
- What factors create an environment of trust?

HOW DO WE MEASURE THE EFFECTIVENESS OF LAW ENFORCEMENT ACTIVITY?

Do we know enough to evaluate the intended consequences of our actions?
Is policy effective?
How do we measure outputs?
How do we measure impact?
What types of disruption work?
How do we measure the impact following a disruption?
How does law enforcement evaluate the threat, balance privacy and morality and operate in an ethical way?
How do we manage activity outside statutory processes?
How do we identify what is important?
How do we keep the focus on the mission?
What level of energy does it takes to disrupt crime?
Who does it actually affect?
How do we best design interventions?
Is there a place for conflict resolution?
How do we measure intangible and tangible benefits?
Can we include measurements from key stakeholders?
Should we focus more on cyber or drugs – which is the bigger threat?

national sponsor for fundamental research into the social and behavioural sciences. We also need to deconflict the competing priorities for funding, and take a long-term approach to providing an environment that will maximise the commercial markets for forensic science, to the benefit of both the public and private sectors.

THE EFFECTS OF CHANGING CULTURAL NORMS ON CRIME

Public confidence in forensic science, and its ability to keep the public safe, are the most important drivers for innovation within forensic science. It operates within an environment of radical uncertainty, where there is greater public scrutiny around its activities, and a greater demand for transparency than ever before.

As well as being adaptable to the changing nature of crime, forensic science has to be flexible enough to cope with the changing requirements of the law, political agendas and policies, organisational cultures, ethical and human rights challenges. This is keenly felt when it comes to personal data held on national databases. The difficulties in accessing and using national crime-fighting data have never been satisfactorily resolved. This hampers academic research so much that it is often too far removed from the criminal investigation to be of value. Better access to crime knowledge and data is required to provide qualitative research, while still respecting the challenges associated with managing confidentiality, security, Criminal Justice System requirements and commercial considerations. It is also vital if we are to reduce the risks of research bias, and to avoid studies simply delivering pre-determined outcomes, rather than producing genuine insights.

All of the examples discussed in this chapter demonstrate that forensic science needs to adapt more quickly to the changing nature of crime if it to remain relevant, trusted and useful.

CASE STUDY

TROJAN OPENS THE GATES TO COMPANY CASH

OLIVER SMITH, *PwC Cyber Threat Operations*

Imagine the following scenario. Police are poised to arrest an employee on suspicion of misappropriating company funds when an investigative interview with the suspect reveals a sequence of strange events. Upon closer examination, it transpires that a sophisticated and targeted attack by cybercriminals had succeeded in siphoning off close to £250,000 to bank accounts held in Cyprus, Ukraine and the United States.

Just days before – after starting a new role in the finance team of a manufacturing company – the employee had received an email purportedly from the company's bank. This email seemed entirely innocuous, and was one of many other emails that the employee had received from the bank as part of the process for setting up their access. However, the email was in fact spoofed, and had been sent by a cybercrime group – a form of cyberattack called 'phishing'. Targeted phishing emails (i.e. those that may refer to the target by name, or contain other information that may resonate with the target) are referred to as 'spear phishing'.

The email contained a piece of malicious software (malware) intended to infect the employee's computer with a carefully crafted program known as a banking Trojan. This malware, which is called a 'Man in the Browser' attack, allows the attacker to not only track and exploit the information being entered by a user, but also to ask for additional information and where necessary redirect the victims to bogus sites. Once executed, the malware was able to operate undetected, intercepting key information intended for the banking site. The victim's banking credentials were transmitted to the attackers, giving them access to the company's bank account.

The employee was then presented with an onscreen message stating that his card reader – a device designed to provide an additional layer of security around the authorisation of transactions – was required in order to complete the logon process. Given the employee's unfamiliarity with the new banking system, he was not suspicious and followed the instructions. However, rather than being a step in the legitimate account access process, the employee had inadvertently provided an authentication code authorising a payment to a new account.

The employee was presented with an error message that asked him to try again, and this process was repeated a number of times in short succession until the employee gave up trying to gain access to the account. The attackers then proceeded to call the victim at his office masquerading as legitimate bank employees, which resulted in additional bogus transfers being authorised (this process is known as voice phishing, or 'vishing'). Although the bank eventually blocked further payments, it had missed several red flags, including that the company never made direct foreign

REGARDLESS OF HOW ROBUST A COMPANY'S CYBER DEFENCES ARE, HUMAN ERROR IS OFTEN A KEY ROUTE FOR CYBER CRIMINALS TO GAIN ACCESS TO INTERNAL COMPANY NETWORKS OR SENSITIVE DATA.

exchange payments, and always used the same intermediary to process any such payments.

Cases such as this demonstrate that regardless of how robust a company's cyber defences are, human error is often a key route for cybercriminals to gain access to internal company networks or sensitive data – and this form of crime is on the rise. PwC's 2015 Information Security Breaches Survey technical report found that inadvertent human error had caused half of the single worst security breaches for all survey respondents in 2015, an increase of over 60% on 2014 (ref. 1).

In this instance, by capitalising on the employee's unfamiliarity with the bank's authentication procedures – and his all-encompassing social media profile, which contained his position and contact details – the criminals were able to steal a significant sum of money and even threaten the innocent employee's liberty. With the benefit of hindsight it was clear that the logon process was different, but at the time it all seemed very normal. As such, employee training and awareness of techniques such as spear phishing and vishing should be seen as crucial elements of any information security and risk management policy.

IDENTITY AND IDENTIFICATION

SUE BLACK, *Centre for Anatomy and Human Identification, University of Dundee*

Identity is a cornerstone of our modern society, and its influence as a central tenet of our culture will only increase and consolidate as citizens willingly surrender parts of their identity to gain, for example, access to commercial products. The expansive ecosystem of government, science, justice, industry and society must find a way to work together to strike a workable balance between an escalating public demand for security and a laissez faire approach that may expedite identity theft.

Identity and identification are two sides of the same coin, but they are, ironically, not identical. Heated philosophical debates on this matter have existed for centuries, and perhaps even from the evolutionary watershed when the most narcissistic of all species – humans – first discerned a sense of self[1]. From then onward, people have sought to guard their identity jealously from others who might wish to steal it; they have also learned to wield it as a powerful tool for both good and bad, and to raise it as a shield for protection. There is an inherent need within structured societies for citizens to be able to prove who they say they are, and for others to be willing to accept that their claim is not only accurate, but that it reflects who they have always been and will continue to be. If there is any doubt in this concept, then we must attempt to resolve it by presenting and evaluating evidence.

The level of trust in this agreement has changed over time, and in today's high-security world it is probably at its most extreme. Yet society has always been fascinated by the concept of identity, of being able to acquire and manipulate it, and as a result confuse and fool the unsuspecting. Alexandre Dumas' 1846 book 'The Two Dianas' was adapted from the real life 16th-century case of identity theft associated with a peasant, Martin Guerre, and his subsequent trial and execution. It is interesting to consider that in today's world of forensic science this case would have been solved very quickly: and this illustrates that the field is not static but that it is ever evolving, and one could argue that it is now progressing at its fastest pace. Indeed, the flexibility and manoeuvrability of identity continues to inspire creative minds, not only in literature and the media but also those intent on nefarious purposes. Such criminal tendencies need to be countermanded by the full focus of legislative, judicial, scientific and investigative capabilities.

'POSSIBLY' IS NOT A HELPFUL ANSWER

The philosophical concept of identity was first addressed within the much-debated three classical laws of logic: the law of identity, the law of non-contradiction and the law of excluded middle. Of course, in the ideal situation identity would follow the simplicity and pleasing symmetry of Aristotle's law of identity (A=A) but this provides no space for extraneous factors including change in the predicate (as recognised by Heraclitus) or uncertainty in the tools available to the evaluator to establish unequivocal exactness (as evidenced by the concept of three-valued logic). Bivalent logic only provides for 'true' or 'false' values, whereas three-value logic permits a third, indeterminate value that occupies the middle ground between the two finite points at the end of an identity continuum (match or exclusion). Therefore, while these exquisite bimodal philosophical concepts might represent the holy grail of standards for modern day identification, such rigid inflexibility, which relies on certainty or indeed uniqueness, cannot be achieved realistically. The degree of confidence that we have in our ability to assign identity to an individual or to a thing must therefore be predicated on probability and whether the likelihood is closer to confirmation or rejection of identity. Identity as it pertains to an individual must therefore, by definition, be a rigid bimodal concept (each person is unique); but identification, which is the process by which certainty of identity is assessed, occupies the middle ground of the third value. This conflict comes into focus through provision of false rejection rates, false acceptance rates and the bimodal requirement of the Criminal Justice System: is it him, or is it not? Under such circumstances, 'possibly' is not a helpful answer.

Identification must also be able to withstand variation not only in time (as an individual ages) but in space (identical twins) and therefore the complexity with which we not only express identity but the mechanisms whereby we detect, recognise, compare, evaluate and communicate it, are complex[2]. There can be no doubt that some of the indicators of our identity are more readily accepted and more familiar than others, and many have stood an incredible test of time. However, current pressures on data security, privacy laws and the almost insatiable fervour to capture information about identity mean that this has become a challenging and fluid environment where our wish to protect our identity comes into daily conflict with society's demands for us to reveal and relinquish it.

While the forensic aspect of identification has very much focused on its role in the Criminal Justice System, it has perhaps missed a prime opportunity to influence the commercial market through collaborative innovation and enterprise. There is a strong value proposition in the forensic approach to identity because it offers a degree of scientific, grass-roots rigour that industry might capitalise upon if it is to weather the brewing storms of the consumer's ebb and flow in confidence and trust. Early discourse, and a trusting environment that facilitates collaborative and honest dealings from the outset, would stand this relationship in good stead and prepare it for future criticism or adversarial conflict, civil or criminal, in the courts. The need to obviate and manage such risk is core to both a robust commercial marketplace and to the enduring legacy of government policymaking, and it is fundamental to the principles of citizens' trust and faith.

BIOMETRICS BOOM

Identification is a natural and necessary process for many forms of social interaction, from productive enterprise to personal security, but only relatively recently has it become the subject of articulated government policies. In the wake of events such as 9/11, the London 7/7 bombings and other security threats, an increasingly security-conscious society demands higher standards from our technologies and our underpinning scientific robustness[3, 4]. Today, this is most commonly achieved through biometric analysis and the matching of source, intelligence or crime scene data with stored reference data[5]. In an early patent application for a personal biometric system, Yong Zhu and colleagues defined a biometric as "a measurable, physical characteristic or personal behavioural trait used to recognise the identity, or verify the claimed identity, of an enrolee"[6]. The important word here for security purposes is 'enrolee', as it requires there to be a stored set of data against which a comparison may be made to establish a match[7]. This is not always the case for those in the forensic field, who must interpret the evidence from a different investigative perspective where the owner of the biometric is not known to the investigator. Therefore we have two communities approaching the same problem from very different angles. Such an interdisciplinary congruence is a rich ground for innovation, enterprise and entrepreneurism.

But how protective is the consumer of their identity and how willing are they to sacrifice it? To gain access to the latest mobile phone, for example, one may have to surrender their fingerprint biometric. Should the consumer be okay with that? The 'Biometrics Market and Industry Report 2004-2008' from the International Biometric Group (IBG)[8] suggested that fingerprint, face, hand and iris recognition accounted for almost 80% of the biometric

WHILE THE FORENSIC ASPECT OF IDENTIFICATION HAS VERY MUCH FOCUSED ON ITS ROLE IN THE CRIMINAL JUSTICE SYSTEM, IT HAS PERHAPS MISSED A PRIME OPPORTUNITY TO INFLUENCE THE COMMERCIAL MARKET THROUGH COLLABORATIVE INNOVATION AND ENTERPRISE.

market in 2006. "It was predicted that by the end of 2013, Automated Fingerprint Identification Services (AFIS) technology would dominate the biometric marketplace with around 33% of the market share but by the end of 2015 this is closer to 50%, driven by large identification programmes and accessible and affordable personal security demands."[9].

While it is true that fingerprint recognition continues to dominate the biometrics industry, it is important to realise that it also dominated the field of forensic investigation for nearly 100 years[10] until it was eventually relegated into second place by DNA analysis[11]. Both DNA and fingerprint analysis have largely weathered the adversarial interrogation of the courtroom, although fingerprint evidence was recently downgraded from a biometric of 'fact' to one of 'opinion' following the public enquiry into the Shirley McKie case[12], and aspects of DNA analysis are also coming under greater scrutiny. Biometrics that are not only able to operate successfully within the security market but can also meet the criteria of evidential admissibility, are extremely important and potentially powerful tools for the analysis and determination of identity in both the forensic and the security related contexts[13, 14, 15]. This border interface between forensic science and the security market is a powerful translational scientific portal where a paradigm shift may be accelerated through the unrestricted bi-directional traffic of knowledge transfer and collaborative strategic alliances. The development of new biometrics, and the support of emerging ones, would be greatly enhanced by a strategic working alliance of forensic science experts with colleagues in the security industries.

Vascular pattern recognition is a less well known biometric, but it is predicted to gain significant market share after years of being viewed as little more than a niche player. This approach relies on the infra-red image capture of the arborescent (tree-like) pattern of the superficial veins, commonly in a finger, the palm or on the dorsum of a hand. Through algorithmic extraction, the pattern is represented as a binary (black and white) image that can be utilised for pattern comparison purposes. According to the IBG, vascular pattern recognition constituted approximately 3% of the overall biometric commercial market in 2006 (ref. 8). However, the IBG correctly predicted a 300% growth in the use of vein recognition technology by 2012 (refs 16, 17) and current market share is approximately 10%. Like fingerprint biometrics, vein pattern analysis has translated successfully into the forensic field as an emerging science, and particularly in the identification of hands from perpetrators of sexual crime, but more specifically child sexual abuse[18, 19] (see case study on p80) . The legal admissibility of this evidence was granted on the basis that the expert was a trained human anatomist who understood human variation[18]. Therefore, vein pattern analysis has successfully crossed from the scientific/medical world into the commercial marketplace as a largely unnoticed conduit, and is now translating onto the forensic arena with significant impact. Capturing this sometimes unexpected flow of knowledge and influence between disciplines is challenging but offers fertile ground for innovation. The Law Commission report on 'Expert Evidence in Criminal Proceedings in England and Wales'[20] clearly provides room within the UK Criminal Justice System for the utilisation and introduction of novel or emerging sciences in the courtroom, but it is also clear on the extent to which opinions and inferences may be made in such circumstances.

First generation (e.g. fingerprints) and second generation (e.g. DNA) forensic-based identification techniques have a track record in terms of evidential admissibility[11] that emergent technologies must acquire. Developing a strong ethical framework is also a critical component to ensure the success of an approach, both in the Criminal Justice System and in the commercial sector[19, 21]. Biometrics that can cross between both fields raise different issues in the different locations, but the interchange offers tremendous

WE HAVE TWO COMMUNITIES APPROACHING THE SAME PROBLEM FROM VERY DIFFERENT ANGLES. SUCH AN INTERDISCIPLINARY CONGRUENCE IS A RICH GROUND FOR INNOVATION, ENTERPRISE AND ENTREPRENEURISM.

opportunity for robust and impactful research. Although this is currently little exploited, it is likely to prove a fertile ground for emerging technologies and new approaches if a productive environment can be created and supported.

This interface of multidisciplinarity requires freedom to explore opportunities, but its impact for policy makers through emerging technologies and economic growth is largely unaddressed and untapped. The emergence of new technology will not only be useful in the detection and capture of identity, but also in improving the accuracy of our comparative abilities, the solidity of our evaluation and the ease of its communication. Of course the value may not only lie in the use of identity but also in its protection, and if we are to continue to exploit biometrics then we must also think about how to develop a means to protect our identity – even if we are prepared to surrender it for goods and services. The opportunities are limited only by imagination, but they must be prepared for with sound policy and governance.

THE DEVELOPMENT OF NEW BIOMETRICS, AND THE SUPPORT OF EMERGING ONES, WOULD BE GREATLY ENHANCED BY A STRATEGIC WORKING ALLIANCE OF FORENSIC SCIENCE EXPERTS WITH COLLEAGUES IN THE SECURITY INDUSTRIES.

REACTIVE OR PROACTIVE?

Given that identity has a value not only to the rightful holder but also to the criminal acquirer, it is inevitable that a black market culture will thrive unless prevention and strong gatekeeping also become a focus. Forensic science has a tendency towards being reactive to the needs of the investigative agencies, whereas the future for crime reduction must surely lie in proactive strategies and policies. CIFAS, the UK's fraud prevention service, has reported that identity theft and identity fraud are among the fastest rising crimes of modern times[22]. With a 5% rise between 2013 and 2014, over 40% of all criminal cases of fraud relate to misappropriation of identity. Not surprisingly, there is a larger incidence in urban compared to rural areas, and major cities including London, Manchester, Birmingham, Leicester, Leeds and Glasgow have been identified as hotspots for such theft[23]. The major purpose of identity fraud is to illegally obtain goods and services in the name of an innocent person, and it is believed that the cost to the economy runs close to £3.3 billion per year for the UK. It is also no longer a crime that can be attributed to a specific demographic in respect of sex, age or geographical location, and the cost of repair and restitution following identity theft is extensive for the victim, typically taking between six months and two years to resolve[24]. Understandably, there is a major commercial and governmental drive to protect identity, to make theft more difficult, and to reduce the financial burden on the economy. This will only increase in importance and prominence as citizens prepare to trade their biometrics, and therefore their identity, as a token. The commercial answer to increasing security is for the customer to give up their biometrics, but that introduces an element of vulnerability that has largely either been ignored or poorly understood to date. Investment of resources needs to focus on prevention as a longer-term strategy for this escalating crime.

A growing global sense of fear and self-protection has catalysed the evolution of, and dependence on, biometrics in all aspects of our daily lives[5] such that it is now forms a very lucrative, buoyant and therefore highly competitive, commercial market. In recent years it has started to move away from the traditional approach of utilising a token or something that is known (e.g. a PIN number), and towards the exploitation of biometrics, which are viewed as offering greater security and confidence. The most common biometrics to be utilised in this way are fingerprints and facial recognition, and it is of great concern how readily the public are prepared to surrender a biometric to gain access to the latest commercial product. A recent survey of CIFAS members revealed that over two-thirds claimed to own an electronic device with a biometric security step installed, showing a dramatic rise from the previous year where only half responded that their mobiles, laptops, tablets etc required biometric (usually face or fingerprint) access mechanisms. If this is the way forward for identification then it is imperative that informed discussions occur to

SUPERIDENTITY

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Modern technology provides a myriad of ways to reveal identity, reflecting both the capabilities of current devices and the options that individuals have to manage their identity. However, threats to communities, coupled with the price of mistaken identifications, make it ever more important that our decisions about identity and identification are accurate. The SuperIdentity project was designed to respond to this need by using novel combinations of information. The result is the capacity to make robust identification decisions, knowing both the confidence in a decision and the means to increase that confidence.

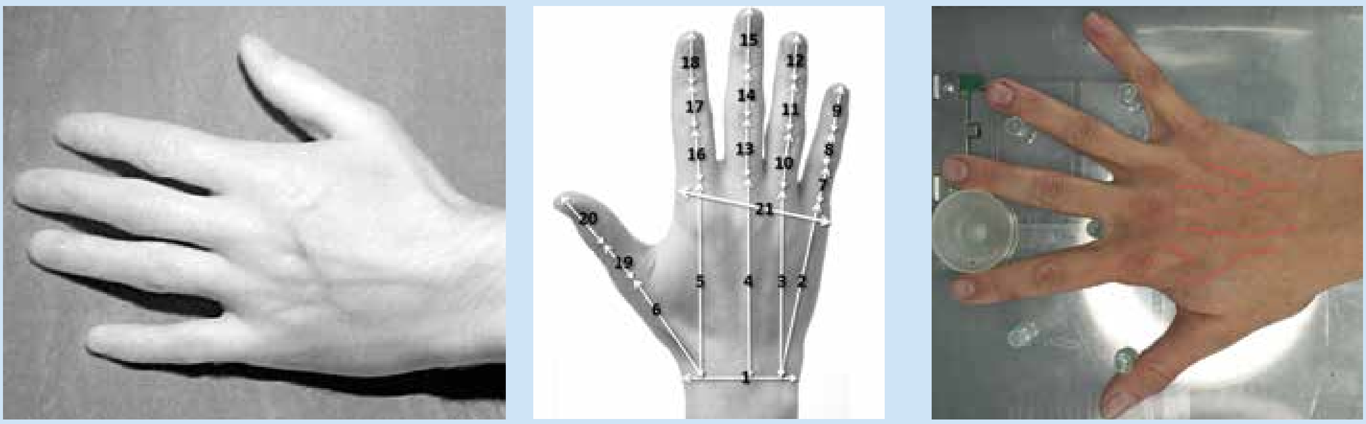
Funded by the Engineering and Physical Sciences Research Council (EPSRC), the SuperIdentity project ran from 2011 to 2015 and represented a multi-disciplinary endeavour bringing together scientists from the universities of Bath, Dundee, Kent, Leicester, Oxford, Southampton and the Pacific Northwest National Laboratories in the US. Its aim was to explore identity and identification through traditional and modern measures, with the iris, the voice and particular characteristics of the hand being amongst the emerging biometric measures under scrutiny (see Figure 1).

Although the team was at pains to demonstrate the reliability of each measure as a cue to identity, using both human and automated processing, the real power of the SuperIdentity project lay in the fusion of these measures. This enabled identification decisions to be boosted in terms of both reliability and confidence – put simply, the more measures that converge to signal identity, the more confident one can be in the resultant identification.

Information fusion also enabled the intelligent use of measures in a different way, allowing previously unknown information to be predicted from what was known. This critical shift from information combination to information prediction heralds a powerful new approach for scientists, with clear benefits in diverse fields such as legal investigations, advertising, marketing and more subjective judgements such as whether we trust someone.

The second notable advance provided by the SuperIdentity project was its consideration of measures from both online and physical contexts. In an era when we live our lives as

Figure 1: The hand offers one of the most valuable new biometrics under scrutiny. After measuring hand geometry (left), infrared light reveals the hand veins in much greater detail than is possible under natural light (centre). Viewing the hand under natural light, with veins superimposed, allows both geometry and vein analysis for matching purposes (right).



THE MORE MEASURES THAT CONVERGE TO SIGNAL IDENTITY, THE MORE CONFIDENT ONE CAN BE IN THE RESULTANT IDENTIFICATION

much online as offline, there is a clear need to be able to identify an individual in either context; and, at times, in being able to link an online individual to their offline counterpart. The SuperIdentity team have explored the reliability of making these links by analysing the finger gestures used when interacting with a smartphone, and avatar-user resemblances. Links between these measures and key characteristics such as personality, age or sex may critically help to narrow a field of search when making an identification.

The final advance provided by the SuperIdentity project was the capacity to create a framework to support identification. The greater the accuracy when identifying an individual from any particular measure, the more valuable that measure becomes. Equally, it also becomes more important to protect that piece of information from unwanted disclosure. Mindful of the prominence of privacy protection and data security, this element of our work reflects on both intelligence needs when gathering information, and citizens' needs when protecting information. As such, the project reinforces the need to balance our technological capabilities alongside individuals' attitudes, concerns and rights to privacy.

Courtesy of Richard Guest, University of Kent, and Helen Meadows, University of Dundee

protect the rights of the individual, the needs of the commercial sector, and the vision for government policy and its enduring legacy.

How certain are we of the security of our fingerprint as it is recorded on our mobile device? The research firm Acuity claimed that 2014 was a "bumper year" for the biometrics industry in the run up to Christmas as shoppers capitalised on mobile payment facilities[25]. Indeed, research by Visa Europe indicated that three-quarters of 16–24 year olds in the UK would feel comfortable using fingerprint scans, facial recognition or retinal scanning in place of traditional passcodes to overcome the 'inconvenience' of having to remember information. This was supported by a recent CSC survey where it was pointed out that the willingness to release security is not a 'generational' issue but one of 'age' and so this must remain an issue for the industry as the views of a population change with time. Next-generation passwords are also under development with a recent US military project to develop 'cognitive passwords'. This Application Programme Interface (API) is based on the emerging field of behavioural-based biometrics using algorithms to identify how a person accesses their desktop or mobile device (see case study on p68 for more on how the relationship between two different forms of our identity, physical and cyber, may be bridged). Behavioural biometrics, as opposed to biological biometrics, will always pose a problem for both the commercial and the forensic markets due to the inherent ability to necessitate compensation for change, and so these are more likely to remain in the realm of 'intelligence' related information rather than evidence.

As the ecosystem grows more complex, there is a move away from accepting single biometrics as being sufficient to meet the needs of heightened security, and the market has geared up towards multimodal biometrics platforms. The intention is to raise confidence in the security measures, but unfortunately there is also a cost impact[26]. Increasing complexity gives a perception of increased confidence, and this is largely achieved not only through more robust statistics for matching but also through the complexities required to spoof the systems, making multimodal approaches less susceptible to attack[27]. If multimodal biometric access becomes the norm, is the consumer aware of what proportion of their physical identity they may have to sacrifice in the future simply to continue to function in the modern world?

PRIVACY IMPLICATIONS

There is considerable debate at present within the different security and biometric communities with regards to the right to privacy and the security of state-collected and stored data, and the case study on p71 considers the importance of this area for enlightened and honest debate. The current media furore relates to the legitimacy of covert capture of faces through recognition software programmes. As we become increasingly security conscious, the importance of the right to remain anonymous is likely to gain momentum and will require redress by data security and privacy legislation, a matter that was raised in the House of Commons Select Committee on 20 November 2014. There is an urgent need to consider and debate the right to privacy over the need to manage a secure society. Are we sure that the Data Protection Act is strong enough to withstand the strains, both internal and external, that manifest as our identity comes under ever closer scrutiny? As we continue to increase our dependence on biometrics, their security and their legal robustness will become a troublesome issue for public confidence. If we lose our bank card or our PIN number then new ones can be issued, but if our biometrics are stolen then we cannot change our fingerprints – consequently, it becomes much more challenging to prove our innocence of a crime in the face of compelling biometric evidence. And if our multimodal biometrics are stolen, at what point are we no longer able to retrieve our identity from the hands of fraudsters and regain control? There are many significant challenges ahead for which we are perhaps not yet fully prepared and it is vital that the policy makers, industry, scientists, investigative forces and the judiciary work together not only to encourage development but also to manage and monitor the inevitable outcomes associated with a fast paced world.

At the core of all aspects of modern identity and identification lies the requirement for an unshakeable certainty of continuity of information, and confidence in verifiable robust data. In times past, proof of identity lay in document-based evidence: producing a birth certificate was sufficient to satisfy most needs. However, UNICEF reported in 2000 that approximately 40% of all births were not officially recorded, which may represent upwards of 50 million babies in a single year. On a rolling basis, this is a large number of individuals who potentially have no officially recorded identity. This lack of documentation may not present as a problem if the individual remains within the confines of a community where that approach is accepted, but when they move outwith those boundaries – perhaps because of displacement following war or famine, fleeing from persecution as refugees, or as illegal economic migrants – their lack of corroborating identification can become a major issue for border controls, immigration and ultimately the civil courts (when human rights are being addressed) or the criminal courts (should the individual either present as a victim or an accused).

A birth certificate, whether original or legally issued, is a 'breeder document' that can be used to obtain other forms of verification of identity. As such it carries an inherent value, and consequently a black market demand. However, the misappropriation and falsification of such documents has gradually eroded the confidence of authorities to accept them without question, specifically for high-risk activities such as crossing borders, opening bank accounts etc. In an attempt to eradicate the need for traditional paper-based documents and replace them with

AS WE BECOME INCREASINGLY SECURITY CONSCIOUS, THE IMPORTANCE OF THE RIGHT TO REMAIN ANONYMOUS IS LIKELY TO GAIN MOMENTUM AND WILL REQUIRE REDRESS BY DATA SECURITY AND PRIVACY LEGISLATION,

CASE STUDY

MANAGING BIOMETRICS

ISABELLE MOELLER, *Chief Executive, Biometrics Institute*

The use of biometrics has become an important tool in the discussion around security and identity management. Biometric authentication has the potential to ease the burden of security, thanks to its simplicity and usability.

The Biometrics Institute Industry Survey confirmed in 2013 that biometrics are at a crossroads. They are moving from large-scale government use to everyday consumer applications. Only the responsible use of biometrics will lead to successful applications. If implemented responsibly, biometrics are certainly a privacy enhancing technology.

When we provide a biometric or other sensitive personal data, we ask questions about trust and control. Governments are typically required to put very robust trust models in place to ensure that end-to-end security is provided, through government accredited networks, compliance processes for privacy, and record-keeping legislation – all assurance mechanisms that involve partnerships and processes around access to data. But in other organisations that end-to-end security and assurance might not exist, an absence that demands far more than just a technology solution.

Other key questions relate to control and data retention. What happens to that biometric? Who looks after it, and when will it be destroyed – after a person leaves school, or a particular job? What processes exist for managing any compromise of identity data, for re-establishing confidence in identity, for redress?

We have seen many successful implementations where biometrics have helped to transform identity management, privacy protection and identity security. Electronic passports facilitate a more efficient and secure travel experience, while large-scale identity management systems facilitate the delivery of government services to the poor and marginalised. But the public requires assurance that biometric managers are giving due consideration to privacy and data protection when they are considering, designing, implementing and managing biometric-based projects.

The Biometrics Institute has therefore developed several best-practice documents to help guide members along the way: the Biometrics Institute Privacy Awareness Checklist and Biometrics Privacy Guideline (available from www.biometricsinstitute.org).

We are also working on a proposal to create a Trust Mark to give consumers confidence in the responsible use of an identity product or service that incorporates biometrics. This will give biometric solutions providers and operators a tool to demonstrate that due consideration has been given to privacy and trust during planning and implementation.

BIOMETRICS ARE AT A CROSSROADS, MOVING FROM LARGE-SCALE GOVERNMENT USE TO EVERYDAY CONSUMER APPLICATIONS.

IDENTITY IS A CORNERSTONE OF OUR MODERN SOCIETY, AND ITS INFLUENCE AS A CENTRAL TENET OF OUR CULTURE IS ONLY GOING TO INCREASE.

an identification card supported by multimodal biometrics, India has embarked on an ambitious project to record biometrics in all 1.2 billion of its citizens. Each man, woman and child will receive a 12 digit unique identification number called an 'aadhar' as a proof of identity and this will be linked to their name, address and biometrics including iris scans and fingerprints[28]. Care is required here to ensure that biometrics collected when the person was 16 are still retrievable and applicable 20, 30 or 60 years later when they may come into question. If technology accelerated so much in that intervening period that the original databases could no longer be searched, then the longevity of the project must be addressed to ensure currency and long term accessibility while retaining the flexibility to advance with new technology. This is the current problem facing the UK's National DNA Database. Over 720 million identification numbers have been issued so far in India, and it is expected to exceed 1 billion by the end of 2015. The cost for the upkeep, security and success of such a system will make an interesting case study, in terms of both risk assessment and its role in criminal activities. The process is not without critics, and it is perhaps not surprising that the complex underpinning legislation is still pending in the Parliament of India. It is a brave move, and only time will be the judge of its success and value.

The US military project to record biometrics in Iraq and Afghanistan has received considerable criticism from human rights supporters. Its aim was to record as many biometrics as possible from much of the Afghan population. This information was used to try to understand the movement and complexity of the insurgent networks, but it has also become an increasingly valuable tool in the workings of the Afghan judicial system and in supporting progressive local and national social aid programmes. The biometrics included a full set of fingerprints, full face photo and iris scan, and were linked to name, address, occupation, tribal name and a military grid reference for where the individual was processed. A subsequent Biometric Enabled Watch List (BEWL) collated individuals who had been determined to be possible threats and linked them to biometrics-enabled intelligence. These so-called battlefield biometrics are a new and powerful tool in the war against terrorism, but there are also possible societal benefits that may emerge. The argument and balance between invasion of privacy and the greater good is one that still requires honest and open debate, and it is a brave stance to hold to one without consideration of the other in our modern world.

CONCLUSION

Identity is a cornerstone of our modern society, and its influence as a central tenet of our culture is only going to increase. It influences our feeling of safety and security, and exposes our feelings of vulnerability. Our apparent willingness to part with it for the latest shiny trinket should be of major concern to governments and institutions – once a biometric becomes a viable route for identity fraud, then the opportunity to recover it and secure it becomes exponentially more challenging. When this is extrapolated to multimodal biometrics then the loss of identity into the hands of the fraudster will result in serious and possibly irreversible issues for law-abiding citizens. This will encroach into the domain of the policymaker, who must balance an escalating public demand for security, a commercial clamour to provide it, and citizens who are willing to relinquish aspects of their identity, against a backdrop of criminal potential. A focus on the young and the elderly is imperative: despite campaigns and warnings, they are the most susceptible to criminals who target the very essence of who we are and see a value in our identity that many do not understand. The expansive ecosystem of government, science, justice, industry and society must find a way to work together to strike a workable balance. Identity, identification and the key players who seek to exploit the differences between the two will be a vital driver in defining and regulating the profile of our future society.

EMERGING BIOMETRICS IN THE COURTROOM

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In the UK, around 16% of children have experienced sexual abuse by 16 years of age; of these, 95% are abused by someone they know. When an individual is found to be in possession of indecent images that include instances of the abuse of minors, it is essential to identify the perpetrator. In many cases, the images will not contain readily identifiable features such as the face of the perpetrator. But if the perpetrator's hands or genitalia are captured in the images, new research has found that these can support the identification process.

In addition to well-established biometrics such as the ridge detail of the palmar surfaces of the hands (e.g. fingerprints), other anatomical features of the hand are widely accepted as commercial biometric identifiers that can verify an individual's identity. Such systems utilise fingerprints, palm-prints and vascular patterns of the hand (see Figure 1) to facilitate access to secure facilities or bank accounts. This information might also be available to investigators who are trying to compare suspects to the perpetrators pictured in indecent images.

When our team from the Centre for Anatomy and Human Identification (CAHID) investigated the first case of this type in 2007, little research had been undertaken into the individuality or uniqueness of certain anatomical features, in terms of their reliability for forensic human identification. But the knowledge gained from centuries of study into human anatomy suggested that these features were highly variable between individuals. The University of Dundee compiled a database of hand images, and subsequent studies have created a core of research investigating the use of such data in forensic comparison for identification purposes[1]. This facilitated methods to make forensic comparisons of anatomical features in suspect and offender images, detailing the similarities and differences between the image of the offender's hand and images of the suspect's hands.

The anatomical information is based on compound analysis of multiple features, such as scars of accidental origin; knuckle crease patterns (see Figure 2); superficial vein patterns (which develop during embryological development); as well as nail bed morphology and freckle patterns, both of which have genetic origins and are also influenced by environmental factors. Comparison of these features between offender and suspect can often provide sufficient information for exclusion of identity.

When defendants are confronted with the results of these comparisons, more than 80% of them change their plea. This reduces the time and money consumed by a lengthy court case and, more importantly, negates the requirement for vulnerable children to give evidence in court, where they would have to face their abuser and relive their experiences.

Figure 1: Superficial vein patterning on the dorsum of a hand

Figure 2: Knuckle creases, nail bed morpholo-gy and scars

CYBERFORENSICS

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Cybercrime costs the UK an estimated £27 billion per year. The growth in internet use, data storage capacity, cloud computing and encryption all pose major challenges for cyberforensics. But along with innovations such as block chain technology, they also offer opportunities for forensic investigators – if they are backed by suitable policy and legal frameworks.

Over the past ten years, the number of people connected to the internet has grown to 3.2 billion. This has enabled a boom in cybercrime – a range of activities that exploit vulnerabilities in the use of the internet and other electronic systems to illicitly access or attack information and services used by citizens, business and governments.

The global cost of cybercrime is currently in excess of $400 billion per year. The cost of cybercrime is difficult to measure, however, in a recent report, the cost to the UK of cybercrime was estimated to be £27 billion per year[1]. The growth in cybercrime has led to an increase in the volume of data, and the number of cyberforensic analyses, involved in investigating a case. In addition, the transnational nature of the internet can hinder the process of acquiring evidence and bringing a criminal to justice.

Recent prosecutions in the UK and US have highlighted the fact that hackers continue to target credit card details and intellectual property. In September 2015, Vladimir Drinkman, a 34-year-old hacker who hails from Russia, confessed to committing cybercrimes before a New Jersey federal court. His felonies, which cost businesses hundreds of millions of dollars in losses, involved breaching the corporate networks of major organizations such as Nasdaq, Dow Jones, Heartland Payment Systems, and JetBlue, among at least a dozen others, according to the US Department of Justice. The initial entry was often gained using an 'SQL injection attack', a simple and well-documented attack that highlights the poor level of security exhibited by most corporate organisations when connecting to the internet. Other cyberattacks worthy of note include:

- In September 2015, Apple announced that its development environment XCode had been subverted to make malicious software available from Apple's App Store. Consequently, Apple has had to remove up to 300 applications from the App Store.
- In June 2015, the US Office of Personnel Management (OPM) announced that it had been the target of a data breach involving the records of as many as 18 million people. Information targeted in the breach included personally identifiable information such as Social Security numbers, as well as names, dates, places of birth, and addresses.
- Silk Road was an online black market launched in February 2011, and the first modern 'dark net' market. In 2013, the Federal Bureau of Investigation (FBI) shut down the website and arrested Ross William Ulbricht under charges of being the site's pseudonymous founder, Dread Pirate Roberts.

Cybercriminals can range from foreign intelligence services and large organised crime groups, to disreputable (but otherwise legitimate) companies and individuals or small groups of opportunists. Elements of cybercrime include:

- Extortion (using techniques such as 'ransom-ware' and 'denial-of-service' attacks)
- Child exploitation, such as sharing and producing illegal images (see case study p80)
- Theft of intellectual property, such as trade secrets and patents
- Copyright infringement, such as illicit file sharing and forging of software
- Malicious misuse (including hacking, worms/viruses and botnets)
- Data protection, such as theft of personal data and credit card details

The past ten years has also seen the growth of the Dark Web – content hosted on 'dark networks' that require specific software to access, thus concealing it from most internet users and enabling anonymous browsing and communication. The Dark Web has become a mature supply chain that supports cybercriminal's activities, selling everything that a cybercriminal needs to engage in a malicious criminal activity. Once successful, the same supply chain allows the criminal to sell what they have stolen.

Meanwhile, the Internet of Things (IoT) is expected to reach up to 100 billion objects by 2020[2]. The Internet of Things is the network of physical objects embedded with electronics, software, sensors, and network connectivity, which enable these objects to collect and exchange data. The Internet of Things allows objects to be sensed and controlled remotely across existing network infrastructure, creating opportunities for more direct integration between the physical world and computer-based systems, and resulting in improved efficiency, accuracy and economic benefit. From a law enforcement perspective, the Internet of Things also offers a rich environment within which evidence can be gathered and validated.

The growth in cloud computing and cloud storage solutions (such as Dropbox, Google Drive, Amazon Cloud and iCloud) means that users now have the ability to share information and access it anywhere at anytime. This has opened up another important target for evidence gathering, but it also offers a useful tool for digital forensics examiners, who will be able to send commands through a cloud environment to other machines, producing faster results with little need to travel to the scene of the crime.

THE CYBERFORENSIC PROCESS

The standard computer forensic process consists of three basic elements (see Figure 1), each of which contains their own set of challenges. The role and function of the forensic process is to acquire and analyse evidence in such a manner that it can be presented in a court of law. This means that the judge, jury and barristers must be able to understand and interpret the evidence, which requires an expert witness to educate them while presenting evidence. As the complexity of cyberattacks grows, so too does the volume of evidence that can be collected in relation to a crime.

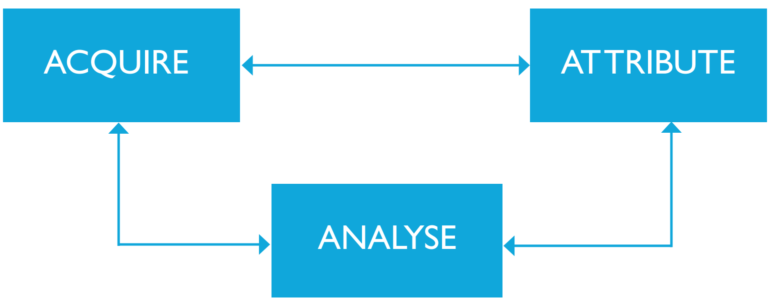
THE GROWTH IN CLOUD COMPUTING AND CLOUD STORAGE SOLUTIONS MEANS THAT USERS NOW HAVE THE ABILITY TO SHARE INFORMATION AND ACCESS IT ANYWHERE AT ANYTIME.

1. Acquire

As was seen with the investigation into the 7/7 bombing in London, the volume of data currently required by law enforcement is growing. In fact, this problem can now be viewed as a 'big data' problem. Investigators must copy this data bit by bit – a process known as imaging – to show that they have not tampered with the evidence. Then they store the original evidence under lock and key, and work with the copy (also known as the forensics image).

Cybercrime can involve complex supply chains spanning the globe (e.g. Silk Road), using anonymity technologies (such as Tor and the Dark Web) that allow individuals to purchase everything from malicious software kits to time on a botnet. As people make use of digital storage media with ever-larger volumes, it takes much more time to create a forensically-sound image and perform a triage on the data inside. This is now starting to approach the time available for law enforcement officials to hold a suspect before charging them. The growth in the number of devices that make up the IoT (including smart meters, smart grids and industrial

Figure 1 – The three elements of cyberforensics



THE VERY DEFINITION OF CYBERCRIME VARIES FROM COUNTRY TO COUNTRY, AS DOES THE LEGISLATION RELATING TO THE ACQUISITION AND ANALYSIS OF FORENSIC EVIDENCE.

process control systems) will pose significant challenges for this data acquisition process.

2. Analyse

The result of the disclosures made by Edward Snowden relating to the level of monitoring and surveillance of people's activities in cyberspace has resulted in an increased use of cryptographic services. These services range from disk encryption and web browsing to mobile chat programs. The major challenge for law enforcement in this area lies in recovering the cryptographic keys that keep this data secure. One can now purchase encrypting hard drives, smart phones and tablets that make it virtually impossible to recover data without the presence of the decryption key.

The growth in the use of anonymity services to hide ones identity during encrypted browser sessions has resulted in the increased need for law enforcement to perform 'live memory' forensics in real time while the machine is at the target's website. With the volume of data now available to investigators, the time and processing capability required is increasing exponentially. The impact is that law enforcement officials need to perform data mining on 'big data' scales of the order of 100 billion items.

The transnational nature of cybercrime means that various law enforcement agencies, both within a country and across geographical borders, must share their data or intelligence. For example, credit card fraud in one area can be used to pay for cybercriminal or terrorist activities in another.

The major challenge associated with the analysis of forensic evidence relates to the identification, collection, acquisition and preservation of large volumes of digital evidence. The growth of cloud computing and the IoT will only exacerbate this problem. The UK's capability to address this challenge is limited to a few academic centres of excellence, and no law enforcement agencies currently possess this capability.

The growth of encryption technology also presents a serious technical challenge, with the creation of unbreakable ciphers such as AES (256-Bit). Modern USB/Flash technology has adopted encryption as a mechanism to protect person data. The placement of such technologies within smartphones is now making it virtually impossible to recover data. On 25 September 2014, FBI Director James Comey criticised Apple and Google for developing smartphone encryption so secure that law enforcement officials cannot easily gain access to information stored on the devices. He said:

"I am a huge believer in the rule of law, but I also believe that no one in this country is beyond the law. … What concerns me about this is companies marketing something expressly to allow people to place themselves beyond the law."

The net effect is that it is getting harder for law-enforcement and intelligence agencies to recover digital evidence from encrypted devices.

3. Attribute

The rising use of technologies such as virtual private networks, cryptographic tunneling, proxies and anonymity services (such as torrents and onion routing) have significantly diminished law enforcement's ability to attribute an attack to an individual. Moreover, the very definition of cybercrime varies from country to country, as does the legislation relating to the acquisition and analysis of forensic evidence. The net effect is that the burden of proof is different in different countries, and the rules of extradition between countries can vary. However, there are efforts to harmonise legislation on cybercrime, such as the Budapest Convention on Cybercrime[3], which entered into force for the UK on 1 September 2011.

In 2015, the US government introduced an executive order allowing for sanctions to be taken against individuals engaged in significant malicious cyber-enabled activities. This executive order aims to give the US the ability to sanction people that are outside its jurisdiction, and where the US has little chance of extradition, by restricting their resources.

DIGITAL EVIDENCE IS OFTEN A KEY FACTOR IN MANY COURT CASES, GIVEN THE PROLIFERATION OF MOBILE DEVICES, EMAIL, TEXT MESSAGING, SOCIAL MEDIA APPLICATIONS AND DIGITAL CAMERAS.

According to the US president, it provides his administration with "a targeted tool for countering the most significant" threats that could be waged against the nation's critical infrastructure. The UK has no such framework within which to sanction individuals

STANDARDS

Over the past few years a number of standards have emerged in the area of cyberforensics. Current guidance from the forensic regulator states that:

"The provider of digital forensic science (the provider) shall comply with the Codes of Practice and Conduct for Forensic Science Providers and Practitioners in the Criminal Justice System (the Codes) and be accredited to BS EN ISO/IEC17020:2012 for any crime scene activity and BS EN ISO/IEC17025:2005 for any laboratory function (such as the recovery or imaging of electronic data)"

Standards such as ISO/IEC17020:2005 and ISO/IEC17025:2005 provide certification of the imaging process, while standards such as ISO/IEC27037:2012 focus on the identification, collection, acquisition and preservation of potential digital evidence.

However, they fail to address the data requirements in relation to:

- The identification, collection, acquisition and preservation of digital evidence located in the cloud, the IoT, and social media
- The presentation of digital evidence in the courtroom

FURTHER CHALLENGES IN CYBERFORENSICS

In recent years, crime labs have faced criticism for a 'lack of validation' in a variety of forensics disciplines. In January 2015, the US National Commission on Forensic Science stated there was "a notable dearth of peer-reviewed, published studies establishing the scientific bases and validity of many forensic methods"[4]. The term "foundation" was used no less than thirty times to emphasise that each forensic discipline must have a scientifically robust and validated basis to its methods, its technologies, and its process of interpreting data.

In April 2015, the Federal Bureau of Investigation (FBI) admitted that microscopic hair analysis contained errors in at least 90% of cases[5]. Peter Neufeld, Co-Director of the Innocence Project, which is affiliated with the Cardozo School of Law in New York, stated: "While the FBI and DOJ are to be commended for bringing these errors to light and notifying many of the people adversely affected, this epic miscarriage of justice calls for a rigorous review to determine how this started almost four decades ago and why it took so long to come to light."

The relatively new discipline of cyberforensics certainly needs more foundational science. Many question the results of initial data-breach investigations for failing to identify who or what group was behind the crime. After a large data breach, Chief Executive Officers grow anxious awaiting an accurate attribution, while a news media frenzy lowers stock prices and threatens jobs. The recent Sony hacking case, with an indication of North Korean state sponsorship, is just one prominent example.

Even more shocking is that some traditionalists fail to recognise digital forensics as a forensics discipline, leaving computer experts out of national committees in this important field of criminal justice. Today, digital evidence is often a key factor in many court cases, given the proliferation of mobile devices, email, text messaging, social media applications and digital cameras. Staying ahead of the cyber technology curve is an important issue for any forensics professional: high-tech apparatus is used in all the forensics disciplines and requires data-centric security and integrity to properly interpret results.

Yet one should question whether computer forensics has really progressed much since the

Yet one should question whether computer forensics has really progressed much since the late 1990s in terms its foundational approaches and techniques. There have undoubtedly been advances in areas such as triage approaches, mobile devices, write-blocking, enterprise forensics to minimize human travel, and internet evidence-finding tools. But producing case results is still very time intensive, with few mathematical techniques being deployed to aid in accuracy and timeliness.

First responders still spend a significant amount of time 'bagging and tagging' digital media and making bit-by-bit image copies. Then they verify this copy through the use of 'hash values' – a unique number that changes if the evidence is tampered with – to show they are exact replicas. Given this backdrop, what is the next trend that will modernise cyberforensics?

BLOCK CHAIN TECHNOLOGY

A block chain is a type of database that gathers data into blocks, and then uses cryptographic signatures to link them together. This approach underlies cryptocurrencies such as Bitcoin, but it is also finding wider use in various financial services and other sectors (see Chapter 13 case study p148).

Block chain technology has the potential to revolutionize cyberforensics, and can be used to prove with mathematical certainty the lineage of data, chain of custody, and data integrity. Permissioned block chain solutions such as Keyless Signature Infrastructure (KSI), which is used today for cybersecurity applications, focus on data integrity and could allow forensics examiners to understand the sequential chain of events faster and with more precision when conducting forensics analysis. Proof of integrity and time from a common block chain (with a common clock) enables unified timeline analysis, no matter where in the world the data is stored, signed and verified by KSI. This could change the primary way that forensics examiners approach their data analysis, producing more accurate and faster results to help resolve insider data theft or

Figure 2: Trends in cyberforensics

TIME	POINT	DETAILS
2007	Defining Digital Forensics	"The application of computer science and investigative procedures for a legal purpose involving the analysis of digital evidence after proper search authority, chain of custody, validation with mathematics, use of validated tools, repeatability, reporting, and possible expert presentation"[6]
2011	Geo-location and cloud forensics	"Examination might require access to computer and network resources involving expanded scope that may involve more than one venue and geolocation"[7]
2012	Cyberforensics certification	"Employing forensics professionals that hold the credibility of a globally accepted and comprehensive certification … provides a strategic advantage for public and private organizations"[8]
2013	Cloud forensics challenges	Outlined in US National Institute of Standards and Technology (NIST) Cloud Computing Forensic Science Challenges[9]
2014	Hackers at home and abroad	Charges against five Chinese military hackers for cyber espionage signal a new era of prosecutions by the US Department of Justice for theft of intellectual property data[9]
2015	Use of block chain encryption	Growing recognition of the value that block chain-based technology provides for cybersecurity, data validation and digital forensics.

isolate external threats exfiltrating data.

The days of spending time making a copy of any digital evidence before starting the analysis are waning. Faster and more accurate methods are now available which include fault-tolerant and anti-tamper features. KSI offers both of these benefits to preserve important digital evidence.

In today's digital forensics lab, only one machine calculates the validation hash; but in the future, one could use pre-case forensic-ready data systems to compute and assign hash values to all data in the system. Not only could a system have a digital fingerprint for each data object or file, it could also have a timestamp with each item afforded a Keyless Signature. Keyless Signatures are small and compact (about 2kB), and are portable and can be imprinted with the data or stored separately. With KSI's common clock, one could understand the chain of events better when conducting the forensics analysis – especially when trying to reassemble system contexts across multiple geographies. This supports the mutual auditability of forensic investigations, ensuring that all e-discovery efforts are immutable preserved against evidentiary items.

Guardtime's global KSI system is currently operational in partnership with Ericsson, one of the world's largest telecommunication service providers. The healthcare industry and the energy sector are also showing interest in this technology; and the transportation industry (with automobiles, airplanes, ships, and trains connected to the internet) has similar data-centric security and safety concerns.

Guardtime plans to have global scale cybersecurity and forensics services, and is working with a major telecommunications company to build a global infrastructure for clients to create pre-case hash values with Keyless Signatures. This data centric security system uses Guardtime's permissioned-based block chain and fault tolerant techniques to ensure the validation of the original files.

This technique does not require a client to share the content of the files – they only need to use the algorithm to create the hash token. From a cybersecurity standpoint, it can also be used to ensure certain files were not changed or deleted, and that no data was added to a volume without following an agreed rule set.

This may help to create a Criminal Justice System with more transparency of their chain of custody. There is public demand for more transparency regarding police arrests, and for conclusive results in high-profile data breach cases. More modernisation that builds on the progress of the past decade (see Figure 2) to include industrial block chain encryption could cause a leap forward.

INTERNATIONAL LEADERSHIP IS REQUIRED TO CREATE INTERNATIONAL CONVENTIONS AND LEGAL FRAMEWORKS THAT WILL FACILITATE THE DETECTION AND PROSECUTION OF CYBERCRIME.

CONCLUSION

The challenges facing cyberforensics are substantial and require solutions at the technical, legal and policy levels. The explosion in the volume of data and data types that are now available to the forensic analyst poses major technical challenges, and there are still problems to solve in acquiring data from some devices (e.g. IoT), partly due to the volatile nature of data on such systems.

Innovations such as block chain technology can help to meet some of these challenges. But legal frameworks across the world are struggling to cope with the internet, because it recognises no geographical boundaries. Although recent court cases have seen the US government attempt to impose its legal framework on all servers owned by US companies, even if located outside of the US, the Supreme Court has yet to give its final ruling. What is clear is that international leadership is required to create international conventions and legal frameworks (such as the law of the sea) that will facilitate the detection and prosecution of cybercrime.

CASE STUDY

CHILD ABUSE IMAGE DATABASE

CHRIS FELTON, *Safeguarding Directorate's Online and Digital Lead, Home Office*

The Child Abuse Image Database (CAID) is a national UK policing system that supports law enforcement in the pursuit of offenders involved in the sexual exploitation of children, and in seeking to safeguard the victims of this crime. The Prime Minister announced the creation of CAID at the WePROTECT Summit at Downing Street in December 2014.

Acting on intelligence received, the police enter a suspect's premises and seize digital devices that may contain illegal images and video. Collectively, the devices seized in a single case can hold terabytes of data – the task of searching for illegal abusive material, and the evidence that will help to identify victims, is daunting. CAID's database of illegal image signatures can quickly help investigators determine which devices are suspect and should be seized for detailed investigation.

In order to bring a successful prosecution for making, possessing or distributing abusive images, the police investigator must present evidence to the court about the quantity and severity of the images discovered in the suspect's possession, because this will significantly affect the sentence in the event of a guilty verdict. To achieve this, the investigator must sift through many thousands of images in order to categorise them. This is both stressful and extremely time consuming. CAID is able to significantly reduce the stress and workload placed on investigators by using its database of known abusive images to pre-categorise the contents of the seized devices following the original triage. The investigator can quickly divide the thousands of image files into three groups: known illegal images; known legal images; and unknown images. The pre-categorised images found by comparison with the CAID dataset may be sufficient in themselves to bring a prosecution, thus saving police time and bringing offenders to justice more promptly. More importantly, the saving in police time allows them to place greater focus on the search for previously unknown victims depicted in the abusive images seized.

Confidence in the quality of the CAID dataset, both by the police and the courts, is absolutely critical to success. An officer must be sure that an image presented as evidence meets the legal criteria regarding both the age of the child and the activity depicted, which can be extremely subjective in some instances. Therefore CAID has incorporated a voting system for the categorisation of abusive images, which requires an image to receive three votes in agreement from different police forces before it is given a confirmed categorisation.

The search for victims passes through two stages. The offender may also be a contact abuser, in which case it is vital to identify any images which may have been taken using the offender's own camera or in premises available to the offender. The local element of CAID provides the investigator with image matching and analysis technology that enables them to make a rapid risk assessment. If the investigator determines that there are no local victims depicted, then the images can be uploaded to the CAID national database and made immediately available to regional and national victim identification specialists for investigation using CAID's powerful image analysis tools. Speed is of the essence in the field of victim identification, and CAID delivers the means of rapidly sharing images and related intelligence with the officers best equipped to tackle this form of crime.

THE GLOBAL PERSPECTIVE

TIM WILSON,
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Rising cross-border crime demands greater international criminal justice cooperation. This presents challenges and opportunities for forensic science – which include developing common standards for procedures, measurements and databases – to facilitate the efficient sharing of evidence and information. The principle issue for decision-makers is to ensure that UK scientists and technologists can fully participate in shaping the global future of forensic science.

Increased cross-border crime is an aspect of global change that affects everyday life. This is particularly true of cyber and financial crime, but many other crimes can have an international dimension. The British diaspora is now as large as about 10% of the UK resident population[2], which means that forensic evidence or information is increasingly received from foreign legal systems, in connection with crimes, accidents and natural disasters involving Britons.

The ethical and pragmatic reasons for participating in international criminal justice cooperation can be seen in the development of UK law and policy on extradition from the 19th century onwards. In contrast to many other jurisdictions, British citizens were not allowed to hide behind its borders to evade justice for crimes committed abroad. The rationale for this approach was restated in the Scott Baker Review of Extradition[3]:

"Extradition operates on the basis of mutual benefit and obligations. Given the ease of movement of people throughout the world, the United Kingdom needs the help of the international community to fight serious crime within its borders, just as much as other states need the assistance of the United Kingdom to deal with crime affecting their interests."

Such cooperation is not simply a matter of mutual advantage. The deontological and retributive (legal, moral and social) significance of the criminal law gives rise to an obligation to assist in the investigation of crimes committed by British citizens abroad, and in efforts to bring them to account. As such, forensic science is an increasingly international exercise.

INTERNATIONAL CRIMINAL JUSTICE COOPERATION

The internationalisation of crime takes several forms:

1. **Transnational offending:** criminal conduct by an individual in a country that is not their country of birth. All the forensic science evidence will be recovered in the country where the offence or disaster took place, but forensically-acquired information (e.g. DNA profiles and fingerprints) may be available in other jurisdictions. These will usually be obtained through cooperation between national police forces, directly assisted in a minority of cases by either Europol or Interpol, but invariably using secure communication channels provided by those organisations.

2. **Transnational crime:** an offence where the judicially-relevant locations (e.g. crime scenes) are in more than one country. International cooperation in such cases is likely to also involve judicial officials (e.g. prosecutors, investigating magistrates and extradition judges) and in some cases this may be facilitated through Europol and Eurojust. There will be similar judicial involvement (e.g. coroners, in England and Wales) in the identification and repatriation of the dead following a natural disaster.

3. **International crime:** an offence that may have been committed in one country, from which the forensic science evidence must be obtained, but which can only be prosecuted elsewhere (e.g. crimes by a state against its own citizens, which are triable at the International Criminal Court (ICC)).

With the increase in international criminal justice cooperation, it has become more important to standardise how information is collected, analysed, stored and exchanged. Greater cost-effectiveness and enhanced legal clarity are also essential when information and evidence crosses borders. For example, highly-standardised information that is already held on police forensic biometric databases (such as fingerprints and DNA profiles) can be exchanged quickly and at comparatively little additional cost.

Even when an alleged offence has no connection with the UK's jurisdiction, UK forensic scientists and clinicians may still be commissioned to analyse evidence or review the work of other scientists. This might be due to the reputational standing of UK experts, or it may reflect global shortages in disciplines such as forensic pathology[4]. Indeed, no country will necessarily have sufficient expertise to deal with the consequences of major natural disasters or terrorist incidents on the scale of 9/11 without international assistance.

UK forensic science makes important contributions to international resilience. This was demonstrated, for example, during the last stage of the Flight MH17 disaster victim identification (DVI) work (see case study p90). Scientists from LGC Forensics were called in, alongside colleagues from Bode Cellmark Forensics (USA) and the International Commission on Missing Persons (ICMP), to help the Netherlands Forensics Institute to accelerate the final DNA analyses of the victims' remains[5]. This activity also illustrates how international requirements have taken the forensic use of DNA beyond its origins in civil or administrative paternity disputes and the investigation of traditional crimes. The 50,000 bone samples and 30,000 unidentified human remains tested to date by, respectively, the ICMP and Bode Cellmark Forensics indicates the scale of activity. This exceeds the amount of DNA analysis ever performed in several EU countries for criminal justice purposes.

Forensic science expertise need not be confined to a reactive role. Knowledge and skills acquired in responding to past crimes can be utilised to prevent crime or make communities more secure. For instance, Swedish document examiners (who are experts in identifying and giving evidence about documents that have

UK FORENSIC SCIENCE MAKES IMPORTANT CONTRIBUTIONS TO INTERNATIONAL RESILIENCE.

been forged or tampered with) assisted the Swedish government with the design of new passports and national identity cards. Their detailed knowledge of how criminals have created counterfeit documents, or altered genuine documents, was used to create a new set of identity documents with greatly enhanced security features. This not only contributes to Sweden's security – it enhances global security, especially relating to international travel.

The nature of the legal framework for cooperation is a key factor in determining its cost. The EU legal instruments for international cooperation between member states (and Schengen Area countries such as Iceland, Norway and Switzerland) are, in the view of experienced lawyers working in this field, "infinitely more efficient" than bilateral arrangements. The latter are "cumbersome, subject to local variation, and often inconsistent; all of which inevitably causes delay and confusion"[6]. The Lyon-Roma Group within the G7 may sometimes provide a suitable forum for creating alternative modes of cooperation using Interpol secure communication channels with Canada, Japan and the USA[7]. The most valuable G7 contribution to international forensic science capability, however, was its decision in 1996 to create the ICMP to identify missing persons from the conflicts in the former Yugoslavia. This decision funded the creation of the specialist DNA expertise needed to develop highly reliable DNA analysis techniques and skills for DVI purposes, particularly from bone[8].

The US Government has made a crucial unilateral contribution to international cooperation, through the free provision of the Federal Bureau of Investigation's CODIS software. CODIS (Combined DNA Index System) is used in over 50 countries to identify matches among DNA profiles, including during the international exchange of DNA data[9].

Over the past two decades, major scientific and technological advances such as ten-print fingerprint scanning, automated DNA and

THE INTERNATIONAL EXCHANGE OF DNA DATA AND FINGERPRINTS CAN ADDITIONALLY IDENTIFY TRENDS AND SPATIAL FEATURES IN CROSS-BORDER CRIME AND OFFENDING.

fingerprint comparisons, and mobile access to databases have made the initial stages of international criminal justice cooperation significantly faster and more efficient. But costs will rise and delays are bound to occur – as they do in national investigations – when forensic-science-derived information is assimilated and appraised with other information in a case; and when there is formal procuratorial or judicial international cooperation, particularly if extradition is required. It is not surprising, therefore, that international cooperation is predominantly focused on "preventing and combating organised crime, terrorism and other forms of serious crime"[10]. This is also reflected in the operation of the EU ('Prüm') arrangements for the systematic exchange of forensic biometric data[11].

THE SCALE AND NATURE OF TRASNATIONAL OFFENDING AND CRIMES

Although the internationalisation of crime may increasingly affect UK society, overall crime rates in this country continue to fall. The most reliable data source, the Crime Survey for England and Wales, last year contained the lowest estimate since it began in 1981 (ref. 12).

Increased movement and migration does not appear to have had a major impact on criminal demographics, and the number of first-time entrants dealt with by English and Welsh criminal justice agencies has halved since 2007. Where data does exist, crime by EU offenders in member states other than their own may be much lower than the proportion of such people within the resident population (approximately 4% of total crime in the Czech Republic; 3% in Italy, Germany and Denmark; 2.5% in the Netherlands; 1.5% in Slovakia; and less than 1% in Austria and Poland)[13, 14].

There are no comparable national statistics for England and Wales, but the most recent analysis of available data reveals a picture consistent with the pattern elsewhere: offending by the citizens of other EU countries is chiefly relatively low-level acquisitive crime, particularly theft from shops. Overall, they account for some 1% of prosecuted offences in the UK (significantly lower than the proportion of such residents in the UK population) and appears to be concentrated geographically in the south-east, eastern counties and Cumbria, rather than dispersed nationally[14].

Knowledge of these outcomes and trends help to frame our general understanding of the criminological impact of globalisation. They do not, however, indicate the scale of the challenge to the Criminal Justice System created by a significant number of extra offences, some of which will be serious, and potential suspects. Bail and sentencing decisions – in addition to the conduct of investigations – require information about criminal careers and real-world identity that can only be obtained through cooperation with other jurisdictions. London exemplifies the increasing internationalisation of British policing. Foreign-born people (not just from the EU) comprised 37% of the population of central London and 33% of the outer boroughs in 2013 (ref. 15), with foreign citizens accounting for 25-30% of arrests[16] and an estimated 25% of high-harm offenders (including organised crime group members and predatory sex offenders)[17]. In many investigations, sharing forensic biometric data will be either the only or the most efficient means of obtaining indispensable information. Experience in the Netherlands demonstrates how the exchange of DNA data has provided potential investigative leads and unlocked access to criminal back histories (see Table 1).

A match between anonymous profiles recovered from crime scenes in one or more countries may have considerable value if analysts can link such information with other crimes. This may eventually lead to the identification of a possible suspect.

The international exchange of DNA data and fingerprints can additionally identify trends and spatial features in cross-border crime and

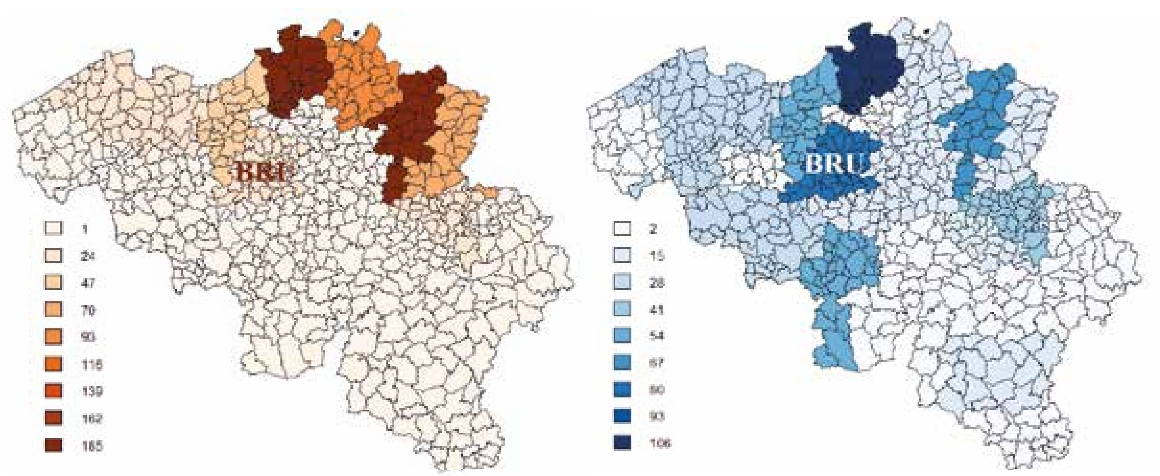
Table 1: Transnational crime and DNA identifications in the Netherlands (at February 2015)[18]

DUTCH DATABASE (PROFILE TYPE MATCHED)	OTHER MEMBER STATE DATABASES (PROFILE TYPE MATCHED)	NUMBER OF MATCHES REPORTED TO DUTCH PROSECUTORS AND POLICE
Anonymous profile (trace) recovered from a crime scene	The profile of a known person	3,100
Anonymous profile (trace) recovered from a crime scene	Anonymous profile (trace) recovered from a crime scene	2,326
The profile of a known person	Anonymous profile (trace) recovered from a crime scene	836
The profile of a known person	The profile of a known person	971

offending. Used in this way, forensic science data analysis can also be used to inform crime prevention strategies at a sub-regional level. For example, the initial exchanges of DNA data between Belgium, France and the Netherlands have shown that although all Belgian judicial districts have cases with an international dimension, some general trends can be discerned (see Figure 1). For instance, matches with France seem to have a greater affinity for southern districts than matches with the Netherlands. Nationality cannot be inferred from the database from which the Belgian matches came, but there may be some correlation between the source of matches and the linguistic regions. Generally, criminals travelling north may go further when committing crimes than offenders who have arrived in Belgium from the north. These considerations are unlikely, however, to explain the concentration of international offending in two regions (Antwerp and Limburg). There, different levels and forms of economic activity may operate as pull factors. If so, such considerations may need to be covered in the international aspects of crime prevention strategies in those areas.

Such analytical techniques will become even more powerful with the help of technological platforms that integrate different types of forensic information. These might make use of knowledge gained from human biological traces, the chemical identification of illicit drugs and large amounts of digital evidence. Meanwhile, the exchange of

Figure 1: These maps of Belgium show the number and distribution of criminal cases associated with matches (sometimes multiple matches in a single case) between DNA profiles held on the Dutch (left) and French (right) databases with DNA profiles on the Belgian database[19].



THE DIFFERENCE BETWEEN SCIENTIFIC AND LEGAL CULTURES CAN BE A STUMBLING BLOCK FOR THE EFFICIENT USE OF FORENSIC EVIDENCE, AND THIS WILL VARY BETWEEN JURISDICTIONS.

ten-prints can rapidly identify serial offenders engaged in cross-border crime who have been arrested elsewhere.

IMPROVING THE INTERNATIONAL USE OF SCIENTIFIC EVIDENCE

The difference between scientific and legal cultures can be a stumbling block for the efficient use of forensic evidence, and this will vary between jurisdictions. UK scientists and informed commentators, including the House of Commons Select Committee on Science and Technology, have complained about a generally low level of scientific knowledge among lawyers and judges[20]. But there is evidence that legal and scientific thinking is converging. The courts, particularly the Court of Appeal and the Privy Council, are becoming increasingly confident and better informed in handling complex scientific questions[21].

Internationally, though, such convergence may be less advanced in some countries, and can be hampered by the disparate procedures and expectations of both lawyers and scientists. In addition, scientists have sometimes reinforced the barriers to efficient and reliable communication between jurisdictions by adopting different standards and analytical processes, for example. This happened with DNA multiplexes, designed to assay sets of genetic markers – known as loci – to ascribe with a high level of confidence unique identity to individuals. Earlier tests in countries such as the UK, other EU member states, the US and China often used different markers in their analyses, and moving towards common international standards has been time-consuming and expensive. This has now been largely resolved, however, and the loci used by these countries increasingly overlap (see Table 2). This will result in major time and cost savings by avoiding the need for confirmatory retesting in order to have confidence in matches between national databases using different multiplexes.

This convergence has also offered greater discriminating power as national databases grew larger, and increased the sensitivity of DNA analyses. These developments have enhanced the value of forensic science for justice, but the increased sensitivity has also intensified the challenges of forensic science. For example, scientists now need to use enhanced anti-contamination measures, and their reports need to be carefully scrutinised, because greater sensitivity could increase the identification of DNA traces that have been indirectly transferred to the crime scene from persons unconnected with the offence.

The development of DNA multiplexes with more overlapping loci is an example of how the international exchange of evidence or information provided by forensic science may bring additional urgency to research. But there are many other areas where collaboration and funding are likely to be concentrated in the continuing quest for global best practice.

1 **Human cognition** explains the risks from cognitive bias (see Chapter 4). Different countries have responded to this issue in various ways, ranging from guidance about cognitive bias issued by the Forensic Science Regulator[22], to the introduction of 'contrarian thinking' (almost a process of peer review) within Dutch police procedures for the investigation of complex and high-impact crimes[23]. The effectiveness of different approaches should be carefully researched and the results shared internationally in order to identify global best practice.

2 **Technological platforms for integrated forensic information.** In several countries, work is being undertaken to develop platforms for the integrated analysis of forensic information. Such a system might make use of knowledge gained from human biological traces, the chemical identification of illicit drugs and large amounts of digital evidence[24]. When such platforms become fully operational, forensic science institutions are likely to become involved in initiating and managing individual investigations, and perhaps even the more general prioritisation

Table 2: The international convergence of DNA multiplexes

YEAR	MULTIPLEX	NUMBER OF MARKERS	OVERLAP WITH UK MULTIPLEX AT THAT TIME		OVERLAP WITH USA MULTIPLEX AT THAT TIME	OVERLAP WITH CHINA MULTIPLEX AT THAT TIME
			ENGLAND AND WALES	SCOTLAND		
1995	UK SGM	7	N/A		N/A	N/A
1998	USA ORIGINAL CODIS	13	6		N/A	N/A
1999	UK SGM+	11	N/A		8	N/A
2010	CHINA SINOFILER	15	9		11	N/A
2014	UK (ENGLAND AND WALES) DNA-17	17	N/A	11	8	10
2015	UK (SCOTLAND) DNA-24	24	17	N/A	13	14
2017	USA CODIS CORE LOCI	20	15	20	N/A	14

of non-scientific criminal justice resources. The automatic processing of combinations of data in this way will also severely test the adaptability and resilience of data protection regulations and the ability to adequately address ethical issues (see Chapter 9 case study p100). In this respect, England and Wales offers a global template for national governance, with the appointment of the Forensic Biometrics Commissioner and the National DNA Database's independent Ethics Group, in addition to the Information Commissioner or equivalent data supervisors who are to be found in all EU and Prüm member states.

3 **Individualisation.** One of the major challenges faced globally in forensic science research includes the development of statistical models for the assessment of fingerprint comparisons, and in translating the results of such research to crime scene and courtroom. Indeed, some of the strongest criticism in the US National Academy of Sciences' 2009 report 'Strengthening Forensic Science in the United States: A Path Forward'[25] was directed at fingerprint analysis. Since then, however, there have been advances in the measurement of the accuracy, reliability, repeatability and reproducibility of the conclusions offered by fingerprint experts[26]. Similarly, higher-resolution CCTV images are enabling the standardisation of facial recognition information, which is emerging as an equally important priority for multi-national research: for example, in a project involving forensic scientists from the Netherlands, Sweden and Switzerland that is investigating the calculation of likelihood ratios when using such images[27].

4 **Human and microbial genetics.** It is likely that forensic genetic analyses will continue to consume a large proportion of forensic science research and operational budgets, and pose new ethical and probative challenges. The global forecast for the biometrics market – including commercial and security applications, as well as criminal justice – is an estimated growth from \$8.7 billion in 2013 to nearly \$27.5 billion by 2019, but many of the new applications arriving on this market have been criticised as being based on "minimal scientific grounding"[28]. Faced with such multi-national market pressures, there should be more international collaboration in determining research priorities, and a greater sharing of the research burden. Significant local or regional socio-economic factors will, however, continue to shape distinctively national scientific priorities.

ANALYTICAL TECHNIQUES WILL BECOME EVEN MORE POWERFUL WITH THE HELP OF TECHNOLOGICAL PLATFORMS THAT INTEGRATE DIFFERENT TYPES OF FORENSIC INFORMATION.

For example, China has more drowning deaths than anywhere else in the world[29], and it is the leading cause of accidental death for children under the age of 14 (ref. 30). China's scientists, therefore, have a major incentive for improving the reliability of techniques for the diagnosis of drowning. For deaths associated with water, pathologists often face a difficult diagnostic challenge in distinguishing accidents from those attributable to suspicious causes. One promising initiative is the development of in China of new DNA barcoding techniques for the detection and analysis of microscopic algae found in the victim's body[31]. Success in this work would be of great value globally, contributing to accident prevention as well criminal justice.

5 **Standardisation of evidential reporting, laboratory processes and governance (including data protection).** Standardisation should not only apply to the methods used in the forensic laboratory; it is equally applicable to the governance of the institutions in which the work takes place, and how the use of data is regulated. The Prüm biometric exchange arrangements require that all participating countries only exchange DNA and fingerprint data that is produced in units accredited to EN ISO/IEC 17025 (ref. 32). All Prüm participating states must also observe specified data protection principles. The international exchange of forensic biometric data must be authorised under a national law that provides a means for citizens to check the lawfulness of the processing of their data, the recording of data exchanges, and random compliance checks by national supervisory bodies. These data protection arrangements have to be in place before the exchange of data (other than for pilot testing) may commence[33].

The demands on forensic scientists or clinicians also vary between countries depending on whether their judicial systems are inquisitorial (a continuing investigation, with the trial as a public verification of its findings) or adversarial (in which parties set out two conflicting sets of arguments). For example, an adversarial system traditionally confers a more proactive role on such expert witnesses.

But criminal law is evolving in such a way that the distinctions between adversarial and inquisitorial systems are less clear cut, and standardised scientific expertise is becoming more portable across international borders. Under either system, the accused should know the nature of the forensic evidence to be brought by the prosecution, receive effective advice about its likely validity and how it might be challenged, and be told about any alternative views on what it might signify. In recent years, however, these principles have been reinforced in the European Union by directives to improve defence rights. The UK government has, with the exception of the Legal Aid Directive, opted into these measures, which include the timely disclosure of the case against a suspect and the right of access to legal advice[34].

These changes have come at a time when professional outlooks in both the scientific and legal communities have undergone remarkable progress. This is partly a result of the testing of the epistemological foundations of DNA evidence. This legal scrutiny has transformed the notion of transparency in forensic science, achieving a high level of consensus about the need for "clarity about how the probative value of the evidence is derived from recognised scientific procedures"[35]. This change in how scientific evidence is regarded also reflects the influence of Case Assessment and Interpretation (CAI) that was pioneered by the former Forensic Science Service[36], and the traditional disclosure duties on the prosecution under English law[37].

The effects of these trends could be seen at the most recent European forensic science meeting, the 7th European Academy of Forensic Science triennial conference, held in September 2015. Events at that conference included debate about proposals for a pan-European initiative for standardising scientific

Table 3: The evolution of admissibility rules

Frye (1923)[39] (still binding in many US state jurisdictions)	**Daubert (1993)[40] and the US Federal Rules of Evidence**	**Reliability limb of the common law admissibility test, informed by Criminal Procedure Rules and related Criminal Practice Direction in England and Wales (2014)**
Has the underlying scientific principle gained general acceptance in the relevant scientific community?	Is the underlying reasoning or methodology scientifically valid and can it properly be applied to the facts?	Is there a sufficiently reliable scientific basis for the evidence to be admitted?
	Can the underlying theory or technique be tested and has it been tested?	
	Has the underling theory or technique been subjected to peer review and publication in refereed journals?	Whether material on which the opinion is based has been reviewed by others (e.g. peer reviewed) and, if so, what the views of those others were
	Has the underlying theory or technique attracted widespread support in a relevant scientific community or communities?	If there is a range of expert opinion in relation to the relevant matter, where the expert's opinion lies and whether the expert has properly explained his or her preference Whether the expert's methods followed established practice and, if not, whether the expert properly explained the reason for divergence
	Known or potential error rate and the existence and maintenance of standards	The extent and quality of the data on which the opinion based and the validity of methods that were used to obtain it Whether the opinion takes account of matters such as the degree of precision or the margin of uncertainty (where it relies on the results of methods such as tests or measurements).
		Whether the opinion properly explains how safe or unsafe an inference from findings on which it relies is (if it relies on such an inference)
		Whether the information which was available to the expert was complete and whether the expert took all relevant information into account
		The extent to which the opinion is based on material which falls outside the expert's field of expertise

CASE STUDY

DISASTER VICTIM IDENTIFICATION: MH17

JEN WILLIAMS, *National Civil Contingencies and Disaster Victim Identification Coordinator, National Police Chiefs Council (NPCC)*

On 17 July 2014, a passenger plane from Malaysian Airlines MH17 was shot down over eastern Ukraine by a missile. The flight was from Amsterdam to Kuala Lumpur and there were 298 people on board.

The bodies landed in Shakhtarsk Region in a war zone with the area controlled by a militia of pro-Russian rebels. Human remains and debris were spread over 34 square kilometres. Access was restricted and controlled by the rebels, and the human remains were collected by local farmers and miners. Of the 298 people killed in this incident, 283 were passengers and 15 were crew members. The nationalities encompassed 10 different countries with the majority being from the Netherlands (193). Ten passengers were travelling on a British passport; 6 people under the age of 21 were British dual nationals travelling on their other passport.

The initial proposal was for the victims' remains to be taken by train to Kharkiv, a city controlled by Ukrainian authorities, for the identification process. Following political negotiations it was agreed that the bodies would be flown to the Netherlands for the identification processes. The first remains arrived in Kharkiv on 22 July, and the first flight to the Netherlands took place on 23 July. This was unusual, as recovery and identification would normally take place in the country where the incident occurred. However, the Netherlands is respected for its disaster victim identification (DVI) and is a member of the Interpol DVI Steering Group.

When UK citizens are killed abroad in suspicious circumstances and the remains returned to England or Wales, a coroner's investigation must be held. Therefore it is important that the investigation into the identity of the victims, and how, where and when they died, meets the Interpol identification standards and provides the additional required information. Scotland and Northern Ireland have other rules, although the integrity of the investigation is equally important.

Interpol identification standards require scientific identification by one of the primary identifiers: odontology, ridgeology (fingerprints and footprints) and DNA. DVI itself involves matching ante mortem samples with post mortem samples to provide a conclusive identification. This means working with the family of the deceased to identify sources for primary identifiers from the family, home and medical sources such as dentists and doctors.

The Dutch lead for the identification processes invited colleagues from the Interpol DVI Steering Group to assist with the management of the operation. The UK provided a DVI manager; a team for the mortuary that included an odontologist, a CT scanner and radiography expertise; and a team for reconciliation and identification files. Forensic and intelligence collection within the UK and 3 other countries (Netherlands, New Zealand and South Africa) provided the ante mortem samples for the British Nationals.

The challenge was immense, due to both the collection methods and the disruption to the bodies, some of which were mere fragments. Victims were identified by odontology (119), fingerprints (64) and DNA (130), with some having more than one primary identifier. Secondary and supporting evidence was also sought in each case. There were 730 initial post mortems, which increased to over 5000 after DNA investigations on co-mingled human remains. To date, 296 of 298 victims have been identified, and after the process was extended to try to find remains for the final 2 victims it was finally closed at the end of August 2015.

In order to improve future international DVI investigations, the Interpol DVI Steering Group has been working to provide standardised practices and has recently reviewed both the Interpol DVI forms and guidance to simplify the DVI process. The UK has designed recovery booklets to assist with a coordinated recovery process, and these have now been endorsed by Interpol. The European Police College (CEPOL) is creating a DVI training course, supported by the Interpol DVI Steering Group, to standardise processes across EU member states and support international interoperability.

INTERPOL IDENTIFICATION STANDARDS REQUIRE SCIENTIFIC IDENTIFICATION BY ONE OF THE PRIMARY IDENTIFIERS: ODONTOLOGY, RIDGEOLOGY (FINGERPRINTS AND FOOTPRINTS) AND DNA. DVI ITSELF INVOLVES MATCHING ANTE MORTEM SAMPLES WITH POST MORTEM SAMPLES TO PROVIDE A CONCLUSIVE IDENTIFICATION.

practice in all key subject areas, thus improving the ability of judges and prosecutors to assess the probative value of scientific evidence; and training for forensic scientists, irrespective of procedural differences between their jurisdictions, in evaluative reporting.

A principle of English law that has been developing in recent years is that forensic science evidence may not be admitted if it is not sufficiently reliable to be put before a jury. Until recently, however, the English threshold for accepting scientific evidence was low compared with US criminal procedure based on the Daubert decision and the Federal Rules of Evidence. Last year, the Court of Appeal indicated that following changes in the Criminal Procedure Rules, "a new and more rigorous approach on the part of advocates and the courts to the handling of expert evidence must be adopted"[38]. The evolution of admissibility rules in Anglo-American jurisprudence is summarised in Table 3.

With the 2014 rule changes, the English judiciary has attempted to achieve a new balance in the admission of scientific evidence. This is intended to combine a more rigorous or critical approach by advocates and the courts to such evidence[38], with continued access to "the advantages to be gained from new techniques and new advances in science"[41]. The reforms are being supported by training organised by the Advocacy Training Council (ATC) "to support advocates in making an informed assessment as to the reliability of experts"[42].

Yet when viewed in the light of international perspectives, two questions arise. First, the promising dialogue now seen in this country between law and science – with senior judges attending a recent Royal Society meeting (see Chapter 1 case study p20) – is personal and has not been institutionalised. For example, there is no formal link between the Forensic Science Regulator and the judicial rule-making bodies. A substantial risk of errors remains because of the random nature by which probative issues come before the Court of Appeal, and the absence of any provision for judicially appointed scientific experts. Secondly, as the authors of the 2009 US National Academy of Sciences report put it, whether judicial review alone can cure "the infirmities

CASE STUDY

FORENSIC ANALYSIS OF CHEMICAL WEAPONS IN SYRIA

CERYS REES, *Head of Chemical and Biological Analysis and Attribution, Defence Science and Technology Laboratory (Dstl)*

Throughout the summer of 2013, the world watched as pictures and videos emerged from Syria suggesting that the use of chemical weapons should be added to the reports of other atrocities taking place in that country. Even before these pictures emerged, the chemical and biological analysis and attribution capability (CBAAC) at Dstl had been analysing physiological samples from victims and environmental samples from the areas that were reportedly affected. This analysis aimed to provide the highest levels of government – in the UK and internationally – with empirical evidence of whether this was indeed the first use of nerve agents in more than 25 years; and to augment the broader analysis of the situation that was already being provided by Ministry of Defence's (MOD) Defence Intelligence Assessment Staff.

The MOD and the Home Office had already recognised that the UK needed the capability to analyse samples for the presence of chemical and biological agents to the highest possible standards. Consequently, much of Dstl's analysis was accredited to the international standard ISO 17025:2005, which is the standard applicable to forensic laboratories. In addition, the Dstl maintained a chain of custody for each sample to demonstrate that they could not have been tampered with, or altered in any way, while in the laboratory. (Based on these procedures, the laboratory has since been successfully reviewed against International Laboratory Accreditation Cooperation G19 – Modules in a Forensic Science Process and the UK Forensic Science Regulator's Codes of Conduct).

Our analysis of blood, hair and urine from casualties showing symptoms consistent with nerve agent poisoning revealed markers characteristic of exposure to sarin. The analysis – of three separate sample types from the same individual – provided compelling evidence that this could not have been a 'spoofed' exposure, but could only have occurred following an attack with sarin. This proved to be the first laboratory confirmation that chemical warfare agents had been used in Syria. Our highly specialised analytical work also revealed traces of sarin and/or its characteristic breakdown products in associated environmental samples such as soil, wood and wire. Further detailed analysis of the environmental samples identified indicators of how the sarin had been produced. When the data from the physiological and environmental samples (and their sourcing) was evaluated in conjunction with the rich intelligence picture, the resulting all-source assessment provided UK government with high confidence information that the chemical weapon sarin had been used on numerous occasions.

When considered in light of The Review of Intelligence of Weapons of Mass Destruction (Butler review, 2004), which stated that "more weight had been placed on intelligence than intelligence could bear", the high-confidence information from laboratory analysis of samples to a 'forensic' standard has now been shown to be highly beneficial for decision makers at the most senior levels of government, when combined with other sources of information.

Research within CBAAC is now focussed on developing techniques to provide attribution information such as: the origins of precursor chemicals used to make the sarin; when the chemical agent was produced;

THE HIGH-CONFIDENCE INFORMATION FROM LABORATORY ANALYSIS OF SAMPLES TO A 'FORENSIC' STANDARD HAS NOW BEEN SHOWN TO BE HIGHLY BENEFICIAL FOR DECISION MAKERS AT THE MOST SENIOR LEVELS OF GOVERNMENT.

and the identity of specific individuals responsible for both the production and use of this type of weapon. Although it is challenging to acquire this information, it could have a profound effect on UK foreign policy, and help to deter states and terrorist organisations from pursuing weapons of this nature in the future.

of the forensic science community"[25]. It is likely that this central test facing forensic science internationally will only be resolved through systematic and extensive research, and that will require significant and sustained funding. This year, $8.5 million of the US National Institute of Standards and Technology (NIST) budget will be devoted to forensic science research, and an additional $4 million has been provided to NIST to fund external research in a Centre of Excellence (COE). In the previous year, the US National Institute of Justice disbursed more than $20 million in research grants into forensic science. Based an equivalent proportion of GDP, matching the US government sponsorship of forensic science research would require targeted budgets of about $5.5 million in the UK, within an aggregate investment of some $34.4 million by the entire European Union[43].

CONCLUSION

The insights of earlier generations of UK scientists in applying fingerprint comparisons and DNA analysis have fundamentally shaped contemporary conceptions of criminal investigation. Pioneering work on the standardisation of laboratory procedures and biometric databases; the use of such techniques in tackling high-volume crime; and the assessment and interpretation of scientific evidence; have all provided benchmarks that have been adopted in other countries or incorporated into international standards. The principle issue for decision-makers today is how to most effectively and efficiently ensure that UK scientists and technologists can participate in the globally-collaborative enterprise of shaping the future of forensic science, and benefit from the knowledge, expertise and ideas to be found in the international community. Achieving those goals would contribute to the resilience of both science in general, and criminal justice in particular, in the UK.

WILDLIFE CRIME

LUCY WEBSTER, *Wildlife Forensic Scientist, Science and Advice for Scottish Agriculture (SASA)*

The illegal wildlife trade is one of the most significant transnational organised crimes, generating billions of dollars each year for those involved[1]. These crimes impact the populations of animals and plants persecuted, including many critically endangered species, as well as the communities where these species are found.

For some endangered species, limited trade is permitted by CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora[2]). Permitted trade is strictly controlled, and export and import permits are required from the relevant CITES management authorities to move specimens internationally. This system for cross-border movement has, however, been abused. For example, legally hunted rhinoceros horn trophies are known to have disappeared after import to the hunter's home country.

One such case involved a hunter in the Czech Republic, who had imported a rhinoceros trophy from South Africa. At an inspection visit by the local CITES Enforcement Authority, no rhinoceros horn trophy was present. The hunter claimed to have had the horn carved into small cups, but the CITES Enforcement Authority were not convinced by this story. To establish whether the cups were rhinoceros horn in origin or not, a sample of a cup was sent to the Wildlife DNA Forensic unit at SASA[3] for DNA analysis. A DNA test to identify the species of origin from the cup sample was applied, identifying the carving as originating from a cow (Bos taurus) contradicting the hunter's claim. This case has not yet been concluded, but it is likely that this rhinoceros horn has become part of the illegal wildlife trade.

The need for specialist wildlife forensic services is clear – without DNA testing, it may have been impossible to refute the hunter's claim. Wildlife forensic science encompasses a range of specialist disciplines including non-human DNA analysis, veterinary pathology, morphological examination and specialist chemical analysis[4, 5]. Outside the mainstream of forensic science provision, and yet providing evidence for criminal investigations, the development of standards in these specialist fields has been driven from within the wildlife forensic community[6, 7, 8]. The Society for Wildlife Forensic Science (SWFS) was established in 2009 to facilitate the development of this field and the standards required[8]. In addition to provision of proficiency testing, the society launched a certification scheme in 2012 for individual practitioners. The standards issued by SWFS are overseen by the Forensic Science Standards Board in the USA[9], although they were written to be applicable at an international level.

SWFS has members representing more than 60 laboratories across 15 countries. This network of wildlife forensic scientists can help to answer investigative questions regarding the origin of seized specimens, making a substantial contribution to combat the illegal wildlife trade.

DESIGNING OUT CRIME

NICK ROSS, *Chairman*
UCL Jill Dando Institute of Crime Science

Forensic science has long focused on crimes that have already occurred. But there is untapped opportunity for the insights and methodologies of science to prevent crimes from happening in the first place.

Forensic science (FS) has contributed greatly to the evidence-base of criminal investigations. It has triumphed in exposing miscarriages of justice. It has evolved from a supporting role to become a front-line analytic tool, often directing the efforts of investigators. The vast majority of serious cases, and a significant proportion of all Crown Court cases, now include presentation of one or more types of forensic evidence, and public confidence in FS is so robust that the Lord Chief Justice of England and Wales has wondered aloud about whether such faith is justified[1].

Many scientists share those doubts, as Itiel Dror observes in Chapter 4. The US National Academy of Sciences concluded in 2009 that, "with the exception of DNA analysis, no forensic method has been rigorously shown to have the capacity to consistently, and with a high degree of certainty, demonstrate a connection between evidence and a specific individual or source."[2]

There are other legitimate concerns about the use of FS in court, not least those of critics like Dror who warn that FS may help legitimise deep-seated weaknesses in court processes. These include a reliance on adversarial methods and on precedent, strict rules which exclude evidence from being aired, and a demand for a binary outcome. No other questions that relate to public safety are now judged in this way.

There is also the matter of cost. The criminal law is facing a financial crisis. Against a trend in which many goods and services have experienced price deflation, the expense and length of court cases has been rising steadily for a century. It is far from clear whether, on balance, FS makes the Criminal Justice System nimbler and more cost-effective (see Chapter 2 case study p29).

PRE-EMPTING CRIME

There are major opportunities for FS to refine its techniques, be more economical, and make itself more relevant to the judicial system. But there may be even greater prospects for it beyond the confines of criminal justice. Since the inception of modern FS, which began with fingerprinting in the 19th century, it has been enlisted to help win a war that, ideally, would have been averted in the first place. Traditionally a criminal investigation follows in the wake of victimisation; a key question for forensic science is the extent to which science could pre-empt the crime. Indeed, it is a remarkable that FS has thus far mostly seen its role as downstream of offending: finding someone to blame has had more importance than finding a solution to future crime.

Blame plainly has its merits. Catching and convicting wrongdoers can create a triple-whammy: providing a much-needed sense of justice, in some cases removing the wrongdoer's freedom to cause more harm, and, ideally, deterring future crime.

But court dispositions seem to have had disappointingly little influence on the ebb and flow of offending. In Britain, this pattern was obscured because of a reliance on data recorded by the police, which capture less than half of crime revealed by other methods[3,4] (see Figure 1) and can be vulnerable to recording error and deliberate obfuscation – so much so that in 2014 the UK Statistics Authority suspended their designation as National Statistics. At least one chief constable has described them as "dead in the water"[5].

Victims surveys such as the Crime Survey for England and Wales (CSEW)[3] have become the preferred method for measuring trends in all but the rarest of crimes. Mark Bangs, senior statistician in the Office for National Statistics' Crime Statistics and Analysis Team, says: "The CSEW provides a better reflection of the extent of crime than police recorded figures, as the survey asks about crimes that are not reported to or recorded by the police. The survey is also unaffected by changes in

Figure 1: Trends in police-recorded crime for England and Wales, compared with Crime Survey for England and Wales[3,4]

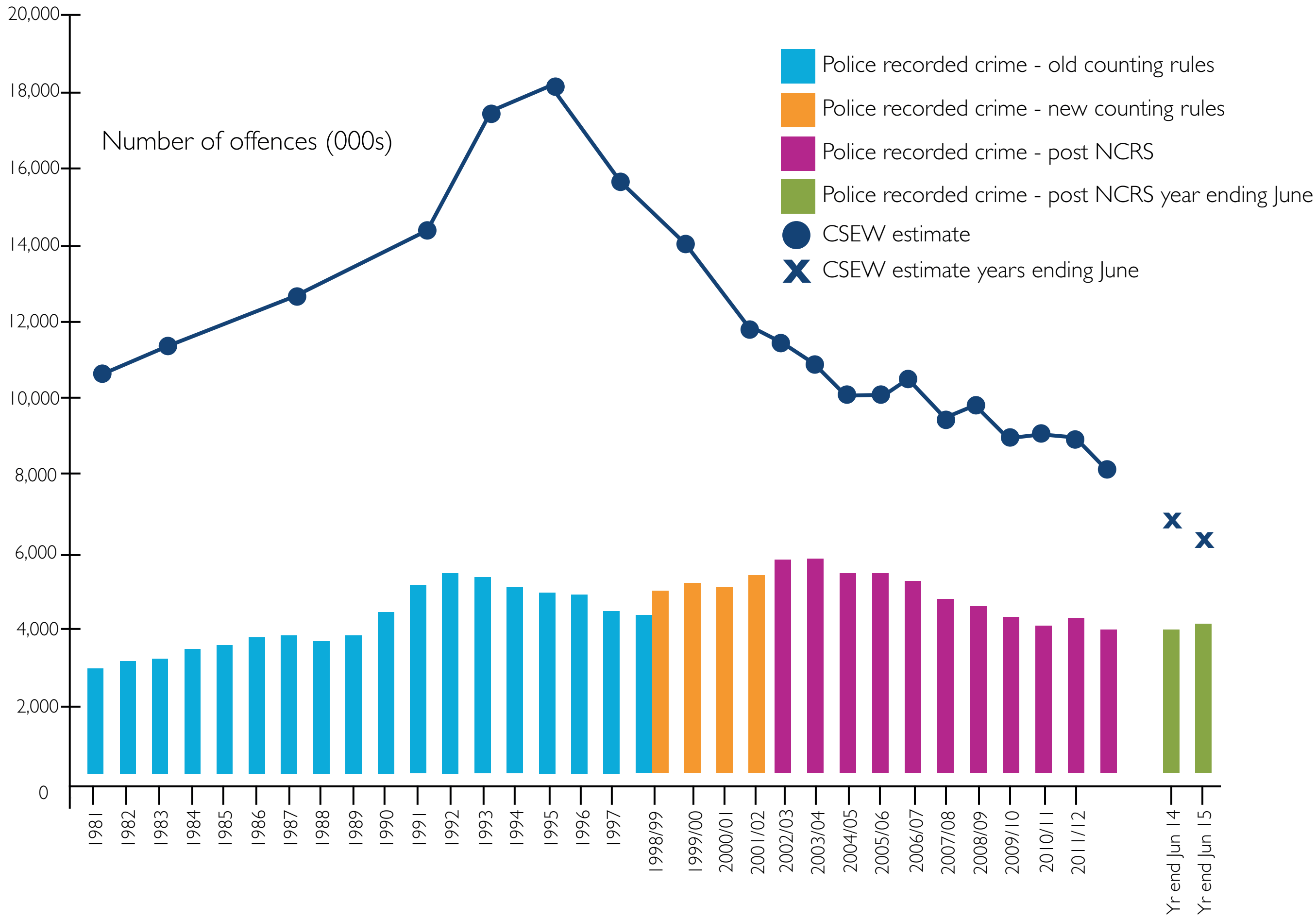
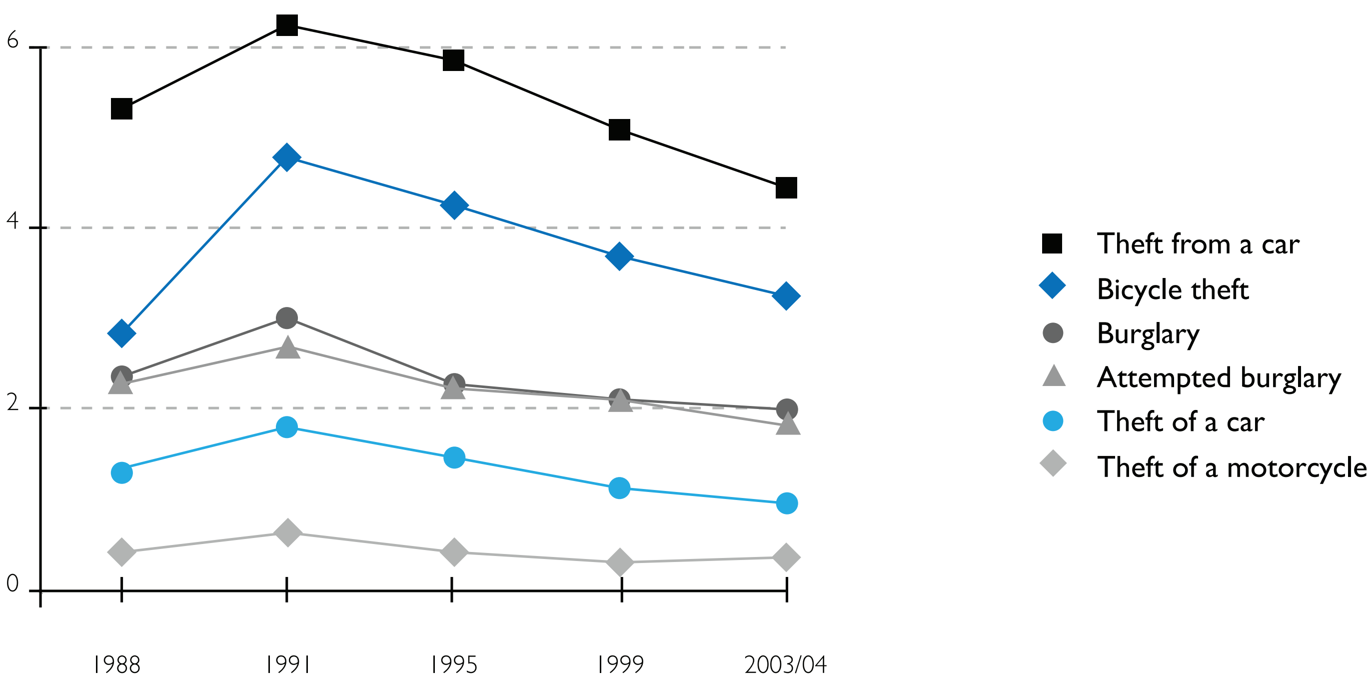


Figure 2: Trends in crime: average of one-year prevalence rates (the number of people who have experienced that crime) for selected property thefts in 15 Western countries[7].



WHEREAS SOMETIMES CRIME IS SIMPLY DISPLACED FROM ONE TARGET TO ANOTHER, MORE FREQUENTLY THERE IS A HALO EFFECT WHEREBY FEWER PEOPLE ARE RECRUITED TO ANTISOCIAL BEHAVIOUR.

police recording practices or levels of public reporting to the police, so it provides a more consistent measure over time." Victim surveys are also less susceptible to classification error or manipulation[6] than police records.

Given this standardised metric there is now overwhelming consensus among statisticians and senior police that crime surged from the 1960s to the 1990s and then fell faster than it had risen. This pattern was broadly common across the industrialised world and the trend was similar in countries with punitive or liberal penal policies (see Figure 2)[7].

In other words, catching people is a necessary response to crime but the Criminal Justice System has rarely been proven to dictate, or even largely influence, rates of victimisation. This is not to say that there is no role for deterrence and incarceration, but that their impact is not always conspicuous. Accordingly, it might be useful for scientists to apply themselves to the factors that are at least closely correlated with the rise and fall of crime.

We do not have to look far. It has long been known that protective measures can enhance security. This is why early people dwelt in caves and later built castles and city walls. It is why we have locks and PIN numbers for our credit cards. There is truth in the old saw that opportunity makes the thief.

Of course there is more to crime than opportunity alone. There has to be a person or population predisposed to cutting corners or being downright antisocial, and there needs to be temptation (which lawyers call a motive). That gives us several angles for potential intervention. But to assume that crime is simply caused by criminals is rather like saying illness is caused by patients, or that driving is caused by motorists. It is tautological rather than useful in designing a response. Moreover it is harder (and usually ethically more challenging) to change people than it is to change the circumstances in which they find themselves.

The disconnect between courts and crime becomes more starkly apparent when checked against individual crime types. Crime, like illness, is really a collection of many different malaises. While individual trajectories can contribute to a common pattern, there can be contrasting undercurrents below the troughs and waves. Yet examination of almost any category of offending has shown little correlation with what happened in courts. For example, homicide in Britain swelled alarmingly after the abolition of capital punishment, but it was already rising before that event, and has fallen dramatically since. Car crime rocketed despite little change in penal tariffs and has subsequently dropped by about three-quarters (see case study p105), again with no dramatic change in court disposals. The same is true of burglary and most other traditional physical and contact crimes.

The steep falls in offending, and particularly blue-collar crime, show that we can reduce crime through better preventative measures, and can do so on a dramatic scale. High-quality research has also shown that whereas sometimes crime is simply displaced from one target to another, more frequently there is a halo effect whereby fewer people are recruited to antisocial behaviour[8]. (Typically the pattern seems to be that growth in opportunities for acquisitive crime leads eventually to a rise in violent crime, but that removing temptations for physical theft causes fewer people to graduate into more serious crime.)

DESIGNING OUT CRIME

Designing out crime is in many ways little different from designing out accidents. Cars provide an obvious example: for many decades manufacturers blamed motorists for road casualties, thereby absolving themselves of the need to engineer solutions, until campaigners like Ralph Nader turned the tide of public opinion. Similarly the industry denied its own responsibility for car theft until vehicle crime became so ubiquitous that the government called business leaders to account and published 'lists of shame' identifying models most likely to be stolen. It might just be coincidence but recorded offences halved within eight years and have continued to plummet.

There are dozens of similar stories where thoughtless innovation led to surges in crime and where sensible interventions led to precipitous drops. Within a few years of the replacement of shop counters in favour of self-service checkouts there was, perhaps inevitably, a surge in shoplifting[9], one in which prominent middle-class people were caught up along with those whom conventional criminology might have predicted to be criminals. When prosecutions failed to stem the losses, retailers began to introduce an array of surrogate shop counters in the form of RF readers, dummy display packaging, CCTV and security guards. Similarly, as consumerism took off and ordinary homes became filled with tempting products such as TVs and video recorders, domestic burglary surged until in 1989 the Association of Chief Police Officers, endorsed by the Home Office and the insurance industry, introduced new standards for new and refurbished properties called Secured By Design. As deadlocks, double-glazing, and intruder alarms became widespread, the rate of burglaries fell emphatically and consistently for quarter of a century.

Violent crime too has been curbed by prudent interventions intended to make circumstances default to safety rather than provocation. Segregating rival football fans and penalising clubs for misbehaviour restored respect for British soccer after years of global infamy. Redesigning spaces so that drinkers are jostled less, provided with food, or supplied with harmless glassware has had a marked effect on casualties where alcohol is implicated. Sometimes circumstantial change has on its own fuelled or quelled crime waves. The rising popularity of mobile phones and portable electronic gadgets propelled a swell of street robberies until their security measures made mugging increasingly redundant – mobile phone theft is now concentrated mostly between children for whom bullying has always been a problem (see case study p102). The link between opportunity and violence is less clear-cut than in acquisitive crime, but correlations like those between knife-carrying and wounding in Scotland suggests that opportunity makes the killer as well as the thief. There are also many theories about the falling rates of violent crime – from abortion leading to fewer unwanted male children, to declining alcohol and drug use, or even a drop in atmospheric lead concentrations – all showing some degree of persuasive correlation, though none consistently. The simplest reason – the Occam's Razor answer – might be that physical theft acts as a recruiting sergeant to more serious offending, so that as stealing declines so, eventually, will assault. There are probably many factors working in tandem, some much more important than others. On the other hand there are unequivocal connections between circumstance and many types of offending. Among these are internet-enabled crimes, such as spamming, scamming, identity theft, child sexual exploitation and fraud; ill-conceived expense-claim systems like those that ensnared so many otherwise honourable MPs; or the multi-billion pound tricks and swindles within poorly supervised financial service industries. Just as we have learned to curb blue-collar offences, we have thrown open vulnerabilities to white-collar ones, tempting largely different populations to offend and demonstrating clearly that the middle-classes are no more immune to temptation and opportunity than are the poor – or for that matter the exceedingly rich.

THE OPPORTUNITIES OF SCIENCE

There is ample opportunity here for the insights and methodologies of science to save us from future harm. Science uses observable, testable and repeatable measurements and experiments to understand how things commonly behave. It is a systematic process of evaluating theories through meticulous control of contaminating

IT HAS LONG BEEN KNOWN THAT PROTECTIVE MEASURES CAN ENHANCE SECURITY. THIS IS WHY EARLY PEOPLE DWELT IN CAVES AND LATER BUILT CASTLES AND CITY WALLS. IT IS WHY WE HAVE LOCKS AND PIN NUMBERS FOR OUR CREDIT CARDS.

CASE STUDY

ETHICS IN FORENSIC SCIENCE

CHRIS HUGHES, *Chair of the National DNA Database Ethics Group*

The application of science to the prevention and detection of crime faces a range of ethical issues that set it apart from most other fields of human endeavour. Those arise from the subject matter of the discipline, the purposes for which it is carried out and the ethical relations of the various parties.

Efforts to prevent crime include the use of psychological and behavioural economic models. These may be applied to 'design out' crime, through techniques such as presenting visual cues to encourage social interaction; or to adjust market behaviour, by restricting sales of some goods or promoting the sales of less harmful competitors; or to 'nudge' pro-social behaviour. But these approaches highlight a conflict between the proponents of a minimal state, and those who consider that society should act collectively to prevent suffering and promote happiness.

The forensic scientist has an overarching duty to tell the truth. But they also have a duty to communicate that to judges, juries and lawyers in a way that they can understand and evaluate fairly: otherwise, both the accused and the victim are denied a fair trial. In forensic science, however, significant aspects of its techniques are either part of the closely-guarded intellectual capital of commercial entities, or seen as sensitive information whose disclosure could assist criminals or undermine national security. The challenge for the scientist and the judge is to ensure that the underlying process is sufficiently understood and testable for a fair trial, without unduly compromising the public interest in other ways.

A third ethical dimension is of particular significance for genomic and cognate investigations. In a forensic investigation, the key driver is to establish the identity of a person in order to determine whether they have committed a criminal offence. They are likely to feel that this amounts to an intrusion into their privacy without consent. This stands in sharp contrast to most other biomedical sciences, where investigations aim to treat an individual's medical condition, or require informed consent from a research subject, or involve minimal interference through the review of medical records. The countervailing ethical arguments, of course, relate to the victims of crime whose rights have been infringed, the duty of society at large to uphold the criminal law by identifying the perpetrator, and the duty of society to protect its members from being harmed by undetected perpetrators.

The fourth substantive dimension lies in the large-scale collection and storage of information about individuals. The non-consensual collection of fingerprints, samples for DNA profiling and custody photographs amounts to an intrusion into the individual's privacy. The retention of CCTV footage and data relating to telephone and internet traffic creates a similar possibility of intrusion.

Those setting the boundaries for what is

WITHOUT PUBLIC DEBATE AND SCRUTINY OF INNOVATIONS, THE ACCEPTABILITY OF FORENSIC PRACTICE MAY BE UNDERMINED. THIS WOULD POSE A SIGNIFICANT CHALLENGE TO THE LEGITIMACY OF THE CRIMINAL JUSTICE PROCESS, ALONG WITH COHESION AND TRUST IN SOCIETY.

acceptable forensic practice in these areas must properly evaluate the harms and benefits that flow from the act of obtaining and using the information – to the individual whose data is gathered, and to other individuals who are affected. This must be balanced against the consequences of not acting: both the act and the omission have moral consequences.

Many factors circumscribe acceptable forensic practice, including the impact on a fair trial, the interference with an individual's privacy and family life, and whether the information was obtained in a lawful manner. When considering the latest scientific and technological innovations of forensic science, however, the norms of what society sees as acceptable are uncertain and fluid. The duty of forensic science in such cases is, above all, to communicate and explain what is proposed and its consequences. Although individuals will ascribe different meanings and values to such actions, providing a clear explanation is the first step towards engaging with society – a process that ultimately determines the desirability or otherwise of developments in forensic science.

International legal instruments (of the UN, and Council of Europe) set norms for the protection of human rights, but they also recognise "the importance of promoting public debate on the questions posed by the application of biology and medicine", as well as the state's duty to provide public information. Without public debate and scrutiny of innovations in forensic science – through the media, ethics committees, professional bodies and legislatures – the acceptability of forensic practice may be undermined. This would pose a significant challenge to the legitimacy of the criminal justice process, along with cohesion and trust in society.

factors such as bias and chance. It is open to peer review and public scrutiny and, if true to itself, regards facts as provisional and subject to revision in the face of further evidence. Science has proved uniquely successful in changing our future for the better (and arguably sometimes for the worse). Its findings have transformed our understanding of ourselves and its discoveries have been more spectacular than anything imagined by fiction writers or by poets.

FS embraces every scientific field from archaeology to zoology. At its best it is multidisciplinary, embracing biology, chemistry, epidemiology, physics, psychology or any other specialty that can help to solve a problem. Science has already been drafted in to tackle politically-motivated crime – scientists are involved in anti-terrorism considerations, for example – and it can bring the same skills to help private or public sector enterprises to foresee danger and design products, policies or services that default to safe. Forensic scientists – those with a ready-honed interest in crime – are well placed to colonise this field.

The enrolment of students in FS has grown strongly in recent years (see Chapter 2 case study p30), to the extent that there have been warnings about falling standards, with some courses even described as "softer sciences"[10]. Many graduates, even the best of them, may find it hard to get employment in their chosen field. There is therefore a push factor, as well as an opportunity, for FS to look beyond the realms of catching offenders or of prosecuting or defending people in the courts.

In doing so, forensic scientists will need to hone their ethical skills and perhaps learn from the model of medicine, which has developed strict protocols for research and even for resource allocation. Security should be emancipating but if it is done badly it can become intrusive and limit our freedoms and quality of life (see case study p100). Moreover, the very concept of crime can be surprisingly elusive, and laws can be capricious or unfair as well as subject to revision. What we should seek is to cut the agony that people suffer unnecessarily. That task, apart from knowledge for its own sake, is surely one of the greatest goals of science, and in particular one of the greatest opportunities for forensic science.

CASE STUDY

MOBILE PHONE CRIME

NICK ROSS, *Chairman, UCL Jill Dando Institute of Crime Science*

Mobile phones exemplify how the ebb and flow of crime is heavily dictated by temptation and opportunity. Their emergence in the 1980s, and the take-up of second-generation technology in the 1990s, spawned an entirely new category of crime – and went on to revitalise an old one.

The new challenge was air-time fraud (i.e. making calls without paying). The old one was footpad robbery, which had come to be called mugging. Had forensic science existed with a remit to prevent crime as well as to detect it, more thought would have been given to designing out the vulnerabilities and provocations of mobile phones, rather than retrofitting them. This failure to think ahead cost billions of pounds, resulted in significant harm to individuals and dented public tranquillity.

As so often happens in product innovation, manufacturers took care to ensure that the new devices were electrically safe, non-toxic and robust, but the potential to incite crime was not considered important. As a result, people quickly found ways to mimic the identity of other people's phones and thereby steal their airtime. In the early 1990s this parasitic fraud grew exponentially, especially in the US where handheld scanners became a craze and cell phone numbers could easily be cloned.

At first the telecom companies sought to pass on the costs to subscribers whose handsets had been compromised. Only when they themselves became obliged to write down the losses did they introduce defences such as encrypting cell phone serial numbers. The result was a drop in crime even steeper than had been the rise (see Figure 1).

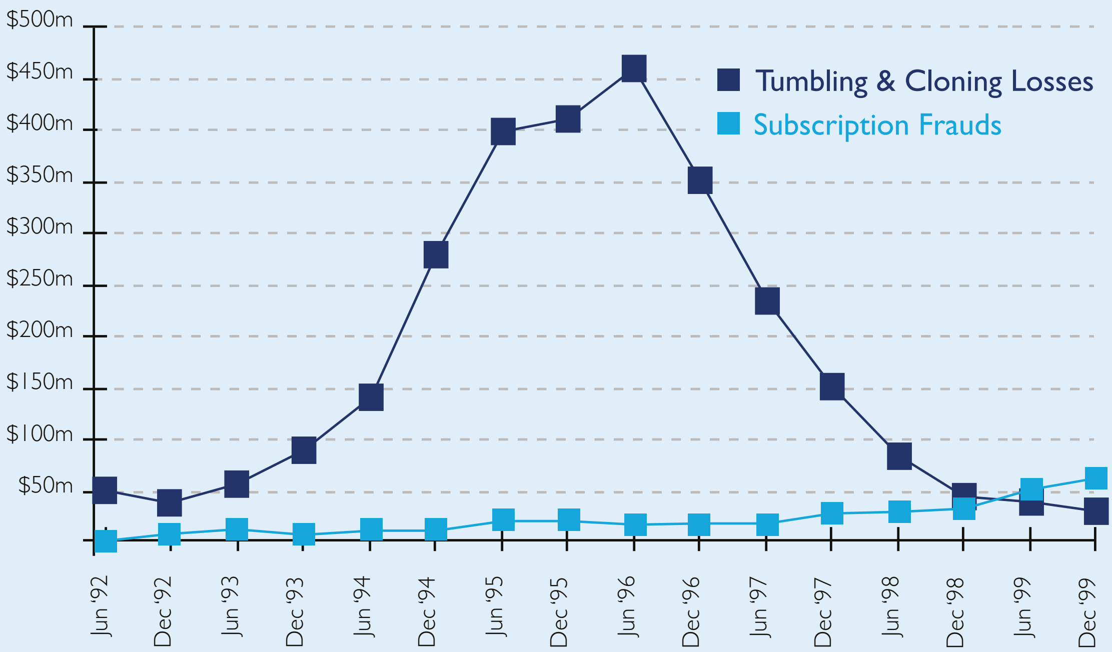
Significantly, the demise of air-time fraud did not appear to cause a switch to other crimes. This is important because classical theories in criminology attribute crime to social disaffection known as anomie, with the fatalistic implication that a crime prevented is a merely a crime displaced elsewhere. Of particular importance to the phone companies was that there was no displacement to subscription fraud, where accounts are opened in false names. Their overall losses to fraud tumbled by 80% within five years.

Meanwhile, phone handsets themselves created a parallel crime wave. As they became smaller and more ubiquitous, they came to embody all six of the classic criteria for theft, which crime scientists call CRAVED (Concealable, easily Removable, widely Available, Valuable, fashionably Enjoyable and Disposable)[2]. In 1993, the government's crime prevention committee warned preventative action was needed. Nothing was done.

By 2001, the Metropolitan Police Service estimated that around 40,000 mobile phones were reported stolen in London each year, accounting for more than half of all street attacks. In 2003, the problem had become so worrying that the government summoned industry leaders to an emergency summit. As a direct result, safeguards were introduced to ensure individual handsets could be tracked when they made contact with the network. Thereafter, phone theft in England and Wales began to fall and continued to do so until around 2010, when a new generations of smart phones unleashed new temptations, especially among the young[3]. (In 2012, two–thirds of handset theft victims reported to the Metropolitan Police were between thirteen and sixteen years old.)

The actual volume of handset theft has been hard to quantify because police figures only count cases reported to them. Thus they inevitably undercount crime and are influenced by many factors, including insurance penetration. The most reliable measure, the one most respected by the Office for National Statistics, came from a sweep by the Crime Survey for England and Wales in 2013/14 (ref. 4). Even this must be treated with caution, because an innocently mislaid phone may

Figure 1: US air-time fraud in the 1990s (ref. 1).

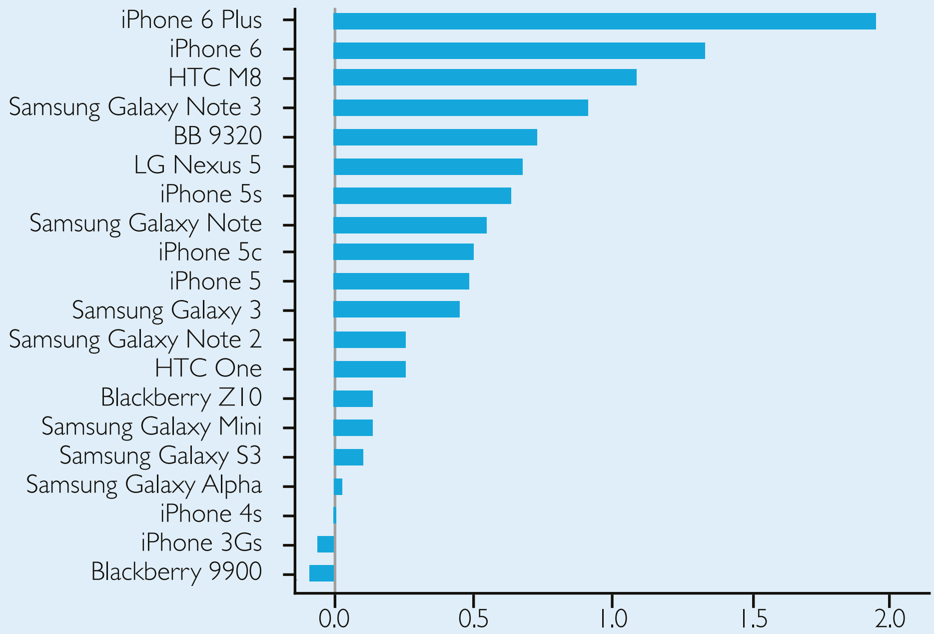


easily be assumed to have been stolen. But it provides the best estimate we have, and suggests a very steep decrease in victimisation over the preceding decade[5]. It seems likely this decline owed much to the fact that trackable phones have little black market value. A causal relationship is hard to prove but there are many precedents, including sustained and precipitous falls in vehicle crime after security features were improved (see case study p105). There is also evidence from phone thieves themselves who, after all, make essentially rational targeting decisions6. Even so, with an estimated 784,000 victims a year in England and Wales in 2013-4, handset theft is still a significant challenge for society[4].

Consequently, the Behavioural Insights Team (BIT) worked with the Home Office and the Metropolitan Police Service to see if some handsets provoked more crime than others. If so, they could rank phones by type and manufacturer, and so bring pressure on suppliers to make their products, and thus their customers, more crime-resistant.

The study involved more than 100,000 mobile phone thefts reported in London between August 2012 and January 2014[7]. As with previous research it found evidence to suggest that phone theft is disproportionately targeted at the young. It also revealed that women were victimised more than men. More importantly for crime prevention, BIT was able to build on others' work[8] to produce the first official Mobile Phone Theft Ratio. The outcome was striking. Crime surveys had already shown that more iPhones were reported stolen than other handsets, but by comparing thefts against volumes of suspected, untargeted thefts, the researchers showed that this was not merely a reflection of how many were in circulation. In fact, Apple products were targeted disproportionately (see Figure 2).

Figure 2: The Mobile Phone Theft Ratio: The top 20 most likely phones to be targeted by thieves between August 2012 and January 2014 (ref. 7). This ratio is derived by dividing the share of thefts of a given model that were plausibly targeted (e.g. a phone that has been snatched) by the share of thefts of a given model that was unlikely to have been targeted (e.g. a phone stolen as part of a burglary).



This ratio is derived by dividing the share of thefts of a given model that were plausibly targeted (e.g. a phone that has been snatched) by the share of thefts of a given model that was unlikely to have been targeted (e.g. a phone stolen as part of a burglary).

This may reflect that iPhones were expensive, which made it tempting to report thefts in order to make insurance claims. Moreover, Apple might protest that its products were especially fashionable in this period and so more desirable to thieves. But the analysis also suggested that suppliers can control crime rates to a great extent. In September 2013, Apple introduced a new operating system called iOS7 with a 'Find My Phone' function that could remotely lock the handset. When the feature was announced, reported thefts of Apple phones subsequently peaked and then declined markedly, unlike those from other manufacturers.

Analysis showed that this decline was unique to Apple, and theft rates for other phones did not drop at the same time. In the months that followed, as more security features were embedded in more devices, recorded mobile phone crime as a whole continued to fall[9]. (BIT proposes to update the Theft Ratio and provide comparison websites to inform consumers, encourage industry innovation and promote wider use of existing security features.)

The research adds weight to the already impressive volume of evidence that crime is not determined by personality or social factors alone but, perhaps more importantly, by the ease and attractiveness of committing an offence. Since a proportion of phone theft involves physical assault, there is evidence that violent crime as well as acquisitive crime can be curbed with increasing effectiveness.

Consumers need to be informed about the relative risks they face, and government and other agencies should recognise they have a role in targeting appropriate and proportionate pressure on those whose products unwittingly create crime pollution.

Cutting victimisation requires forensic science techniques to be applied at the design stage, not after poorly thought-through products, services or policies have already been subject to misuse.

CASE STUDY

TRENDS IN VEHICLE CRIME

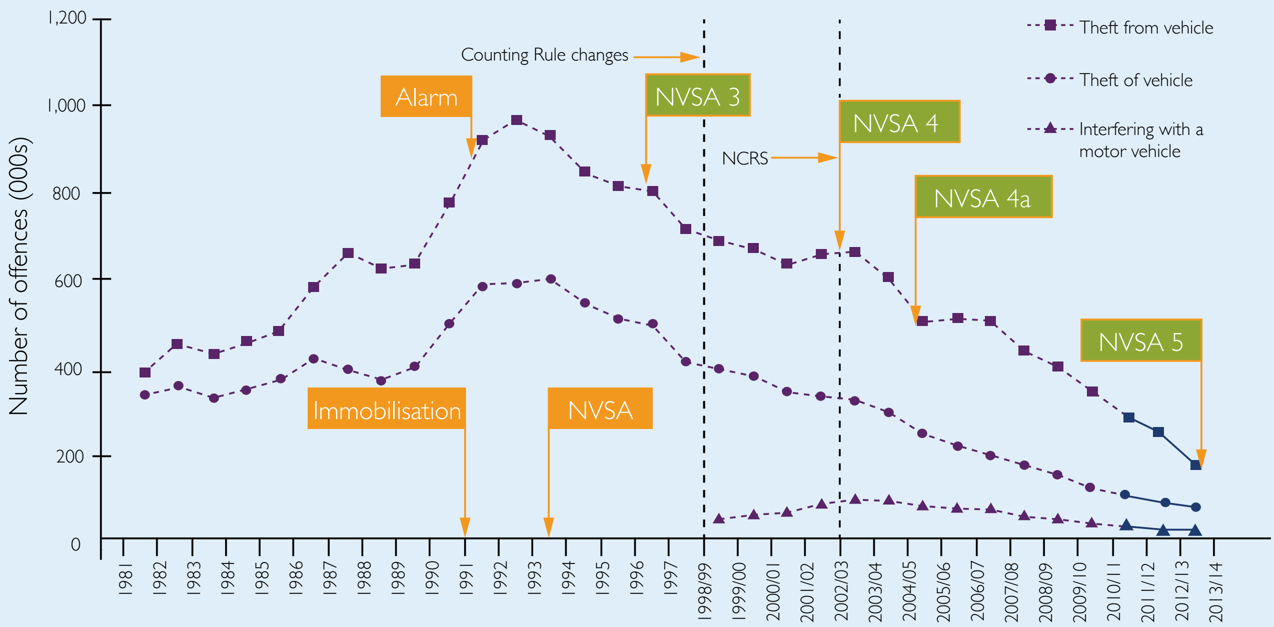
MIKE BRIGGS, *Crime Research Manager at Thatcham Research*

The impact of vehicle crime goes far beyond car theft – it enables many other crimes, from joy riding and fraud to terrorism. Twenty years ago, the rate of vehicle crime was high and getting worse, so the UK government persuaded the motor insurance industry to set security standards that would counteract this trend. Efforts to tackle criminals in this area, by undermining their systems and knowledge, are still being led by the United Kingdom.

Those security standards included fitting vehicles with an immobiliser and insurance-certificated alarm. But manufacturers could also take components off the vehicle – reducing the number of door locks, for example – in order to defend those components at less cost. These changes, based on standards set by Thatcham, started the trend for a dramatic reduction in vehicle theft (see Figure 1). The UK branch of the International Association of Auto Theft Investigators (IAATI UK) now acts as an important forum for those involved in tackling vehicle crime to share information and best practice.

However, vehicle crime rates may now be at a turning point. When manufacturers bring in new technology, so too do organised criminal gangs (OCGs). As soon as we find ways to raise security standards, OCGs find new weaknesses in those systems. Over the past 4 years, we have seen a rise in OCGs attacking vehicles and, in some cases, removing them more effectively than the owners could themselves. Indeed, vehicle recovery rates are now at their lowest since records begin (see Figure 2), and the costs of the crimes are rising because younger vehicles are being stolen.

Figure 1: UK domestic vehicle theft has fallen dramatically over the past two decades.



1. New Counting Rules for recorded crime were introduced in 1998/99 and the NCRS was introduced in April 2002.
2. Interfering with a motor vehicle became a notifiable offence in 1998/99.

That means my team and I must set security standards that anticipate a thief's next move.

We focus on three key areas:

1 Body security

- Protecting on-board diagnostic (OBD) systems
- Additional locks, including wheel security
- Catalyst converter protection

2 Electronic security

- Alarm Systems
- Immobiliser Systems
- Tracking systems

3. Vehicle identification

- Parts marking, with details recorded in a database available 24/7
- Glass etching, with details recorded in a database available 24/7
- General vehicle identification, through security schemes such as CESAR or MASTER

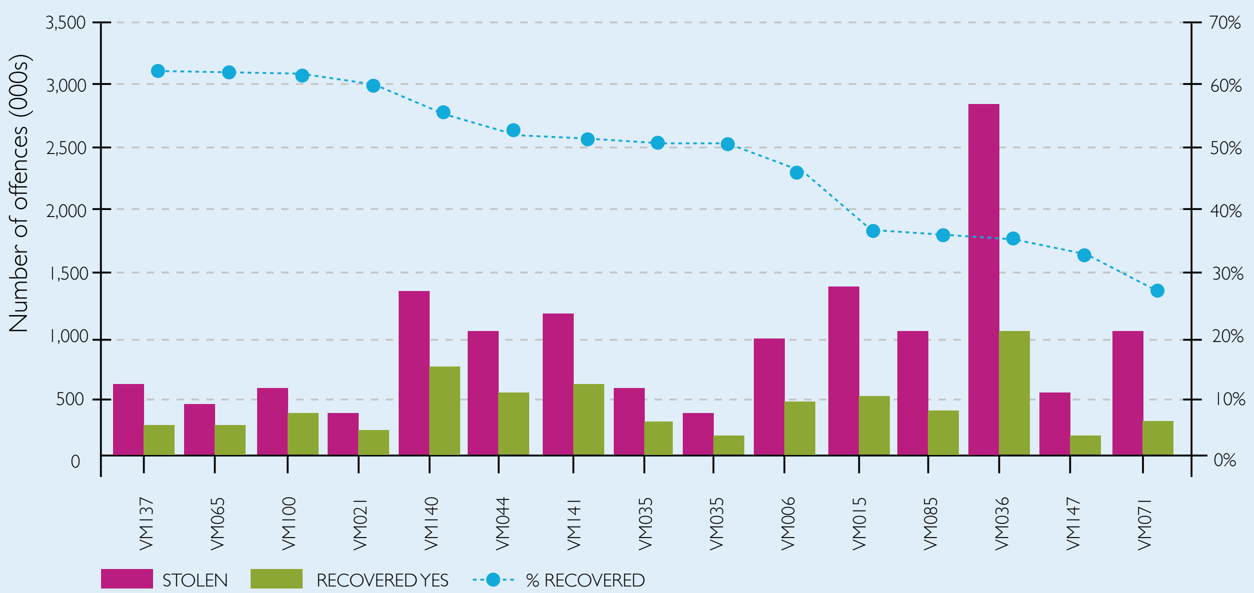
Original equipment manufacturers (OEMs) are designing new ways to combat criminal gangs. But generally it is the aftermarket industry that fills the gap, as they once did with immobilisers and alarms. Today we see the same happening with vehicle tracking systems.

Tracking and navigation systems allow us to recover evidence, and we also gain vital data from keys and vehicle control units. But the falling costs of technologies such as fully-keyless door unlock and keyless engine start means that criminals can also exploit them to steal vehicles, and we are in danger of seeing a fresh surge in joy riding.

Beyond that, cybercrime is the next big threat to tackle. Criminals have been interfering with vehicle software since the late 1990s, but they are now able to carry out these attacks much more rapidly: the times required to code a key or start the engine have fallen from over 30 minutes to 6 seconds.

Further information can be found at www.thatcham.org

Figure 2: UK domestic vehicle recovery has declined substantially over the past two decades.



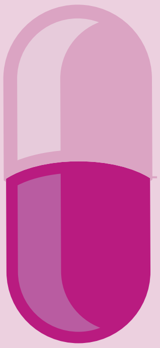
SECTION 3:

FORENSIC SCIENCE: BEYOND THE COURT

FORENSIC SCIENCE: BEYOND THE COURT

Today, economic adulteration and counterfeiting of global food and consumer products is expected to cost industry

$10 - $15 billion per year



WHO's international Medical Products Anti-Counterfeiting Taskforce (IMPACT) estimate that up to

25% of the total medicine supply

in less-developed countries is counterfeit

Microtags are micrometre-sized particles uniquely encoded with multiple layers of security information within the space of 50-110 micrometres (the size of a speck of dust)

10

food products that are most at risk of food fraud

Currently **713** GPHF-Minilab units are used globally across **92 countries** to fight the counterfeit drug trade.

In 2009 the OECD reported that the trade in fake goods was as high as

$250 billion

Larger than the national GDPs of approx.

150 economies

In 2014, over

35 million

fakes were detained at EU borders. Of these, **25%** were potentially dangerous to the health and safety of consumers

Around half

of some air pollutants in the UK come from other parts of Europe

AUTHENTICITY AND PROVENANCE

DEREK CRASTON, *Government Chemist, LGC*

New forensic approaches in detection and identification offer potential solutions to fraud or product quality issues in many areas of public protection. But they would benefit from the wider availability of high-quality reference databases, greater use of anti-counterfeit measures, and more collaboration between policymakers, industry and the measurement community.

Consumers seek a range of desirable attributes when purchasing goods, but some qualities are self-evidently common across many product types: safety, provenance, utility and value for money. The seller is responsible for being honest about what is claimed for their goods – either directly or by implication – and society expects regulation of legal or quality standards in associated markets. Subversion of such standards, ranging from cutting corners to outright criminality is, unfortunately, increasingly common. Indeed, according to reports[1,2], the annual international global trade in counterfeit goods alone is measured in the hundreds of billions of pounds.

Consumers and businesses place a premium on the authenticity and integrity of goods and services. The converse – involving fraud or poor quality standards – jeopardises honest businesses, consumer trust and health. Examples include the horse meat episode[3], the dangers associated with trade in counterfeit pharmaceuticals[4], the economic impact of counterfeit electronics, the well recorded morbidity and mortality caused by counterfeit alcoholic drinks[5,6] and risks to people with food allergies due to inadvertent exposure to allergens[7]. The extent and impact of these at a sector level is described in Chapters 11, 12 and 13.

Consumers rely on retailers and regulators to assure the quality and authenticity of goods, and it is unlikely that emerging technology will change this dependence in the immediate future. So how can a retailer be sure of the products it provides? Such assurance depends on an understanding and monitoring of risks; and related to this, managing and auditing product, ingredient and component supply chains, as well as production processes. The aim should be to establish trust in the supply chain, earned by demonstrated (and audited) competence and integrity; but also backed up by systems able to secure the supply chain against criminal infiltration. Risk assessment is also a critical component of regulatory enforcement strategies. Allied to both enforcement and supply-chain management is the need for detection tools that can be deployed in specialised laboratories or in the field to test for conformity.

THE DETECTION CHALLENGE

Detection involves compositional analysis, to test whether a product contains what is claimed. This can uncover the potential substitution, extension or adulteration of the product with similar but cheaper ingredients; the presence of undeclared ingredients or components that may be added to reduce production costs or increase the sale price; the over-declaration of key or quantitative ingredients; and compliance issues such as non-declaration or false declaration of processes. Investigators also need tools that can verify claims about the origins of product ingredients, and the location of production: in other words, who made it and what did they make it from?

For example, whether a wine or whiskey is of the age and from the location indicated on the bottle; or whether clothes or cosmetics were

CONSUMERS AND BUSINESSES PLACE A PREMIUM ON THE AUTHENTICITY AND INTEGRITY OF GOODS AND SERVICES. THE CONVERSE – INVOLVING FRAUD OR POOR QUALITY STANDARDS – JEOPARDISES HONEST BUSINESSES, CONSUMER TRUST AND HEALTH.

made by the company named on the label. Is it Scottish beef? Or Parma ham? The range of potential issues is wide and changing, and often motivated by the high financial gains that can be made through illegal activity.

The most counterfeited products are those of higher price, by virtue of intellectual property or brand equity, and/or the scarcity of components or ingredients, or the cost of complex production or processing. This provides a degree of predictability that can be built in to risk assessments, and which enables better targeting of enforcement resources. Prediction of risk forms an important part of the National Intelligence Model[8], which is also informed by horizon-scanning: using global data feeds of recalls or incidents, for example, as well as local information from whistleblowers. Regulatory bodies monitor incidents and recalls at national, regional and global levels. For pharmaceuticals, national authorities such as the UK's Medicines and Healthcare products Regulatory Agency (MHRA) post information on local recalls[9] while the World Health Organization provides information on counterfeit medicines at a global level[10]. Similarly in the foods area, EU member states have national systems for reporting non-compliance incidents relating to food and feed that has been inspected on the market or at the border, and if appropriate these are shared across geographies through the Rapid Alert System for Food and Feed[11] operated by the European Commission.

Although incidents or recalls report events after they have happened, they provide an insight into the potential for similar events to occur in the future and are consequently useful data feeds for organisations that review risk (such as the European Food Safety Authority's Stakeholder Group on Emerging Risks, and the EU Food Fraud Network). However, better prediction of quality or authenticity issues requires complex interpretation of multiple information sets that include an understanding of influencing factors such as price, production cost, supply chain and manufacturing complexity, regulatory activity, ease of ingredient or component substitution, likelihood of identification, and ease of detection. Each of these influencers is subject to change in response to macroeconomic factors such as oil price, consumer confidence, materials demand and global outputs (e.g. crop yields) and technology advancement.

THE RANGE OF POTENTIAL ISSUES IS WIDE AND CHANGING, AND OFTEN MOTIVATED BY THE HIGH FINANCIAL GAINS THAT CAN BE MADE THROUGH ILLEGAL ACTIVITY.

This complexity might in future benefit from developments in 'big data' by capturing, combining and analysing multiple and variable information sources to improve risk assessment and incident prediction. As yet, there is insufficient information sharing across multiple interfaces: from agency to agency, and especially between some parts of industry and government. Until our intelligence systems improve, it remains highly likely that incidents and criminal activity will continue to be detected on a regular basis through health events (as is still the case for the many deaths caused by counterfeit medicines, particularly in the developing world) or by targeted surveillance by Trading Standards and government programmes (as was the case with horse meat). It is also worth reflecting that improved intelligence can only partially mitigate the likelihood of fraud, since those involved in related criminal activity have a very wide field of opportunity and are normally adept at reacting to intelligence-led activities.

DEVELOPMENTS IN MEASUREMENT SCIENCE

Given the challenges of identifying areas of future concern, detection technology is needed that can not only analyse for specific ingredients ('known knowns'), but also screen for potential adulterants ('known unknowns') and ideally for anything that should not be present within the end product ('unknown unknowns'). The later, often termed 'untargeted analysis', creates a major challenge in measurement science and will most likely require the flexible application of multiple techniques to deliver the necessary range of sensitivities and chemical or biological diversity.

Fortunately, developments in measurement science continue to enhance investigative capability. The major trends include an increased ability to screen for multiple chemicals or biological forms; improvements in sensitivity; and

CASE STUDY

NUCLEAR FORENSICS

VLADIMÍR ŠUCHA, MARIA BETTI AND KLAUS LÜTZENKIRCHEN, *Joint Research Centre, European Commission*

Since the early 1990s, the Joint Research Centre (JRC) of the European Commission has assisted government authorities by analysing nuclear materials intercepted from illicit trafficking, unauthorised possession and illegal disposals. Nuclear forensic analysis provides information about where and when the seized material was produced, as well as its intended use.

Nuclear forensic investigation uses many different analytical techniques, such as gamma spectrometry, several different types of mass spectrometry, and electron microscopy techniques. In recent years it has focused on characteristic parameters called nuclear forensic signatures, which are found in uranium ore concentrates and other uranium products from the nuclear fuel cycle. These signatures include the ratios of stable isotopes of elements such as sulphur, strontium and neodymium; the relative concentrations of rare earth elements; and the ratio of thorium-230 to uranium-234, which can enable investigators to determine the origin and the age of the material.

The following example highlights the potential for a nuclear forensic investigation to resolve a case of illicit possession of nuclear material. In 2007, several items – presumably pellets of nuclear fuel – were seized by the police in Northern Germany. The JRC's Institute for Transuranium Elements (ITU) in Karlsruhe was asked to characterise the material and to provide clues on its origin. The pellet material was identified by mass spectrometry as low-enriched uranium with 3.4% of fissile uranium-235, typical of nuclear reactor fuel.

Adding the information on the pellets' dimensions, measured by microscopy, allowed investigators to identify the production facility. This origin was corroborated by the low trace-element content of the pellets, which was consistent with the fabrication process used in that particular facility; as well as by the measured

NUCLEAR FORENSIC INVESTIGATION USES MANY DIFFERENT ANALYTICAL TECHNIQUES, SUCH AS GAMMA SPECTROMETRY, SEVERAL DIFFERENT TYPES OF MASS SPECTROMETRY, AND ELECTRON MICROSCOPY TECHNIQUES.

age of the pellets (the uranium used for pellet production was prepared in November 1990, with an uncertainty of three months).

The knowledge that the JRC gains from its wide experience in case work, and its continuous research and development activities, is transferred to national governmental organisations by providing training courses in nuclear forensic investigations. This training covers areas including: national response plans; basic training for first responders (e.g. at radiological crime scenes); specialised training for measurement experts; and tailor-made training courses for laboratory scientists in specific methods and instruments.

International cooperation in nuclear forensics is of the utmost importance, because nuclear security is a border-crossing challenge. Illicit trafficking incidents, and the responses of government authorities, often involve more than one country. The JRC has been co-chairing the International Technical Working Group in Nuclear Forensics since its foundation in 1995 – which includes co-operation with the UK's Atomic Weapons Establishment (AWE – see case study on p116) and National Nuclear Laboratory – and is involved in the activities of the Global Initiative to Combat Nuclear Terrorism (GICNT). It also cooperates closely with the International Atomic Energy Agency (IAEA) in many areas related to nuclear security, particularly in nuclear forensics.

the facility to deploy tools out in the field. More sophisticated tools are also being developed that, for example, provide evidence relating to the source of ingredients or production, or to the authenticity of associated packaging.

Untargeted investigations applying chemometrics (the application of mathematical approaches to handing complex data sets) to spectroscopy is a well known research area[12]. There are a number of other measurement techniques that can screen samples for multiple small and large molecules, such as proteins and DNA, and these have advanced over the past decade in response to market needs and to new requirements in areas like biomarker identification and 'omics' investigation. For example, the measurement of multiple small organic molecules by nuclear magnetic resonance[13] (NMR) or mass spectrometry[14] (MS) has been applied extensively to study the so-called metabolome – the range of small molecules that appear in biological samples as a consequence of, for example, the activities of human metabolism. MS combined with liquid or gas chromatography (which can separate the chemical components of mixtures) is now a routine tool within analytical laboratories. It is used in a wide range of areas that require analysis for multiple chemical forms, including the screening of food and environmental samples for the presence of pesticide and drug residues, studies of drug metabolism, and investigations in forensic toxicology.

Advances in chromatography now allow hundreds of chemicals to be screened in a single measurement run, generating information-rich datasets that can be stored for future interrogation should knowledge of new threats subsequently emerge. With the continued growth in MS databases, and the advances being made in data mining and analysis, it is now possible to generate 'fingerprints' for particular product types, and to identify the presence of unexpected or unknown compounds[15]. These approaches have already shown promise in studies of food authenticity and for identifying unknown 'designer steroids' in sport doping investigations[16], and are expected to gain more widespread usage as the technology continues to evolve.

Accurate mass MS is now also routinely applied in protein (peptide) analysis and in 'proteomics'. As Government Chemist, we have

THE REQUIREMENT FOR APPROPRIATE REFERENCE DATABASES IS A RECURRING THEME. THEY ARE ESSENTIAL FOR INTERPRETING VARIATIONS FROM A PRODUCT'S EXPECTED COMPOSITION.

used this technology to analyse for differences between closely related fruit species, and thereby identify chemical targets that indicate the trace adulteration of foods with allergenic ingredients[17]. Broad screening of proteins is also possible through techniques such as highly multiplex immunoassays and array technology[18]. Protein microarrays are used for both analytical and functional applications, such as studies of protein interaction, biochemical activity and immune response. These analyses mostly involve arrays of antibodies that bind to specific proteins, and are applied primarily in clinical chemistry. However, the low cost and sensitivity of antibody detection methods also lends itself to many other applications relating to biological origin (including authenticity and allergenicity), and the simplicity of related detection methods could a powerful way to move from laboratory measurement to field-based application (see below) if issues in specificity and cross-reactivity can be resolved.

Medium-density microarrays have also seen a recent resurgence in molecular biology. They are used to identify multiple genetic variants, for example, and for the broad screening of multiple genes and RNAs. As such, they add to a molecular biology tool kit that includes other measurement techniques including next-generation sequencing (NGS), high-throughput genotyping and multiplexed real-time PCR. Such techniques are extremely powerful in determining biological origin because they can discriminate closely-related (sub) species, and even pin down a sample's geographic origin if high-quality reference sequence databases are available.

Indeed, this requirement for appropriate reference databases is a recurring theme. Reference databases are essential for interpreting variations from a product's expected composition, and apply equally to methods that measure the overall response of a product to an

OUR ABILITY TO EXTRACT AND AMPLIFY DNA IS NOW SUCH THAT, IN PRINCIPLE, IT IS POSSIBLE TO DETECT SINGLE GENE COPIES, EVEN AGAINST A HIGH BACKGROUND OF GENETIC MATERIAL.

external input, as well as those that seek specific chemicals or chemical sequences. Approaches that depend on reference databases include:

- multi-spectral imaging for determining food authenticity[19]
- near infra-red (NIR) and Raman spectroscopy, which are useful for pharmaceutical counterfeit detection[20] due their discriminating power, portability and relatively simple operation (see Chapter 12, case study p138)
- electrical and optical testing, and digital imaging, of electrical components[21]
- spectroscopic methods for detecting counterfeit clothing[22]

TEASING OUT TRACES

Advances in measurement science have not only improved our ability to screen multiple components – they have also allowed investigators to detect compounds at increasingly diminishing levels. Forensic science remains a catalyst for this trend: it aims to generate DNA data whenever possible; to find traces of chemical warfare agents and their derivatives, which may inform security activities; and to provide evidence of criminal activity, such as the handling of drugs.

Our ability to extract and amplify DNA is now such that, in principle, it is possible to detect single gene copies, even against a high background of genetic material. For example, digital PCR[23] (dPCR), an approach first developed in the 1990s, is a technique that is used to quantify the amount of DNA in a sample by counting amplifications from single molecules.

Improvements in MS are leading to selective methods that can detect molecules at less than a picogram (10^{-12} g) per kilogram of sample. Even higher sensitivities are possible using immunoassays, in which improved affinities, better methods and novel forms of detection have enabled signal generation with femtogram (10^{-15} g) to attogram (10^{-18} g) levels of input material[24]. Indeed, the combination of sensitive detection with solution partition or imaging has led to a number of approaches that can detect and count individual molecules. These advances offer great potential for diagnostics, for research at the cellular level and for identifying potentially harmful contaminants. However, the application of ultra-sensitive techniques in forensics and compliance testing needs to be approached with appropriate interpretative caution.

For example, as the relevance and value of DNA profiling to forensic investigations has increased, so too has the desire to generate this information from smaller amounts of DNA. When the level of DNA in a sample falls well below the recommended threshold it is still possible to generate interpretable profiles, but these need to be evaluated more carefully: contamination raises the risk of misidentification, and there is a greater likelihood of obtaining partial profiles and seeing other imperfections in the DNA amplification process that might lead to incorrect interpretation of the data[25]. These challenges in DNA apply equally to issues in authenticity and compliance, such as the presence of trace levels of species (for example, genetically modified organisms) in processed foods and other products.

Many synthetic chemicals can now be detected at background levels in the environment. These levels and variations need to be understood before setting meaningful action or compliance limits, as do the current limitations of associated measurement capability (see Chapter 14). As such, regulation and policy that is based on based on zero tolerance, such as banned veterinary residues in food and drugs in sport, will become increasingly difficult to enforce without effective guidelines for interpretation. Such guidelines should recognise well-developed statistical techniques in hypothesis testing and advances in toxicology such as margin of exposure[26] comparative risk assessment. We need further exploration and dissemination of approaches to establish practical yet suitably precautionary approaches to essentially unanswerable questions such as "Is it nut free?" or "Is it carcinogen-free?".

Can anything ever be claimed as 'pure'? (see case study on p120). To what extent does the presence of chemicals at ultra-trace levels really indicate contamination or adulteration, or represent a meaningful risk to consumers? These are questions that will need to be addressed as our measurement tool kit continues to advance. Moreover, there is an unmet need for the development and teaching of end-to-end interpretative skills across multiple disciplines in areas such as forensic science and food crime.

Traditional crime scene forensic investigations draw together all of the available evidence and then apply multiple techniques in order to build up a picture of what occurred, and the roles of the specific individuals that were present when the offence was committed. There are analogies here with the more general fight against fraud and counterfeiting, where the article is often distributed with additional components, and where potential surface contamination can provide useful intelligence. These additional and rich sources of information reside, for example, in the form of external packaging and blister packs for pharmaceuticals; labels and logos for designer goods; and packaging and identification numbers for electronic devices.

Similar to crime scene forensics, analysing products and their associated articles for authenticity and compliance often requires multiple measurement techniques, including specialist methods that are not routinely applied in product quality control and assurance (see Chapter 11). Notable in this respect is the emergence of isotope ratio measurement[27], which exploits the subtle geographic differences in the ratios of stable isotopes of common elements to investigate claims about a product's origin. This is potentially the most challenging of all authenticity issues e.g. is this Atlantic or Pacific cod? Was this chemical made in factory X or factory Y? Was this wine made from grapes produced in region A or B? (see case study on p118).

Although both elemental and isotope-based measurements provide the basis for much of the information pertaining to the point of origin of animals, plants and food products, alternative rapid and cost effective methodologies are also being examined. For example, molecular biology approaches that focus on DNA-based techniques are increasingly being evaluated for use in traceability studies, as is evident from the number of national and international traceability projects now in existence (e.g. Labelfish, the Atlantic Network on Genetic Control of Fish and Seafood Labelling and Traceability). Approaches including end-point PCR, real-time PCR, and DNA sequencing can identify and capitalise upon minute differences in the genome of geographically-isolated populations of the same species, and can be used to augment the more routinely used elemental and isotope-based measurements for point-of-origin studies.

IN THE FIELD

All of the advanced detection and identification technology described so far is normally operated in controlled laboratory environments, with documented and accredited quality systems that incorporate procedures for calibration (by using appropriate certified reference materials, for example).

These laboratory measurements can provide reliable data that is quantified to a known level of uncertainty, satisfying the needs of regulators and our legal system. However, laboratory measurement requires samples to be taken from the field, transported and administratively processed prior to analysis. This takes time (typically days) and requires systems to be in place for tracking and ensuring continuity of evidence. Ultimately, though, the data generated is only representative of the sample provided, and hence interpretation is needed to elucidate how this relates to the entire batch of product under investigation.

These limitations mean that there is now significant interest in techniques that can be applied in the field to provide real-time information, and to assist in product sampling strategies to maximise the likelihood of detecting non-compliant or fraudulent events. A range of technologies are under development for field application, and there are already a number

LABORATORY MEASUREMENT REQUIRES SAMPLES TO BE TAKEN FROM THE FIELD, TRANSPORTED AND ADMINISTRATIVELY PROCESSED PRIOR TO ANALYSIS.

CASE STUDY

PROVENANCE OF NUCLEAR MATERIALS

DANIEL THOMAS, *Nuclear Threat Reduction, AWE*

Imagine the following scenario, and the questions it raises:

- Police receive a phone call claiming that a 'dirty bomb' has been placed in central London. Is this real, or a hoax? Is there anything to find? How to find it?
- Police then find a suspect package. Is this what they're looking for? Is it a radiological or nuclear device? What precautions are needed?
- Investigators confirm that the device contains nuclear material and explosives. But is it an improvised nuclear device (IND)? What could the consequences be if it is detonated?
- The device is made safe, and nobody is injured. But who was involved in building and planting the device? How did it happen? Where did the material come from? How was the material removed from normal regulatory control? Is this our material? If not, where did it come from? Could there be other devices, or more lost material of concern?

Throughout this scenario it is clear that the government, the police service and supporting agencies would be faced with a multitude of urgent issues before investigative and forensic questions can be addressed. Nuclear materials that represent the gravest concerns – those which can be used to build a nuclear device – typically have half-lives longer than tens of thousands of years, giving them an enduring potential for misuse.

But provenance will ultimately become a key question, asked by the most senior decision-makers. They will want to know where and how the material was acquired, and who was involved. Nuclear forensics has a key role to play in answering these questions, by using forensic analysis to assess these radioactive substances as well as items contaminated by them.

Nuclear forensics can draw out links between a scene, an object, a person or persons, identify the radioactive material and show where it could have originated. This relies on the longstanding capabilities of AWE (the Atomic Weapons Establishment) in this area, which have been enhanced in recent years by the Ministry of Defence in order to respond to developing needs such as provenance. The Office for Security and Counterterrorism in the Home Office also funded the Conventional Forensic Analysis Capability (CFAC) at AWE, which provides the capability to carry out recovery of fingerprints, DNA, fibres, hairs, and digital information from radioactively-contaminated items.

The approach taken at AWE, on behalf of the UK government, has been to ensure that nuclear forensics can be carried out in an integrated fashion, by bringing normally disparate technical disciplines together. Experts from a range of disciplines will increasingly need to work together in order to solve the forensic puzzles presented by perpetrators.

Nuclear materials have been produced globally over many decades in facilities that were focused on producing material and meeting the required specifications; personnel were not tasked with helping to establish provenance following the loss and subsequent discovery of that material. Consequently, there will probably not be a predetermined 'unique fingerprint' for identifying the provenance of many materials, nor will historical records necessarily provide the fidelity of data required for provenance assessments that use a data matching approach.

The challenges arising from questions of provenance mean that new interpretive knowledge is being developed, in addition to the analytical capabilities to measure the properties of materials. New technical skills such as chemical modelling and statistical analysis will be needed to understand the properties of materials produced long ago in the UK, so that we can assess the future unknowns. This is particularly important as the people who worked in these production and manufacturing domains retire.

By measuring various properties of the material (isotopic, chemical and physical), identifying the type of process that may have produced it, and knowing whether UK-produced materials are consistent with those measured properties, investigators will be able to use an exclusion-based approach that allows them to rule out known sources from their investigations. Nuclear forensics and provenance is an evolving discipline, and it has great intellectual and technical opportunities for scientists to apply themselves to matters of national security concern.

of good examples of where these are being deployed, including the use of transportable ion-mobility spectrometers (IMS) in airports and border crossings to detect explosives and drugs. Recently it has become possible to augment IMS at these sites using Raman spectroscopy to screen for the same types of compounds in packaged materials and solutions[28]. Raman and NIR have also been extensively investigated and used for the detection of pharmaceutical counterfeits, and hand-held versions of both are now available for enforcement and surveillance[20]. A range of other portable diagnostic devices is emerging, which could transform enforcement and supply chain monitoring. These include sensor systems based on affinity reagents (immunoassays) with, for example, optical, electrochemical or surface acoustic wave detection, and DNA diagnostics with on-board amplification systems that are capable of providing information in relatively short timeframes (typically 10-60 minutes). Indeed, DNA intelligence tools are already available for crime scene investigation[29] and for rapid diagnosis of disease – further development is likely to lead to instruments that can be deployed for bio-security applications, and for food safety and authenticity screening.

However, even with the support of portable measurement instruments, detection tools will not be sufficient on their own to eliminate or identify all forms of fraud. Fraudsters will adjust their tactics, evading different forms of detection by exploiting weaknesses in measurement methods. This was most notably illustrated in China, when melamine was added to milk that had been watered down. The nitrogen-containing melamine was intended to fool the methods for determining milk content, which were based on the analysis of nitrogen as a quantitative measure of related proteins. Conversely, some organisations specifically add markers to their products to aid detection: drinks manufacturers may add combinations of chemicals (and macromolecules like DNA) to readily differentiate their products from counterfeit versions; and many companies add physical features such as watermarks or holograms as an anti-counterfeiting measure.

Designing anti-counterfeit or safety and compliance measures into products, packaging and processes offers optimal protection to

CASE STUDY

FORENSIC GEOSCIENCE

LORNA DAWSON, *Head of the Soil Forensic Group, James Hutton Institute; and* RUTH MORGAN, *Director of the UCL Centre for the Forensic Sciences*

Forensic geoscience is an increasingly important discipline that studies soils, minerals, dusts, plants and rock fragments to help determine their provenance (i.e. a chronology of their ownership, custody or location). These materials have been used as forensic trace evidence for many years and are often highly distinctive from one region to another.

Such traces are extremely useful in a forensic context, because of their environmental specificity; their high levels of transferability; their ability to persist on items such as clothing, footwear, tools and vehicles; and their high levels of preservation after long periods of time, even after activities such as burning and washing. This resilience makes geoforensic trace materials – frequently present at crime scenes, and in forensic exhibits – highly valuable forms of intelligence and evidence that can aid crime investigations and reconstructions.

There have been significant advances in forensic geoscience over the past decade, both in the development of analytical approaches and also in understanding of the behaviour, transfer, persistence and preservation of sediments, soils and plant material. Evidence samples can now be analysed by a wide range of complementary methods that address their physical, chemical and biological components with greater precision, speed and accuracy than ever before. This allows samples of less than 10 milligrams to be accurately characterised, and mobile platforms are increasingly enabling real-time decisions that aid investigations.

These developments have enabled geoscience techniques to be applied in a greater range of cases, and in helping to review 'cold cases'. Improved analytical capabilities, coupled with the development and availability of relevant databases, allow forensic geoscientists to help police to search for unknown objects or people, prioritise areas for investigation or search, and provide robust and reliable evidence in court.

Advances in forensic geoscience have also underscored the importance of developing the empirical evidence base that we need to interpret and assign the significance and importance of these materials in specific scenarios. Without these established evidence bases, it would not be possible to offer such reliable evidence for presentation in court.

The full potential of forensic geoscience has only truly begun to be recognised in the past decade. Since many criminals now show a high level of forensic awareness in relation to evidence such as fingerprints, blood and other body fluids – along with an ability to fake products with forensic precision – police and security agents are encouraging the use of geoforensic evidence applications. To date, forensic geoscience has mainly been used in the context of high-impact crimes such as murder, rape, aggravated burglary and terrorism investigations, where resources allow it. However, techniques are increasingly becoming cheaper and faster, and have the potential, once fully tested, to become regularly used forensic tools.

Forensic geoscience is also being applied in a wider range of investigations, including wildlife crime, fraud identification, food adulteration, kidnapping, trafficking and smuggling. Using state-of-the-art techniques in chemistry, biology, and microscopy, it is possible to identify if particular foods have come from a claimed location. For

THESE DEVELOPMENTS HAVE ENABLED GEOSCIENCE TECHNIQUES TO BE APPLIED IN A GREATER RANGE OF CASES, AND IN HELPING TO REVIEW 'COLD CASES'.

example, elemental composition can indicate the type of soil in which garlic cloves were grown; isotope and trace chemical values can indicate in which distillery a whisky was produced; isotopes and elemental profiles show where cheeses, oils or soft fruit were produced; organic compound analysis can determine cultivar level identification; strontium isotopes can discriminate between zones where beef has been produced; and grain shape and texture can identify the beach where drugs were imported from.

Forensic geoscience can also help investigators to reconstruct journey histories, often a critical issue when reconstructing crime scenes and establishing pertinent time lines. Current research is demonstrating that sediments can be transferred to the components of improvised explosive devices (IEDs) or high-value goods, which can indicate where they were manufactured. This type of intelligence can indicate locations of interest in terrorism and illegal trafficking investigations, or reveal important social networks integral to terrorist activities. The sediments on footwear and vehicles can indicate where a crime may have taken place, and may provide evidence of a person being at a particular place of interest.

With the developments in analytical technology, and an increasing understanding of how soils and sediments move within natural and anthropogenic environments, forensic geoscience has more power to answer questions such as: "Where did the trace material come from?" or "Where has this item been?". Understanding the context of a specific case is crucial in helping to answer such questions. In addition, being able to explain the significance of the evidence that has been analysed, and demonstrating logically and transparently how a conclusion has been reached, remains important for forensic geoscience specifically and trace evidence generally.

THE GLOBAL ILLICIT ECONOMY HAS ALREADY INFILTRATED AND CORRUPTED LEGAL MARKETS, REDUCED CONSUMER CONFIDENCE, IMPACTED TRADERS, PROVIDED A DISINCENTIVE TO INVESTMENTS IN R&D, AND RAISED PUBLIC HEALTH RISKS.

traders and the public (see Chapter 9). Other related measures include the ability to follow production process, and to track the movements and associated environmental exposures of ingredients, components and finished products from source to retail. This approach is already being used in a number of areas: ear-tagging individual cattle allows meat to be traced up the food chain; quality-by-design and process monitoring tools support good manufacturing practice (GMP); radio-frequency identification technology (RFID) tracks product movements; and continuous temperature monitoring ensures the integrity of cold supply chains (see case studies on p112 and p116 for further examples about nuclear materials).

CONCLUSION

The global illicit economy is growing rapidly, due to a wide spectrum of activities that include counterfeiting goods. It has already infiltrated and corrupted legal markets, reduced consumer confidence, impacted traders, provided a disincentive to investments in R&D, and raised public health risks.

This threat is preventing fair markets from reaching their potential and endangering our health and safety. Technology – including advances in measurement science – must continue to evolve to meet this challenge.

NOTIONS OF PURITY:
AN ANTHROPOLOGICAL PERSPECTIVE

FRANCESCA BRAY, *Social Anthropology, University of Edinburgh*

Purity and pollution were initially treated in anthropology as exclusively religious concepts[1–3], and they remain a central concern in the anthropology of religion today. Though variously defined in different religions, purity is everywhere a spiritual precondition for communicating with the gods through prayer or ritual.

Purity can be defiled by inappropriate emotions or thoughts, acts or contacts, by sickness and by passages through the life cycle, notably birth, menstruation and death. Some categories of people, things or acts are inherently and irrevocably tainted: a Hindu untouchable cannot become touchable however pious his behaviour; in ancient Greece or imperial China there was no redemption for parricide. Much pollution, however, is transitory and an affected individual can achieve or regain purity through rituals, discipline, pilgrimage, fasting or simply the passage of time. For example, Christianity requires the 'churching' of a woman who has given birth; in Chinese Buddhism the taint of a family death dissipates gradually, aided by a sequence of sacrifices for the soul of the departed and their transformation into an ancestral spirit. Typical prohibitions for saints and priests, and for the laity before conducting major rituals or undergoing rites of passage, include bans on sexual intercourse, eating meat or expressing anger. Views on alcohol differ between religions: in some it is permanently forbidden to all the faithful, in others one should abstain before praying, some require officiants to share blessed wine with their congregation, while some require anyone offering a sacrifice to be roaring drunk[4–12].

How do we explain similarities and differences in how purity and pollution are construed? Anthropologists have taken two distinctive approaches. One pragmatic, materialist school has sought to explain 'native' rules about purity as proto-scientific systems of hygiene, for instance interpreting the Judaic taboo on pork as a latent understanding that pigs' meat carries parasites dangerous to human health. This common-sense interpretation, popular among cultural ecologists through the 1950s and 1960s and most vividly formulated by the cultural materialist Marvin Harris, today attracts little anthropological but much popular interest[13, 14]. "Comparative religion has always been bedevilled by medical materialism," Mary Douglas remarks tartly[15].

The second school of thought about purity and pollution originated in 19th and early 20th century studies by Robertson Smith, Émile Durkheim and others who argued that religions are neither divinely inspired nor materially rooted. Rather, they are an expression of collective values. Sacred and secular must therefore be analysed not as separate domains but as interdependent elements of a single moral-symbolic system. It was the structuralist anthropologists of the 1960s who breathed new life and vigour into this approach. The landmark study was 'Purity and Danger' by Mary Douglas. A focus on purity and pollution, Douglas showed, can illuminate the deepest workings of any society, including our own. While the categories of purity and pollution may be most evident in the religious and ritual domain, they reflect deeper structures of symbolic thought manifested in secular values and everyday practices, from the preparation of meals to definitions of nationality[10, 16].

Dirt is matter out of place, Douglas famously remarked, and its threat to purity must therefore be approached through order: "Uncleanness or dirt is that which must not be included if a pattern is to be maintained," she wrote[17]. Danger lies not in the existence of the unclean per se, but in the transgression of boundaries, the mingling of categories, the contamination of pure by impure[4, 12]. Douglas's important insight has inspired a succession of groundbreaking anthropological studies of the imperatives of purity in such diverse fields as racial science, nationalism, victims of

EVEN IN THE STRICTLY MATERIAL SENSE, PURITY IS NOT A STATE OF NATURE, NOR IS IT UNCONDITIONALLY DESIRABLE.

atomic disasters, etiologies of AIDS, and views of genetic engineering[18–23].

The underlying assumption here is that purity is the desired state which any taint impairs. But this attitude is more culture-bound than we realise. The development of modern science is a history of purification. In order to extract better knowledge, chemists, engineers and physicists have quarried the messy material stuff that surrounds us; isolated and purified it in order to classify it and study its properties. Nature is then rendered into its very purest form – abstract thought: theories or laws of universal validity, expressed in terse, uncontextualised verbal or numerical form[24].

As Bruno Latour observes, a defining premise of modern sciences, both natural and social, and indeed of our modern life generally, is that objectivity is considered both possible and necessary. We have supposedly escaped the primitive entanglement of mind, soul and body, of moral and material. Instead we bring an effective approach to the world and its problems that categorically separates the social and the natural, the human and the artefact, the mind and the objectively observable fact – a universal science beyond politics or creed[25].

But in reality such purification is impossible, as Latour and his fellow researchers in science and technology studies have shown. Science depends on funding and politics. Politics and power permeate every human act. Researchers are cultural, political and often religious beings: nuclear scientists conduct rituals and rites of passage as part of their research; particle physicists and molecular biologists evaluate the quality of evidence in quite distinctive ways[26]. Environments are co-produced by the collectivity of their denizens, and humans more than any other life form have remade 'nature' in their own image throughout their existence. Scientists do not discover nature in the raw; they define the categories they will research, seek effective catalysts for the reactions they want to produce, design instruments, carefully select and breed experimental animals to fit the experiments, pre-select the ecological niches or soil cores with which they investigate 'nature'[27–29]. In the process, definition and distinction become increasingly complex and challenging. Is a pest-resistant GM eggplant more or less pure, natural and organic than a non-GM eggplant treated with pesticides? From atmospheric levels of sulfur dioxide to the meat content of a proper sausage, scientists, regulators, legislators, corporations, farmers, shopkeepers, activists and consumers wrangle continually over definitions and degrees of safe, acceptable or simply workable purity, impurity or contamination[30–32.]

Even in the strictly material sense, then, purity is not a state of nature, nor is it unconditionally desirable. While regimes of purification bring greater control, more predictability and increased efficiency, they also contain the threat of inbreeding, sterility and vulnerability. Purity and hybridity become inextricably entangled[33]. Pure lines of wheat cannot rival hybrids for yields. They are painstakingly bred not to grow in their own right but to cross breed into high-yield hybrids. Hybrids, however, do not breed true and must be replaced yearly. In the case of wheat, pure lines must be maintained to reproduce the essential hybrids. One could argue that in the case of human societies, a similar if not identical dialectic between purity and hybridisation, analogous processes of hybridisation, miscegenation and tincture, are essential for long-term health and survival. And yet, as anthropological studies of assisted reproductive technologies or of immigration vividly illustrate, they are widely viewed with misgiving, resentment or fear[16, 19, 34, 35]. The anthropology of purity reminds us that culture, politics and morality are intrinsic to any scientific or legislative attempt to classify or to purify.

FOOD AND DRINK

VLADIMÍR ŠUCHA, ELKE ANKLAM AND FRANZ ULBERTH, *Joint Research Centre, European Commission*

Food adulteration is as old as trade itself, but it has grown into a global criminal enterprise that costs billions of pounds in lost revenue every year, and may also put consumers at risk of harm. Authorities and policymakers must have access to up-to-date knowledge about fraud detection and prevention technologies to safeguard the integrity of the food chain.

The adulteration of foods has a history dating back to ancient times. Cato gave one of the earliest accounts of adulteration of foodstuffs in his treatise 'On Agriculture' (around 160 BC) when he reported on the adulteration of wine. Likewise, Roman legislation was aware that olive oil can be a target of fraudulent co-mingling. Food adulteration practices are as old as trade, and strict punishment of fraudsters, when detected, was announced and implemented.

One of the earliest known modern accounts on food fraud was given by Frederick Accum, who published 'A Treatise on Adulterations of Food and Culinary Poisons' in 1820. He described common malpractices such as adding chalk to flour, and sawdust to bread, as well as recycling spent tea leaves and coffee grounds. Intentional food adulteration increased considerably during the Industrial Revolution following the separation of the direct link between farmers/food producers and town dwellers. Unfortunately, some of the known malpractices raised concern for food safety. Examples include the introduction of chemical hazards through adding, for instance, strychnine to beer to save on the more expensive bitter hops; colouring candies and preserves with toxic metal salts; or diluting vegetable oils with industrial oils.

Fraudulent malpractice creates unfair competition, leading to market distortions, which in turn may impact the local or even the international economy. Today, economic adulteration and counterfeiting of global food and consumer products is expected to cost the industry \$10 billion to \$15 billion per year[1]. Preventing fraud in the agri-food chain, and promoting authentic products, are key goals to assure the commercial success of European high-value agri-food products on international markets. Marketing standards and EU quality schemes aim to ensure that consumer expectations are met, and enable the functioning of the internal market and global trade in agricultural products. Losing reputation in this area will negatively impact on competitiveness and profitability of the agri-food sector in the EU.

CHALLENGES IN FOOD AND DRINK AUTHENTICITY CONTROL

The driving force behind food adulteration is to maximise revenues by either using a cheap ingredient to (partially) substitute a more expensive one; or to (partially) remove the higher-valued component in the hope that the altered product passes undetected by the final user or consumer. For example, fraudulently watering down milk or skimming off cream have both been practised for a long time.

Certain production methods, notably for organic foods or those where animal welfare practices are promoted (e.g. free-range products), have gained a significant market share in developed countries. The popularity of these production methods arises from widely-held beliefs about their superior nutritional qualities resulting from their 'naturalness', which should be preserved to a higher degree.

Similarly, the marketing of agricultural products has been focused recently on the promotion of premium goods in Western countries. Such products command a premium because they were produced within a well-

FOOD CONTROL AUTHORITIES NEED TO CONTINUALLY ADAPT EXISTING TECHNIQUES AND DEVELOP NEW METHODOLOGIES TO DETECT FRAUD defined geographical location, and/or applying only traditional methods of production, and/or using only certain ingredients (see case study p125). Similar considerations apply to other speciality products, such as foodstuffs that respect fair-trade principles or religious beliefs (e.g. halal or kosher) or care for the environment (e.g. food miles). To capitalise on market demands and improve profits, goods of lower economic value may be co-mingled into higher priced commodities. This harms honest producers who suffer from unfair competition, and consumers whose fundamental rights are violated by fraud.

Extension of a product with a cheap ingredient, or counterfeiting of a branded product, does not usually carry a health hazard for consumers. But there are notable exceptions. In 1981, the Toxic Oil Syndrome in Spain affected nearly 20,000 consumers who ate rapeseed oil denatured with aniline that was refined and sold to consumers as olive oil[2]. In 2008, the Chinese milk scandal sickened more than 50,000 children after they consumed milk tainted with melamine[3]; and in 2012, 38 people died in the Czech Republic following the consumption of spirits in which part of the ethanol was replaced by methanol[4].

The need to detect the intentional addition of hazardous chemicals gave a great impetus to the development of analytical chemistry applied to food, and the establishment of food chemistry as a scientific discipline enabled society to adopt appropriate countermeasures to pursue fraud. But unscrupulous purveyors of fraud also benefited from this development, because the availability of compositional data enabled them to fine-tune their illicit manipulations in order to evade legal action. In general, fraudsters tend to be quite innovative and well informed about weak points in food inspection systems. Therefore, food control authorities need to continually adapt existing techniques, and develop new methodologies, to detect fraud and protect the fundamental rights of consumers.

Food fraud can have various levels of complexity, from diluting milk with water to a very complex practice of adding gently-deodorised olive oil to extra virgin olive oil. Correspondingly, methods for detecting fraud range from simple to highly sophisticated approaches. In principle, the food forensic scientist faces three problems[5]:

FRAUDULENT MALPRACTICE CREATES UNFAIR COMPETITION WHICH MAY IMPACT THE LOCAL OR INTERNATIONAL ECONOMY. TODAY, ECONOMIC ADULTERATION AND COUNTERFEITING OF GLOBAL FOOD AND CONSUMER PRODUCTS IS EXPECTED TO COST THE INDUSTRY $10 BILLION TO $15 BILLION PER YEAR.

1 Identification of a marker (or markers) that allow discrimination between the genuine and the adulterated state of a food or food ingredient. Detection can be rather simple if the commodity used for extending the authentic product introduces a substance (marker) that is not naturally present in the original. For example, the addition of vegetable oils or fats to butter can be easily detected by tracing phytosterols, which do not occur in measurable amounts in genuine butter fat. In most cases, however, such fundamental differences do not exist, and scientists need to rely on empirical differences in the composition of constituents of the genuine and the adulterated product. Quite often, advanced statistical techniques are necessary to turn analytical data into information for decision-making.

2 Access to authentic samples to establish the markers and develop diagnostic tests. Physical access to samples can sometimes represent a bottleneck, particularly when the food has been grown or produced overseas. Repositories of authentic samples are difficult to maintain, so characteristic features (e.g. compositional data, spectra, molecular markers, etc) are stored in electronic format. Creating and curating such databanks is a resource-intensive process, and access in certain cases is only possible on a subscription or fee-for-service basis, which could limit their public use. The EU wine databank, established already in the 1990s in accordance with Regulation (EU) 1306/2013 (ref. 6) and. operated by the European

THE FIGHT AGAINST FOOD FRAUD CALLS FOR AN INTERNATIONAL APPROACH INVOLVING COOPERATION AND CONSULTATION AMONG ALL STAKEHOLDERS, AT ALL LEVELS OF THE FOOD CHAIN. INVESTIGATIONS CARRIED OUT BY EUROPOL SUGGEST THAT ORGANISED CRIME SYNDICATES ARE INCREASINGLY RESPONSIBLE FOR CASES OF FOOD FRAUD AND ADULTERATION.

Commission's Joint Research Centre (JRC), is one of the few examples where compositional data of a premier agricultural product are systematically collected. The databank contains the isotopic composition of wines, which are made available to the competent authorities in the Member States when disputes regarding watering or sugaring of wine arise.

3 Creating reliable forensic evidence and confidence in the data that will stand up to scrutiny in the judicial system. Cases where only one marker forms the basis for discriminating the genuine and the adulterated product are relatively straightforward to handle, taking into consideration the empirical distribution of the marker, as well as the uncertainty in the measurement of the marker. But things get more complicated when complex statistical models using many input variables (e.g. those generated by spectroscopy) have to be used for decision-making. The judicial system does not always accept evidence generated by such approaches.

In the EU, Article 8 of the EU General Food Law[7] stipulates that the interests of consumers shall be protected by preventing fraudulent or deceptive practices misleading the consumer. In addition, national laws in EU Member States provide various definitions for the violation of statutory agri-food chain requirements. They are qualified by the intention to deceive, and the motive of financial or economic gain, though constitutive elements vary from one national system to the other. In a number of Member States, those facts may be relevant for the application of criminal penalties and of procedural rules on criminal prosecution. According to a statement by the UK Food Standards Agency[8], for example, food fraud is committed when food is deliberately placed on the market, for financial gain, with the intention of deceiving the consumer.

Certain diagnostic tests, in particular those based on DNA analysis, are highly sensitive and can indicate the presence of exogenous DNA as a result of contamination due to cross-contact with other foodstuffs. To decide whether the presence of a foreign substance is due to accidental contamination or intended co-mingling requires an assessment of the amount of the substance present, which is not straightforward to derive from the quantity of foreign DNA. This kind of uncertainty needs to be taken account of when weighing the forensic evidence in a court of law.

The horsemeat adulteration scandal showed that one of the weaknesses of the current system of enforcement along the food chain was that Member States' competent authorities found it difficult to communicate efficiently with their counterparts in other Member States — which is essential in cases where violations have cross-border impact.

The Commission decided therefore to activate a dedicated network of administrative assistance liaison bodies that would handle specific requests for cross-border cooperation in cases of 'food fraud'. The dedicated liaison bodies are referred to as Food Fraud Contact Points (FFCP). They act, as do all administrative assistance liaison bodies, within the legal framework provided in Title IV of Regulation (EC) No 882/2004. The group of FFCPs is collectively referred to as the Food Fraud Network (FFN)[9].

On 14 January 2014, the European Parliament published a resolution on the control of fraud in the food chain[10], calling on the European Commission to take all

CASE STUDY

SCOTCH WHISKY: AUTHENTICITY, PROVENANCE AND ASSURANCE

JULIE HESKETH-LAIRD, *Deputy Chief Executive of the Scotch Whisky Association*

Scotch Whisky is a prestigious spirit drink with a global reputation. Sold in around 200 markets worldwide, Scotch Whisky exports are worth around £4 billion each year.

The Scotch Whisky Association (SWA) works to sustain Scotch Whisky's place as the world's leading high-quality spirit drink and secure its long-term growth in the market.

Scotch Whisky is protected as a 'geographical indication' (GI) to safeguard the industry's intellectual property and underpin our cultural heritage and employment. We want consumers to be assured that they are getting the best product, traditionally produced to strict standards. Scotch Whisky's reputation has taken years to build and we are committed to maintaining and building on that.

That is why a major part of the SWA's work is to safeguard Scotch Whisky against fraud. At any one time our legal team has about 70 actions in courts around the world, and many more investigations under way. Crucial in the fight against fakes is the need to determine whether the suspected product is consistent with Scotch Whisky.

Investigations require forensic support in the form of authenticity analysis of the liquid. As well as determining spirit strength and the presence of additives — which are not permitted in Scotch Whisky — sophisticated techniques are employed to check authenticity.

The raw materials and production processes used to produce Scotch Whisky result in a spirit with certain chemical characteristics that can be checked by analysis. This is because the production of genuine Scotch Whisky leads to the presence of certain components in the finished product. Many of these components will contribute to the colour, aroma and taste of scotch. The relative and absolute concentrations of particular components allow conclusions to be drawn on how the product has been made.

Brand owners may build up unique and confidential authenticity indictors underpinning the analytical fingerprints of their brands. Fast and reliable field tests have even been developed for use in market.

Our strategy for generic analysis has involved developing an analytical fingerprint for Scotch Whiskies as a whole. This fingerprint can then be used to show how Scotch Whisky is distinct from whiskies of other origins, other distilled spirits or cheaper neutral alcohol, each of which may contribute to the composition of products falsely claiming authenticity.

For example, Scotch Whisky must be matured in oak barrels for at least three years. Maturation changes the chemical composition of the spirit, with the lignin in the wood broken down into compounds that can be identified by analysis. Chemical analysis can therefore indicate whether the maturation compounds are consistent with aging in oak for at least three years, and identify flavourings that have been added to mimic the effects of maturation.

The SWA instructs an independent laboratory set up by the Scotch Whisky industry, the Scotch Whisky Research Institute (SWRI), to analyse products described as 'Scotch Whisky', but suspected to be fake. We are one of several customers of the SWRI, which also assists enforcement authorities in the UK and abroad. The SWRI has access not only to published research on the analysis of Scotch Whisky, but also has its own extensive database on the analysis of Scotch Whiskies collected over many years. Every year around 160 suspect 'whisky' samples sourced by the SWA are tested by SWRI, which also provides expert evidence in legal proceedings in respect of many of the samples tested.

Robust protection of Scotch Whisky requires robust science, and the Scotch Whisky industry has both.

necessary steps to make combating food fraud an integral part of EU policy. It also encouraged the commission to consider developing an EU reference laboratory for food authenticity, and called for the establishment of an anti-food fraud network as a means of improving coordination among the competent European bodies (Europol, Eurojust), in order to prevent and detect food fraud more efficiently. The associated report[11] identified the top 10 food products that are most at risk of food fraud (see Table 1); a US Congressional Research Service report came to similar conclusions[12]. In response to the horsemeat scandal, the UK government commissioned Chris Elliott of Queen's University Belfast to review the integrity and assurance of food supply networks. His report identified several systemic gaps and suggestions for addressing them, including the need for unannounced audits of food business operators; intelligence gathering; strengthening the Public Analyst system; and setting up a food crime unit and crime prevention activities within the UK Food Standards Agency[13] (see case study p129).

Table 1: Top 10 food products that are most at risk of food fraud

COMMODITY	FRAUD CASES
OLIVE OIL	Extension with other vegetable oils, notably hazelnut oil Misdescription of geographical origin and olive variety Misdescription of olive oil quality (refined oil sold as extra virgin oil)
FISH	Substitution of high-value fish, particularly filets, by cheaper varieties Substitution of 'wild-caught' fish by farmed fish Misdescription of geographical origin (particularly for salmon) Misbranding of ordinary catch as coming from sustainably managed stocks
ORGANIC FOOD	Misdescription of production method
MILK	Addition of water and salts Substitution of milk from other species (ovine, caprine, ewes, human) by cow's milk Substitution of milk protein or fat by non-milk ingredients (plant proteins, animal and vegetable fats) Addition of nitrogen-rich substances (e.g. melamine, urea) to increase apparent protein content Misdescription of milk reconstituted from milk powder as fresh milk
GRAIN	Misdescription of soft wheat as hard wheat (durum wheat) Misdescription of long grain rice as Basmati rice
HONEY	Extension of honey by sugar syrups obtained from sugar cane, sugar beet, maize, wheat, rice, agave, maple Misdescription of geographical origin and botanical variety
COFFEE	Misdescription of geographical origin and variety (Coffea robusta, Coffea arabica) Extension with roasted cereals, chicory, figs, caramel, malt
TEA	Misdescription of geographical origin and variety Extension with twigs and leaves from other plants, coloured sawdust, used tea leaves
SPICES	Addition of synthetic dyes (e.g. Sudan red) Extension with extraneous substances
WINE	Addition of water and sugaring of must (chaptalisation) Misdescription of geographical origin, grape variety and vintage year Addition of chemicals (e.g. diethylenglycol)
FRUIT JUICES	Addition of water, sugars or pulp wash Extension of authentic juice with cheaper alternatives

Table 2: Fingerprinting techniques used in food forensics, grouped by type and/or analysis target

ELECTROPHORETIC (PROTEINS)	DNA ANALYSIS	SPECTROSCOPIC	CHROMATOGRAPHIC
Protein electrophoresis	Restriction fragment length polymorphism (RFLP)	UV/Visible	Thin-layer (TLC)
Isoelectric focusing	Random amplified polymorphic DNA (RAPD)	Fluorescence	Gas-liquid (GLC)
Two-dimensional electrophoresis	Amplified fragment length polymorphism (AFLP)	(Fourier-transform) infrared	High-performance liquid (HPLC)
	Simple sequence repeats (SSR)	Raman	
	Single-nucleotide polymorphism (SNP	Mass (MS)	
		Nuclear magnetic resonance (NMR)	

FORENSIC TECHNIQUES

The fight against food fraud calls for an international approach involving cooperation and consultation among all stakeholders, at all levels of the food chain. Investigations carried out by Europol suggest that organised crime syndicates are increasingly responsible for cases of food fraud and adulteration.

Consequently, the detection and prevention of food fraud requires strategic planning and investment at the national and European level with a proportionate and sustainable budget. It also requires access by the enforcement authorities to state-of-the-art analytical tools, which enable them to detect (and provide judicial evidence of) fraudulent practices.

Modern measurement science offers a wealth of technologies that can be used to detect fraud in the food chain. Traditionally, chemical composition analysis has played a dominant role, particularly where marketing standards for certain commodities (e.g. edible oils, honey, etc) exist. Where the test results of a suspect product do not conform to the standard, fraudulent manipulations may be the obvious reason. Simple physicochemical methods, such us freezing-point depression (e.g. for detecting the watering of milk), electrical conductivity and refractive index (e.g. for honey authenticity) are suitable to detect gross violation. But more refined techniques need to be applied to identify more sophisticated cases of adulteration.

Analysts will use a targeted technique if they know what kind of adulterant has been used (e.g. a DNA-based assay for detecting horsemeat, or a chromatographic method for detecting melamine added to a dairy product); or they will resort to an untargeted technique if no prior information exists. In the former case, analysts will only detect what they are looking for ('known knowns'), whereas the latter tries to address the 'unknown unknowns'. Since many different adulterants can be used, the effectiveness of targeted testing for detecting food fraud is limited; methods that assess the 'integrity' of the food are, therefore, becoming popular.

Analytical approaches used in food forensics are based on separation science; spectroscopy; molecular biology; and analysis of stable isotopes of light elements. The first approach tries to unravel the composition of mostly small organic molecules (metabolites) of a particular food or food ingredient to create a detailed, quantitative profile, or a qualitative fingerprint that is characteristic of the authentic product. Several forms of spectroscopy (UV/Visible, fluorescence, Fourier-transform infrared, Raman, or nuclear magnetic resonance) create fingerprints without prior separation of individual components and are consequently viewed as 'holistic' methods, which use the whole information content of the created spectra.

Methods based on DNA analysis are

EU QUALITY POLICY HAS CREATED QUALITY SCHEMES THAT GRANT PROTECTED DESIGNATION OF ORIGIN LABELS TO AGRICULTURAL PRODUCTS AND FOODSTUFFS, WHICH ARE PRODUCED, PROCESSED AND PREPARED IN A GIVEN GEOGRAPHICAL AREA USING RECOGNISED KNOW-HOW.

invaluable for the discrimination of food-producing animal and plant species. The power inherent in DNA analysis has enabled law enforcement in difficult cases where certain varieties of a given species command different prices, or are used for distinguishing quality levels. DNA-based assays have been used to discriminate, for example, Arabica from Robusta coffee beans, mandarin from orange juice, several meat species, Basmati rice from other long-grain rice, grape varieties used in wine making, and olive cultivars for olive oil production[14]. Real-time quantitative polymerase chain reaction (PCR) based tests are even able to estimate the amount of the adulterant added (e.g. the amount of horsemeat in beef burgers). The PCR products (amplicons) can further be manipulated and separated by electrophoresis to generate specific fingerprints, which are of diagnostic value. Table 2 gives an overview of fingerprinting techniques used in food forensics[15].

Combinations of techniques exist: the most widely used combines GLC or HPLC with mass spectrometry (MS). In using these techniques, an enormous number of 'features' (fragments of molecules, which are eluted from the chromatographic system at a characteristic time) are generated per analysis. Similarly, spectroscopic techniques (where the whole spectrum is considered) also generate massive amounts of data. Only the combination of data processing by advanced mathematical algorithms and subsequent multivariate statistics allows the recognition of patterns that are useful for discriminating between genuine and adulterated products. Among the more widely applied statistical techniques are principal component analysis (PCA), linear discriminant analysis (LDA), soft independent modelling of class analogy (SIMCA), partial least squares discriminant analysis (PLS-DA), and artificial neural networks. Some of the statistical routines even allow quantification of added substances. Chemometrics, which is the use of advanced statistics for the analysis of chemical and biological data, has been developed, refined and applied with success in academic research related to food forensics. However, the criminal courts have been slow to accept its utility for evaluating and weighing evidence, despite the existence of solid knowledge in the field of forensic statistics[16].

An important quality characteristic of certain food products or ingredients is their geographical origin. EU quality policy has created quality schemes that grant Protected Designation of Origin labels to agricultural products and foodstuffs, which are produced, processed and prepared in a given geographical area using recognised know-how. Verifying that claim is a delicate task, requiring isotopic ratio mass spectrometry (IRMS) analysis of the stable isotopes of light elements (hydrogen/deuterium, carbon, nitrogen, oxygen, sulphur), which are related to the region where the products were grown (see Chapter 10 case study p118). Specifically, stable isotope ratios of hydrogen (H) and oxygen (O) in produce relate to the environmental water of the growing region. Isotope effects fractionate H and O isotopes through evaporation, condensation and precipitation as they move through the hydrological cycle. These effects are well understood and have led to the production of isotope landscapes (isoscapes), allowing investigators to predict the isotopic composition of food grown in a particular region. This gives the forensic scientist a powerful tool to check whether a geographical origin claim is correct.

Stable isotope ratios of carbon determined by IRMS can discriminate between plants that use C4 carbon fixation rather than the C3 photosynthetic pathway. This plays an important role in determining whether sugar or sugar syrups produced by a C4 plant (maize and sugar cane) has been added to, for example, wine must or fruit juice, without

CASE STUDY

STOPPING FOOD FRAUD

SUE DAVIES, *Chief Policy Adviser, Which?*

In 2013, the discovery of widespread adulteration of beef products with horsemeat outraged consumers and brought food fraud into the spotlight. It prompted a government-commissioned review of the integrity of food supply chains by Professor Chris Elliott of Queen's University Belfast. His recommendations[1] for a 'consumer first, zero tolerance' approach were accepted and led to a number of changes, including the creation of a new National Food Crime Unit within the Food Standards Agency (FSA).

Estimating the true scale of food fraud is one of the first tasks of the new unit. It is already clear that substituting cheaper ingredients can be lucrative. In some cases it can also lead to safety concerns, as seen with potentially carcinogenic Sudan I dyes added to chilli powder and, more recently, the substitution of ground almonds with peanuts has caused allergy risk. Fraud also causes wider consumer harm: causing them to pay for something of poorer quality than they expected, and also potentially leading to inadvertent consumption of ingredients that people avoid for religious or other cultural reasons.

Keeping one step ahead of fraudsters across complex global supply chains is a challenge. Tackling it demands effective intelligence gathering, economic analysis and regular auditing and testing by food companies and public authorities. Ensuring analytical availability and capability is a crucial aspect of this. As a result of the Elliott report, a network of centres of excellence is now being established.

Over the past two years, testing by Which? as part of its Stop Food Fraud campaign has found problems with a spectrum of products. The results have been shared with the FSA for investigation. In April 2014, 40% of 60 lamb take-aways tested were found to be adulterated with other meats, mainly chicken and beef. In September 2014, we discovered haddock substituted with cheaper whiting in 5 out of 15 Glasgow fish and chip shops. Goat's cheese tested by Professor Elliott in October 2014

KEEPING ONE STEP AHEAD OF FRAUDSTERS ACROSS COMPLEX GLOBAL SUPPLY CHAINS IS A CHALLENGE. TACKLING IT DEMANDS EFFECTIVE INTELLIGENCE GATHERING, ECONOMIC ANALYSIS AND REGULAR AUDITING AND TESTING BY FOOD COMPANIES AND PUBLIC AUTHORITIES.

found that 9 of 76 samples were adulterated, and 6 of these were more than 50% sheep's cheese. Further work with Professor Elliott in August 2015 found that 25% of 74 dried oregano samples analysed containing cheaper leaves such as olive and myrtle. While the analysis for meat substitution was relatively routine, Elliott's team developed an innovative approach using both Fourier-transform infrared spectroscopy (FTIR) and liquid chromatography high-resolution mass spectrometry (LC-HRMS) to screen and confirm oregano adulteration.

Stopping food fraud has to remain a priority, with effective, preventative action from both the food industry and government. Which? consumer research has shown that failing to act would have a long-term negative impact on consumer confidence; and that consumers expect public authorities to ensure their food is what it says it is. A September 2014 survey found that over half (55%) of people were worried that a food fraud incident would happen again. A quarter (23%) said that in the past 12 months they had changed the type of meat products they bought because they were worried about food fraud.

With local authority resources under strain and food standards work in decline in many parts of the country, the FSA and its new National Food Crime Unit will have a crucial role to play.

CASE STUDY

EXPLOITING THE MICROBIOME

PAUL BRERETON, *Head of Agri-food Research, Fera Science Ltd.*

The microbiome is the combined genetic material of all the micro-organisms that typically inhabit a particular environment. Although usually associated with studies of the human gut, understanding the nature of the microbiome of animals, plants, and their environments is a potentially new and powerful method for assessing where items originate and where they have been.

Many geological, biological, and environmental markers (such as the composition of chemical elements, or the shape of a sand grain – see Chapter 10, case study on p116) are already used to match items with a particular point of origin. But the microbiome has been under-utilised in forensics.

Given the increased regulatory emphasis on accurate labelling of a food's geographical origin, there is a need for systems that accurately assess provenance. One approach exploits micro-floral signatures – the genetic profile of all the algae, fungi and bacteria present in a sample. These signatures could be used to identify where a sample was originally produced, but also link samples to particular environments where they have been, a crucial aspect for forensic analysis.

Until recently, it has been difficult to measure and interpret the microbiome due to the diversity of micro-floral populations, and the limitations of the tools used to measure them. But the advent of Next Generation Sequencing (NGS) has provided a step change in analysis that now permits rapid interrogation of the RNA/DNA sequences that make up the genome; as such, it offers for the first time the potential for forensic analysis to exploit the microbiome.

Attributing a geographical origin to a sample ("Where does it come from?") is usually more challenging than confirming a match between an unknown sample and a reference control ("Is it from here?"). To answer the former question, investigators need to understand the relationship between the micro-floral markers, and how the characteristic signatures of these markers vary from one place to another. Large numbers of data points are needed to understand the potential variability of markers within particular target regions; this requires resource-intensive production, analysis and storage of these data, limiting the application of the technique.

Fera (formerly the Food and Environment Research Agency) has developed a method that uses the latest NGS technology to facilitate rapid and wide-ranging interrogation of microbial genomes. Funded by the Department for Environment, Food and Rural Affairs (Defra) and the Food Standards Agency, Fera has undertaken a pilot study of the microbiome concept that aims to confirm the geographical origin of oysters from beds around the UK coastline[1].

We focused on genomic sequence data from a particular bacterial gene that is commonly used to differentiate bacterial species. Our hypothesis was that it could also be used to differentiate samples of Pacific oysters, according to their production site and related conditions such as how they were grown and the origin of the spat ('larvae') that the oysters grew from. 110 oysters were collected directly from 11 major production sites around the UK. Bacterial gene sequences were generated by sequencing oyster gill tissue. After analysing the sequence data using bioinformatics techniques, differences in bacterial communities between locations and substrate were identified using statistical procedures.

We found strong links between the microbiome and the oysters' geographical origin; and also between the microbiome and the oysters' substrate (e.g. whether they were grown on trestles or on the sea bed). The length of time that oysters had been grown at the sampling location was also weakly linked to the composition of their microbial community, although this correlation was less strong than with the sampling location itself, indicating that the oyster microbiome is influenced most

IT HAS BEEN DIFFICULT TO MEASURE AND INTERPRET THE MICROBIOME DUE TO THE DIVERSITY OF MICRO-FLORAL POPULATIONS, AND THE LIMITATIONS OF THE TOOLS USED TO MEASURE THEM AGAIN.

strongly by the water in the locality. Further work is assessing the impact of seasonality on the oyster microbiome in the different production sites, in order to ensure that the microbiome markers are robust and not affected by the season in which the samples are taken.

This approach has many potential applications in broader areas, such as:

- Forensics: being able to link an item/person to a particular location
- Food waste (spoilage): using analysis of the microbiome to better understand and extend shelf life
- Microbial epidemiology: using micro-floral signatures (including those from non-pathogenic sources) to trace pathogen outbreaks
- Food authenticity: using a food's microbiome as an authenticity marker or specification

declaration. In combination with a specialised NMR technique called site-specific natural isotope fractionation (SNIF), even the addition of beet sugar (a C3 plant) to wine must (chaptalisation) can be detected.

INNOVATIVE TECHNOLOGIES

Traceability is a key element in ascertaining the safety of the food chain, but it is also an important tool to ensure its integrity.

Anti-counterfeiting technologies play an important role in ensuring product safety, as well as authenticity, although the technology only allows track-and-trace of the package and not the package content. Authentication packaging technology offers many levels of varying sophistication either using overt technology (holograms, security threads, watermarks, colour shifting ink) or covert technology (UV ink, fluorescence fibres added to packaging paper, biological or chemical tags such as DNA printing inks). Synthetic and unique DNA can be incorporated in packaging material for authentication of genuine products that encodes product-specific information, which are impossible to forge.

Hyperspectral imaging, which marries spectroscopy to image analysis for providing spectral, as well as spatial information, is a powerful tool that can be used for rapid non-destructive quality and authenticity assessment of food, particularly meat and spices.

Next-generation sequencing (NGS), at least theoretically, makes it possible to identify all species present in a food product. The technique holds great promise for identifying pathogens isolated from clinical material and food to support trace-back investigations to identify the source of an outbreak (see case study p130). NGS has the potential to advance food authenticity testing, but requires further refinement and development, particularly related to data analysis (bioinformatics), before finding its way into routine laboratory use.

Competent authorities and policymakers in the EU must have access to up-to-date knowledge related to fraud detection and prevention technologies, as well as the relevant databases, to safeguard the integrity of the food chain. Responding to this need, the JRC is putting in place dedicated research infrastructures to provide the European Commission and EU Member States with the necessary knowledge to fight food fraud.

COUNTERFEIT PHARMACEUTICALS AND METHODS TO TEST THEM

HARPARKASH KAUR,
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Pharmaceutical counterfeiting is a global threat that can kill patients, contributes to the rise of drug resistance, and increases citizens' mistrust of health systems. To monitor drug quality, governments and health programs must invest in regulations, technologies, and infrastructure, including anti-counterfeiting measures, specialised analytical facilities run by experienced staff, and portable technologies for screening medicines in the field.

The United Nations Office on Drugs and Crime has identified pharmaceutical counterfeiting as a global threat[1]. Although health professionals assume that they are prescribing good-quality medications, and patients believe that these medications will cure them, counterfeit drugs are often revealed only after a patient fails to recover[2].

The medicines supply is carefully monitored in the UK, but this is not the case in resource-constrained countries, where a range of factors are contributing to pharmaceutical counterfeiting. These include: lack of legislation; weak or absent regulatory authorities; demand exceeding supply; the high price of 'innovator drugs' (i.e. brand-name drugs); the difficulty in tracking transactions involving many intermediaries; and the lack of laboratories or field-tests to assess the quality of drugs.

Poor-quality medicines are divided into four main classes: counterfeit, falsified, substandard or degraded. But there are no universally-accepted definitions of these categories[3]. The World Health Organization (WHO) defines spurious/falsely-labelled/falsified/counterfeit (SFFC) drugs as follows[4]:

"A counterfeit medicine is one which is deliberately and fraudulently mislabelled with respect to identity and/or source. Counterfeiting can apply to both branded and generic products and counterfeit products may include products with the correct ingredients or with the wrong ingredients, without active ingredients, with insufficient active ingredient or with fake packaging"

Falsified (fake) medicines do not contain the stated active pharmaceutical ingredient (SAPI) and may carry false representation of their source or identity. (A falsified drug could signal a potentially counterfeit product, which does not comply with intellectual property rights or may infringe trademark law)[5]. Substandard drugs are produced with inadequate attention to good manufacturing practices and may have contents or dissolution times that are outside accepted limits, due to poor quality control[6]. Degraded formulations may result from exposure of good-quality medicines to light, heat, and humidity. It can be difficult to distinguish degraded medicines from those that left the factory as substandard, but the distinction is important because the causes and remedies will be different.

The WHO's International Medical Products Anti-Counterfeiting Taskforce (IMPACT) estimates that up to 25% of the total medicine supply in less-developed countries is counterfeit[7]. Obtaining exact figures is very difficult, however, as the very nature of this trade means that it attempts to operate below the regulatory radar, and many suspect drugs remain undetected. The prevalence of poor quality drugs can only be known after a formal drug quality survey has been performed, and objective evidence of the quality of drugs available from most countries is lacking.

Alarmingly, if a medicine contains too few active pharmaceutical ingredient (APIs) to kill all the pathogens in a patient's body, it encourages the emergence of drug resistant strains. And because the poor are often limited to buying not just the cheapest product, but also the smallest pack size, that also makes it more likely that they receive inadequate doses of an active ingredient, further accelerating drug resistance. Poor quality medicines may also lead to distrust in the healthcare system and threaten decades of progress in public health. It is simply unacceptable that the quality of drugs is poor or uncertain for the most disadvantaged people, who have the least resources and are attracted by the lower prices of counterfeit drugs.

ANTI-COUNTERFEITING TECHNOLOGIES

Several countries have recently ratified legislation to combat the sales of falsified medicines. The United States passed the drug quality and security act[8], while China and India have brought in legislation to use bar codes and adopt track-and-trace systems to check that quality-assured medications reach patients. Tagging technologies include radio-frequency identification or RFID[9], Microtags[10], NanoEncryption™ [11] and AuthentiTrack® [12], which allow manufacturers and distributors to track medicines through the supply chain. Microtags are micrometer-sized particles uniquely encoded with multiple levels of security information within a space of 50–110 micrometers (the size of a speck of dust). The tags are made of inert materials, are safe for human consumption and will not alter the potency of the medicine. The information they carry can be decoded with laser pens, optical scanners or other scanning technologies provided by the Microtag maker.

Global alarm about the emergence of antibiotic-resistant 'superbugs' is prompting wider use of these tagging technologies. In developing countries, generic antibiotics can be obtained without a prescription and little is known about their quality. Misuse of antibiotics – through unnecessary over-prescribing and sub-optimal dosing resulting from substandard antibiotics – engenders the development of resistance. The sheer volume of antibiotics sold daily, and their relatively low production cost, makes them a vulnerable target for counterfeiters, illegitimate internet pharmacies, and drug manufacturers who use poor manufacturing practices.

Antimalarial drugs are another vulnerable target. Considerable technical, financial and human resources are required to inspect, analyse and police the drug supply, all of which are lacking in most malaria-endemic countries. A systematic review of the literature reported that few surveys of antimalarial medicines used robust methodology, and that the majority

> THE SHEER VOLUME OF ANTIBIOTICS SOLD DAILY AND THEIR RELATIVELY LOW PRODUCTION COST MAKES THEM A VULNERABLE GROUP OF DRUGS FOR TARGETING BY COUNTERFEITERS

did not differentiate between substandard and counterfeit medicines[13]. Surveys require epidemiological knowledge, and an adequate sample size from as wide a range of outlets as possible, to provide a reliable estimate of the frequency of poor quality drugs.

Reliable surveys are essential to justify and promote the political action that would create the mechanisms needed to assure drug quality[14].

METHODS TO TEST MEDICINES

1. Visual and physical inspection

The first step in determining the quality of a medicine is to look for the key features of any high-quality medicine. The package should include a list of active ingredients, the name and address of the manufacturer, storage conditions, batch or lot number, dates of manufacture and expiry, and directions for use. An instruction leaflet (in the appropriate language and without any spelling errors) should be enclosed with the tablets. The tablets themselves should match the authentic product in their shape, size, and colour. If the solid dose formulation is crumbling, chipped or cracked, it may indicate a substandard or degraded medicine. However, in my experience it can be difficult to persuade manufactures to supply genuine product for comparison. Pharmaceutical manufacturers employ overt anti-counterfeiting strategies such as visible holograms, as well as invisible covert features to mark the authenticity of their products. Sadly, holograms can also be counterfeited, as was the case for packages of antimalarial artesunate in South East Asia that claimed to be manufactured by Guilin Pharmaceutical Co. Ltd[15].

2. Laboratory tests

A well-equipped medicines quality control laboratory (MQCL) is a crucial component of any drug quality assurance system. It should be equipped with a range of analytical equipment (see below), as well as quality-assured reference standards, all of which is cost intensive. An MQCL also requires staff with a high level of technical expertise and experience of method development.

High-performance liquid chromatography (HPLC) is an analytical technique used to separate specific compounds, and then identify and quantify them based on how long they take to separate, and their spectrophotometric properties. HPLC can be coupled to various detectors, but the **ultraviolet photodiode array (UV-PDA)** is regarded as the 'gold standard' for drug quality analysis because it offers accuracy, specificity and precision in quantifying the amount of APIs present. It is, however, relatively expensive and requires greater expertise to operate, which demands extensive training and technological support.

HPLC can also be coupled to a **mass spectrometer (LC-MS)**. Although this gives analysts abundant chemical information, it also relies on tedious, time-consuming sample preparation, and typically requires a reference standard to determine API levels.

However, more recent MS technologies avoid sample preparation and give almost instantaneous results. Direct analysis in real time **(DART)** MS allows the analyst to hold a tablet in front of a mass spectrometer and get information about its composition in seconds[16], while desorption electrospray ionization **(DESI)** MS involves spraying a solvent at the tablet to free APIs for analysis[17].

Dissolution testing offers a valuable prediction of the in vivo bioavailability and bioequivalence of tablets and capsules, by measuring the amount of drug released into a dissolution media (liquid) over time. The presence of incorrect excipients, as well as poor manufacturing processes, may contribute to poor dissolution resulting in lower bioavailability. Indeed, an epidemic of malaria on the Afghan-Pakistan border was confirmed to result from the poor bioavailability of locally-procured substandard antimalarial drugs[18]. These tests require a sophisticated dissolution apparatus, as well as analytical equipment (HPLC with UV-PDA) and reference standards, which are expensive and may be difficult to obtain. Furthermore, analysts need to have access to the dissolution information that is expected for each medication, and the tests are both labour- and cost-intensive.

Nuclear magnetic resonance (NMR) spectroscopy is a powerful tool that allows analysts to determine the structures and relative concentrations of molecules in a sample without active pharmaceutical reference standards. For example, NMR analysis of the hydrogen and phosphorous (^{1}H and ^{31}P) atoms in the anti-leishmanial drug miltefosine helped to prove that a generic version procured from Bangladesh did not contain the SAPI[19].

3. Screening techniques

Thin layer chromatography (TLC) is an inexpensive, simple, flexible and effective method for verifying the identity of a formulation. It requires a variety of chemical reagents and plates, reference standards of the SAPIs, and some basic training for the analyst. For example, two TLC-based tests can check the quality (falsified or authentic) of the most effective antimalarial drugs, artemisinin combination therapies (ACTs), in the absence of a MQCL[20].

Many developing countries do not have the technical, financial, or human resources required to inspect and police the drug supply[7]. Thus simple and affordable field methods provide a practical means of rapidly monitoring drug quality. Portable labs – in particular the **Minilab®**, a ready-to-use TLC

CONVENIENCE SURVEYS CONDUCTED IN SOUTH EAST ASIA IN 2000/1 AND 2002/3 SUGGESTED THAT 38% AND 53% OF THE ARTESUNATE BLISTER PACKS OBTAINED FROM PHARMACIES AND SHOPS WERE COUNTERFEIT.

kit from the German Pharma Health Fund (GPHF)[21] – provides a versatile means for initial screening of many drug formulations, including antimicrobials, antimalarials, and antiretrovirals. Currently 713 GPHF-Minilab units are used globally across 92 countries to fight the counterfeit drug trade.

The Tanzanian Food and Drugs Authority pilot-tested the Minilab® and found it to be relatively inexpensive and rapid, but that it detected only grossly substandard or wrong-drug samples. Ultimately, the Minilab® should be used in conjunction with robust laboratory-based testing[22]. This approach was recently used to assess the quality of two brands of antibiotics, amoxicillin and co-trimoxazole, manufactured in six countries and purchased in Ghana, Nigeria and Nigeria. All of the samples of amoxicillin complied with United States Pharmacopeia (USP) tolerance limits for dissolution testing, but 60% of co-trimoxazole tablets did not. But there was some disparity in the Minilab® results, highlighting that this portable laboratory should not be relied upon to make regulatory decisions[23].

4. Portable instruments

Hand-held devices based on spectroscopic methods are now being investigated as screening tools that can rapidly detect poor-quality drugs throughout the supply chain (see case study p138). Non-destructive spectroscopic techniques such as **Raman spectroscopy** and **near infrared (NIR)** are currently being evaluated for their ability to scan drug samples through the blister pack, without using the toxic chemicals or flammable solvents typically found in a MQCL. Both techniques rely on comparing characteristic spectral 'fingerprint' of a suspect medicine with a genuine sample. This necessitates access to a database of spectra, created by investigators, for every brand of medications from every manufacturer (see case study, p140).

One potential drawback of using Raman spectroscopy is that only the sample surface is probed, so if the SAPI is not evenly distributed throughout the entire tablet, the resulting content information may be inaccurate. Additionally, many pharmaceutical preparations contain highly fluorescent excipients, thus

A RECENT META-ANALYSIS REPORTED THAT 35% OF ANTIMALARIAL DRUG SAMPLES FROM 21 SUB-SAHARAN AFRICAN COUNTRIES, FAILED CHEMICAL CONTENT ANALYSIS.

affecting the quality of the spectrum. The TruScan® hand-held Raman device has successfully detected some counterfeits in the field, but it has not been useful to detect substandard medicines[24].

Unlike Raman spectroscopy, infrared (IR) spectroscopy has a larger depth penetration into the sample surface. Near-infrared spectroscopy (NIR) can reveal whether excipients are not in the correct proportions, suggesting that the medicine is counterfeit, but it cannot detect substandard medicines[25]. NIR is also relatively simple to miniaturise: for example, the SCiO NIR device, at present under validation, is a smart-phone-sized instrument that promises to be highly effective at checking the quality of medications in the absence of a MQCL[26]. Meanwhile, the US Food and Drug Administration (FDA) has recently started using its Counterfeit Detection Device CD-3 to screen tablets, packaging and even documents at ports of entry or in remote areas, although further development is still needed[27].

QUALITY OF ANTIMALARIAL DRUGS IN MALARIA-ENDEMIC COUNTRIES

A recent meta-analysis reported that 35% of antimalarial drug samples from 21 Sub-Saharan African countries, failed chemical content analysis[28]. The underlying research predominantly used the 'convenience' sampling approach, where research teams purchased medicines from drug sellers who were easily-accessible, or who were already thought to sell poor-quality medicines. Results based on this low-cost sampling approach can be useful in drawing attention to a potential problem. For example, convenience surveys conducted in South East Asia in 2000/1 and 2002/3 suggested that 38% and 53% of the artesunate blister packs obtained from pharmacies and shops were counterfeit[29].

But the convenience approach may not be

Table 1: Comparative strengths and weaknesses of the three sampling approaches used

SAMPLING APPROACH	ADVANTAGES	DISADVANTAGES
CONVENIENCE	• Rapid • Low cost	• Lack of defined sampling frame of standardised approach • Uncertainty in whether sampling is representative and therefore reliability of the estimates of drug quality obtained • Generalisability of findings may be weak • Results may be difficult to replicate
MYSTERY CLIENTS	• Use of defined sampling frame • Can yield representative sample from all types of outlets and/or brands • Low risk of sampling bias in samples collected, as outlets are unaware of survey • Reliability and generalisability of results should be strong • Results can be replicated	• Sample will only be as comprehensive and/or representative as the sampling frame that was used • Need to authenticate and update sampling frame increases time and cost of survey • Information on sources of poor quality drugs is limited to brand, batch and country of manufacture as stated on packaging
OVERT	• Use of defined sampling frame • Can yield representative sample from all types of outlets and/or brands • Results can be replicated • Can collect additional information at minimal additional cost to mystery approach	• Sample will only be as comprehensive and/or representative as the sampling frame that was used • Need to authenticate and update sampling frame increases time and cost of survey • Possible risk of sampling bias in samples collected, if some outlets refuse to be sampled or are aware of which samples might be poor quality and differentially withhold these • Reliability and generalisability of results may be compromised if sampling bias occurs

representative of the places where patients actually buy their medicines, and it may also be biased: for example, if the collector consciously or subconsciously set out to procure or not procure poor-quality formulations (see Table 1)[30].

In 2006, the WHO banned malaria medicines that contain just one active ingredient (such as artesunate), in favour of artemisinin combination therapies (ACTs) that contain more than one active ingredient. This treats the disease more rapidly: the artemisinin component kills the majority of the parasites at the start of the treatment, while the more slowly-eliminated partner drug clears the remaining parasites, in the hope that resistance will be slowed enough to allow for the development of a pipeline of efficacious drugs. Once ACTs had been enforced in malaria-endemic countries, it was believed that they would be in danger of being counterfeited. Hence, the Artemisinin-based Combination Therapy Consortium Drug Quality programme purchased over 10,000 artemisinin-containing antimalarials (ACAs) in 6 malaria endemic countries, from private sector retail outlets such as pharmacies and drug shops, following representative sampling approaches[31]. Outlets were selected at random in most countries from lists obtained from the relevant government's ministry of health; whereas in other countries we initially conducted a pilot study by collecting samples using the 'convenience' approach to gain perspective on the type of outlets and brands of ACAs available.

Medicine samples were subsequently purchased using one of two approaches. Through the 'mystery client' approach, the person purchasing the medicines posed as a malaria patient or their relative; through 'overt sample collection', vendors were informed that we were going to analyse the quality of the medicines they sold, and samples were purchased once they consented. This allowed us to interview the vendor to obtain data on the availability and supply of antimalarials, their storage conditions, and the training of providers.

The collected samples were analysed in three different laboratories in the UK and the US. First, they were sent to the London School of Hygiene and Tropical Medicine (LSHTM), where they were logged and their packaging and blister packs scanned. Each tablet was weighed and its dimensions recorded on the database. Each sample was analysed using HPLC UV-PDA to measure the amount of APIs, which was then expressed as the percentage of the SAPIs and used to classify the quality of the sample. Duplicate samples from each packet of tablets analysed at LSHTM were sent to the US Centers for Disease Control and Prevention in Atlanta, where a random 10% were analysed for confirmatory HPLC-PDA results. A duplicate set was also sent to the Georgia Institute of Technology, Atlanta, for ambient MS analyses to verify the pharmaceutical ingredients present and identify any unstated compounds. Samples were classified as 'acceptable quality' if the SAPIs were present at between 85% and 115% of the SAPI quantity. Medicines outside this range, for either or both of the partner compounds, were classified as substandard. These substandard medicines were also examined to detect the presence of degradation products, caused by poor storage conditions such as heat and humidity. Medicines were regarded as falsified when either one of the SAPIs was not present. All results were compiled into a report and disseminated to the relevant ministries of health before being submitted as a manuscript to peer reviewed journals.

WE NEED GREATER INVESTMENT IN DEVELOPING AND VALIDATING PORTABLE TECHNOLOGIES THAT CAN BE USED IN THE FIELD.

In these investigations of ACAs, we found no evidence of falsified medicines in 4,928 samples (over 50 brands) from Cambodia, Ghana, Rwanda and Tanzania. Of the 5,151 samples that were collected in Bioko Island (Equatorial Guinea) and Nigeria (over 142 brands), 1.9% were falsified i.e. they contained neither of the SAPIs. Instead, they contained compounds including chlorzoxazone (a muscle relaxant), ciprofloxacin (an antibiotic) or acetaminophen (paracetamol, a commonly used painkiller). The falsified medicines found in this research are far fewer than the 35% fakes suggested in previous reports. However, it is worth noting that substandard drugs were found in all the countries that we studied, with the most in Cambodia (31.3%), Ghana (37%) and Tanzania (12%); others were less than 8%.

The key strengths of this investigation are that representative sampling approaches were used to purchase a sizeable number of samples; these were analysed in three independent laboratories, using two different detection methods (HPLC with UV-PDA and MS)[30].

Representative methods to sample medicines are important for generating reliable estimates of the prevalence of poor quality drugs in a given country. However, this type of study is cost intensive, both for the purchase and analysis of drugs. It is important to establish affordable systems that sample medicines in a representative way, and develop robust laboratory techniques to analyse them on a regular basis. This will enable for the accurate quantification and tracking of the scale of poor-quality medicines that threaten the treatment of this life threatening disease.

CASE STUDY

OPERATION PANGEA

GIFT MINTA, *Senior Criminal Intelligence Analyst, Medicines and Healthcare products Regulatory Agency*

Operation Pangea is an International Internet Week of Action (IIWA) to tackle the online sale of illicit and counterfeit medicines, and highlighting the dangers of buying medicines online. Coordinated by Interpol, the annual operation brings together customs, health regulators, national police and the pharmaceutical industry from countries around the world. Activities target the three principal components used by illegal websites operators to conduct their trade: internet service providers (ISP), payment systems, and delivery services (including ports). The operation has gained significant momentum since its launch in 2008, growing from 10 participating countries to 115 countries in 2015. Operation Pangea VIII (9–16 June 2015) resulted in the record UK seizure of 6.2 million doses of falsified, counterfeit and unlicensed medicines, with a total value of £15.8 million. This marks an increase of 97% on the preceding year's operation.

Operation Pangea traces its origins back to a threat assessment conducted by the MHRA Enforcement Group that revealed a disturbing increase in internet-facilitated medicines crime between 2000 and 2005. At that time, approximately 85% of the total referrals to the Enforcement Group were internet-facilitated crimes. The MHRA consequently launched the UK Internet Day of Action (IDA Operation Bali) in April 2006, to investigate internet sites offering illegal medicines, and followed that with Operation Latvia in 2007. Realising that the fight against the online sale of illicit and counterfeit medicines required a global effort; this approach was introduced to some European member states via Interpol in 2008.

OPERATION PANGEA VIII RESULTED IN THE RECORD UK SEIZURE OF 6.2 MILLION DOSES OF FALSIFIED, COUNTERFEIT AND UNLICENSED MEDICINES, WITH A TOTAL VALUE OF £15.8 MILLION

The MHRA Enforcement Group now uses several different strategies to combat the activities of criminals responsible for the illegal sale and supply of medicines online. This includes collaboration with the UK's Border Force to intercept medicines and medical devices at ports, for example, and uses intelligence analysis to adapt to the criminals' changing tactics.

In recognition of the growing threat from cyber related criminality, the MHRA has developed a specialist role of Internet Infrastructure Investigator, whose activities has significantly reduced the number of websites on the UK domain tree that illegally sell medicines. This disruption-based approach has forced criminals to relocate their businesses outside UK jurisdiction, and transfer their wares from manufacturers to the UK public – a tactic known as drop shipping. Nevertheless, thanks to effective profiling through intelligence analysis, the MHRA has helped to increase the volume of seizures of unlicensed, falsified and counterfeit medicines and devices.

The MHRA Enforcement Group also works with forensic science providers to combat pharmaceutical crime. By testing seized medicines using various chromatographic and spectroscopic analytical techniques, reports and witness statements are generated to support investigations and prosecutions. Scientists can be called as expert witnesses, or help with court proceedings by corroborating scientific findings and confirming criminality.

And many of these techniques are now being used in the field. Raman and near infra-red spectroscopy have helped to the increase the volume of illicit medicine seizures since they were first used at the Coventry International Hub in Operation Pangea IV. When Raman equipment was used at the Heathrow Worldwide Distribution Centre (HWDC) in Operation Pangea VIII, it resulted in the interception of approximately 20,000 doses of unlabelled or unmarked tablets, which contained medicinal and controlled substances indicated for weight loss, anxiety and hormone therapy.

It is clear that Operation Pangea has been a significant success story, and demonstrates the importance of working in partnership, evidenced by the high volume of seizures during the weeks of activities at the ports. But criminals continue to evolve their methods: recent seizures of unlicensed medicines by the MHRA Enforcement Group indicate that consignments were not imported via the known ports of entry and modes of transport. It is assumed that criminals involved in this illicit trade have turned to alternative fast parcel and courier companies to avoid detection, which emphasises the importance of effective working relationships with the industry and Border Force.

CONCLUSION

Producing counterfeit drugs is an easy endeavour, requiring only a tablet press, a printer, commonly-found household materials and a malevolent mentality. In August 2015, the US FDA approved for the first time a drug made using 3D-printing technology[32]. This technology is a potential danger in the hands of counterfeiters. Enormous effort is spent in determining the most efficacious drug for treating a disease, and supporting its use in nationwide programs. It is essential that the quality of these drugs is monitored to maintain good quality, not least to avoid the development of drug resistance caused by falsified and substandard medicines.

We need greater investment in developing and validating portable technologies that can be used in the field, to ensure good-quality drugs reach the patient. The techniques mentioned in this article can be used to determine the quality of drugs, but are not available in the majority of resource-constrained countries. Hence, there are few data to inform policy or interventions.

We need more research funding to uncover the extent of the counterfeiting problem; to evaluate appropriate methods for drug-quality assessment; and to estimate the impact of poor-quality drugs used to treat various diseases. In addition, better collaboration between academic researchers, the Pharmaceutical industry, medicine regulatory authorities and law enforcement agencies will greatly help to ensure that the vulnerable are protected from poor-quality medicines. Enhanced regulation and quality assurance of genuine manufacturers would also help reduce the problems of substandard and falsified medicines.

Sensitive and specialised chemical techniques (HPLC, dissolution testing, LC-MS, NMR and MS), operated by experienced staff, are needed in bio-analytical laboratories in disease-endemic countries, so that they can be utilised relatively quickly determine the quality of drugs to treat fatal diseases.

Both national and international programs must take steps to ensure that they use quality-assured drugs in their effort to eliminate diseases such as malaria and visceral leishmaniasis. As more people travel around the world, there is an urgent need to ensure that medicines available globally are of good quality.

CASE STUDY

THE COUNTERFEITING OF HEALTHCARE PRODUCTS

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The counterfeiting of healthcare products represents an unacceptable threat to patients' welfare. There is no such thing as a 'good' counterfeit. A combination of inappropriate ingredients and lack of adherence to strict conditions of quality assurance, testing and hygiene in manufacturing mean they are never safe to use. As technology improves, counterfeit packaging becomes increasingly sophisticated and more difficult to detect. Patients buying or being given counterfeit medicines are unlikely to know that what they have is not genuine and could be harmful. This risk is particularly high when obtaining medicines from unauthorised websites.

The prevention and detection of counterfeits is primarily a matter for national governments worldwide, but the pharmaceutical industry has an important role to play in helping to minimise the counterfeiting of its products. Forensic techniques, for example, can differentiate genuine from counterfeit products.

Medicinal tablets consist of the drug plus other ingredients. These other ingredients reflect how they are manufactured, and how they are designed to dissolve when swallowed. Counterfeit medicines may contain more or less of the originator drug, a different drug or no drug at all, together with any combination of other ingredients. The possibilities are endless – but detectable.

In any investigation, a number of techniques are used in combination to prove or disprove authenticity. These two case studies illustrate the power of individual techniques to generate essential clues in the form of unique analytical fingerprints.

CASE STUDY 1

Raman microscopy highlights that even counterfeits are not the same

In Raman spectroscopy, a monochromatic laser beam is shone onto (or through) a sample, and the resulting scattered light is analysed for changes in wavelength. This leads to a spectral 'molecular fingerprint', highly sensitive to the structure and crystalline form of the material under investigation. With Raman microscopy, it is possible to collect Raman spectra from single points on a sample as well as spectral maps from larger areas.

In Figure 1, Raman microscopy has been used in a fast, non-contact, non-destructive way to generate mean fingerprints of a number of tablet samples purporting to be the same as the authentic tablet. Not only do the fingerprints of the other tablets demonstrate that all the samples are counterfeit – the counterfeits themselves appear to belong to four different types.

CASE STUDY 2

Fourier Transform-Infra Red Spectroscopy (FT-IR) and Liquid Chromatography-Mass Spectroscopy (LC-MS) determine the active drugs in the counterfeit

In IR spectroscopy, a beam of infra-red light is passed through a sample. The transmitted light from the sample shows how much energy is absorbed at each wavelength, and this absorption gives information about the molecular structure of the sample. It can provide characteristic fingerprint spectra of a particular molecule in minutes, so the technique can be used to determine chemical identity.

In Figure 2, the FT-IR spectrum of a suspect headache powder highlights that there are differences relative to the authentic product.

In Figure 3, comparison of the counterfeit product spectrum with the spectra of authentic active ingredients – paracetamol, aspirin and caffeine – reveal that aspirin is not present, because characteristic peaks are missing in the counterfeit spectrum.

LC-MS combines the ability of high-performance liquid chromatography to separate components of a mixture, with the ability of mass spectrometry to provide information about the mass of individual molecules. Using a high-resolution mass spectrometer with accurate mass measurement enables investigators to determine a specific molecular formula for each component of a separated mixture.

In this example, investigators found that aspirin (or acetylsalicylic acid) had been replaced by salicylic acid, a different active ingredient that is only used in products for the treatment of skin conditions such as verrucae.

Other industries – particularly those in the consumer products sector – apply similar forensic analysis and investigative techniques to determine product authenticity and to differentiate between counterfeit and genuine products. For example, the food industry applies many of the same techniques used in pharmaceutical investigations to confirm authenticity of food products, including the determination of whether products have been contaminated maliciously or inadvertently (see Chapter 11). The cosmetic industry applies comparable tools to differentiate genuine products from counterfeit cosmetics in the same way.

Ultimately, these are specialist means of detection, but significant advances in technology and the widespread availability of portable instruments mean that it is becoming much easier to deploy them in mobile laboratories, or even through the use of hand-held devices, so that real-time determinations can be made in the field.

Figure 1: Comparison of mean Raman spectra for an authentic tablet and 4 counterfeit tablets

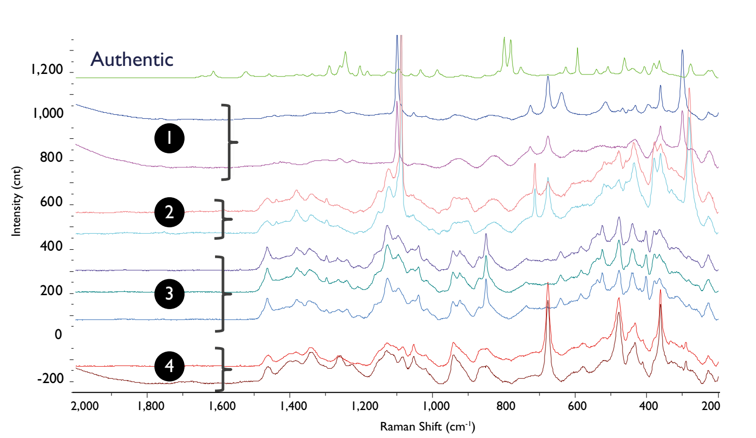


Figure 2: FT-IR spectra shows that a suspect headache powder does not match an authentic product

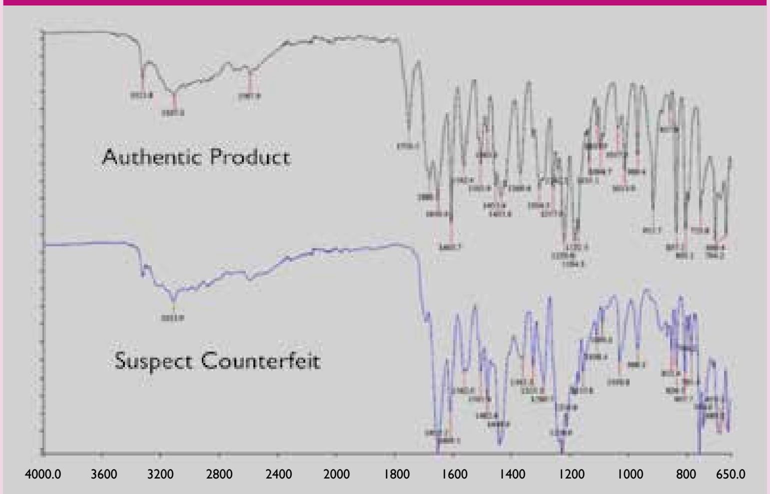
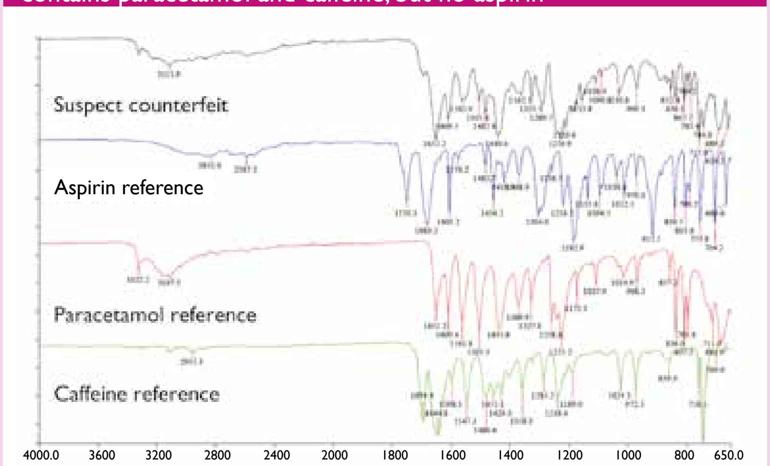


Figure 3: FT-IR comparison shows that the suspect powder contains paracetamol and caffeine, but no aspirin



CONSUMER PRODUCTS

MELISSA DRING,
ROBYN ELLISON
Director of Policy, and Policy Officer, Chartered Trading Standards Institute

Over the past 15 years, product counterfeiting has become one of the most prolific areas of economic crime, enabled by the rapid growth of the internet. Investment in forensic analysis techniques and capability, as well as advanced anti-counterfeiting measures, is essential to tackle this criminal threat – but it could also stimulate significant growth within genuine markets.

The production and sale of counterfeit consumer goods damages both producers and consumers. It deprives our creators, inventors, artists and designers of their just rewards; and means that consumers spend money on fraudulent, sub-standard goods, while exposing themselves to the potential harm caused by a disregard for safety standards in counterfeit products. It also denies the government much needed tax revenue to fund essential public services.

In addition, Interpol and Europol have outlined a clear connection between the trafficking of counterfeit goods and other types of organised crime[1], with the profits from counterfeit products being channelled into areas such as the trafficking of drugs and people, and related financial crimes such as money laundering and corruption.

Over the past 15 years, product counterfeiting has become one of the most prolific areas of economic crime. As far back as 2009, the Organisation for Economic Co-operation and Development (OECD) reported that global trade in fake goods was as high as $250 billion[2]. This amount was described as being larger than the national GDPs of approximately 150 economies. However, despite efforts by organisations such as the OECD, it is still not possible to calculate the true scope, scale and impact of the problem. This makes it extremely difficult to influence enforcement agendas and key decision makers, and to focus resources correctly in order to take appropriate and decisive action.

THE INTERNET EFFECT

As part of its study, the OECD highlighted why the situation was likely to worsen. It envisaged that a major threat would be the potential for counterfeiters to increase the use of the internet to peddle their fakes. In fact, the OECD accurately predicted that the Internet would:

- Make it easier for counterfeiters to conceal their true identities and lower the risk of detection
- Enable counterfeiters to establish enticing sales sites and then quickly take them down or move to markets where enforcement is perceived to be weaker
- Provide opportunities for criminals to develop vast numbers of illicit e-commerce sites and listings and make it very difficult to find and take action against them
- Allow sellers to reach a huge global audience at low cost, 24 hours a day
- Make software and images widely available to make it easy for counterfeiters to create 'clone' websites, which look identical to legitimate online stores and sales platforms.

The OECD's forecasts have largely proved to be true. Online shopping has snowballed, and the opportunity to buy and sell almost every conceivable type of product has burgeoned beyond anticipation. In the UK alone, it is predicted that online retail sales will reach over £52 billion in 2015 (ref. 3). This is over 15% of all retail sales made in the UK and means that, on average, UK consumers will spend £1,174 online in 2015, making us the most regular internet shoppers in Europe.

Unfortunately, as the OECD also predicted, legitimate traders have not been the only ones to recognise the value and opportunities of e-commerce. Through the internet, counterfeiters are now able to engage with consumers directly and deliver millions of imitation products directly to their homes.

European Commission statistics back this up. Its latest report on the subject, produced in 2014, highlights the fact that over 35 million

CASE STUDY

MAKING THE MOST OF TRADING STANDARDS SERVICES

MELISSA DRING, ROBYN ELLISON, *Director of Policy and Policy Officer, Chartered Trading Standards Institute*

Enforcement and regulation can be incredibly challenging in this ever-evolving environment. Indeed, reflecting on the local authority model, it is clear that the current structure of Trading Standards services hampers enforcement in this specific area. As discussed in this chapter, the manufacture and distribution of counterfeit goods has resulted in a surge of large-scale criminal operations that cross borders at both national and local authority levels.

In recent years, Trading Standards services, as with other local authority services, have adapted in the face of austerity. On average, staff numbers have dropped by 40% and budgets by 50% (ref. 1). However as the primary enforcement agency tasked with tackling the import and distribution of dangerous counterfeit goods, Trading Standards services also have responsibility for the legislative enforcement of a diverse array of other consumer protection issues, including underage sales, tackling rogue traders, combatting scams, animal health issues and weights and measures. Some Trading Standards services currently operate with just one part-time member of staff, yet they must still attempt to enforce all statutory legislation assigned to Trading Standards. Unfortunately, in this climate of diminishing resources and increased legislative burdens, many individual Trading Standards services are struggling to cope with tackling this large-scale cross-border crime.

In an attempt to address this issue, National Trading Standards has begun work to organise a more coordinated effort to tackle the distribution of dangerous consumer goods with their Safety at Ports and Borders project. The team works with 14 local authority services across ports, airports and postal hubs to intercept and detain unsafe or illegal counterfeit consumer products. They also act as a single point of contact for border authorities, and utilise an intelligence-led approach to prioritise their resources effectively. Between April and December 2014, a staggering 1.9 million non-compliant or unsafe goods were intercepted at UK ports through the ports project. Of those, over 670,000 were faulty or non-compliant cosmetic products[2].

Despite the successes of the project, it is clear that these efforts are only really addressing the tip of the iceberg in terms of the types of dangerous consumer products entering the UK. The patchwork of coverage provided by local authority Trading Standards services remains of concern in terms of tackling locally-based online sellers, who can easily move their operations from one locality to another in order to evade detection.

Furthermore, for those Trading Standards and border agencies involved in the ports project, it is clear that they are unable to open every container and intercept every potentially dangerous import. Thus for the tens of thousands of products that are successfully intercepted and seized by the team, there are many thousands more that make it onto market stalls, into shops and directly through the doors of UK consumers. Technological advances that would enable automated verification of certain types of goods at UK borders would go a long way in helping to tackle the stream of counterfeit goods entering the UK, especially during out-of-hours periods when Trading Standards inspectors are unavailable to monitor imports.

Furthermore, outside of the work directly conducted at UK ports in tackling dangerous counterfeits, advances in forensics that would make it easier and more cost-effective for Trading Standards officers to test products that are manufactured and dispatched primarily within the UK would also enable quicker and more effective enforcement to tackle these issues at home.

OVER THE PAST 20 YEARS, ENFORCEMENT IN THE UK HAS TENDED TO FOCUS ON REDUCING THE VOLUME OF AVAILABLE COUNTERFEIT PRODUCTS.

fakes were detained at our borders, many of which were small parcels being delivered through express and postal traffic, as a result of internet orders[4]. Demonstrating the increasing trend in globalisation for online retailing, over 83% of all counterfeits seized by customs authorities actually originated in China and Hong Kong.

Perhaps the most worrying fact produced by the Commission was that over 25% of all counterfeits detained at the borders were potentially dangerous to the health and safety of consumers. Many counterfeit electrical appliances are sold without a ground-fault circuit interrupter (GFCI), which protects users against electrical shock, for example in the event that a hair dryer falls into water. The purchase of counterfeit batteries may damage genuine electrical appliances such as tablets and smart phones. These batteries have not been subjected to the correct consumer tests, and have been known to cause overheating, explode or even catch fire under conditions in which a genuine product would survive.

Counterfeiting can no longer be considered to be an innocuous, small time, criminal sideshow. Moving massive volumes of product around the world, and evading enforcement authorities in the process, requires vast resources, wide-reaching transport chains and sophisticated networks. What has become clear in recent years is that the criminals involved in counterfeiting are extremely determined, and have not only become adept at manufacture and distribution – they have become shrewd marketing and sales people. By building impressive online websites and stores that appear to sell original products at discounted prices, they continually attract individual consumers and businesses to buy nothing more than inferior and substandard replicas. The added attraction for buyers is that the sites appear to be owned by UK or EU-based companies, but in reality they are mostly based in China or Russia.

A more recent development that has aided counterfeiters has been the attention given to social media (see case study p147). Using multiple auction sites, and social media platforms such as Facebook and Twitter, criminals are gaining the confidence of users through images of genuine goods, fake labels and packaging, and prices that are actually close to those being charged for real products. This latest ploy is used to deceive buyers into believing they are getting a bargain. However, the end result is that, once again, they often end up receiving cheap tat and potentially having their identities stolen and their bank accounts infiltrated as well.

A FORENSIC APPROACH

Responding to the growing threat of counterfeiting requires new and innovative approaches and initiatives. Over the past 20 years, enforcement in the UK has tended to focus on reducing the volume of available counterfeit products. This has meant an emphasis on disrupting manufacturing, distribution and sales chains so that potential buyers are unable to get access to products.

However, due to a run down on resources; continuously extending enforcement responsibilities (local authority Trading Standards services are tasked with enforcing over 250 pieces of statutory legislation); and more effective manufacturing, transportation, distribution and selling models used by international criminals; it is clear that this work has been unable to effectively stem the supply for counterfeit goods. For more background on the Trading Standards situation, see the case study on p143.

Diverse legal frameworks across the world also contain obstacles that affect practices used in enforcement and information exchange. The fact that penalties differ between jurisdictions has an effect on the courts and the mind-set of the general public in disparate ways.

As a result, there is a need for central government to work with enforcement authorities to identify successful best practices and build greater understanding and collaborative strength to adopt alternative strategies – including forensic analysis – that focus on other areas. An increase in the

Table 1: Consumer products, potential safety concerns, and analytical techniques used in investigations

CONSUMER PRODUCT: SAFETY CONCERN	ANALYSIS TECHNIQUES EMPLOYED TO TEST PRODUCTS
Food products: presence of toxins, permitted and not permitted colours and additives, sugar content and nutritional value	Liquid Chromatography Mass Spectrometry (LCMS) Analysis using chemical reagents
Imported food and animal feed products: high levels of residual pesticides or heavy metals like mercury	Gas Chromatography Mass Spectrometry (GCMS) High Performance Liquid Chromatography (HPLC) Cold Vapour Atomic Absorption Spectrometry (CVAFS)
Counterfeit food products: authenticity and harmful ingredients	HPLC Gas Chromatography (GC)
Melamine kitchenware: release of formaldehyde	Spectrophotometry
Toys: compliance with BS EN71 (the British Standard for toy safety), including tests for heavy metals in paint, flammability and detachability of small parts	Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) Rate of spread of flame test within a flammability chamber Tension, torque, drop, impact, compression and soaking tests to determine mechanical properties
Cosmetics: prohibited substances such as lead, mercury, hydroquinone or phenol; restricted substance such as hydrogen peroxide or p-phenylenediamine (PPD); and levels of permitted preservatives such as benzoic acid, sorbic acid, phenoxyethanol and parabens	Atomic Absorption Spectrometry CVAFS HPLC Titration

availability of forensic data would help to define the scope and methods of illicit goods trading in the UK, and focus the appropriate amount of resources to stop illegal trade. In other words, enforcement needs to be reshaped to change perceptions and understanding, rather than solely being aimed at wiping out the availability of fake goods.

This strategy requires forensic analysis built on robust statistics and certified measurement methods, and has enormous potential to strengthen the value of genuine goods. This in turn ensures real financial advantages to the manufacturing economy, on a huge scale: the sale of counterfeit goods has a serious detrimental effect on the economy, with a projected cost of thousands of jobs. This forensics-based approach would also inspire consumer confidence, and enable secure supply chains that result in economic growth with an increase in employment.

To ensure the authenticity of traded goods in the UK, the local authority Trading Standards services work in collaboration with the public analyst laboratories. Public Analysts provide scientific and calibration services ensuring product safety and compliance with all relevant UK legislation. In doing so, they use a variety of forensic techniques to both protect the consumer from harm and support enforcement services, particularly Trading Standards Officers.

Examples of forensic techniques used to identify and investigate issues relating to consumer products are detailed in Table 1.

FUTURE OPPORTUNITIES

An important growth area in the forensic analysis of consumer goods involves putting the process of authenticity verification in the hands of consumers, rather than relying on a governmental body to validate genuine goods

IMPROVING THE SECURITY AND VERACITY OF SUPPLY CHAINS, THROUGH THE USE OF ADVANCED NEW TECHNOLOGIES, REQUIRES INVESTMENT IN INNOVATION.

through targeted sampling within centralised laboratories.

Researchers at the Massachusetts Institute of Technology (MIT) have recently developed inks using nanocrystals[5], dyed with rare earth minerals in unique polymer stream patterns, which can be used to identify legitimate products through the printing of unique security tags or barcodes. These patterns glow under UV light and can be detected with a smartphone.

Another important threat to the purchase of genuine consumer goods is the growth in 3D printing and additive manufacturing technology. Engineering firms are adopting these techniques as a means of cheaper and more efficient manufacturing. But the technology can also make it easier to produce counterfeit goods if the drawings for a genuine part are leaked online, or even reverse engineered. A striking example of this can be found in a 2014 Washington Post article[6], which accidentally published a leaked photograph of the US Transportation Security Administration's master key for its approved locks that are used on millions of suitcases worldwide. Although the photo was removed from the website within hours, a set of computer automated design (CAD) files had been uploaded to the internet in an equally short amount of time, with 3D printed keys produced and successfully used to open TSA locks the same day.

A recent report[7] from the information technology research and advisory company Gartner predicted that the emergence of 3D printing will create major challenges with regards to intellectual property (IP) theft, resulting in a loss of "at least $100 billion per year in IP globally" by 2018. New safeguarding techniques are required to counter the threat from this novel technology. One possible solution has been put forward by the US company Quantum Materials Corp[8], which has developed a technology that uses embedded nanocrystals within 3D inks to produce a physically unclonable signature known only to the manufacturer of the product. While this enables the secure identification of genuine parts, it does not stop the production and use of unauthorised copies.

In developing innovative technologies in consumer protection, we must be mindful that these advances create the following benefits:

- More focused and targeted deterrence of the trafficking of dangerous products and organised criminality
- Enable greater collaboration between the relevant authorities, such as those in the UK, EU, international enforcement bodies, and policymakers (including Europol, Interpol, the World Customs Organization, and the European Commission)
- Empower harm reduction tactics within local and global markets
- Facilitate assurance of provenance throughout the supply chain, from manufacturer to consumer, to raise confidence and therefore value in genuine goods

From the consumer viewpoint, more should be done to make the online shopping arena a safer space. The most recent Ofcom Communications Market report[9] found that smartphones have now overtaken computers as the preferred method of browsing the internet. While the use of virus protection and firewall software may be common knowledge in protecting computers from online attacks, few smartphone users install specialist smartphone security software and are therefore at risk of fraud through malicious websites and phishing attacks. Although dedicated store apps offer a level of protection, not all companies have their own apps and a large amount of trade is still carried out through browser-based shopping.

There are a number of accreditation schemes designed to enable safe internet shopping, including Brand-i[10] (a shopping directory that only lists webstores selling genuine products), VeriSign Trust[11] (a seal awarded to the website when the company's identity has been verified and the site has passed daily tests for malware), and the Trusted Shops scheme[12] (an online shop certification system resulting the display of the

CASE STUDY

CONSUMER PROTECTION AND SOCIAL MEDIA

MIKE ANDREWS, *National Trading Standards eCrime Team*

There is little doubt that efforts to confront intellectual property (IP) infringement have seen major changes in recent years. Traditionally, Trading Standards was, quite rightly, focused on counterfeit products being offered for sale at car boot sales and local markets. While this does still take place, the past decade has seen a significant shift towards online infringement. Initially centred on auction websites, this has moved in the past few years towards social media. Indeed, the most recent IP Crime Report[1] makes specific reference to the significant opportunities and challenges that social media present. Figures published in the report show that products sourced from social media are now the second-largest source of reports made to Crimestoppers regarding IP infringement. An unfortunate side-effect of this increase is an associated increase in issues of product safety. There are numerous recorded incidences of serious injury and even death associated with the sale of counterfeit products bought online.

A recent case investigated by the National Trading Standards eCrime Team (NTSeCT) highlights the growing phenomenon of products sold through social media. Initially, a quantity of potentially IP-infringing products was uncovered through the diligent work of Trading Standards officers at one of the ports of entry on the south coast of England. Intelligence suggested the products were destined for sale online, so the case was referred to NTSeCT. The products recovered included various cosmetics, manicure kits and associated electrical devices (nail-gel dryers and electric nail-files etc). The electrical products were of particular concern because they were specifically intended for use in nail salons, which would then expose countless consumers to potentially significant risk of injury.

The ultimate destination of the products was traced to a warehousing and storage facility in the south-west of England. Following the execution of an entry warrant, further significant quantities of similar products were uncovered along with business records and various electronic devices such as laptops and mobile phones. As is routine in Trading Standards cases, the electronic devices were examined by digital forensic specialists within the eCrime Team – a key component in successfully identifying and prosecuting offenders.

Digital forensic examinations regularly uncover evidence of the products' supply chain; communications concerning their purchase; and evidence of the intended outlet for the products. This is not only vital in securing successful prosecution outcomes, it is also a rich source of intelligence when trying to identify the wider organised crime networks that are known to be associated with counterfeiting. In this case, the forensic analysis uncovered details of the product manufacturers in China, the shipping company, the importer and evidence to indicate that the products were ultimately destined for retail online through social media. This intelligence helped Trading Standards to prevent further shipments from entering the UK, while ensuring that products already in the country were destroyed and prevented from entering the supply chain.

CASE STUDY

BLOCK CHAIN: AUTHENTICITY AND PROVENANCE

JESSI BAKER, *CEO of Project Provenance Ltd*

Product supply chains are often complex and opaque. It can be difficult to prove where materials, ingredients and products have come from, or how they were created. Up and down supply chains, there is a call for more transparency and an increasing demand for products with proven origin. Information about how products are made and used can inform better purchasing decisions – based on more than just their price, quality and brand – but that information needs to be both available and trusted.

This end-to-end transparency is almost impossible to achieve with existing systems, because the information would have to be pooled into large data silos. This has technological, economic, and organisational limitations:

- Pooling data creates a single point of weakness and failure that also acts as a bottleneck; it can also lead to potential biases and selective disclosure
- The future costs of such data silo projects are highly opaque, and joint initiatives are often impractical because there is little incentive for individual partners to join when they can freely benefit from the results – for example, in a sprawling food supply chain where middlemen may fear being cut out if data is exposed
- Partners may fear an undesired disclosure of critical business information, causing a loss of competitive advantage
- NGOs or third parties that could be commissioned as a neutral operator often lack the technical expertise to do so

Block chain technology now offers a solution. A block chain is a form of database that groups data into blocks, and links them using cryptographic signatures. Crucially, these blocks are shared across a global peer-to-peer network. This provides an open data platform that can deliver neutrality, reliability and security.

The basic block chain mechanism was originally proposed as part of a solution for administering the shared accounting ledger underlying Bitcoin. Beyond this financial application, block chains can be generalized and used to implement arbitrary digital contracts that no one – neither the users nor the operators of the system – can break. This makes block chains a unique platform for applications involving multiple parties with little trust in each other: for example, fragmented product supply chains or complex chains of custody.

One key attribute of block chains that make them well suited to storing and transferring material is the public/private key infrastructure. It mimics a physical signature by provably registering an identity with a digital document or instruction, without giving others the ability to reproduce those signatures. Consequently, it is possible to hold a small piece of data (known as a secret, or private key), and use it to demonstrate that you have explicitly sanctioned a particular piece of information (a document, image, order or other such digital item) without ever uncovering that secret to another party.

Provenance has developed a block chain to handle supply chain data. Suppliers, manufacturers, brands and certifiers can employ this framework to access, publish and transfer records of ownership of physical assets, along with key information about their creation, transformation or ownership. This is linked to physical items with smart tags and IDs (e.g. barcode and batch number).

This framework provides an immutable, public (although pseudo-anonymous) record that is interoperable across all data systems. It is also auditable, cost-efficient, and offers guaranteed continuity because it is independent of any single company or data operator. This allows the authenticity or provenance of an item to be tracked along even the most complex chain of custody.

INFORMATION ABOUT HOW PRODUCTS ARE MADE AND USED CAN INFORM BETTER PURCHASING DECISIONS – BASED ON MORE THAN JUST THEIR PRICE, QUALITY AND BRAND – BUT THAT INFORMATION NEEDS TO BE BOTH AVAILABLE AND TRUSTED.

European Trustmark). Research is needed to ascertain whether a universal verification scheme is achievable across all platforms: that would require close collaboration between regulatory bodies, banks, retailers and phone manufacturers.

Improving the security and veracity of supply chains, through the use of advanced new technologies, requires investment in innovation. The first steps in this space were made with the advent of radio-frequency identification (RFID) technology, and stamping of goods with holographic logos. Further advantages for increasing the efficiency and effectiveness of operations within the supply chain are afforded through the use of block chain technology, for example (see case study p148). Lab on a chip (LOC) technology, combined with the rapid expansion of smartphone technology, has shown great promise in transforming the biomedical landscape[13]. In this case, the analysis environment is shifting: from centralised laboratories with long turn-around testing routines, to point-of-care diagnostics that almost instantly put information into medical practitioners' hands. The same type of technology could be leveraged to produce a similar revolutionary change in the detection and policing of counterfeit goods.

CONCLUSION

In tackling the ever-growing issue of consumer fraud, we should be mindful that advances in manufacturing and communications technology presents opportunity not just to the criminals producing and distributing counterfeit goods, but can also stimulate significant growth within genuine markets.

By creating the right conditions within the UK to facilitate innovation in the area of forensic evaluation of consumer goods, as well as expert consumer protection services that can call upon these to react to criminal threats, we create value for the UK manufacturing market.

The authors would like to thank Kent Scientific Services and The Anti-Counterfeiting Group for their assistance with the research for this chapter.

ENVIRONMENTAL FORENSICS

IAN L. BOYD
Chief Scientific Adviser, Defra

We breathe, eat and drink other people's pollution. Yet it has proved difficult to design market solutions to deal with this equitably, so that the individuals who cause environmental degradation carry the costs of those actions. To promote good environmental outcomes, micro-innovation in measuring environmental variables needs to be matched by macro-economic innovation to build market-based solutions.

Forensics is not a discipline commonly associated with environmental issues. Whether tracing the source of environmental pollution based on a chemical signature or holding a nation to account for its non-compliance with internationally-agreed standards (e.g. in trans-boundary pollution), this requires measurements to assess whether the law has been broken. In broad terms, this can be described as 'environmental forensics'.

This chapter is addressed to policy developers, regulators and NGOs. Like other developed countries, the UK is on a journey from understanding that it is essential to regulate the effects that people have on the environment, to understanding how regulation can be implemented most effectively and efficiently. UK environmental law is largely led from the European Union, and the legal process has not proceeded much beyond the imposition of legally-binding regulation, often measured against standards and targets. Prevention through improved behaviour would be a better mechanism than regulation, but moving social and cultural norms to a position where environmental protection is part of the reward structure is still a long way off. This chapter sets out where the challenges lie for achieving this transition, and the role of science in driving this progress.

WE BREATHE, EAT AND DRINK OTHER PEOPLE'S POLLUTION. THE 'TRAGEDY OF THE COMMONS' HAS A POWERFUL PRESENCE ACROSS THE ENVIRONMENT. IT HAS PROVED DIFFICULT TO DESIGN MARKET SOLUTIONS TO DEAL WITH THESE ISSUES OF EQUITY.

The rationale for setting environmental standards and measuring compliance is strongly driven by the concept of equity. Around half of some air pollutants in the UK come from other parts of Europe[1] – and, of course, the UK contributes to the air quality problems of other European countries. Water contaminated by sewage washed out to sea has the potential to contaminate seafood, which could be distributed widely through the food chain. The choices people make about how to dispose of waste can have widespread effects, sometimes with long time lags between the release of pollutants and the ultimate effect, and this has become an issue driving global politics when it comes to different national responses to the need to reduce carbon emissions.

We breathe, eat and drink other people's pollution. The 'tragedy of the commons' has a powerful presence across the environment. It has proved difficult to design market solutions to deal with these issues of equity, so that the individuals who cause environmental degradation carry the costs of those actions. Indeed, costing environmental degradation is itself difficult. It has become a duty of government to hold polluters to account for their compliance with standards of behaviour designed to try to account for these costs.

The market itself is unsympathetic to this need and the activities to cost them through regulation for public good are often one step behind market innovations. Even establishing strong principles such as 'the polluter pays', which forms a basis of European environmental law, has a mild effect on this process. There is a need to better align the common goods derived from the environment with market behaviours.

Measurement is at the root of providing assurance around compliance with standards, and for invoking direct action to detect and remedy environmental problems, sometimes by prosecuting offenders. These measurements span traditional forensics and involve: provision of post-hoc proof of illegal action, such as the release of toxic chemicals; preventative monitoring through regular measurement and reporting of compliance against a standard; and provision of evidence used to inform decisions about environmental permitting.

Forensic methods also apply where there is a need to control the emergence of bad outcomes. The investigation that led to the understanding of bovine spongiform encephalopathy (BSE) involved detailed analysis that ultimately enabled the detection and control of the disease agent. A similar kind of investigation led to the discovery of the tropospheric ozone hole and the subsequent establishment of the Montreal Protocol, which regulates the release of ozone-depleting chemicals in to the atmosphere; and to the identification of tributyltin (TBT) as a potent endocrine disrupter, which has now been eliminated from anti-fouling paints used on ships. Forensics merges almost imperceptibly with investigative epidemiology and environmental science.

WHY TAKE A FORENSIC APPROACH TO THE ENVIRONMENT?

We value the environment for the benefits it provides. These benefits take many forms, including the goods and services from the environment that support our health and welfare. According to the Office for National Statistics (ONS), nearly one-quarter of the net worth of the UK is accounted for by the environment, although this is likely to be only a partial view of its true worth because it is difficult to estimate the non-market values derived from the environment.

Recent work under the National Ecosystem Assessment[2] and by the Natural Capital Committee[3] has gone a long way to improving explicit valuation of the environment in ways that could eventually result in environmental assets appearing as part of a national infrastructure balance sheet. In the long term, one objective would be to build market-based mechanisms to sustain environmental benefits. The corollary of such a mechanism is that there would also be mechanisms to cost the impact of different activities on the environment, based on the rate at which they would deplete the environmental asset base. Ensuring that people pay this cost would be an important feature of any market-based mechanisms applied to a more generic form of regulation. For the time being these mechanisms largely do not exist, so it is for governments to safeguard the benefits through statutory, voluntary and regulatory mechanisms. This has led to the development of a doctrine of market intervention in order to design environmental resilience.

There is now a long and contentious history about how the safeguards have been built in to European and national legal and administrative instruments, such as European Directives. A similar process has happened within the United States. The contentious nature of the issue has largely revolved around the absolute and relative valuations that different sections of society have placed on the environment. Individual actors operating rationally but with self-interest are rarely rewarded for acting in the wider public good. The lack of an agreed basis for constructing objective valuations of environmental goods leaves a lot to play for, often seen in political debates that continue to the present.

Government regulation to prevent the misallocation of environmental resources is consequently a very blunt instrument. The resulting complex mesh of environmental regulation has the characteristics of an over-engineered construction produced by designers who neither understood the forces they were attempting to control, nor the materials used to build the structure. Arguably, the designers were also unsure of the structure's purpose. In the absence of a common currency for valuing (and possibly trading) environmental assets, there is now a plethora of different variables used as end points, or objectives, in themselves.

CASE STUDY

ENVIRONMENTAL DNA ANALYSIS FOR WILDLIFE CONSERVATION

PETER BROTHERTON, *Director of Specialist Services and Programmes, Natural England*

Some wildlife species are hard to find. When elusive creatures are also in decline and strictly protected under European law, difficulties in detecting them can be problematic for conservationists and businesses alike. One such species is the great crested newt (*Triturus cristatus*), our most charismatic amphibian. Great crested newts have declined across Europe due to losses of their ponds and other habitats, but they are still widespread and locally common in some parts of the UK. As a European Protected Species, it is an offence to kill, injure or disturb great crested newts or damage their habitat. To avoid committing an offence, businesses are required to assess whether they are present in any suitable ponds likely to be impacted by a development. Traditionally, this assessment has been a skilled and time-consuming process: each pond requiring at least four night-time visits during the breeding period by licensed surveyors who use three separate survey methods to search for the newts. The complexity of this traditional survey technique imposes significant costs and delays on developers, while also making it hard to plan their effective conservation.

In 2013, Natural England and the Department for Environment, Food and Rural Affairs (Defra) supported research to investigate whether emerging environmental DNA (eDNA) techniques could offer a solution to the problem of surveying for great crested newts. eDNA is nuclear or mitochondrial DNA that is released from an organism into its environment, and initial proof of concept studies had demonstrated that its detection could be an effective survey technique in aquatic environments. The government-funded study conclusively showed that eDNA surveys were at least as effective as the traditional technique, while also providing estimated savings of up to £1000 per pond[1]. Natural England was quick to approve the new technique, and industry was quick to respond. Over 2500 eDNA tests were carried out in 2015, suggesting that businesses are likely to have saved over £2 million in survey costs this year alone thanks to the introduction of the eDNA test; time-related savings are likely to be even more significant. A growing number of laboratories are also coming forward to offer the test.

Innovation feeds innovation. Our ability to more easily detect great crested newts has made it possible to engage the public in the first national survey of the species, begun in 2015. Even more significantly, Natural England is now working with local authorities to use eDNA to develop a detailed understanding of local great crested newt populations. This information will enable the piloting of a new, strategic approach to the conservation of the species across planning authority areas, doing more to protect and enhance the most important locations for the species, while making it easier for development to proceed in other, less significant great crested newt areas. This transformative approach will see a shift in the emphasis of Natural England's licensing decisions towards achieving better conservation outcomes for newt populations as a whole instead of seeking to protect newts in locations that are unlikely to be viable in the long-term. This is good news for business and good news for newts.

As DNA detection techniques become more advanced, we can expect to see a rapid growth in wildlife applications, from early detection of invasive species and diseases through to understanding soil communities. The innovations we are achieving with great crested newts are only the start of this story.

Whether these actually reflect meaningful outcomes varies with circumstances, but in many cases the connection between these and the values placed on the environment by society are tenuous. These values are themselves inconsistent and therefore difficult to compare; and, where conflict arises, it becomes impossible to provide an objective assessment of where priorities should lie. The implicit claim made of these variables is that they are surrogates for valuation, but this sometimes lacks credibility. For example, 'waste recycling' is a measurement that has been treated as an end in itself, rather than one possible route to reduce residual waste and improve resource extraction. Focus on this measurement is potentially distorting action away from reducing our use of resources and reusing 'waste', both of which are the real objectives.

Consequently, the UK is mandated to measure an immense amount of information about everything from the chemistry of rivers to the number of birds on farmland and the noise emitted by human activity in the ocean. Efforts to focus attention on the features that genuinely inform us about the health of the environment have been hampered by a lack of underlying knowledge about their impacts. For example, we know almost nothing about the consequences of man-made noise in the ocean, but we have created binding commitments to measure noise within certain sound frequency ranges – without even knowing whether those frequency ranges are important, or what the dose-response might be. In this particular case, we do not even know how the response might manifest itself, whether in fish, marine mammals, plankton, corals, jellyfish, or seaweed. Noise could affect any or none of these species, and there is even uncertainty about whether we need to study populations or individuals in this context. The rationale for actions like this hinges on the hazard-avoidance doctrine commonly used today. This doctrine suggests that any changes caused by human presence must be avoided, even if (as in this case) the changes most probably lie within the normal range of natural variability.

Seen in this context, the direction of travel in environmental forensics – towards measuring and controlling more and more, at finer and finer levels of detail, just in case it might be important in future – is clearly untenable.

This is the practical consequence of the 'Precautionary Principle', stimulated by a systemic pessimism about the ways in which innovation can imperceptibly draw down environmental capital without paying a proper cost, but without also recognising that innovation has a double edge because it is both a threat and a solution. The need for the measurement or monitoring of environmental indicators through time was initially driven by a sincere search for those surrogate indicators within the environment that most effectively represented societal valuation. But this has gradually mutated into a process of measurement and reporting of data as an end in itself, which supports the doctrine of designed resilience, often closely associated with the doctrine of hazard avoidance. Both are hungrier for evidence showing compliance to potentially flawed standards than they are for evidence to improve the basis upon which those standards are designed. Across Europe, feeding the resulting appetite for environmental data is now an industrial-scale process requiring governments to establish bodies like the UK's Environment Agency, which also has regulatory powers. At European scale, coordination and thought leadership is in the hands of the European Environment Agency, while regulation sits with the European Commission. The data are used to prosecute the miscreants – a process known within the European structure as 'infraction' – and to produce reports intended to illuminate the state of the environment[4]. Some, like the volume 'Late Lessons from Early Warnings'[5], seemed intentionally designed to magnify the

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THE ABILITY TO REPORT MEASUREMENTS IN REAL TIME, AND AT A REDUCED COST, IS MAKING SOME DATA MORE ACCESSIBLE, HELPING DECISION-MAKING AT ALL LEVELS OF SOCIETY AND MOVING US TOWARDS THE GOAL OF ENSURING THAT PEOPLE HAVE THE INFORMATION THEY NEED

negative consequences of not adopting the doctrines of hazard avoidance and designed resilience.

PREVENTION VERSUS DETECTION

Functional environmental forensics can perhaps be seen to bifurcate along two interacting tracks. One track involves detecting and correcting incidents where an agreed standard has been exceeded (detection); the other uses feedback from forensic measurements to change behaviours within society, thus reducing the probability of exceedance in the first place (prevention).

Detection is usually linked with operational management to support trade regulations and protect human health, for example. Prevention concerns long-term objectives that seek progressive environmental improvement, or attempt to prevent the slide towards declining baselines of environmental quality, a process that has been suggested to have happened for marine fish populations.

Prevention is often seen to be the most cost-effective option; the very high costs of environmental remediation often mean that investments in prevention are likely to be worthwhile. Consequently, the considerable infrastructure that has emerged to support prevention within Europe probably has a strong economic rationale, although this has not, as far as I am aware, been tested adequately against any counterfactual. The current range of different infrastructure and bureaucratic solutions applied to environmental regulation across the developed world provides an opportunity to build a better understanding of the relative merits of investment in detection and prevention. It is a moot point whether prevention is always more effective than a combination of risk-based detection and proportionately large penalties. The latter is more likely to achieve a culture of deterrence and build a sense of devolved responsibility than the former, where there are few incentives for individuals to take responsibility for their own actions. Developing countries would be well placed to benefit from such an analysis when contemplating how to design their own systems of compliance with environmental standards.

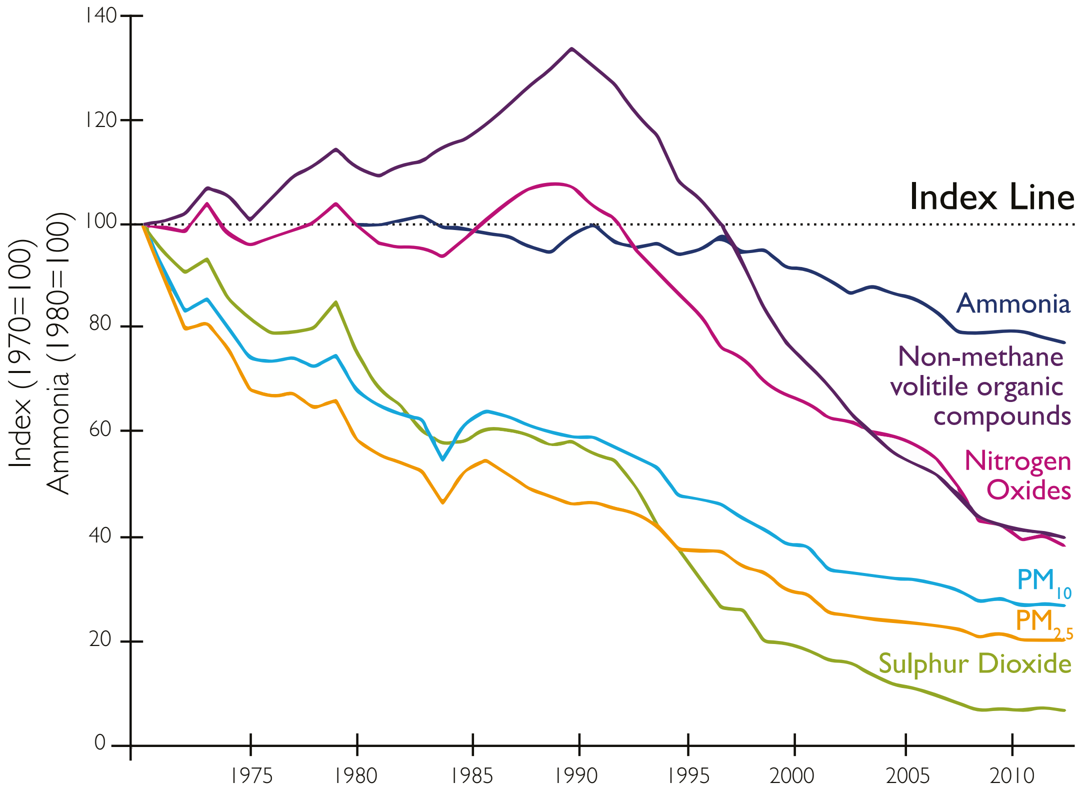
A potential strength of the doctrine of designed resilience and investment in prevention is the prospect it provides for progressive improvement of environmental quality. Ramping up the thresholds of compliance over time has been critical to achieving reductions in residual waste, improved beach water quality and reduced vehicle emissions. This can only be achieved against a background of effective measurement using standardised methods.

One example of the aggregated progress enabled by this approach can be found in improvements in air quality (see Figure 1). Although the speed of change in this and other cases is slower than many would wish for, the rate of change is probably proportional to the rate of evolution of the delivery process. This, in turn, is a complex function of several rate-limiting processes, including the rate of innovation in technology and business systems; depreciation and obsolescence of past investments; and the discounting applied to the future benefits derived from current investments. However, none of these would operate effectively unless there was a system for setting evidence-based standards, and the field of environmental forensics provides this foundation.

WHAT SHOULD BE MEASURED?

The environment is a complex place, with many variables that could be measured to assess compliance, control outcomes and adapt to emerging challenges. Environmental data

Figure 1: Annual emissions of major air pollutants relative to levels in 1970 (ref. 1). Solid lines show the measured relative emissions. The introduction of measured standards and targets has been an important factor in achieving improvements in air quality.



are becoming increasingly accessible through automated measurement and new sensors. The ability to report measurements in real time, and at a reduced cost, is making some data more accessible, helping decision-making at all levels of society and moving us towards the goal of ensuring that people have the information they need to make decisions based on the costs of their actions. Increasing volume, accessibility and precision of measurements presents challenges to this goal, because data are not equivalent to information for those without the expertise to interpret the data. Greater precision means that dose can be measured to phenomenally low levels, but that precision is not necessarily matched by the same level of understanding of dose-response at these low levels.

The doctrine of hazard avoidance tends to perpetuate and amplify ignorance of the importance of dose. For example, it is attractive to some environmental pressure groups to play strongly on the recent assessments concluding that glyphosate, a commonly used herbicide, is probably carcinogenic. Because we can now measure glyphosate in food and other environmental products to extraordinary precision, it follows that we are increasingly aware of its presence at very low doses. However, this does not equate to the presence of a pharmacologically important dose, and this point is often ignored by those making these kinds of claims.

The DPSIR (driver, pressure, state, impact, response) framework has provided a further guide to the construction of environmental measurement and the application of regulation. DPSIR captures the concept of cause-effect, which is probably not sufficiently central to thinking within the field of environmental forensics. In principle, it is better to regulate the driver that creates an environmental pressure,

DNA IN THE WIDER ENVIRONMENT CAN PROVIDE EVIDENCE OF THE PRESENCE OF KEY CRYPTIC SPECIES AT A SMALL FRACTION OF THE COST.

because it is earlier in the sequence of causation.

The problem for many regulators is that causation is often poorly understood, and the public perception of causation in contested areas is susceptible to propaganda – as has happened with the controversy around changes in populations of pollinators. In this case the public perception is that some forms of pesticide are responsible for declines in bee populations, whereas it is much more likely that a wide range of factors are responsible, including weather, long-term trends in land use, increasing disease and poor data about pollinator populations, as well as pesticides. That makes it difficult to develop regulations that will help pollinator populations to recover: not only are there many contributing drivers, but there is also uncertainty about the actual direction of change in many of these populations, and there are asymmetrical views about causation amongst some of the stakeholders who need to be persuaded to adapt their behaviour. In this case, forensics provides the evidence that will shift behaviours in such a way as to achieve the objective – by distributing the costs among those who value the benefits brought by pollinators, and by incentivising those whose valuation is lower than the cost they would have to pay to adapt their behaviours. These incentives are often provided through direct payments for specific activities, as happens in environmental stewardship schemes delivered under the Common Agricultural Policy.

The case of pollinators is perhaps an example of how market-based solutions may tend to emerge in future. Public concern becomes reflected in a shift in the valuation of an environmental asset, leading to a greater proportion of people being willing to carry a cost of supporting the asset. A similar process may have begun with air quality. However, in each case there is a need to present good quality evidence to the public in ways that they can understand and act upon.

TYPE AND QUALITY OF MEASUREMENT

Technology is driving innovation in environmental forensics in the same way as it is in other forensic applications. Harnessing the power of non-targeted analytical techniques such as metagenomics, isotope analysis, DNA finger printing and next-generation sequencing is essential (see Chapter 10).

These can be applied to a wide range of approaches, including understanding the sources and legality of supply of food to timber and fish[6]. DNA in the wider environment can provide evidence of the presence of key cryptic species at a small fraction of the cost of previous methods (see case study on p152). Further examples of progressive technological improvements include: rapidly increasing availability and spatial and temporal resolution of Earth-observation data at declining cost; and intelligent, statistically-robust sampling designs that make measurements cheaper and more effective, and which allows adjustment of precision to be scaled to the appetite for risk.

The way in which the UK implements air quality measurements is an example where a sparsely distributed network of monitoring stations is supplemented by modelling of the dispersal process for different chemicals and particles. This approach merges accurate, site-specific monitoring data with metrological models. This system remains compliant with EU regulations but costs significantly less to support than other more extensive air quality monitoring networks in other EU member states.

Genomics methods are used to help direct action, rather than to apply standards to improve water quality. This is especially the case when distinguishing human and animal bacteria on bathing water pollution, and the methods can now also distinguish animal species, allowing more targeted management responses at local scales.

Greater capability to measure also has a double edge. Forensic investigation of the presence of viruses and bacteria in shellfish, based on

THE MOVE TOWARDS BETTER, CHEAPER, SMALLER AND LOWER-POWER SENSORS HAS THE POTENTIAL TO REVOLUTIONISE ENVIRONMENTAL MEASUREMENT AND, WITH IT, TO CHANGE ENVIRONMENTAL FORENSICS.

genetic signatures, has driven a discussion about higher standards for shellfish flesh that would impose significant impacts on the industry. There is no method for distinguishing live or infectious material from dead or non-infectious material, and deeper investigation often shows that tell-tale fragments of viral DNA do not represent the presence of 'live' virus. Similarly when *Cryptosporidium* entered the water supply to over 300,000 homes in Lancashire during August 2015, the local water company issued a 'boil notice'. There were no cases of illness that could be linked to the contamination, and there was a strong suspicion that the oocysts of *Cryptosporidium*, a protozoan parasite, were unviable. Again, the detection methods had a high sensitivity, but a low capacity to distinguish the viability of the infectious agent.

The move towards better, cheaper, smaller and lower-power sensors has the potential to revolutionise environmental measurement and, with it, to change environmental forensics. Taking the laboratory to the field, and disseminating information from sensors embedded in everyday devices such as cars and phones, will place the power of detection and analysis in the hands of many more people. This will help to transfer the power to make informed decisions closer to those for whom the costs and benefits matter most, and could incentivise behavioural choices in ways that reward individuals for working in the common good. If car drivers had access to simple air quality measurements about their own car's contribution to air pollution, it would probably create a very different culture of car ownership, and manufacturers would respond accordingly.

CONCLUSION

Environmental forensics provides the supporting evidence for a complex set of legislative, regulatory and voluntary instruments that support many of the normal functions within society. As a field, environmental forensics has expanded rapidly in the past 30 years and is now supported by an industry that generates the forensic data required to assess the environmental performance of everything from individuals to multi-national governance processes, or machines to entire industrial processes.

This rapid growth has been driven by the joint doctrines of hazard avoidance and designed resilience, a result of the failure to find (or even to seek) market solutions that help to couple individual incentives to broader public goods derived from the environment. While the processes in place have been built for very sound and pragmatic reasons, there is a need to shift towards more risk- and market-based solutions.

There will always be a need for regulation and statute in this field, and a strong role for government, but the nature of environmental forensics needs to change. The current system, illustrated by the approaches adopted in Europe and to some extent the United States, is arguably unaffordable in the long term, especially if it was to be rolled out across the developing world. Technology innovation can help to sustain the system, by delivering more data at greater precision closer to the events that affect behavioural choices. But the down sides associated with the interpretive capacity of decision-makers needs to be addressed through sophisticated information delivery processes. Micro-innovation in measuring environmental variables needs to be matched by macro-economic innovation to build market-based solutions. Internalising and accounting for the economic costs of alternative actions for the environment – while providing forensic evidence to support this approach – is most likely to be the best way forward. Transitioning developed economies such as the UK to this alternative way of working needs leadership and vision.

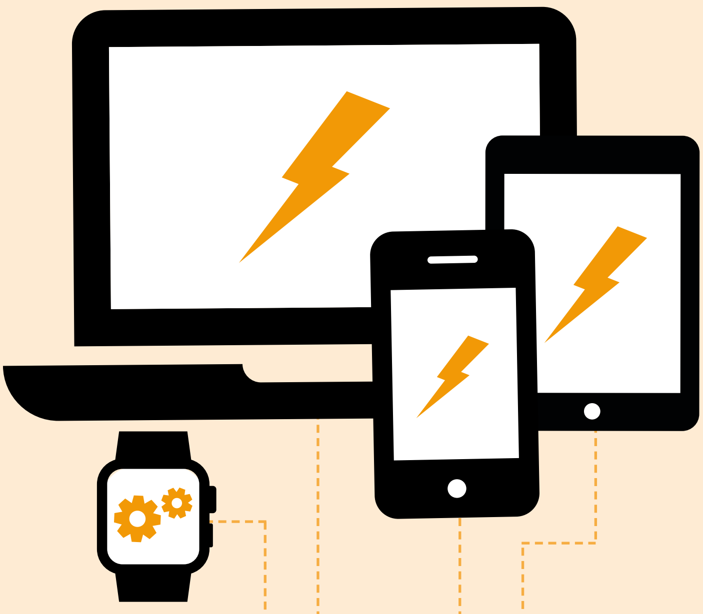
AS A FIELD, ENVIRONMENTAL FORENSICS HAS EXPANDED RAPIDLY IN THE PAST 30 YEARS AND IS NOW SUPPORTED BY AN INDUSTRY THAT GENERATES THE FORENSIC DATA REQUIRED TO ASSESS THE ENVIRONMENTAL PERFORMANCE OF EVERYTHING FROM INDIVIDUALS TO MULTI-NATIONAL GOVERNANCE PROCESSES, OR MACHINES TO ENTIRE INDUSTRIAL PROCESSES.

SECTION 4:

SECURING THE FUTURE OF UK FORENSIC SCIENCE

SECURING THE FUTURE OF UK FORENSIC SCIENCE

The UK has a long-standing reputation for being at the forefront of forensic science innovations, including developing fingerprinting and DNA profiling.



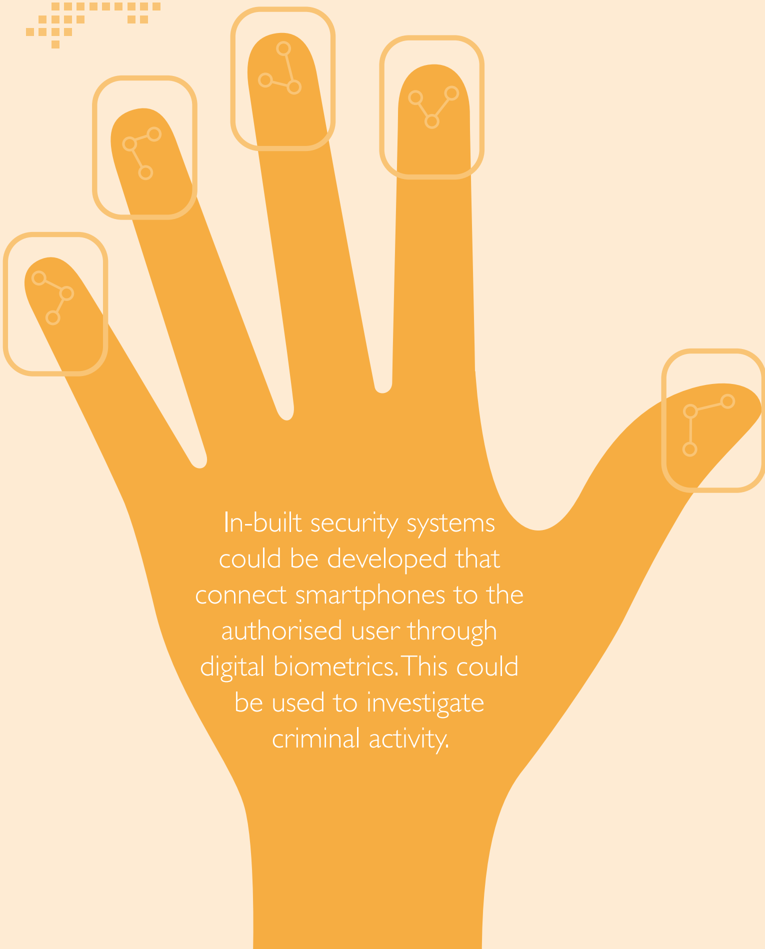
By 2020, there will be an estimated

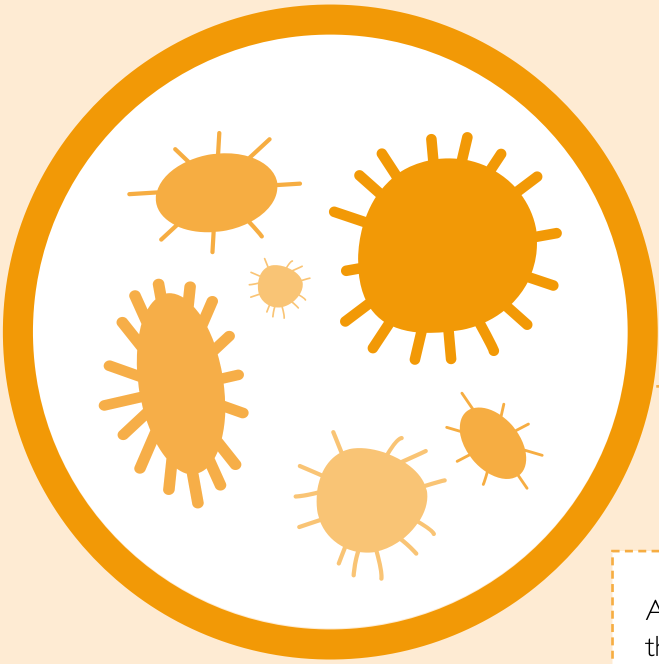
5 billion

internet users and up to

100 billion

connected devices worldwide.





In the future, we may be able to identify a person's activity or where they have been by studying microbial communities in their bodies, known as the **'microbiome'**.

Advances in technology that allow the human genome to be mapped in hours rather than weeks will accelerate the availability of genetic information.

The high cost and judicial impact of failing to meet standards means forensic techniques must be validated and backed by a strong evidence base before being used.

Miniaturisation and innovations such as RapidHIT DNA or paraDNA will bring conventional laboratory techniques closer to crime scenes and speed up the identification of offenders.

Forensic investigators will use 'big data' gathered from the Internet of Things and different databases, using algorithms to give advance warning of events.

FUTURE APPROACHES IN ANALYTICAL SCIENCES

By 2025, forensic science will be transformed by large-scale data analysis, automation, novel analytical techniques, and digital forensics. The UK has the potential to be at the forefront of these developments if basic science, commercial technology development and government policy can be better coordinated.

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Looking ahead to 2025, what are the new technologies that are likely to impact upon forensic science and its ability to keep pace with – or ahead of – new forms of criminal activity? What is the best way to manage that innovation? And how can UK businesses benefit from innovations in forensic techniques? This chapter will address these questions by considering the following points:

- The future technological trends that will help to tackle criminal threats, and the changing face of crime, out to 2025
- The new sciences that might be relevant
- The use of a wide range of digital traces to determine who is where, and when
- The challenges presented by new technologies, and whether there is a point at which advances in science become counter-productive
- Automation of forensics and the wider legal system, along with the impacts of managing large volumes of data

There are also several critical factors that we need to consider when emerging technologies or sciences present opportunities to enhance public safety. These are:

- Credibility: Is the proposed method a credible technique that can be validated for use in the context of a legal arena, both criminal and civil?
- Accessibility: In order for the technique to be used, it should be accessible to legal professionals from both a prosecuting and defence basis
- Admissibility: If the technique is to be used for purposes other than investigation, it needs to be legally admissible within the rules of evidence
- Affordability: While this should not be a barrier to delivering safe and secure justice, the cost of the technique relative to the challenge it is meeting is an important factor (you would not expect expensive analytical time to be used for low-level minor crime, for example).

Perhaps the largest transformation in forensic science over recent years has been the reduction in the costs of analytical services. This has been delivered through a blend of more effective procurement and advances in automation and miniaturisation, as well as a much sharper focus on the needs of the end user. In this environment, this trend will need to continue to provide comparable services that are affordable, as well as developing opportunities to be more effective and innovative in the way forensic science can be utilised as a tool for public safety. There is a significant risk that the drive to reduce costs will impact on future capability, with limited investment in research and development activities. Short-term cuts in forensic research and development will inevitably lead to longer-term problems. The community and government should be considering the end-to-end process of forensic techniques and the associated investments required to ensure that there is a sustainable research and development capability. The UK has had a long-standing international reputation for being at the forefront of forensic science innovations: for example, the application of DNA in a criminal investigation and enhancement techniques for fingermarks, and it is of obvious importance that this should be maintained and enhanced.

FUTURE TECHNOLOGY TRENDS

Without doubt, technology will play a significant role in the future of forensic science and how it is used in both civil and criminal applications. The exponential growth of accessible electronic devices has touched every aspect of everyday life, from the way we communicate through to business transactions that never see human interaction. While these advances bring opportunities, they also come with the potential for risk and harm to anyone engaged in using them.

The speed of change in computer technology shows no sign of decreasing. Developments in mobile devices and storage technology now mean that data is no longer always stored on a dedicated device but can be distributed over a variety of networks and devices located anywhere. This development of cyber-based devices shows no sign of slowing down. It is very difficult to predict where, for example, social media will develop in the next ten years, but it will clearly be operating at a different level to that experienced today. There is currently a global internet population of 2.4 billion users that sends around 204 million email messages and searches Google 4 million times every minute. By 2020, there will be an estimated 5 billion internet users and up to 100 billion connected devices worldwide, representing a step change in the use of technology[1].

These internet users will be linked through the internet of things (IoT), a vision to connect physical devices and objects to a network that allows remote monitoring to gather information (see case study p170). This trend towards connectivity of everyday items will in the future provide links to criminal activity that could pinpoint an individuals' location through wifi, ZigBee, Bluetooth and RFID monitoring; provide information about physical characteristics such as exertion; and even monitor personal metabolic information. This interaction could be through clothing that incorporates wearable technology, vehicles, or access control systems, and there needs to be a balance between public safety and the privacy of the individual to gain public acceptance for using these data sources

WITHOUT DOUBT, TECHNOLOGY WILL PLAY A SIGNIFICANT ROLE IN THE FUTURE OF FORENSIC SCIENCE AND HOW IT IS USED IN BOTH CIVIL AND CRIMINAL APPLICATIONS.

in forensic investigations.

In the future, forensic investigators will be gathering much larger amounts of data with far more complex analytical techniques. This is often referred to as 'big data', and it takes large amounts of conventional processing power to convert this data into useful information. In complex investigations this often exceeds current capability, and the future of large-scale data analytics could be in grid computing, which is distributed across multiple processing facilities and unlocks rapid data analysis for investigators. Although this is probably beyond the scale of high-volume crime (such as burglary), it will be used in counter terrorism and serious and organised crime. Add to this the potential of cognitive computing, which will make autonomous decisions without human intervention; as a result, many forensic processes providing interpretive evidence could be speeded up through automation, removing human error rates and increasing efficiency.

There are already forensic identification processes in place using 'lights out' approaches, such as the confirmation of identity by checking ten-print fingerprint forms in the criminal record collection without any human intervention. In addition, the ability to fuse datasets together, combining information from different databases so that they can be handled by a single analytical tool, will enable the interrogation of information across a wide range of sources. The 'fusing' of the data could identify valuable information that would be missed when considering the data in isolation.

This will also lead to the development of algorithms that will be much smarter in predictive computing, able to interpret data in a way that can start to give advance warnings of events based upon the analysis of a range of data sets. The value to the Criminal Justice System is likely to be in spotting trends, particularly when linked with datasets from hospitals or social services, for example, to identify hidden crimes like child sexual abuse.

The analysis of data as a science is becoming more evident in government initiatives such as the Data Science in Government programme, which emphasises the importance of a structured approach and wider involvement of those outside the traditional forensic communities. As the volumes of data increase, our understanding of the complexities needs to grow concurrently. The potential for poor analysis of large data sets to be masked by computer analytics can be mitigated by fostering the right blend of skills in those developing and performing the analysis.

There is an increasing trend for miniaturisation of technology that will allow law enforcement and other users to bring conventional large-scale laboratory techniques closer to the scene of crime. Examples that are being developed include rapid DNA units that provide one-stop analysis of samples at the scene in less than two hours and portable hand held GCMS (gas chromatography-mass spectrometry) equipment for rapid analysis of drugs. These will evolve into more portable integrated units that deliver real time information to investigations through immediate on-site analysis linked remotely to databases that autonomously identify people and materials. Improvements in energy sources beyond conventional lithium ion batteries will enable extended usage without the need to connect to mains supplies.

Advances in robotics offer a range of opportunities, including carrying out hazardous tasks and thereby reducing the risk of harm to human operators. Examples of this could be the initial assessment of chemical, biological, radiological, nuclear and explosive (CBRNE) incidents using intelligent robotic ground-based or aerial units with a sensor array that detects a range of hazardous materials and relays analytical information in real time back to incident controllers. Other applications are the expansion of robotics in laboratory and process functions, to automate tasks and provide the potential for 24-hour operating. While robotics will not replace humans, in the future they have the potential to make processes more efficient and effective.

WE ARE PUSHING THE BOUNDARIES OF SENSITIVITY TO THE POINT WHERE BACKGROUND INFORMATION IS STARTING TO INTERFERE, CREATING COMPLEX MIXTURES THAT ARE UNINTERPRETABLE.

NEW SCIENCES RELEVANT TO FORENSICS

In many cases, forensics sciences can be regarded as an applied use of a traditional scientific discipline. The use of DNA in investigations, for example, is taken from conventional biology techniques but with a different application. James Watson and Francis Crick first described the double helix structure of DNA in 1953, and the discoveries that followed were applied in many disciplines before DNA analysis was first used in a law enforcement context in 1984.

It is therefore commonplace that the forensic world will utilise advances in other areas, because the level of research and development investment in medicine, defence and food is far greater than in forensic science. Advances in synthetic biology may speed up the process and offer new methods of working that are far more efficient than current techniques. It may also complicate the analysis through the introduction of manufactured genetic material. The challenge is to ensure that the forensic world reacts to these developments in a far quicker and coordinated manner to maximise the opportunities they present.

In a forensic context, current DNA technology is very effective at determining the probability of two samples originating from the same source, by comparing a set of common genetic markers. We are pushing the boundaries of sensitivity to the point where background information is starting to interfere, creating complex mixtures that are uninterpretable. Although UK forensic standards focus on seventeen markers, there are around 23,000 genes within the human genome that we largely ignore. The use of phenotypic profiling – studying the traits that result from the expression of genes – is understood in other sectors, and forensics should harness this to allow the determination of information such as physical characteristics, susceptibility to medical conditions and perhaps even behaviours.

Advances in next-generation sequencing (NGS) technology currently produce information at a greater rate than the computer processing can deal with, so there will be a need in the future to develop a means of processing large amounts of bio-informatics data. The advances in technology that allows the genome to be mapped in hours rather than weeks will accelerate the availability of rapid genetic information. One of the significant barriers is the ethical implications of further genetic sample analysis, which could provide sensitive information that needs to be managed carefully. But the science does open up opportunities never seen before.

The analysis of biological material to determine its origin is a valuable tool. However, there is potentially even more information to be gleaned from biochemical analytical techniques that can identify substances in secretions and other body fluids. The future will bring us smaller portable equipment, such as portable Raman infrared devices with live links to real-time libraries of source material, that will enable users to identify not only source material but also identify contaminants, building a unique picture of a person's lifestyle and movements. These techniques will also be utilised to consider the provenance of samples in terms of origins and sources of material e.g. confirmation of genuine pharmaceutical or food products, which is a growing problem for society (see Chapter 12, case study p138; and Chapter 11, case study p125).

The human body is a complex machine made up of different cells that each contain copies of the human genome. But the body also contains microbial communities, collectively known as the human microbiome, which is largely unexplored from a forensic context. We utilise examinations of this nature for the analysis of soil and vegetation but not for humans, which may provide a unique and diverse profile of an individual. The potential is that in the future we may be able to identify a person's activity by their microbiome or even identify where a person has travelled by testing for characteristics within the microbiome (see Chapter 11, case study p130). Early studies have been able to link office workers to their keyboards through microbiological analysis, so although this approach is still in its embryonic stages, it could offer valuable information to end users. However, to exploit the information available from the biome, we need to develop solid reference data sets before this becomes a routine forensic activity.

Material sciences bring both threats and opportunities to the forensic world. The growing trends of recycling and reusing materials means that products are becoming less 'pure' and represent a more blended constituency. This makes it more difficult to maintain reference techniques for analysis, as they perform differently depending upon the

THE POTENTIAL IS THAT IN THE FUTURE WE MAY BE ABLE TO IDENTIFY A PERSON'S ACTIVITY BY THEIR MICROBIOME

ingredients of the sample. Although this will impact evidence recovery, the wider societal benefits needs to be considered. Conversely, products such as powders can be engineered at the nano-scale to be far more effective that conventional micron-sized powders which increases performance and will become the routine approach for developing powdering techniques to recover fingermarks at scenes.

Imaging has been used in the forensic world since the early examinations of crimes in the 19th century, recording and preserving the scene for a range of different reasons. It enables those not present to visualise the scene from a distance, and the techniques adopted over the years have improved significantly. There is now a step change available in bringing the crime scene to the individual, rather than a physical visit. The ability to provide a high-definition virtual crime scene using augmented reality that can be visited by many experts and investigators without fear of contamination or conflict has many advantages. Transmission of information in real-time to investigators and specialists, with direct interaction in the examination, will revolutionise scene examinations and prove to be a much more effective means of recovering and analysing evidence. Other areas of imaging that are emerging are the use of computed tomography (CT) and magnetic resonance imaging (MRI) for forensic autopsies, which have the potential to reveal far more information that conventional examinations; and may in future reduce the need for surgical interventions, which will preserve the dignity of the deceased and improve their family's acceptance of the investigation.

As well as imaging techniques, we should also consider imagery and video as a source of evidence that comes directly from a wide range of sources, including CCTV, body-worn video and unmanned aerial vehicles. Indirectly, there will be access to more imagery from open sources on the internet such as Facebook and YouTube uploads. The key issue is that there will be more higher-quality imagery available from more sources, which will require improved algorithms and software to deploy video analytical techniques. This

CASE STUDY

SKILLS AND COMPETENCY FOR

ANYA HUNT, *CEO, The Chartered Society of Forensic Sciences*

The Chartered Society of Forensic Sciences (CSFS) is the UK professional body representing the forensic sciences. With 3,000 members worldwide, it offers a huge resource of knowledge and experience that shapes the forensic sciences globally. The CSFS was formed in 1959 as the Forensic Science Society (FSSoc), and was renamed after being granted a Royal Charter in 2013. The CSFS is at the forefront of standards development, education and training, and is committed to supporting its members throughout their career in forensic science.

The society has developed a wide-reaching quality standards framework that includes:

- An accreditation, recognition and endorsement scheme for setting standards in forensic science education
- Competency assessment for graduates and experienced forensic science practitioners
- An extensive and expanding programme of continuing professional development (CPD) conferences and events
- A publication bundle with monthly releases of peer-reviewed and general interest content for the dissemination, discussion and evaluation of innovations in the field.

The CSFS is a registered charity that receives no public funding, and is responsible for supporting the entire forensic community with extremely limited resources. Indeed, many of its activities are unfunded, and rely on the good will of its members.

EDUCATION

In the mid-1990s, forensic science degree-level courses were being developed across the country, many born out of failing analytical science departments. As part of its 2004 inquiry 'Forensic Science on Trial'[1], the House of Commons Science and Technology Committee asked the FSSoc to develop its accreditation system in line with UK National Occupational Standards, while keeping the costs of accreditation to a minimum.

In 2004, the FSSoc piloted and launched its Accreditation Scheme, which is now world-renowned. The aim was to map and measure the forensic science content of full undergraduate and postgraduate programmes (level 6–7) against recommended component standards that are recognised by industry. This has now being expanded to incorporate a recognition and endorsement scheme for courses with a smaller amount of forensic content, and for courses offered at levels 3–5. The overarching aim is to give students and employers confidence in the quality and quantity of forensic science educational provision. While this scheme continues to develop and grow, the scheme does not attract any public subsidies and some valued educational institutions find the costs of accreditation preclusive.

COMPETENCY ASSESSMENT

In 2010, following the demise of the Council for the Registration of Forensic Practitioners (CRFP), the CSFS was approached by a number of niche forensic practitioners looking for assurance that their discipline and its practitioners were recognised as professionals by the courts. This led to the society developing an ever-expanding suite of Certificates of Professional Competence. The aim is that individuals work with the society to have their knowledge, experience and skills assessed independently against defined core standards. The assessment, together with a demonstrable commitment to CPD, builds towards the individual's professional portfolio of ongoing competency.

This potentially benefits the entire Criminal Justice System, yet there are currently no tangible resources available that would allow this scheme to grow. Countries such as the Netherlands have benefitted from public funding to develop the highly-acclaimed Nederlands Register Gerechtelijk Deskundigen (NRGD), or Netherlands Register of Court Experts.

In 2013, the changing forensic science

THE FUTURE

landscape resulted in a large-scale migration of staff between different organisations in the sector. Forensic employers, police and private-sector companies asked the CSFS to find ways to assess the suitability of potential new entrants to the forensic profession, based on their balance of educational achievement, skills and experience. As a result, the society launched its Pre Employment Assessment of Competence (PEAC) scheme this year. The pilot saw 28 forensic science graduates undergo a range of assessments to demonstrate their knowledge and skills in realistic case-work scenarios. PEAC is being well received by industry to assist in their recruitment process.

PROFESSIONAL ACCREDITATION

The UK forensic science community is now more diverse than ever before, with a mixture of sole traders, small and medium-sized enterprises (SMEs), large multinationals, and in-house police facilities. The Forensic Science Regulator's Code of Practice[2] specifies that all organisations providing work for the prosecution must be accredited to the relevant ISO standard by 2020. The society is engaged with practitioners across the sector to develop resources to support them in achieving this goal.

By the end of 2015, for example, the CSFS will have a register of consultants (made up of its highly experienced members) who will be available to assist others with all aspects of their accreditation journey, including bespoke support on validation and peer review where such expertise is not available internally.

Throughout 2015–2016, the CSFS is also working with the UK Accreditation Service (UKAS) to develop a realistic, proportionate accreditation model suitable for SMEs. These efforts could have wide reaching implications, and have an important role to play in ensuring a full and varied forensic provision.

then opens up the possibilities of automated real-time facial recognition, and a more widespread use of video analytics.

All the information gathered – whether it is large volumes of data from genomic sources, right through to fingerprint information – must be interpreted in some way to identify an individual. The volume of data suggests that there will be a change in the standard approaches to calculating and presenting scientific evidence, for example by using Bayesian Networks (BNs). BNs are graphical models that allow reasoning when uncertainty is present, even when the interdependence between different types of evidence is very complex. A BN approach can also model the strength of connection between evidence types and update predictions (sometimes referred to as a probabilistic belief) as new information becomes available. This is just one type of statistical model, and their use in general will increase as it becomes impossible to provide the degree of uniqueness traditionally demanded of the forensic process by court presentation. An illustrative example is the case of fingerprints. Historically, fingerprint evidence was not presented with any form of statistical basis, but improvements in the understanding of and advancements in statistical models could improve the way such identification evidence is used.

DIGITAL TRACES

In conventional forensic science, Edmund Locard's principle that every contact leaves a trace is fundamental to the application of scientific techniques to connect physical items together. This applies equally to the digital world, where at some point there will be a connection that will leave a digital trace. Everyone casts a digital shadow or footprint though their deliberate or inadvertent interactions with technology.

This could be as innocuous a carrying a mobile telephone, driving a vehicle, watching a smart TV or surfing the internet – your presence will be left in some way unless you are extremely tech savvy and make a deliberate intention to block these traces. Even then, with the right forensic analytical techniques, traces can be found with enough effort. In the future, it might be possible to delve deeper into technology to reveal even more useful information (see case study p172). In this context we should consider how the forensic examination of these digital traces can be used in delivering public safety.

The trend towards storing data remotely from mobile and network-based applications is increasing rapidly. The challenge lies in how to retrieve data that is stored in cloud systems and gain a complete picture, as it may be distributed across different geographical locations and jurisdictions. There is a balance to be found between the privacy of individual's data and the needs of law enforcement to access data. There is active encouragement from government for manufacturers to make devices more secure to reduce theft, but this makes the legitimate interrogation of the devices more challenging.

The Internet of Things (IoT) will enable a hyper-connected world in which devices and objects interact with each other. The future city will operate in an environment where the physical, digital and virtual worlds converge, and communicate to provide information across a range of platforms connected to sensors gathering data. This volume of data will provide a mass of information intended to make life easier and more efficient, but it also offers opportunities for a safer community. In an extreme case, this could involve intelligent sensor networks that take advantage of connected real-time analysis to monitor for explosive traces in public areas such as transport hubs; or automatically monitoring changes in the home and reporting them to a person's smart phone. This may offer more novel sources of evidence in an investigation.

The smart phone of the future will be very different to that of today. It will evolve into a more flexible, longer-lasting device that brings functions that interface with the IoT, offering rapid access through the next generations of wireless mobile connectivity. In-built security could be developed that directly connects the device to the authorised user through a range of digital biometrics, such as vein identification or heartbeat monitoring. The phone will develop further into a digital assistant that allows you to control many aspects of life with verbal communication. These digital interactions will leave an electronic trail that tracks your financial interactions, social habits, locations and lifestyle habits, all of which could be interrogated and used to investigate criminal activity (subject to the correct approvals and authority).

It is clear that the availability of information from open sources such as the internet are becoming increasingly relevant to routine investigations, not just in what is considered as cybercrime. It may well be that a person's online identity (email or social media profile, for example) will be a more reliable source of identity than a physical address or telephone number. Many people already retain their email address longer than a physical address.

While conventional biometrics are measurements used to uniquely identify a person, digital biometrics are those captured through electronic means. This includes voice, hand geometry (see Chapter 6 case study p68), and keystroke dynamics, along with the well-used face and fingerprint biometrics. Many of these are associated with verifying personal identity, which then allows access to a system or physical space; it could also be used as an investigative tool for corroboration purposes.

IMPACT OF AUTOMATION

Advances in robotic technology will allow humans to be removed from a range of forensic processes. These could be repetitive laboratory processes or hazardous tasks that present problems to human operatives, digital examinations of electronic data or assessments of CBRNE incidents. There are many positives in automating some activities, but there are downsides: the initial development and outlay costs can be expensive, and removing humans from the process could lead to a deskilling of the workforce. Although this could actually reduce the costs over the whole lifecycle of the automation programme, it really depends whether there is sufficient appetite to manage the risk of investment.

Other areas to consider are improved productivity, as machines would be able to work 24/7 to produce DNA profiles, for example. Unless the whole process of interpretation and identification is automated, however, the initial benefits may not be realised. Consistency and reliability will be improved by removing humans from these processes, leading to more accurate

EMERGING TECHNOLOGIES AND APPROACHES TO APPLYING SCIENTIFIC METHODS IN FORENSIC DISCIPLINES CLEARLY OFFER GREAT OPPORTUNITIES, BUT THEY ALSO BRING CHALLENGES.

results that are not subject to any form of cognitive bias that may influence the decision making process.

The use of robotics and automation of hazardous processes will enable a far safer working environment to be developed. The de-risking of activities deemed too dangerous for human intervention will mean that hazardous crime-scenes – which may not be fully examined today – could in the future be subject to the same recovery of evidence afforded to less hazardous scenes.

One of the areas requiring automation is the management of large volumes of data that cannot be effectively processes using current capabilities. As we recover and produce greater volumes of data, grid computing will become an important way to manage this information.

CHALLENGES: NEW TECHNOLOGY AND SCIENCES

Emerging technologies and approaches to applying scientific methods in forensic disciplines clearly offer great opportunities, but they also bring challenges. The application of new scientific methods to any illicit activity will require the courts to accept these methods. This will involve a full validation and accreditation process to provide reassurance to the courts that the technique is fit for purpose and sufficiently reliable to, in extreme cases, take away a person's liberty for many years. It is therefore essential that the technique is safe, secure and reliable. The evidence threshold for civil courts is lower, but the science should still be valid if it is to be used.

The first real breakthrough in applying science to criminal investigations came in the late 19th century, when fingerprints were used to investigate crime on the basis of their uniqueness. This has been accepted over the years as a primary identifier, and in the UK we identify roughly 50,000 offenders from crime scenes each year using fingerprints.

The first use of DNA in a forensic context in 1984 revolutionised the way that crime was investigated, and has proved to be a mainstream technique with the formation of a national database. This required a step change in our approach, which disrupted business processes, infrastructure requirements, cultural acceptance as well as significantly changing the operating model for forensic science. But it has brought significant benefits to public safety, and there are 25,000 DNA matches between crime scenes and offenders each year.

We are, however, now at a point where the

THE FIRST USE OF DNA IN A FORENSIC CONTEXT IN 1984 REVOLUTIONISED THE WAY THAT CRIME WAS INVESTIGATED, AND HAS PROVED TO BE A MAINSTREAM TECHNIQUE WITH THE FORMATION OF A NATIONAL DATABASE.

boundaries of sensitivity have been stretched to the point where it becomes increasingly difficult to separate the sample from the background mixture. There needs to be careful consideration that further sensitivity, in its current form, will need advanced analytical software to interpret the complex information present in a sample to ensure that DNA profiling not become counter-productive.

CONCLUSION

The UK has a vibrant science base that has generated many advances in science across a range of sectors. It is clear that there is significant opportunity to consider where there is transferrable science that can be applied in a forensic context: for example, the medical and agriscience fields are already very advanced in their use of Next Generation Sequencing, which the forensic community could learn from. There needs to be a mechanism that enables the identification of transferrable science. This could be through virtual networks of academic institutions or the formation of a dedicated research institute across existing capability that considers both digital and traditional forensic future requirements.

In terms of the functional challenges, any significant innovation in forensic science will be disruptive to a certain extent. The key is to consider the benefits against the disruption, and only then can the decision be made. Any innovation needs to be cost effective in its application, and while early adopters of innovation may pave the way for others, this can be done in a controlled manner through structured coordination. This will identify all the issues such as affordability, regulatory constraints, and future-proofing workflow impact, as well as the wider societal impact such as public acceptance and privacy concerns.

The relevant professional community will scrutinise any new innovation to critically review

CASE STUDY

FORENSICS AND THE INTERNET OF THINGS

ALASTAIR COOK, *Director of Critical Insight Security Ltd*

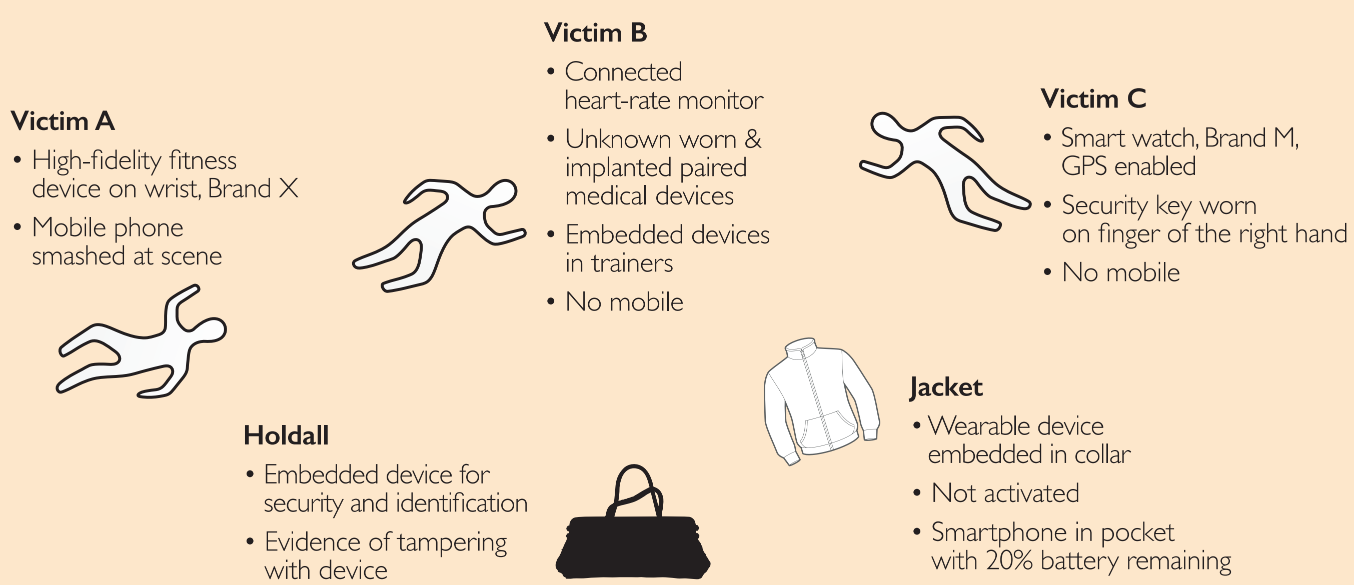
The Internet of Things (IoT) increasingly connects people and services to a plethora of wireless-enabled devices, presenting opportunities for both investigators and criminals. Appropriate treatment and use of data generated by IoT devices could yield crucial leads in a complex investigation, and in some circumstances it could be the primary source of evidence.

Consider a scenario where three murder victims are found in a park, with signs of a struggle plus a number of items left by at least one other party at the scene. Although some mobile phones were present at the scene, one has been intentionally smashed. The second mobile had charge in its battery, but had been remotely wiped by an unknown person using an app that was supplied with the phone's operating system (see Figure 1).

To enable a productive digital forensic analysis, investigators need a high-integrity method to obtain, store, share and analyse the data associated with these devices, so that they can use this knowledge to infer the sequence of events that led to the crime. These methods could include:

1 A trusted framework that allows the data to be imported and preserved in its original form, while also enabling a team of investigators with varying technical skills to interact with it.

Figure 1: Crime scene evidence



As some of the data may not be immediately available – it might be stored in public or private clouds, for example – this environment must be 'live', so that diverse sources of data relevant to the investigation can be imported as they become available.

2 At the point of import, any relationships in the data should be automatically discovered, tagged and highlighted to the team. Linked Data techniques (which allow semantic analysis by both machines and investigators) can be used to generate human and machine-readable statements about the data and its context. Using terminology and identifiers that are recognised by the team, as well as open source or internationally-recognised standards, would significantly increase the utility of the data and draw upon global knowledge in a way that is almost impossible with current methods.

3 Semi-automated identification of appropriate analytic techniques could allow niche methods to advance the investigation, or associate people and places with the devices. This may draw on international data sets or online services that have greater statistical significance, better reference methodologies and more rigorous scrutiny than national or regional teams would be able to achieve. Some of these may not be from the forensics community – they could include online medical or personal fitness services, for example.

This approach could efficiently yield the following summary of assertions that inform an investigation, and may be of sufficient integrity to identify participants in the crime, or even be admissible in a criminal prosecution:

"The team found that the 3 victims regularly shared the same running route. On the day of the crime they exhibited elevated signs of stress and changed their route 16 minutes into the run. There were indicators of a physically intense struggle for the last 3 minutes of the run. A security device on the hand of one victim was linked to a car that was infrequently used by the victim and some other, subsequently identified, persons linked to the crime. The bag was procured in Europe, and carried a device that a non-UK criminal gang used to track the delivery of stolen assets or weapons. The jacket was procured in Antwerp and had been worn in the UK for 3 weeks prior to the crime. This allowed a possible CCTV image of the wearer to be obtained. It appears that Victim B was followed by the wearer of the jacket for 2 days prior to the crime."

Such information could routinely enhance investigations if the three highlighted methods can be implemented alongside forensic advances in other domains. This will allow investigators to adapt to changes in technology, users' behaviour and criminals' tactics at a scale that current methods cannot achieve. It should also provide a sound basis for the scientific scrutiny and investigative integrity that should be expected of all areas of forensics.

SEMI-AUTOMATED IDENTIFICATION OF APPROPRIATE ANALYTIC TECHNIQUES COULD ALLOW NICHE METHODS TO ADVANCE THE INVESTIGATION, OR ASSOCIATE PEOPLE AND PLACES WITH THE DEVICES.

CASE STUDY

NEXT-GENERATION DIGITAL FORENSICS

GRAHAM BROMELOW, *MCM Solutions*

Child sexual exploitation and abuse (CSEA) was reported in every UK policing region in 2014 (ref. 1), and remains a priority in police investigations. Digital forensics is at the heart of investigations into indecent images of children (IIOC), and 'traditional' digital data recovery (triage) and analysis tools are used throughout UK law enforcement and intelligence agencies.

The evolution from complex and slow 'traditional' forensic tools to next-generation IIOC solutions has allowed investigators to close the opportunities criminals have to hide illegal data on their devices. The development of cutting-edge extraction and analysis tools is an iterative one, with constant feedback and consultation from end users and organisations.

The challenge is to develop an easy-to-use and reusable system that handles complexity, can be deployed from on-scene to lab based environments, and rapidly extract or process large amounts of data while maintaining a high-quality output. Alongside these challenges, new technologies are helping to overcome barriers such as budget cuts, lack of manpower and socio-political reluctance to arm first responders with forensic skill sets. Indeed, the business case for moving to next-generation IIOC solutions is a 'no brainer': it can bring down the costs of prosecuting a single case from approximately £40,000 to less than £1,000.

As the amount of IIOC content grows, along with the proliferation of personal devices and data storage, both front line and rapid laboratory-based forensics are now critical in preserving life and convicting criminals while decreasing the length, budgets and backlogs of investigations. New, easy-to–use digital technologies, licenced on removable USB devices, provide non-technical investigators with a lightweight portable tool that dramatically cuts investigation lengths. The most powerful extraction tool (a patented capability originally developed as a military capability) can forensically 'image' a 1TB laptop in under 35 minutes; another 'military' tool enables IIOC content to be located on a target computer within a few minutes. This offers non-technical investigators the capability to perform the initial investigations themselves, producing reliable court-admissible results on their own.

Simple-to-use user-interfaces allow the non-technical investigator to run a full digital acquisition, or effortlessly select granular search criteria for a 'sniper forensic' analysis. Unskilled users could potentially damage digital evidence during a traditional triaging process, making it redundant in a court case. Now, highly configurable search profiles ensure that such 'collateral digital intrusion' is eliminated, assisting with compliance and any warranty issues of IIOC investigations.

Advanced technologies have simplified and streamlined the process of analysing items with evidential value. Despite criminals becoming better at hiding IIOC content, innovative technologies can rapidly uncover them with techniques including skin tone and face detection (see Chapter 6 case study p68), video frame caching, checking video signatures, EXIF extraction (file metadata), preconfigured file signatures, keyword lists, and many more.

Another challenge within digital forensics is helping to overcome the growing concerns from social networking sites, cloud storage, email file sharing, online gaming platforms and search engines that digital environments use to store and share CSEA and IIOC content. Equally as concerning is the expansion of Tor anonymity software, which masks users' identities and makes it harder to locate IIOC users and distributors.

Nevertheless, the National Crime Agency recorded[1] a decline in open searches to access IIOC, which is now even lower due to web giants Google, Facebook and Twitter removing millions of IIOC images from the internet in 2015. Analytical tools can now dive deep into hundreds of internet artefacts, such as instant messaging and chat apps, browser history, Facebook and Twitter feeds to recover and display evidence.

Our digital evidence is so powerful that most people charged with possessing IIOC material plead guilty when shown a report detailing what was found on their computers. The judicial system is also supporting these new capabilities and making changes so that offenders are subject to speedier justice. Other technological developments can ensure victims of abuse can be identified more quickly.

The evolution of computer technology and the internet has undoubtedly led to a growth in the number of of educated computer criminals. They are now using a range of anti-forensic techniques and tools – including cryptography, disk cleaning and file wiping utilities that focus on destroying and altering data – to affect the integrity of an investigation and the reliability of evidence in court., Law enforcement and intelligence agencies will have to face this growing challenge over the next 5 to 10 years.

the validity of the science or technology, in order to determine if the approach is scientifically sound. The end users will review this and assess the outlay costs, business benefits and impact of introducing a disruptive innovation. The legal professionals will consider the use of innovations in the context of the current legislative framework, and decide if it needs to be amended to accommodate such changes. The policymakers will consider the societal impact and the maintenance of public trust in the context of the political environment. The industry approach is critical, in that it must take account of all these factors: ultimately, there has to be a product or service that can be converted from an innovative idea into a marketable commodity that will generate income.

The introduction of new sciences and automation to forensic techniques will not remove the scientist from the equation. But the forensic scientist of the future will be a very different person to those of previous years (see case study p166). They will interact with more automated processes, have a greater understanding of the complexities of large-scale data analytics, and present their findings utilising statistical methodology. This will require a step change to the development programmes that are building the future forensic scientists. In line with this, the judiciary will need to be far more aware of the implications of science and technology in the court room. All of this must operate within an appropriate regulatory framework that maintains the standards required for the delivery of assured science.

The UK has traditionally held a strong position globally in the field of forensic science, and we need to ensure that this global position is maintained and enhanced through government support to academia, industry and the end users of such innovations. This can only be done by providing an open innovation channel that ensures academic research is supported and, where appropriate, converted into commercial opportunities that the end user community will buy into. That means providing access to test databases that act as operational environments to provide a far better understanding of the requirements. This applies as much to the civil applications of forensic science as it does to the criminal uses. Greater coordination of a tripartite arrangement, focussed on forensic science and technology driven by government policy, will enable the UK to grow both capability and reputation on a national and international basis.

ENCOURAGING INNOVATION

GERAINT MORGAN
The Open University
THOMAS BASSINDALE,
Sheffield Hallam University
MARK PEARSE
LGC

The UK has a strong track record of innovation in forensic science, and its forensic science providers have a close working relationship with the police. Engaging all of the partners involved in taking innovations through to market adoption – including academia, industry, end users and government – gives the UK an opportunity to become a global leader in the forensic science market. The government now has an important role to play in helping innovators to bridge the 'valley of death' as they seek to turn proof-of-principle techniques into commercial products.

Forensic science is a multidisciplinary field that relies on technologies and methodologies from a wide range of sectors. Although it primarily addresses questions relating to crime, it also covers a wider spectrum of activities such as consumer and environmental protection, health and safety, the authenticity and provenance of goods, and civil proceedings such as breach of contract and negligence. Intelligence, gathered overtly or covertly, can also predict when crimes are about to take place, enabling pre-emptive interventions or better evidence-gathering. As a result, forensic science makes a significant contribution to our justice and security systems, ensuring our economic stability.

The UK has a strong track record of innovation in this area, including the development of fingerprinting, and more recently DNA profiling. Forensic science provides innovators with potential opportunities in a diverse range of disciplines, as well as a truly global market for its scientific and technological developments. Moreover, England and Wales remain the only countries to have privatised all of their forensic science services. This has created a closeness between the private sector and police service users that is relatively unique compared with the rest of the world.

These factors mean that the UK could become the best place in the world to commercialise forensics innovations in the future – as long as the right market dynamics can be created. In particular, all of the partners involved in taking proof-of-principle innovations through to market adoption – including academia, industry, end-users and government – need to work together to bridge the 'valley of death' that so often prevents high-technology products from realising their commercial potential.

MAPPING THE INNOVATION LANDSCAPE: FROM CONCEPT TO IMPLEMENTATION

According to the Crown Prosecution Service's (CPS) Code for Crown Prosecutors, evidence may only be used in court if the prosecutor is satisfied that it is reliable, credible and admissible. The high cost and judicial impact of failing to meet these standards means that any forensic technique must be validated to a high level, and backed by a strong evidence base, before it is used in criminal investigations. That makes the innovation landscape for forensic science more complex, with a diverse range of stakeholders at all points on the route from concept development through to implementation (see Box 1). Chapter 17 contains a more detailed look at these stakeholder groups, and their interactions.

This complexity and diversity means that no two stakeholders have the same strategic priorities or pressures, and all have different perspectives and interpretations about what forensic science is, and what it can and cannot do. Another consequence, not unusual in multidisciplinary innovation, is the lack of a common taxonomy.

All stakeholders need to engage and communicate directly with all other members of the value chain. In particular, the pull from the Criminal Justice System (CJS) must not be lost in the noise. Engagement should take place in the context of a national strategy, with universal buy-in. Scientific excellence, commercial success and just outcomes will depend on consistent implementation of government strategy, including sufficient funding and open communication. Potential mechanisms for such engagement are discussed further in the chapter.

RISKS, BARRIERS AND CHALLENGES TO INNOVATION

In 2014, The Government Chief Scientific Adviser has previously said[1]:

"Advances in science and technology can yield significant societal benefits and drive economic growth. The challenge for society is to channel existing evidence about innovative technologies and their risks to improve decision making in the area of regulation and policy making."

This accurately summarises the cost-benefit analysis that must be completed before new technologies are applied within the forensic science sector. This poses several challenges for any innovator or technology developer, who must identify:

- The unmet need within forensic science that can provide a suitable return on investment and that is compatible with their existing capabilities
- The customers that require and are willing to pay for the service or product
- The key opinion leaders within the sector that will champion the innovation through to its eventual implementation
- The value proposition of providing such a solution, i.e. what level of investment is required, and how long before a return is achieved
- Who are the main competitors
- The regulatory hurdles prior to implementation
- The risks associated with translating the technology from the laboratory to the real world (e.g. degradation of analytical performance, in terms of reproducibility and false positives or false negatives)
- The sources of financial input at each stage of innovation

FORENSIC SCIENCE PROVIDES INNOVATORS WITH POTENTIAL OPPORTUNITIES IN A DIVERSE RANGE OF DISCIPLINES.

Courts require that forensic evidence is based on processes and scientific principles that have very little uncertainty. This inevitably means that there will be some inertia against new technologies, due to the serious impacts caused by the failure of a forensic method. These risks can be reduced by ensuring that any new innovations are compliant with existing standards and best practice, in particular the Forensic Science Regulator's Codes of Practice and Conduct, CPS guidance, and the relevant legislation. These codes include guidance on the processes to be used for validation, accreditation and implementation of an innovation, from the initial research and development phase, followed

Box 1: Forensic science stakeholders in the UK

- **Academia** (e.g. universities)
- **Funding bodies** (e.g. Research Councils UK, Innovate UK, Police Innovation Fund)
- **Forensic service providers, including larger companies** (e.g. LGC Ltd, Key Forensic Services Ltd, Cellmark Forensic Services) and small and medium-sized enterprises (SMEs)
- **Law enforcement agencies** (e.g. Police service, National Crime Agency, Operational Counter Terrorism users)
- **Government departments** (e.g. Home Office, Ministry of Defence)
- **Regulators** (e.g. Forensic Science Regulator)
- **Guidance and best-practice providers** (e.g. Crown Prosecution Service, College of Policing, National Police Chief Council, Centre for Applied Science and Technology, Defence Science and Technology Laboratory, Forensic Science Special Interest Group, European Network Forensic Science Institute)
- **Accreditation Providers** (e.g. UKAS: see Chapter 3 case study p34)
- **Networking** (Chartered Society of Forensic Science, Association of Forensic Science Providers, Forensic Science Special Interest Group, European Network Forensic Science Institute)
- **End users** (Crown Prosecution Service, Courts, Counter Terrorism and Intelligence)
- **Journalists**
- **General public, including victims of crime**

by pilot studies, use on live samples, first CPS case management and its first test in court. The codes also detail how the whole process should be monitored and reviewed. Direct communication between scientists and end-users in the CJS is key to ensuring that innovation is implemented in a timely manner.

Other potential end-users of forensic science are the military, counter-terrorism and intelligence agencies. Their operational needs are likely to be different from those of the courts, and therefore a dialogue with organisations such as the Defence Science and Technology Laboratory (Dstl) and the Centre for Defence Enterprise (CDE) are essential to establish end-user needs and ensure that the innovation will be fit for purpose. Forensic tools can also be used to determine authenticity in areas including clothes, foods or perfumes, which require liaison with industry and regulatory bodies.

But the primary customers (and budget holders) for most innovations in forensic science are law enforcement agencies or forensic service providers (FSPs). Increasingly, police forces are bringing more forensic services within their organisations, blurring the lines between themselves and FSPs. The main risk for the law enforcement agency is that their investment results in a procedure that is not suitable for use in the Criminal Justice System. Once again, early engagement between scientists and the CJS is key.

For an FSP, there is an additional risk that their investment in an innovation does not provide a return. That financial return is only possible if the innovation is monetised and adopted by a sizeable market, with a proportion of the revenue returned to the service provider and ultimately the innovator. This monetisation could be through the provision of a service directly to the customer, or more likely through the licensing of the intellectual property to one of the leading service providers in the sector. For any innovation to be widely implemented, it must either speed up a current methodology or satisfy an unmet need; have limited competition; and be successfully transferred from the controlled environment of the laboratory into the real world, where it can be used by non-experts. The overall cost of implementing the technology into the forensic workflow will also need to be minimised to avoid driving up costs to the customer.

It is clear from both case studies in this chapter that securing funding to move from the initial research and development phase at an academic institution, through to the development of a commercial product, remains difficult (see case studies on p179 and p181).

Partnerships between academic institutions and end-users can help to guide innovations through this development process. Potential innovators – who may be new to the sector – should be made aware of the wider global markets, and their high esteem for UK forensic science; as well as existing networking opportunities. For example, the Forensic Science Special Interest Group (FoSci SIG) is a community that includes everyone involved in forensic science, and enables closer networking and better communication between all stakeholders for improved research and development. FoSci SIG is run by the Knowledge Transfer Network (KTN) and was set up in July 2012 following a recommendation in June 2011 by the Home Office Chief Scientific Adviser in his review of 'Research and Development in Forensic Science'. FoSci SIG has an online searchable database of challenges in forensic science, which helps to match key questions with innovators' potential solutions[2].

FOR ANY INNOVATION TO BE WIDELY IMPLEMENTED, IT MUST EITHER SPEED UP A CURRENT METHODOLOGY OR SATISFY AN UNMET NEED; HAVE LIMITED COMPETITION; AND BE SUCCESSFULLY TRANSFERRED FROM THE CONTROLLED ENVIRONMENT OF THE LABORATORY INTO THE REAL WORLD.

TURNING SCIENCE INTO FORENSIC SCIENCE

Fundamental 'blue skies' research usually takes place in universities with the support of research council funding. Some of these activities will result in capabilities that may be of benefit to forensic science. The challenge for the community is in identifying those projects,

ACADEMIC RESEARCHERS NEED TO HAVE A CLEAR UNDERSTANDING OF THE REALITIES OF THE END-USER NEEDS AND ENVIRONMENT, WHICH CAN ONLY BE GAINED THROUGH INTERACTION WITH AN END-USER, AND IDEALLY WITH THE WIDER STAKEHOLDER COMMUNITY.

especially when the innovation is initially applied in a different discipline.

If the project is more applied, then the academic researchers need to have a clear understanding of the realities of the end-user needs and environment, which can only be gained through interaction with an end-user, and ideally with the wider stakeholder community. Increasingly, the importance of applied research is being acknowledged within universities and the research councils. All research council proposals must demonstrate 'Pathways to Impact', including how researchers will communicate, engage and collaborate with stakeholders and potential beneficiaries of the research.

There is also a growing expectation within universities that research should be translated, with any revenue generated being returned to the university. This strategy is further encouraged through the Quality Related-Business Research Element (QR-BRE) funding from the Higher Education Funding Councils of both England and Wales, and by the fact that an assessment of impact now makes up 20% of the Research Excellence Framework, and therefore directly influences future mainstream Quality Related (QR) research funding in all UK universities.

However, it should also be acknowledged that the current requirement for an academic to achieve traditional 'outputs' for their research (80% weighting) is also a barrier to investing time in activities such as validation, which may not be publishable in peer-reviewed journals but is crucial for the end-stage of adoption of a technology.

To help these applied projects, it is important that the sector establishes and supports events that actively engage all stakeholders and generate opportunities for networking; offers funding for proof-of-principle studies and/or staff exchanges; and provides commercial training on how to develop an initial idea into a business plan, so that innovators can attract follow-on funding from agencies such as Innovate UK. The Network+ schemes being organised by the Science and Technology Facilities Council (STFC) and the Engineering and Physical Sciences Research Council (EPSRC) provide such funding, but the field also needs a forensic science champion for these schemes, with a proven track record of engaging with the other key stakeholders in the sector.

Any intellectual property generated by this research could be exploited in two ways. It could be licensed to an FSP or commercial organisation, which would then develop the product and take it to market, eventually providing a revenue stream to the university. Alternatively, the academics involved could form a spin-out company to further develop their value proposition, with a view to either providing a service directly or exiting through a trade sale.

Very few academics choose the latter option. But those who do take this brave step need financial support and mentoring. Incubation centres such as the STFC/European Space Agency Business Incubation Centre in Harwell, and the associated funding available from Innovate UK through the Harwell Space Launchpads, offer an excellent model of how start-up companies can develop if they have a funding roadmap to facilitate growth and to support it in securing investment capital.

The Security Innovation and Demonstration Centre (SIDC)[3], launched by the Home Office in 2014, could provide another important incubation facility for forensic science. As an open innovation centre focused on security challenges, it will enable innovators to access end users and their environments for rapid real-world evaluation of new concepts, using a shared laboratory and demonstration space hosted at the Home Office's Centre for Applied Science & Technology (CAST). The SIDC aims to support start-ups through links to mentors and investors, thereby de-risking the introduction of new technologies. It will also host demonstrations to overseas delegations to

INNOVATION IS NOT JUST ABOUT MAKING BREAKTHROUGHS OR DEVELOPING A NOVEL INVENTION. INCREMENTAL INNOVATIONS ARE FAR MORE COMMON, AND RESULT IN IMPROVED PERFORMANCE FOR EXISTING TECHNOLOGIES.

support UK security exports.

More established companies typically decide whether to develop a new technology based on an assessment of strategic need, and the potential return on their investment. A purely commercial environment, where market forces alone drive the agenda, may hamper further development of an existing technique for several reasons. Some companies may be unwilling to invest in a new 'market leading' technology if the legal process requires that the methodology is disclosed, thus allowing other companies to develop rival products. Or they may wish to only employ members of staff who directly provide services (and therefore bring in income). As a consequence of these factors, in the future most commercial companies may not have dedicated research and development departments to bring through innovative new technologies or methods.

But innovation is not just about making breakthroughs or developing a novel invention. Incremental innovations are far more common, and result in improved performance for existing technologies. They may offer better accuracy or precision, lower the limit of detection, or improve reproducibility; or they can increase the throughput of an analytical process, or reduce costs. One recent example is the availability of commercial robotic auto-samplers that interface with gas chromatography-mass spectrometers, which now enable the majority of sample preparation and analysis to be performed automatically, without the need for skilled human intervention. However, the source of funding for such incremental developments remains an open question, especially as one moves further away from the market and the level of risk increases for the innovator.

OPPORTUNITIES FOR THE UK IN A GROWING MARKET

Some police services are now approaching universities to undertake research projects on their behalf. Regional meetings (e.g. in Yorkshire and the Humber) have allowed universities to present their capabilities and the possible analytical tools they have available, and for the police to present the problems they would like to investigate. A simple summary of what police services typically require is: "What we do now, but quicker and on site, please".

As part of its remit to enable closer networking and better communication between forensic science stakeholders, the FoSci SIG promotes an annual networking event called the Forensic Science Technology Showcase. The aim is to bring together funders and potential buyers so that innovators can showcase new technologies, in order to help them find a market[4].

Innovators can also make these connections through the Chartered Society of Forensic Sciences, which has members from all aspects of forensic practice, crime scene investigation, policing, military, medical, dentistry and legal professions[5]. It offers continuing professional development (CPD), scientific meetings (with CPD points), qualifications, social and networking events, professional recognition and scholarships. The society also provides an accreditation system for academic institutions that deliver forensic science undergraduate and postgraduate courses (see Chapter 2 case study p30).

The Association of Forensic Service Providers (ASFP) could also play an important role. It is an independent, representative body that seeks to facilitate the effective delivery of justice and promote public confidence in forensic science[6]. The AFSP was constituted on 1 July 2010 with a mission to represent the common views of the providers of independent (i.e. non-police) forensic science within the UK and Ireland, while maintaining and developing best-practice in forensic science and providing expert opinion in support of the justice system, from scene to court. As such, it could act as a single voice for FSPs in the UK and Ireland, help to share international best practice, and promote global market opportunities.

CASE STUDY

INNOVATE UK AND THE FORENSIC SCIENCE SPECIAL INTEREST GROUP

MEEZ ISLAM, *Teesside University*

Blood represents one of the most frequently encountered and useful types of physical evidence found at violent crime scenes. Investigators typically identify the presence of blood by using 'presumptive tests': these indicate whether a substance is likely to be blood, but do not offer absolute proof. Current methods such as the Kastle-Meyer test, the leuco-malachite green test, and the luminol test, all use indicator chemicals that either change colour or glow when exposed to haemoglobin.

THERE IS A NEED FOR A MORE RELIABLE MEANS OF DETECTING AND IDENTIFYING BLOOD STAINS AT CRIME SCENES OR FROM RECOVERED EVIDENCE, IN A NON-CONTACT, NON-DESTRUCTIVE MANNER.

Although these tests are useful in many circumstances, they are also subject to false positives (i.e. they can indicate blood when none is actually present) and they may also detrimentally affect subsequent DNA tests. There is consequently a need for a more reliable means of detecting and identifying blood stains at crime scenes or from recovered evidence, in a non-contact, non-destructive manner. Recent research by my group at Teesside University has investigated the potential of visible-wavelength hyperspectral imaging, which can identify the spectral signature of haemoglobin in blood, with high specificity and sensitivity. Using a prototype instrument, we have obtained promising preliminary results showing that hyperspectral imaging can detect and identify both visible and latent blood stains on a range of backgrounds[1].

Since obtaining our initial results, we have faced a number of challenges in disseminating our results to the police service and forensic laboratories; making contact with potential end users; and in obtaining funding to develop our prototype. Fortunately we have received support from Innovate UK, through its Forensic Science Special Interest Group (FORSIG). Its meetings and Technology Showcase events have allowed us to demonstrate our instrument to relevant end users in the police service, as well as forensic service providers. This has allowed us to make useful contacts and get valuable feedback on our prototype.

FORSIG highlighted relevant funding calls and was instrumental in pushing for a relevant Small Business Research Initiative (SBRI) phase 1 funding call from the Home Office. They provided advice which allowed us to make a successful bid for proof-of-concept funding from that call, which has led to further development of our prototype.

FORSIG also suggested that we set up a spin-out company to help commercialise our technology. Consequently, we have recently founded Chemicam Ltd, which currently consists of five partners and which aims to develop a commercial blood detection instrument. Significant challenges remain before we commercialise the technology – we are looking for more funding, and need to clear various regulatory hurdles, for example – but Innovate UK and FORSIG have clearly helped us to get closer to that goal.

THE LIMITED SIZE OF THE FORENSIC SCIENCE MARKET IN ANY ONE COUNTRY MEANS THAT INNOVATORS AND SERVICE PROVIDERS MUST ALSO CONSIDER OPPORTUNITIES AND NEEDS IN THE GLOBAL FORENSIC SCIENCE MARKET.

The main growth market for UK forensics is likely to be in:

- **Digital forensics:** Many crime investigations now involve mobile phones (tracking someone's whereabouts, for example, or video evidence of an incident); or crime committed through the internet (see Chapters 7 and 15). These all need better approaches to retrieving and analysing electronic data.
- **Rapid Identification of Offenders:** The Association of Chief Police Officers (ACPO) Live-time Forensics strategy aims to speed up the identification of offenders by using innovations such as RapidHIT DNA or paraDNA analysis.

But the limited size of the forensic science market in any one country means that innovators and service providers must also consider opportunities and needs in the global forensic science market. Potential routes for innovators to access overseas markets, in addition to the above named organisations, include:

- The Science and Innovation network, funded by the Foreign and Commonwealth Office and the Department for Business, Innovation and Skills
- Innovate UK
- UK Trade and Investment
- Other UK government departments – such as Ministry of Defence – that share best practice with other nations
- European Network of Forensic Science Institutes
- Horizon 2020 Secure Societies programme, which includes calls in 'big data' analysis; in situ forensic tools for the crime scene; remote control technologies for monitoring and examining scenes; internet forensics; 'stand-off' body scanning

THE ROLE OF GOVERNMENT

The government has an important role to play in helping forensic science innovation to thrive in the UK. Its CAST and SIDC can help to bring innovations through to market-readiness. And the Home Office is currently establishing a National Strategy for Forensic Science that will provide direction on the future opportunities for innovation, taking into consideration all members of the stakeholder community. In developing this, the Home Office may wish to explore how the UK healthcare sector has recently addressed the issue of clinical innovation and adoption. The NHS Five Year Forward View sets out additional steps that the NHS will take to accelerate innovation to find better ways of delivering health and care. This strategy includes the establishment of fifteen regional Academic Health Science Networks (AHSN), a similar number of Clinical Research Networks (CRNs) and the recent global call for the establishment of five 'test beds' that will receive national support for implementing high-potential innovations that respond to local clinical needs.

Each of the AHSNs has been given significant funding and a five-year license from NHS England to "facilitate the adoption of innovative practices, products and services at scale and more quickly than has previously been achieved in the NHS".

The NHS has also recognised that "too often, new technologies have been tested alone, in isolation from complementary innovations in how NHS services are delivered, limiting the value they produce". AHSN, CRNs and test beds are seen as the mechanism by which this can be addressed, and similar bodies could have a positive impact on forensic science.

A national strategy for the sector is essential, along with appropriate funding. That strategy should include mechanisms for academia, industry, customers, end-user communities and the government to engage and communicate more effectively, to ensure that innovations are fit-for-purpose and that CJS requirements are not over interpreted, potentially stifling innovation.

CASE STUDY

BIOSENSORS IN FORENSICS

BARBARA DANIEL, *Head of Forensic Science Unit, King's College London*

In January 2006, our group at King's College London (KCL) was awarded a £178,613 research grant from the Engineering and Physical Sciences Research Council (EPSRC) under its 'Think Crime' funding programme. Our research proposal had been prompted by a discussion with the Director of Forensic Services at the Metropolitan Police Service (FS-MPS), who asked whether it was possible to detect a 5-microlitre blood spot somewhere on a black tracksuit. Quite a challenge – but one we thought we could overcome by using fluorescently-labelled antibodies that would bind specifically to red blood cell surface antigens.

The major problem, in this forensic context, was how to get rid of any antibodies not specifically bound to the blood on the tracksuit. We came up with the idea of attaching the antibodies to magnetic nanoparticles and removing the excess with a magnet, a method that worked surprisingly well, even on fabrics. In 2009, we applied for follow-on funding to develop the technology, but it was deemed to be too far away from the market to be eligible. We then fell into a gap where the research was either 'not innovative enough' or 'too far from the market'. This illustrates an all-too-common difficulty in bringing forensic science techniques from the laboratory into routine use.

We continued to work on the problem, with the cost of consumables covered by the FS-MPS. This resulted in some positive proof-of-concept work in the development of biosensors for the detection of body fluids in a forensic context, and formed the basis of an application for funding to the EPSRC in 2013. This application was unsuccessful, after a reviewer from the forensic community reported that new technology would have little impact on forensic science because existing methods for body fluid detection are available and effective.

Yet two very high profile cases would have been resolved much more quickly if a better method for the detection of body fluids was available. In the case of Stephen Lawrence, a minute trace of blood was missed and only discovered after many years, following hours of painstaking searching by an exceptional forensic scientist. Meanwhile, the blood spot missed on the shoe of Damilola Taylor's assailant was attributed to human error.

OUR TECHNOLOGY COULD RESULT IN A FIFTY-FOLD REDUCTION IN THE TIME AND EXPENSE SPENT ON ROUTINE BIOLOGICAL SEARCH METHODS.

Our technology could result in a fifty-fold reduction in the time and expense spent on routine biological search methods. In light of these advantages for policing, the Police Innovation Fund awarded a grant to the FS-MPS and KCL in August 2014 to develop this method. The results are promising[1], and we are currently seeking industrial partners to fully develop the technique.

Biosensors rely on substrate-specific recognition moieties (similar to antibodies) capable of working efficiently within a mixture, without cross-reacting or giving false-positive results. They must also be able to perform under the many and varied conditions encountered in forensic investigations. Developing these moieties is essential but time-consuming, and is therefore particularly vulnerable to falling into the 'funding gap' well known to researchers.

Fundamental research may be high risk and complex, but is important for the forensic community and funding bodies to recognise that it is vital to the implementation of revolutionary approaches to forensic investigation.

ACCESSING FORENSICS AS A NEW MARKET

MARK LITTLEWOOD, *co-ordinator of the Forensic Science Special Interest Group;* GILLIAN TULLY, *Forensic Science Regulator*

Although the UK market for forensic science is small and declining, the global market continues to grow and expand into new areas of science. The UK should maintain its current high standing in the traditional forensic disciplines, while seeking opportunities to access overseas markets and developing new expertise in emerging areas such as digital forensics.

This chapter examines the forensic science sector as a new market, and offers insights into some of the key considerations of bringing a new technology into the Criminal Justice System (CJS). It describes the size and growth rate of the sector, potential areas for knowledge transfer, the processes involved and how to interact with key stakeholders, ethical considerations and resources to facilitate market entry. This chapter draws extensively on, and uses updated sections from 'Taking Forensic Science R&D to Market'[1], a report by Gillian Tully and Kevin Sullivan that was published by the Forensic Science Special Interest Group (FoSci SIG) in 2013. It offers a much more comprehensive view of what is involved in bringing a new technology to market.

MAPPING THE FORENSIC MARKET

The forensic market can be divided into two sectors: traditional forensics and digital forensics.

1. Traditional forensics

Forensic science provision in the UK is fragmented, making it difficult to estimate the current size of the market. This, combined with differing approaches across the world, mean that a global figure is even more elusive. The forensic science market is further complicated by the split between external and in-house work such as scene of crime analysis and fingerprinting. The UK's external market was predicted to fall from £170 million to £110 million between 2009 and 2015 (ref. 2). However, more recent estimates have been more pessimistic, with the largest forensic service providers indicating a 2015 market value of £70 million to £100 million, the Home Office indicating £70 million to £80 million, and the Association of Chief Police Officers (ACPO – now called the National Police Chiefs' Council) £63million to £70 million. Various explanations for this decline have been offered, including disproportionate cuts to forensics compared with other police work; lower crime rates resulting in a reduced demand for forensic services; and a reduction in costs due to technological advances[3]. Previous attempts at estimating the size of the in-house market have proved inconclusive[4].

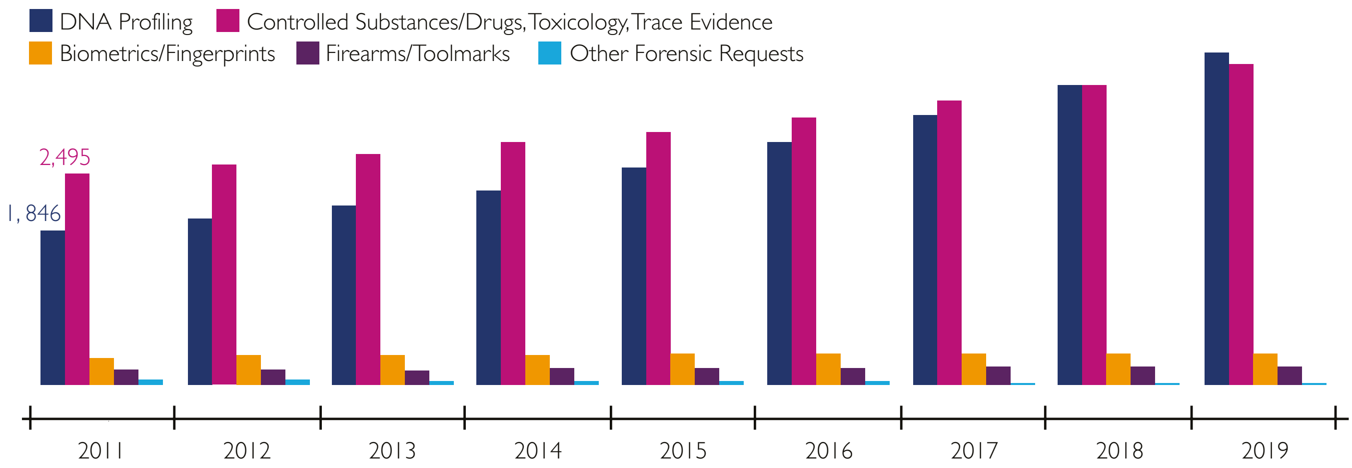
The global market has been predicted to grow at a compound annual growth rate (CAGR) of 8.34% between 2014-2019 (ref. 5) to reach \$17.7 billion[6], with developed countries accounting for more than 50% of the total market. However, automated processing is likely to force down the costs of standardised tests, reducing the total spent on forensic technologies in these regions. This, combined with increased investment in infrastructure, modern equipment, DNA databases etc in developing countries, will see the Asia-Pacific and other regions outside North America and Europe accounting for 60% of the global forensic science market in the future[6].

The forensic technologies market has been segmenting into 4 broad categories[6]:

- DNA Profiling
- Biometrics / fingerprint analysis
- Chemical analysis (drugs / explosives / toxicology)
- Firearms identification and analysis

Of these, DNA profiling and chemical analysis typically account for the vast majority of the market (see Figure 1).

Figure 1: North American forensic technologies market 2011-2019, by services (USD Million)[6].
Data for the UK and rest of the world are not currently available.



Source: KOL Opinions, Expert Interviews, Press Releases and TMR Analysis

2. Digital forensics

The data above do not include the field of digital forensics, which is becoming an ever more significant part of forensic investigations. The use of smart phones and tablet computers is growing exponentially, and along with technologies such as smart home and smart vehicle systems they generate and contain masses of data, which can be used to investigate a suspect.

Forensic specialists face huge difficulties in this area, considering:

- The number of devices that could be associated with a single suspect
- The number of different devices on the market, which would each require a protocol to analyse their contents
- Operating systems with different encryption, each having regular updates that could change the analysis protocols
- The globalised nature of the digital world: these devices are probably manufactured overseas, which may make it more difficult to seek support for them

Thus, greater resource is likely to be put into digital forensics in the future. This might grow the total forensic market, or could take financial resources away from traditional forensic disciplines.

In summary, the UK market for forensic science is small and declining. However, the global market continues to grow and expand into new areas of science. The UK should maintain its current high standing in the traditional forensic disciplines, seeking opportunities to access overseas markets while developing new expertise in emerging areas such as digital forensics.

PROCESS STEPS NEEDED TO BRING A NEW TECHNOLOGY TO MARKET

The Criminal Justice System (CJS) has requirements that must be met before a new technology will be adopted by the police service, courts and other stakeholders. Technologies not only need to produce admissible evidence, they also need to be accepted as being credible. To demonstrate credibility, technologies need to be fully validated and documented to allow the potential for all development materials to be reviewed in future court cases.

1. Key stakeholders and how to interact with them

In order to more effectively target limited R&D funding, constructive dialogue between innovators, end users and stakeholders is required. The nature and timing of dialogue will vary depending on the drivers for the research, its strategic importance and its distance from market. For example, if research is required to build strategic capability, the Forensic Policy

Group should provide appropriate leadership. Conversely, fundamental academic research is required in all disciplines to generate the knowledge and understanding that is essential for a new generation of ideas for forensic applications to emerge. This fundamental research should not be constrained by current needs for policing or defence, and needs no approval from forensic science stakeholders.

Whatever the nature of the innovation, continuing end-user input is required throughout the development cycle. Key requirements of the dialogue between innovators, end users and stakeholders include:

- Shared set of values based on supporting open justice and enhancing public safety
- Segregation of market engagement from sales and marketing or procurement activity, to ensure that:
  - end users have no commitment to buy at market engagement stage
  - the same information is made available to all groups innovating in the same field
  - the innovators' intellectual property is respected
- Understanding the strategic and operational priorities of, and the pressures on, all parties, both public and commercial sector (see below for examples).

2. Stakeholder landscape, priorities and pressures

No two stakeholders have the same strategic priorities or pressures, so to aid effective communication a brief summary is given below.

Academia

- Priorities: High-quality and high-impact publications are required for the Research Excellence Framework; fundamental research as well as applied research is critical
- Pressures: Funding environment is very challenging; university business development offices keen to commercialise research

Chartered Society of Forensic Sciences

- Priorities: Accrediting university courses, working to promote links between academic researchers, liaising with funding councils
- Pressures: Rapid expansion of forensic science degree courses (see Chapter 2, case study p30), changing forensic science landscape

College of Policing (CoP)

- Priorities: As the professional body for policing, the CoP partnered with the Economic and Social Research Council (ESRC) to establish the What Works Centre for Crime Reduction, funding academic research into crime reduction[7]
- Pressures: Looking to establish an evidence-based profession with tight budgets; forensic science is a very small part of the CoP's remit

Crown Prosecution Service (CPS) and Courts

- Priorities: All researchers in this field should be familiar with the Code for Crown Prosecutors[8] – novel scientific methods will need to pass the tests within the code. Researchers also need to know the principles of case management[9] and streamlined forensic reporting (SFR)[10], to ensure that any methods they develop are tailored to the process; CPS guidance to summarise requirements for FSPs should be followed[11]
- Pressures: CPS restructuring and reductions in resource.

Defence Science & Technology Laboratory (dstl)

- Priorities: "To maximise the impact of science and technology for the defence and security of the UK"[12]. Dstl manages the roughly £400 million Defence Science & Technology Programme, outsourcing where possible to industry and academia (about 60%) and internally providing capability for chemical and biological defence, counter-terrorism and counter-insurgency, as well as analysis for evidence-based decision making
- Pressures: Dstl is facing challenges from the ongoing efficiencies and streamlining within the Ministry of Defence, central government and the wider public sector; there are challenges in coping with cuts while demand remains strong

Forensic Service Provider (FSPs)

- Priorities: Quicker, cheaper, more discriminating, more automated tests that can offer a competitive advantage
- Pressures: Intense competition, reduced margins, and demand for faster results have all increased companies' need to show a return

CASE STUDY

BRINGING A FORENSIC PRODUCT TO MARKET

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The UK's forensic science marketplace has undergone major changes in recent years, and presents a challenging environment for companies. The market has been commoditised under the National Forensic Framework, with forensic companies competitively tendering for individual 'lots' of work. Each lot comprises a number of very specific 'products' with associated 'service specifications'.

But financial cuts have placed significant pressure on police budgets, causing the police service to dictate which scientific tests are carried out rather than working with forensic scientists to develop the most appropriate strategy for the case. There is pressure to carry out the minimum amount of work, with less interpretation of the findings in the context of the case. This is compounded by the police's drive to deliver work in-house. Consequently, developing a new technique and then bringing a new service to market – with all of the associated validation and accreditation costs – entails significant resource and expenditure, and a not inconsiderable amount of commercial risk.

Meanwhile, a decline in the use of traditional evidence types – such as fibres, paint and glass – along with a growing reliance on DNA and fingerprints, has focused companies' research and development budgets on new, innovative services that will give them a commercial edge and generate financial returns.

For example, ArroGen has developed a technique called Fingerprint Molecular Identification (FMID) that relies on mass spectrometry to provide a molecular profile of latent fingerprints at a crime scene. This allows investigators to combine latent fingerprint examination with chemical analysis, which can potentially identify illicit drugs, medications and their metabolites, gender, explosives and more. It has, however, been a challenge to bring the technique to market.

Companies such as ours first need to identify customers' requirements for the technique, and understand their differing requirements around the world. That requires us to spend sizeable sums on running and attending numerous specialist conferences, and gathering feedback from police forces and other law enforcement agencies. In this respect, ArroGen has benefitted from having operations in the United States as well as the UK.

The technology must then be tailored to meet customers' needs. In our case, ArroGen has developed FMID Crime Scene and FMID Slide kits, taking into account the standard fingerprint and DNA requirements.

Forensic technology providers also need to validate their techniques in each of the countries where they will be used. Our FMID system went through initial proof-of-concept studies, followed by validation on fingerprints left by volunteers (an exercise that requires careful consideration of all the legal implications involved). We are now field-testing the technique within a true crime scene environment.

The UK forensic market has seen a welcome focus on accreditation, the final step for any forensic product. We hope that FMID will achieve that by demonstrating appropriate peer review and suitability for evidential use in the Criminal Justice System. Meanwhile, the company is preparing for service delivery; we have developed a pricing model and e-commerce site; instrumentation is in place; and new staff have been recruited and trained.

Our work on FMID illustrates the considerable effort involved in bringing a new forensic product to market, but we believe that it offers real potential to provide valuable intelligence and corroborative evidence to support law enforcement agencies and the courts.

on investment, while reducing the emphasis on R&D Delays in implementation have a major impact on business

Forensic Science Regulator (FSR)

- Priorities: Validation must conform to standards within Codes of Conduct and Practice; for a completely new field, quality standards will need to be defined
- Pressures: Rapidly changing and fragmented forensic science landscape

Funding Bodies

- Priorities: The UK's seven Research Councils fund academic research judged to be excellent, and which has an impact on the growth, prosperity and wellbeing of the UK. A variety of mechanisms are used, including support for international collaborations, support for academic career development and development of scientific infrastructure. Innovate UK seeks to promote UK innovation and hence economic growth
- Pressures: Maximising the impact of research funding is increasingly important, and partnerships between funding organisations such as the Research Councils, Innovate UK, the UK's Higher Education Funding Councils, business, government, and charitable organisations have been established.

Home Office

- Priorities: The Home Office is committed to producing a forensic science strategy by the end of 2015, in which 5 areas have been considered: legitimacy, market/supply chain, digital forensics, forensic futures, skills and knowledge
- Pressures: Closures of the Forensic Science Service (FSS) and National Policing Improvement Agency (NPIA); National DNA Database (NDNAD) now within Home Office Science; public sector spending cuts; reduction in spending on forensic science; criticism from House of Commons Science and Technology Committee.

Industry

- Priorities: The UK is a small and decreasing part of a relatively small global market in forensic science. Ideally, technology needs to feed more than one market to increase attractiveness e.g. by crossing over to security and counter-terrorism markets or medical markets. Funding to bridge the gap from academic work is often required
- Pressures: The global downturn means that access to capital for investment has been limited. Requirement to show a return on investment. Delays in implementation have a major impact on business

National Crime Agency (NCA)

- Priorities: The NCA's goal is to tackle serious and organised crime, using a combination of approaches such as: traditional law enforcement methods; gathering high-quality intelligence to know where, when and how to strike with best effect; monitoring serious career criminals and confiscating criminals' assets
- Pressures: Delivering operational priorities; disruption of criminal markets; systematic management of persons of interest involved in organised crime; and delivery of more law enforcement activity against more organised criminals

Police

- Priorities: At the highest level, the police service's goal is to improve public safety, so it wants to know how science can make people safer; and when things do go wrong, how can it help to identify offenders and bring them to justice?
- Pressures: intense budgetary pressure; new Policing and Crime Commissioners; police reform; reform of the NPCC; closure of the National Policing Improvement Agency and establishment of the CoP

Operational counter-terrorism (CT) users

- Priorities: The government has laid out its counter-terrorism strategy in CONTEST[13]
- The strategy is based on four areas of work:
    - Pursue: to stop terrorist attacks
    - Prevent: to stop people becoming terrorists and supporting terrorism
    - Protect: to strengthen our protection against a terrorist attack
    - Prepare: to mitigate the impact of a terrorist attack

Forensic science has a significant part to play in much of that strategy.

3. Ethical considerations

Use of forensic science is governed by the state of the science, the legislative framework, the policy framework (including funding), interaction with society (including civil society groups) and commercial actors.

This happens at two levels:

- Sites of operation: where forensic science is applied (labs, crime scenes etc) and developed within a case, involving interaction between many players
- Sites of deliberation: where legislative and policy decisions are made

Social and ethical decisions arise at both levels. Ethical oversight is essentially a collaborative process, shaped by all participants in forensic science. Historically, ethical considerations in forensic science have lagged far behind ethical considerations in medical research. A lag in public engagement and debate has arguably contributed to challenges at the European Court of Human Rights[14,] resulting in policy changes regarding the retention of samples and data on the National DNA Database. It is therefore important that innovators in the forensic science field ensure that the social and ethical issues arising from their work are highlighted and debated (see ref. 1 for a more extensive review of ethical considerations).

In summary, the forensic science market is more complicated than other sectors because there is a large number of stakeholders to interact with; a need to test a technology in both research and real-world scenarios; documentation and validation processes; and ethical questions to consider.

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RESOURCES TO FACILITATE MARKET ENTRY

Due to the diverse range of technologies that might offer solutions to the forensic sciences, the funding landscape in this area is fragmented. The majority of academic funding is provided through the UK Research Councils (RCUK), as detailed below. However, RCUK's main remit is to fund 'blue skies' research, whereas forensics is a more applied science. Similarly, most UK funding for businesses goes through Innovate UK, whose main remit is to "work with people, companies and partner organisations to find and drive the science and technology innovations that will grow the UK economy". As discussed above, forensic science is a relatively small market, and therefore not a priority for Innovate UK funding. Nonetheless, there are options where funding can be applied to the forensic sciences, as discussed below.

1. Research Council funding

Academic institutions and some independent research organisations are eligible. Beacuse the employment of specialist staff or staff exchanges between organisations are eligible as costs for realizing the impact of research, academics applying for funding should consider at the outset whether to budget for forensic scientist, police or other end-user input in their 'Pathways to Impact' proposal.

Biotechnology and Biological Sciences Research Council (BBSRC)

The BBSRC's strategic priorities are food security, industrial biotechnology and bioscience underpinning health. Grant proposals in responsive mode will have an advantage if they address one of these priorities, although research excellence remains the overriding priority.

The BBSRC also prioritises building partnerships: proposals that include collaborative research with users, research to inform public policy or increased international collaboration would be well suited to forensic science. Schemes for new academics may also be of value for forensic scientists commencing an academic career.

CASE STUDY

CYBER SCIENCE AND CONSUMER INTELLIGENCE

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The work of Lancaster University is a prime example of how forensic science research can be exploited to contribute to the UK economy in numerous ways. The Security Lancaster research centre, one of the UK's Academic Centres of Excellence in Cyber Security Research, has pioneered a new field in online child protection called Digital Persona Analysis (DPA).

DPA was developed over a decade and is the product of interdisciplinary research that combines computer and behavioural science with linguistics – it has already delivered significant impact in the fields of law enforcement, education and internet governance. It automates the process of detecting sexual predators online by using comparative language algorithms. DPA analyses large amounts of data to identify and report individual personas and behaviours of concern. It relies on a system known as the Isis Toolkit, developed to detect criminals who hide behind multiple identities (often adults posing as children). Live trials have been carried out with various UK police forces, and separate evaluations have shown that the Isis Toolkit can detect with 94% accuracy an adult masquerading as a child.

The initial research was funded by grants from the Engineering and Physical Sciences Research Council (EPSRC) and the Economic and Social Research Council (ESRC). In 2012 a separate company, Relative Insight Limited, was spun out from the university to commercialise this work. While it continues to operate with law enforcement, it has adapted the technology for use in a marketing context, turning language into data to give brands valuable intelligence on consumers and competitors. Relative Insight's platform allows efficient analysis of a brand's messages, and the language that people use to talk about them. This offers insights into overall consumer attitudes toward brands, as well as how those attitudes shift over time, allowing brands to accelerate their research, develop better-informed marketing strategies, and measure campaign success.

Relative Insight Limited is currently undergoing its third venture capital funding round having received earlier backing from the North West Fund for Venture Capital, Lancashire's Rosebud Fund, and other investors. In a little over a year it has developed a blue-chip client list, working with corporations such as Microsoft, Unilever, Twitter and many of the world's leading advertising agencies. The world-class marketing department at Lancaster University also helped to develop this client base by introducing Relative Insight to a number of key agencies and brands. In return, the company contributes to marketing courses run by the university and is already recruiting from its student pool as the business expands.

The development and exploitation of DPA highlights the significant commercial value that can be created by the translational and multidisciplinary approach inherent to forensic science. In commercial terms, forensics is the science of identification, and the market for its applications will grow rapidly with increasing demand for more effective solutions to the challenges posed by such issues as terrorism, food contamination, counterfeiting and data management and security.

THE DEVELOPMENT AND EXPLOITATION OF DPA HIGHLIGHTS THE SIGNIFICANT COMMERCIAL VALUE THAT CAN BE CREATED BY THE TRANSLATIONAL AND MULTIDISCIPLINARY APPROACH INHERENT TO FORENSIC SCIENCE.

Engineering and Physical Sciences Research Council (EPSRC)
EPSRC has a number of highly relevant themes for forensic science research, including:
- Digital economy
- Engineering
- Global uncertainties, including cybersecurity, disasters and emergencies, CBRN proliferation, terrorism, threats to infrastructure and transnational organised crime
- Healthcare technologies
- ICT
- Mathematical sciences
- Physical sciences

Economic and Social Research Council (ESRC)
ESRC's strategic priorities are:
- Economic performance and sustainable growth
- Influencing behaviour and informing interventions
- A vibrant and fair society

Innovative, high-quality collaborative proposals between social scientists and physical scientists may find cross-research council funding.

Medical Research Council (MRC)
Although medical research may be peripheral to forensic science, areas such as understanding the genetic determinants of complex traits, or major genetic studies, have potential forensic applications. Collaborative research may be able to demonstrate impact in both health and forensic applications.

Natural and Environmental Research Council (NERC)
Niche areas such as development of methods to detect crime against endangered species may find funding through NERC

2. Innovate UK
Innovate UK's funding is aimed at industry, particularly SMEs, although precise eligibility differs between schemes.

Collaborative R&D
Encourages businesses and researchers to work together on innovation
- Co-funds partnerships between businesses, and business and academia
- Helps create successful new products, processes and services

Feasibility Studies
- A single-company or collaborative R&D grant scheme
- Lets businesses investigate the technical feasibility of a new idea
- Winners showcase and share their ideas at Collaboration Nation events (see Chapter 16, case study on p179)

Innovation vouchers
- Encourage businesses to look outside their network for new knowledge
- Available for UK start-ups and small- and medium-sized enterprises (SMEs)
- A £6 million fund to help stimulate innovation where few businesses invest. One of the current priority areas for innovation vouchers is cybersecurity

Knowledge Transfer Partnerships (KTPs)
- KTPs let businesses work in partnership with academic institutions
- This allows businesses to access knowledge, technology and skills

Small Business Research Initiative (SBRI)
- Uses the power of government procurement to drive innovation
- Lets companies engage with the public sector to solve problems
- 100% of the funding is provided through a contract not a grant

Smart
- Funding for innovation projects in high-growth-potential SMEs
- Grants let you assess the commercial viability of a project
- Smart funding is available to single companies

3. Horizon 2020
Horizon 2020 is the funding mechanism to realise the EU's Europe 2020 goals. It is open to companies, research organisations, academic institutions or individuals in EU member states, associated countries, EU candidate countries and selected other countries. Innovate UK coordinates all Horizon 2020 activity in the UK. Horizon 2020 aims to ensure that more good

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ideas get to market, and as such will fund more near-to-market solutions than its predecessor, FP7. Its key objectives are: supporting the EU's excellent science base; building industrial leadership in Europe; and tackling societal challenges for a better society. Horizon 2020 will simplify participation by having a single set of rules for all participants, a single funding rate of 100% of eligible costs, and reduced process complexity.

There have been a number of opportunities for funding for forensic science research under the Secure Societies theme. Future calls are also expected to contain a significant interest in forensics.

4. Other government funding

Centre for Defence Enterprise (CDE)

CDE calls are open to a broad range of science and technology providers, including academia and SMEs, and can be applied for through two routes:

- Enduring Challenge: a competition that is always open for applications for proof-of-concept research funding
- Themed competitions

Police Innovation Fund

For the past few years, the government has been setting aside significant amounts of money to fund projects aimed at transforming policing through innovation and collaboration. In 2014, £50 million was provided; this increased to £70 million in 2015. Although this fund covers the whole of policing, forensics projects are included. Projects should be led by a UK Police Force, but can involve both academic and industrial partners.

Key areas of forensics and potential technologies for knowledge transfer

The Knowledge Transfer Network (KTN) is the UK's Innovation Network. Its remit is to connect people to speed up innovation, solve problems and find markets for new ideas. The KTN exists to accelerate innovation, stimulating and facilitating the conversion of ideas into new products and services that benefit the UK economically, socially and environmentally. KTN spans all technology domains and applications, and connects end-user problems / opportunities with people who can deliver solutions.

Innovate UK established KTN through a grant in April 2014, following the merger of 14 separate networks that each had a separate remit to address individual business and technology sectors that are important to the UK economy. Many communities represented by KTN could have an impact on innovation in the forensic sciences, but the main sectors offering immediate opportunities could include:

- Biotechnology
- Improved recovery of DNA
- Amplification of low copy number DNA
- More rapid production of DNA profiles
- Health
- Use of biomarkers for identification
- ICT & mathematics
- Tools and techniques for the management of large datasets
- Encryption tools for digital forensics applications
- Algorithms to improve the speed and accuracy of identification
- Materials and chemistry
- Techniques for the analysis of materials – age, origin etc
- Electronics, sensors and photonics
- Biosensors for biometric analysis
- Handheld devices for the characterisation of samples at the crime scene

In his review of research and development in forensic science in 2011 (ref. 15), Bernard Silverman recommended that "the Technology Strategy Board should consider whether forensic science could be facilitated through a Knowledge Transfer Network or similar mechanism". The KTN's Forensic Science Special Interest Group (FoSci SIG) was formed to fill this role, acting to improve communication and work to build a forensic community through collaboration with existing organisations. The FoSci SIG is a focal point for innovation and has a remit to facilitate knowledge sharing across disciplines.

Even though there are options for support from the public purse, the diverse and multidisciplinary nature of the forensic sciences, along with its small market size, means that funding forensic science is not a priority for most agencies. Recent use of the SBRI scheme has seen a handful of funding calls in the forensic areas, but these are rare. Perhaps the best opportunity is to access the Horizon 2020 Secure Societies funding calls.

Technologies from different disciplines need to be brought to bear on forensic science problems, thereby leveraging work that has already taken place. The UK has a mechanism to do this through KTN and, in particular, the FoSci SIG.

CONCLUSIONS

Accessing the forensic science market is not straightforward. The market is small, fragmented and, in many countries, the main customer base is the police service or other government agencies. A company approaching forensic science for the first time needs to have a strong business case, ideally based on multiple jurisdictions, to ensure that the effort will yield a return on investment. However, the UK's Forensic Science Special Interest Group (FoSci SIG) has invested in mapping the key stakeholders involved, and detailing the process steps required to bring a new technology to market.

Two of the main considerations are ethics and validation. The rise (and projected increase) in the use of biometric techniques in the forensic sciences means that ethics and privacy considerations become ever more important. Researchers are developing DNA techniques that will allow them to determine details of a suspect's physical characteristics (eye colour, ethnicity, hair colour etc), along with other biomarkers that could offer insights into areas such as health. Thus ever more data on the individual will be collected, which is useful to the Criminal Justice System but also poses privacy issues. There is much to learn from other areas, such as the clinical sciences, in the ethical management of data.

All new techniques and procedures need to be backed up by full, traceable and auditable validation studies. Documentation of these studies must be disclosed if the techniques are ever challenged in the courts. While academics and companies will routinely keep records of their research, the requirements of the Criminal Justice System are much more stringent than in other fields. Missing or inaccurate documentation can result in evidence being thrown out and confidence in a technology disappearing.

While there is little direct public funding for new forensic products, there are some sources from government agencies in the UK. Help is also on hand from the Knowledge Transfer Network and the FoSci SIG. The UK is historically strong in both the forensic sciences and in the development of new technologies for use in other markets. The KTN and the SIG can help to bring the two together, by pulling technologies proven in different sectors over to forensics, and leveraging funding that has already been committed from other areas.

THE RISE (AND PROJECTED INCREASE) IN THE USE OF BIOMETRIC TECHNIQUES IN THE FORENSIC SCIENCES MEANS THAT ETHICS AND PRIVACY CONSIDERATIONS BECOME EVER MORE IMPORTANT.

REFERENCES

SECTION 1

CHAPTER 1: FORENSIC SCIENCE IN CONTEXT

1. House of Commons Science and Technology Committee 'The Forensic Science Service: Seventh Report of Session 2010-2012' HC855. Available from *http://www.publications.parliament.uk/pa/cm201012/cmselect/cmsctech/855/855.pdf*
2. House of Commons Science and Technology Committee 'Forensic Science: Second Report of Session 2013–14' HC610. Available from *http://www.publications.parliament.uk/pa/cm201314/cmselect/cmsctech/610/610.pdf*
3. Hester M 'Making it through the Criminal Justice System: Attrition and Domestic Violence' Social Policy and Society 2006: volume 5, pages 79-90. Available from *http://jounals.cambridge.org/action/displayAbstract?fromPage=online&aid=378481&fileId=S1474746405002769*
4. Ministry of Justice 'Transforming the CJS: A Strategy and Action Plan to Reform the Criminal Justice System' June 2013. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209659/transforming-cjs-2013.pdf*
5. Fuller S 'Kuhn Vs. Popper: The Struggle for the Soul of Science' Icon Books Ltd 2003
6. Peterson JL and Sommers I 'The Role and Impact of Forensic Evidence in the Criminal Justice Process' National Institute of Justice 2010. Available at *https://www.ncjrs.gov/pdffiles1/nij/grants/231977.pdf*
7. Peterson JL and others 'Forensic evidence and the police: The effects of scientific evidence on criminal investigations' National Institute of Justice 1984. Available from *https://www.ncjrs.gov/pdffiles1/95704.pdf*
8. Roman JK and others 'The DNA field experiment: Cost-effectiveness analysis of the use of DNA in the investigation of high-volume crimes' Justice Policy Center, Urban Institute 2008. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/222318.pdf*
9. Pyrek K 'Forensic science under siege: the challenges of forensic laboratories and the medico-legal death investigation system' Elsevier Academic Press 2007 (Amsterdam).
10. Strom KJ and Hickman MJ (editors) 'Forensic Science and the Administration of Justice: Critical Issues and Directions' Sage Publications 2014.
11. Burrows J and others 'Understanding the attrition process in volume crime investigations' Home Office Research, Development and Statistics Directorate November 2005: Home Office Research Study 295. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/115828/hors295.pdf*
12. Independent Police Commisson 'Policing for a Better Britain' 2014: Appendix 10: Forensic science services for the Criminal Justice System of England and Wales, pages 211-225. Available from *http://independentpolicecommission.org.uk/uploads/37d80308-be23-9684-054d-e4958bb9d518.pdf*
13. Gallop A and Brown J 'The Market Future for Forensic Science Services in England and Wales' Policing 2014: volume 8, pages 254-264. Available from *http://policing.oxfordjournals.org/content/8/3/254*
14. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council 'Strengthening Forensic Science in the United States: A Path Forward' 2009. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf*

Case Study: A paradigm shift in UK forensic science

1. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council 'Strengthening Forensic Science in the United States: A Path Forward' 2009. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf*
2. The Royal Society 'The paradigm shift for UK forensic science' 2015. Available from *https://royalsociety.org/events/2015/02/forensic-science/*
3. Nic Daeid N and Black S (editors) 'Discussion meeting issue: The paradigm shift for forensic science' Philosophical Transactions B 2015: volume 370, issue 1674. Available from *http://rstb.royalsocietypublishing.org/content/370/1674*
4. The Royal Society 'The paradigm shift for UK forensic science – further discussion' 2015. Available from *https://royalsociety.org/events/2015/02/forensic-science-satellite/*

CHAPTER 2: FORENSIC SCIENCE IN PRACTICE

1. National DNA Database Strategy Board 'Annual Report 2013-14' Home Office 2014. Available *from https://www.*

gov.uk/government/uploads/system/uploads/attachment_data/file/387581/NationalDNAdatabase201314.pdf

2. Law Commission 'Expert evidence in criminal proceedings in England and Wales' 21 March 2011, Law Com Number 325. Available from *lawcommission.justice.gov.uk/areas/expert-evidence-in-criminal-trials.htm*
3. Forensic Science Regulator 'Codes of Practice and Conduct for forensic science providers and practitioners in the Criminal Justice System' August 2014. Available from *https://www.gov.uk/government/publications/forensic-science-providers-codes-of-practice-and-conduct-2014*
4. Ministry of Justice 'Rules and Practice Directions' October 2015. Available from *https://www.justice.gov.uk/courts/procedure-rules/criminal/rulesmenu-2015*
5. Courts and Tribunals Judiciary 'Criminal Practice Directions: Amendment No.2' July 2014. Available from *https://www.judiciary.gov.uk/publications/criminal-practice-directions-amendment-no-2/*
6. R v. Doheny & Adams [1997] 1 Cr. App. R. 369; (CA Crim Div)
7. European Network of Forensic Science Institutes 'ENFSI guideline for evaluative reporting in forensic science' 2015. Available from *https://www.unil.ch/esc/files/live/sites/esc/files/Fichiers%202015/ENFSI%20Guideline%20Evaluative%20Reporting*
8. House of Commons Science and Technology Committee 'Forensic Science: Second Report of Session 2013–14' HC610. Available from *http://www.publications.parliament.uk/pa/cm201314/cmselect/cmsctech/610/610.pdf*

Case Study: Forensic science in higher education

1. Quality Assurance Agency for Higher Education 'Subject benchmark statement: Forensic science' 2012. Available from *http://www.qaa.ac.uk/en/Publications/Documents/Subject-benchmark-statement-forensic-science.pdf*
2. Rankin BWJ, Taylor G and Thompson TJU 'Should Higher Education respond to recent changes in the forensic science marketplace?' New Directions 2012: volume 8, pages 27-32
3. Times Higher Education 'Teaching Excellence Framework (TEF): everything you need to know' 2015. Available from *https://www.timeshighereducation.co.uk/news/teaching-excellence-framework-tef-everything-you-need-to-know*
4. The Chartered Society of Forensic Sciences 'The Accreditation Process' 2015. Available from *http://www.csofs.org/accreditation*

Case Study: The commercial providers' perspective

1. National Audit Office 'Briefing for the House of Commons Science and Technology Committee: The Home Office's oversight of forensic services' December 2014. Available from *http://www.nao.org.uk/wp-content/uploads/2015/01/The-Home-Office%E2%80%99s-oversight-of-forensic-services.pdf*
2. Science and Technology Committee 'Forensic Science' Second Report of Session 2013-14: HC 610. Available from *http://www.publications.parliament.uk/pa/cm201314/cmselect/cmsctech/610/610.pdf*
3. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council 'Strengthening Forensic Science in the United States: A Path Forward' 2009. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf*

CHAPTER 3: ASSURANCE — STANDARDS, VALIDATION AND ACCREDITATION

1. Criminal Procedure Rule Committee 'Criminal Procedure Rules' Ministry of Justice 2015
2. ISO 'ISO/IEC 17025:2005 General requirements for the competence of testing and calibration laboratories'
3. ISO 'ISO/IEC 17020:2012 General criteria for the operation of various types of bodies performing inspection'
4. Criminal Procedure Rule Committee 'Criminal Procedure Rules 2014 and Criminal Practice Directions'. Available from *https://www.gov.uk/government/publications/criminal-procedure-rules-2014-and-criminal-practice-directions*
5. Forensic Science Regulator. Available from *https://www.gov.uk/government/organisations/forensic-science-regulator/about*
6. Home Office 'Government response to the consultation on new statutory powers for the Forensic Science Regulator' July 2015. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/447338/2015-07-15_-_Government_response_to_the_consultation_on_new_statutory.pdf*
7. Forensic Science Regulator 'Our Governance'. Available from *https://www.gov.uk/government/organisations/forensic-science-regulator/about/our-governance*
8. Forensic Science Regulator 'Codes of Practice and Conduct for Forensic Science Providers and Practitioners in the Criminal

Justice System, version 2.0' August 2014. Available from *https://www.gov.uk/government/collections/forensic-science-providers-codes-of-practice-and-conduct*
9. Home Office 'Consultation on new statutory powers for the forensic science regulator' 2013
10. International Organization for Standardization (ISO). Available from *http://www.iso.org/iso/home.html*
11. United Kingdom Accreditation Service 'UKAS Guidance on the Application of ISO/IEC 17025 Dealing with Expressions of Opinions and Interpretations' LAB13. Available from *http://www.ukas.com/download/publications/publications-relating-to-laboratory-accreditation/LAB13ed2.pdf*
12. Laboratory Accreditation Bureau 'Program Requirements: Forensic Science Laboratory Accreditation Program' LABPR 413 2012. Available from *http://l-a-b.com/wp-content/uploads/LABPR-413-Forensic-Science-Rev-2-5-29-12.pdf*
13. UKAS 'M3003: The Expression of Uncertainty and Confidence in Measurement' 2012. Available from *http://www.ukas.com/download/publications/publications-relating-to-laboratory-accreditation/M3003_Ed3_final.pdf*
14. Forensic Science Regulator 'Guidance: Validation' FSR-G-201, 2014
15. ILAC 'Application of ISO/IEC 17020:2012 for the Accreditation of Inspection Bodies' ILAC P15:06/2014. Available from *http://ilac.org/news/ilac-p15062014-published/*
16. ILAC AIC and BIPM 'Joint ILAC – CIPM Communication regarding the Accreditation of Calibration and Measurement Services of National Metrology Institutes' 2012. Available from *http://www.bipm.org/utils/common/pdf/ilac-cipm_joint_communication.pdf*
17. BIPM 'Joint Working Groups'. Available from *http://www.bipm.org/en/committees/cipm/joint-working-groups.html*
18. ILAC 'Modules in a Forensic Science Process' ILAC G19:08/2014. Available from *http://ilac.org/news/ilac-g19082014-published/*
19. *ISO 'Information technology --* Security techniques -- Guidelines for identification, collection, acquisition and preservation of digital evidence' ISO/IEC 27037:2012. Available from *http://www.iso.org/iso/catalogue_detail?csnumber=44381*
20. Home Office 'Research and Development in Forensic Science: a Review' 2011. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/118916/forensic-science-review-report.pdf*
21. Forensic Science Special Interest Group 'Forensic Science UK Innovation Database'. Available from *https://connect.innovateuk.org/web/forensics/innovation-database*
22. National Audit Office 'Briefing for the House of Commons Science and Technology Committee: The Home Office's Oversight of Forensic Services' December 2014. Available from *http://www.nao.org.uk/wp-content/uploads/2015/01/The-Home-Office%E2%80%99s-oversight-of-forensic-services.pdf*
23. House of Commons Science and Technology Select Committee 'The Forensic Science Service - Science and Technology Committee: 2. The forensics market'. Available from *http://www.publications.parliament.uk/pa/cm201012/cmselect/cmsctech/855/85505.htm*
24. UK Accreditation Service. Available from *http://www.ukas.com/*
25. CPS 'Core Foundation Principles for Forensic Science Providers' 2010. Available from *http://www.cps.gov.uk/legal/s_to_u/scientific_evidence/core_foundation_principles_for_forensic_science_providers/*
26. The Chartered Society of Forensic Sciences 'Membership'. Available at *http://www.csofs.org/membership/accredited*

Case Study: UKAS accreditation: providing confidence in forensic science

1. ISO/IEC 17025:2005 'General requirements for the competence of testing and calibration laboratories'. Available from *http://www.iso.org/iso/catalogue_detail.htm?csnumber=39883*
2. ISO/IEC 17020:2012 'Conformity assessment - Requirements for the operation of various types of bodies performing inspection'. Available from *http://www.iso.org/iso/catalogue_detail?csnumber=52994*
3. ILAC-G19:08/2014 'Modules in a Forensic Science Process'. Available from *http://ilac.org/news/ilac-g19082014-published/*
4. Forensic Science Regulator 'Codes of Practice and Conduct for forensic science providers and practitioners in the Criminal Justice System' (Version 2.0 August 2014). Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/351197/The_FSR_Codes_of_Practice_and_Conduct_-_v2_August_2014.pdf*

CHAPTER 4: COGNITIVE AND HUMAN FACTORS

1. Matlin M 'Cognition' 8th Edition, Wiley Press 2013
2. Posner MI 'Foundations of Cognitive Science' MIT Press 1989
3. Dror IE 'Practical Solutions to Cognitive and Human Factor Challenges in Forensic Science' Forensic Science Policy & Management 2014: volume 4, pages 105-113

4. Dror IE 'The paradox of human expertise: Why experts get it wrong' in Kapur N (Ed.) 'The Paradoxical Brain' Cambridge University Press 2011, pages 177-188
5. Raymond NS 'Confirmation Bias: A ubiquitous phenomenon in many guises' Review of General Psychology 1998: volume 2, pages 175–220
6. Alameddine M and others 'The intensive care unit work environment: Current challenges and recommendations for the future' Journal of Critical Care 2009: volume 24, pages 243–248
7. Dror IE and others 'Cognitive issues in fingerprint analysis: Inter-and intra-expert consistency and the effect of a 'target' comparison' Forensic Science International 2011: volume 208, pages 10-17
8. Dror IE and Cole S 'The vision in 'blind' justice: Expert perception, judgment and visual cognition in forensic pattern recognition' Psychonomic Bulletin & Review 2010: volume 17, pages 161-167
9. Dror IE and Hampikian G 'Subjectivity and bias in forensic DNA mixture interpretation' Science & Justice 2011: volume 51, 204-208
10. Coble M 'Interpretation Errors Detected in a NIST Inter-laboratory Study on DNA Mixture Interpretation in the U.S. (MIX13)' Presentation at the International Symposium on Forensic Science Error Management – Detection, Measurement and Mitigation. Washington DC 2015
11. Ulery BT and others 'Repeatability and Reproducibility of Decisions by Latent Fingerprint Examiners' PLoS ONE 2012: volume 7, e32800
12. Stammers S and Bunn S 'Unintentional bias in forensic investigation' Houses of Parliament 2015: POSTbrief PB-15. Available from *http://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PB-0015#fullreport.*
13. Dror IE 'Cognitive neuroscience in forensic science: Understanding and utilising the human element' Philosophical Transactions of the Royal Society 2015: volume 370, 20140255
14. Berger v. United States, 295 U.S. 78, 88 (1935)
15. Kozinski A. Criminal Law 2.0, 44th Annual Review of Criminal Procedure. Georgetown Law Journal, 44, iii-xliv (2015)
16. Mnookin JL, Cole SA, Dror IE, Fisher BA, Houck MM, Inman K, Kaye DH, Koehler JJ, Langenburg L, Risinger M, Rudin N, Siegel J, and Stoney DA. (2011). The need for a research culture in the forensic sciences. UCLA Law Review, 58 (3), 725-779.
17. R v Shahiriar Firouzian, case T20110667, Blacfriars Crown Court.
18. Edmond G and others 'Contextual bias and cross-contamination in the forensic sciences: The corrosive implications for investigations, plea bargains, trials and appeals' Law, Probability, and Risk 2015: volume 14, pages 1-25
19. Found F 'Deciphering the human condition: the rise of cognitive forensics' Australian Journal of Forensic Sciences 2015: volume 47, pages 386-401
20. Dror IE and Rosenthal R 'Meta-analytically quantifying the reliability and biasability of forensic experts' Journal of Forensic Sciences 2008: volume 53, pages 900-903
21. Bressan P and Dal Martello MF 'Talis Pater, Talis Filius: Perceived resemblance and the belief in genetic relatedness' Psychological Science 2002: volume 13, pages 213–218
22. Nakhaeizadeh S and others 'Cognitive bias in forensic anthropology: Visual assessments of skeletal remains is susceptible to confirmation bias' Science & Justice 2014: volume 54, pages 208–214
23. Osbourne NKP and others 'Does contextual information bias bitemark comparisons?' Science & Justice 2014: volume 54, pages 267–273
24. Kerstholt JH and others 'Shoe print examinations: effects of expectation, complexity and experience' Forensic Science International 2007: volume 165, pages 30–34
25. Kerstholt J and others 'Does suggestive information cause a confirmation bias in bullet comparisons?' Forensic Science International 2010: volume 198, pages 138–142
26. Dror IE and others 'Contextual information renders experts vulnerable to making erroneous identifications' Forensic Science International 2006: volume 156, pages 74–78
27. Laber T and others 'Reliability assessment of current methods in bloodstain pattern analysis' Final Report for the National Institute of Justice. Award # 2010-DN-BX-K213: 2014. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/247180.pdf*
28. Bieber P 'Measuring the impact of cognitive bias in fire investigation' International Symposium on Fire Investigation Science and Technology 2012: pages 3–15. Available from *http://thearson-project.org/charm/wp-content/uploads/2013/12/Cognative_Bias_ARP.pdf*
29. Murrie D and others 'Are forensic experts biased by the side that retained them?' Psychological Science 2013: volume 24, pages 1889–1897
30. Dror IE and Mnookin J 'The use of technology in human expert domains: Challenges and risks arising from the use of automated fingerprint identification systems in forensics' Law, Probability and Risk 2010: volume 9, pages 47-67

31. Dror IE and others 'The impact of human-technology cooperation and distributed cognition in forensic science: Biasing effects of AFIS contextual information on human experts' Journal of Forensic Sciences 2012: volume 57, pages 343-352
32. Stacey RB 'Report on the erroneous fingerprint individualization bombing case' Journal of Forensic Identification 2004: volume 54, pages 706-718
33. Campbell A 'The Fingerprint Inquiry Report' 2011. Available from *http://www.webarchive.org.uk/wayback/archive/20150428160103/http://www.thefingerprintinquiryscotland.org.uk/inquiry/files/TheFingerprintInquiryReport_Low_res.pdf*
34. The High Court Of Justice Court Of Appeal (Criminal Division), Regina and Peter Kenneth Smith 2011: EWCA Crim 1296.
35. Garrett BL and Neufeld PJ 'Invalid forensic science testimony and wrongful convictions' Virginia Law Review 2009: volume 95, pages 1-97
36 Dror IE and others 'Context management toolbox: A linear sequential unmasking (LSU) approach for minimizing cognitive bias in forensic decision making' Journal of Forensic Sciences 2015: volume 60, pages 1111-1112
37. Kassin SM and others 'The forensic confirmation bias: Problems, perspectives, and proposed solutions' Journal of Applied Research in Memory and Cognition 2013: volume 2, pages 42-52
38. Dror IE and others 'New application of psychology to law: Improving forensic evidence and expert witness contributions' Journal of Applied Research in Memory and Cognition 2013: volume 2, pages 78-81
39. Forensic Science Regulator 'Cognitive bias effects relevant to forensic science examinations' 2015. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/470549/FSR-G-217_Cognitive_bias_appendix.pdf*

Case Study: Statistics in Court

1. Fenton NE and Neil M 'Avoiding legal fallacies in practice using Bayesian networks' Australian Journal of Legal Philosophy 2011: volume 36, pages 114-151
2. Kahneman D 'Thinking, Fast and Slow' Penguin 2012
3. Newell BR, Lagnado DA and Shanks DR 'Straight choices: the psychology of decision making' Psychology Press (2nd edition) 2015
4. European Network of Forensic Science Institutes 'ENFSI guideline for evaluative reporting in forensic science' 2015
5. Taroni F, Biedermann A, Bozza S, Garbolino, P and Aitken CG 'Bayesian networks for probabilistic inference and decision analysis in forensic science' Wiley 2014
6. Fenton N, Lagnado DA and Neil M 'A general structure for legal arguments using Bayesian networks' Cognitive Science 2013: volume 37, pages 61-102

SECTION 2

CHAPTER 5:
THE CHANGING NATURE OF CRIME

Case Study: Trojan opens the gates to company cash

1. PwC. '2015 Information Security Breaches Survey'. http://www.pwc.co.uk/assets/pdf/2015-isbs-technical-report-blue-03.pdf

CHAPTER 6:
IDENTITY AND IDENTIFICATION

1. Fearon JD 'What is identity (as we now use the word)' (1999). Available from *http://www.seminario2005.unal.edu.co/Trabajos/Fearon/What%20is%20identity%20(as%20we%20now%20see%20the%20world).pdf* (accessed September 2015)
2. Black SM and Nic Daeid N 'Time to think differently: Catalysing a paradigm shift in forensic science' Philosophical Transactions B 2015: volume 370, article 20140251
3. Harper J 'Identity Crisis: How Identification is oOverused and Misunderstood' CATO Institute, Washington International Association for Biometrics 2006
4. Bandyopadhyay SK and others 'Information security and assurance' ISA 4th International Conference, Springer-Verlag (Berlin) 2010: pages 108-115
5. European Commission 'Biometrics at the frontiers: Assessing the impact on society' Transportation Research Board of the National Academies, Technical Report Series 2005: accession number 1010900. Available from *http://www.biteproject.org/documents/EU_Biometrics_at_the_Frontiers.pdf* (accessed September 2015)
6. Zhu Y and others 'Biometric personal identification system based on iris pattern' Chinese Patent Application 1999: number 9911025.6
7. Kisku DR and others 'Advances in Biometrics for Secure Human Authentication and Recognition' CRC Press (Florida) 2013
8. International Biometric Group 'Biometrics Market and Industry Report 2004-2008' (2006). Available from *http://www.ereleases.com/pr/international-biometric-group-releases-biometrics-market-and-industry-report-20042008-3254* (accessed September 2015)
9. Planet Biometrics 'Global biometric forecast to 2012' (2011). Available from *http://www.rncos.*

com/Report/IM140.htm (accessed September 2015)

10. Galloway V and Charlton D 'Fingerprints' in 'Forensic Human Identification: An Introduction' (editors Thompson T and Black S) CRC Press (Florida) 2007, pages 57-72
11. Murphy E 'The new forensics: Criminal justice, false certainty and the second generation of scientific evidence' California Law Review 2007: volume 95, pages 721-797
12. Campbell A 'The Fingerprint Inquiry' 2011. Available from *http://www.thefingerprintinquiryscotland.org.uk/inquiry/3127-2.html* (accessed September 2015)
13. Jain AK and Ross AA 'Introduction to Biometrics' in 'Handbook of Biometrics' (editors Jain AK, Flynn P and Ross AA) Springer (New York) 2008: pages 1-23
14. Jain AK and Ross AA 'Bridging the gap: From biometrics to forensics' Philosophical Transactions B 2015: volume 370, article 20140254
15. Black SM and others 'SuperIdentity: Fusion of identity across real and cyber domains' Refereed Proceedings of 'ID360: Global Issues in Identity' (Texas) 23-24 April 2012
16. Wilson C 'Vein Pattern Recognition: A Privacy Enhancing Biometric' CRC Press (Florida) 2010
17. Wagley J 'Vein Recognition Use Grows' Security Management 2011. Available from *http://www.securitymanagement.com/article/vein-recognition-use-grows* (accessed September 2015)
18. Black SM and others 'Forensic hand image comparison as an aid for paedophile investigations' Police Professional 2009: volume 184, pages 21-24
19. Ferguson PR and Raitt FE "If a picture paints a thousand words….": The development of human identification techniques in forensic anthropology and their implications for human rights in the criminal process' The International Journal of Evidence & Proof 2013: volume 17, pages 127-156
20. Law Commission 'Expert Evidence in Criminal Proceedings in England and Wales' The Stationery Office (London) 2011: report number 325
21. Pyrek KM 'Forensic Science Under Siege: The Challenges of Forensic Laboratories and the Medico-Legal Investigation System' Academic Press (California) 2007
22. CIFAS 'Fraudscape: UK fraud trends' 2014. Available from *http://www.cifas.org.uk/secure/contentPORT/uploads/documents/External%20-%20Fraudscape%20main%20report%20for%20website.pdf (accessed September 2015)*
23. CIFAS 'Fraudscape: Depicting the UK's fraud landscape' 2014. Available from *https://www.cifas.org.uk/secure/contentPORT/uploads/documents/Cifas%20Reports/External-Cifas-Fraudscape-2014-online.pdf* (accessed September 2015)
24. CIFAS 'Identity crime on your doorstep' 2013. Available from *https://www.cifas.org.uk/secure/contentPORT/uploads/documents/External-IDcrime_onyourdoorstep_Cifas_OS.pdf* (accessed September 2015)
25. Techweek Europe " Floodgates have opened" for biometrics industry following Christmas demand' 22 December 2014. *http://www.techweekeurope.co.uk/e-innovation/biometrics-mobile-payments-christmas-157920* (accessed September 2015)
26. Sahoo SK and others 'Multimodal biometric person authentication: A review' IETE Technical Review 2012: volume 29, pages 54-75
27. Rodrigues RN and others 'Evaluation of biometric spoofing in a multimodal system' from 'Biometrics: Theory applications and systems' 4th IEEE International Conference 27-29 September 2010: pages 1-5
28. Zelazny F 'The evolution of India's UID program' CGD 2012: policy paper 008. Available from *http://www.cgdev.org/files/1426371_file_Zelazny_India_Case_Study_FINAL.pdf* (accessed September 2015)

Case Study: Emerging biometrics in the courtroom

1. Black S, Macdonald-Mcmillan B and Mallett X 'The incidence of scarring on the dorsum of the hand' International Journal of Legal Medicine 2014: volume 128, pages 545-553

CHAPTER 7:
CYBER FORENSICS

1. Detica and the Office of Cyber Security and Information Assurance in the Cabinet Office 'The Cost of Cyber Crime' 2011. Available from *https://www.gov.uk/government/publications/the-cost-of-cyber-crime-joint-government-and-industry-report*
2. Government Office for Science 'The Internet of Things' (2014). Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/409774/14-1230-internet-of-things-review.pdf*
3. Foreign and Commonwealth Office 'Convention on Cybercrime' Budapest, 23 November 2001, Cm8309. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/238194/8309.pdf*
4. National Commission on Forensic Science 'Scientific Literature in Support of Forensic Science and Practice' January 2015. Available from *http://www.justice.gov/sites/default/files/ncfs/pages/attachments/2015/01/21/scientificliteraturereviewsdocumentfinaljan2015.pdf*
5. FBI 'FBI Testimony on Microscopic Hair Analysis Contained Errors in at Least 90 Percent of Cases in Ongoing Review' April 2015.

Available from *https://www.fbi.gov/news/pressrel/press-releases/fbi-testimony-on-microscopic-hair-analysis-contained-errors-in-at-least-90-percent-of-cases-in-ongoing-review*
6. Zatyko KR 'Commentary: Defining Digital Forensics' Forensic Magazine January 2007. Available from *http://www.forensicmag.com/articles/2007/01/commentary-defining-digital-forensics*
7. Zatyko KR and Bay J 'The Digital Forensics Cyber Exchange Principle' Forensic Magazine 2011. Available from *http://www.forensicmag.com/articles/2011/12/digital-forensics-cyber-exchange-principle*
8 International Information System Security Certification Consortium 'Leadership for the Field of Cyber Forensics'. Available from https://learning.isc2.org/sites/learning.isc2.org/files/CCFP-WEB.pdf
9 NIST 'NIST Cloud Computing Forensic Science Challenges' June 2014. Available from *http://csrc.nist.gov/publications/drafts/nistir-8006/draft_nistir_8006.pdf*
10 Zatyko KR and Cohen A 'Trust no one: fighting the hackers abroad and at home' Intellectual Property Magazine July 2014. Available from *http://www.intellectualproperty-magazine.com/patent/trust-no-one-fighting-the-hackers-abroad-and-at-home-101781.htm*

CHAPTER 8: THE GLOBAL PERSPECTIVE

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2. Finch T and others 'Global Brit: Making the most of the British diaspora' Institute for Public Policy Research 2010, page 7
3. Baker S and others 'Review of the United Kingdom's Extradition Arrangements' Home Office 2011. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/117673/extradition-review.pdf*
4. Goudge ST 'Inquiry into Paediatric Pathology in Ontario' 2008: volume 1, page 36. Available at *http://www.goudgeinquiry.ca*
5. Heijnen W 'DVI aspects of forensic investigation' Plenary session iv, 7th European Academy of Forensic Science Conference, 11 September 2015
6. The Bar Council of England and Wales 'Response to the Select Committee on the European Union Sub-Committee E (Justice, Institutions and Consumer Protection) and Sub-Committee F (Home Affairs, Health and Education) Call for Evidence on the UK's 2014 Opt-out Decision (Protocol 36)' 2012. Available from *http://www.barcouncil.org.uk/media/210686/bar_council_of_e__w_response_to_hl_inquiry_on_opt-out_2014final.pdf*
7. Interpol 'Interpol network links forensic laboratories in G8 countries' 6 July 2007. Available from *http://www.interpol.int/News-and-media/News/2007/PR029*
8. ICMP 'ICMP joins INTERPOL in Responding to Malaysian Airlines Flight MH 17 Crash' 19 July 2014. Available from *http://www.ic-mp.org/press-releases/icmp-joins-interpol-mh-17-crash/*
9. Federal Bureau of Investigation 'CODIS Brochure'. Available from *https://www.fbi.gov/about-us/lab/biometric-analysis/codis/codis_brochure*
10. The Council of the European Union 'Council Decision of 6 April 2009 establishing the European Police Office (Europol) (2009/371/JHA) Official Journal of the European Union 15 May 2009: L121/37
11. The Council of the European Union 'Council Decision 2008/615/JHA of 23 June 2008 on the stepping up of cross-border cooperation in combating terrorism and cross-border crime' Official Journal of the European Union 6 August 2008: L210/1
12. Ministry of Justice 'Criminal Justice Statistics Quarterly Update to March 2015: England and Wales' 13 August 2015. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/453309/criminal-justice-statistics-march-2015.pdf.pdf*
13. Johnson D 'E.U. migrant criminal activity: Exploring spatial diversity and volume of criminal activity attributed to inter EU migrants in England' Applied Geography 2014: volume 50, pages 48-62
14. Johnson D and others 'The Prüm Implementation, Evaluation and Strengthening (P.I.E.S.) of Forensic DNA Data Exchange' Northumbria University Final Report 2015. Available from *http://nrl.northumbria.ac.uk/23383/1/Final_report.pdf*
15. Rienzo C and Vargas-Silva C 'Migrants in the UK: an Overview' 2014. Available from *http://www.migrationobservatory.ox.ac.uk/briefings/migrants-uk-overview*
16. Commissioner for the Retention and use of Biometric Material 'Annual Report 2014'. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/387573/BiometricsAnnualReport201314Print.pdf*
17. Home Office 'Serious and Organised crime Strategy' 2015. Available from *https://www.gov.uk/government/publications/serious-organised-crime-strategy*
18. Netherlands Forensic Institute 'Dutch DNA database has result-

ed in 25,000 international matches' 2015. Available from *http://www.forensicinstitute.nl/about_nfi/news/2015/dutch-dna-database-has-resulted-in-25000-international-matches.aspx*

19. Information provided by the Nationaal Instituut voor Criminalistiek en Criminologie (NICC) / Institut National de Criminalistique et Criminologie (INCC) from work undertaken by Dr Patrick Jeuniaux under the PIES project - The Prüm Implementation, Evaluation, and Strengthening of Forensic DNA Data Exchange (HOME/2011/ISEC/AG/PRUM/4000002150)
20. House of Commons Science and Technology Committee 'Forensic Science on Trial' HC 2004–05: volume 1, pages 74-80. Available from *http://www.publications.parliament.uk/pa/cm200405/cmselect/cmsctech/96/96i.pdf*
21. Lundy v R [2013] UKPC 28
22. Forensic Science Regulator 'Forensic science providers: codes of practice and conduct, 2014'. Available from *https://www.gov.uk/government/publications/forensic-science-providers-codes-of-practice-and-conduct-2014*
23. Salet R and Terpstra J 'Critical Review in Criminal Investigation: Evaluation of a Measure to Prevent Tunnel Vision' Policing 2014: volume 8, pages 43–50
24. Kloosterman A and others 'The interface between forensic science and technology: how technology could cause a paradigm shift in the role of forensic institutes in the criminal justice system' Phil. Trans. R. Soc. B 2015: volume 370, article 20140264. Available from *http://dx.doi.org/10.1098/rstb.2014.0264*
25. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council 'Strengthening Forensic Science in the United States: A Path Forward' 2009. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf*
26. Champod C 'Fingerprint identification: advances since the 2009 National Research Council report' Phil. Trans. R. Soc. B 2015: volume 370, article 20140259. Available from *http://dx.doi.org/10.1098/rstb.2014.0259*
27. Information from a briefing by Dr Elisabet Leitet, Swedish National Forensic Centre.
28. House of Commons Science and Technology Committee 'Current and Future Uses of Biometric Data and Technologies' HC 2014–15
29. Zhu Y and others 'Mortality among drowning rescuers in China, 2013: a review of 225 rescue incidents from the press' BMC Public Health 2015: volume 15, page 631
30. Yin Z and others 'Burden and trend analysis of injury mortality in China among children aged 0–14 years from 2004 to 2011' BMJ Open 2015: volume 5, article e007307
31. Zhao J and others 'The establishment of Multiplex PCR-Capillary electrophoresis method for forensic algae test' Presentation at the 7th European Academy of Forensic Science Conference 2015
32. Council Framework Decision 2009/905/JHA of 30 November 2009 on Accreditation of forensic service providers carrying out laboratory activities.
33. Council Decision 2008/615/JHA of 23 June 2008 on the stepping up of cross-border cooperation, particularly in combating terrorism and cross-border crime
34. Directive 2010/64/EU of The European Parliament And of The Council of 20 October 2010 on the right to interpretation and translation in criminal proceedings; and Directive 2012/13/EU of The European Parliament and of The Council of 22 May 2012 on the right to information in criminal proceedings
35. Lynch M and others 'Truth Machine: The Contentious History of DNA fingerprinting' University of Chicago Press 2008: pages 332-333
36. Wilson TJ and Gallop AMC 'Criminal Justice, Science and the Marketplace: The Closure of the Forensic Science Service in Perspective' The Journal of Criminal Law 2013: volume 77, page 63
37. Roberts P and Zuckerman A 'Criminal Evidence' 2nd edition, Oxford University Press 2010: 60-61
38. Stephen Hamilton v R [2014] EWCA Crim 1555 44
39. Frye v US, 54 App DC 46; 113 S Ct 2786 (1923)
40. Daubert v Merrell Dow L 25 Ed 2d 46; 293F 1013 (1993)
41. R v. Clarke [1995] 2 Cr App R 425 429
42. The Lord Chief Justice, Lord Thomas of Cwmgiedd 'Criminal Bar Association Kalisher Lecture' 2014. Available from *http://www.judiciary.gov.uk/wp-content/uploads/2014/10/kalisher-lecture-expertevidence-oct-14.pdf*
43. Comparative GDP Data from the World Bank website: *http://data.worldbank.org/country?display=graph* Accessed 06.11.15

Case Study: Wildlife Crime

1. United Nations Office on Drugs and Crime 'Wildlife and Forest Crime'. Available from *https://www.unodc.org/unodc/en/wildlife-and-forest-crime/*
2. CITES 'What is CITES?'. Available from *https://cites.org/eng/disc/what.php*
3. *http://www.sasa.gov.uk/wildlife-environment/wildlife-crime*
4. Huffman JE and Wallace JR

'Wildlife forensics: methods and applications' Volume 6, John Wiley & Sons 2012
5. Forensic Working Group 'Wildlife crime: A guide to the use of forensic and specialist techniques in the investigation of wildlife crime'. Available from *https://www.gov.uk/government/publications/wildlife-crime-forensic-and-specialist-techniques*
6. Ogden R 'Forensic science, genetics and wildlife biology: getting the right mix for a wildlife DNA forensics lab' Forensic science, medicine, and pathology 2010: volume 6, pages 172-179
7. Linacre A and others 'ISFG: recommendations regarding the use of non-human (animal) DNA in forensic genetic investigations' Forensic Science International: Genetics 2011: volume 5, pages 501-505
8. Society for Wildlife Forensic Science. Available from *http://www.wildlifeforensicscience.org/*
9. NIST 'Organization of Scientific Area Committees'. Available from *http://www.nist.gov/forensics/osac/index.cfm*

CHAPTER 9: DESIGNING OUT CRIME

1. Lord Thomas of Cwmgiedd 'Expert evidence: the future of forensic science in criminal trials' Criminal Bar Association Kalisher Lecture 14 October 2014. Available from *https://www.judiciary.gov.uk/wp-content/uploads/2014/10/kalisher-lecture-expert-evidence-oct-14.pdf*
2. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council 'Strengthening Forensic Science in the United States: A Path Forward' 2009: page 7. Available from *https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf*
3. Crime Survey for England & Wales (available from *http://www.crimesurvey.co.uk/*)
4. Home Office 'Police recorded crime and outcomes open data tables' (available from *https://www.gov.uk/government/statistics/police-recorded-crime-open-data-tables*)
5. The 34th Annual Cumberland Lodge Police Conference 'Policing Professionalism: Leadership, Ethics, Public Confidence' April 2015. Available from *http://www.cumberlandlodge.ac.uk/Resources/CumberlandLodge2011/Documents/Programme/Reports/Police%20Conference%20Summary%20Report.pdf*
6. House of Commons Public Administration Select Committee (PASC) 'Caught red-handed: Why we can't count on Police Recorded Crime statistics' 2014: HC760. Available from *http://www.publications.parliament.uk/pa/cm201314/cmselect/cmpubadm/760/760.pdf*
7. John van Kesteren 'Some main results on international comparison and trends: results from the International Crime Victims Survey and the European Survey on Crime and Safety' Intervict, Tilburg University 2008. Available from *http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1117972*
8. Sherman L and others 'Preventing Crime: What Works, What Doesn't, What's Promising' Report to US Congress, National institute of Justice, July 1998: pages 7-48. Available from *https://www.ncjrs.gov/pdffiles/171676.PDF*
9. Carter C 'Shoppers steal billions through self service tills' Daily Telegraph 29 January 2014. Available from *http://www.telegraph.co.uk/finance/personalfinance/household-bills/10603984/Shoppers-steal-billions-through-self-service-tills.html*
10. House of Lords Select Committee on Science and Technology 'Higher Education in Science, Technology, Engineering and Mathematics (STEM) subjects' 2nd Report 2012-13. Available from *http://www.publications.parliament.uk/pa/ld201213/ldselect/ldsctech/37/37.pdf*

Case Study: Designing out mobile phone crime

1. Clarke R and others 'Controlling cell phone fraud in the US' Security Journal 2001: volume 14, pages 7-22
2. Fisher BS and Lab SP 'Encyclopaedia of Victimology and Crime Prevention' Sage 2010: Volume 1
3. Hall P 'Mobile phone ownership and theft' in 'Home security, mobile phone theft and stolen goods: Supplementary Volume 3 to Crime in England and Wales 2007/08' Home Office, London, May 2009: pages 31-49. Available from *webarchive.nationalarchives.gov.uk/20110218135832/rds.homeoffice.gov.uk/rds/pdfs09/hosb1009.pdf*
4. Office for National Statistics 'Chapter 1: Property Crime - Overview' in 'Crime Statistics, Focus on Property Crime, 2013/14 Release'. Available from *http://www.ons.gov.uk/ons/dcp171776_386643.pdf*
5. BBC News 'Mobile-phone 'sting' reveals honesty of Sussex pubgoers' 17 July 2012. Available from *http://www.bbc.co.uk/news/uk-england-sussex-18871267*
6. Farrell G 'Preventing phone theft and robbery: the need for government action and international coordination' Crime Science 2015: volume 4, article 4. Available from *http://www.crimesciencejournal.com/content/4/1/4*
7. Behavioural Insight Team 'Reducing Mobile Phone Theft and Improving Security' 2014. Available from *http://www.behaviouralinsights.co.uk/publications/reducing-mobile-phone-theft-and-improving-security/*
8. Mailley J and others 'Phone

theft index' Security Journal 2008: volume 21, pages 212-227. Available from *http://www.palgrave-journals.com/sj/journal/v21/n3/full/8350055a.html*
9. Office for National Statistics 'Crime in England and Wales, Year Ending March 2015'. Available from *http://www.ons.gov.uk/ons/rel/crime-stats/crime-statistics/year-ending-march-2015/index.htm*l

SECTION 3

CHAPTER 10: AUTHENTICITY AND PROVENANCE

1. OECD 'The economic impact of counterfeiting and piracy' 2008
2. Frontier Economics 'Estimating the global economic and social impacts of counterfeiting and piracy' 2011
3. Walker MJ, Burns M and Thorburn Burns D 'Horse meat in beef products, species substitution' Journal of the Association of Public Analysts (Online) 2013: volume 41, pages 67 – 106
4. Deisingha AK 'Pharmaceutical counterfeiting' Analyst 2005: volume130, pages 271-279
5. Arslan MM and others. 'Analysis of methanol and its derivatives in illegally produced alcoholic beverages' Journal of Forensic and Legal Medicine 2015: volume 33, pages 56-60.
6. McKee M, Adany R and Leon DA 'Illegally produced alcohol' The British Medical Journal (Clinical Research Edition) 2012: volume 344, page e1146.
7. Gowland MH and Walker MJ 'Food Allergy, a summary of 8 cases in the UK criminal and civil courts: effective last resort for vulnerable consumers?' Journal of the Science of Food and Agriculture 2015: volume 95, pages 1979-19
8. National Criminal Intelligence Service 'The National Intelligence model' 2000
9. MHRA 'Alerts and recalls for drugs and medical devices'. Available from *https://www.gov.uk/drug-device-alerts*
10. World Health Organisation 'Essential medicines and health products - Drug Alerts'. Available from *http://www.who.int/medicines/publications/drugalerts/en/*
11. European Commission 'The Rapid Alert System for Food and Feed'. Available from *http://ec.europa.eu/food/safety/rasff/portal/index_en.htm*
12. Riedl J, Esslinger S, and Fauhl-Hassek C 'Review of validation and reporting of non-targeted fingerprinting approaches for food authentication' Analytica Chimica Acta 2015: volume 885, pages 17-32.
13. Wishart DS 'Quantitative metabolomics using NMR' Trends in Analytical Chemistry 2008: volume 27, pages 228–237
14. Neumann S and Böcker S 'Computational mass spectrometry for metabolomics: Identification of metabolites and small molecules' Analytical and Bioanalytical Chemistry 2010: volume 398, pages 2779-88
15. For example, Rubert J, Lacina O, Fauhl-Hassek C and Hajslova J 'Metabolic fingerprinting based on high-resolution tandem mass spectrometry: a reliable tool for wine authentication?' Journal of Analytical and Bioanalytical Chemistry 2014: volume 406, pages 6791-803
16. Hudson S and others 'Use of high resolution mass spectrometry to detect reported and previously unreported cannabinomimetics in "herbal high" products' Journal of Analytical Toxicology 2010: volume 34, pages 1 -9
17. Government Chemist technical note 'Cumin analysis: DNA test for mahaleb developed'. Available from *https://www.gov.uk/government/news/cumin-analysis-dna-test-for-mahaleb-developed*
18. Vashist SK 'Immunodiagnostics: Major Advances and Future Insights' Biochips and Tissue Chips 2013: Volume 3, Issue 2
19. Waltho A, Wilkes T, Nixon G, Bushell C, and Burns M 'Testing Wheat Grain Authenticity with Fast, Non-destructive Multispectral Image Analysis" LABMATE online: March 2015
20. Kalyanaraman R, Dobler G and Ribick M 'Portable spectrometers for pharmaceutical counterfeit detection' American Pharmaceutical Review April 2010
21. Guin U, Huang K, DiMase D, Carulli JM, Tehranipoor M, and Makris Y 'Counterfeit integrated circuits: A rising threat in the global semiconductor supply chain' Proceedings of the IEEE 2014: volume 102, pages 1207-28.
22. Molloy J and Naftalya M 'Wool textile identification by terahertz spectroscopy' The Journal of The Textile Institute 2014: volume 105, pages 794-798
23. Baker M. 'Digital PCR hits its stride' Nature Methods 2012: volume 9, pages 541–544
24. Comley J 'ELISA Assays: recent innovations take analyte detection to new levels' Drug Discovery World Fall 2012: pages 23-45
25. Van Oorschot RAH, Ballantyne KN and Mitchell RJ 'Forensic trace DNA: a review' Investigative Genetics 2010: volume 1, article 14
26. For example, Lachenmeier DW, Przybylski MC and Rehm J 'Comparative risk assessment of carcinogens in alcoholic beverages using the margin of exposure approach' International Journal of Cancer: volume131, pages E995-E1003.
27. Benson S, Lennard C, Maynard P and Roux C 'Forensic applications of isotope ratio mass spectrometry – A review' Forensic Science International 2006: volume 157,

pages 1-22
28. Loeffen PW, Maskall G, Bonthron S, Bloomfield M, and Tombling C 'Chemical and explosives point detection through opaque containers using spatially offset Raman spectroscopy (SORS)' Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XII. Proc. SPIE 8018, 80181E (2011)
29. Dawnay N, Ahmed R and Naif S 'The ParaDNA® Screening System – A case study in bringing forensic R&D to market' Science and Justice 2014: volume 54, pages 481– 486

Case Study: Notions of Purity: an Anthropological Perspective

1. Frazer JG 'The Golden Bough'. New York: Macmillan (1890)
2. Robertson Smith W 'The Religion of the Semites'. University of Aberdeen: Burnett Lectures (1894)
3. Durkheim É 'Elementary Forms of the Religious Life'. New York: Macmillan (1954 [1912])
4. Ahern E 'The power and pollution of Chinese women', in Wolf A (ed), 'Studies in Chinese Society'. Stanford: Stanford University Press (1978) pages 269-90
5. Fuller C 'Gods, priests and purity: on the relation between Hinduism and the caste system' Man (1979) volume 14, pages 459-76
6. Dumont L 'Homo hierarchicus: The Caste System and its Implications'. Chicago, University of Chicago Press (1980 [1966])
7. Taussig M 'The Devil and Commodity Fetishism in South America'. Chapel Hill: University of North Carolina Press (1980)
8. Seaman G 'The sexual politics of karmic retribution'. In Ahern E and Gates H (eds) 'The Anthropology of Taiwanese Society', Stanford: Stanford University Press (1981) pages 381-96
9. Daniel VE 'Fluid Signs: Being a Person the Tamil Way'. Berkeley: University of California Press (1984)
10. Rouse C and Hoskins J 'Purity, soul food and Sunni Islam: explorations and the intersection of consumption and resistance' Cultural Anthropology (2004) volume 19, pages 226-49.
11. Gauvain R 'Ritual rewards: a consideration of three recent approaches to Sunni purity law' Islamic Law and Society (2005) volume 12, pages 333-93.
12. Masquelier A 'The bloodstain: spirit possession, menstruation and transgression in Niger' Ethnos (2011) volume 76, pages 157-182
13. Harris M 'Cows, Pigs, Wars and Witches: The Riddles of Culture'. London: Hutchinson (1975)
14. Thompson B 'Scientific Foreknowledge and Biblical Accuracy' Reason and Revelation (1993) volume 13, page 78 *http://www.happinessonline.org/MoralCode/LiveWithTruth/p11.htm* (accessed 23.08.2015).
15. Douglas M 'Purity and Danger: An Analysis of the Concepts of Pollution and Taboo'. London: Routledge & Kegan Paul (1966) page 29
16. Kravel-Tovi M 'National mission: biopolitics, non-Jewish immigration and Jewish conversion policy in contemporary Israel' Ethnic and Racial Studies (2012) volume 35, pages 737-56
17. Douglas M 'Purity and Danger: An Analysis of the Concepts of Pollution and Taboo'. London: Routledge & Kegan Paul (1966) page 41.
18. Tilley H 'Racial science, geopolitics, and empires: paradoxes of power' Isis (2014) volume 105, pages 773-81
19. Munasinghe V 'Nationalism in hybrid spaces: the production of impurity out of purity' American Ethnologist (2002) volume 29, pages 663-692
20. Petryna A 'Life Exposed: Biological Citizens after Chernobyl'. Princeton, NJ: Princeton University Press (2002)
21. Farmer P 'AIDS and Accusation: Haiti and the Geography of Blame'. Berkeley: University of Californa Press (1993)
22. Shao J 'Fluid labor and blood money: the economy of HIV/AIDS in rural Central China' Cultural Anthropology (2006) volume 21, pages 535-69
23. Taussig K-S 'Bovine abominations: genetic culture and politics in the Netherlands' Cultural Anthropology (2004) volume 19, pages 305-36
24. Bray F 'Science, technique, technology: passages between matter and knowledge in imperial Chinese agriculture' British Journal for the History of Science (2008) volume 41, page 322
25. Latour B 'We Have Never Been Modern'. Cambridge, Mass: Harvard University Press (1993)
26. Gusterson H 'Nuclear Rites: A Weapons Laboratory at the End of the Cold War'. Berkeley: California University Press (1996)
27. Latour B 'The Pasteurization of France'. Cambridge, Mass: Harvard University Press (1988)
28. Haraway D 'Modest_Witness@Second_Millennium.FemaleMan_Meets_Oncomouse: Feminism and Technoscience'. New York: Routledge (1997)
29. Mody CCM 'A little dirt never hurt anyone: knowledge-making and contamination in materials science' Social Studies of Science (2001) volume 31, pages 7-36
30. Burghart R 'The purity of water at hospital and home as a problem of intercultural understanding' Medical Anthropology Quarterly (1996) volume 10, pages 63-74
31. Dunn EC 'Standards and per-

son-making in Eastern Europe: a tale of two sausages' In Ong A and Collier SJ (eds) 'Global Assemblages: Technology, Politics, and Ethics as Anthropological Problems'. Blackwell, Oxford (2005) pages 173-193
32. Dunn EC 'Postsocialist spores: disease, bodies and the state in the Republic of Georgia' American Ethnologist (2008) volume 35, pages 243-58
33. Bray F 'Purity and promiscuity', in Bray F, Coclanis PA, Fields-Black EL and Schäfer D (eds) 'Rice: Global Networks and New Histories'. New York: Cambridge University Press (2015) pages 37-40
34. Inhorn M and Balen F (eds) 'Infertility Around the Globe: New Thinking on Childlessness, Gender, and Reproductive Technologies'. Berkeley: University of California Press (2002)
35. Appadurai A 'Fear of Small Numbers: An Essay on the Geography of Anger'. Durham NC: Duke University Press (2006)

CHAPTER 11:
FOOD AND DRINK

1. Grocery Manufacturers Association (GMA) and Kearney AT 'Consumer product fraud: Deterrence and detection' 2010. Available from *http://www.gmaonline.org/downloads/research-and-reports/consumerproductfraud.pdf*
2. Terracini B 'Toxic oil syndrome – Ten years of progress' World Health Organization 2004. Available from *http://www.euro.who.int/__data/assets/pdf_file/0005/98447/E84423.pdf*
3. Pei X and others 'The China melamine milk scandal and its implications for food safety regulation' Food Policy 2011: volume 36, pages 412-420
4. Mika OJ and others 'Mass methanol poisonings in the Czech Republic' Toxin Reviews 2014: volume 33, pages 101-106
5. Primrose S and others 'Food forensics: methods for determining the authenticity of foodstuffs' Trends in Food Science and Technology 2010: volume 21, pages 582-590
6. Regulation (EU) 1306/2013 of the European Parliament and of the Council of 17 December 2013 on the financing, management and monitoring of the common agricultural policy. Available from *http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32013R1306*
7. Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. Available from *http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32002R0178*
8. UK Food Standards Agency 'Reporting Food Fraud'. Available from *https://www.food.gov.uk/enforcement/the-national-food-crime-unit/foodfraud*
9. European Commission Directorate General Health and Food Safety 'Food Fraud'. Available from *http://ec.europa.eu/food/safety/official_controls/food_fraud/index_en.htm*
10. European Parliament resolution of 14 January 2014 on the food crisis, fraud in the food chain and the control thereof (2013/2091(INI)). Available from *http://www.europarl.europa.eu/sides/getDoc.do?type=TA&reference=P7-TA-2014-0011&language=EN&ring=A7-2013-0434*
11. Report on the food crisis, fraud in the food chain and the control thereof (2013/2091(INI)). European Parliament, Committee on the Environment, Public Health and Food Safety. Available from *http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//NONSGML+REPORT+A7-2013-0434+0+DOC+PDF+V0//EN*
12. Johnson R 'Food fraud and "economically motivated adulteration" of food and food ingredients' Congressional Research Service 2014. Available from *https://www.fas.org/sgp/crs/misc/R43358.pdf*
13. HM Government 'Elliott Review into the Integrity and Assurance of Food Supply Networks – Final Report. A National Food Crime Prevention Framework' 2014. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/350726/elliot-review-final-report-july2014.pdf*
14. Madesisa P and others 'Advances of DNA-based methods for tracing the botanical origin of food products' Food Research International 2014: volume 60, pages 163-172
15. Zhang J 'Review of the current application of fingerprinting allowing detection of food adulteration and fraud in China' Food Control 2011: volume 22, pages 1126-1135
16. Ahlinder J and others 'Chemometrics comes to court: evidence evaluation of chem–bio threat agent attacks' Journal of Chemometrics 2015: volume 5, pages 267-276

Case Study: Exploiting the microbiome

1. Hird H, Sapp M, Thygesen H, Glover R, Chisolm J, Thwaites R, Lewis E, Brereton P 'Exploiting the microbiome: a new approach for determining the provenance of food- case study using Pacific oysters' Recent Advances in Food Analysis (RAFA), Prague, 3-6 November 2015

Case Study: Stopping food fraud

1. HM Government 'Elliott Review into the Integrity and Assurance of Food Supply Networks – Final

Report' 2014. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/350726/elliot-review-final-report-july2014.pdf*

CHAPTER 12: COUNTERFEIT PHARMACEUTICALS

1. Chaccour CJ and others 'Travel and fake artesunate: a risky business' Lancet 2012: volume 380, page 1120
2. New W 'UN Office On Drugs And Crime Launches Anti-Counterfeit Campaign Aimed At Organised Crime' Intellectual Property Watch 2014. Available from *http://www.ip-watch.org/2014/01/14/un-office-on-drugs-and-crime-launches-anti-counterfeit-campaign-aimed-at-organised-crime/. Accessed 05/10/2015*
3. Attaran A and others 'How to achieve international action on falsified and substandard medicines' BMJ 2012: volume 345, e7381
4. WHO 'Medicines: spurious/falsely-labelled/ falsified/counterfeit (SFFC) medicines' 2012. Available from *http://www.who.int/mediacentre/factsheets/fs275/en/. Accessed 27/09/2015*
5. ACT Consortium 'Analysing the quality and authenticity of ACT drugs' 2008. Available from *www.actconsortium.org/drugquality.* Accessed 24/09/2015
6. WHO 'Counterfeits: Frequently Asked Questions'. Available from *http://www.who.int/medicines/services/counterfeit/faqs/QandAsUpdateJuly11.pdf*
7. WHO 'Counterfeit Drugs Kill!'. Available from *http://www.who.int/impact/FinalBrochureWHA2008a.pdf?ua=1. Accessed 24/09/2015*
8. The Center for Safe Internet Pharmacies 'U.S. Track and Trace Law Signed' 2013. Available from *http://www.safemedsonline.org/2013/12/us-track-trace-law-signed.* Accessed 2/10/2015
9. FDA 'RFID: Protecting the Drug Supply' FDA Consumer March-April 2005. Available from *http://www.fda.gov/Drugs/DrugSafety/ucm169918.htm.* Accessed 2/10/2015
10. TruTag Technologies 'Product Authentication and Brand Protection Solutions'. Available from *http://www.trutags.com/.* Accessed 2/10/2015
11. 'NanoGuardian and Capsugel Announce Global Anti-Counterfeiting Collaboration' Pharmaceutical Manufacturing 2010. Available from *http://www.pharmamanufacturing.com/industrynews/2010/039/.* Accessed 2/10/2015
12. Covectra. Available from *http://www.covectra.com/about/*. Accessed 2/10/2015
13. Almuzaini T, Choonara I and Sammons H 'Substandard and Counterfeit medicines: a systematic review of the literature' BMJ Open 2013: volume 3, e002923
14. Newton PN and others 'Guidelines for field surveys of the quality of medicines: a proposal' PLoS Med. 2009: volume 6, e52
15. Newton PN and others 'Collaborative epidemiological investigation into the criminal fake artesunate trade in South East Asia' PLoS Med. 2008: volume 2, e32
16. Cody RB, Laramee JA, Durst HD 'Versatile new ion source for the analysis of materials in open air under ambient conditions' Anal. Chem. 2005: volume 77, pages 2297-2302
17. Takáts Z and others 'Mass Spectrometry Sampling Under Ambient Conditions with Desorption Electrospray Ionization' Science 2004: volume 306, pages 471–473
18. Leslie T and others 'An epidemic of Plasmodium falciparum malaria in Afghan refugees in the Tribal Areas of Pakistan fuelled by substandard antimalarial drugs' Emerg Infect Dis 2009: volume 15, pages 1753-1759
19. Kaur H and others 'Chemical and bioassay techniques to authenticate quality of the anti-leishmanial drug miltefosine' Am J Trop Med Hyg 2015: volume 92, pages 31-8
20. Ioset JR and Kaur H 'Simple field assays to check quality of current artemisinin-based antimalarial combination formulations' PloS ONE 2009: volume 4, e7270
21. GPHF 'The GPHF-Minilab™ - Protection Against Counterfeit Medicines'. Available from *http://www.gphf.org/web/en/minilab.* Accessed 24/09/2015
22. Risha PG and others 'The use of Minilab® to improve the testing of regulatory authorities in resource limited settings: Tanzanian experience' Health Policy 2008: volume 87, pages 217-22
23. Fadeyi I and others 'Quality of the Antibiotics - Amoxicillin and Co-trimoxazole from Ghana, Nigeria and the United Kingdom' Am J Trop Med Hyg 2015: volume 92, pages 87-94
24. Hajjou M and others 'Assessment of the performance of a handheld Raman device for potential use as a screening tool in evaluating medicines quality' J Pharm Biomed Anal. 2013: volume 74, pages 47-55
25. Yoon WL and others 'Application of near-infrared spectroscopy to the determination of the sites of manufacture of proprietary products' J. Pharm. Biomed. Anal. 2004: volume 34, pages 933-44
26. SCiO 'Near Infra-Red Spectroscopy at the palm of your hand'. Available from https://www.consumerphysics.com/myscio/technology. Accessed 05/10/2015
27. Tabernero P and others 'A Repeat Random Survey of the Prevalence of Falsified and Substandard Antimalarials in the Lao PDR: A

Change for the Better' Am J Trop Med Hyg. 2015: volume 92, pages 95-104
28. Nayyar GMI 'Poor-quality antimalarial drugs in Southeast Asia and sub-Saharan Africa' Lancet Infect Dis 2012: volume 12, pages 488–96
29. Newton PN and others 'Counterfeit artesunate antimalarials in southeast Asia' Lancet 2003: volume 362, page 169
30. Kaur H and others 'Quality of Artemisinin-Based Combination Formulations for Malaria Treatment: Prevalence and risk factors for poor quality medicines in public facilities and private sector drug outlets in Enugu, Nigeria' PLoS ONE 2015: volume 10, e0125577
31. ACT Consortium 'Poor quality malaria drugs: how many and where? (Research brief)' 2015. Available from *http://www.actconsortium.org/publications.php/130/poor-quality-malaria-drugs-how-many-and-where-research-brief.* Accessed 24/09/2015
32. Nair AS 'In a first, drug using 3D printing technology gets FDA nod' Reuters 2015. Available from *http://www.reuters.com/article/2015/08/03/us-fda-3ddrug-idUSKCN0Q81YC20150803*. Accessed 6/10/2015

CHAPTER 13: CONSUMER PRODUCTS

1. Interpol 'Against Organized Crime: Interpol Trafficking and Counterfeiting Casebook 2014'. Available from http://www.interpol.int/Media/Files/Crime-areas/Trafficking-in-Illicit-Goods/Against-Organized-Crime-INTERPOL-Trafficking-and-Counterfeiting-Casebook
2. OECD 'Magnitude of counterfeiting and piracy of tangible products: an update' 2009. Available from *http://www.oecd.org/sti/ind/44088872.pdf*
3. Centre for Retail Research 'Online Retailing: Britain, Europe, US and Canada 2015'. Available from *http://www.retailresearch.org/onlineretailing.php*
4. European Commission 'Protecting Intellectual Property Rights: Customs authorities detain nearly 36 million fake goods at EU borders in 2013' 2014. Available from *http://europa.eu/rapid/press-release_IP-14-890_en.htm*
5. J Lee and others 'Universal process-inert encoding architecture for polymer microparticles' Nature Materials 2014: volume 13, pages 524-529, doi: 10.1038/nmat3938. Available from *http://www.nature.com/nmat/journal/v13/n5/full/nmat3938.html*
6. Halsey A 'The secret life of baggage: Where does your luggage go at the airport?' The Washington Post 2014. Available from *https://www.washingtonpost.com/local/trafficandcommuting/where-oh-where-did-my-luggage-go/2014/11/24/16d168c6-69da-11e4-a31c-77759fc1eacc_story.html.* Accessed October 2015
7. Gartner 'Predicts 2014: 3D Printing at the Inflection Point' 2014. Available from *http://www.gartner.com/doc/2631234*
8. Quantum Materials 'Quantum dot inks' *http://www.qmcdots.com/products/products-securityink.php.* Accessed October 2015
9. Ofcom 'The Communications Market 2015'. Available from *http://stakeholders.ofcom.org.uk/market-data-research/market-data/communications-market-reports/cmr15/*
10. Brand-i. Available from *www.brand-i.org.* Accessed October 2015
11. Symantec Safe Site. Available from *http://www.symantec.com/trustseal/.* Accessed October 2015
12. Trusted Shops. Available from *http://www.trustedshops.co.uk/.* Accessed October 2015
13. Erickson D and others 'Smartphone technology can be transformative to the deployment of lab-on-chip diagnostics' Lab Chip 2014: volume 14, pages 3159-3164, doi: 10.1039/c4lc00142g. Available from *http://pubs.rsc.org/en/Content/ArticleLanding/2014/LC/C4LC00142G#!divAbstract*

Case Study: Consumer protection and social media

1. Intellectual Property Office 'IP Crime Report 2014/2015'. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/461792/ip-crime-report-2014-15.pdf*

Case Study: Making the most of Trading Standards services

1. Trading Standards Institute 'Trading Standards Workforce Survey' June 2014. Available from *http://www.tradingstandards.uk/policy/WorkforceSurvey2014.cfm*
2. National Trading Standards 'Safety at Ports and Borders Teams'. Available from *http://www.nationaltradingstandards.uk/work-areas/safety-at-ports-and-borders-teams/*. Accessed October 2015

CHAPTER 14: ENVIRONMENTAL FORENSICS

1. Defra 'Emissions of air pollutants in the UK, 1970 to 2013' (2014). Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/388195/Emissions_of_air_pollutants_statistical_release_2014.pdf*
2. UK National Ecosystem Assessment: *http://uknea.unep-wcmc.org/*
3. Natural Capital Committee: *https://www.gov.uk/government/groups/natural-capital-committee*
4. European Environment Agency 'SOER 2015: The European environment — state and outlook

2015'. Available from *http://www.eea.europa.eu/soer*
5. European Environment Agency 'Late lessons from early warnings: science, precaution, innovation' 2013. Available from *http://www.eea.europa.eu/publications/late-lessons-2*
6. Fera 'Next Generation Sequencing & Genomics'. Available from *http://fera.co.uk/detectionSurveillance/nextGenSequencing.cfm*

Case Study: Environmental DNA analysis for wildlife conservation

1. Biggs J and others 'Using eDNA to develop a national citizen science-based monitoring programme for the great crested newt (Triturus cristatus)' Biological Conservation 2015: volume 183, pages 19–28. Available from *http://dx.doi.org/10.1016/j.biocon.2014.11.029*

CHAPTER 15:

Case Study: Next-generation digital forensics

1. National Crime Agency 'National Strategic Assessment of Serious and Organised Crime 2015'. Available from *http://www.nationalcrimeagency.gov.uk/publications/560-national-strategic-assessment-of-serious-and-organised-crime-2015/file*

Case Study: Skills and competency for the future

1. House of Commons Science and Technology Committee 'Forensic Science on Trial' 2005: HC96-I. Available from http://www.publications.parliament.uk/pa/cm200405/cmselect/cmsctech/96/96i.pdf
2. The Forensic Science Regulator 'Forensic science providers: codes of practice and conduct' 2014. Available from *https://www.gov.uk/government/publications/forensic-science-providers-codes-of-practice-and-conduct-2014*

CHAPTER 16: ENCOURAGING INNOVATION

1. Annual Report of the Government Chief Scientific Adviser 'Innovation: managing risk, not avoiding it' Government Office for Science 2014: page 3. Available from *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/381906/14-1190b-innovation-managing-risk-evidence.pdf*
2. FoSci SIG 'Forensic Science UK Innovation Database'. Available from *https://connect.innovateuk.org/web/forensics/innovation-database*
3. Home Office 'Security Innovation and Demonstration Centre'. Available from *https://www.gov.uk/government/groups/security-innovation-and-demonstration-centre*
4. FoSci SIG 'Forensic Science Technology Showcase 2015'. Available from *https://connect.innovateuk.org/web/forensics/events-view/-/events/27824644*
5. The Chartered Society of Forensic Science. Available from *http://www.csofs.org/*
6. The Association of Forensic Service Providers. Available from *http://www.afsp.org.uk/*

Case Study: Innovate UK and the Forensic Science Special Interest Group

1. Li B and others 'The application of visible wavelength reflectance hyperspectral imaging for the detection and identification of blood stains' Science & Justice 2014: volume 54, page 432

Case Study: Biosensors in forensics

1. Frascione N, Gooch J, Abbate V and Daniel B 'Fluorogenic displacement biosensors for PSA detection using antibody-functionalised quantum dot nanoparticles' RSC Advances 2015: volume 5, pages 6595-6598

CHAPTER 17: ACCESSING FORENSICS AS A NEW MARKET

1. Tully G and Sullivan K with Vidaki A and Anjomshoaa A 'Taking Forensic Science R&D to Market' Forensic Science Special Interest Group 2013
2. Science and Technology Committee 'The Forensic Science Service' Seventh Report of Session 2010-12: HC 855, para 31
3. Science and Technology Committee 'Forensic Science' Second Report of Session 2013-14: HC 610, para 11
4. Science and Technology Committee 'Forensic Science' Second Report of Session 2013-14: HC 610, para 12
5. Research and Markets 'Global Forensic Technologies Market Report 2015-2019' (June 2015)
6. Transparency Market Research 'Forensic Technologies Market (Physical Crime Forensics, Laboratory Forensics, Portable Forensics, Forensic Tools and Products) - Global Industry Analysis, Size, Share, Growth, Trends and Forecast, 2013 – 2019' (August 2013)
7. 'About the What Works Centre'. Available from *http://whatworks.college.police.uk/About/Pages/default.aspx*
8. CPS 'The Code for Crown Prosecutors'. Available from *http://www.cps.gov.uk/publications/code_for_crown_prosecutors/*
9. Ministry of Justice 'Rules and Practice Directions'. Available from *http://www.justice.gov.uk/courts/procedure-rules/criminal/rulesmenu-2015*
10. CPS 'Streamlined Forensic Reporting Guidance and Toolkit' *http://www.cps.gov.uk/legal/s_to_u/scientific_evidence/sfr_guidance_and_toolkit/*
11. CPS 'Core Foundation Principles for Forensic Science Providers'. Available from *http://www.cps.gov.uk/legal/s_to_u/scientific_evidence/core_foundation_principles_for_forensic_science_providers/*

12. Dstl 'About us'. Available from *https://www.gov.uk/government/organisations/defence-science-and-technology-laboratory/about*
13. Home Office 'Counter-terrorism strategy (CONTEST)' 2011. Available from *https://www.gov.uk/government/publications/counter-terrorism-strategy-contest*
14. Council of Europe 'CASE OF S. AND MARPER v. THE UNITED KINGDOM' 2008. Available from *http://www.coe.int/t/dghl/standardsetting/dataprotection/Judgments/S.%20AND%20MARPER%20v.%20THE%20UNITED%20KINGDOM%20EN.pdf*
15. Silverman B 'Research and Development in Forensic Science: A Review' 2011. Available from *https://www.gov.uk/government/publications/research-and-development-in-forensic-science-review*

ANNEXE

Bayes' Theorem

Bayes' theorem gives a rational method for updating our beliefs in the light of new evidence. In our example the prosecution hypothesis (H) is that the defendant left the footprint, and the defence hypothesis (~H) is that someone else left the footprint.

The expert tells us the probability of the match evidence (E) given the defence hypothesis: P(E|~H) = 1/1000. The probative value of this evidence is given by the likelihood ratio (LR), which compares the probability of the evidence under the prosecution and defence hypotheses:

In our example, we assume that P(E|H) = 1. Thus the LR = 1000. In words, the evidence is a thousand times more likely on the prosecution rather than the defence hypothesis. So the evidence is positive support for the prosecution.

But what we really want to know is the probability that the defendant left the print given the evidence, P(H|E). Bayes' theorem tells us how to compute this. It is easiest to use the odds version:

Posterior odds = prior odds x LR

In words, our updated belief in the hypothesis given the evidence is our prior belief multiplied by the likelihood ratio.

The prior odds for H is simply P(H)/P(~H). In our example we assumed P(H) = 1/10000, and thus P(~H) = 9999/10000.

Putting these values into Bayes' theorem:

Thus after updating on the evidence, the defence hypothesis is about ten times more likely than the prosecution hypothesis. Converting the posterior odds to the posterior probability:

P(H|E) 1/11, and therefore P(~H|E) 10/11.

The prosecutor's fallacy involves conflating P(E|~H) with P(~H|E). This is a logical error, and the two probabilities are very different in this example. They will only take approximately the same values if P(H) = P(~H); but in most cases P(~H)>P(H) and the fallacy will greatly underestimate P(~H|E) and thus overestimate P(H|E).

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