Chapter 8
The Forensic Disciplines: Some Areas of Actual or Potential Application

8.1 Crime Scenario Modelling: The Dead Bodies Project, and a Scenario Space Generated Using an ATMS

8.1.1 Generating Crime Scenarios Automatically

Jamieson (2004) discussed the methodology of *crime scene investigation* (*CSI*), involving human scenarios.[1] Ross Gardner and Tom Bevel's (2009) *Practical Crime Scene Analysis and Reconstruction* addresses[2] every aspect of the analysis and reconstruction of the events surrounding a crime, and comprises an introduction and history of *crime scene analysis*, followed by theoretical and practical considerations, and then *event analysis*, this being a practical methodology for *crime scene reconstruction* (*CSR*). Event analysis in the form introduced and presented by Gardner and Bevel uses specially designed worksheets that cover internal, external, and terminal ballistics as they apply to understanding trajectories. Next, significant investigative questions of CSR are discussed in Gardner and Bevel (2009), before turning to *crime scene protocols* and their effect on reconstruction. This is followed by a chapter on *bloodstain pattern analysis*,[3] and then by a chapter by Matthew Noedel about shooting scene processing and reconstruction, a chapter by Scott Wagner on *forensic pathology* about *dead bodies*, in relation to CSR, and finally by chapters by Gardner and Bevel about writing crime scene reconstruction reports, about arguments and ethics, and about developing and using demonstrative exhibits in support of the crime scene analysis. The latter is about crime scene analysts testifying in court cases.

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[1] Concerning fact investigation in general, see Binder and Bergman's book (1984), as well as, e.g., Zander (1979). In a British context, Cook and Tattersall (2008) is a pocket-sized handbook about the processes and actions involved in the role of Senior Investigating Officer. The issues covered comprise, among the other things, crime scene examination and investigative strategies.

[2] In the shorter compass of a book chapter, crime scene investigation is the subject of an introductory article by Marilyn Miller (2003, 3rd edn. 2009).

[3] For which, Section 8.8 below; it is also the subject of a book by those same authors (Bevel & Gardner, 2008, 3rd edn.).

E. Nissan, *Computer Applications for Handling Legal Evidence, Police Investigation and Case Argumentation*, Law, Governance and Technology Series 5,
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Studies of crime scene investigation conducted in a cognitivist vein include Schraagen and Leijenhorst (2001) and Ormerod, Barrett, and Taylor, (2008). In an article entitled "Distributed Cognition at the Crime Scene", Chris Baber (2010) from the University of Birmingham discussed in the journal *AI & Society* a conceptualisation of *crime scene examination*, in terms of *distributed cognition.*[4] "In this paper, Distribution is defined by the number of agents involved in the criminal justice process, and in terms of the relationship between a Crime Scene Examiner and the environment being searched" (ibid., from the abstract). Baber's approach combines cognition and ergonomics. Baber pointed out (2010, p. 423):

> Crime Scene Examination presents an interesting and challenging domain in which to consider the notion of Distributed Cognition for the simple reason that it is not always apparent where the act of 'cognition' is situated. The ultimate aim of the criminal justice process, of course, is to acquire evidence which can be combined with information from other sources in order to produce a case that can be tried in Court. Contrary to its representation in popular fiction, the examination of a crime scene is unlikely to yield evidence that immediately links a suspect to a crime. Rather, the collection of evidence is part of a complex web of investigation that involves many individuals, each considering different forms of information in different ways.

Baber situates the role of *crime scene* examiner (*CSE*) within the criminal justice process (ibid.):

> The CSE is part of a much larger investigative system, each member of which has their own skills and roles (Smith et al., 2008). In a sense, Crime Scene Investigation involves sets of ad-hoc teams pursuing independent goals with quite limited overlap (Smith et al., 2008). Thus, there is typically a demarcation between roles. Having said this, the nature of this demarcation has been subject to significant shifting over the years, with the ongoing digitisation of Crime Scene Examination leading to further changes. For example, there used to be a specific role of Crime Scene Photographer whose function was to capture and process images of the crime scene (either prior to evidence recovery or at stages during the recovery process, depending on the nature of the crime). However, with the growing use of digital cameras by CSEs, this role has (in some Police Forces) changed. This has the interesting implication that the function of a photograph taken by the Crime Scene Photographer was to capture the scene as clearly as possible in order to aid discussion of the scene in Court (or during subsequent investigation), but the function of a photograph taken by the CSE could be to illustrate the evidence recovery process; [. . .]

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[4] For this concept, see Dror and Hamard (2009). Baber remarks (2010, p. 424): "While I suggest that Crime Scene Examination necessarily involves several agents performing cognitive activity, this is not to argue that this results in an 'extended mind' across these agents; as Dror and Hamard (2009) point out, to argue for an extended mind is analogous to arguing for extended migraine – just because an event occurs in one brain does not inevitably mean that other brains will share this event. Dror and Hamard's (2009) argument is that one should not separate cognitive states from mental states. This criticism raises a core problem for the notion of 'Distributed Cognition', because it implies that cognition cannot be 'distributed' across agents because one cannot share mental states. A primary assumption of 'Distributed Cognition' is that it is not 'cognition' which is distributed so much as objects-in-the-world, which plays a role in supporting, structuring and aiding the activities of cognition."

Baber explains (2010, p. 426):

> What is happening in Crime Scene Examination is the mediation of cognition through the collection, manipulation and dissemination of a variety of artifacts; each artifact is interpreted in particular ways by the agents who come into contact with it. My argument will be that, for the various agents involved in this evidence chain, each artifact can 'afford' a particular set of responses, that is, the artifacts are resources for action, and the actions will be recognised by different agents according to their training and experience. I am using the notion of 'afford' in the sense introduced by Gibson (1977, 1979), as a form of perception–action coupling in which the physical appearance of an object in the world supports particular physical responses (e.g., a pebble 'affords' grasping in the hand).

Once recovered, evidence is shared (Baber, 2010, p. 429):

> The preceding discussion implies that the search of a scene is guided by experience, expectation and the ability to recognise items of evidential value. In this respect, the notion of Distributed Cognition can be interpreted in terms of the use of objects in the world as resources-for-action. The Crime Scene Examiner recognises objects as resources-for-action which may well differ from untrained observers. For example, while the untrained observer might assume that a pane of glass in a window could yield fingermarks, they might be less inclined to immediately assume that it could also yield footwear marks, and still less inclined to recognise its potential for yielding DNA (the latter two could arise from someone climbing in through the window, or from pressing their forehead against the window to see if anyone is at home).
>
> So far, this description looks very much like a process that involves the mental states of an individual; the CSE interprets the scene, recognising objects as resources-for-action, and then recovers the evidence. However, what makes the Crime Scene Examination process different from a Sherlock Holmes story is that the CSE submits the evidence for interpretation by other people. Indeed, it is unlikely for the CSE's notes and reports from the scene to include any deduction. Rather the report will be as descriptive as possible.[5] This representation, of the scene and its evidence, is passed along the recovery train. So we have a set of processes that could ostensibly represent the stimulus (or input) to a cognitive processing system. This processing is (formally) undertaken by people other than the CSE.

Prakken et al. (2003) discussed appropriate argument structures for reasoning about evidence in relation to hypothesising crime scenarios. It was a paper on using argumentation schemes for reasoning on legal evidence, mainly by way of an exploration of applying *Araucaria*, the argument visualisation system from the University of Dundee in Scotland,[6] to an analysis in the style of Wigmore Charts. Case-based

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[5] Baber (2010, p. 430) concedes that there may be problems with striving to be objective by only providing descriptions, in that some useful information may be missed: "One could make a strong argument that this lack of information helps an analysis to be as objective as possible, by focussing only on the item at hand (and avoiding the potential for bias that Dror et al. (2005) demonstrated). On the other hand, it might be useful to have some knowledge of the item in situ, so as to decide how best to conduct analysis. If the Forensic Scientist had recovered the item herself then such information would be recalled by her, but when it is delivered in a batch of bags then such information is not obviously available. As an example of why this could be problematic, consider a finger-mark left on a window. This mark might not be detailed enough to form a print, but could indicate whether the window has been forced up or whether someone climbed down the window, knowing the orientation of the mark on the window can help decide how best to analyse it, but this might not have been provided in the evidence log."

[6] Araucaria is available for free at http://www.computing.dundee.ac.uk/staff/creed/araucaria

reasoning was applied by Toland and Rees (2005) to the task of recalling similar instances of volume crime, when confronted with a crime being investigated: the task was the identification of crimes with similar *modus operandi*, and the reasoning involved potential repeat offenders. Ribaux and Margot (1999) applied case-based reasoning to the categorisation of cases of burglary, with the retrieval of cases with similar profiles. The work reported about in Oatley et al. (2004) is concerned with assisting the police in detecting the perpetrators of burglary from homes, which is a high-volume crime with low detection rates; that project made use of a variety of data mining techniques, including: classification and association rules,[7] neural network clustering, survival analysis and Bayesian belief nets, case-based reasoning, as well as ontologies and logic programming.

A team that was initially led in Edinburgh by John Zeleznikow, in the early 2000s, worked on projects whose aim was to produce software tools assisting in the assessment of evidence in given limited, specialist domains. Jeroen Keppens and Burkhard Schafer were members of that team. Eventually, as various persons moved around to other affiliations, sequel projects emerged at different locations. The present section is concerned with one of those lines of research.

Keppens and Zeleznikow (2002, 2003) and Keppens and Schafer (2003a, 2003b, 2004) have reported about a project whose application is in post-mortem inquests, with the goal of determining whether death occurred through natural causes, homicide or suicide. In their Dead Bodies Project,[8] a so-called "truth maintenance system", or ATMS (a well-known AI approach to consistency)[9] is resorted to, in order to maintain a space of "possible worlds" which correspond to hypothetical scenarios. The architecture is shown in Fig. 8.1.1.1.

The project resorts to neither conventional expert systems, nor case-based reasoning. Any case is potentially unique. Crime investigation is very difficult to proceduralise. The design solution adopted for this project was to develop a model-based reasoning system, i.e., such a system that given a problem instance, a model of the problem is constructed, and a problem-independent technique is applied. In the same project, dynamic preference orderings are assigned to uncertain events. Default orderings may be overruled by inferred orderings.

An article by Keppens and Schafer (2005) "characterises an important class of scenarios, containing 'alternative suspects' or 'hidden objects', which cannot be

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[7] A definition of *association rules* as a form of data mining is found in fn. 36 in Chapter 3.

[8] Ronald Wright (2005, 2nd edn.; 2009, 3rd death) provides an overview of the *investigation of traumatic deaths*.

[9] In Section 2.1.2 above (see in particular some historical information in fn. 1 in Chapter 1) we have already come across the approach known in artificial intelligence as *Assumption-based Truth Maintenance System* (*ATMS*). An ATMS is a mechanism that enables a problem solver to make inferences under different hypothetical conditions, by maintaining the assumptions on which each piece of information and each inference depends (de Kleer, 1986, 1988). The goal of computation with an ATMS is to find minimal sets of premises sufficient for the support of each node. One has to find all minimally inconsistent subsets (NOGOODSs), and to find all maximally consistent subsets (GOODSs).

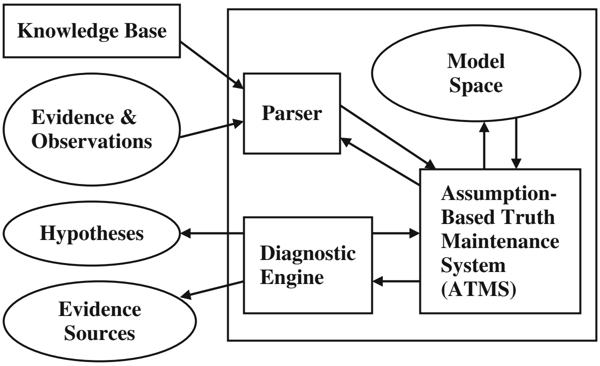

Fig. 8.1.1.1 The early architecture of the Dead Bodies Project of Keppens and Zeleznikow (2002, 2003)

synthesised robustly using conventional abductive inference mechanisms. The work is then extended further by proposing a novel inference mechanism that enables the generation of such scenarios."

Keppens and Schafer (2006) reported about a more advanced state of the same project applying artificial intelligence to crime scenario modelling. The prototype of a decision-support system was presented, for crime scenario construction. It is component events, rather than entire scenarios, that are stored. (By *scenario*, a description of a combination of events and situations is meant.) The component events are composed into useful scenarios by an algorithm. The input is a description of the available evidence. A network of plausible scenarios is then generated. Those scenarios in turn can be analysed, with the goal of devising effective evidence collection strategies. The algorithm was allegedly highly adaptable to unanticipated cases, by allowing a major crime being investigated to be matched by component events in several different ways. One advantage hoped for was the avoidance of such pitfalls of human reasoning as *premature case theories*, or rather *premature convergence*, such that police investigators tend to focus on the more likely suspects they had identified early on.[10]

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[10] Keppens and Schafer (2006, section 2.1), citing McConville, Saunders, and Leng (1991) and Greer (1994). Once investigators think they already have the culprits, they tend to apply *confirmationism*, also known as *cognitive dissonance*, by which they privilege such information that confirm their preconceptions, and tend to disregard contrary evidence. "While the police service might pay lip service to a falsificationist model of rationality ('asking witnesses to come forward to eliminate them from the inquiry') existing reward structures make it difficult to implement this in practice. Our proposed system accounts for this by combining a 'backchaining' abductivist model of reasoning with a 'forward chaining' model that is based on the idea of indirect proof, sidestepping the issue of falsification and induction in a universe with only finitely many alternatives" (Keppens & Schafer, 2006, section 2.2). *Forward chaining* and its opposite, *backchaining*, are standard concepts from rule-based knowledge-based systems in artificial intelligence.

Therefore, that project belongs to a category of software tools known as *compositional modellers*, and introduced by Falkenhainer and Forbus (1991) in their paper 'Compositional modeling: finding the right model for the job'. Compositional modelling was also discussed by Keppens and Shen (2001). In compositional modellers, small, generic and reusable rules called *model fragments* capture a domain's first principles. These are "fundamental theories describing the behaviours and mechanisms that occur in the domain of interest [. . .]. The compositional modelling paradigm is adapted to the crime investigation domain by employing causal rules describing how combinations of assumed states and events lead to new states and events in plausible crime scenarios" (Keppens & Schafer, 2006).

Another category in which the system described by Keppens and Schafer (2006) is *abductive diagnosers.* In abductive diagnosis (Console & Torasso, 1991), what the conditions are of a physical system under investigation are determined by comparing observations as predicted by models, to such observations that are extracted from the real world. The generation of models, in an abductive diagnoser, is done by resorting to a knowledge base of *first principles* about the given domain. First principles are general rules, independent from the decision procedure, and in this they differ from the *heuristic rules* (i.e., *rules of thumb*) found in rule-based expert systems. In the project of Keppens and Schafer (2006),

> the first principles are expressed by means of causal rules describing how some states and events are triggered by other known or assumed states and events. The possible causes of a given set of available evidence are inferred by means of an abductive inference procedure. These causes form the hypothetical scenarios describing plausible crimes. Potential additional evidence that may confirm or contradict these scenarios is then deduced using the same causal rules. This abductive, first-principles based approach recognises that while the individual scenarios encountered in a major crime investigation may be virtually unique and vary widely, the underlying domain knowledge on evidence and the types of events that create it are not. It also encourages a principled hypothetico-deductive investigative methodology because it hypotheses all (known) possible causes of the available evidence, composes these causes into plausible scenarios and deduces additional evidence from the plausible scenario. This promotes consideration of many scenarios, instead of individual ones, in deciding on future investigative actions. Finally, the approach also allows making expert domain knowledge available to less experienced investigators.

The architecture of the decision-support system described by Keppens and Schafer (2006) is shown in Fig. 8.1.1.2. An *assumption-based truth maintenance system* (*ATMS*) is the central inference mechanism in this architecture. A *scenario space* is maintained by means of the ATMS. "All" possible scenarios that explain the available evidence are stored in the scenario space. The scenarios are represented as logic predicates; these predicates denote events and states, or causal relations between events and states. Causal relations between assumptions, states, and events are represented as *scenario fragments*, each of these being a tuple comprising a set of variables, a set of relations called *preconditions*, a set of relations called *postconditions*, and a set of relations called *assumptions.* There also is a representation of inconsistencies, e.g., "a person can not kill himself both with such an intention (i.e. in a suicide) and without this intention (i.e. in an accidental self-killing)"

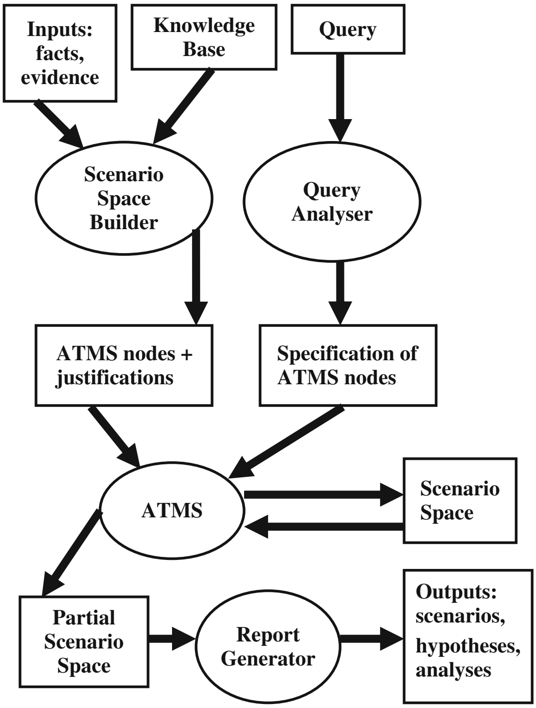

Fig. 8.1.1.2 The architecture of the decision-support system described by Keppens and Schafer (2006), redrawn and rearranged from their figure 2. Data structures are shown in this figure as rectangles, whereas ellipses correspond to the inference mechanism

(Keppens & Schafer, 2006, section 4.4). The knowledge base comprises property definitions, a set of scenario fragments, and a set of inconsistencies. "*Property definitions* describe which types of predicate correspond to a symptom, fact, hypothesis or investigative action" (ibid., section 4.5). An example of scenario fragment is this one (Keppens & Schafer, 2006, section 4.3):

> if a person P suffers from ailment or injury C, C is the cause of death of P, and there is a medical examiner E, and assuming that E determines the cause of death of P and makes the correct diagnosis, then there will be a piece of evidence in the form of a cause of death report indicating that according to E, the cause of death of P is C.

Keppens and Schafer explained (2006, section 3.2):

> Once constructed, the scenario space is analysed through a series of *queries*. Queries are questions about the scenario space. Their answers are computed by extracting relevant parts from the scenario space and reported back in an understandable format. To interface between the human and scenario space, a *query analyser* translates standard types of user queries into a specification of ATMS nodes of interest, and a *report generator* provides the means to represent a partial scenario space back to the user.

What the scenario space is made to initially contain, is based on the initial set of given *facts* and *evidence*, and is constructed by means of a *knowledge base*.

For example, these five pieces of evidence appear in an example from Keppens and Schafer (2006): n_1: "A hanging corpse of a person identified as johndoe has been found"; n_{11}: "A report by a psychologist identified as frasier (n_{15}) stating that johndoe may have been suicidal prior to his death"; n_{14}: "The observation of suicide trial marks on the body of johndoe"; n_{16}: "The body of johndoe exhibits signs of petechiae" (i.e., small red to purple spots on the eyes or skin, caused by either disease or asphyxiation); n_{20}: "A report by a medical examiner identified as quincy (n_7) stating that the cause of death of johndoe was asphyxiation".

One possible scenario based on this evidence is suicide by hanging. For example, "The hanging corpse (n_1) and the summed cause of death (n_{20}) are the consequents of johndoe's hanging (n_5), which he was unable (unwilling) to end (n_4). The petechiae is caused by asphyxiation (n_{15}) resulting from the hanging. johndoe's suicide by hanging requires that johndoe is suicidal (n_7) and the last two pieces of evidence are a consequence of his suicidal state" (Keppens & Schafer, 2006, section 4.1).

Each scenario was represented as a *causal hypergraph.* A hypergraph is a generalisation of a graph, such that an edge may appear not just between two nodes, but between a set of nodes including two or more nodes. But scenarios were represented as directed acyclic hypergraph, whose nodes are events or states, whereas the edges are directed hyperarcs, each one from a set of at least one event or state, towards one and only one event or state. The scenario of suicide by hanging was shown in Keppens and Schafer (2006, figure 3), but we find it more convenient to translate here that hypergraph into a ruleset and a list of propositions. The ruleset is shown here in Table 8.1.1.1 (where $\wedge$ stands for *and*); each rule corresponds to one of the hyperarcs of the causal hypergraph of the scenario of suicide by hanging. The correspondence between node identifiers and particular propositions is listed in Table 8.1.1.2. In Table 8.1.1.1, each row stands for a directed hyperarc of the causal hypergraph, and here in the order we chose to reflect the arrangement in Keppens and Schafer's (2006) original diagram of their figure 3, from top to bottom. The meaning of the nodes is defined in Table 8.1.1.2.

Keppens and Schafer (2006, section 4.2) classify information by distinguishing *facts* ("pieces of inexplicable, certain information") from *evidence* ("information that is certain and explicable"), by distinguishing three kinds of "uncertain and

Table 8.1.1.1 The hyperarcs of the scenario of suicide by hanging (from figure 3 in Keppens & Schafer, 2006)

n_1	←	$n_4 \wedge n_5$
n_{16}	←	n_{15}
n_{20}	←	$n_{15} \wedge n_{17} \wedge n_3 \wedge n_{18} \wedge n_{19}$
n_{15}	←	n_5
n_{17}	←	$n_4 \wedge n_5$
n_4	←	n_6
n_5	←	n_6
n_{21}	←	n_6
n_{15}	←	$n_2 \wedge n_{10} \wedge n_9 \wedge n_7$
n_6	←	$n_7 \wedge n_8$
n_{14}	←	$n_7 \wedge n_3 \wedge n_{13} \wedge n_{12}$

Table 8.1.1.2 Which event or state the nodes stand for

n_1:	`observe(hanging-dead-body(johndoe))`
n_2:	`psychologist(frasier)`
n_3:	`medical-examiner(quincy)`
n_4:	`impossible(end(hanging(johndoe)))`
n_5:	`hanging(johndoe)`
n_6:	`suicide(johndoe, hanging)`
n_7:	`suicidal(johndoe)`
n_8:	`suicide-action(hanging, johndoe)`
n_9:	`psychological-examination(frasier, state-of-mind(johndoe))`
n_{10}:	`correct-diagnosis(frasier, state-of-mind(johndoe))`
n_{11}:	`psychological-evaluation(frasier,state-of-mind(johndoe),suicidal)`
n_{12}:	`medical-examination(quincy, body(johndoe))`
n_{13}:	`correct-diagnosis(quincy, body(johndoe))`
n_{14}:	`medical-report(quincy, body(johndoe), suicide-trial-marks)`
n_{15}:	`suffers(johndoe, asphyxiation)`
n_{16}:	`observe(eyes(johndoe), petechiae)`
n_{17}:	`cause-of-death(johndoe, asphyxiation)`
n_{18}:	`correct-diagnosis(quincy, cause-of-death(johndoe))`
n_{19}:	`medical-examination(quincy, cause-of-death(johndoe))`
n_{20}:	`medical-report(quincy,cause-of-death(johndoe),asphyxiation)`
n_{21}:	`suicidal-death(johndoe)`

explicable" information (*uncertain states*,[11] *uncertain events*,[12] and *hypotheses*[13]), and by distinguishing three types of *assumptions*, i.e., of "uncertain and inexplicable information":

- *Default assumptions* describe information that is normally presumed to be true. In theory, the number of plausible scenarios that explain a set of available evidence is virtually infinite, but many of these scenarios are based on very unlikely presumptions. Default assumptions aid in the differentiation between such scenarios by expressing the most likely features of events and states in a scenario. A typical example of a default assumption is the presumption that a doctor's diagnosis of the cause of death of person is correct (e.g. n_{18}).
- *Conjectures* are the unknown causes of certain feasible scenarios (e.g. n_7). Unlike default assumptions, conjectures are not employed to differentiate between the relative likelihood of scenarios.
- Uncommitted *investigative actions*, i.e. possible but not yet performed activities aimed at collecting additional evidence, are also treated as assumptions. At any given stage in the investigation, it is *uncertain* which of the remaining uncommitted investigative actions will be performed. The reasoning required to perform such an action involves looking at its consequences instead of its causes, and therefore they are *not* (causally) *explicable*. As such, investigative actions assume a similar role as default assumptions and conjectures: i.e. they are employed to speculate about the plausible (observable) consequences of a hypothetical scenario.

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[11] An example of *uncertain state* is node n_4, "johndoe was unable to end his hanging".

[12] An example of *uncertain event* is node n_{15}, "johndoe asphyxiated".

[13] An example of *hypothesis* is node n_{21}, "johndoe's death was suicidal".

8.1.2 The Structure of ATMS Inference in the Scenario Space Builder

The scenario-space builder instantiates scenario fragments as well as inconsistencies, into an ATMS. In the *initialisation phase*, an ATMS is generated that contains one node per piece of available evidence. Next, a *backward chaining phase* is executed. All plausible *causes* of the available evidence are added to the ATMS. A process is repeated, until exhausting all possible unifications[14] of individual consequents of a scenario fragment with a node already in the ATMS. That process does the following for each possible unification: it instantiates the antecedents and assumptions of that scenario fragment; the process adds a node to the ATMS for antecedent instance that does not already have a node; it adds an assumption node to the ATMS for each assumption instance that does not already have a node; and the process adds to the ATMS a *justification* (i.e. a rule like the rows in Table 8.1.1.1, but also added nodes such as assumption nodes can be included) "from the nodes corresponding to the antecedent and the assumption nodes corresponding to the assumptions, to the node corresponding to the consequent" (Keppens & Shafer, 2006, section 5.2.1).

Once the backward chaining phase is exhausted because action as described was taken for each possible unifications, execution enters the *forward chaining phase.*

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[14] Take for example the syllogism "All men are mortal, and Socrates is a man; therefore Socrates is mortal". In predicate calculus, the three expressions

$$\forall \mathsf{X}(\mathsf{man}(\mathsf{X}) \Rightarrow \mathsf{mortal}\,(\mathsf{X})).$$
$$\mathsf{man}(\mathsf{socrates}).$$
$$\mathsf{man}(\mathsf{socrates}) \Rightarrow \mathsf{mortal}(\mathsf{socrates}).$$

respectively stand for "All men are mortal", "Socrates is a man", and "Socrates is a man, therefore Socrates is mortal". *Unification* is an algorithm that an automated problem solver can use in order to determine that socrates may be substituted for X. For it to apply inference rules, "an inference system must be able to determine when two expressions are the same or *match.* In propositional calculus, this is trivial: two expressions match if an only if they are syntactically identical. In predicate calculus, the process of matching two sentences is complicated by the existence of variables in the expressions. Universal instantiation allows universally quantified variables [that is: for all X] to be replaced by terms from the domain. This requires a decision process for determining the variable substitutions under which two or more expressions can be made identical (usually for the purpose of applying inference rules). Unification is an algorithm for determining the substitutions needed to make two predicate calculus expressions match" (Luger & Stubblefield, 1998, section 2.3.2., p. 68). "Generally, a problem-solving process will require multiple inferences and, consequently, multiple successive unifications. Logic problem solvers must maintain consistency of variable substitutions. It is important that any unifying substitution be made consistently across all occurrences of the variable in both expressions being matched" (ibid., p. 69). "Once a variable has been bound, future unifications and inferences must take the value of this binding into account. If a variable is bound to a constant, that variable may not be given a new binding in a future unification. If a variable X_1 is substituted for another variable X_2 and at a later time X_1 is replaced with a constant, then X_2 must also reflect this binding" (ibid.). Unification substitutions are combined and returned thanks to the composition of unification substitutions.

What this phase does, is adding to the ATMS all possible *consequences* of the plausible scenarios. Whereas the *backward chaining* phase repeated its process until exhausting all possible unifications of individual *consequents* of a scenario fragment with a node already in the ATMS, by contrast the *forward chaining* phase carries out the following process for each possible unification of the set of *antecedents* of a scenario fragment with a set of nodes already in the ATMS. That process instantiates the assumptions and consequents of that scenario fragment; the process adds an assumption node to the ATMS for each assumption instance that does not already have a node; the process adds to the ATMS a node for each consequent instance that does not already have a node; and the process adds to the ATMS a justification for each consequent instance, "from the nodes corresponding to the antecedent and the assumption nodes corresponding to the assumptions, to the node corresponding to the consequent instance"(Keppens & Shafer, 2006, section 5.2.1).[15]

The forward chaining process is repeated until exhausting all unifications of scenario fragment antecedents with sets of nodes in the ATMS. And finally, the *consistency phase* is carried out: "inconsistent combination of states and events are denoted as nogoods. This involves instantiating the inconsistencies from the knowledge base based on information in the ATMS and marking them as justifications for the nogood node." (ibid.). In the terminology of ATMS, a *nogood* is such a justification that has lead to an inconsistency, that is to say, from its node there is an arc $\rightarrow\perp$ and this implies that one of the propositions conjoined by *and* in the nogood must be false. With an ATMS, one has to find all minimally inconsistent subsets (NOGOODSs), and to find all maximally consistent subsets (GOODSs).

Keppens and Schafer (2004, section 3) pointed out similarities between what the ATMS does in their Dead Bodies project, and what a defence solicitor would do:

> In developing alternative scenarios consistent with the evidence, the ATMS performs some of the scrutiny a good defence solicitor would subject the prosecution case to. A defence solicitor has broadly speaking two strategies available to him. First, he can question the factual correctness or the legal admissibility of evidence presented by the prosecution. Second, he can accept the evidence at face value and argue that alternative explanations for their presence are possible that do not incriminate his client. We are concerned here primarily with this second strategy. However, it is here that we encounter a certain ambiguity, an ambiguity explicitly recognised by the Scots law of evidence. The defence has in fact again two strategies available to it. The first can be dubbed the "Perry Mason Stratagem". Like the fictitious advocate, the defence can pursue its own investigation and "point to the real culprit". In Scots law, this is known as the special defence of incrimination [Field & Raitt, 1996], recently used (unsuccessfully) in the Lockerbie trial

for an atrocity ascribed to an act of terror: an PanAm passenger aircraft exploded while flying over Scotland in 1988 because of a bomb on board.

---

[15] In the section 5.2.2 in their article, Keppens and Shafer (2006) supplied the formal algorithm for generating the scenario space.

> This strategy has a number of psychological and legal advantages. The same reason that makes it the solution of choice for crime writers also works well with juries: no loose ends are left and the crime is avenged. Procedurally, it allows the defence to submit also other pieces of evidence. This corresponds to the "forward chaining" aspect of our ATMS: The party named by the defence will have interacted causally with the crime scene. This will have created evidence which can strengthen the defence case. This allows introduction of additional "suspect specific" evidence (such as alibi) evidence about other people, which otherwise might be ruled out as irrelevant. The defence of course need not prove the guilt of the other party; it only needs to establish it as a plausible alternative. [. . .]

8.1.3 An Extension with Bayesian Networks, Entropy, and Returned Evidence Collection Strategies

Keppens, Shen, and Lee (2005a) described an extension of the scenario space generation, resorting to Bayesian modelling: "this paper shows a compositional modelling approach to synthesise and efficiently store a space of plausible scenarios within a Bayesian Network (BN) [. . .]. Furthermore, it presents an application of the maximum entropy reduction technique to determine which investigative actions are most likely to reduce doubt" (ibid., section 1). In this extension of the work already described earlier in the present Section 8.1, scenario fragments also incorporate a set of probability distributions, one for each combination of the antecedent and assumption variables.

> Thus, the following scenario states that if a victim V has petechiae on his eyes and the investigators examine V's eyes, then evidence of petechiae is discovered with a certain probability:

```
if {petechiae(eyes(V))}
assuming {examination(eyes(V))}
then {evidence(petechiae(V))}
distribution evidence(petechiae(V)) {
true, true -> true:0.99, false:0.01}
```

Keppens et al. (2005a, section 2.1) explained that, by adopting the notation shown in Table 8.1.3.1, the general representation for a scenario fragment, incorporating probability distributions, is as follows:

Table 8.1.3.1 A notation for the predicates and values involved

$\{p_1, \ldots, p_k\}$	the set of antecedent predicates
$\{p_1, \ldots, p_m\}$	the set of assumption predicates
p_n	the consequent predicate
v_i	any of the values that variable p_i can take
q_j	a real value in the range [0,1]

```
if $\{p_1, \ldots, p_k\}$
assuming $\{p_l, \ldots, p_m\}$
then $\{p_n\}$
distribution $p_n$ {
                    ⋮
   $v_1, \ldots, v_k, v_l, \ldots, v_m$ -> $v_{n1} : q_1, \ldots, v_{nj_n} : q_{j_n}$
                    ⋮          }
```

By contrast, the general representation of an inconsistency is as a special kind of scenario fragment, as follows:

```
if $\{p_1, \ldots, p_k\}$
then {nogood}
distribution nogood {
  $v_1, \ldots, v_k$ -> $\top : 1, \ldots, \bot : 0$}
```

where ⊤ stands for the value *true*, and the reversed ⊤ stands for the value *false.* Moreover, in the knowledge base there also are prior distributions for assumed states and events. In order to enable the compositional modelling of Bayesian networks, presumptions concerning the scenario fragments include the presumption that the causal hypergraph is acyclic ("There are no cycles in the knowledge base": Bayesian networks are inherently acyclic), and the presumption that "*Any two probability distributions taken from two scenario fragments involving the same consequent variable are independent*. Intuitively, this assumption indicates that the outcome of an influence implied by one scenario fragment is not affected by that of another" (ibid.).

Entropy was adopted as a measurement of doubt, this being a concept from information theory. It is also adopted in machine learning (Mitchell, 1997) and in model-based diagnosis (Hamscher, Console, & de Kleer, 1992). Keppens et al. (2005a, section 3.2) explained that the entropy over an exhaustive set of mutually exclusive hypotheses

$$H = \{h_1, \ldots, h_m\}$$

is given by:

$$\epsilon(H) = -\sum_{h \in H} P(h) \log P(h)$$

By resorting to conventional techniques from Bayesian networks, it is possible to compute the values $P(h)$. As in crime investigation, additional information is generated through evidence collection, Keppens et al. (ibid.) proposed that given e set of pieces of evidence

$$E = \{e_1 : v_1, \ldots, e_n : v_n\},$$

"the entropy metric of interest for the purpose of generating evidence collection strategies is the entropy over a set of hypotheses *H*", as per the formula:

$$\epsilon(H \mid E) = -\sum_{h \in H} P(h \mid E) \log P(h \mid E)$$

Conventional Bayesian network techniques allows computing the conditional probability values $P(h|E)$. Keppens et al. (ibid.) also proposed that selecting investigative

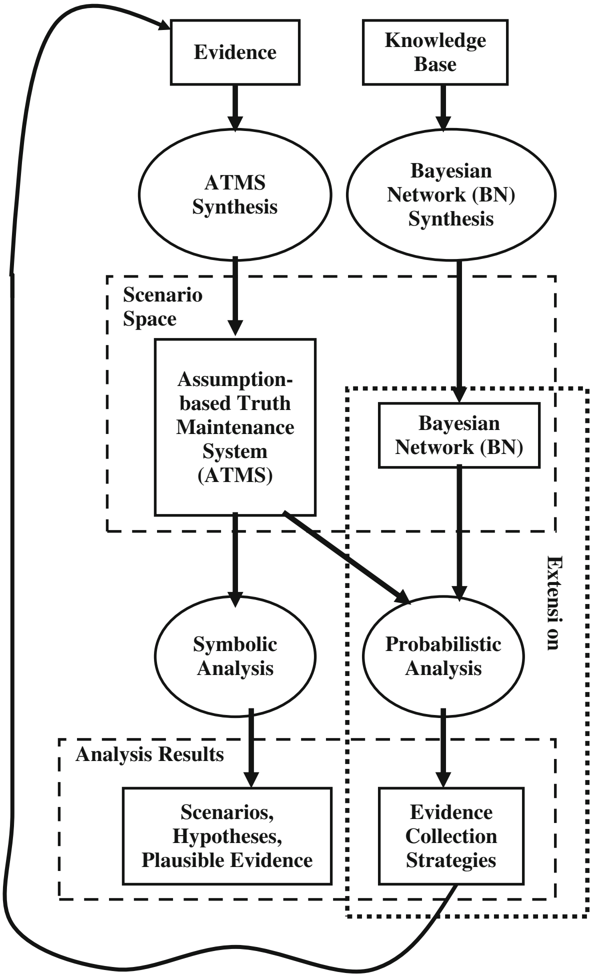

Fig. 8.1.3.1 The extended architecture, redrawn from Keppens et al. (2005b, section 3, figure 2): Bayesian networks appear in the knowledge representation, and evidence collection strategies appear in the output

actions from a given set A according to the following criterion is a useful evidence collection strategy:

$$\min_{a \in A} E(\epsilon(H \mid E), a)$$

They discussed minimal entropy-based evidence (EPE) collection in their section 3.3. They conceded however (Keppens et al., 2005a, in their section 3.4) that whereas that "technique guarantees to return an effective investigative action, it does not ensure globally optimal evidence collection". They proposed a remedy, in order to reduce the "likelihood of obtaining poor quality locally optimal evidence collection strategies". This is done by only "considering the EPEs after performing a sequence of actions", although this incurs computation overheads. They then proposed a simplified equation for that remedy. Next, they turned to discussing how to allow multiple evidence sets, or multiple hypothesis sets instead of just one.

In Fig. 8.1.3.1, we redraw from Keppens, Shen, and Schafer (2005b, section 3, figure 2) the architecture of their system, as extended with Bayesian networks in the knowledge representation, and with evidence collection strategies in the output.

8.1.4 Further Research

Jeroen Keppens

As argued by Schum (1994), a key aspect of evidential reasoning concerns the development of hypotheses. Indeed, as demonstrated by Aitken and Taroni (2004), probabilistic approaches to evidential reasoning tend to favour the statistics paradigm of hypothesis testing. This idea is not only useful when assessing evidence in court, it has been embraced by a part of the forensic science community, such as Cook, Evett, Jackson, Jones, and Lambert (1998), as a means to assess the probative force of evidence during the investigation of a (alleged) crime. But while hypotheses are readily available for testing once a case reaches court, the formulation of hypotheses during the investigative stage is not straightforward.

As argued by Keppens and Zeleznikow (2003), this requires what Peirce (1903) termed abduction or abductive reasoning. Keppens and Schafer (2006) have developed an abductive reasoning approach to produce the hypotheses required for evidential reasoning during a crime investigation. Being a knowledge based approach, it employs a knowledge base and a corresponding inference mechanism. The knowledge base consists primarily of generalised and reusable fragments of plausible scenario, such as one predicting the medical symptoms generated by a blow to the head and another indicating those resulting hitting one's head against the ground in a fall. Generally speaking, these scenario fragments express cause-effect relationships. The inference mechanism instantiates these scenario fragments to specific circumstances and combines them to compose plausible scenarios, which can then be analysed further.

The overall approach is inspired by earlier work on compositional modelling by Keppens and Shen (2004), an family of methods designed to generate formal models of real-world or hypothetical scenarios. Compositional modelling works on the idea that while the specific combination of circumstances contained within an individual scenario are relatively rare, and therefore difficult to generalise, the constituent elements appear rather more frequently. For example, while the circumstances of the murder of one of the victims of the serial killer Dr Harold Shipman might be relatively rare, the component elements such as injection with an overdose of diamorphine and the resulting evidence reoccur more frequently. Therefore, the use of compositional modelling helps to tackle, to some extent, significant knowledge acquisition problem involved with a system of this kind.

More recent developments in this strand of research have sought to further address the knowledge acquisition bottleneck and to allow more useful modes of inquire with the resulting scenario models. One extension concerns the modelling problem that arises when there are an unknown number of plausible instantiations. For example, an unknown number of unknown persons can be involved in a plausible crime scenario, such as the person a fingerprint belongs, the person who has been seen fleeing the scene of the alleged crime and the suspicious person observed in CCTV footage near the scene prior to the alleged crime. During the investigation it is not known whether this concerns three distinct individuals, two individuals (with two pieces of evidence referring to the same person) or just a single individual (to whom all evidence relates). Keppens and Shafer (2004, 2005) have proposed a *peg-unification* technique that involves representing all unknown instantiations as so-called pegs and employs an algorithm to explore all possible assumptions of equivalences between pegs simultaneously.[16]

---

[16] *Peg unification* is useful for *coreference resolution.* Keppens and Schafer explained (2003b, section 4):

> The task of identifying different references to the same entity is known as *coreference resolution* in computational linguistics. In the analysis of a discourse, it is important that references to the same entity are correctly associated with one another because each of the expressions that contains one of these references may add some information about the entity in question. For example, in the sentence "Every farmer who owns *a donkey*, beats *it*." "a donkey" and "it" refer to the same entity. The first half of the sentence conveys that the entities of interest are all donkeys owned by farmers. The second half of the sentence communicates that the entities of interest are beaten. Thus, the sentence as a whole imparts the knowledge that all donkeys owned by farmers are beaten.
>
> A wide range of techniques has been devised to perform coreference resolution tasks, such as the one illustrated in the example. The vast majority of these techniques specialise in examining texts for discourse analysis or information extraction. An important property of the existing approaches is that they tend to consider only a single possible solution at any one time, while the present problem domain requires a method that can represent and reason with multiple possible worlds simultaneously.

As to *pegs* (Keppens & Schafer, 2003b, section 4.1):

> The objective of this work is to identify possible references to the same unknown or partially specified entities in the scenario space. In order to correctly distinguish such entities, the notion of *pegs* is adopted from the literature on coreference resolution [(Karttunen,

Another extension of the work has augmented the original purely symbolic representation of scenarios with probabilities. More specifically, Keppens, Shen, and Price (2010) have devised a method to compose conventional conditional probability distributions from partial specifications thereof and incorporated the partial ones into the scenario fragments. This allows the original abductive reasoning approach

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> 1976; Landman, 1986)]. Pegs refer to a specific entity whose exact identity remains unknown (or partially specified). In this paper, each peg is identified by an expression of the form _n, where n is a non-negative natural number. At the start of the scenario space generation algorithm n = 0, and n is incremented by 1 after each generation of a new peg. As such, each new peg is identified uniquely.
>
> New pegs may be introduced into the scenario space during the instantiation of causal rules of the form `if` $\{\mathrm{A_n}\}$ `assuming` $\{A_s\}$ `then` $\{c\}$, where An is a set of antecedent predicates, A_s is a set of assumption predicates and c is a consequent predicate. Whenever a rule, whose antecedent or assumption predicates contain variables that do not occur in the consequent sentence, is applied during the inverse modus ponens phase of the scenario space generation algorithm (i.e. step 2), then those variables are instantiated by pegs. Consider, for instance, applying inverse modus ponens on rule
>
> $$\begin{array}{l}\texttt{if}\ \{\mathrm{scene}(S)\}\ \texttt{assuming}\ \{\mathit{person}\,(P)\,,\mathrm{took}\,(P,G)\}\\ \texttt{then}\ \{\neg\mathrm{evidence}\,(\mathit{recover}\,(G,S))\}\end{array}$$
>
> given the piece of evidence: ¬evidence(recover(handgun, home(victim))}. The required substitution {*G*/handgun, *S*/home(victim)} does not provide an instance for *P*. Here, *P* refers to an unknown entity and it is therefore substituted by a peg, say, _0. Therefore, the assumptions person(_0) and took(_0, handgun) are added to the scenario space. Similarly, pegs may also be introduced during the modus ponens phase of the scenario generation algorithm (i.e. step 3). In this case pegs are introduced when a rule whose consequent predicates contain variables that do not occur in the antecedent or assumption sentences, is applied.

Keppens and Schafer (2003b, section 4.2) explained *peg unification* as follows:

> Because a peg refers to an unknown entity, it can be treated as a constant that uniquely identifies that entity, or it can be unified with a ground term, including another peg or terms containing other pegs. In the latter case, the unification is possible if it is hypothesised that the entity represented by the peg and the entity represented by the term unified to the peg are the same one. This hypothesis must therefore be made explicit by means of an assumption whenever an inference is made that depends on the unification of a peg and a ground term. In the remainder of this paper, such assumptions are referred to as *peg unification assumptions*.
>
> In this paper, each peg unification assumption takes the form bind(*_n, t*), where *_nψ* is a peg and *t* is a ground term (which may include a peg). A peg unification assumption bind(*_n,ψt*) is added to the scenario space for each pair of predicates that can be matched using a substitution that contains a mapping of the form *_n/t.*
>
> The binding relation implied by these assumptions is transitive. Therefore, peg unification can not only be assumed, but also be entailed by other peg unification assumptions. This knowledge is represented explicitly in the scenario space: for each pair of peg unification assumptions
>
> $$\mathrm{bind}\,(\_i,\ t_1\,(\ldots,\ \_j,\ldots))\qquad\text{and}\qquad \mathrm{bind}\,(\_j,\ t_2\,(\ldots,\ \_k,\ldots))\,,$$
>
> the following new justification is added to the emerging scenario space:
>
> $$\begin{array}{l}\mathrm{bind}\,(\_i,\ t1\,(\ldots,\_\mathrm{j},\ldots))\wedge\mathrm{bind}\,(\_j,\ t2\,(\ldots,\_k,\ldots))\\ \rightarrow\mathrm{bind}\,(\_i,\ t_1\,(\ldots,\ t_2\,(\ldots,\_k,\ldots)\,,\ldots))\end{array}$$

to be used to produce Bayesian networks describing sets of plausible scenarios. Such a Bayesian network can, in turn, be employed to assess the usefulness of investigative actions based on the informativeness of the evidence they might produce. This extension also enables the knowledge engineer to express his/her lack of certainty regarding cause-effect relationships expressed by the scenario fragments.

However, the integration of probabilities with the approach potentially introduces a further knowledge acquisition challenge: the elicitation of suitable probabilities. Keppens (2007, 2009) has sought address this concern by employing qualitative and semi-quantitative abstractions of conditional probability tables. Fu, Boongoen, and Shen (2010) have independently developed another approach based on a similar idea, exploiting fuzzy sets[17] as a means of qualitative abstraction instead.

8.2 Processing Human Faces: A Panoply of Contexts

8.2.1 Computer Tools for Face Processing: Preliminary Considerations

Mike Redmayne of the London School of Economics in London, writing (Redmayne, 2002) in *The Modern Law Review*, describes a problematic case of face recognition on the part of a forensic expert: “Stephen Hookway was convicted of the robbery of a bank in Salford.” (Salford is in the Greater Manchester area.) The following is quoted from Redmayne (ibid., pp. 23–24):

> The only evidence against him was the testimony of a “facial mapping” expert. The expert carried out a detailed examination of photographs of Hookway, and compared them to photographs of the robbery. He found a number of similarities between them. His findings were, he said, “very powerful support for the assertion that the offender was the appellant”. He could not, however, say for sure that Hookway was the robber. “He conceded that, if a trawl were made through Manchester, it may be possible to find one or two people of similar appearance”. The Court of Appeal acknowledged that, in the absence of a database, “it is impossible to know how many others may look the same as a particular accused”. As in *Smith* [a case in which recognition depended on DNA evidence], relatives complicated the case: the defendant’s brother was produced in court, at which the expert admitted that “he could not exclude the possibility that there was somebody else who closely resembled the

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Scenario space generation first *unifies* the relevant sentences (i.e. the consequent of the causal rule during inverse modus ponens, the antecedents of the causal rule during modus ponens, or the inconsistent sentences of the constraint) with nodes in the emerging scenario space, and return the substitution σ required to achieve the unification. Next, scenario space generation *records* each binding that unifies a peg with a term in the scenario space and a newly created set A_p. Then, the process *instantiates* the remaining sentences (i.e. the antecedents and assumptions during inverse modus ponens or the assumptions and consequent during modus ponens) by applying the substitution σ and the process adds those that do not already exist in the scenario space as new nodes. And finally, scenario space generation *generates* a justification if applying a causal rule, or a nogood if applying a constraint.

[17] Fuzzy approaches are the subject of Section 6.1.15 in this book.

> defendant". A similar point about the parity of evidence against Hookway and his brother can be made. Despite all this, the Court of Appeal refused to quash the conviction.

Victor S. Johnston and Craig Caldwell, of the Department of Psychology of New Mexico State University, Las Cruces, pointed out (Johnston & Caldwell, 1997):

> Humans are experts in facial recognition. They can recognize and discriminate between a very large number of faces seen over a lifetime, often following a single short exposure.[18] In contrast, humans have poor recall ability; they may not be able to recall the features of a close associate, or even a family member, in sufficient detail to construct a facial composite (Ellis, Davies, and Shepherd, 1986; Goldstein and Chance, 1981; Rakover and Cahlon, 1989). As a consequence, current facial composite procedures, which depend heavily on recall rather than recognition, may not be using the best approach for generating an accurate composite of a target face.

"Face processing touches upon a variety of contexts, and is investigated in different disciplines (Young & Ellis, 1989). Rakover and Cahlon (2001) is on face recognition in cognition and computation, and, while offering an overview of theories and models, it proceeds to present an original approach (the Schema Theory and the Catch Model) with criminological applications. It proposes a cognitive law of Face Recognition by Similarity (FRBS). Davies, Ellis, and Shepherd (1981), *Perceiving and Remembering Faces*, introduces issues in face recognition and its associated mental processes. Raymond Bruyer's edited volume (1986) provided an overview of the neuropsychology of face perception.

A forensic context is only one of the many facets of face recognition. The neuropsychology of face perception and face recognition is treated in Ellis et al. (1986). To psychologists, face recognition is a major challenge for human cognition. Apart from varying facial expressions, let alone disguises, even the views of a face when a head is rotated by different angles do not lend themselves to straightforward recognition on the part of humans exposed to such sights from real life, or by watching a video clip, or at a glance from photographs shot on the fly.

To human cognition, the challenge of recognising a given person in a photograph is not the same as recognising the face of a person who is standing in front of the cognitive agent. Face processing belongs in cognitive science as well as, in a different perspective, in computer science. Techniques from automated image recognition are involved in automated recognition or identity validation systems for security or other identification purposes (Nissan, 2003b, pp. 360–361).

8.2.2 Face Recognition Tools for Identification

8.2.2.1 Facial Recognition Classification, from a Database of Mug Shots

Face recognition is a major area within image processing, in computer science. To say it with Mena (2003, p. 167):

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[18] There are studies in the psychology of eyewitness testimony that researched the effects of exposure duration on eyewitness accuracy and confidence (e.g., Memon, Hope, & Bull, 2003).

> Facial recognition software works by measuring a face according to its peaks and valleys – such as the tip of the nose, the depth of the eye sockets – which are known as *nodal points*. A human face has 80 nodal points; however, facial recognition software may require only 14 to 22 to make a match, concentrating on the inner region of the face, which runs from temple to temple and just over the lip, called the "golden triangle". This is the most stable area because if an individual grows a beard, puts on glasses, gains weight or ages, this region tenjds not to be affected. The relative positions of these points are converted into a long string of numbers, known as a face print.

Databases of photographic images of suspects or convicted perpetrators are available to the police. Such photographs are usually *mug shots:* the face of the person is shown frontally. Suppose the police have a facial photograph of a suspect they are searching for. They want to identify that suspect, among the individuals whose mug shots are in the database.

For such a task of classification, the facial recognition tool of Attrasoft is useful (Mena, 2003, section 6.7, pp. 165–167). The firm, Attrasoft,[19] applies neural networks to tasks in facial recognition and, more generally, image processing. "Its facial recognition product is highly accurate, versatile, and capable of searching millions of images, easily handling over a terabyte of data" (ibid., p. 196).

The technique resorts to neural networks with supervised learning (i.e., the network is trained to recognised a predefined correct output). The tool is first *trained* to recognise the face of the suspect whose photograph is the input. This step is carried out by unsing the ImageFinder interface. The window of ImageFinder shows the Image, a toolbar (whose keys include: Train, Search, Classify, Batch, Example, Biometrics, and help), and an array of keys for various functions (for image processing, or for training or retraining, or for saving, sorting, classifying, undoing, and so forth).

In an example given by Mena (ibid., section 6.7), the given photograph is matched to a photograph of (apparently) the same man, smiling and wearing a hat. It also retrieved a photograph of the same man with a beard. What the user did, was to click on the *Train* button and wait a little bit until the message "Training End!" appears. Mena explains (ibid., p. 166):

> The user can modify the setting parameters, like blurring, sensitivity, external weight cut, image type, segment size, etc. Once training is complete, the system can be directed to go out and look for images that match the training sample, with the output having an integer, representing a similarity value. The higher the score between the training image(s) and the retrieved images, the better the match.

Another kind of situation is when the person is physically present, and a decision needs to be taken as to whether to let that individual in. In the United States, facial recognition systems are used by casinos, but it is potentially valuable for other kinds of situations when prescreening is necessary or advisable.

Similarity search for images can be specialised for human faces, which is the case of face recognition software. Bear in mind however that there is thriving research

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[19] http://attrasoft.com

into general image similarity search. For example (*ERCIM News*, October 2010, p. 11), Andrea Esuli from ISTI-CNR in Pisa has been researching

> highly efficient similarity search, for which he has developed a novel algorithms based on prefix-permutation indexing. [. . . He] has turned this algorithm into a working search engine for images (http://mipai.esuli.it) that currently allows image similarity search on CoPhIR, the largest image dataset availbale for research purposes. Esuli's algorithm allows similarity searches to be conducted on CoPhIR in sub-second response times, a feat currently neither attained nor approached by competing systems.

In fact, MiPai is based on the PP-Index data structure for approximated similarity search (Esuli, 2009a, 2009b, 2010; Bolettieri et al., 2009). In the demo provided at Esuli's website, one can perform similarity search on the about 106 million images currently available in the CoPhIR collection.[20] Esuli explains[21]:

> The similarity measure used in this demo is based on a linear combination of the five MPEG-7 visual descriptors provided by the CoPhIR collection. The resulting concept of similarity is rather general, which is in line with the generalized nature of the images in the collection.
>
> This means that this may be considered a "general purpose" search system, where one may retrieve images globally similar to the one given as the query, for many aspects: color palette, distribution of colors in the image, presence of similar edges or textures.
>
> This does not means that this is an "all purpose" search system, i.e. you can't change the general similarity criterium with a more specific/specialized one. For example, you can't find shots of your cat climbing a wall given a shot of him sleeping on the sofa. You'll likely find shots of cats/dogs/teddy bears similar to your cat placed on a sofa similar to your sofa.

Efficiency comes at a cost, and a trade-off is made with accuracy[22]:

> One thing to be noted is that MiPai is an approximated method, thus the efficiency is paid with accuracy, i.e., the 100 selected images may not identify the exact (with respect to the MPEG–7 similarity measures) 100 most similar images. The MiPai algorithm offers multiple possibilities, both at index and search time, to trade efficiency for accuracy of results.

8.2.2.2 Reconstructing a Face from Verbal Descriptions: Mug Shots, vs. Sketches and Composites

Let us consider to faces in forensics in particular. Facial portraits, or *mugs*, may just be a photograph (a *mug* shot) of a suspect or convict; otherwise, if the portrait was made based on the verbal description of a victim or eyewitness, it used to be drawn by a sketch artist manually (such a portrait is sometimes called an *Identi-kit*). See Laughery and Fowler (1980) on the sketch artist and Identi-kit procedures for recalling faces, in a psychological perspective. An early example of a sketch produced manually in order to identify a perpetrator is from the Renaissance: a man and his child (who was to become a famous painter) were robbed, and on reaching

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[20] http://cophir.isti.cnr.it/

[21] http://mipai.esuli.it

[22] http://mipai.esuli.it

the town of Bologna, the boy skilfully drew a sketch, based on which the authorities promptly identified the robbers.

An alternative to the sketch of a sketch artist is a *composite*, by which initially a photographic *photofit* was intended. The term *photofit* is still in use in the U.S., whereas in the U.K. the more general term *composite* is preferred. Research was conducted on the photofit method during the 1970s (Penry, 1974; Ellis, Shepherd, & Davies, 1975; Davies, Ellis, & Shepherd, 1978). Its shortcoming is that a face is composed of different photographic segments, for the eyes and for the mouth, and the separation lines are visible and interfere with recognisability. See Wogalter and Marwitz (1991), on the construction of face composites.

Photofit evidence is not without problems. It is "a method to obtain details of the appearance of a suspect, which when first introduced was expected to be more useful than it has proved" (Osborne, 1997, p. 308). "It was widely assumed that such photofit pictures were merely for incidental use in establishing a suspect that could then be put on an identification parade. A very strange result however occurred in the [English] case of *R* v *Cook* [1987] QB 417" (ibid.), and Osborne describes it as follows:

> In *Cook* the accused was convicted on the basis of a photofit prepared by the victim. After the photofit had been prepared the police arrested the suspect and put him in an identification parade. The victim identified him. In the course of the trial the photofit was put in evidence, the judge ruled it admissible as 'part of the circumstances of the identification'. This was upheld on appeal. It was considered that neither the hearsay rule [for excluding evidence] nor the rule against admission of a previous consistent statement applied to this situation because in preparing the photofit the officer was merely doing what a camera would have done. This result has been much criticised and it is suggested that it is wrong. A photofit is nothing like a camera because there is the interposition of human intelligence. It is suggested that a photofit is hearsay, just as a verbal description of the accused would have been and should have been ruled inadmissible. The decision however, has been upheld in another case, *R* v *Constantinou* (1989) 91 Cr App R 74, on somewhat similar facts.

In France, face composites (in French: *portrait robot*) were developed by a police chief in Lyons during the 1950s, and only consisted of three sliding parts (*bandes coulissantes*), respectively for the hair and forefront, the eyes and eyebrows, and the mouth and chin. A sketch artist used to complete the composites with scars or moles. Eventually the police in Paris adopted the American *identity kit*. From 1993, the French police resorts to computerised face composites, which in French are called *portrait robot informatisé* (Tribondeau, accessed 2006, s.v. *portrait robot*).

Internationally, there exist various computerised systems, including E-FIT, PROfit (CD-FIT), and Mac-A-Mug Pro.[23] These old computerised systems appear to be less satisfactory than the manual method, with faces drawn by a sketch artist. Apparently E-FIT is good at recognising the faces of famous persons, whereas PROfit is good for recognising faces of persons with low distinctiveness. In the CRIME-VUs project (see below), an attempt has been made to improve on those

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[23] The E-FIT website is interesting; Amina Memon recommends it in her course handouts: http://www.visionmetric.com/index.php?option=com_content&task=view&id=17&Itemid=25

older systems. Bear in mind that composites are an *indicative tool* rather than an *implicative tool* (DNA evidence is an implicative tool, instead); nevertheless, composites are used in courtroom situations as evidence, even though it is not a weighty one.[24]

Johnston and Caldwell claimed (1997):

> One of the most widely used systems for generating composite faces was developed by Penry (1974), in Britain, between 1968 and 1974. Termed "Photofit", this technique uses over 600 interchangeable photographs, picturing five basic features: forehead and hair, eyes and eyebrows, mouth and lips, nose, and chin and cheeks. With additional accessories, such as beards and eyeglasses, combinations can produce approximately fifteen billion different faces. Alternatives to Photofit include the Multiple Image-Maker and Identification Compositor (MIMIC), which uses film strip projections, Identikit, which uses plastic overlays of drawn features, and several computerized versions of the Photofit process, such as Mac-A-Mug Pro and Compusketch. Using Compusketch, a trained operator with no artistic ability can assemble a composite in less than an hour. Because of such advantages, computer aided sketching is becoming the method of choice for law enforcement agencies.

Nevertheless, there is a shortcoming (Johnston & Caldwell, 1997):

> Systems such as Photofit and Compusketch depend on the ability of a witness to accurately recall the features of a suspect and to be aware of which features and feature positions of the generated composite require modification. Such systems may actually inhibit identification by forcing a witness to employ a specific cognitive strategy; namely, the recall of isolated features. Davies and Christie (1982) have shown that this single feature approach is a serious source of distortion, and Baddeley [(1979)] has concluded that any exclusively feature-based approach is misconceived.

Frowd et al. (2010a) explain:

> Face recognition essentially emerges from the parallel processing of individual facial features and their spatial relations on the face (see Bruce & Young, 1986, for a review). In contrast, face production is traditionally based more on the recall of information: the description and selection of individual features. While we are excellent at recognising a familiar face, and quite good at recognising an unfamiliar one, we are generally poor at describing individual features and selecting facial parts (for arecent review, see Frowd, Bruce, & Hancock, [2008]).

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[24] Frowd et al. (2005) presented what they referred to as being a forensically valid comparison of facial composite systems. Brace [sic], Pike, Kemp, Tyrner, and Bennet (2006) discussed whether the presentation of multiple facial composites improves suspect identification. Bruce [sic], Hancock, Newman, and Rarity (2002) had claimed that combining face composites yields improvements in face likeness. McQuiston-Surret, Topp, and Malpass (2006) discussed the use of facila composite systems in the United States. Frowd, McQuiston-Surret, Anandaciva, Ireland, and Hancock (2007) provided an evaluations of some systems for making facial composites, from the United States. Frowd, McQuiston-Surret, et al. (2007) tried to apply caricature in the attempt to improve the recognition of facial composites. Hasel and Wells (2006) claimed that applying morphing to facial composites helps with identifications, but Wells and Charman (2005) had claimed that building composites can harm lineup identification performance.

8.2.2.3 *FacePrints* for Generating Facial Composites

Caldwell and Johnston (1991) describe how a tool, *FacePrints*, based on an interactive genetic algorithm (GA) has been useful in assisting a witness to build a facial composite of a criminal suspect. That genetic algorithm[25] "can rapidly search a 'face-space' containing over 34 billion possible facial composites" (ibid., p. 416). An important feature of *FacePrints* is that it "relies on recognition rather than recall" (Johnston & Caldwell, 1997). *FacePrints* "begins by generating a set of thirty random binary number strings (genotypes) and developing these into composite faces (phenotypes)" (ibid.), where the binary string expresses a sequential set of coordinates in six position axes, corresponding to the shape and position of facial features. The witness views, one at a time, the thirty composites of the "first generation" of the algorithm, "and rates each face on a ten point scale according to its resemblance to the culprit" (ibid.); "the witness may not be aware of why any perceived resemblance exists" (ibid.). Then "the genotype of the fittest face and a second genotype, chosen in proportion to fitness from the remaining twenty-nine faces, are paired for breeding" (ibid.). In personal communication with the present author (13 December 1996), Victor S. Johnston remarked about the advantages of his approach: "The advantages of the GA are: 1. based on recognition rather than recall, 2. no interview required that could bias witness, 3. no exposure to mug shots. It is difficult to see how any bias could be introduced into a procedure that is driven only by the witness' recognition ability".[26]

8.2.2.4 The CRIME-VUs and EvoFIT Projects

Innovative tools for suspect recognition from facial composites include EvoFit (Frowd, Hancock, & Carson, 2004, 2010a)[27] and EFIT-V (Gibson, Solomon, Maylin, & Clark, 2009). In the United States, the leading tool is FACES. In South Africa, the ID software was developed (Tredoux, Nunez, Oxtoby, & Prag, 2006). "The basic operation of these 'recognition-based' systems is similar. They present users with a range of complete faces to select. The selected faces are then 'bred' together, to combine characteristics, and produce more faces for selection. When repeated a few times, the systems converge on a specific identity and a composite is 'evolved' using a procedure that is fairly easy to do: the selection of complete faces" (Frowd et al., 2010a). But (ibid.):

> One problem with the evolutionary systems is the complexity of the search space. They contain a set of face models, each capable of generating plausible but different looking faces. The models, which are described in detail in Frowd et al. (2004), capture two aspects of

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[25] Genetic algorithms are the subject of Section 6.1.16.1 in this book.

[26] For the application of genetic algorithms to evolving facial images, also see Hancock (2000), Hancock and Frowd (2001).

[27] The EvoFIT website is at http://www.evofit.co.uk/ Charlie Frowd's website is at this other address: http://www.uclan.ac.uk/psychology/research/people/Frowd.html

> human faces: *shape* information, the outline of features and head shape, and pixel intensity or *texture*, the greyscale colouring of the individual features and overall skin tone. The number of faces that can be generated from these models is huge, as is the search space. The goal then is to converge on an appropriate region of space before a user is fatigued by being presented with too many faces.

At the Face Perception Group (Faces Lab) at the Department of Psychology of the University of Stirling, in Scotland, the combination of facial composites, as well as sketches, and the effects of morphing between facial composites of the same depicted person, are studied in relation to effectiveness for recognition, in the framework of the CRIME-VUs project (Combined Recall Images from Multiple Experts and Viewpoints). The project, which was a predecessor of the EvoFIT project and produced an early version of the tool EvoFIT, had the aim of "examin[ining] the effectiveness of developing methods to construct and view composite images in 3D, and explor[ing] whether combining judgements from different witnesses could result in better composites" (Bruce & Hancock, 2002).

In CRIME-VUs, multiple techniques were resorted to, in forensically friendly format, and combining information from witnesses in different ways. One image processing technique used is morphing, for blending images into each other or to various degrees. Apparently the morph (of four composites) performs better than the best (and the worst) composite.

Hancock, Bruce, and Burton (1998) compared computer systems for face recognition with human perceptions of faces. Different image formats are compared, as to their impact on human and automatic face recognition, in Burton, Miller, Bruce, Hancock, and Henderson (2001). Bruce et al. (1999) were concerned with recognising persons from images captured on video. Importantly, in face recognition by humans, the recognition of unfamiliar faces (Hancock, Bruce, & Burton, 2000) is distinct from familiar face recognition (Burton, Bruce, & Hancock, 1999).

At the University of Central Lancashire (in Preston, northwest England) and the University of Stirling (in Scotland), Charlie Frowd and collaborators (Vicki Bruce, Peter Hancock, and Leslie Bowie, and others) has developed a novel "facial composite system", called *EvoFIT*. "Face construction by selecting individual facial features rarely produces recognisable images", whereas EvoFIT works by the repeated selection and breeding of complete faces" (Frowd et al., 2010a). EvoFIT is based on a holistic face coding scheme and an evolutionary interface[28]:

> Using this system, witness choose from a selection of faces that bear a resemblance to an assailant (a composite is 'evolved' over time by breading together the selected faces). In recent experiments, EvoFIT has outperformed other current composite systems (in the most recent realistic study, EvoFIT reached a level of naming roughly twice that of another UK composite system [...]). [...] EvoFIT has also been used in a criminal investigation, Operation Mallard (Northants). [...] (note that this system has the additional advantage that a verbal description is NOT required).

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[28] The quotation is from http://www.psychology.stir.ac.uk/staff/cfrowd/index.php ABM is the industrial partner for EvoFIT; they also produce PRO-fit, one of the two facial composite systems used in the UK (the other one is E-FIT).

> EvoFIT is now available for police and research use. It also has a construction 'wizard', rather like a wizard use to install software on a computer, and allows a composite to be constructed by a novice user. Please see www.evofit.co.uk

When a witness (or in general, a user) has to use EvoFIT, EvoFIT "presents users with screens of 18 such faces. Users select from screens of face shape, facial textures and then combinations thereof before the selected faces are bred together using a Genetic Algorithm,[29] to produce more faces for selection. This process is normally repeated twice more to allow a composite to be 'evolved'" (Frowd et al., 2010a).

Concerning a field trial of EvoFIT in 2007 with the Lancashire constabulary, developers claim[30]:

> Given that it is not essential for a witness or victim to describe a face in detail to use EvoFIT, which was a limitation with previous composite systems, the number of potential crimes that can benefit from this technology is very large. To date, about 20 police personnel have been trained, and there has been great success in a range of crimes in Lancashire from theft to burglary to indecent assault [. . .]. Lancashire police are delighted with the effectiveness of the system. They are also using the new caricature animation format to present their EvoFITs of wanted persons to the public, a procedure that has been shown to substantially improve recognition rates.

Frowd et al. (2010a) "explored two techniques. The first blurred the external parts of the face, to help users focus on the important central facial region. The second, manipulated an evolved face using psychologically-useful 'holistic' scales: age, masculinity, honesty, etc. [. . .] Performance was best using both techniques". Frowd et al. (2010a) shows that the latest techniques, *external feature blurring* and *holistic tools*, enable a composite to be created from a two day-old memory of a face with fairly-good correct naming rates, 25%. This is compared to 5% from a traditional feature system under the same conditions. Charlie Frowd kindly provided for publication in this book, in August 2010, a screenshot of the first generation of faces from which the genetic algorithm of EvoFIT starts, as well as a screenshot showing the blur. Refer to Figs. 8.2.2.4.1 and 8.2.2.4.2.

Also, by the summer of 2010, Frowd's team had just finished developing a new interview for EvoFIT. It is called the *Holistic-CI*, and promotes an even better quality composite – a correct naming rate of 40%, which is clearly quite remarkable. The experiment for this is described in Frowd et al. (2010b). Frowd et al. (2010b) explain:

> Facial composites are normally recovered from a witness's memory after a cognitive interview (CI). Here, we investigated the effect of different types of interview on composites produced from a newer evolving system, EvoFIT, which is based on the selection and breeding from arrays of complete faces. The holistic-cognitive interview (H-CI) promoted better likenesses and much more identifiable images than composites produced after the CI. Composites from both the hair-recall interview (HairI) and the holistic interview (HI) were identified similarly, and worse than composites from the CI.

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[29] Genetic algorithms are the subject of Section 6.1.16.1 in this book.

[30] At http://www.evofit.co.uk/ (accessed in 2010).

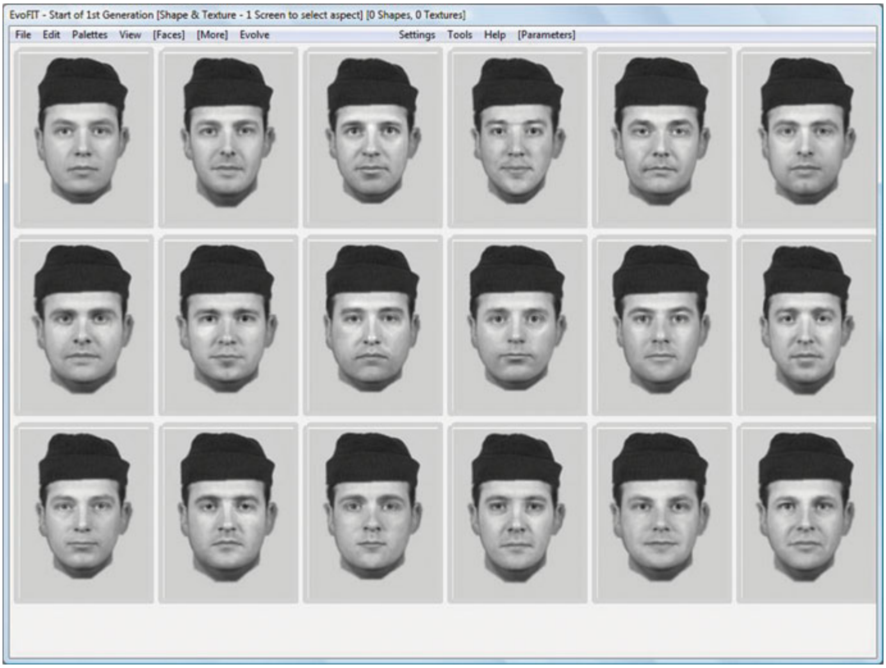

Fig. 8.2.2.4.1 A screenshot from EvoFIT. Courtesy of Charlie Frowd

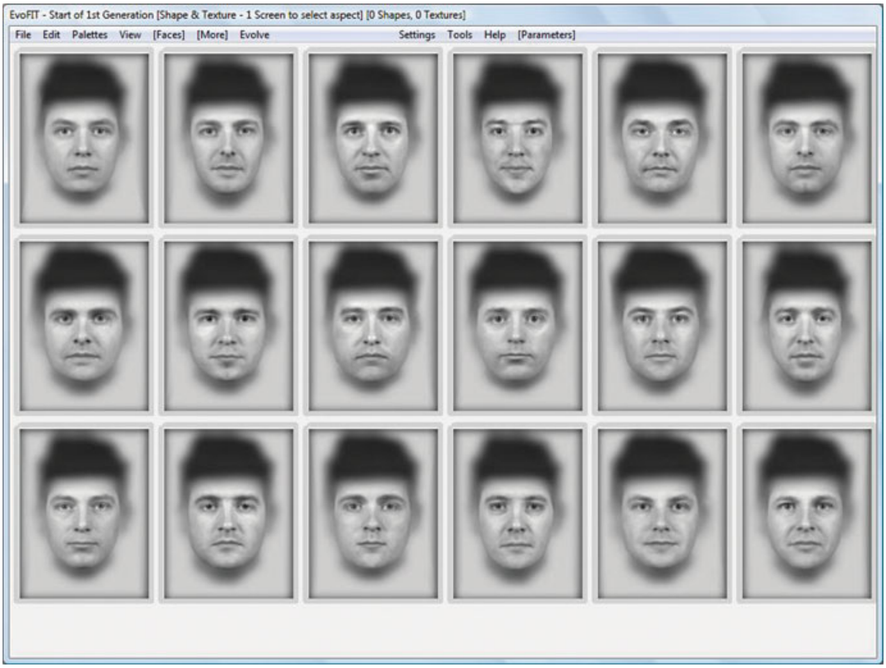

Fig. 8.2.2.4.2 A screenshot from EvoFIT, showing the blur. Courtesy of Charlie Frowd

Frowd explained (pers. comm., 19 August 2010) the relation between the CRIME-VUs and EvoFIT projects: “The CRIME-VUs project developed EvoFIT to a level where people could name the images at about 12% under the long delay. This gave us the evidence to take to the EPSRC government funding body to develop the blurring and the holistic tools, to essentially make it work as well as it does today”.

8.2.3 Age-Progression Software and Post-Surgery Face Recognition

There is a different kind of application of computer graphics for face processing, that is in use in various contexts as explained below. It is *age-progression software.* Based on a facial image, this kind of software predicts how the particular person would age, or would have aged, for some parameter of assumed wear. To the police, age-progression software is potentially useful for the purposes of getting a better idea of how a given person would look, when trying to locate missing persons.

Aprilage Development Inc.[31] in Toronto produces the APRIL Age Progression Software is the only statistically based age progression software. This software generates a stream of aged images of faces from a standard digital photograph. The wrinkling/aging algorithms are based upon two sources: (a) published data regarding facial changes associated with aging; (b) research of several thousand people of all ages, ethnicities and lifestyle habits, even though the widening of the range of racial backgrounds was gradual, by segmenting additional populations: Version 2.4 (released in 2007) also included South Asian facial aging, and a Hispanic/Latino component was scheduled to be released soon afterwards. That same version also includes a 3D Component, which allows the user to work with an image of a face in various positions, in three dimensions. Version 2.4 reportedly enabled more flexibility with starting age: that version can age a child as young as 6, or an adult as old as seventy-two years of age. The same version also included a new flipbook feature, intended to improve the workflow for repetitive tasks.

Moreover, adjustment of the output images is possible, in order to take into account whether a person will age as a smoker versus a non-smoker (Smoking Simulation Software), if he or she adds excessive weight or experiences a high degree of unprotected sun exposure. APRIL ages an individual’s face from adolescent to adulthood both as a non-smoker and as a pack-a-day consumer. It graphically predicts the premature wrinkling and unhealthy skin tone caused by cigarettes. The APRIL software was originally developed for use in science exhibits at Science Museums. Another context of use is as a health education tool, warning against smoking, obesity, and sun exposure (the latter possibly resulting in skin cancer: the

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[31] http://www.aprilage.com “Founded in 1998, Aprilage Development Inc. has developed APRIL® Age Progression Software in association with the Ontario Science Centre and with the support of the National Research Council of Canada. The software is used in more than a dozen countries for health and science education, entertainment and product marketing.”

software graphically predicts the premature wrinkling in the face by the effects of UV exposure). And indeed, the Roswell Park Cancer Institute in Buffalo, NY, was instrumental in helping develop the first version of APRIL.

Additional applications were envisaged, to assist in finding lost and missing children, and to help to identify criminals. In fact, APRIL can be used to help predict what an individual would look like after many years. For example, the tool could show how a pre-teen child who went missing may look as a teenager. APRIL was reportedly being used alongside a facial recognition software, for such applications to law enforcement and security. An application in a medical setting is that the software can be used in hospitals or in doctors' offices to illustrate how aging affects various medical, cosmetic, or surgical procedures. Reportedly, the tool was also being used at academic courses in gerontology.

Figures 8.2.3.1, 8.2.3.2, 8.2.3.3 and 8.2.3.4 were kindly supplied by Deirdre Hogan, Director of Sales at Aprilage, with permission to reproduce them here. These are pairs of images, the one on the left side in each pair being the photograph of a child or young adult, and the one on the right side in the same pair being a prediction of how that same individual would look as an adult or in old age. Respectively,

1. Figure 8.2.3.1 is file "gray_hair_example_Aprilage.jpg" from Aprilage, and shows normal aging of a white male young adult, the image on the right side showing him with grey hair, at age 72. The grey hair was obtained by applying the grey hair function.
2. Figure 8.2.3.2 is Aprilage's file "smoker-1-hi-res 45.JPG" and shows a girl, and how she would look aged 45, by assuming she smokes. The smoking factor was applied.

Fig. 8.2.3.1 Normal aging of a white male young adult (*left*), to age 72 (*right*). The grey hair was obtained by applying the grey hair function. Compliments of Aprilage Progression software (www.aprilage.com/www.age-me.com)

Fig. 8.2.3.2 A girl (*left*), and how she would look aged 45, by assuming she smokes. The smoking factor was applied. Compliments of Aprilage Progression software (www.aprilage.com/www.age-me.com)

Fig. 8.2.3.3 A boy (*left*) of South Asian background, with a projection reflecting normal aging of the same person (*right*), the way he would look aged 60. The image of this person as an old man did not have the grey hair function applied. Compliments of Aprilage Progression software (www.aprilage.com/www.age-me.com)

3. Figure 8.2.3.3 is Aprilage's file "male SA org 2.5_3.jpg" and shows a boy of South Asian background, with a projection reflecting normal aging of the same person, the way he would look aged 60. The image of this person as an old man did not have the grey hair function applied.
4. Figure 8.2.3.4 is Aprilage's file "male Lat org 2.5._2.jpg" and shows a young male of Latino background, and how he would look with normal aging at age 70. The image as an old man did not have the grey hair function applied.

Fig. 8.2.3.4 A young male (*left*), and how he would look with normal aging at age 70 (*right*). The image as an old man did not have the grey hair function applied. Compliments of Aprilage Progression software (www.aprilage.com/www.age-me.com)

8.2.4 Facial Expression Recognition

Lisetti and Schiano (2000) reported about an automated facial expression recognizer they were developing. Moreover, they

> present some of the relevant findings on facial expressions from cognitive science and psychology that can be understood by and be useful to researchers in Human-Computer Interaction and Artificial Intelligence. We then give an overview of HCI applications involving automated facial expression recognition, we survey some of the latest progresses in this area reached by various approaches in computer vision (ibid., from the abstract).

They went on to "propose an architecture for a multimodal intelligent interface capable of recognizing and adapting to computer users' affective states" (ibid.). Their article is part of a multidisciplinary special issue of *Pragmatics & Cognition* on facial information processing in human cognition (Dror & Stevenage, 2000); see there, e.g., Anna Wierzbicka's (2000) "The semantics of human facial expressions".

8.2.5 Digital Image Forensics

Digital image forensics consists of computational methods of detection of image tampering. Such tampering is also done by computer (*digital forgeries*). Images typically portray people, and tools from image forensics work on models in three dimensions of the bodies that appear in the picture. Distinguish between computer models of the reasoning of and about deception, and computer techniques intended to enable the detection of forgeries, within forensic science. This is the case of a technique that maps inconsistencies in lighting in doctored, composite photographs, by associating a sphere with its own index of lighting with different regions of the photograph (Johnson & Farid, 2007a).[32]

The need for such technology was made acute by the spread and level of sophistication of digital imaging technology that can be used for manipulating digital images, including the production of photo hoaxes[33] or maliciously doctored photographs. Johnson & Farid remarked (2007a, p. 250):

> The field of digital forensics has emerged over the past few years to combat this growing problem. Several techniques have been developed to detect various forms of digital tampering. Statistical techniques have been developed for detecting cloning [(Fridrich et al., 2003; Popescu & Farid, 2004)]; splicing [(Ng & Chang, 2004)]; re-sampling artifacts [(Popescu & Farid, 2005a; Avcıbaş et al., 2004)]; color filter array aberration [(Popescu & Farid, 2005a)]; and disturbances of a camera's sensor noise pattern [(Lukáš et al., 2006)]. Optical techniques have been developed to detect chromatic aberrations [(Johnson & Farid, 2006a)], and geometric techniques for rectifying perspectively distorted planar surfaces [(Johnson & Farid, 2006b)]. More recently two related approaches have been developed for detecting inconsistencies in lighting [(Johnson & Farid, 2005, 2007b)]. Building specifically on this work, and more broadly on all of these forensic tools, we describe a new lighting-based digital forensic technique.

Johnson's dissertation (2007, p. 54) explains:

> Lighting environments can be captured by a variety of methods, such as photographing a mirror sphere [(Debevec, 1998)], or through panoramic photography techniques. These methods produce high dynamic range images, known as light probe images, that represent the lighting environment function $L(V)$. The spherical harmonic coefficients are computed by integrating the lighting environment function $L(V)$ against the corresponding spherical harmonic basis function [(Ramamoorthi & Hanrahan, 2001)]:

$$l_{n,m} = \int_{\Omega} L(\vec{V}) Y_{n,m}(\vec{V})\, d\Omega$$

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[32] A popularistic introduction to this branch of image processing was provided by Hany Farid (2008), whereas Popescu and Farid (2005b) is a technical journal article, and Micah Kimo Johnson's dissertation (2007) is available online. Farid's team is at Dartmouth College.

[33] Johnson and Farid (2007a, figure 1) gave a poignant example, by showing a fake cover of a celebrity magazine. The original *Star* magazine cover showed actress Katie Holmes on the right side, with her left hand on the left shoulder of actor Tom Cruise. The cover headline claimed: "TOM & KATIE Are They Faking It?". The fake cover, instead, showed the paper's first author, Kimo Johnson, in place of Tom Cruise, and the pre-headline read "KIMO & KATIE". One could tell it was fake, however, because there was a shadow on the right side of Kimo's face, whereas there was mcuh light in the environment (as could be seen from Holmes' own face, and also from Cruise's face in the original). In Johnson (2007, p. 26), figure 3.1 shows a "photograph of the *American Idol* host and judges" which "is a digital composite of multiple photographs. The inconsistencies in the shape and location of the specular highlight on the eyes suggest that these people were originally photographed under different lighting conditions." Enlarged details show the eyes of the various persons in that photograph.

Johnson's dissertation (2007, pp. 54–55) shows several light probe images,[34] each on a sphere, and captured at places like inside Grace Cathedral in San Francisco, Galileo's Tomb and the Uffizi Gallery in Florence, and so forth. From each such light probe image, lighting environment coefficients were computed. Next, these lighting environment coefficients were each used to render a Lambertian sphere, characterising the respective lighting environment. Being *Lambertian* means that is reflects light isotropically (ibid., p. 7).[35] Johnson (ibid., p. 47, figure 4.4) showed how lighting environments could be rendered on spheres, by displaying the first three orders of spherical harmonics as functions on the sphere: from top to bottom, that figure showed the order zero spherical harmonic, $Y_{0,0}(\cdot)$; the three order one spherical harmonics, $Y_{1,m}(\cdot)$; and the five order two spherical harmonics, $Y_{2,m}(\cdot)$. "Irradiance describes the total amount of light reaching a point on a surface. For a Lambertian surface, the reflected light, or radiosity, is proportional to the irradiance by a reflectance term ρ. In addition, Lambertian surfaces emit light uniformly in all directions, so the amount of light received by a viewer (i.e., camera) is independent of the view direction. A camera maps its received light to intensity through a camera response function" (ibid., p. 48). Moreover, "the change in the intensity profile due to an increased exposure time t_2 can be modeled by a linear change to the profile of exposure time t_1" (ibid., p. 49). The relationship between image irradiance and intensity is expressed by a formula that can itself be rewritten in terms of spherical harmonics. Lighting environments can be estimated (ibid., section 4.1.3) and compared (ibid., section 4.1.4).

By introducing results, Johnson explained (2007, p. 54, section 4.2):

> We tested our technique for estimating lighting environment coefficients on synthetically generated images and real images of natural lighting environments. The synthetic images were rendered using the pbrt environment [(Pharr & Humphreys, 2004)] with data from a gallery of light probe images maintained by Paul Debevec [(1998)]. The natural images were obtained in two different ways. For the first set, we photographed a known target in a variety of lighting conditions. For the second set, we downloaded twenty images from Flickr, a popular image sharing website [[36]]. Results from four visually plausible forgeries are also presented. For all images, the lighting environment coefficients were estimated from the green channel of the image. Although all three color channels could be analyzed, we find that this is often unnecessary since the estimation is invariant to both multiplicative and additive terms.

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[34] Light probe images by Paul Debevec, available at http://www.debevec.org/Probes.

[35] "The standard approaches for estimating light direction begin by making some simplifying assumptions about the surface of interest: (1) it is Lambertian (i.e., it reflects light isotropically); (2) it has a constant reflectance value; (3) it is illuminated by a point light source infinitely far away; and (4) the angle between the surface normal and the light direction is in the range 0°–90°" (Johnson, 2007, p. 7).

[36] Flickr home page, at http://www.flickr.com.

In the discussion section in Johnson and Farid (2007a, section IV),[37] they pointed out the following, which is relevant to doctored images that show side by side persons who were originally not photographed together:

> When creating a composite of two of more people, it is often difficult to exactly match the lighting, even if the lighting seems perceptually consistent. The reason for this is that complex lighting environments (multiple light sources, diffuse lighting, directional lighting) give rise to complex and subtle lighting gradients and shading effects in the image. Under certain simplifying assumptions (distant light sources and diffuse surfaces), arbitrary lighting environments can be modeled with a 9-dimensional model. The model approximates the lighting with a linear combination of spherical harmonics. We have shown how to apporximate a simplified 5-dimensional version of this model from a single image, and how to stabilize the model estimation in the presence of noise. Inconsistencies in the lighting model across an image are then used as evidence of tampering.
>
> We showed the efficacy of this approach on a broad range of simulated images, photographic images, and visually plausible forgeries. In each case, the model parameters can be well approximated, from which differences in lighting can typically be detected. There are, however, instances when different lighting environments give rise to similar model coefficient – in these cases the lighting differences are indistinguishable.

In conclusion: "While any forensic tool is vulnerable to counter-measures, the precise matching of lighting in an image can be difficult, although certainly not impossible" (ibid.). The analysis of three forgeries (ibid., figure 12) associate differnetly shaded spheres characterising different lighting environments to different elements in the composite. For example, in one doctored photograph, ducks standing on the ground were added very close to players at a match. The shading effect on the spheres associated with two of the ducks are identical, but different from the shading effect on the spheres associated with two of the players. In another photograph, three men are standing side by side. The first one to the left is a football coach wearing sunglasses, a red shirt and white trousers. The other two men are soldiers holding rifles and wearing camouflage. The two spheres associated with the two soldiers have an identical shading effect, but the latter is different from that of the sphere associated with the football coach. Another photograph (ibid., figure 12) "is a forgery where the head of rapper Snoop Dogg has been placed on the body of an orchestra conductor" (with crossed arms, besuited, and with a white papillon; but the skin of a hand is that of a black person, like the face). Spheres rendered from the estimated lighting coefficients are associated with the head and the trunk, and the shading effect on the two spheres is different.

8.2.6 Facial Reconstruction from Skeletal Remains

Forensic *facial reconstruction* is the reproduction of an individual human's face from skeletal remains. To say it with Aulsebrook, Iscan, Slabbert, and Becker (1995): "Forensic facial reconstruction is the reproduction of the lost or unknown

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[37] Understandably, Johnson and Farid's article (2007a) shares very much with the doctoral dissertation (Johnson, 2007).

facial features of an individual, for the purposes of recognition and identification. It is generally accepted that facial reconstruction can be divided into four categories: (1) replacing and repositioning damaged or distorted soft tissues onto a skull; (2) the use of photographic transparencies and drawings in an identikit-type system; (3) the technique of graphic, photographic or video superimposition; (4) plastic or three-dimensional reconstruction of a face over a skull, using modelling display".

Whereas Aulsebrook et al. (1995) is a review of "work done on both superimposition and plastic reconstruction", nevertheless "the authors believe that only the latter category can correctly be termed facial reconstruction". Computer-graphic techniques fit in categories (2), (3), and (4).

Caroline Wilkinson (2004) presents the Manchester method of forensic facial reconstruction. She also discusses how to reconstruct the faces of children. Her book collates all published facial tissue data, and describes tissue variations with reference to age, sex, stature and ethnic origin, for use by practitioners. Wilkinson also evaluates the accuracy of current methods.

There are factors which militate in favour of one candidate reconstruction rather than another one. In one case from England, in which a man's body was found at a stage of decomposition in which it looked like a lump of fat, two facial reconstructions were developed, one with a European likeness, and the other one with a Near Eastern likeness, whose appropriateness was suggested by the fact that on the teeth of the skull there were traces of *kat*, a recreational drug in common use in Yemen (and by some in Saudi Arabia). Eventually it was discovered that the man was a Yemeni-born grandfather who had been murdered by his own son.

In another case, a large set had been developed of possible face reconstructions for the body of a young woman, and when she was eventually identified, and it was possible to verify the accuracy of the reconstructions from photographs, it turned out that none of those reconstructions looked anywhere close to how she actually looked like when alive.

Not always facial reconstruction is for forensic purposes. A professor in Sheffield who reconstructed the face of ancient Egypt's Queen Nefertiti, related, at a workshop in Edinburgh in the summer of 2004, how after a television broadcast on that project of his, a lady phoned to inform him that he got it wrong. He conceded to her that there may be errors, but then she claimed: "**I** am Nefertiti". She promised she would send him evidence in support. John Prag and Richard Neave (1997) are concerned with reconstructing the facial appearance of ancient people; one of these is the famous King Midas, and another one is Philip II, the powerful father of Alexander the Great. The portrait of Philip II from coins provided cues for reconstruction. Another category also treated in the same book is ancient human remains retrieved from bogs. Prag and Neave's book caters to a broad audience, yet includes moderately technical detail. An early example is a sculpture of the head of Tamerlane (see Fig. 8.2.6.1): a "[p]ortrait head of Timur [was] made by the Soviet scholar M. M. Gerasimov. This sculpture is very accurate as it is based upon the skull found in Timur's grave. By closely studying such skulls and then working out the exact position of muscles, eyes, skin, hair and so on, Gerasimov pioneered the

Fig. 8.2.6.1 The portrait head of Timur (i.e., Tamerlane), as reconstructed by Mikhail Gerasimov

reconstruction of the portrait heads of long dead people" (Nicolle, 1990, p. 144, in a caption to a photograph).

Archaeologist and anthropologist Mikhail Mikhaylovich Gerasimov (1907–1970) "developed the first technique of forensic sculpture based on findings of anthropology, archaeology, paleontology, and forensic science. He studied the skulls and meticulously reconstructed the faces of more than 200 people, including Yaroslav the Wise, Ivan the Terrible, Friedrich Schiller and, most famously, Tamerlane" ([Gerasimov] 2007). Gerasimov's early work, from 1927 on, was on skulls of prehistoric or exotic humans. "It took a decade of studies and experiments to come close to individual portrait resolution quality of historical persons", yet "his first public work of this type is dated 1930", this being the "face of Maria Dostoyevskaya, mother of Fyodor Dostoyevsky" (ibid.). He worked on the skulls of Yaroslav the Wise in 1938, and of Tamerlane in 1941. "In 1953 the Soviet Ministry of culture decided to open the tomb of Ivan the Terrible and Gerasimov reconstructed his face" (ibid.). See Eve Conant's article (2003), and Mikhail Gerasimov's own *The Face Finder* (Gerasimov, 1971), originally of 1968. The earliest version of his memoirs appeared in Russian in 1949.

Facial reconstruction, as mainly developed for forensic purposes, when applied in an archaeological context has enabled even glaring departure with respect to ancient portraits (conditioned by cultural conventions) to be ascertained. Olga Wojtas (1996) reported that "[f]orensic techniques used by the police to establish the identity of unknown bodies have revealed what sixteenth-century Scottish humanist, classicist, historian and poet George Buchanan looked like. [. . .] Most of the portraits of the time pay tribute to his brain power by depicting a man with an enormous forehead, a literal "highbrow". But Buchanan's skull [. . .] is relatively small, with an average-sized forehead". Anatomist Matthew Kaufman "decided to find out whether any of the portraits were accurate", and then, having had the face reconstructed from a plaster cast, "was staggered" as "it turned out to be almost identical to a portrait of Buchanan now hanging in the Royal Society in London" and which, significantly, "avoids the convention of linking exceptional intellect to a large forehead". The newspaper report concludes with the interviewee remarking that head size as an indicator of intellect is a widespread belief. Nevertheless, a distinction is to be made between beliefs and pictorial or other culture-bound representational conventions.

It must be noted that whereas, when discussing forensic archaeology, we mentioned that there is a perception that this discipline is ahead in the application of scientific techniques to forensics for some applications, this is not the case of face reconstruction. An expert in forensic face reconstruction was skeptical, during her lecture at a workwhop in Edinburgh, of forensic archaeology precisely inasmuch face reconstruction is involved. In fact, in forensic face reconstruction, once human remains are identified and photographs of the dead person are obtained, it happens sometimes that face reconstructions that had been developed are found to be wide of the mark, and in some real case it can be seen that alternative reconstructions that had been proposed, could be seen to be quite different even before the identification was made. (It basically depends on the methods, and on assumptions.)

By contrast, no such validation is possible, when the face of a person from antiquity is reconstructed. In turn, this is different from peat bodies, which may be well conserved even after a millennium, and what one sees is a blackened face that is not a reconstruction; such is the case of the body of a garrotted man who was found in Denmark. His face, short facial hair, and hat are well preserved, but the mangling of his neck is an effect of his execution, before his body was thrown into the bog.

8.2.7 Considerations about Socio-Cultural Factors in Portraiture That Have Been Analysed with Episodic Formulae

In Section 5.3, we have been concerned with the representation of narratives by means of *episodic formulae*. One of the models that adopt that approach it TIMUR

(Nissan, 2008b). In Section 5.3.1, among the other things I explained that the analysis in TIMUR is of

> a perhaps apocryphal anecdote about the emperor Tamerlane. He invited three painters in turn, and commissioned from each, his own portrait. The first painter painted the king as a very handsome man, and Tamerlane had him beheaded, to punish him for his excessive flattery. The second painter represented the king realistically, if one means by that: warts and all. Tamerlane had him beheaded, as he found it intolerably offensive to see himself represented with hideous features. The third painter portrayed the king in the act of shooting an arrow, and did so "realistically", yet without revealing the physical defects, because the posture was such that these would not be apparent. How did the third painter portrait Tamerlane? In fact, in order to shoot the arrow from his bow, Tamerlane was kneeling down, so one would not notice that one leg was shorter. To aim, Tamerlane shut an eye, so one could not tell out the squint which affected his eyes (because you need to see both of them open, to tell out). This way, the life of the third painter was saved.

I also pointed out that this story of Tamerlane and the three painters involves fairly complex epistemic structures of belief and intentionality, and these are involved in the characters' reasoning about the human body of one of them, and about the depiction of that body in a portrait (i.e., in a given kind of representation). There are factors involving *ontologies:* Tamerlane shares with the three painters their all's being instances of kind 'human being', but, Tamerlane doesn't possess the specific skills associated with kind 'painter'. At any rate, he contracts out to painters the task of painting his portrait. The painters are utterly at his mercy, because his authority is absolute. Tamerlane, being an instance of kind 'absolute ruler', of which there only is (at most) one in a given polity, possesses a very high degree of authority on all other agents within the polity, and they in turn not only do not possess authority on him (except his doctor, if he considers him authoritative and follows his advice), but also hardly can resist his orders. Therefore, it is extremely dangerous for them to provoke his susceptibility, which is both affected by emotion, and is rational at the same time. He does not need to be concerned about the same in the reverse relation (unless he does so to so many and to such a degree, that the polity would rebel as well as his own otherwise obedient army).

Now refer to Fig. 8.2.7.1. This is figure 4 from Nissan (2008b, p. 574). The diagram shows an agent's mind, action, and structure, in relation to norms and to the potrait which in turn represents one of the agents, namely, Tamerlane. In section 3.6 of Nissan (2008b), 'Intentions and Effects of Portraying the Ruler' (ibid., pp. 546–555), I discussed eight examples from different cultures and historical periods, of cultural factors and effects associated with the portrait of a person in power. In section 3.15 in Nissan (2008b), 'Tamerlane Reading the Mind of Painter1' (ibid., pp. 564–565), episodic formulae express how Tamerlane may have reasoned about the first painter's own reasoning when choosing to paint him in the manner he did. The value of this kind of analysis is that is provides a formal means for representing reasoning about an individual's portrait, and also the fact that there is a difference between a portrait and an image unaffected by cultural factors. Even a photograph, for example a mug shot, carries an important luggage of cultural traditional conventions.

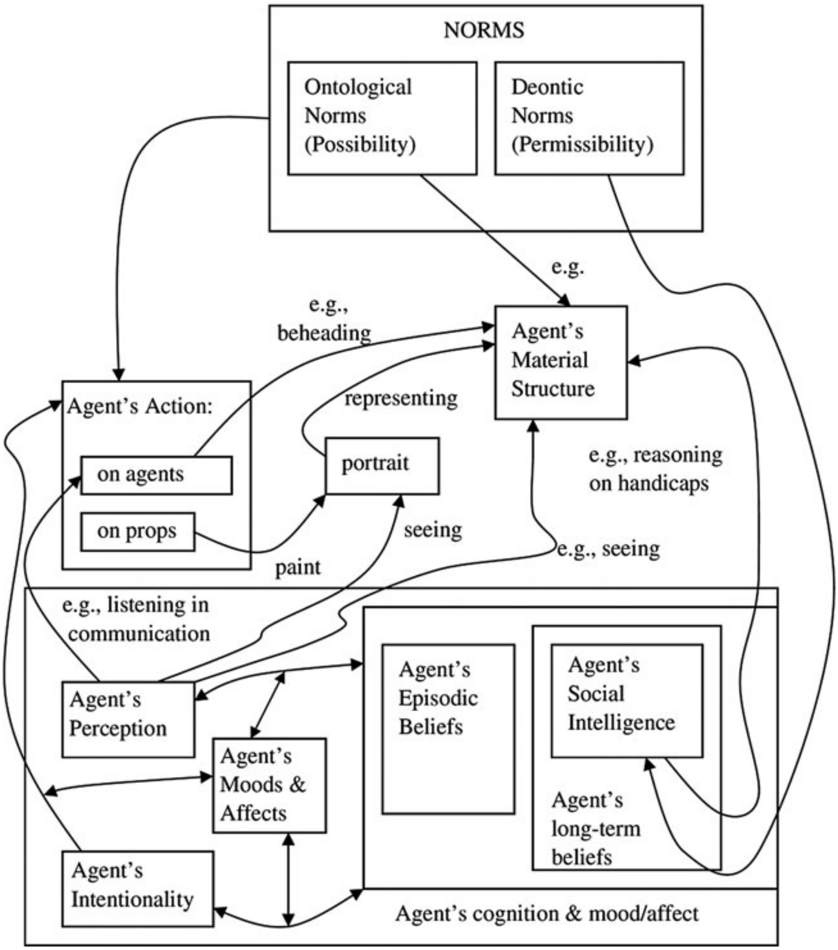

Fig. 8.2.7.1 An agent's mind, action, and structure, in relation to norms and to the portrait which in turn represents one of the agents. This is relevant for making sense of the story of Tamerlane and the three painters who, in turn, endanger themselves by painting his portrait

8.3 The Burgeoning Forensic Disciplines of Expert Opinion

8.3.1 General Considerations, and Some of the Specialties

Franke and Srihari (2008) provided an overview of *computational forensics*, at the very beginning of the proceedings of an international workshop about that domain. By *computational forensics*, what is meant is computer techniques for any discipline within forensic science.[38] Concerning the booming of forensic specialties, Hans Nijboer remarked[39] (2000, p. 3):

> [W]e can observe the fast development of forensic techniques and forensic specialties in the broader sense. Between archaeology or accountancy in its forensic form and the forensic zoology we indeed see over [one] hundred different forensic disciplines, of which some are well-established (like forensic psychiatry) and some have just started in developing 'objective' standards (shoe-print comparison)

– a development among whose critics he is.

> It has become clear that DNA based techniques are in fact not perfect but they are not too weak. But at the same time it was discovered that many techniques and methods lack a sound basis in a broader scientific sense. Very often objective standards and information about the validity and reliability of specific forensic techniques are simply unknown (ibid., p. 7).

Student enrolment is affected by the blooming of the forensic sciences.[40] An exception to the generally declining enrolment in chemistry at U.K. university departments, is the number of students who want to study forensic chemistry. In the present Section 8.3, we are going to raise some points concerning an array of forensic disciplines, combining forensic science, engineering-related issues, and forensic psychology. In the remaining sections of this chapter, we are going to deal with sample areas, each in turn. These areas in which computing or electronics, or sometimes more specifically knowledge-based systems of pattern-matching software, have actually been applied. Or then, they are areas in which there may be some potential for application.

Reliance on expert testimony may be problematic,[41] from the viewpoint of legal evidence theory, in that (in an Anglo-American perspective) there is a risk of tacitly

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[38] *Computational forensics* is about what computing can do for forensic science. It should not be mistaken for *computer forensics* (itself part of *digital forensics*), i.e., the forensic discipline concerned with illegal actions involving a computer. In a sense, we find here a distinction similar to the one between *computational science* – i.e., *scientific computing:* what computing can do for science – and *computer science*, the science of computing.

[39] Nijboer's (2000) was an overview of current issues in legal evidence. In the tenth anniversary issue of the e-journal *International Commentary on Evidence*, published at Berkeley in California, Nijboer (2008) provided comparative comments on current issues in evidence and procedure from a Continental perspective, as have emerged during the 2000s. He "discusses three dimensions of generality in evidence and procedure: (1) generality of fundamental issues in evidence and fact-finding and insights about them across national borders, (2) generality of issues of criminal evidence across various relevant disciplines (and professions), and (3) generality with respect to specific issues of criminal evidence and its principles and rules addressing the various probanda of specific crimes (murder, theft, rape, arson, negligence causing a serious traffic accident, et cetera)." Nijboer (2008) made frequent references to case law of the European Court of Human Rights (ECHR).

[40] Brenner (2000) is a glossary of forensic science. James and Nordby (2003, 3rd edn. 2009) is an edited volume with overview chapters on various forensic disciplines. In that volume, Zeno Geradts (2005, 2nd edn.; 2009, 3rd edn.) provides an overview of the *use of computers in forensic science.*

[41] There is a literature about expert evidence. For example, Carol Jones (1994) is concerned with expert evidence in Britain.

shifting paradigm from fact-finding by courts because the court has freely formed an opinion (*free proof*), to some form of binding reliance on expert testimony. In itself, reliance on expert witnesses may be problematic, perhaps because they may be misunderstood, but also because, in all frankness, trained judges tend to have a better reputation that both lawyers (whose reviled variant is the "shyster"), and expert witnesses (whose reviled variant is reputed to be the "hired gun", or to no lesser degree the more benign, if unfortunately rather benighted, astrologer-type; at any rate, lawyers during cross-examination typically try to discredit the expert witness of the other side).

If the perspective we are to adopt is historical, it will be important to point out that *free proof* (that has its detractors, among legal theorists in Anglo-American jurisdictions) was an achievement, especially as meant, or in the form it took, in Continental Europe. It replaced the so-called *legal proof* (in Latin *probatio legalis*, in French *preuve legale*, in German *gesezliche Beweistheorie*), and emancipated the judicial evaluation of the evidence from the older law of proof. This also involved the demise of torture as means for obtaining evidence; torture was deemed necessary for obtaining proof as necessary, in turn, to secure conviction, according to the system of legal proof, as opposed to the system of free proof that replaced it. In Continental Europe, free proof replaced rules of *quantum and weight;* these did not use to be part of the English and American judiciary systems.

Another kind of problem is that some important areas of expert testimony, such as forensic psychology or psychiatry, are treated variably, according to the country in which the court is, apart from the diffidence that lawyers are claimed to have of psychologists (see, e.g., Nissan, 2001f). Whatever negative may happen without expert testimony? In a section entitled "Evidence sans Expert", barrister and consultant psychiatrist Mahendra (2007, p. 1490), writing in England, commented on a recent court case:

> That expert evidence plays a crucial role in modern litigation is well accepted. It is required by a court which acknowledges its lack of expertise on the relevant issues on which it requires the assistance of experts. But this does not mean that evidence which would normally be within the province of the expert is not present in the course of a trial even while no expert is present. This evidence may influence the judge and, where present, a jury.
>
> One such area concerns mental disorder which, being commonly found, may then play some part in these deliberations and, yet, may not be subject to expert opinion in these circumstances. As lay individuals are known to hold all manner of views, not all reliable or valid, on psychiatric matters there may be scope for misunderstanding and even injustice. The issue came up in *R v Osbourne* [2007] EWCA Crim 481, [2007] All ER (D) 206 (Mar).

Forensic psychology[42] is not necessarily about the state of mind of a perpetrator, or of a victim. It has important things to say about the reliability of identification from memory. Uncertainty about an identity turns out in a broad array of forms, when

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[42] See for example a volume, *Forensic Psychology*, edited by Joanna Adler (2010, 2nd edn. [originally of 2004]). In that book, section 1, entitled 'Forensic Psychology in Context', comprises chapter 1, 'Forensic psychology: concepts, debates and practice', by Joanna R. Adler; and chapter 2, 'Public perceptions of crime and punishment', by Jane Wood and G. Tendayi Viki.

it comes to legal matters. Oftentimes, it is about personal identity: the identity of a human individual, possibly a culprit (not just in real life, but in whodunit fiction as well) or one otherwise liable, or, then, a victim. Identification is oftentimes required of witnesses.

The literature on the assessment of witness reliability is very extensive; writing about eyewitness identification would be a book in its own right.[43] In her 2008 course handouts in *Psychology, Law and Eyewitness Testimony* at her website at the University of Aberdeen in Scotland, psychologist Amina Memon has provided useful entry points into the scholarly literature: “Gary Wells (USA) has an excellent website containing numerous articles on eyewitness memory”[44]; “Maryanne Garry (New Zealand) provides access to all her publications on false memories”.[45] “Loftus also provides access to her articles on misinformation and false memory as well as some good links”.[46] “Paul Ekman makes his papers on deception available on his website”.[47] “Gary Well’s website [has] lots of good links”[48]; and so forth. Other

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Section 2, ‘Investigation and Prosecution’, comprises chapter 3, ‘USA and UK responses to miscarriages of justice’, by Tom Williamson; chapter 4, ‘The interpretation and utilisation of offender profiles: a critical review of ‘traditional’ approaches to profiling’, by Laurence Alison and Emma Barrett. Section 3, ‘Testimony and Evidence’, comprises chapter 5, ‘Eliciting evidence from eyewitnesses in court’, by Mark R. Kebbell and Elizabeth L. Gilchrist; and chapter 6, ‘The ageing eyewitness’, by Amina Memon, Fiona Gabbert and Lorraine Hope. Section 4, ‘Correlates of Criminality – sensations and substances’, comprises chapter 7, ‘The status of sensational interests as indicators of possible risk’, by Vincent Egan; chapter 8, ‘Drug use and criminal behaviour: indirect, direct or causal relationship?’, by Ian P. Albery, Tim McSweeney and Mike Hough; and chapter 9, ‘Drug arrest referral schemes and forensic perspectives on the treatment of addiction’, by Andrew Guppy, Paul Johnson and Mark Wallace-Bell. Section 5, ‘Persistent Offending’, comprises chapter 10, ‘Life-course persistent offending’, by Alex R. Piquero and Terrie E. Moffitt; and chapter 11, ‘Stalking, Lorraine Sheridan and Graham Davies’. Section 6, ‘Intervention and Prevention’, comprises chapter 12, ‘Domestic violence: current issues in definitions and interventions with perpetrators in the UK’, by Elizabeth L. Gilchrist and Mark Kebbell, chapter 13, ‘Effective programmes to prevent delinquency’, by Brandon C. Welsh and David P. Farrington; and chapter 14, ‘Parenting projects, justice and welfare’, by Anthony H. Goodman and Joanna R. Adler. Section 7, ‘Punishment and Corrections’, comprises chapter 15, ‘Women in prison’, by Nancy Loucks; and chapter 16, ‘Applied psychological services in prisons and probation’, by Graham Towl.

[43] For a treatment of the psychology of person identification, see Clifford and Bull (1978). In Bull and Carson (1995), the chapter ‘Assessing the Accuracy of Eye-witness Identifications’ (Cutler & Penrod, 1995) has long been a useful entry point to the subject. Eyewitness psychology (e.g., Loftus, 1974 sqq, Ross et al., 1994) is but one area of forensic psychology. The *American Journal of Forensic Psychology* was established in the early 1980s; the British *Journal of Forensic Psychiatry & Psychology*, at the end of that same decade.

[44] http://www.psychology.iastate.edu/faculty/gwells/homepage.htm (cf fn. 19in Chapter 4).

[45] http://www.vuw.ac.nz/psyc/staff/maryanne-garry/index.aspx

[46] http://www.seweb.uci.edu/faculty/loftus/

[47] http://www.paulekman.com/downloadablearticles.html

[48] http://www.psychology.iastate.edu/~glwells/

than concerning witnesses, forensic psychology may, e.g., concern the custody of children of divorced parents.[49] And then there is forensic psychiatry.[50]

Cutler and Penrod (1995) are concerned with eyewitness identification of criminals in the United States, and Ross, Read, and Toglia (1994) are likewise concerned with criminal investigations with adult witnesses. In Bull and Carson (1995), Daniel Yarmey's chapter (Yarmey 1995) 'Earwitness and evidence obtained by other senses' is also about the identification of a person, such as a perpetrator. Hammersley and Read (1993), which appeared in a volume on the identification of suspects and its psychology, deals with voice identification by humans and computers.[51]

Henry Lee's Crime Scene Handbook (Lee, Palmbach, & Miller, 2001) is devoted to how to conduct an investigation,[52] starting by protecting and managing a crime scene; the *Handbook* includes a chapter, "Logic Trees", that could justifiably be of interest to such computer scientists who are interested in formalising general reasoning for the purposes of assisting crime analysis. One of the case studies in that volume is on shooting scene reconstructions. For a treatment of science in the criminal investigations, see, e.g., Kaye (1995) and Saferstein (1995); the latter considers forensic ballistics,[53] chemistry, and medicine. Cook et al. (1998)

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[49] For a U.S. perspective, see Ackerman (1995).

[50] See, e.g., Lonsdorf (1995), Belfrage (1995), Chiswick and Cope (1995), Faulk (1994), Lloyd (1995), Gunn and Taylor (1993). Eigen (1995) considers forensic psychiatry in the context of British history.

[51] Also see Hollien (1990), about voice in forensic contexts.

[52] Kaye's (1995) *Science and the Detective: Selected Reading in Forensic Science* is a useful introduction. Lane, Tingey, and Tingey (1993) is a specialised encyclopaedia, but in a rather popularistic perspective.As to the *Encyclopedia of Forensic Sciences* (Siegel, Knupfer, & Saukko, 2000), its 1440 pages contain more than 200 articles.

[53] Concerning forensic ballistics, http://en.wikipedia.org/wiki/Ballistics states the following: "In the field of forensic science, forensic ballistics is the science of analyzing firearm usage in crimes. It involves analysis of bullets and bullet impacts to determine the type. Rifling, which first made an appearance in the fifteenth century, is the process of making grooves in gun barrels that imparts a spin to the projectile for increased accuracy and range. Bullets fired from rifled weapons acquire a distinct signature of grooves, scratches, and indentations which are somewhat unique to the weapon used. The first firearms evidence identification can be traced back to England in 1835 when the unique markings on a bullet taken from a victim were matched with a bullet mold belonging to the suspect. When confronted with the damning evidence, the suspect confessed to the crime. The first court case involving firearms evidence took place in 1902 when a specific gun was proven to be the murder weapon. The expert in the case, Oliver Wendell Holmes, had read about firearm identification, and had a gunsmith test-fire the alleged murder weapon into a wad of cotton wool. A magnifying glass was used to match the bullet from the victim with the test bullet. Calvin Goddard, physician and ex-army officer, acquired data from all known gun manufacturers in order to develop a comprehensive database. With his partner, Charles Waite, he catalogued the results of test-firings from every type of handgun made by 12 manufacturers. Waite also invented the comparison microscope. With this instrument, two bullets could be laid adjacent to one another for comparative examination. In 1925 Goddard wrote an article for the Army Ordnance titled 'Forensic Ballistics' in which he described the use of the comparison microscope regarding firearms investigations. He is generally credited with the conception of the term 'forensic ballistics', though he later admitted

and Jamieson (2004) are important articles, proposing rational approaches to crime scene investigation. Dixon (1999) discusses police investigative procedures.

In situations which involve forensic scientists, sometimes human remains[54] are only an incomplete skeleton. Consider the problem of determining whether the person was a man or a woman. "The estimation of sex from skeletal remains is often difficult because of the great overlap of the ranges of the measurements between both sexes in general", in the words of Riepert, Drechsler, Schild, Nafe, and Mattern (1996, p. 140), a study whose "data from a large sample [being radiographs of the ankle] provide an objective basis for sex identification. The single measurement of the calcaneus length allows an estimation of sex with nearly 80% accuracy" (ibid.).

Sometimes, it is the identity of an object or other asset that is of interest; this, in turn, is amenable to the detection of the values of some attributes of the object, such as the owner, or geographic origin. To clarify the difference between (i) personal identification, (ii) the identification of attributes of a human individual other than one's unique identity as partly captured by one's full name, and (iii) the identification of attributes of an object other than ownership, consider such differences within the scope of the practice of one of the forensic disciplines: forensic entomology.[55]

Identifying a corpse is an example of (i), whereas identifying its whereabouts at death or shortly afterwards is an example of (ii). The latter is exemplified in the following quoted passage (Turner, 1987, p. 134), which, next, also illustrates (iii), concerning the geographic area of origin of a consignment of marijuana:

> Human corpses, whether they have been produced naturally or as the result of foul play, are processed by [. . .] insect decomposers in the same way as any other piece of carrion. Forensic entomology is concerned with interpreting the insect evidence. This involves providing information about the time of death, and possibly changes in the location of the body based on a study of the insects present in the corpse when it is found. A good illustration of this is provided by a Russian case history (Arutyunov, 1963, in Keh, 1984). Living fly larvae found on a partially skeletonized body in a seawater tank were identified as species that are intolerant of salt-water. It was therefore deduced that the body had been dumped in the tank only a short time before it was discovered. The age of the larvae suggested death occurred about 2 weeks prior to the finding of the corpse. These observations were confirmed by the murderer's confession. The victim had been shot 2 weeks previously and then the body had been moved by car and put into the tank the day before it was discovered.
>
> A detailed knowledge of insects, their habits, life histories and delectations have also been useful in solving less macabre forensic problems. In an interesting and well-publicized recent case [(Joyce, 1984)] the New Zealand police intercepted a large consignment of marijuana. When the usual chemical analyses failed to identify the source of the marijuana the consignment was examined for insects. The bodies of sixty insects were recovered and

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it to be an inadequate name for the science. In 1929 the St. Valentine's Day Massacre led to the opening of the first independent scientific crime detection laboratory in the United States."

[54] Boddington, Garland, and Janaway (1987) and Cox and Mays (2000) are at the interface with forensic osteology within forensic pathology. In Krogman and İşcan (1986), the topic is the human skeleton in forensic medicine.

[55] Forensic entomology is the subject of Catts and Goff (1992), Catts and Haskell (1990), Keh (1984), Stærkeby (2002). An overview of forensic entomology is provided by Gail Anderson (2005, 2nd edn.; 2009, 3rd edn.).

> from these entomologists were able to precisely pinpoint the origins of the marijuana to a region 200 km SW of Bangkok, near a stream or lake where fig trees and termites are found. As in the previous case the detailed entomological evidence was of paramount importance in convicting the suspects.

As seen, one of the areas of application of forensic entomology is in the service of *post mortem* analysis. Also related to the latter (within forensic pathology) – though not necessarily so, as there are other applications as well in criminal investigation – are techniques from the forensic analysis of soils and geological evidence: Junger (1996) set "to determine the discriminative qualities of the various procedures to discern at what point soils become indistinguishable from one another" (from the abstract).

> One hundred samples were collected from three different sites; a beach, an island isolated by a river, and a bus parking lot. The samples were analysed using color determination, particle size distribution analysis and mineralogical profiles of the twenty-five most common soil minerals. Of the three hundred samples examined, over one-half could be discriminated by color alone, the remainder needing only particle size distributions analysis for differentiation, negating the need for lengthy mineralogical examinations (ibid.).

Moreover – cost being a factor in decision-making about how to analyse the evidence – these tests required only "very inexpensive equipment", and the calculations were not demanding in terms of either training or cost (ibid.). Cole and Ackland (1994) provide case studies in homicide investigation, in respect of forensic pathology, and in a British context.

In general on legal medicine, see, e.g., Schneider, Nagano, and Geserick (1994). Legal medicine's aims (not confined to perpetrator identification) include, e.g., problems hospitals are faced with, in care for the critically ill newborn. Clements (1994) is on forensic obstetrics, in respect of safety and liability for malpractice in British law. Clark and Crawford (1994) is on the history of legal medicine and of medical jurisprudence. Sometimes, veterinary surgeons act as witnesses (BVA, 1979).

And then, there is (human) forensic odontology, or forensic dentistry (Bowers, 2002; Glass, 2005, 3rd edn. 2009). Whereas the dentist who used to have a person in care may help in identification by means of stored X-ray items, there is, as well, a different kind of application: "Bite marks left on human tissue and bitten material have become an important aspect of scientific evidence used for the conviction or acquittal of a suspect", to say it with the abstract of Nambiar, Bridges, and Brown (1995), where use of a computer program for shape analysis is described.

Forensic chemistry and toxicology,[56] while sometimes resorted to in relation to forensic medicine, have a wider range of applications. In general, note that particular classes of techniques find disparate applications in the forensic sciences. Bob Ardrey (1994) is concerned with mass spectrometry, for such purposes. Or, then, consider chromatographic analysis; Ian Tebbett (1992) is concerned with gas chromatography in forensic science.

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[56] See Molina's (2009) *Handbook of Forensic Toxicology for Medical Examiners;* as well as, e.g., Pardue (1994), Cone and Deyl (1992).

Ukpabi and Peltron (1995) provide a review of the use of the scanning electron microscope is made in order to identify the cause of fibre damage, for application within "forensic textiles" (*sic*) as being an area of textile studies.[57] Trace evidence analysis is discussed in Deedrick (2001) concerning fabric processing, and in Ballou (2001) on fibre from wigs. Biermann and Grieve (1996) reported about a database of mail order garments and its statistical evaluation, for the forensic purpose of estimating the frequency of fibre types found in clothing. But see in Section 8.3.2.

8.3.2 Statistics Comes into the Picture

At the end of Section 8.3.1, we mentioned textile fibre types and their frequency as found in clothing. Allen and Pardo (2007a, pp. 116–119) offered a critique, in terms of the *reference-class problem* (see Section 2.4 above) of how probability theory was applied to juridical proof concerning carpet fibres in Finkelstein and Levin (2003). The problem, Allen and Pardo claim (2007a, pp. 117–118),

> arises from an ambiguity in the sentence, "Based on manufacturing records, an expert testifies the frequency of such fibers in carpets is less than 1 in 500." What does this mean? Whose records? Which records? Does the statistic refer to those who make a particular kind of carpet, or all U.S. manufacturers, or all manufacturers in the world? Or all carpets ever made in the history of the world to date? And once we know the class to which it applies, why is this the appropriate class in which to place Jones [a suspect, a neighbour of where a crime was perpetrated] and his carpet sample [i.e., carpet fibres taken from Jones's house, and matching an unusual carpet fibre found at the scene]? Is the fiber more or less prevalent in his part of the world, country, state, region, age group, gender, profession, socioeconomic class, and so on? Each of the different classes suggested by these questions would reveal different probabilities and likelihood ratios, but the evidence under consideration has not changed. Indeed, the evidence would likely have widely varying likelihood ratios. The probative value of the evidence cannot be simply the ratio derived from any arbitrarily chosen reference class. [...] A second problem with their conclusions concerns how the fiber evidence connects with other evidence.

In fact, had there been the case that there is (ibid., p. 119)

> conclusive evidence that the crime scene fiber had been planted after the fact to frame Jones would reduce the value of the fiber evidence to zero. Even if we have no evidence about this possibility, how do we know that it was brought from the suspect's home? Even if it was, how do we know that it was from carpeting in his home rather than, say, from having been picked up on the shoes of the actual perpetrator when he was at a party at the home of the person wrongly accused of the crime? These possibilities further show the disjunct between the value of evidence, on one hand, and the likelihood ratio calculated on the basis of a specified reference class, on the other. [... T]here may be no data for other plausible reference classes, which means that the mathematics can be done only by picking these or some variant. [...] Using the data one has does not kake the proffered analysis correct or true in some sense; instead, it is reminescent of relying on the lamppost more for support than illumination.

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[57] Those authors themselves were affiliated with the Department of Clothing and Textiles, at the Faculty of Human Ecology of the University of Manitoba in Winnipeg, Canada.

Statistics turns up in a multitude of contexts from forensic science. Actually, application in legal contexts dates back from the early modern period.[58] "Legal applications of probabilistic and statistical reasoning have a long history, having exercised such pioneers as Nicolas Bernoulli, Condorcet, Laplace, Poisson and Cournot (Zabell, 1988). After a period of neglect interest has resurfaced in recent years, and the topic has given rise to many challenging problems" (Mortera & Dawid, 2006).

> Many pioneers of probability and statistics, including the Bernoullis, Condorcet, Laplace, Poisson and Cournot, were motivated by problems of quantification and combination of legal evidence and judgement. But the trail they blazed became disused and overgrown as statisticians lost interest in such questions while legal evidence scholars confined themselves to issues of admissibility, precedent and other such formal rules, paying remarkably little attention to problems of interpretation. Very occasionally some aspect of statistical evidence or argument would break surface – significant legal cases include the 1865 Howland will case and the 1894 Dreyfus case – but it was not until the 1968 Californian case of People v. Collins, in which the prosecution presented a fallacious statistical argument in an attempt to magnify the impact of eye-witness identification evidence, that the issues became subject to serious discussion and argument. This stimulated what became known in the academic legal community as "the new evidence scholarship" [. . .] The probabilities debate remained academic until 1985 when, with the advent of DNA profiling and its numerical "random match probabilities", presentation of, and argument about, statistical evidence of various kinds started to become much more common in the courts (Dawid, 2004b).

Dawid and Mortera (1994) suggest a reason for the delay in the actual emergence of statistics in court: "The infamous trial *People v. Collins* (1975) was one of the first cases where statistical analysis of evidence was made. Unfortunately the analysis was so poor that it set back the introduction of statistical evidence in court for many years" (ibid., p. 2).[59]

A critic of Bayesianism in judiciary contexts, Ron Allen remarked about probability levels (Allen, 2008a, p. 320):

> The equally obvious probabilistic interpretation to give to these numbers is that they are relative frequencies, as propensity and classical accounts are plainly inapposite. That raises an immediate difficulty because virtually never is the data presented at trial in relative frequency formats, and even when it is (DNA evidence, good statistical evidence of disparate treatment), it must be combined with evidence that is not ("The defendant raped me", "I was treated in a way that people with different skin color were not").

Allen (2008a, pp. 320–321) proceeded to claim:

> The solution to this probelm appears equally obvious: subjective Bayesianism. One can translate impressions about evidence into subjective beliefs and then compute posterior probabilities in the light of new evidence. This not only maintains consistency among belief states, but has the added advantage of seeming to approximate what trials seem to be about, which is updating beliefs in the light of new evidence. Yet another advantage of

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[58] See on this Nissan (2001b), reviewing Rosoni (1995).

[59] In the context of forensic science, see the book on Bayesian networks by Taroni et al. (2006), Aitken (1995), Aitken and Taroni (2004), Robertson and Vignaux (1995). An introduction to statistics for forensic scientists was authored by David Lucy (2005).

> this approach is that it provides an answer to other important questions such as the meaning of relevance, prejudice, and probative value. "Relevance" means a likelihood ratio of anything other than 1:1; "prejudice" means that the evidence is likely to affect the rationality of appraising the likelihood ratio, and "probative value" means how far from a 1:1 ration the likelihood ratio is.

And yet: "I believe it is wrong allo the way down, from the most general questions of the basic structure of proof at trial to the most detailed question of the probative value of discrete pieces of evidence" (ibid., p. 321). In the rest of that paper, and in much of his published *oeuvre*, Allen shows why. His arguments are cogent, and cannot be safely ignored. We have given more space to them in other places throughout this book. At any rate, there is a raging controversy between those endorsing probabilisitc accounts of judicial proof, and those opposing that kind of approach. Computing scientists turning to modelling legal evidence can only ignore the controversy at their risk and peril.

Gastwirth and Miao (2009), concerned with race discrimination in employment practices, provided a statistical analysis of the data in disparate impact cases from the United States. They took issue with the specific rationale behind a court ruling, petitioners' brief, and respondent's brief. The petitioners were claiming reverse discrimination at a Fire Department after an examination was cancelled. Baldus and Cole (1980) is a book on statistical proof of discrimination.

David Kaye (1982) was concerned with statistical evidence of unlawful discrimination of various kinds: discrimination in *ad hoc* decision making, discrimination in the application of a rule, discrimination in the formulation of a rule, and discrimination in the operation of a rule. Michael Finkelstein (1980) discussed the judicial reception of multiple regression studies in race and sex discrimination cases. Kaye (1982, pp. 775–776) was especially concerned with

> how statistical proof fits into discrimination litigation in two areas in which such evidence commonly is employed. The courts have relied heavily on statistical evidence in cases in which a criminal defendant alleges that he was indicted by an unconstitutionally selected grand jury or an unconstitutionally empanelled petit jury (Finkelstein, 1978, pp. 18–58). In essence, a claim of disparate treatment is presented, and statistical analysis of the pattern of selection is therefore appropriate. There is no constitutionally per-missible basis for systematically excluding, say, members of defendant's race from the population of citizens who are eligible for jury duty. Where direct evidence of dis-crimination is unavailable, statistical methods have been pressed into service.

Writing in 1980, Kaye concluded that, among the other things (1982, p. 782–783):

> The courts tend to adopt a fairly realistic attitude to-ward such matters as defining the relevant population, and recent opinions reveal increasing awareness of classical hypothesis testing in evaluating measured differences. However, the process of drawing a conclusion for legal purposes entails an integration of statistical and non-quantitative information, making classical hypothesis testing inapposite to factfinding in litigation. A full-fledged Bayesian analysis of the probability of discrimination is theoretically more satisfying but is too controversial and, in a sense, too powerful to have much chance of becoming judicially accepted and of contributing to accurate decision making by judges or juries. Presenta-tion of the likelihood function avoids the objections to Bayesian inference, but a more mundane calculation of the probability that an observed difference would arise in the absence of discrimination might be more easily comprehended by a court. Such a calculation should be

> the starting point for any formal analysis, and consideration should be given to supplementing this calculation with fuller presentations, such as displays of prediction intervals and likelihood functions.

Houck (1999) discussed statistics in relation to trace evidence. "The inability to place a specific probability estimate on chance association has led to a widespread view that trace evidence is much weaker than DNA evidence, a problem which has been referred to as "the tyranny of numbers" [(Houck, 1999)].

However, as noted by Houck (1999, p. 3), "the tyranny of numbers is a consequence of an over-reliance on deduction and mathematics, and these ultimately limit a discipline by requiring it to fit in a preordained model. [. . .]" Bayesian statistical approaches have become popular in many branches of forensic science in recent years" (Pye, 2006, pp. 24–25). Pye further remarks (ibid., p. 25):

> Quantitative methods, including formal hypothesis testing, clearly have an important role to play in the assessment of all forms of trace evidence, but they can rarely provide a complete answer. Issues of "uniqueness", "rarity", "randomness" and "representativeness" in relation to trace evidence are usually difficult to quantify in an exact mathematical or meaningful statistical way. Statistical estimates of frequency of occurrence are usually context-dependent, based on the extent and timing of any sampling carried out, and on the methods used for sample collection and data analysis.
>
> As pointed out by Houck (1999), "context, is in fact, the crucial component to a proper grasp of the significance of trace evidence. Without context, we are communicating mere facts with no foundation of meaning, much in the way Poincar[é]'s pile of stones is not a house". The existence of a suitable context for the evaluation of the significance of trace evidence depends partly on the experience/knowledge of the trace evidence examiner, the availability of database information relating to the materials under examination, and the willingness of those instructing the forensic examiner to provide relevant information relating to the circumstances of the case. The examiner is not always provided with information which may have an important bearing on the assessment of the *evidential value* of the scientific findings. Partly for this reason, the examiner should, normally restrict his/her assessment to the likely *scientific significance* of any apparent similarity. The wider issue of evidential significance is more properly a matter for the court. Over the past fifteen years there have been great improvements.

Richard Overill and Jantje Silomon devoted a paper (2010) to what they term *digital metaforensics*, i.e., "quantifying the investigation" into digital crime cases (cf. Section 4.3.4 above). Their article, in line with those authors' record of research, resorts to statistics, and concerns (ibid., from the abstract):

> two related areas of digital forensics. The first involves quantifying the extent to which the recovered digital evidential traces support the prosecution's contention that a particular digital crime has been committed. The second addresses the issue of quantifying the cost-effectiveness of the digital forensic investigative process, in order to optimise the deployment of valuable and scarce resources for maximum efficacy.

Their thrust is to provide metrics that would appear to be more precise than such qualitative statements as "very likely".

> Not surprisingly, defence lawyers assigned to digital crime cases have become aware of this discrepancy and have attempted to exploit it to persuade the court that the prosecution does not possess evidence of sufficient probative value. However, the development of potentially

> suitable methodologies and techniques for the quantitative interpretation of digital forensic investigations is underway [. . .] and offers the prospect of bringing a degree of numerical certitude to the recovered evidence in such cases.

It remains to be seen whether this is not merely an illusion. The skeptics concerning Bayesianism in a judicial context may point out that merely quantifying does not ensure that the quantification, apart from sounding grand, is also credible for good reason.

8.3.3 Some More Forensic Disciplines

Apart from subserving legal medicine, forensic toxicology is also involved in environmental poisoning (Sigmund, 1995). Other forensic disciplines are concerned with the environment; such is the case of forensic engineering for environmental cases (Shuirman & Slosson, 1992), or, then, of forensic economics as applied to the liability for environmental damages, caused by hazardous substances pollution.[60] When it comes to engineering, there are fields of application (other than assessment of environmental damage) which correspond to subareas of expertise within forensic engineering. Forensic engineering may be in the realm of civil engineering (in cases of structure collapse), or, for example, automotive engineering.[61] There is a role, in court, for computer-aided accident reconstruction (Bohan, 1991). Johnson (1985) was concerned with the (mis)interpretation of the causes of motorcycles collision vis-à-vis driver behaviour.[62] A car crash involves impact. Another kind of impact is involved in forensic ballistics.[63]

William Bodziak published (2000) the book *Footwear Impression Evidence*. He also provided an overview of forensic footwear evidence in the form of a book chapter (2005b), preceded by a chapter (Bodziak, 2005a) concerning vehicles, namely, about forensic tire impression and tire track evidence. Let us consider the Wikipedia entry[64] for “Forensic footwear evidence”. The incentive to resort to such expertise is

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[60] Ward and Duffield (1992) is in a U.S. perspective.

[61] Within automotive engineering, Peters and Peters (1994) is relevant for U.S. law.

[62] Also see José Almirall’s paper (2001), “Manslaughter Caused by a Hit-and-Run: Glass as Evidence of Association”.

[63] Sellier and Kneubuehl (1994) is in forensic ballistics, in a medical context.

[64] It is remarkable that there are concise, yet valuable introductions to various forensic science disciplines, posted as entries on Wikipedia. These include a general entry “Forensic science”; various entries from the physiological sciences (“Forensic pathology”, “Forensic dentistry”, “Forensic anthropology”, “Forensic entomology”); entries with affinity to the social sciences (“Forensic psychology”, “Forensic psychiatry”); entries in other specdialisations (“Fingerprint analysis”, “Forensic accounting”, “Ballistics”, “Bloodstain pattern analysis”, “DNA analysis”, “Forensic toxicology”, “Forensic footwear evidence”, “Questioned document examination”, “Explosion analysis”); entries on cybertechnology in forensics (“Information forensics”, “Computer forensics”); entries related to engineering (“Forensic engineering”, “Fire investigation”, “Vehicular accident reconstruction”); entries on people in forensics (“Edmond Locard”, “Bill Bass”); and related articles (“Crime scene”, “CSI effect”, “Trace evidence”). For all of these, see

because of the availability of footprints. The problem is that how strong the evidence is is questionable. The same entry admits: “The Unabomber, Theodore Kaczynski, was known to keep shoes with smaller soles attached to the base in order to confuse investigators about the size of the suspects.”[65] The introduction to a Wikipedia entry for “Forensic footwear evidence”[66] reads as follows:

> *Forensic footwear examination* is the study of footwear impressions evidence created. Such evidence is used in legal proceedings to determine the identities of persons at the crime scene. Footwear evidence is often the most abundant form of evidence at a crime scene and in some cases can prove to be as specific as a fingerprint. Initially investigators will look to identify the make and model of the shoe or trainer which made an impression. This can be done visually or by comparison with evidence in a database both methods focus heavily on pattern recognition and brand or logo marks. Information about the owner of any footwear can be gained from the analysis of wear patterns which are dependant on angle of footfall and weight distribution. Detailed examination of footwear impressions can help to link a specific piece of footwear to a footwear imprint as each shoe will have unique wear charateristics.

Perhaps the value of such evidence is especially for excluding suspects. Many people can be expected to wear shoes of the same model and size. Nevertheless, the shoe itself may be available, and more solid evidence can be obtained from it, for identifying the person who was wearing it: *“Footwear insole imprints* are imprints left in the inside of footwear caused by contact from the person’s foot. Analysis of the insole imprints can be used to link a person(s) to a piece of footwear.” Moreover:

> *Footwear trace evidence* is trace evidence that is recovered from footwear. Types of trace evidence that could be recovered include skin, glass fragments, body hair, fibres from clothing or carpets, soil particles, dust and bodily fluids. The study of this trace evidence could be used to link a piece of footwear to a location or owner.

For our present purposes, it is interesting that information technology is helpful in the form of *footwear databases:*

> Forensic investigators can use computerized footwear databases to quickly compare the class characteristics between footwear impression and outsole profile of footwear outsoles stored in the database. This greatly reduced the time required to match shoeprint to. Examples include the Footwear Intelligence Technology (FIT) launched by the Forensic Science Service (FSS) in February 2007. Such systems contains information on thousands of footwear patterns with daily updates from both manufacturers and police forces.

A team at the University of Buffalo led by Sargur Srihari reported (Ramakrishnan, Malgireddy, & Srihari, 2008; Ramakrishnan & Srihari, 2008) about shoe-print extraction from latent images, by resorting to *conditional random fields.*

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http://en.wikipedia.org/wiki/ followed with the name of the entries, with each blank space replaced with an underscore.

[65] Don Foster’s stylometric analysis (see Foster, 2001, chapter 3) was important for identifying the Unabomber. Also the latter’s sister-in-law, a professor of philosophy came to believe she knew he was the Unabomber because of what he wrote and the way he wrote. See in Section 6.1.10, and in fn. 94 in Chapter 6 in particular.

[66] http://en.wikipedia.org/wiki/Forensic_footwear_evidence.

Let us turn to a few other specialties. If real estate is involved in a case, this may concern situations where a structure did or may collapse, or where there was a fire and structural engineering and fire simulation experts need investigate (either concerning negligence, or arson).[67] Their models in fire simulation within a building are in *computational fluid dynamics.* In less dramatic circumstances involving real estate, surveyors may testify as expert witnesses in court (Clarke, 1985; Watson, 1975).

Forensic accounting (e.g., for *fraud investigation*) is specialised per countries: see Lemar and Chilvers (1995) for Britain; Frank, Wagner, and Weil (1994) and Bologna and Lindquist (1995) for the U.S.A.; and Zier (1993) for Canada. The Wikipedia entry[68] remarks in the introduction:

> *Forensic Accounting* is the specialty practice area of accounting that describes engagements that result from actual or anticipated disputes or litigation. "Forensic" means "suitable for use in a court of law", and it is to that standard and potential outcome that Forensic Accountants generally have to work. *Forensic Accountants*, also referred to as *Forensic Auditors* or *Investigative Auditors*, often have to give expert evidence at the eventual trial. All of the larger accounting firms, as well as many medium-sized and boutique firms, have specialist Forensic Accounting departments. Within these groups, there may be further sub-specializations: some Forensic Accountants may, for example, just specialize in insurance claims, personal injury claims, fraud, construction, or royalty audits.

We have already seen how link analysis and data mining have been put to good use in order to uncover frauds: by mining email databases in the Enron case

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[67] As http://en.wikipedia.org/wiki/Fire_investigation points out: "Fire investigation is one of the most difficult of the forensic sciences to practice. In most forensic disciplines, even the basic question of whether a crime has been committed is normally obvious. During a fire investigation, an entire process must be undertaken just to determine if the case involves arson or not. The difficulty of determining whether an arson fire has occurred or not arises because fires destroy evidence. A fire investigator looks at what is left behind after a fire and obtains information to piece together the events that occurred in the moments leading up to the fire. One of the challenging aspects of fire investigation is the multi-disciplinary base of the investigator's job. Fires can be caused by or involve most things people see or use. For this reason, fire investigators need to know not only basic science of fire behavior, but knowledge of many different areas of study (including construction, electricity, human behaviour, vehicles etc.) is helpful. If the fire origin has, for example, a gas appliance, an investigator should know enough about appliances to either include or exclude it as a possible cause of the fire. Fire investigators must also know their own limitations and call upon experts to assist when needed. Accordingly, fire investigators sometimes work with forensic electrical engineers (when examining electrical appliances, household wiring, etc.) or others skilled in forensic engineering (gas-powered appliances, air handling equipment, gas delivery systems, etc.)." Concerning certification of the experts, the same entry explains: "In the USA, some states require that fire investigators obtain certification as a Certified Fire Investigator (CFI). The International Association of Arson Investigators, a professional group of fire investigators, grants CFI certification. The National Association of Fire Investigators (NAFI), a professional association of fire and explosion investigators, offer several National Board Certified fire investigation certifications, including Certified Fire and Explosion Investigatior (CFEI), Certified Vehicle Fire Investigator (CVFI), and Certified Fire Investigation Instructor (CFII). For more information, please visit their website at http://www.nafi.org."

[68] http://en.wikipedia.org/wiki/Forensic_Accounting.

(Section 6.2.1), by trying to identify fraudsters and accomplices at online auction sites (Section 6.2.3), the U.S. Federal Defense Financial Accounting Service's EDS project (Section 6.2.6), and the tool for detecting fuel frauds developed in Poland (Section 6.2.8). The latter project is a case in point for how conventional forensic accounting is in practice powerless when faced with very complex flows of transactions, unless use is made of link analysis or data mining technology.

8.4 The Contribution to Forensic Science of Anthropology and Archaeology

8.4.1 Forensic Archaeology and Anthropology

Some interdisciplinary interfacing of forensics sometimes occurs with kinds of reconstruction other than forensic; for example, forensic archaeology applies techniques from archaeology to criminal investigation.[69] Forensic archaeology applies techniques from archaeology to criminal investigation: see Hunter et al. (1997). The following is quoted from a call for participation in a workshop on Archaeology and Forensic Science, held at the British Academy in London on 27 February 2007, in concomitance with the Council for British Archaeology's 2007 Winter General Meeting.

> Forensic archaeology is a relatively new concept in Britain and these presentations explore how archaeology in its many facets has developed from its traditional roots into the arena of criminal investigation. As these talks show, this is mostly, but not exclusively, concerned with searching for and excavating clandestine graves, including mass graves. Search involves systematic sequencing of various techniques including the use of aerial imaging, geophysical survey, as well as cadaver dogs but, unlike more traditional archaeology, is affected by the decay dynamic of buried human remains. Recovering modern buried human remains also poses problems in that the type of evidence needed can be very different from the evidence archaeologists and anthropologists normally identify. It also needs to be obtained within the constraints of a novel legal framework and presented in court. These issues are pursued and, using case studies, a number of different scenarios are outlined which detail the different methodologies used in excavation and the different types of evidence – archaeological, anthropological and environmental – that could be used to obtain a successful conviction.

The titles of the talks are indicative of how disciplines meet within forensic archaeology: "Archaeology and the crime scene", "Physical anthropology: forensic identification, trauma and case studies", "Geophysics: divergence, human decay dynamics and case studies", "Applications of ecology, botany, and palynology to criminal investigation". *Palynology* (see Section 8.5.5 below) is the study of pollen, in respect of morphology, biochemistry, and biogeography. The public consisted of archaeologists: active, retired, or students.

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[69] See Hunter et al. (1997).

Even though the quotation given earlier states that forensic archaeology is rather new in Britain, it must be said that whereas in the United States, forensic science is strong in physical anthropology, apparently Britain is ahead in other disciplines for forensic identification (including of human remains), that are grounded in forensic archaeology. Various scientific disciplines contribute techniques to archaeology, and experts conversants with both archaeology and forensics find more rigour within the former disciplinary tradition, which has much to contribute to forensics.

In the rest of this chapter, as well as in Sections 8.4.2, 8.5.2, and 8.5.5, I am going to provide information from notes I took at the 2007 London workshop referred to. John Hunter of the University of Birmingham is an archaeologist who moved into forensic archaeology, and (like the other speakers from the workshop) assists the police and appears in court as an expert witness. He started his talk by dispelling the misconception that forensic archaeology (i.e., archaeology used in forensic environments) is forensic science used in archaeology.

Around a serious crime event, the incident is attended to by an array of professionals: the scene of crime officer, the senior investigating officer, the coroner, the Home Office pathologist, the Forensic Science Service, the scientific support manager, the Crown Prosecution Service, and others.

A common ground fo archaeology and forensic science is the search and recovery of human remains, skeletal analysis, and analytical science. Key divergences include: the timeframe of operation (archaeologists choose when going out, whereas a police investigation cannot be deferred, e.g., because of bad weather), hierarchies (Hunter referred to himself as being quite powerful within his archaeological team, whereas when he is called to assist the police, or is called to testify in court, the mutual positioning is different), a two-way knowledge base (which is not the case of archaeological practice), legal constraints (on disclosure), the role of the expert witness (as opposed to an archaeologist addressing scholars), and "publication" to a jury (as opposed to a peer-reviewed journal).

Concerning appearing in court as an expert witness, Hunter (like another speaker on the same day) pointed out that whereas one usually thinks about trials in terms of justice being done, actually trials are games, and the barrister who has been most persuasive, wins. It is the task of the barrister of the other side to try to ruin your professional reputation as an expert witness.

Moreover, unlike archaeology, forensic archaeology deals with the recent dead and the living. When dealing with graves, in archaeology it is necessary to distinguish between context and non-context. In contrast, in forensic archaeology is is necessary to distinguish between context and contamination. Preserving the integrity of the grave can facilitate finding out about identity, cause and manner of death, and the interval since death. Have the remains *been* buried (by somebody), or have they *become* buried? A buried body may cause different types of vegetation change: the vegetation is different from the surroundings, for example, either higher, or lower. It is lower on the grave than surrounding vegetation, is the grave was originally covered with stones. Apart from the vegetation change, there also is a topographic change. There can be expected to be a disturbance caused by body remains. There may be linkage between sites. The cues on (or in) the terrain may be artefactual, ecological, or ecofactual (e.g., intrusive vegetation).

There is a window of opportunity that should not be lost, when the police is looking for a body after a death presumed to be recent. After three weeks from death, the body is decaying, and this continues for other three weeks, during which the body is emitting temperature. Thermal imaging in order to find out a burial, when there has been a crime, needs to exploit that window of opportunity. Non-invasive imaging techniques are available, and recommended. The more invasive a forensic technique, the greater the risk of losing forensic evidence, because of various reasons. A non-invasive imaging technique can reconstruct the volume and shape (inside the ground) of a mass grave: how deep it is, how long, and so forth. This can be visualised by computer in three dimensions, as a volumetric model, and animated (by having the system of reference with the three axes rotate). The same example was made during the same workshop by Cheetam, in a talk about the forensic and archaeological application of survey methods from geophysics; the given volumetric model was developed by applying a technique that measures earth resistivity (see in Section 8.5.2 below).

Hunter pointed out that the search for a grave may have a positive outcome, i.e., recovery, or a negative outcome, i.e., elimination. It may be a search concerning a recent incident, with a named victim, with a suspect being identified, and with an unknown disposal site, yet with the body remains being recovered. Or then it may be an old incident, with no name to the victim, with no suspect, but with a specific location. An example of the latter kind of situation is the case of a witness who reports seeing (or that a relative had seen), thirty years before, a child being buried at a specific location. This is a more usual kind of intelligence.

When searching for a grave, there are distinctions to be made concerning spatial scope. It may be a search in the backgarden of a given urban house, using imaging techniques from geophysics. Or then, the scope may be broader, and aerophotography may be resorted to. It is only if and once the remains *are* found, that one can look into the matter and say whether there was a murder or not. Questions proper to ask include: How was the grave dug? Was it dug in a hurry, or carefully prepared? Is there foreign material in the grave? Did the perpetrator leave any traces in or around the grave? The grave is a very rich source of material. There is a pattern to how people tend to dispose of bodies. They tend to dispose of bodies in places they know. The expert in court only gives information. It is the barrister's task to interpret. For example, the expert may say whether the material taken out of the grave was taken off site, or whether the material found in the grave was put there from on-site or off-site.

Taphonomics studies decay. Analysis in taphonomics interacts with other disciplines. The expert is likely to ask the entomologist, the climatologist, and so forth. One of the examples illustrated by Hunter was a mass grave excavation, showing depositional events and taphonomic variables. One may find commingled, saponified remains. An important notion is joints: fifteen main points on the body. As mentioned earlier, a computer-generated section of the mass grave can be visualised in three dimensions and rotated (actually, such imaging matters because it delimits the outer contour of the mass grave).

8.4.2 Factors Involved in Forensic Anthropology

8.4.2.1 Preliminaries

The second lecture at the workshop on Archaeology and Forensic Science, held at the British Academy in London on 27 February 2007, was given by forensic archaeologist and anthropologist Corinne Duhig, affiliated with Anglia Ruskin University and with Wolfson College of the University of Cambridge, and a consultant for "Gone to Earth", a small firm (with three consultants in all, operating individually in the whole of Britain). The logo of "Gone to Earth is the profile of a fox excavating a bone. Actually, scavengers such as foxes (and crows) disturb burials and sometimes cause remains to be uncovered. It must be said that in Britain there is a policy different from policies from the Continent concerning foxes: as there is no rabies in the country, foxes are not systematically culled. Foxes are frequent in urban backgardens. (What they do to your garden may prompt unprinted expletives.)

By the late 2000s, body remains (even ancient) are more likely to be reported in the United Kingdom that it used to be a few decades ago. The forensic anthropologist's[70] (and apparently Duhig's own) breakdown of casework by type is: ca. 75% non-forensic (non human, or archaeological), the rest being forensic (homicide, suicide, misadventure, or open), or "other". Physical anthropology as applied to forensic identification, trauma and case studies, is different from physical anthropology as done in mainstream archaeology. The role of the forensic anthropologist is search and excavation, assistance to the Home Office Pathologist (who by the late 2000s has been more receptive to the anthropologists than, say, twenty years earlier), defleshing and reconstruction (a body still with soft tissue is reduced by the anthropologist to a skeleton, and then rebuilding is carried out; in archaeology, too, there is cleaning and rebuilding, but of course there is no recent soft tissue).

Then the anthropologist develops an anthropological profile for identification. A lot of it is exclusion; for example, the pathologist is notified by the anthropologist that the body does not match the profile. Other tasks of the anthropologist include skeletal trauma mapping, sequencing and interpretation, and taphonomic interpretation.[71] The remains may be fresh, or decomposing, or fully skeletonised, or burnt, or cremated (usually perpetrators don't know how to cremate well), or disrupted (e.g., because of a road accident, or an airplane crash), of dismembered (which was deliberately done by a perpetrator), or processed (by a perpetrator, to make the remains less identifiable).

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[70] Marcella Sorg (2005; 3rd edn. 2009) provides an overview of *forensic anthropology.*

[71] William Haglund (2005; 3rd edn. 2009) provides an overview of *forensic taphonomy*, which is about burial.

The Big Four of identification are: ethnology, sex, age, and stature. Ethnology for the forensic anthropologist at present in the United Kingdom involves a greater range than archaeologically (as, e.g., now there are people from South Asia, the Far East, and sub-Saharan Africa in the country, and that wasn't the case in antiquity or the early Middle Ages). It is concerning the identification of sex and age, that anthropologists are most useful to the police. Homicide demographics involve mainly young adult males. This is very different from archaeological remains. As to stature, one ought to bear in mind two things:

(a) informant error, as people quite frequently overestimate the height of others, and moreover (especially males) their own stature;
(b) size for postulated activity, e.g., a required limb length to do something: the forensic anthropologist has to work out from length and angulation of limbs, whether it is possible for the given person to have done a given activity, e.g., movement. Could that child have extended an arm and picked up that given thing?

8.4.2.2 Ante-mortem Skeletal Pathology, and Para-, Peri-, and Post-mortem Traumas

As explained by Corinne Duhig in the same lecture, the identification of a person from body remains involves various factors. It depends on reliable record or recollection of informants, as well as preservation in remains. For *ante-mortem skeletal pathology*, the range of values includes: life-history trauma (battery, torture); evidential trauma; and non-trauma. Identification as based on preservation in remains also depends on epigenetic/non-metric traits (e.g., dental variables can be extremely variable); on body build (degree of muscularity: it depends on how much tissue you have, in the available remains); on handedness (was that person left-handed?); and on shoe size (the latter is something that is not asked in archaeology).

Let us turn to *"para-mortem" trauma.* This is a term invented by Duhig herself. Identifying para-mortem trauma properly has important implications at a criminal trial. Violence may have been directed at a person alive or perceived to be alive, or, in contrast, at or close to the time of death. Violence may have been for the purpose of homicide or suicide, or of causing pain, or of mutilation. Injuries may have been produced by blunt weapons, or by sharp weapons, or by projectiles. The latter, in turn, may include, e.g., bomb fragments. Moreover, para-mortem trauma may have resulted from accidental injury and death (e.g., in an air crash). Forensic anthropologists do not have the responsibility for determining the type of death.

Types of para-mortem trauma include: blunt trauma, sharp-weapon trauma, and projectile wounds. In particular, blunt trauma (which is involved, e.g., in crimes of passion) may be: simple depressed fracture of skull; various crushed features of skull; or fracture of the post-cranial skeleton (i.e., of the skeleton other than the skull). Kinds of post-cranial fracture importantly include defence injury to a forearm (as a person under physical attack usually rises the forearms to protect him- or herself).

Sharp-weapon trauma consists of incisions. These may be stab wounds (which tend to be on the edge of ribs), or cut/slash wounds. The latter often are superficial; they are common in accidents. As to projectile wounds, they may be entry wounds (more regular; if in the skull); or exit wounds (less regular, larger; if in the skull). Small calibre projectiles often stay in, and have no exit, so there would be an entry wound, but no corresponding exit wound. Holes in the skull, which in a forensic context are identified as projectile wounds, if found in archaeological remains instead, at first sight may be believed to be due to the skull being damaged because of defective preservation. For the forensic anthropologist analysing para-mortem trauma, it is important to determine *wound sequencing*, i.e., the direction and sequencing of wounds. May I add that this is interesting in view of *models of time* from artificial intelligence or, more broadly speaking, from computer science (see Section 8.4.2.3). Constraints preclude some candidate sequencing. This could be a promising direction for computer application to forensic anthropology.

Having dealt, with *para-mortem trauma*, let us turn to *peri-mortem trauma.* This concerns early decomposition stages. It also concerns violence directed at a body: dismemberment, defleshing, and so forth, as having been carried out by a perpetrator. It is also of interest to determine for which purpose, such violence directed at a dead body was carried out. And finally, there is *post-mortem trauma.* It concerns later decomposition stages. Post-mortem trauma may be due to human activity (accidental disturbance, or second burial), or to animal activity (damage, scattering), and so forth. Peri-mortem and post-mortem processing wounds include, e.g., cutting by blades or by saws, for the purpose of dismemberment.

8.4.2.3 A Digression on Formal Models of Time

An important class of temporal representations from artificial intelligence is such methods that are based on variants of *temporal logic.* We are not referring to formal representations of tense in natural language. Temporal logics are independent of natural language, and therefore are not directly concerned with tense. Temporal logics as used in artificial intelligence[72] were introduced by Allen (1983b, 1984, 1991),[73] and originally were only concerned with intervals (by means of an *interval calculus*, rather than with time points. Temporal logics have been used, for example,

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[72] Within artificial intelligence, see e.g. Shoham and McDermott (1988) about temporal reasoning.

[73] A useful online survey of temporal logic is Galton (2008). van Benthem (1995) is more detailed and more technical; whereas van Benthem (1983, 2nd edn. 1991) is a book on temporal logic. Fisher, Gabbay, and Vila (2005) is a handbook. Cf. Antony Galton's book (1987) and critique (1990) of James Allen's *theory of action and time.* Also consider Alur, Henzinger, Kupferman (2002) *alternating-time temporal logic*, which eventually gave rise to Wooldridge and van der Hoek's (2005) *Action-based Alternating Transition Systems* (*AATS*), used by Bex et al. (2009) in order to represent reasoning about the narrative of an alleged crime (see Section 3.4.4.4 in this book).

Surveying the broader context of kinds of temporal representations, Fabio Alberto Schreiber explains (1994, section 3): "In the logicians' community there is a strong debate on the need of creating a non standard *Temporal Logic.* Scholars having mathematical and physical background and interests claim that times can be designated by terms in a first order theory, which is more for tasks in engineering (e.g., Knight, Ma, & Nissan, 1999). In James Allen's interval calculus, there is a composition table of basic interval-to-interval relations, e.g., if they contain each other, or partly overlap. That approach to qualitative reasoning about time inspired Tony Cohn's approach to qualitative reasoning about space. It is based on Clarke's *calculus of individuals* and uses a set of eight basic relations on spatial regions, i.e., how one region connects to another. Cohn, Gooday, and Bennett (1995) compare structures in spatial and temporal logics. Cui, Cohn, and Randell (1992) show how space and time are both taken care of in their formalism. Cohn et al. (1994) show how temporal continuity is exploited in their qualitative spatial calculi. The papers Nissan (2001g, 1997b) are about formalisms of space, more broadly meant.

In Section 5.3.3.2 we considered *time granularity*, different *grainsizes* being, for example, a year or a day. Bettini et al. (2000), a book on time granularities and how they are processed in representations from computer science, in particular from the viewpoints of database design, of constraint reasoning, and of automated knowledge discovery. Also see Bettini, Wang, and Jajodia (2002); cf. Schreiber (1991, 1994).

By contrast to temporal logics, different kinds of representation were developed for linguistics by semanticists, in order to represent the semantics of *tense*, as intended by linguists: Alice ter Meulen's book (1995) was reviewed by Nissan (1998b), a review reworked into appendix B of Nissan (2011a). In her book, "temporal reasoning is considered a form of logical reasoning, in which quantificational force, binding, and context change are core concepts" (ter Meulen, 1995, p. 3). Her structured semantic objects are *Dynamic Aspect Trees* (*DATs*).

Computer science also has temporal representations for concurrency. One which is considerably complex, and is used to modelling concurrent computation, is is Tony Hoare's notation (and respective theoretical framework) known as *Communicating Sequential Processes (CSP)*, which he published in a book by the same title (Hoare, 1985). It is a powerful technique, and requires a good understanding of the theory behind it. A current textbook on the subject is Roscoe's *The Theory and Practice of Concurrency* (Roscoe, 1998). The latter book is about the untimed version of CSP, with modelling without measuring the passage of time. By contrast, for modelling also such measurements (in either real numbers, or as discrete time points), there exists a version of Hoare's approach that has been named *Times CSP*:

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than adequate for time modeling. Besides [Bertrand] Russel and [Willard] Quine, these authors – referred often to as *detensers* – comprise [James] Allen, [Drew] McDermott, [Robert] Kowalski and others. People interested in linguistic aspect of logic, on the other hand, feel that time is tightly woven into languages, under the form of different tenses of the verb, and they relate modal to temporal notions [...] [Arthur] Prior and [Georg Hendrik] Von Wright belong to this *tensers* school. Just to show how things become complicate, we only mention that, in his theory of tense, [Hans] Reichenbach defines three different times for each tense: an *utterance* time, at which the sentence is expressed, a *reference* time, which we refer to in the sentence, and an *event* time, which is the object of the sentence".

it reinterprets CSP over time, records the exact time at which each event occurs, it associates with events non-negative real numbers.[74]

A simpler representation for concurrent processes and temporal constraints is *Petri nets.* Think of such a variant of a flipper game, that little balls (we are going to call them *tokens*) are scuttling along routes between obstacles, that can be figured out as being small doors, or closed valves (these we call *transitions*). There are one or more such conduits that each reaches such a valve (i.e., incoming arcs upstream of the transition), and one or more conduits that proceed forth from it (outgoing arcs downstream of the transition). In each conduit, there will be at most one ball at a time. One or more balls will stop at the transition, and this valve will not open, unless from each and every incoming arc, a ball has arrived. If all such balls are there, then the valve would open (i.e., the transition *fires*), and the balls would move further. There is a major departure with respect to the real physical world. In the latter, you would expect that if you had, say, three marbles right before the valve, and the valve opens, then beyond that valve those marbles will still be three balls. Not so with the kind of directed graphs that are known as *Petri nets.* If beyond the valve there only is one outgoing arc, then those three marbles would turn into just one marble, whereas if two arcs leave the open valve, then those three balls will become two: one for each outgoing arc. Petri nets are such directed graphs, that along every route (itself made up of arcs), there is an alternation of *places* (drawn as hollow circles), and *transitions* (drawn as a barrage: a short line drawn across). Moreover, *tokens* move through the graph according to rule we have described. See Fig. 8.4.2.3.1.

As I wrote in Nissan (2011a, appendix A):

> Petri nets have proved to be a major paradigm for other computer application domains, e.g., for scheduling in manufacturing, or for logic validation when modelling digital systems. This has not been the case in legal computing. Petri nets were applied to legal systems

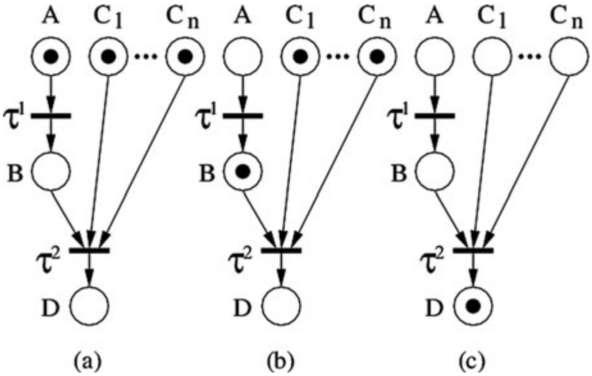

Fig. 8.4.2.3.1 Three successive states in the execution of a sample Petri net

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[74] It is covered in a textbook by Steve Schneider (1999). Also see Schneider (2001). He has also co-authored a book on security protocols (Ryan, Schneider, Goldsmith, Lowe, & Roscoe, 2000).

in Holt and Meldman (1971).[75] In the literature of the discipline of artificial intelligence and law, a few papers are concerned with temporal structure (Bauer-Bernet, 1986; Poulin et al., 1992; Vila and Yoshino, 1995, 1998;[76] Knight, Ma, and Nissan, 1998), and Petri nets have been applied quite sporadically, less frequently than temporal logic, the latter being an approach in artificial intelligence which was introduced by Allen ([1983a, 1983b], 1984). Farook and Nissan (1998) have applied Petri nets to the representation of mutual wills. Valette and Pradin-Chézalviel (1998), in the same journal special issue as the former, applied time Petri nets to the modelling of civil litigation. Rossiter et al. (1993) described an application of Petri nets (within a formal model for quality assurance) to legal documentation organized as hypertext. Raskin et al. (1996) modelled by means of Petri nets, *deontic* states, i.e., states of obligation or permissibility.

For most purposes, the representation of *asynchronous, concurrent processes* is best suited by Petri nets indeed. The representation of concurrency among processes is not well suited by *finite state automata*, because for a large number of tasks, the number of states becomes unwieldy. Petri nets were originally defined by Petri in 1962 (Petri, 1966), and then refined and named after him by Holt (e.g., Holt, 1971; cf. Miller, 1973). Research into this paradigm developed during the 1970s and boomed in the 1980s. The literature is vast, with a choice of general works and a variety of proceedings. Among the books, see, e.g., Proth and Xie (1996), Peterson (1981), David and Alla (1992), Reutenauer (1990), Fernandez and Best (1988). Over the years, several different classes of Petri net formalisms were introduced, but we confined ourselves, in this article, to a simple application of the standard kind. As to fancy kinds of Petri nets, it may be that some amongst the present readership may find it useful to find about *predicate/transition nets* and then apply it in their own research (Genrich & Lautenbach, 1979). Reutenauer (1990) was concerned with the mathematics of Petri nets. Brown (1989a, 1989b) provides a treatment of Petri nets in terms of formal logic. In algebraic logic, the *box calculus* is a causal algebra with multilabel communication, within the Petri nets paradigm (Best & Hall, 1992; Esparza & Bruns, 1994). Olderog (1991) draws a comparison of three formalisms for representing concurrent processes; these include Petri nets.

8.4.2.4 Software Tools for Human Anatomy

There exists software for anatomy. For example, a workshop on the Mathematical Foundations of Computational Anatomy (MFCA'06) was held in September 2006

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[75] Also by Anatol Holt, cf. Holt (1971, 1988). In Holt (1988), *diplans* were introduced, for the purposes of studying coordination in the workplace and of automation. "Diplans are the expressions of a new graphical language used to describe plans of operation in human organizations. With diplans, systems of constraint, which may or may not take the form of procedure definitions, can be specified. Among the special strengths of diplans is their ability to render explicit the interactive aspects of complex work distributed over many people and places – in other words, coordination. Diplans are central to coordination technology, a new approach to developing support for cooperative work on heterogeneous computer networks." (ibid., from the abstract).

[76] Cf. Vila and Yoshino (2005), and cf. Fisher et al. (2005) on temporal logics in AI.

in conjunction with the MICCAI'06 conference. Works in computational anatomy are also presented, for example, at the Annual International Conferences of the IEEE Engineering in Medicine and Biology Society (EMBS), and at the Annual Meetings of the International Society for Computer Assisted Orthopaedic Surgery (CAOS).

Arbabi, Boulic, and Thalmann (2007a, 2007b) described a fast method for finding the range of motion in the human joints, and in the hip joint in particular. The context is the diagnosis of hip disease: "Finding the range of motion for the human joints is a popular method for diagnosing", and the claim was made that it is both more trustworthy "and easier to find the range of motion by employing computer based models of the human tissues. In this paper we propose a novel method for finding range of motion for human joints without using any collision detection algorithm. This method is based on mesh classifying in a cylindrically segmented space" (Arbabi et al., 2007b, from the abstract). The method illustration was the determination of the range of motion in the human hip joint, but actually the method could be applied more generally to the joints in the human body.

From that same Swiss team in Lausanne, also see Abaci et al. (2007a), on object manipulation and grasping "in an object manipulation context. Our proposal is a novel method that combines a tubular feature classification algorithm, a hand grasp posture generation algorithm and an animation framework for human-object interactions. This method works on objects with tubular or elongated parts, and accepts a number of parameter inputs to control the grasp posture" (ibid., from the abstract).

Being able to model grasping by computer, as well as being able to determine by computer the range of motion in the human joints (even though this is for the purposes of diagnosis in vivo), is arguably relevant for questions akin to the one asked at the end of Section 8.4.2.1 above: "Could that child have extended an arm and picked up that given thing?".

The history of the project of modelling hip joints is related in the following, which is quoted from Magnenat-Thalmann and Gilles (2007, p. 25)[77]:

> Since 2002, Prof. Nadia Magnenat-Thalmann of the Swiss National Center of Competence in Research Co-Me has been leading a project on interactive clinical visualization for hip joint examination. The goals of this research are to build a 3D patient-specific functional model of the hip joint, of the hip joint, and to develop interactive tools allowing clinicians to examine hip behaviour. Such tools will be invaluable aids in diagnosis and treatment planning, particularly for osteoarthritis and impingement syndrome pathologies.

Also consider, e.g., *MuscleBuilder*, a computer-graphic modelling tool for human anatomy (Aubel & Thalmann, 2007; cf. 2000, 2001, and Gutiérrez et al., 2005, 2007). In cultural terms, this is an extension of the genre of anatomy handbooks, which itself is grounded in the history of the ideas, as well as of the arts. Jonathan Sawday's (1996) is a book in cultural history, concerned with the dissection of the human body in the culture of the English Renaissance, in relation to conceptualisations of the body in several domains, including the arts.

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[77] Nadia Magnenat-Thalmann leads a team in Geneva, whereas Daniel Thalmann leads a team in Lausanne. Cf. in Section 5.2.15 above.

Take illustrations in anatomy handbooks, through history, as made by illustrators by observing dissected bodies. Bernez (1994) discussed the aesthetics of seventeenth-century Dutch painter Gérard de Lairesse's illustrations for Bidloo's *Anatomia Humani Corporis.* Bernez shows how anatomic drawings within the history of art actually reflected moralising intents, about life and death, on the part of the artists, and, paradoxically, aesthetic ideal as well. Bernez shows that de Lairesse's anatomic drawings are somehow amenable to a seventeenth-century Dutch genre he practised, the *Vanitas:* "Anatomy as Vanitas: the allegorical representations of life's brevity [. . .]" (ibid., p. 213). "The Vanitas was a genre of still-life painting in which certain objects representing the fruitfulness of nature or the value of human activities were contrasted with elements which evoked the triumph of death" (ibid.).

EnVision (2002) relates about a project led by Michael I. Miller, director of the Center for Imaging Science at Johns Hopkins University, concerning the application to neuroscience of computational anatomy:

> "Computational anatomy could be described as a digital textbook of anatomy, with all its variability in healthy humans, adjusted for things like gender, age, and ethnicity, and also in pathological situations that affect anatomy", said Grenander. "The main difficulty is that anatomical substructures form highly complex systems, with variation being the rule", Miller said. As he said in an interview published earlier this year [(Taubes, 2002)], "If machines can compute structures that are equivalent to the structures we see in the world, then we can begin to understand them. In computational anatomy, we now have equations that describe how tissues can grow and bend and morph and change. These equations seem to generate very realistic structures".

Miller's application is to the brain, a soft tissue, "to learn how tissues grow, assume new shapes, and 'morph' into mature structures" (ibid.). Miller is quoted as saying: "Our mathematical formulation deforms structures in a coordinate space, and thus the original structures are entirely recoverable computationally. That is the difference between morphing and morphometrics" (ibid.). In morphing, just a photometric transformation is carried out, without any coordinate system allowing recovery of the previous shape. "For the past decade, Miller's group has been developing computational methods to analyse gross anatomical structures in the human brain, with the objective of creating tools to help neuroscientists and diagnosticians learn from changes in brain substructures. The underlying mathematics are supplied by metric pattern theory, a formalism developed by Ulf Grenander in the Division of Applied Mathematics at Brown University" (ibid.).

Several of the short papers in the special issue on "The Digital Patient" of *ERCIM News* (April 2007) describe such projects that revolve around computational models of human anatomy, and being carried out in various European countries. For example, Xavier Pennec (2007) introduces a project applied to the brain (one of Pennec's partners in France is also a partner of Miller).[78]

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[78] At http://www-sop.inria.fr/asclepios/projects/ARCBrainVar/ a description is found of Pennec's project.

Among the applications, two that are generally relevant for our present concerns include “the spatial normalization of subjects in neuroscience (ie mapping all the anatomies into a common reference system) and atlas-to-patient registration in order to map generic knowledge to patient-specific data” (Pennec, 2007). Arguably, atlas-to-patient mapping is relevant for computational anatomy to be of any use to forensic anthropology.

González Ballester, Büchler, and Reimers (2007) “are constructing advanced statistical digital models of bone shape and biomechanical properties. These models will lead to the design of a new breed of orthopaedic implants that will guarantee an optimal fit for the whole range of patients” (ibid., p. 27). “During this project, we have extended our ability to analyse the surface shape of anatomies to also include internal structures and bone density information. This results in a compact statistical description of the variability in bone shape and density, and the correlation between them” (ibid.). This suggests, I would say, that conceivably, some similar model could be of use to forensic anthropology and perhaps to forensic ballistics, in order to simulate what may have brought about the conditions observed in a dead human body in a forensic setting.

Computational models of human anatomy find expression also other than through the 3D visualisation of the anatomy. The simulation of pain in robotics has been reported about. Reportedly in the late 2000s, the University of Gifu was expecting to make use of a patient-robot for medical training, in particular in the palpation of patients, before having the trainees exercise in palpation directly on humans. The patient-robot was developed by Yuzo Takahashi. The robot has 24 internal sensors, and if touched in a body part (corresponding to a human body part), it speaks up and conveys the physical distress being simulated. Eight kinds of symptomatologyare recognised in the prototype, and the inclusion of more is envisaged. Its skin produces the sensation, when touched, of human skin.

Victor Ng-Thow-Hing is active both in robotics (e.g. Hauser & Ng-Thow-Hing, 2010), and in biomechanical anatomical models of human and animal bodies, a field in which he was supervised by Eugene Fiume in Toronto (Ng-Thow-Hing, 1994, 2001; Agur, Ng-Thow-Hing, Ball, Fiume, & McKee, 2003; Teran et al., 2005; Wu, Ng-Thow-Hing, Singh, Agur, & McKee, 2007). Musculotendon units were built by sketching interactively profile curves directly onto the bones; the curves can be subsequently adjusted to interactively edit the shape of the resulting muscle. As an alternative for producing an initial shape of the muscle, it is also possible to load into the system pre-built muscles from an anatomical library. The muscle models generated were used as *force actuators*, in a robotic simulation sense. The simulation framework allows muscles to be visualised, and the simulation combines the muscles with articulated skeletons. These are made up of rigid bones and of joints; there are various joint constraints.

Hutchinson, Ng-Thow-Hing, and Anderson (2007) applied an anatomical model to reconstruct the turning and running performance of the dinosaur *Tyrannosaurus rex*. This is an example of *computational palaeontology*. That model combined *mass models* as those used by Ng-Thow-Hing in *digital human modelling* at Honda, the *B-spline model* he was using for muscle, and generated a versatile shape primitive for estimating mass properties of body tissue. Just as he could do that for extant animal species or for humans, he was able to do that for the fossil species, and the model was validated with an ostrich carcass.

8.5 Aspects of the Contribution to Forensic Science of Geology, Geophysics, and Botany

8.5.1 Forensic Geology

Forensic geology (also called *geoforensics*, or *forensic geoscience*) is an important discipline, for criminal investigation as well as for the purposes of litigation, e.g. concerning environmental damages.[79] Laurance Donnelly (2003, p. 8) pointed out: "Over the past one hundred years or so, several crimes have been solved due to the expertise provided by geologists. However, due to the sensitive and confidential nature of police investigations, only occasionally are these reported in the scientific literature". In a 1893 German-language handbook for examining magistrates, "Hans Gross, a criminal investigator and professor of criminology [. . .] was one of the first to advocate the use of microscopes in mineralogical studies analysing 'dust' and 'dirt' on shoes and 'spots' on cloth" (Donnelly, 2003, pp. 8–9). This approach was "subsequently used by George Popp in 1904, during a murder investigation (the Eva Disch case), in Frankfurt, Germany" (ibid., p. 9). In France, Edmond Locard (1877–1966), a star of criminalistics who used inventively a variety of techniques (see Section 8.7.1 below), concerned himself with the analysis of dust traces, too, and described them at length (Locard, 1930). "The Federal Bureau of Investigation (FBI) have been using forensic geology since 1935, initially to help solve the Matson kidnapping case" (Donnelly, 2003, p. 9).

Turning to the 2000s, Bergslien et al. (2006) have been trying to apply field portable X-ray fluorescence (FPXRF) spectrometry to both forensic and environmental geology. "There are many environmental applications that may also intersect the forensic arena, such as tracking pollutants in the environment to their source" (ibid., p. 19). A forensic application they reported about "involves analysis of mineral and rock deposits on automobile tires, shoes, carpets etc. and direct comparison with materials found at the crime scene. Knowledge of compositional changes in geological formations may aid in tracing movements of a crime suspect or victim" (ibid.).

At the inaugural meeting of the Forensic geoscience Group of the Geological Society of London, on 20 December 2006 (Ruffell, 2006), Donnelly pointed out (Donnelly, 2006, pp. 3–4):

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[79] Books on forensic geology, or geoforensics, as it is also called, include Pye and Croft (2004), Pye (2007), and Murray and Tedrow (1975).

> There are a number of geologists in the UK, and internationally, who currently work with, or have recently worked with the police, other law-enforcers, environmental agencies and humanitarian organisations to help bring some types of crimes to successful conclusions. Some geoscientists have also been involved in forensic investigations in the mining, engineering, minerals and water sectors of industry, or during the investigations of geohazards (also known as natural disasters). The common ground for all these sub-disciplines is that geoscience practice and results may end up as part of a public, international or legal enquiry by government or in courts of law.
>
> Forensic Geoscientists may be broadly divided into two principal fields, depending on their skills, expertise and capabilities. Firstly, there are the laboratory-based geologists who may include for example; geochemists, mineralogists, petrologists, micro-palaeontologists and isotope specialists. These may be involved with forensic investigations to; provide physical evidence for use in court, assist in an investigation, provide intelligence or identify the location of a crime scene. In short, geoscientists may link an offender (or object) to the scene or link the victim to an offender. Secondly, there are field-based geologists, who use their skills in exploration (including for example: geophysics, geochemistry, geomorphology, hydrogeology, environmental geology, remote sensing and geotechnics) to search the ground (to locate murder victim's graves, weapons and other objects).

As opposed to "[t]raditional police methods of finding graves [which] often involve large-scale 'finger-tip searches' and 'trial-and-error' excavations", which apart from inefficiency, "may even destroy evidence and ignore subtle ground disturbances", geologists "are trained to 'read the ground'" (Donnelly, 2003, p. 9).

Donnelly proceeds to enumerate the main geologists' techniques for crime scene investigations: the *mineralogical, petrological*, and *geochemical analysis* of rock and soil, or even *fossils* (resorting to palaeontology), for evidence in both criminal and civil cases.

Another method is the use of *geological maps* (and conceivably, *geographical information systems* produced by information technology, indeed a category within *geoinformatics* or *geomatics*, could be somewhat customised to reflect, e.g., ease to excavate).

> In the UK, maps published by the British Geological Survey (BGS) have been used in police investigations to identify potential burial sites and topographic features mentioned in witness or suspect statements. Since search investigations were usually undertaken under a limited budget, geological maps can be used to eliminate areas of ground which are less likely to conceal buried objects [... E.g., in Kent, w]here the cretaceous bedrock was exposed, the use of a spade was considered unlikely. (Donnelly, ibid.).

McCann, Culshaw, and Fenning (1997) proposed that (in the words of Fenning & Donnelly, 2004, p. 11) "an initial desk or background study of the survey area" – as distinct from a visit to the site "in order to obtain what can only described a 'feel' of the site (i.e. putting the desk study into context)" – should collect all available relevant information about the site, including, among the other things, "Present and historical topographical maps, usually from the Ordnance Survey", "Geomorphological research studies and reports", "Present and historical geological survey maps and associated descriptive memoirs from the British Geological Survey", "Aerial and satellite photography, both current and historical", "Present and historical soil survey maps with surface vegetation detail", "Web search of the English Heritage database of geophysical survey results related to archaeological investigations (Linford, 2002)", "Library/web search for relevant scientific and press publications and photographs, including university research papers", "Information on the nature and physical properties of the survey target (e.g. buried metallic weapon, victim's discarded clothing, or buried human remains)" – in the words of Fenning and Donnelly (2004, ibid.), where the method of McCann et al. (1997) is adapted to forensic investigations.

G*eomorphological observations* enable to interpret "subtle natural ground disturbances arising from the particular crime. These might include vegetation changes, undulations, spring lines, breaks in slope, convex and concave slopes, disturbed ground, periglacial deposits, the occurrence of loose soil, drag marks, and the compaction of ground" (Donnelly, ibid.). The interpetation needs to discern whether these exhibit the effects of natural physical processes, or result from human activity, "for example mining subsidence, waste disposal, tipping and digging" (ibid.). Besides, *remote sensing* is another category of forensic techniques from geology.

Several other techniques of forensic geology belong in *geophysics*, and are treated in Section 8.5.2 below; as we are going to see, geophysical techniques for forensic investigations involve information technology, and there appears to be an important potential for more applications of computing. Donnelly (2003) explains the basics of geophysics in a forensic context as follows: "Geophysical surveys provide an alternative, more cost-effective method for locating disturbed ground and buried objects. Geophysical surveys measure the vertical and lateral variation of physical properties of the ground. These include electrical conductivity, magnetic, electromagnetic and gravity, etc. If a buried object provides a property contrast this can be used to detect its presence" (ibid., p. 9).

It is to be remembered that specialists from different disciplines are involved in the forensic science side of criminal investigations, whether on the crime scene, or afterwards (or before the scene of the crime is identified). "Search teams are inter-disciplinary and involve the integration of specialists such as ground search personnel, dog handlers, helicopter pilots, forensic scientists, pathologists, mountain rescue, photographers, divers, forensic anthropologists, forensic archaeologists and scene of crime examiners" (Donnelly, 2003, p. 11).

Donnelly (2003, pp. 10–11) provides a case study: the Moor Murders from the 1960s. Several young children were abducted and murdered, and the perpetrators buried them in unmarked graves on Saddleworth Moor, a remote region in the Pennines, Northern England, on the Lancashire and West Yorkshire border. In the mid 1980s the case was reopened, as not all children had been found. During the 1990s, Donnelly himself had been involved in the search for the last remaining body (Donnelly, 2002b, 2004). In personal communication (26 June 2007, reproduced by kind permission) he explained the background and latest developments:

> I have been working with the Police for 13 years now. Originally, most of my work was undertaken covertly and without the knowledge of others outside the police. However, since my 2002 presentation at Westminster Palace (see *Geoscientist* [Donnelly] 2002[c]), on forensic geology, there has been a steady increase in UK geologists' involvement in forensic geology, including both research and case work. There are now several universities, research organisations and consultancies. This is of course, fantastic news. Before this

> event there were a few geologists in the UK working with the Police, mainly involved with the identification of rock and soil for helping to solve some crimes.
>
> My primary objective has, and continues to be, to find the grave of a young boy, I believe to be buried in a remote location in part of northern England. In December 2006 I set up the Geological Society of London Forensic Geoscience Group. The first inaugural meeting was held in London, in December 2006 (see attached). Working with the police has presented unique opportunities and enabled me to explain the skills, capabilities, expertise and role of geologists, in police and forensic investigations. As a result, there is now little doubt in the police the valuable role geology may bring to help solve/investigate a crime, but only if geologists' are incorporated properly, with both the police understanding the role of the geologists, and the geologists understanding the role of other investigators (and also his/her limit of expertise).
>
> The setting up of the FGG, in the Geological Society of London [. . .] is aimed at advance the study and understanding of forensic geology. Our inaugural meeting, held at Burlington House in December 2006, was successful [. . .]. In October 2007, FGG are supporting the 'Soil Forensic Conference' in Edinburgh [. . .]. This event will give UK geologists the opportunity to discuss and debate the role of geologists with the police and to identify the ways forward for our profession.

In geology, there exist *soil fingerprinting techniques*, and these can be used for forensic applications. Consider the *SoilFit* project: "The UK SoilFit project (http://www.macaulay.ac.uk/soilfit/) [. . .] aims to integrate data from state-of-the-art soil fingerprinting methods with data currently held in spatially referenced soils databases. This approach could potentially improve both matching of evidential soil samples and prediction of probable geographical origin" (Dawson et al., 2006).

> A decision support tool is being developed to assist the forensic scientist in selecting the most appropriate analytical strategy depending on sample size, type and condition. A software prototype has been written to process the data and identify, with probabilities, the soil type. This information is then fed into a prototype rulesbased GIS model to identify areas with appropriate soils, which can be narrowed down by layering intelligence of other spatial data (e.g. distance from roads, broad vegetation types). These prototypes have been built to demonstrate and evaluate the approach for crime investigation. (ibid.)

8.5.2 Techniques from Geophysics in Forensic Archaeology vs. in Archaeology

One branch of forensic geology is forensic geophysics. Geophysical survey consists of surveying the subsurface of the earth by the measurement of its physical properties. "An individual survey may take hours, days or months to complete. Geophysical surveys provide an alternative, more cost-effective method for locating disturbed ground and buried objects, but the choice of instrument, methodology and interpretation need to take several inter-related factors into account.

These include the physical properties of the target (human remains, buried ransom money, jewellery, weapons), the geological profile, depth of burial, topography, ground conditions, age of the burial and the experience and – of course – skills of the operators" (Donnelly, 2002a). Fenning and Donnelly (2004) remarked: "[I]n the last twenty years, the application of geophysical methods in archaeological surveying, plus advances in geophysical instrumentation and computing technology, has allowed geophysicists to conduct high-resolution surveys of the top 1–2 m below ground surface" (ibid., p. 11).[80]

The third lecture at the workshop on Archaeology and Forensic Science, held at the British Academy in London on 27 February 2007, was given by Paul Cheetham, on "Geophysics: Application to Forensic Science". Cheetham's affiliation is with the School of Conservation Science at Bournemouth University. His early formation was in statistics and computing, before he turned to geophysics. He is the foremost authority, in Britain, on geophysics application to forensic science. He started his lecture by pointing out that forensic science being fashionable sometimes causes journalists to describe as "forensic" excavations, such excavations which have nothing forensic about them and are archaeological (or possibly carried out for historical purposes, e.g., excavating remains of Napoleonic troops for the purposes of studying their body parasites). Nevertheless, he stressed, oftentimes archaeologists employ better techniques than forensic science.[81] He stated that he sometimes gasps at articles published in forensic science journals, because of how they lag behind things well established from scientific methods as applied to archaeology.

Moreover, in pursuing some directions of research, one may notice discontinuity in the forensic literature, e.g., three isolated papers (whose respective authors did not continue in the given direction) may not cite each other, and no referee apparently pointed that out, and moreover that technique is considerably more advanced as used in archaeology. Such a picture with sporadic papers in forensic science about techniques from geophysics that don't even cite each other, and of research projects being discontinued, was contrasted to the situation in archaeological science, that has a tradition of steady work building upon previous work, when it comes to applying techniques from geophysics.

What are the chances, for a given technique, to be applied again and again in crime scene investigation (or, for that matter, while assisting the scientific police)? "If you do it quicker and cheaper, the police will call you back". During his talk, Cheetam also specifically considered different techniques from geophysics, and the likely reasons why their ranking according to prominence for forensic science vs. archaeology is different.

The big growth area in geophysics has been in smaller scale higher-resolution near-surface survey in what is loosely termed applied engineering, environmental geophysics, or industrial geophysics. This rise has run coincident with a decline in mineral prospection. In a sense, this was an incentive for geophysics to change the direction of its main thrust for application.

Types of geophysics required for forensic science include: near-surface survey; delineation of discrete small features of the terrain (this requires good lateral resolution); and part of the recovery process. It is archaeological geophysics, which is leading. Forensic geophysics may learn from it. When surveying the subsurface of

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[80] Also Bevan (1991) is concerned with the search for graves resorting to geophysics. By contrast, the approach to the detection of clandestine graves in Davenport et al. (1992) is multidisciplinary.

[81] See Gaffney and Gater (2003), Mellett (1996).

the earth by geophysical techniques, normally measurements are taken above the surface, and are non-intrusive. When the application is forensic, one looks for specific kinds of evidence (e.g., graves), not for anything (just defined by scale) as in archaeological geophysics. When what has to be found is bodies and neonates, such bodies are too small for most techniques from geophysics.

Methods from geophysics that are frequently used in archaeology include: magnetometry; earth resistivity; topsoil magnetic susceptibility; ground penetrating radar (not as good as the previous methods); and electomagnetics. The latter technique for archaeology was developed by the French; according to Cheetham, it is the Cinderella among those techniques. In contrast, forensically, the ranking of the techniques is different. Ground penetrating radar is a good technique, Cheetham stated, for forensic purposes. (Fenning and Donnelly (2004) describe it as enjoying popularity and acclaim in the forensic domain: see below).

Cheetham went on, remarking that earth resistivity can be used for looking for graves or for metal, but is not often used in forensic contexts (see below). Electromagnetics is often recommended, but is almost not used. Magnetometry is applies in metal detectors. Topsoil magnetic susceptibility is only employed for specific uses, within a forensic context, and ranks lower with respect to its rank among techniques for archaeology. We are going to be more precise further down in this chapter, thanks to an invaluable survey by Fenning and Donnelly (2004).

Forensic graves are very different from archaeological graves, in respect of the effectiveness of detecting graves and cremations with the most frequently used geophysical survey techniques. Ground penetrating radar works especially well in sand, rather than in other kinds of terrain. (Cheetham brought as an example a commercial ad for the technique, with a picture showing a demonstration on the sand in front of the Sphinx in Egypt. He pointed out that for an advert, it made sense, because this technique works very well in sand.) Ground penetrating radar is not good for finding small objects.[82] In archaeometry, ground penetrating radar is put to good use for intensively recording an area, slicing the data into images, possibly animating the images by *time-slice* (e.g., to show ancient cultivations or archaeological features). Our Section 8.5.3 is devoted to the concept of *time slicing*. Time-slicing from geophysics is applied, then, to archaeometry, using computational methods.

Earth resistivity, Cheetham claimed during his lecture, is the Cinderella of forensic techniques from geophysics. Nevertheless, Cheetham pointed out, it is a superbly reliable technique in archaeology, with variants: resistivity electrode arrays are applied to archaeology, even though they are cumbersome. Earth resistivity is good for finding graves. Nevertheless, it is almost never used in forensics, because it is regarded as a low technique by geologists: two hours were reported, for surveying a 7×6 m area. But in archaeology, better is done. Apparently there is no good reason for not applying the method in forensics: it is a matter of lack of investment.

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[82] Also Fenning and Donnelly (2004) point out that, e.g., coins could be located at depths up to 0.5 m using a sophisticated instrument, but only larger objectsd would be detected if buried deeper (ibid., p. 15).

Reluctance to employ this method for forensic purposes has been its perceived slowness; nevertheless, in applications in archaeology this problem has been overcome. An important application of earth resistivity is in volumetric models, rotated by computer animation, of graves or mass grave. Cheetham brought as an example of application to mass graves the same computer graphic model we had already mentioned by reporting about Hunter's talk (see at the end of Section 8.4.1).

Table 1 in Fenning and Donnelly (2004, p. 12)[83] summarises features of various geophysical survey methods.

- The *seismic* method's measured parameter is the travel times of reflected/refracted seismic waves, and the 'operative' physical parameters are the density and elastic moduli that determine the propagation velocity of seismic waves. The seismic method "is either applied to layered geological structures or used to determine depth of bedrock beneath superficial deposits. As such, it is rarely applied in forensic geophysics where a distinct target, such as a buried human body, is the survey objective" (Fenning & Donnelly, ibid., p. 13).
- In the *gravity method*, the measured parameter is the spatial variations in the strength of the gravitational field of the Earth, whereas the operative physical parameter is "the density difference between local rocks and an air-filled cavity" (ibid.), and in fact it is "usually employed to detect subsurface cavities, such as caves, graves and disused mine shafts" (ibid.). Fenning & Donnelly (ibid.) describe the gravity method as costly, time-consuming, and rarely applied in forensic geophysics.
- In the *magnetic* method, the measured parameter is spatial variations in the strength of geomagnetic field, whereas the operative physical parameter is magnetic susceptibility and remanence. This method would not be forensically useful if a corpse was buried naked. "The naked human body has virtually no associated magnetic anomaly and, when buried, is very unlikely to be detected by a magnetic survey. However, a fully clothed body is a different matter. Clothing may include metal buttons, zip-fasteners, shoe eyelets and belt buckles, while pockets may contain spectacles, keys, pens and other ferrous metallic objects" (Fenning & Donnelly, ibid.).
- The [*electrical*] *resistivity* method comes in a range of techniques, which "[a]ll involve inserting four steel electrodes into the ground and measuring vertical and horizontal variation in resistivity" (ibid.). Or, then, a *multi-electrode* array is sometimes used. In the resistivity method, the operative physical parameter is electrical conductivity, whereas the measured parameters are earth resistance, polarisation voltages or frequency-dependent ground resistance.
- The *induced polarisation* method has the same measured parameters as the resistivity method, but the operative physical parameter is electrical capacitance in

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[83] It is based on Kearey and Brooks (1984). Incidentally, a current edition of that book is Kearey, Brooks, and Hill (2002).

stead of conductivity. Reportedly, it is less effective and slower a method than resistivity surveys (ibid., p. 14).

- In the *self-potential* method, which is reportedly inexpensive (ibid.), the measured parameter is "naturally occurring ground [electrical] potential due to electrochemical reactions between different rock and groundwater levels and flow" (ibid.), and the operative physical parameter is electrical conductivity. Fenning & Donnelly (ibid.) suggest that, notwithstanding the lack of publications about using this method for forensic purposes of discovering dead bodies, the self-potential method has potential (our pun intended) in that domain.
- In the *electromagnetic* methods, the measured parameter is the response to electromagnetic radiation, whereas the operative physical parameters are electrical conductivity and inductance. "An effective and rapid surveying alternative to resistivity profiling is the electromagnetic inductive conductivity (IC) profiling method, which allows continuous recording of the subsurface conductivity at a walking pace. Electrical conductivity is the reciprocal of electrical resistivity" (ibid.). "No case histories relating to direct detection of buried human remains are known", but in the literature applications of the method were described, "in defining archaeological features such as graves and tombs" (ibid.).
- In the *ground-penetrating radar (GPR)* method (e.g., Hammon, McMechan, & Zeng, 2000; Mellett, 1996), the measured parameter is the response to high-frequency electromagnetic radiation, and the operative physical parameters are electrical conductivity and the dielectric constant. Whereas in the electromagnetic inductive conductivity method, "instruments are one-man, portable and operat[ing] in the frequency range of 10–15 kHz", "[t]he much higher frequency range of 25 MHz to 2 GHz is the realm of GPR which has received substantial publicity for its ability to produce high-resolution cross-sections of the surface" (Fenning & Donnelly, 2004, p. 14). Reportedly, Hildebrand, Wiggins, Henkart, and Conyers (2002), who "compared seismic reflection and GPR imaging over a dead pig buried in a wooden coffin at a test site in Illinois" (Fenning & Donnelly, 2004, p. 13), found that "the GPR survey was many times faster than the seismic reflection survey" (ibid.).
- Moreover, *metal detector* methods involve a "one-man, portable hand-held scanning devic[e] with an audible signal or meter output" (Fenning & Donnelly, 2004, pp. 14–15). The smaller the metal object, the shallower the underground range of the instruments. A large object would be detected even if buried somewhat deeper (ibid.).
- And finally, "[t]he advantages of using mobile multi-sensor systems in forensic studies are clearly apparent where there are large tracts of survey and copious detailed data points are required" (ibid.); such mutisensor systems consist of arrays of sensors "which can be man-carried or vehicle-mounted and walked/towed across site" (ibid.), sometimes making use of *differential global-positioning systems (DGPS).*

The general rule for all those methods is that "[t]he physical property contrast between a target and the surrounding host material of soil and rocks is essential if geophysical methods are to be effective" (Fenning & Donnelly, 2004, p. 12). "In addition to an understanding of the capabilities of geophysical methods, it is essential that the limitations of these methods be clearly understood.

MacDougall et al. (2002) point out various limitations which can make areas unattractive for geophysical surveys" (Fenning & Donnelly, ibid.). For example, "gates, buildings, fences, overhead power cables, parked or moving vehicles and machinery", being "man-made metallic features at ground surface", are detrimental for a survey to be conducted, and so it the "[p]resence of man-made metallic and non-metallic features below ground surface e.g. cables, pipes, sewers, reinforced concrete" (ibid.). This is also the case of "[e]lectrical interference e.g. mobile phones, electrical machinery, power cables", of "[c]urrent construction or farming activities", of "[s]evere ground topography", of access problems such as bushes and vegetation, of the "[p]resence of farm animals", and of "[s]easonal factors e.g. tourists, weather" (ibid.).

Fenning and Donnelly's article (2004) has been invaluable for writing part of this section. That article also analyses three case histories. The interested reader is urged to refer to that paper. Whatever we have quoted from it here, can only be an appetiser, not the main course.

8.5.3 A Clarification About Time Slicing

Time-slicing (mentioned in the Section 8.5.2, with data from ground-penetrating radar) is a concept that occurs in a number of different disciplines. Time-slicing can be found in computer operating system design; in cinematography; in synchrotron radiation from physics; in power engineering; and so forth. In a computer's operating system which, on a serial machine, has to simulate the parallel execution of a large number of programs, this is achieved by means of time slicing: at each time slice, a small number of instructions are executed for each program, one at a time. If the strategy is that a fixed number of instructions is to be executed for each program at each time slice, longer programs will take more time slices. Other strategies are possible.

In contrast, in telecommunications, time slices (i.e., burst, or time slots when the data are transmitted) enable a reduction in power consumption, e.g., of mobile receivers, because when the relevant data are not available, the front end (i.e., the receiver) is switched off, and later on it is informed when to wake up, when the next burst (intended for it) is expected.

As to special effects in cinematography and computer animation, the Wikipedia entry for "Bullet time"[84] remarks that "Technical and historical variations of this effect have been referred to as time slicing, view morphing, flo mo, mort temps and virtual cinematography":

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[84] http://en.wikipedia.org/wiki/Bullet_time (accessed in March 2007).

> a computer-enhanced variation of slow-motion special effects used in some recent films and computer games. It is characterized both by its extreme permutation of time (slow enough to show normally imperceptible and un-filmable events, such as flying bullets) and by the ability of the camera angle – the audience's point-of-view – to move around the scene at a normal speed while events are slowed. This is almost impossible with conventional slow-motion, as the physical camera would have to move impossibly fast; the concept implies that only a 'virtual camera', often illustrated within the confines of a computer-generated environment such as a game or virtual reality, would be capable of 'filming' bullet-time types of moments.

In beam physics, a report in the *Advanced Light Source (ALS) News* (ALS News, 2000) stated that

> [i]n early 1996, Alexander Zholents and Max Zolotorev of Berkeley Lab's Center for Beam Physics proposed the laser time-slicing technique as a way to achieve effective bunch lengths in the femtosecond range. At the heart of the proposal was the use of a high-power, femtosecond laser synchronized with the electron bunches so that a pulse of laser light passed collinearly with an electron bunch through an undulator or wiggler. The high electric field of the shorter laser pulse modulated a portion of the longer electron bunch, with some electrons gaining energy and some losing energy. Subsequently, when the energy-modulated electron bunch reached a bend magnet (or other section of the storage ring with a nonzero dispersion), a transverse separation occurred. A collimator or aperture selected the synchrotron radiation from the displaced bunch slices.

Later on, according to the results of Schoenlein et al. (2000), a Berkeley team – in the words of ALS News (2000) –

> generated 300-femtosecond pulses of bend-magnet synchrotron radiation at the Advanced Light Source (ALS) with the aid of a laser 'time-slicing' technique. Their proof-of-principle experiment demonstrates that this technique is a viable one for producing ultrashort pulses of x rays. An ALS bend-magnet beamline will soon be commissioned that will be dedicated to time-resolved x-ray diffraction, EXAFS, and other techniques capable of probing the long-range and local structure of matter on a femtosecond time scale.

Readers conversant with artificial intelligence are likely to know about *slice* from the terminology of *naive physics:* that notion of *slice* was introduced in Patrick Hayes' (1985) so-called *ontology for liquids*, a naive physics model that can handle phenomena in fluid dynamics, and involves spatio-temporal histories of objects. On p. 90, Hayes wrote the following concerning the difference between the formal concepts of *history* and *situation*:

> A history differs from a situation in being restricted spatially and extended temporally: it is a connected piece of space-time in which 'something happens', more or less separate from other such pieces. Histories, unlike situations, have a *shape*: much of [Hayes' treatment is] devoted to ways of describing their shape.
>
> Examples of histories include the inside of a room during the afternoon, a horserace and the pouring of water from one cup into another. The idea is that a history shall contain an event, isolating it temporally and spatially from other events. We include the special case in which nothing happens at all. A *state* [. . .] is an instantaneous 'slice' of a history at a certain time-instant. [. . .] If *h* is a history and *t* a time-instant (we assume a global timescale od some sort with an inequality defined on it), the *h@t* (read *h* at *t*) is the 'slice' of *h* at *t*. This is a state, that is, a spatial entity at a particular time.

8.5.4 From Soil to Scent: Between Current Practice and Imagining the Digital Potential

8.5.4.1 Scent-Detection, Odorology, Cadaver Dogs, and Gas Soil Surveying: The Detection of the Scent of an Individual, vs. the Detection of a Kind (Graves)

Tribondeau (accessed 2006) credits a country in Eastern Europe with the origination of a particular technique for identification, *odorology* (s.v. *odorologie*, quoted here in my own translation):

> Developed since recently by the French police, this practice, which appeared about thirty years ago in Hungary (where it enables solving over 4000 cases per year), enables the identification of perpetrators through their olfactive print (*empreinte olfactive*). Concretely, investigators places cotton ribbons on the scene of the crime; then these conserved inside hermetically closed phials. It just takes, for especially trained dogs, to sniff a piece of cloth imbued with the scent of a suspect who eventually turns up, and subsequently the various phials who are opened in front of these dogs. Like with explosives and narcotics, the dog will stop in front of the phial with the same scent as the suspect. In Hugary, over 18,000 olfactive prints are collected every year. A phial may last during at least ten years.

This is a further development of the widespread employment of dogs for *scent-detection*. The latter method is "Relatively nondestructive. Proven effective even 170 years after burial. Effective over water" (Davenport et al., 1992). These are advantages, whereas disadvantages are as follows: "Most effective when air, ground moist. Dog may be trained for other uses and not properly trained for this type of work; handler may overstate qualifications" (ibid.). Davenport et al. (1992) were concerned with the detection of clandestine graves, and the dogs used were *cadaver dogs*. Using dogs or pigs is also widespread for finding truffles underground, or the method is also in use for detecting landmines, typically for the purpose of demining an area. Davenport et al. (ibid.) had carried out experiments with the detection of pig carcasses, and adopted a multidisciplinary approach to their detection:

> Excessive heat causes some discomfort to the dog and this may affect the dog's ability to locate a scent. When the temperature is extremely high the dog will still locate the scent; however in most cases, it will need to be within approximately a meter of the source. Even if the temperature is high, the results will improve if the ground is moist. Extremely low temperatures also limit the dog's ability to detect the scent from a distance, especially if the source is buried. If the source is buried in snow with temperatures allowing only minimal melting, the dog must be directly over the source to locate it. If the temperature is warm enough to allow for significant melting the dog can locate the source from a greater distance.

Apart from scent-detection by cadaver dogs, also *soil gas* surveying was carried out (ibid.):

> The soil gas surveying performed at the research site holds promise of providing a useful, albeit labor intensive, technique to locate graves. Organic gases were detected within three meters of two of the grave sites; however, the investigators had the privilege of knowing in advance the locations of these sites. Soil gas surveying is best in soils with a low clay content (so as not to clog the probes) and over unfrozen ground.

What can possibly be the use of computing for the techniques mentioned in this chapter? Arguably, even unsophisticated computing methods can be used for the purposes of organisation and classification, e.g., of the dogs and their records. In odorology, such relatively unsophisticated methods from information technology may be nevertheless useful. On the other hand, it may be that chemical sensors as in *electronic noses* are not sophisticated enough; they would only pick up the sort of scent components they were devised to detect. Dogs are much more sensitive. Nevertheless, pattern matching methods, and perhaps data mining methods, from computing could perhaps complement the use of dogs. At any rate:

> Despite the importance of the olfactory sense to mankind, the sense of smell in man is often considered the least refined of the human senses, far less sensitive than that of other animals. For example, the human nose possesses only about one million aroma receptors that work in tandem to process olfactory stimuli whereas dogs have about 100 million receptors that distinguish scents at least 100 times more effectively than the average human [(Ouellette, 1999)]. Furthermore, the ability to detect chemicals in the environment is critical to the survival of most prokaryotic and eukaryotic organisms. A clear indication of the importance of olfactory systems in higher eukaryotes is the significant proportion (up to 4%) of the genome that is devoted to encoding products used in building olfactory sensory tissues [(Firestein, 2001)]. The relatively low sensitivity and discrimination capabilities of the human nose, coupled with the common occurrence of olfactory fatigue, has led to the need for electronic instruments with sensors capable of performing repeated discriminations with high precision to eliminate human fatigue.[85]

There are smells that humans could not identify accurately, and electronic noses can, either more accurately or more safely. Electronic noses may not be as good as dog noses (but some are claimed to be as good instead, as we are going to see), but when the task is to smell such substances that would be dangerous even to such police dogs that regularly detect narcotics, electroni noses may be the solution. We devote the next section to electronic noses indeed.

8.5.4.2 Electronic Noses

Odour assessment in industry resorts to any of the following:

- human sensory analysis,
- chemosensors, or
- gas chromatography.

With *gas chromatography*, information is obtained about volatile organic compounds, "but the correlation between analytical results and actual odor perception is not direct due to potential interactions between several odorous components".[86] Moreover, the police resorts to police dogs; individuals searching for truffles resorts

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[85] Wilson and Baietto (2009, p. 5101).

[86] http://en.wikipedia.org/wiki/Electronic_nose (when accessed in April 2011, it had been last modified in March of the same year).

to truffle dogs or pigs; and personnel searching for landmines may resort, among the other things, to dogs or even pigs, but in that case this is not only because the olfaction of such animals is superior to human olfaction, but also because casualties among such animals in case landmines detonate are more acceptable than human casualties. There also is a technique that resorts to wasps: "In the Wasp Hound odor-detector, the mechanical element is a video camera and the biological element is five parasitic wasps who have been conditioned to swarm in response to the presence of a specific chemical".[87]

Electronic sensing (or *e-sensing*) technologies aim at endowing devices with the capability of reproducing human senses using *sensor arrays* and *pattern recognition* systems. In e-sensing, an *electronic nose* is such a device that is intended to detect odours or flavours. One also speaks of *machine olfaction* in order to denote the automated simulation of the sense of smell. Electronic-nose technology[88] is the subject of a fifty-page survey by Alphus Wilson and Manuela Baietto (2009).

> Since 1982, research has been conducted to develop technologies, commonly referred to as electronic noses, that could detect and recognize odors and flavors. The stages of the recognition process are similar to human olfaction and are performed for identification, comparison, quantification and other applications. However, hedonic evaluation is a specificity of the human nose given that it is related to subjective opinions. These devices have undergone much development and are now used to fulfill industrial needs.[89]

Wilson and Baietto explain (2009, p. 5100):

> The sensor technology of artificial olfaction had its beginnings with the invention of the first gas multisensor array in 1982 [(Persaud & Dodd, 1982)]. Advances in aroma-sensor technology, electronics, biochemistry and artificial intelligence made it possible to develop devices capable of measuring and characterizing volatile aromas released from a multitude of sources for numerous applications. These devices, known as electronic noses, were engineered to mimic the mammalian olfactory system within an instrument designed to obtain repeatable measurements, allowing identifications and classifications of aroma mixtures while eliminating operator fatigue [[90]]. Unlike other analytical instruments, these devices allow the identification of mixtures of organic samples as a whole (identifiable to a source that released the mixture) without having to identify individual chemical species within the sample mixture [[91]]. Hundreds of different prototypes of artificial-nose devices have been developed to discriminate complex vapor mixtures containing many different types of volatile organic compounds (VOCs) [[92]]. These prototypes collectively represent various

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[87] http://en.wikipedia.org/wiki/Electronic_nose Also see http://en.wikipedia.org/wiki/Wasp_Hound

[88] Also see Pearce, Schiffman, Nagle, Nagle, & Gardner's (2002) *Handbook of Machine Olfaction: Electronic Nose Technology.*

[89] http://en.wikipedia.org/wiki/Electronic_nose.

[90] Davide, Di Natale, and D'Amico (1995); Pelosi and Persaud (1988); Persaud (1992); Persaud, Bartlett, and Pelosi (1993), Shirley and Persaud (1990); Shurmer (1990).

[91] Davide et al. (1995); Gardner (1991); Lonergan et al. (1996).

[92] Ouellette (1999); Yea, Konishi, Osaki, and Sugahara (1994).

> electronic aroma detection (EAD) technologies that utilize different sensor types including metal-oxide [[93]], semiconductive polymers [[94]], conductive electroactive polymers [[95]], optical [[96]], surface acoustic wave [[97]] and electrochemical gas sensors [[98]].

These electronic noses are typically used for recognition, rather than quantification[99]:

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[93] Egashira and Shimizu (1993); Nanto, Sokooshi, and Kawai (1993); Shurmer et al. (1989).

[94] Yim et al. (1993); Pisanelli, Qutob, Travers, Szyszko, and Persaud (1994).

[95] Lonergan et al. (1996); Freund and Lewis (1995); Hatfield, Neaves, Hicks, Persaud, and Tavers (1994); Persaud, Qutob, Travers, Pisanelli, and Szyszko (1994).

[96] Staples (1999).

[97] Again in Staples (1999).

[98] On pp. 221–245 in Gardner and Bartlett's (1999) *Electronic Noses: Principles and Applications.*

[99] But nevertheless, *olfactometers* (when used in one of the senses of that terms) are used to both qualify and quantify. The following is quoted from http://en.wikipedia.org/wiki/Olfactometer

> An *olfactometer* is an instrument typically used to detect and measure ambient odor dilution. Olfactometers are utilized in conjunction with human subjects in laboratory settings, most often in market research, to quantify and qualify human olfaction. Olfactometers are used to gauge the odor detection threshold of substances. To measure intensity, olfactometers introduce an odorous gas as a baseline against which other odors are compared. Many scientists use the term "olfactometer" to refer to a device used to study insect behavior in presence of an olfactory stimulus. It consists of a tube with a bifurcation (with "T" or "Y" shape) where an insect walks and decides between to choices, usually clean air versus air carrying an odor. This is why this device is also called dual choice olfactomenter. Alternatively, an *olfactometer* is a device used for producing aromas in a precise and controlled manner.

The following sense (as defined ibid.) is unrelated to electronic noses: "A flow-olfactometer is a complex instrument for creation of well defined, reproducible smell or pain stimuli in the nose without tactile or thermal stimulation. Stimulus rise time is fast enough to allow for recording of Olfactory Evoked Potentials (OEPs)." This device "produces a constant heated and humidified flow of pure air. This air flow runs continuously to the subjects nose. For the length of the stimulus pulse the continuous air flow is replaced by a bloc of odorized air" (ibid.). Contrast this to *dynamic dilution olfactometers* (ibid.):

> The new generations of dynamic dilution olfactometers quantify odors using a panel and can allow different complementary techniques:
>
> - odor concentration and odor threshold determination
> - odor suprathreshold determination with comparison to a reference gas
> - hedonic scale assessment to determine the degree of appreciation
> - evaluation of the relative intensity of odors
> - allow training and automatic evaluation of expert panels
>
> These analyses are often used in site diagnostics (multiple odor sources) performed with the goal of establishing odor management plans.

A concept related to the latter is *electrogustometry*, i.e., the measurement of *taste threshold*, i.e., the minimum amount of electrical current required to excite the sensation of taste. When using an *electrogustometer*, current is made to pass through the tongue, and a metallic taste is perceived.

> Conventional electronic noses are not analytical instruments in the classical sense and very few claim to be able to quantify an odour. These instruments are first ‘trained’ with the target odour and then used to ‘recognise’ smells so that future samples can be identified as ‘good’ or ‘bad’ smells. Electronic noses have been demonstrated to discriminate between odours and volatiles from a wide range of sources.[100]

Electronic noses have a range of applications including *at-line quality control*,[101] various tasks in research and development (R&D),[102] and in process and production departments.[103] A possible application is to olfactive nuisance monitoring, but typical applications have been in the food & beverage sector (e.g., in order to detect spoiled produce), or to flavour & fragrance, or to cosmetics & perfume, as well as to packaging, and in the pharmaceutical and chemical industries.

The working principle of an electronic nose is that is should mimic human (or at any rate, natural) olfaction (it is said sometimes: “the mammalian sense of smell”), and that is should do so as a *non-separative mechanism.* That is to say, an odour (if this is what the device is intended to detect) or a flavour (if this is the device’s target instead) should be perceived as a *global fingerprint.* An electronic nose is an instruments that consists of the following:

- head space sampling,
- sensor array,
- pattern recognition modules.

The latter generate signal patterns which in turn are used for characterising odours. “As a first step, an electronic nose need to be trained with qualified samples so as to build a database of reference. Then the instrument can recognize new samples by comparing volatile compounds fingerprint to those contained in its database. Thus they can perform qualitative or quantitative analysis”.[104] The architecture of the system is as follows[105]: “Electronic Noses include three major parts: a sample delivery

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“Electrogustometric taste threshold depends on the duration of current pulse and area of contact of electrode and tongue” (http://en.wikipedia.org/wiki/Electrogustometry).

[100] http://en.wikipedia.org/wiki/Machine_olfaction (when accessed in April 2011, it had been last modified in February of the same year).

[101] As listed at http://en.wikipedia.org/wiki/Electronic_nose tasks of electronic noses within quality control include: conformity of raw materials, as well as of intermediate and final products; batch to batch consistency; detection of contamination, spoilage, or adulteration; origin or vendor selection; and monitoring of storage conditions.

[102] Tasks of electronic noses at R&D laboratories include: formulation or reformulation of products; benchmarking with competitive products; shelf life and stability studies; selection of raw materials; packaging interaction effects; simplification of consumer preference test (ibid).

[103] Tasks of electronic noses in process and production departments include: managing raw material variability; comparison with a reference product; measurement and comparison of the effects of manufacturing process on products; following-up cleaning in place process efficiency; scale-up monitoring; and the monitoring of cleaning in place (ibid.).

[104] http://en.wikipedia.org/wiki/Electronic_nose

[105] Ibid.

system, a detection system, a computing system". Electronic noses "generally comprise: an array of sensors of some type; the electronics to interrogate those sensors and produce the digital signals, and finally; the data processing and user interface software".[106] In particular[107]:

> The **sample delivery system** enables the generation of the headspace (volatile compounds) of a sample, which is the fraction analyzed. The system then injects this headspace into the detection system of the electronic nose. The sample delivery system is essential to guarantee constant operating conditions.

Let us turn to detection[108]:

> The **detection system**, which consists of a sensor set, is the "reactive" part of the instrument. When in contact with volatile compounds, the sensors react, which means they experience a change of electrical properties. Each sensor is sensitive to all volatile molecules but each in their specific way. Most electronic noses use sensor arrays that react to volatile compounds on contact: the adsorption of volatile compounds on the sensor surface causes a physical change of the sensor. A specific response is recorded by the electronic interface transforming the signal into a digital value. Recorded data are then computed based on statistical models.
>
> The more commonly used sensors include metal oxide semiconductors (MOS), conducting polymers (CP), quartz crystal microbalance, surface acoustic wave (SAW), and Metal Oxide Semiconductors- Field Effect Transistors (MOSFET), Based on Ion Mobility Spectrometry (IMS), Based on Optical Florescence.
>
> In recent years, other types of electronic noses have been developed that utilize mass spectrometry or ultra fast gas chromatography as a detection system.

The one remaining component of the architecture is the computing system:

> The **computing system** works to combine the responses of all of the sensors, which represents the input for the data treatment. This part of the instrument performs global fingerprint analysis and provides results and representations that can be easily interpreted. Moreover, the electronic nose results can be correlated to those obtained from other techniques (sensory panel, GC, GC/MS). Many of the data interpretation systems are used for the analysis of results. These include artificial neural network (ANN),[109] Fuzzy logic,[110] pattern recognition modules, etc.[111]
>
> The entire system being a means of converting complex sensor responses into an output that is a qualitative profile of the odour, volatile or complex mixture of chemical volatiles that make up a smell.[112]

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[106] http://en.wikipedia.org/wiki/Machine_olfaction

[107] http://en.wikipedia.org/wiki/Electronic_nose

[108] Ibid.

[109] Neural networks are the subject of Section 6.1.14 in this book.

[110] Fuzzy logic is the subject of Section 6.1.15 in this book.

[111] http://en.wikipedia.org/wiki/Electronic_nose

[112] http://en.wikipedia.org/wiki/Machine_olfaction

A particular application of machine olfaction is to the discovery of explosives.[113] This is the case of the *Fido Explosives Detector*.[114] This is a tool of ICx Technologies, Inc.,[115] and is based on a proprietary technology invented in 2007 by Timothy Swager of the Massachusetts Institute of Technology. Fido detects trace levels of explosive materials. The name *Fido* reflects the claim that the device's performance at detecting explosives is comparable to that of highly trained explosives detection dogs. There are several configurations of the device: handheld, desktop, or robot-mounted. It has been integrated into both *Packbot* (of the firm iRobot) and *Talon* (of Foster-Miller), and put to use by the U.S. Army in both Iraq and Afghanistan.

The vapour pressure of the chemicals in explosives is low, and this makes the task of discovering explosives by means of an electronic nose more difficult (Jha & Yadava, 2010, p. 364):

> An electronic nose consists of chemical sensor array with pattern recognition system to detect and identify vapour prints of target chemical compounds in gaseous phase. Its applications range from monitoring of hazardous chemicals in the environment, detection of disease through body odour or breathe, smell sensing and monitoring of food degradation through bacterial metabolites emission, to detection of explosives and narcotics through sniffing of the suspects. The detection of trace vapours emanating from hidden explosives is of paramount importance to homeland security and forensics. The security applications include sniffing hidden bombs, landmines, and suspected baggages or persons. The forensic uses involve early identification of devices and contraband activities for prevention of difficult countermeasures later. However, developing a portable electronic nose technology for these purposes is a difficult task due to extremely low vapour pressure of most of the chemical compounds comprising modern explosives.

Moreover, there are environmental differences which complicate the challenge (ibid.):

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[113] Electronic noses for the detection of explosives are the subject of Pamula (2003); Yinon (2003); Gardner and Yinon (2004); Jha and Yadava (2010). Of course, there are venues of research into the detection of explosives, other than resorting to electronic noses. For example, David Moore (2007) provided a survey of advances in trace explosives detection instrumentation. In particular, section 4.2 in Morre (2007) is concerned with *vapour concentration methods*, and also section 5 is on *trace vapour detection*. Wang (2004) discussed microchip devices for detecting terrorist weapons. Brenda Klock's project plan (2001) concerns aviation in the United States: her plan outlined "the field evaluation for threat detection in X-ray images of bags containing explosives at full and sub-certification weights" (ibid., from the abstract). "X-ray systems in airports are designed to display images of baggage and its contents, including guns, knives, other weapons, and explosives. X-ray systems include a function designed to maintain on-the-job vigilance. Threat Image Projection (TIP) was developed to increase the proficiency of the primary skills required of a screener to interdict threats at the checkpoint. TIP exposes screeners to images of threats (e.g., weapons or explosives) by randomly projecting these threat images onto passenger bags as the bags move through the X-ray system. Alternately, TIP can also project the image of an entire bag containing a threat when there is a suitable gap between passenger bags" (ibid., p. iv).

[114] http://en.wikipedia.org/wiki/Fido_Explosives_Detector Also see: http://www.icxt.com/products/detection/explosive/fido/

[115] http://www.icxt.com/

> The reliable detection of explosives vapour signature or vapour prints at such low concentrations is a challenging task even for some most advanced detection techniques today. The difficulty is further compounded as the trace explosive vapours are usually camouflaged in complex background of several interfering volatile organic compounds. The compositions of latter vary wildly over various kinds of sites of interest. For example, ambient air over landmines will be drastically different from that near the body of a person boarding an aircraft hiding a bomb or a busy market place threatened with a hidden bomb.

It is far from being the case that only one class of methodologies is employed in electronic noses for detecting explosives. Jha and Yadava (2010) resort to a surface acoustic wave (SAW) platform (ibid., pp. 364–365):

> The reliable detection of explosives vapour signature or vapour prints at such low concentrations is a challenging task even for some most advanced detection techniques today. The difficulty is further compounded as the trace explosive vapours are usually camouflaged in complex background of several interfering volatile organic compounds. The compositions of latter vary wildly over various kinds of sites of interest. For example, ambient air over landmines will be drastically different from that near the body of a person boarding an aircraft hiding a bomb or a busy market place threatened with a hidden bomb. them all. Most interesting aspects of SAW sensors are their continuous upgradability in performance through increase in operation frequency, modification in device design, improvement in polymer interface18, and planar technology.

In the model reported about by Jha and Yadava (2010), pattern recognition is performed by means of a neural network[116] with error backpropagation. Actually their article "proposes simulated SAW sensor array model as a validation tool for pattern recognition algorithms" (ibid., p. 369). Data preparation was by dividing the output of each sensor by the respective vapour concentrations and frequency shifts due to polymer coatings. Let

$$\Delta f_{ij} \quad C^{i} \quad \Delta f_{p}^{j}$$

respectively stand for the output of each sensor, the respective vapour concentrations, and frequency shifts. Their logarithms are taken to define a new matrix as

$$\Delta f_{ij} \leftarrow \log(\Delta f_{ij} / C^{i} \Delta f_{p}^{j})$$

This is followed by the step of this data matrix being mean-centred and variance-normalised with respect to the vapour samples for each sensor in the array. This is called *dimensional autoscaling* (Osuna & Nagle, 1999). It is implemented as

$$\Delta f_{ij} \leftarrow (\Delta f_{ij} - \overline{\Delta f_{j}}) / \sigma_{j}$$

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[116] Neural networks are the subject of Section 6.1.14 in this book.

where

$$\overline{\Delta f}_{ij} = (1/N)\sum_{i=1}^{N} \Delta f_{ij}$$

and

$$\sigma_j = \sqrt{(1/N)\sum_{i=1}^{N} (\Delta f_{ij} - \overline{\Delta f}_j)^2}$$

“represents the column mean and standard deviation, respectively. Then, the denoising was done by truncating the full rank SVD [i.e., singular value decomposition] expansion of the redefined data matrix by a matrix of lower rank. The procedure implicitly assumes that the rank of the data matrix is lower than the number of sensors in the array. The details of SVD denoising are presented. The data matrix regenerated on the basis of truncated SVD approximates the original data with reduced noise. The preprocessed data matrix as explained above is then PCA [i.e., principal component analysis] processed, and the first few principal components are taken to define the set of features to represent vapour identities. The classification is done by artificial neural network based on the training by error backpropagation algorithm” (Jha & Yadava, 2010, p. 369).

There even exist an application of electronic noses to medical pathology. Dogs can smell some human diseases: “The connection between differences in the aroma of diseased vs. healthy human tissues and diagnostic detection of human pathogenesis is supported by studies using the extraordinarily keen olfactory abilities of well trained dogs whose sense of smell is one million times greater than human’s in the ability to detect melanoma tissues [(Pickel, Manucy, Walker, Hall, & Walker, 2004)], bladder cancer [(Willis et al., 2004)], as well as lung and breast cancers [(McCulloch et al., 2006)].”(Wilson & Baietto, 2009, p. 5125). But electronic noses can also be used for the purposes of detecting diseases: “Many medical researchers have published experimental data in the last ten years to demonstrate the feasibility of using the electronic nose to diagnose human diseases and to identify many different pathogenic microorganisms through the detection of the VOCs [i.e. volatile organic compounds] they emit both in vitro and in vivo [(Casalinuovo, Di Pierro, Coletta, & Di Francesco, 2006)]” (Wilson & Baietto, 2009, p. 5125).[117]

One also talks about electronic tongues (Wilson & Baietto, 2009, p. 5134):

> New emerging technologies are continually providing means of improving e-noses and EAD capabilities through interfaces and combinations with classical analytical systems for rapid discrimination of individual chemical species within aroma mixtures. E-nose instruments are being developed that combine EAD sensors in tandem with analytical detectors such as with fast gas chromatography (FGC) [[118]]. More complicated technologies such as

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[117] Also see Persaud’s (2005) ‘Medical applications of odor-sensing devices’.

[118] Staples (2000).

> optical gas sensor systems also may improve on traditional e-nose sensor arrays by providing analytical data of mixture constituents [[119]]. These technologies will have the capability of producing recognizable high resolution visual images of specific vapor mixtures containing many different chemical species, but also quantifying concentrations and identifying all compounds present in the gas mixture. Similar capabilities for identifying components of solid and liquid mixtures may be possible with devices called electronic tongues [[120]]. Several recent reviews provide summaries of electronic tongue technologies and discuss potential applications for food analyses [[121]].

Whereas Wilson and Baietto (2009) did not mention forensic science specifically, it stands to reason that electronic noses and electronic tongues could find there application as well.

8.5.5 Forensic Palynology

Patricia E. J. Wiltshire gave the fourth and last lecture, at the workshop on Archaeology and Forensic Science, held at the British Academy in London on 27 February 2007. The talk had the title "From Archaeology to CSI" (i.e., crime scene investigation), but the analysis of pollen or other plant remains (a field in which Europe is ahead of the United States, in forensic contexts) played an important part in it. The speaker (who was also introduced to the audience by a nickname, "Pollen Pat", by which colleague in the Forensic Science Service sometimes refer to her), is affiliated with the Forensic Science Service as well as with the University of Aberdeen. She has worked on about 200 crime cases, and often appears in court as an expert witness. Originally she was an environmentalist. From palynology (i.e., the analysis of pollen), she spread into all of forensic science, and in fact, that was the talk in which more, and the most shocking, photographs of decaying human bodies were shown. Nevertheless, it was a lucid, well-argued talk extolling the role of palynology in solving forensic cases.

As exemplified during the talk, these typically were cases of of murder. For example, a girl of 15 had been beaten to death. Her boyfriend was suspected, but he denied the charge, and denied he had been in a schoolyard where the girl was believed to have been beaten by a gang of youngsters. Nevertheless, Wiltshire found the pollen of a tree from his garden all over the body of the girl, as well as on the knees of the young man's trousers. He eventually got a life sentence, and his mother was convicted for covering up for him.

In some other cases brought as examples, no murder was involved; e.g., the speaker had advised the police whether some marks visible on a package had been

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[119] White, Kauer, Dickinson, and Walt (1996).

[120] Winquist, Holmin, Krantz-Rülcker, Wide, and Lundström (2000); Söderström, Borén, Winquist, and Krantz-Rülcker (2003).

[121] Gutés, Céspedes, and del Valle (2007); Winquist (2008); Scampicchio, Ballabio, Arecchi, Cosio, and Mannino (2008).

made in Europe or in Mombasa, Kenya. In another case, she belied a rape accusation: a girl claimed she had been pushed on a garden wall, but none of the pollen from the wall appeared on her garments. In the case that concluded the talk, namely, the case of a man wounded in the bottom, the speaker enabled the police to recategorise what at first the police had been believed to be a vicious sex crime, with the criminal still at large. She advised them to wait, before taking that direction of inquiry. Pollen analysis enabled her to reconstruct how the critically wounded man, with two very long stabs entering his body from his anus, got those wounds. Apparently he had been drunk, and tried to climb on a wall at a park, but in so doing, he had impaled himself.

Wiltshire began her talk by pointing out that where microorganisms are inhibited, plant remains (seeds, leaves, stems, pollen, spores) can be preserved for thousands of years. In such cases, the taxonomical identification of the plant to which the well-preserved pollen belongs can be straightforward. Analysis of assemblages of these plant remains has allowed the reconstruction (or at least this is what some think) of ecological environments. Such ideal preservation does not obtain, in most cases, for pollen from archaeological or even recent, forensic contexts. Poor preservation makes it difficult to determine the taxonomical identification of pollen remains.

Botany has been used extensively in archaeology over the last thirty years, through macrofossil analysis and palynology. It can be applied to analysing the function of artefacts (food or medicine remains), or the function of features: retting (soaking), water and food storage, textiles. To be precise, palynology is the study of palynomorphs, i.e., any microscopic objects from the reproduction of plants, such as pollen grains, plant spores, fungal or fossil spores, and so forth. (Actually, palynology studies morphological, biochemical, and biogeographical aspects of these.) When palynology is forensic, it is interfaced to other forensic disciplines, some of them also from ecology, e.g., pedology, i.e., soil analysis. Clearly pedology is important for forensic purposes (e.g., for analysing soil in or around graves, or as traces found on shoes).

Palaeoecological pollen (e.g., as found in blank peat) is easy to identify, whereas, as mentioned, archaeological or forensic pollen is not, as it is in phases of decomposition. This is a problem, for the forensic application of palynology, because what is “forensic” must be defensible in court, and an expert witness is under attack by the barrister of the other side (whereas ethically, the duties of the prosecution expert witness are to the court, rather than to the police). Wiltshire mentioned an authority who once said that palynology is rubbish, because it cannot be proven. Forensic analysis has shown that palynology is very crude (whether paelaeoecological, or forensic). Still, the discipline is not alone in that situation. Take medicine. Ecology is not an absolute science; it is like medicine, in that you cannot test hypotheses. What you do have, is symptoms. The discipline not being exact hasn’t prevented Wiltshire from working on about 200 crime cases. Some of her work is clandestine, and involves dressing up, e.g., as a shop assistant.

A forensic expert has to recognise anomalies, and one must know what *is* right, to know what is *not* right. An ecosystem can be recognised by proxy indicators of the place: wood, leaves, seeds, pollens, spores, diatoms, and so forth. Like in medicine, these are symptoms. From the state of the flora on which a human body fell, it was understood it (a dead girl) was dumped in early August.

Any proxy indicator picked up by an offender might be traced back to the source: this is *Locard's Principle*.[122] Petrol cans, because of static electricity, have palynological indicators stick to them. Parasitic worm eggs of such worms that parasitise frogs are yet another proxy indicator, and they indicate that there must be a stream or pond. The worm eggs are secondary proxy indicators of frogs, and frogs are secondary proxy indicators of a stream or pond. Worm eggs do not belong in palynology, but by their very nature, they are relevant to the work of a forensic expert who is a palynologist. Palynology can be useful at all stages of decomposition of a corpse. Nevertheless, it is important to avoid contamination of the evidence while dissecting (like the crime scene or the perpetrator of a crime, also staff handling the evidence could leave traces, and it is paramount to be able to tell which is what.)

Let us broaden the discourse about palynology, before turning to software for that discipline. *Palynology* is the study of palynomorphs, both living and fossil. The term was introduced by Hyde and Williams (1944). *Actuopalynology* (as opposed to *palaeopalynology*) is "the study of palynomorphs which are either living, still retain their cell contents, or whose cell contents have been removed by maceration"; one of its branches is *forensic palynology* (used to "to determine the past location of items or persons based on the pollen and spores on or in them"). Note that whereas the antonym of *palaeopalynology* is *actuopalynology*, the antonym of *palaeontology* is *neontology* (i.e., the study of still extant or recent animal or vegetal taxa).

As to applications of *archaeological palynology* ("the analysis of pollen, spores, and other palynomorphs from archaeological sites"), they "include the reconstruction of prehistoric diet, funary practices, artifact function and source, archaeological feature use, cultivation and domestication of plants, and human impact on vegetation", according to definitions at a webpage by Owen Davis (1999). Archaeological palynology and quaternary palynology are part of *environmental palynology*, i.e., "The use of palynomorphs, their identification, distribution, and abundance to determine past changes in the biota, climate, or surficial geology of an area" (ibid.). A distinct area is *stratigraphic palynology*, i.e., "The use of palynomorphs, their identification, distribution, and abundance to correlate among sedimentary sequences of any age, or to provide chronological control for these sedimentary sequences" (ibid.); "the study of sedimentary sequences often includes both stratigraphic and environmental palynology" (ibid.). One of the areas of palynology is *mellisopalynology*, i.e., the study of pollen in honey or other bee products. Another area is *aeropalynology.* Another subdiscipline is *pollen analysis.*

According to a somewhat circular definition provided by Peter Hoen (1999), *palynomorph* are "A general term for all entities found in palynological preparations"; with the useful addition that: "In addition to pollen grains and spores, the

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[122] On Edmond Locard, a star in the history of French and world criminalistics, see in Section 8.7.1 below.

term encompasses acritarchs, dinoflagellates and scolecodonts, but not other microfossils, such as diatoms, that are dissolved by hydrofluoric acid". Therefore, the delimitation is according to a technique of analysis. According to a broad definition, provided by Owen Davis (1999), *palynomorphs* "include pollen, embryophyte spores, algae, fungal spores, dinoflagellates [which are unicellular aquatic organisms], microforaminifera, chitinozoans [marine fossils, shaped like flasks, occurring individually or in chains, usually assumed to be animal remains], acritarchs [consisting of a central cavity enclosed by a wall of single or multiple layers and a chiefly organic composition], and amoebas. Thus, they "include both plant and animal structures that are microscopic in size (from about 5 μm to about 500 μm), and are composed of compounds that are highly resistant to most forms of decay other than oxidation, being composed of sporopollenin, chitin, or related compounds. In the strict sense, palynomorphs are recognized as microscopic structures that are abundant in most sediments and sedimentary rocks, and are resistant to the routine pollen-extraction procedures including strong acids, bases, acetolysis, and density separation. In a broader sense, other microfossils sometimes are given 'courtesy appointments' as 'palynomorphs' even they do not survive routine pollen-extraction procedures" (Davis, 1999). The term *palynomorph* was introduced in Tschudy (1961).

References in forensic palynology include Bryant and Mildenhall (1996), Bryant, Jones, and Mildenhall (1996), and Faegri and Iversen (1989, p. 174 ff). Also refer to the webpage on forensic palynology of the California Criminalistic Institute,[123] to Terry Hutter's forensic palynology website,[124] to the website of Dallas Mildenhall's Foresic Services in New Zealand,[125] and to a website of Lynne Milne,[126] at the University of Western Australia.

There exist software resources for palynology. For example, the European Pollen Database (EPD) can be queries through its website.[127] It also publishes a newsletter. "The EPD is a relational database handled by Borland's (now Corel) PARADOX software. It contains raw data of pollen counts, C14 dates, geographical location and description of sites, lithological description of the records, chronologies, and bibliographic references. [. . .] The EPD tables can be downloaded and read directly either by PARADOX or by other software such as Microsoft Access. Single files are available in other formats (ASCII and Tilia)" (from the EPD main page), Tilia being "a free software program written by Eric Grimm", and on which, information is provided at the Tilia website.[128]

The EPD website refers to "Web tools provided by the World Data Center for Paleoclimatology [and used in order] to retrieve basic information about a site, as

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[123] http://www.ns.net/cci/Reference/Pollen/pollen.htm

[124] http://www.geoscience.net/Forensic_Palynology.html

[125] http://www.gns.cri.nz/help/laboratory/foren.html

[126] http://science.uniserve.edu.au/faces/milne/milne.html

[127] http://www.ncdc.noaa.gov/paleo/epd/epd_main.html

[128] http://www.ncdc.noaa.gov/paleo/tilia.html

well as summary pollen diagrams: the Pollen Data Search Engine allows you search by P.I., place, or time; Webmapper is a visual map tool for locating data". The Pollen Data Search Engine is accessible online,[129] whereas at another address one can access Webmapper.[130] The EPD e-list is hosted at the University of Colorado.

Pierre A. Zippi's PAZ Software[131] develops Mac-supported (but allegedly cross-platform) specialty scientific software solutions, applications having been developed for geological, biostratigraphic and earth science. Biostratigraphic services, such as data analysis, paleo data digitisation, and charting, are available[132]; whereas Paleontology sample preparation services are available at another website of the same firm.[133] One of the products of PAZ software is Palynodata Table Maker 1.0, which (as advertised) "Converts unwieldy Palynodata references and taxa list to tab-delimited ASCII text files. The resulting tab-delimited text files may be imported into spreadsheets, databases or mail merge applications. Greatly increases the usefulness of this large stratigraphic database". TILIA.12 To Spread (for MacOS) is used to "convert older Tilia 1.12 ASCII data files to tab-delimited spreadsheet files. NAPDToSpread will convert Tilia 2.0 files to spreadsheets. Free with WellPlot"; and so forth. Stephen Juggins' webpage[134] provides information on more software for palynology.

8.5.6 Computing in Environmental Forensics

There exist applications of computing to environmental law (McBurney & Parsons, 2001; de Vey Mestdagh, 1999), and there exist computer tools for environmental forensics. The latter field is the subject of Murphy and Morrison (2002), which I reviewed (Nissan, 2003g). Practitioners of environmental forensics are concerned with chemistry, materials science, fluid dynamics, statistics, possibly biology, and they are required to know what the law is, how it works, and how they can construct and present their case effectively, which is typically but not exclusively when they are heard during litigation as expert witnesses. "Environmental forensic investigations frequently deal with the release of contaminants" (ibid., p. xiii). Site history (Bookspan, Gravel, & Corley, 2002, i.e., chapter 2 in Murphy & Morrison, 2002), e.g., at a landfill, requires acquiring documents, from archives or verbal depositions. I see a potential for dedicated software tools for assisting in this: not so much for retrieval (the paper trail is, after all, on paper, and archive material may well date back from before the computer era), as for organizing the development of the investigation report (Nissan, 2003g, p. 572).

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[129] At http://www.ncdc.noaa.gov/paleo/ftp-pollen.html

[130] http://www.ncdc.noaa.gov/paleo/pollen.html

[131] In Garland, Texas. See the website http://www.pazsoftware.com/

[132] At the website http://www.biostratigraphy.com

[133] At the website http://www.paleolab.com

[134] Accessible at http://www.staff.ncl.ac.uk/stephen.juggins/int_nn.htm

Computing is explicitly covered in the next chapter in Murphy and Morrison (2002), as the need for aerial photos (current or historical) of a site lends the subject to that book's chapter 3 (i.e., Ebert, 2002),[135] on photogrammetry, photointerpretation, and digital imaging and mapping. Electronics is on occasion linked to chemical spillages: a case study (section 3.5.2 in that same book) involves circuit board fabrication plants.

Chapter 5 in Murphy and Morrison's book, namely, Philp (2002), is on isotope measurements. "Bulk isotopic values have been readily available for many years but one of the most significant analytical advances in geochemistry in the past few years has undoubtedly been the development of combined gas chromatography – isotope ratio mass spectrometry (GCIRMS)" (ibid., p. 111). Computing and plotters are conspicuous in such analyses.

When it comes to environmental forensics rather than just environmental science, there is a factor that need be considered, considering computer-assisted modelling as pertaining to various areas of environmental science. "There are currently in excess of 400 groundwater flow (advective) and contaminant transport models" (ibid., p. 338, which is in chapter 8: Morrison, 2002). "In the United States, it is estimated that computer-based predictions of contaminant transport influence legal and policy decisions involving the allocation of at least 1 billion dollars each year" (ibid., p. 339). Several sources of uncertainty affect models.

The calculation-intensive subsurface models (Morrison, 2002) include, e.g., vapour, liquid, colloidal, or cosolvent transport through pavement or soil. "Preferential flows" of infiltrating liquid exploit preferential pathways, either artificial (dry wells, cisterns, utility line backfill, etc.), or natural: "worm channels, decayed root channels [. . .], soil fractures, slickenslides, swelling and shrinking clays, highly permeable soil layers, and insect burrows" (ibid., p. 335). This is fertile ground for computational science ($\neq$ computer science).

"The origin of inverse modeling for contaminant transport in groundwater is predated by research in the heat transfer literature" (ibid., p. 339). Inverse (or reverse) models are also called "backward extrapolation models", "hindcasting" 125 (patterned after "forecasting"), and "backward random walk" (339). "In its simplest application, inverse modeling relies upon measured properties or contaminant concentrations to extrapolate to some point in the past, the age and the location of a contaminant release, most frequently by using geostatistical and optimization approaches" (ibid., p. 339). "In cases where light non-aqueous phase liquids (LNAPLs) are of interest, numerical models are available to predict LNAPL plume migration over time [. . .] and to age date the release using a direct estimate and nonlinear parameter estimation approach" (ibid., p. 342).

Potential sources of uncertainty affecting inverse models include: "The reasonableness of the sected porosity and hydraulic conductivity value(s)" (ibid., p. 343),

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[135] James I. Ebert is an envirnmental and forensic scientist who is also a certified photogrammetrist, and a trained archaeologist and anthropologist who has taken part in a project in palaeoanthropology and environmental research at Olduvai Gorge in Tanzania.

"The consistency of the groundwater flow direction and velocity over time", "The validity of the selected hydraulic gradient(s) values over time and distance from the release", "The number of data points and time interval during which the data were collected", "The nature of the release (steady versus non-steady", "The loading rate" (possibly based on production records), "The value(s) selected for aquifer(s) thickness (model specific)", "The horizontal and transverse dispersivity values" (ibid., p. 343), "Contaminant retardation and/or degradation rates" (ibid., p. 344), "Identification of the leading edge of the contaminant plume (model specific)", "The effect of recharge/discharge rates (if applicable) of water into the system and its impact on plume geometry and contaminant velocity" (ibid., p. 344). Bear in mind that a court may have to decide on whether some aspect of the model was reasonable, e.g., rejecting the defendant's model. Robert D. Morrison, the author of Ch. 8 in the same book, actually provides legal illustrations for a few of the items listed above. This way, for the "effect of recharge/discharge rates", he states (ibid., p. 344):

> In the *Velsicol* case, for example, the court wrote, 'the district court rejected the defendant's water model as inaccurately under representing the extent of chemical contamination in the groundwater supply. In refuting the defendant's model, the court reasoned that Velsicol had failed to factor in the massive dumping of liquid waste, the ponding of water in the trenches, and the draw down on the aquifer caused by new homes.'

Chapter 9 in Murphy and Morrison (2002), "Forensic Air Dispersion Modeling and Analysis", features techniques such as the Gaussian plume model analysis. A "case study is a toxic tort in which the plaintiffs claimed dioxin and furan exposure" (ibid., p. 385). "Chapters 10 through 12 [in Murphy & Morrison (2002)] introduce statistical aspects associated with an environmental forensic investigation. Chapter 10 summarizes statistical tests for comparing data sets and evaluating temporal or spatial relationships. Chapters 11 and 12 present advanced pattern recognition techniques, of increasing utility within today's greater computing power. Chapter 11 discusses particulate pattern recognition techniques used for source identification" (ibid., p. xiv).

Thomas D. Gauthier's "Statistical Methods" (chapter 10 in Murphy & Morrison, 2002) points out that of the "variety of statistical analysis techniques[, m]ost examples in the literature involve rather sophisticated applications including principal components analysis and chemical mass balance receptor modeling (discussed elsewhere in [Murphy & Morrison, 2002]). These techniques are powerful analytical tools and provide useful insights for data interpretation but the results can be difficult to explain to a judge or jury" (ibid., pp. 391–392). "Relatively simple statistical analysis techniques can be used in environmental forensic investigations to compare data sets, characterize associations between variables, evaluate trends, and make predictions. Moreover, it is often possible to assign a degree of confidence to the results. This advantage is particularly useful in litigation scenarios where experts are often asked to assign a probability to the correctness of their opinion" (ibid., p. 425).

For the identification of air pollution sources, dispersion or receptor modeling (Watson & Chow, 2002, i.e., chapter 11 in Murphy & Morrison, 2002) is a relevant tool. Modeling small particles suspended in the air goes by the name “particulate pattern recognition”. “Receptor models use the variability of chemical composition, particle size, and concentration in space and time to identify source types and to quantify source contributions that affect particle mass concentrations, light extinction, or deposition” (ibid., p. 430). Such models include, e.g., *multiple linear regression on chemical markers* (ibid., p. 432), *temporal and spatial correlation eigenvectors* (ibid., p. 433),[136] and (which is of particular interest in our present book) *neural networks* (ibid., section 11.2.6, pp. 433–434): “Training sets that have known source–receptor relationships are used to establish the linkages in the neural net that are then used to estimate source contributions for data sets with unknown relationships. The network assigns weights to the inputs that reproduce the outputs. Neural networks can provide functional relationships that are solutions to the MLR and CMB equations” (ibid., p. 433), i.e., respectively, to the multiple linear regression and to the chemical mass balance equations. Moreover (ibid., p. 434):

> Spectral analysis [. . .], intervention analysis [. . .], lagged regression analysis [. . .], and trend analysis [. . .] models separate temporal patterns for a single variable and establish temporal relationships between different variables. These models have been used to identify sources, to forecast future pollutant concentrations, and to infer relationships between causes and effects. It is especially important to include meteorological indicators in time series models [. . .] and to use data sets with comparable measurement methods and sampling frequencies.

Glenn Johnson, Robert Ehrlich, and William Full (2002, i.e., chapter 12 in Murphy & Morrison, 2002) provide an in-depth tutorial into the use of principal components analysis and receptor models in environmental forensics. Such numerical methods are used in order to determine the three parameters enumerated at the end of the following quotation (ibid., p. 462):

> The identification of chemical contaminant sources is a common problem in environmental forensic investigations. Successful inference of sources depends on sampling plan design, sample collection procedures, chemical analysis methods, and knowledge of historical industrial processes in the study area. However, in compex situations where multiple sources contribute similar types of contaminants, even careful project training and design may not be enough. If sources cannot be linked to a unique chemical species (i.e., a tracer chemical), then mapping the distributions of individual contaminant concentrations is insufficient to infer source. If, however, a source exhibits a characteristic ‘chemical fingerprint’ defined by diagnostic proportions of a large number of analytes, source inference may be accomplished through analysis of multiple variables; that is, through use of multivariate statistical methods. The objective of a multivariate approach to chemical fingerprinting is to determine (1) the number of fingerprints present in the system, (2) the multivariate chemical composition of each fingerprint, and (3) the relative contribution of each fingerprint in each collected sample.

Out of the spectrum of numerical methods from the past twenty years, more recently developed “procedures are designed to solve more general problems, which take

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[136] For *eigenvectors*, see in fn. 24 in Chapter 6.

into account complications such as bad data, commingled plumes (i.e., mixing of source fingerprints), and the presence of sources not assumed or anticipated at the start of an investigation" (ibid., p. 462). "In terms of experimental design, the source apportionment problem in environmental forensic investigations falls between two extremes.

At one extreme, all potential sources are known in terms of their chemical composition, location, history, and duration of activity. At the other extreme, none of these are known with certainty. Chemicals at the receptor (e.g., estuary sediments, groundwater at a supply well) may be the result of activities long absent from the vicinity of the site" (ibid., p. 462). Morever (ibid., p. 463):

> In the first case (a priori knowledge of all sources) the problem is a relatively simple one. Appropriate sampling locations can be determined using a conventional experimental design, which is part of conventional experimental statistics. Determination of contribution of each source can be extracted using a variety of linear methods, such as chemical mass balance receptor models (see chapter 11 of [Murphy & Morrison, 2002]). However, even when the contributing sources are known, environmental forensic investigations often proven to be more complex than initially anticipated. Chemicals in the environment may not retain their original composition. [. . .] The result of degradation will be resolution of one or more fingerprints, not originally anticipated.

When knowledge is uncertain, or unavailable, *exploratory data analysis* is to be used. indeed (ibid., p. 463):

> At the other extreme, where nothing is known with certainty, potential sources may be suspected, but samples of the sources (i.e., fingerprint reference standards) may not have been collected, and may not exist in the literature. The industrial history of a region may be imperfectly known. Often, a small, low profile operation may be a major but completely overlooked source of contamination. For cases towards this end of the spectrum, we must take leave of the elegance of conventional experimental statistics, and move into the realm of exploratory data analysis (EDA). The fundamental difference between these two approaches (experimental statistics and EDA) is the former is associated with creation of explicit hypotheses, and evaluation of data in terms of well-defined tests and strong probabilistic arguments. In contrast, the objective of EDA is to find patterns, correlations and relationships in the data itself, with few assumptions or hypotheses [. . .]. If the fruits of an EDA result in a map where the concentrations of a multivariate fingerprint increase monotonically towards an effluent pipe, and the fingerprint composition is consistent with the process associated with that source, the obvious inference is that the potential source is the actual source. We recognize that we are not working in the realm of classical statistics or formal hypothesis testing, and that EDA is based on less rigirous probabilistic statement. However, such an approach should not be construed as 'second best'. In environmental forensic, an EDA approach may be the only valid option.

Besides, it is important to consider that there may be bad or questionable data: "Unfortunately such errors rarely manifest themselves as random noise. More often, they contribute strong systematic variability. If unrecognized, the result may be derivation of 'fingerprints' which have little to do with the true sources. Therefore, a necessary adjunct to any data analysis in environmental forensics is identification of outliers" (ibid., p. 464). Nevertheless, even "inclusion of vigilant outlier identification and data cleaning procedures" may "resul[t] in deletion or modification of data", and then "the data must be clearly identified, and justification for the action must be provided in the narrative that accompanies the analyses" (ibid.).

To infer the sources of contaminants and their contribution, receptor modeling as described in chapter 12 ofd Murphy and Morrison (2002) is used. The *receptor modeling problem* is formally introduced in section 12.1.2 (ibid., p. 464):

> The objectives are to determine (1) the number of chemical fingerprints in the system; (2) the chemical composition of each fingerprints; and (3) the contribution of each fingerprints in each sample. The starting point is a data-table of chemical measurements in samples collected from the receptor (e.g., estuarine sediments, ambient air in a residential area). These data are usually provided in spreadsheet form where rows represent samples and columns represent chemical analytes. To the multivariate data analyst this table is a matrix. We will refer to the original data table as the m row by n column matrix **X**, where m is the number of samples and n is the number of analytes. We wish to know the number of fingerprints present (k) and chemical composition of each (objectives 1 and 2 above). This can be expressed as a matrix **F**, which has k rows and n columns. We also wish to know a third matrix **A**, which has m rows and k columns, and represents the contribution of each fingerprint in each sample (objective 3 above). Thus the following linear algebraic equation formally expresses the receptor modeling problem.

$$\begin{array}{lcccc} & \mathrm{X} & = & \mathrm{A} & \mathrm{F} \\ \text{Matrix dimensions} & (m \times n) & & (m \times k) & (k \times n) \end{array}$$

Subsequent sections in chapter 12 are devoted to methodological categories and are themselves further subdivided rather densely. They include "Principal Components Analysis" (section 12.2) – the acronym is PCA – as applied to environmental chemometrics, and "Self-Training Receptor Modeling Methods" (section 12.3), which in turn includes

- polytopic vector analysis (PVA): this is an algorithm that evolved over forty years, and whose roots are "in principal components analysis, pattern recognition, linear algebra, and mathematical geology" (ibid., p. 498),
- the unique vector rotation method, and
- the so-called SAFER method (the acronym stands for Source Appointment by Factors with Explicit Restrictions), which "is used in extended self-modeling curve resolution" (ibid., p. 508).

"These three [of section 12.3 in Murphy & Morrison (2002)] are analogous in that (1) they do not require a training data set; (2) they are PCA based methods; (3) they involve solution of quantitative source appointment equations by development of oblique solutions in PCA space; and (4) each involves the use of non-negative constraints" (ibid., p. 498). In fact, this is a particular class of algorithms, in Johnson et al. (2002), that deserves special attention in the book your are reading now, which is specifically concerned with the uses of artificial intelligence for legal evidence. Machine learning, as well as self-training algorithms (such as in artificial neural networks) are well-known to artificial intelligence practitioners. But self-training methods are also known from multivariate statistical analysis. Section

12.3 in Johnson et al. (2002), "Self-training receptor modeling methods", is about "models designed to resolve three parameters of concern in a multivariate, mixed chemical system: (1) the number of components in the mixture, (2) the identity (i.e., chemical composition or fingerprints) of each component, and (3) the relative proportions of each component in each sample" (ibid., p. 497). Before Johnson et al. (2002), the full polytopic vector analysis (PVA) algorithm had not been set in any single paper (ibid., p. 498).

"PVA was developed for analysis of mixtures in the geological sciences, but it has evolved over a period of forty years, with different aspects of the algorithm presented in a series of publications, by a number of different authors" (ibid.). The originator was a palaeontologist, John Imbrie (1963), and this initially resulted in a series of Fortran programs. This eventually became CABFAC (*C*algary *a*nd *B*rown *FAC*tor Analysis), which "quickly became the most commonly used multivariate analysis algorithm in the geosciences" (ibid., p. 499). Later on, "William Full, as a PhD candidate at the University of South Carolina in the early 1980s, developed the DENEG algorithm, which allows end-members (sources) to be resolved without a priori knowledge of their composition, and without use of a training data set (Full et al., 1981, 1982)" (Johnson et al., 2002, p. 499). PVA involves resolution of oblique vectors as source compositions. This vector analysis is polytopic, because "PVA involves resolution of a $k - 1$ dimensional solid, a "simplex" or "polytope", within k dimensional principal component space" (ibid.). So if $k = 4$, the polytope is a tetrahedron. The algorithms at the core of PVA are implemented under default options in the commercial versions of the SAWVECA software of Residuum Energy, Inc., Dickinson, Texas. Johnson et al. explained (2002, pp. 506–507):

> PVA is one 'self-training' method that allows source profiles to be derived in absence of *a priori* knowledge of their chemical composition, but other such methods have seen considerable application in environmental chemical data. One of these is target transformation factor analysis (TTFA), which developed within analytical chemistry/chemometrics rather than mathematical geology/geochemistry (Roscoe and Hopke, 1981; Gemperline, 1984; Hopke, 1989; Malinowski, 1991).
>
> In TTFA, the subroutine that allows estimates of source composition in the absence of known sources is the unique vector rotation method [. . .]. This method begins by establishing a $n \times n$ matrix where each row vector is 100% of a single analyte (i.e. 'unique vectors'). In turn, each of these vectors is iteratively rotated within principal component space.

Moreover (Johnson et al., 2002, pp. 508–509):

> Another receptor modeling method, SAFER (Source Apportionment by Factors with Explicit Restrictions) is used in extended self-modeling curve resolution (ESMCR: Henry and Kim, 1990; Kim and Henry, 1999). Unlike PVA and TTFA, ESMCR does not typically involve transformation to unit length. [. . .] The SAFER method begins by defining the 'feasible region' where the simplex vertices and edges may reside. The inner boundary of the feasible region is defined by the convex hull of the data cloud [. . .]. The non-negativity constraints on the analytes define the outer boundary of the 'feasible region'. [. . .] For a three-component sistem [. . .], a feasible mixing model may be defined by direct inspection of the data plotted in the principal component space, and manually located within the fea-

> sible region (this method is termed SAFER3D). A method of resolving higher dimensional mixing models has recently been described (Kim and Henry, 1999). That method calls on the use of additional explicit physical constraints. Examples of additonal constraints may include (1) total mass of samples, (2) *a priori* knowledge of a subset of contributing sources, (3) upper and lower limits on ranges or ratios of analyte compositions, or (4) constraints based on laws of chemistry (Kim and Henry, 1999). As was the case for the unique vector iteration method, SADER has been applied primarily in source apportionment studies in air (Henry et al., 1997).

8.6 Forensic Engineering

Forensic engineering is a discipline[137] practised by such engineers who appear in court as expert witnesses, or at any rate are involved in dispute resolution and have to develop hypotheses and argue for them in a legal setting, including in front of arbitration panels, or in mediation and conciliation; for the difference between trial, arbitration, and mediation, see Hohns (1987), from the perspective of the forensic engineer in construction related disputes. Specter (1987) provides the following definition: "Forensic engineering may be generalized as the art and science of practitioners who are qualified to serve as engineering experts in matters before courts of law and in arbitration proceedings" (ibid., p. 61). The definition on Wikipedia[138] is as follows:

> Forensic engineering is the investigation of materials, products, structures or components that fail or do not operate/function as intended, causing personal injury for example. The consequences of failure are dealt by the law of product liability. The subject is applied most commonly in civil law cases, although may be of use in criminal law cases. Generally the purpose of a forensic engineering investigation is to locate cause or causes of failure with a view to improve performance or life of a component, or to assist a court in determining the facts of an accident. It can also involve investigation of intellectual property claims, especially patents.

Forensic engineering typically concerns failure: the failure of structures, foundations, materials, or machinery, or of construction as a process. See, e.g., Lewis and Hainsworth (2006). The journal in the field is *Engineering Failure Analysis.* Construction related disputes are just one of the areas within forensic engineering, and involve civil engineers. A special area is automotive engineering, for investigating car crashes. "Forensic engineering involves more than engineers. We have on our roster chemists, architects, contract administrators, fire cause investigators, and experts in packaging, radiology and computer technology" (Garrett, 1987, p. 17).

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[137] In James and Nordby (2005, 2nd edn.; 2009, 3rd edn.), a volume on forensic science, the chapters about forensic engineering comprise one about structural failures, by Randall Noon (2005a; 2009a, 3rd edn.), then a chapter about basic fire and explosion investigation, by David Redsicker (2005, 2009, 3rd edn.), and a chapter on vehicular accident reconstruction, by Randall Noon (2005b; 2009b, 3rd edn.).

[138] http://en.wikipedia.org/wiki/Forensic_engineering.

Typically, scholarship in the field concerns failure theories, hypothesis testing, and failure investigations. It also concerns legal problems, practices, and policy connected with the testimony of forensic engineers. Not only engineers, but also trial lawyers and insurance adjusters are involved. In 1987, Pergamon Press (now Elsevier) started to publish a journal in the domain, entitled *Forensic Engineering*. In the United States, there is the *Journal of the National Academy of Forensic Engineers*. *Expert* (1985) is a guide for forensic engineers, published by the Association of Soil and Foundation Engineers. Suprenant (1988) is a textbook. Other books in forensic engineering include Noon (1992, 2000), and Lewis, Gagg, and Reynolds (2004). The latter was authored at the Open University in Britain, and it is interesting to see how the website of that institution promotes both its forensic service to external clients, and its curriculum in forensic engineering;[139] as can be seen, the academic disciplinary compartment is Materials Engineering, home the focus there is on product failure, and individual researchers are specialised in a rather narrow category of materials:

> Product failure has been studied in the Materials Engineering Department since its inception, and forms the basis of several courses presented by the department (T839 Forensic Engineering). The loose grouping of individuals study a very wide range of cases, from metal fatigue of crankshafts ([. . .]), stress corrosion or ozone cracking of fuel lines ([. . .]), breakage of glass bottle causing personal injury ([. . .]), failure of power hand tools ([. . .]) to infringement actions in medical devices and garden products ([. . .]). Cases are studied within a framework set by litigation, enquires by insurers, or companies and institutions. Work has also been funded by the Consumer Research Laboratories in order to improve the design of handpumps and rising mains for use in developing countries. Independent research by the group has revealed new and unsuspected failure modes in both traditional and entirely new materials. All members have had recent experience of court procedure and giving expert advice before tribunals. This group has links with the *Fracture and Fatigue* and *Residual Stress* groups in the department. [. . .]

"[T]he insurance industry and the legal profession [are] the primary users of forensic engineering services" (Garrett, 1987, p. 17). Clients typically require "quality technical people to help them solve the puzzle of 'What happened?'" (ibid., p. 17). "[Y]ou are hired by an insurance company, a lawyer, a builder, a manufacturer, or an irate or injured citizen" (Knott, 1987, p. 11). "We ask clients to refrain from deciding in advance what kind of an expert they need. They may ask for a metallurgist when what they really need is a traffic engineer. And they may need several experts, not just one" (Garrett, 1987, p. 18). "If your client is an insurance company, it is usually interested in proof that it should or should not pay a claim" (Knott, 1987, p. 11) "The work is done to determine the probable cause of a failure or an accident. The lawyer will have to prove the case in court, and a proof in law is not the same as a proof in engineering" (ibid.). There are different categories of what is to be proven, in such cases in which a forensic engineer may be called to testify. "The law has evolved into distinct arenas. For example, strict liability, negligence,

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[139] http://materials.open.ac.uk/research/res_forensic.htm.

and warranty. You may be able to show that the manufacturer had a first-rate quality control program. This is an excellent defense in negligence but has absolutely no application in strict liability" (ibid.).

Software for engineering, especially simulations for *failure analysis*, or then software for *structural risk evaluation*, or software modelling the plasticity and fracture of solid materials, will be of use to the forensic engineer in some categories of cases. Importantly, the entry for "Forensic engineering" in Wikipedia makes a distinction between forensic science and forensic engineering:

> There is some common ground between forensic science and forensic engineering, such as scene of crime and scene of accident analysis, integrity of the evidence and court appearances. Both disciplines make extensive use of optical and scanning electron microscopes, for example. They also share common use of spectroscopy (infra-red, ultra-violet and nuclear magnetic resonance) to examine critical evidence. Radiography using X-rays or neutrons is also very useful in examining thick products for their internal defects before destructive examination is attempted. Often, however, a simple hand lens suffices to reveal the cause of a particular problem. Trace evidence is often an important factor in reconstructing the sequence of events in an accident. For example, tyre burn marks on a road surface can enable vehicle speeds to be estimated, when the brakes were applied and so on. Ladder feet often leave a trace of movement of the ladder during a slipaway, and may show how the accident occurred.

Section "methods" (ibid.) remarks:

> Methods used in forensic investigations include reverse engineering, inspection of witness statements, a working knowledge of current standards, as well as examination of the failed component itself. The fracture surface of a failed product can reveal much information on how the item failed and the loading pattern prior to failure. The study of fracture surfaces is known as fractography. Fatigue often produces a characteristic fracture surface for example, enabling diagnosis to be made of the cause of the failure. The key task in many such investigations is to identify the failure mechanism by examining the failed part using physical and chemical techniques. This activity is sometimes called root cause analysis. Corrosion is another common failure mode needing careful analysis to determine the active agents. Accidents caused by fire are especially challenging owing to the frequent loss of critical evidence, although when halted early enough can usually lead to the cause. Fire investigation is a specialist skill where arson is suspected, but is also important in vehicular accident reconstruction where faulty fuel lines, for example, may be the cause of an accident.

8.7 Individual Identification

8.7.1 The Cultural Context: The History of Identification Methods

It is important to understand the history of the use of fingerprints for identification purposes, in order to realise how the mutual expectations of law enforcers and of perpetrators have evolved. This in turn is potentially useful for the purposes of future AI tools that would reason about the evidence. Understanding the dynamics of how both law enforcers and perpetrators had to become more and more clever, makes one realise that one cannot come up as well with the ultimate technique of detection.

Hardware and software you may produce may prove useful for a while, or even for a long time, but requirements will change, and older techniques will either have to change, or have to be supplemented with something else. Within AI, the area concerned with how to reason with an agent's beliefs about the beliefs of another agent is known as *agents' beliefs* (e.g., Ballim, By, Wilks, & Liske, 2001; Barnden, 2001).

The following example shows how a course of action taken by perpetrators with the intention of suppressing the evidence, actually backfired. During the Troubles in Northern Ireland in the 1970s and 1980s, bombs prepared by terrorists sometimes contained the gloves they had been using. Their assumptions was that the blast would destroy the gloves, but it was not so. Law enforcers hoped to find, inside the remains of such gloves, the fingerprints of perpetrators – that is to say, evidence that the terrorists had placed inside the bombs by believing that by so doing, they would destroy the evidence.

Those fingerprints were detected, because of their coating of lipids (traces of the fat on the skin of fingertips). Radioactivity was used, in order to make that coating of lipids (fat from the fingertips) apparent, using a photographic technique or based on luminescence, and the former appeared to be better than the latter.[140] Let us recapitulate, with more technical details:

- The people making bombs would wear gloves.
- When they finished they would place the gloves with the device.
- The fingerprints (contrary to what the bombers had assumed) could then be recovered from the inside of the gloves.
- The radioactive SO2 (sulfur dioxide) absorbed could then be detected[141] by luminescence or by photographic techniques (using silver halides).[142] The graphite

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[140] Around 1980s, such circumstances were still secret, but by 2010, when I was informed verbally, they were in the public domain.

[141] E.g., in Goode, Morris, and Wells (1979), a team from the Atomic Weapons Research Establishment of the British Ministry of Defence, based at Aldermaston, Berkshire, described the application of radioactive bromine isotopes for the visualisation of latent fingerprints. A vapour phase bromination procedure was investigated for reaction with unsaturated lipids present in a fingerprint deposit.

[142] The light-sensitive chemicals used in photographic film and paper are silver halides. A *silver halide* is one of the compounds formed between silver and one of the halogens, namely: silver bromide (AgBr), silver chloride (AgCl), silver iodide (AgI), and three forms of silver fluorides. As a group, they are often given the pseudo-chemical notation AgX. Silver halides, except for silver fluoride, are extremely insoluble in water.

"Silver halides are used in photographic film and photographic paper, as well as graphic art film and paper, where silver halide crystals in gelatin are coated on to a film base, glass or paper substrate. The gelatin is a vital part of the emulsion as the protective colloid of appropriate physical and chemical properties. Gelatin may also contain trace elements (such as sulfur) which increase the light sensitivity of the emulsion, although modern practice uses gelatin without such components. When absorbed by an AgX crystal, photons cause electrons to be promoted to a conduction band (de-localized electron orbital with higher energy than a valence band) which can be attracted by a sensitivity speck, which is a shallow electron trap, which may be a crystalline defect or a cluster of

> fine powder for conventional fingerprint recording could not be used. The photographic techniques proved to be the most efficient.

A medal dated 1969, designed by Jiri Harcuba, was struck in Czechoslovakia, in bronze, silver, and for the first time, with a golden proof, for the centenary of the death of Jan Evangelista Purkyně, a physician considered the discoverer and founder of *dactyloscopy*, i.e., the identification of persons based on their fingerprints. (Defying the Soviet invasion, the Czech mint also struck Harcuba's medal, also dated 1969, commemorating Jan Palach, the student who set himself ablaze in protest.) Purkyně (1787–1869) is actually much better known as the father of histology: the middle cortex of the cerebellum were named *Purkinje cells*, after him. Outside the Czech Rebublic or Slovakia, his family name is usually spelled *Purkinje.*

No mention of Purkyně is made in the entry for "dactyloscopie" in Nathanaël Tribondeau's glossary of criminalistics (Tribondeau, accessed 2006). About the origination of the technique, it just states: "Utilisée pour la première fois en 1880 par l'Anglais William J. Herschel" ("Used for the first time by an Englishman, William J. Herschel"). He got an entry in his name: "Born in 1738 and deceased in 1922, he is the inventor, along with Francis Galton [Darwin's cousin], of dactyloscopy (the collection and analysis of fingerprints). It was looking for some surer means than just a signature, for the authentication of commercial documents, that this English official seconded to Bengal conceived of the idea, from 1880, of having his suppliers mark contracts with their fingerprints, to avoid future disputes. It was only later on, that this procedure was used by the scientific police, with the success we all know about" (my translation).

What Tribondeau does not say about the adoption by fingerprints in France, is related in an article by Jean-Marc Berlière (2005) about the Scheffer Affair, about the first conviction of a suspect, in France, revolving around on identification by fingerprints. Berlière explains that with the emergence, in the positivist era, of the realisation, turned into an obsession in France, that recidivists are responsible for most crimes (this actually came along with now discredited theory of Cesare Lombroso about the born criminal), perpetrators smarted up to the challenge, and

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silver sulfide, gold, other trace elements (dopant), or combination thereof, and then combined with an interstitial silver ion to form silver metal speck" (http://en.wikipedia.org/wiki/Silver_halide).

Apart from applications to photography, experiments have been conducted for medical purposes: silver halide optical fibres for transmitting mid-infrared light from carbon dioxide lasers, allow laser welding of human tissue, as an alternative to traditional sutures. Another use is in the making of lenses, exploiting photochromism: Silver halides are also used to make corrective lenses darken when exposed to ultraviolet light. "When a silver halide crystal is exposed to light, a sensitivity speck on the surface of the crystal is turned into a small speck of metallic silver (these comprise the invisible or latent image). If the speck of silver contains approximately four or more atoms, it is rendered developable – meaning that it can undergo development which turns the entire crystal into metallic silver. Areas of the emulsion receiving larger amounts of light (reflected from a subject being photographed, for example) undergo the greatest development and therefore results in the highest optical density" (ibid.).

law enforcement was faced with the problem of how to identify a person who has been using several false names.

Alphonse Bertillon proposed for identification to consider the *identité anthropométrique*, based on measurements of the bones of adults. The French police adopted this technique in 1883. There is a sense in which it was of little help, as perpetrators were unlikely to leave their bones around, yet it was rather useful for identifying recidivists who were using a false name, provided they had been *bertillonnés*, i.e., had their anthropometric measurements taken before. On 16 February 1883, a recidivist was recognised for the first time, based on anthropometric measurements.

By the end of 1883, 49 ex-cons had been identified that way; 241 during the next year (ibid., p. 350, fn. 3). The technique featured, arousing much interest, at the international exposition of Paris of 1889. "Its zenith was when, in the spring of 1892, it enabled Bertillon to identify 'Ravachol', who at the time was terrifying Paris, with a Koenigstein who had been *bertillonné* at Saint-Étienne prison two years earlier" (ibid., p. 350, my translation). The technique could tell apart two dissimilar persons, but similar anthropometric data could not be ascribed with certainty to the similar person. This was a major flaw.

Fingerprints were to prove a better technique. Fingerprints were observed by Italian anatomist Marcello Malpighi (1628–1694). That Purkyně described fingerprints in 1823 is mentioned by Berlière (who wrongly Hispanicises his first name as *Juan*). So is empirical use in British-ruled India, as well as the role of the physician Henry Faulds, or the classifications developed by Francis Galton, Edward Henry, and Juan Vucetich during the 1890s.

Berlière relates the role which Bertillon had, in the first conviction in France based on fingerprints.[143] On 16 October 1902, the body of a male servant was discovered inside the Parisian apartment of a dentist. The motive appeared to be theft. On a broken glasscase, many fingerprints were found. On one side of the glass, there was the print of a thumb, the prints of three other fingers being on the other side: these were the fingerprints of a person who has held the glass after it was broken.

One difficulty was that the fingerprints were overlapping, because of the transparency of the glass. An advantage for Bertillon was that he got the fingerprints of four adjacent fingers of the right hand, i.e., the only hand for which fingerprints had been stored. Bertillon searched the archives, card by card, without classification criteria to guide the search, and identified Henri-Léon Scheffer, born in 1876, who had been arrested and had had his fingerprints taken on 9 March 1902.

Bertillon's report to the examining magistrate, stating this identification, is dated 24 October 1902. Berlière points out (p. 351, fn. 7) that this case is usually misrepresented as though it was the first time that a perpetrator was identified based only

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[143] The historical origins of identification by fingerprints have been discussed, e.g., by Simon Cole (1999), a criminologist who is prominent among those who question the accuracy, sufficiency, and individuality of fingerprint identification.

on fingerprints. That was not the case, as an intimate relation had been discovered between the victim and Scheffer, and the latter had been among the suspects.

For Berlière, Bertillon's role in identification by fingerprints becoming an established technique is paradoxical, as Bertillon was aware of publications about fingerprints from other countries, yet had been quite reluctant to adopt this method, mainly because of the difficulty to classify fingerprints, but also because he considered them not to be distinctive enough (a laughable claim, vis-à-vis the weakness of his own anthropometric method). Locard was sarcastic about Bertillon in that respect. Edmond Locard (1877–1966) was a younger star of French criminalistics, who established France's first scientific police laboratory (*Laboratoire de Police scientifique*) in Lyons in January 1910, and published during the 1930s a *Traité de criminalistique* in seven volumes of lasting value to forensic laboratories worldwide. Locard's thesis on legal medicine is dated 1902.

Berlière remarks that stubbornness was a trait of Bertillon's personality, and that this played a role in his determined attitude against Dreyfus, when, an expert witness in court, he insisted on interpreting the graphological evidence unreasonably. Berlière points out that this was one reason Locard disliked Bertillon quite intensely. Berlière mentions a major error made by Locard himself: in 1945, a woman was sentenced to forced labour for life, having been identified by him as the anonymous Nazi collaborator who had denounced a partisan in the French Resistance; she was only freed after the error was recognised as such in 1956.

Locard himself developed (among the other things) *graphometrics*, and solved some cases based on graphological evidence; e.g., he solved a case in which a husband guided the hand of his dying wife in writing a will in his favour (in 1923, Locard published a paper about 'L'Écriture à la main guidée' in the *Revue de droit pénal et de criminologie et Archives internationales de médecine légale* in Bruxelles). Vols. 5 and 6 of Locard's *Traité de criminalistique* were published in 1935, and in fact they are entitled *L'Expertise des documents écrits*, being devoted to the analysis of written documents. Vol. 1 appeared in 1931, and was devoted to fingerprints and to other traces (*Les Empreintes et les traces dans l'enquête criminelle*). Vols. 3 and 4 appeared in 1932, and were about identification evidence (*Les Preuves de l'identité*).

Apparently Bertillon's endorsement of fingerprints came after the physician Lacassagne (one of the founders of criminalistics) and Galton had extolled to him the method. He remained reluctant to see his own method, based on anthropometric measurement, made obsolete by fingerprint identification. His successor who took over from him at the police, quoted by Berlière (p. 358), testified that in February 1914, upon Bertillon's death, out of the 1,200,000 cards held by the scientific police, only 60,000 had been classified based on the fingerprints. France adopted classification based on fingerprints considerably later than Argentina, the United Kingdom, and other countries (ibid.). Argentina was pioneering in criminalistics, and there actually is an anecdote (it was even related in the *Reader's Digest*) about Locard, in his student days, becoming enthralled with the discipline one day, when he was accompanying his medicine professor, the famous Lacassaigne. They had to wait because of the rain, and Lacassaigne gave him an Argentinean journal, asking Locard to translate an article for him on the spot. What Locard read on that occasion determined his professional future. Alexandre Lacassagne (1843–1924) became “Professeur de Médecine Légale” in 1880, and established research in the domain in Lyons, where it was carried further by Étienne Martin, Pierre Mazel, Jacques Bourret, as well as by his most famous continuator, Edmond Locard.[144]

In his memoirs of the First World War, ‘Aziz Bek, Head of Intelligence of the Fourth Ottoman Army, described an episode, which started when a spy stole documents (being unable to photograph or copy them on the spot) and then returned them. The commander of the 43th Division in Syria had noticed the disappearance of the defence plans, and on their reappearance he would not touch them. He had a laboratory detect fingerprints, then discreetly obtained the fingerprints of all officers, soldiers and clerks at the division headquarters. A circular was distributed, that had to be signed and returned. This way, a signature would identify the fingerprints unwittingly left on the paper. This led to the identification of an officer and of a soldier, and further investigation uncovered their links to a spy ring (‘Aziz Bek [1933–1937] 1991, pp. 116–117).

Twenty years earlier, a course of action such as this one hadn’t been taken, in France, with the *bordereau* ascribed to Alfred Dreyfus, but then such forensic “expertise” that had been sought at the time, had the goal of confirming his alleged guilt, rather than discovering the actual identity of the spy. “Evidence” had included supposed similarities in the handwriting, as well as the fact that when Dreyfus was ordered to write down under dictation a text identical with that of the dossier, he was visibly shaking (who wouldn’t, in his shoes?).

The example of the forensic “expertise” seeking to confirm that Dreyfus had written the given document, illustrates the pitfalls of *confirmationism* (tests seeking to confirm rather than disprove a hypothesis),[145] and more broadly, of tunnel thinking. The forensic experts were so committed to the claim that the suspect was guilty, that it was almost a foregone conclusion that they would find what they were looking for. This suggests that cognitive science and artificial intelligence research producing computational simulations of tunnel thinking could provide some clarification

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[144] Berthold Laufer, who was the United States leading Sinologist during the first three decades of the twentieth century, also authored a report on the history of fingerprinting (Laufer, 1913, 1917). Berthold Laufer was born in Cologne, Germany, in 1874. After earning his doctorate at the University of Leipzig in 1874, Berthold Laufer moved on the following year to the United States. He had obtained an invitation to the American Museum of Natural History in New York City, thanks to the famous anthropologist Franz Boas (1858–1942). Laufer eventually became curator of Asiatic Ethnology and Anthropology at the Field Museum of Natural History, Chicago, where he had moved in 1907, leaving a lectureship in Anthropology and East-Asiatic Languages at Columbia University. He died in 1934, upon leaping from the roof of the hotel in which he lived in Chicago, but the mode of his demise goes unmentioned in Latourette’s (1936) biographical memoir of Berthold Laufer for the U.S. National Academy of Sciences.

[145] *Confirmation bias* as occurring in the police interrogation rooms, see e.g. Kassin, Goldstein, and Savitsky (2003), Meissner and Kassin (2002), and Hill, Memon, and McGeorge (2008). Confirmationism is sometimes referred to as *cognitive dissonance.* This name for the concept was spread by a book by Leon Festinger (1919–1989), *A Theory of Cognitive Dissonance* (Festinger, 1957).

at the theoretical level, which would eventually be put to use in the design of tools for assisting with reasoning about the evidence. It would be blue sky research eventually finding (hopefully) practical application in a better design of tools. One possibility would be to develop an AI tool that would test protocols or possibly other software, trying to ensure that they are not marred by pitfalls of the kind mentioned earlier. In a sense, such pitfalls have already been sometimes argued to affect widespread techniques. The adoption of the Dempster-Shafer statistical technique is rather widespread in AI tools, but a major problem stemming from the adoption of Dempster-Shafer is that it is apparently tilted towards *confirmationism* instead of *falsificationism.*

8.7.2 DNA and Fingerprints

8.7.2.1 DNA Evidence: A Brief Introduction

Computational methods for determining individuality (Srihari & Su, 2008) encompass several domains in forensic science, from fingerprint analysis to handwriting recognition. In the 1990s and 2000s, DNA has become the evidence per excellence for personal identification. DNA evidence is usually considered to be hard evidence about a person's identity.[146] Nevertheless, DNA fingerprinting is not uncontroversial.[147] Concerning DNA evidence, consider the application to paternity claims.[148]

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[146] An overview of techniques of DNA analysis is provided by Duncan, Tacey, and Stauffer (2005, 2nd edn.; 2009, 3rd edn.), whereas in the same volume, Susan Herrero (2005, 2nd edn.; 2009, 3rd edn.) provides an overview of legal issues in forensic DNA. DNA fingerprinting is treated, e.g., in Baldin (2005), Inman and Rudin (2002), National Research Council (1996), Stockmarr (1999), Lauritzen and Mortera (2002), Meester and Sjerps (2004), Easteal, McLeod, and Reed (1991), Krawczak and Schmidtke (1994), and Butler (2001). See a brief, yet important debate (Krane et al., 2008), with useful bibliographies by the various commentators, about *sequential unmasking* in DNA identification. It was republished in www.bioforensics.com under the rubric *forensic bioinformatics.*

[147] Roberts (1991) is about the controversy about DNA fingerprinting. Nielsen and Nespor (1993) is on human rights in relation to genetic data and screening, in various contexts.

[148] Of course, historically there was interest in ascertaining paternity even before medical knowledge and technology would enable such checks credibly. For example, discussing early modern English midwifery books, Mary Fissell remarks (2003, p. 65): "Midwifery books of the 1670s and 1680s were obsessed by the issues of fatherhood. How could you know the father of a child? In certain circumstances, such as illegitimate births, knowing the father had long been important. These texts devoted much more attention to resemblance between parents and their children than did previous midwifery texts. This crisis in paternity had multiple roots. There was no sudden increase in illegitimate births that might have prompted such an interest. Some of the crisis may be due to longer-term intellectual changes that gradually made similitude a happenstance rather than an indicator of profound connection. No longer did resemblance mean something important about relatedness." Fissell further explains (ibid., pp. 65–66): "The crisis can also be understood in political terms. In [the] 1670s and 1680s, the question of monarchical succession – the transmission from one generation to another – became ever more pressing. Charles II did not have any legitimate sons, and his brother James's Catholicism made him a highly problematic successor. The

An article by an Oslo-based team, Egeland, Mostad, and Olaisen (1997), describes PATER, a software system for probabilistic computations for paternity and identification cases, in cases where DNA profiles of some people are known, but their family relationship is in doubt. PATER is claimed to be able to handle complex cases where potential mutations are accounted for.

Another project resulted in, e.g., Dawid, van Boxel, Mortera, and Pascali (1999), Dawid, Mortera, and Pascali (2001), and Dawid, Mortera, and Vicard (2010), Vicard, Dawid, Mortera, and d Lauritzen (2008), and Vicard and Dawid (2006), specifically about the statistics of disputed paternity. A prominent statistician, Philip Dawid, now at the University of Cambridge, at the time when he was affiliated with University College, London was remarking as follows at his research interests webpage[149]:

> I have been interested in the application of Probability and Statistics to a variety of subject areas, in particular to Medicine (especially medical diagnosis and decision-making), Crystallography, Reliability (especially Software Reliability) and, most recently, *Legal Reasoning.* I have acted as expert advisor or witness in a number of legal cases involving DNA profiling. This has led me to a thorough theoretical examination of the use of Probability and Statistics for *Forensic Identification.* I head an international research team focusing on the analysis of complex forensic DNA identification cases using Probabilistic Expert Systems. These legally inspired investigations have also highlighted the many logical subtleties and pitfalls that beset evidential reasoning more generally. To address these I have established a multidisciplinary research programme on *Evidence, Inference and Enquiry* [[150]] at University College London. This is bringing together researchers from a wide diversity of disciplinary backgrounds to seek out common ground, to advance understandings, and to improve the handling of evidence.

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duke of Monmouth's rebellion (the duke being the king's illegitimate son), the Rye House Plot, the Popish Plot [i.e., a libel against Catholics leading to executions] – all kept political instability at the forefront of popular awareness. The high politics of legitimate succession moved right into the birthing room in the Warming Pan Baby scandal, which erupted when James II's wife, Mary of Modena, gave birth a male heir – or did she? She had had eight previous pregnancies, all stillbirths or very short-lived infants. This baby was full-term and healthy, and some observers claimed it was a fraud. They suggested that a healthy baby had been smuggled into the birthing room, concealed in a warming pan, and substituted for Mary's sickly or stillborn babe."

From antiquity to the mid eighteenth century, the *theory of maternal imagination* had currency. It claimed that white parents could have a black child (or vice versa) if the mother, at the time of conception, saw or imagined a man with the other skin colour. A pregnant woman seeing an image of St. John the Baptist wearing hairy skins (or himself hairy) was believed to have given birth to a hairy daughter, who was depicted on the frontispiece of several 17th and early eighteenth century midwifery books. Fissell discussed such imagery. And books sometimes even suggested, Fissell points out, that a woman could deceive her husband by imagining her husband while having intercourse with her lover, so her illegitimate child would resemble her husband rather than her lover.

[149] It can be accessed at http://www.ucl.ac.uk/~ucak06d/research.html Philip Dawid's work on identification evidence, disputed paternity, and in forensic statistics includes Dawid (1994, 1998, 2001a, 2001b, 2002, 2004a, 2005a, 2005b, 2008), Dawid and Mortera (1996, 1998), Dawid and Evett (1997, 1998), Dawid and Pueschel (1999), Dawid et al. (1999, 2001), Dawid, Mortera, Pascali, and van Boxel (2002), Dawid, Mortera, Dobosz, and Pascali (2003), Dawid, Mortera and Vicard (2006), Mortera, Dawid, and Lauritzen (2003), Vicard and Dawid (2004, 2006).

[150] www.evidencescience.org

The Wikipedia entry for “Genetic fingerprinting” contains much detail.[151] Its introduction states:

> Genetic fingerprinting, DNA testing, DNA typing, and DNA profiling are techniques used to distinguish between individuals of the same species using only samples of their DNA. Its invention by Dr. Alec Jeffreys at the University of Leicester was announced in 1985. Two humans will have the vast majority of their DNA sequence in common. Genetic fingerprinting exploits highly variable repeating sequences called minisatellites. Two unrelated humans will be unlikely to have the same numbers of minisatellites at a given locus. In STR profiling, which is distinct from DNA fingerprinting, PCR is used to obtain enough DNA to then detect the number of repeats at several loci. It is possible to establish a match that is extremely unlikely to have arisen by coincidence, except in the case of identical twins, who will have identical genetic profiles.Genetic fingerprinting is used in forensic science, to match suspects to samples of blood, hair, saliva or semen. It has also led to several exonerations of formerly convicted suspects. It is also used in such applications as identifying human remains, paternity testing, matching organ donors, studying populations of wild animals, and establishing the province or composition of foods. It has also been used to generate hypotheses on the pattern of the human diaspora in prehistoric times.

Genetic testing is subjected to regulations (ibid.):

> Testing is subject to the legal code of the jurisdiction in which it is performed. Usually the testing is voluntary, but it can be made compulsory by such instruments as a search warrant or court order. Several jurisdictions have also begun to assemble databases containing DNA information of convicts. The United States maintains the largest DNA database in the world: The Combined DNA Index System, with over 4.5 million records as of 2007. The United Kingdom, maintains the National DNA Database (NDNAD), which is of similar size. The size of this database, and its rate of growth, is giving concern to civil liberties groups in the UK, where police have wide-ranging powers to take samples and retain them even in the event of acquittal.

There exist computer tools for carrying out statistical analysis concerning DNA evidence. “[U]sing object-oriented Bayesian networks we have constructed a flexible computational toolkit, and used it to analyse complex cases of DNA profile evidence, accounting appropriately for such features as missing individuals, mutation, silent alleles and mixed DNA traces” (Mortera & Dawid, 2006, section 8, p. 26).[152] Aitken, Taroni, and Garbolino (2003) described their own graphical model for the analysis of possible cross-transfer of DNA material, affecting DNA profiles intended for use as evidence. They resorted to Bayesian networks.

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[151] http://en.wikipedia.org/wiki/Genetic_fingerprinting

[152] The kind of situations across which one may come is illustrated, e.g., by *DNA mixtures:* “A *mixed DNA profile* is typically obtained from an unidentified biological stain or other trace thought to be associated with a crime. This commonly happens in rape cases, in robberies where an object might have been handled by more than one individual, and also in a scuffle of brawl. For a mixed DNA trace there is no constraint on the number of distinct alleles observed for each marker, since the trace might have been formed as a mixture of biological material from more than one person” (Mortera & Dawid, 2006, section 6.3, p. 16).

8.7.2.2 Statisticians' Disagreements About How to Evaluate DNA Samples

Whereas suspect recognition based on facial composites (let alone on an artist's sketch) is an *indicative tool*, DNA evidence and fingerprint evidence are *implicative tools*. Even though one would have thought that DNA evidence is one area in which the use of statistics faces less challenges than other uses of Bayesianism in law, actually statisticians' disagreements about how to evaluate DNA samples shows that here, too, there are severe problems.[153] Even though controversies about DNA evidence only very rarely reach the public, they received a popular treatment in two issues of Britain's *New Scientist* magazine in August 2010. The second report was introduced as follows (Geddes, 2010, p. 8):

> Last week, a *New Scientist* investigation showed how different forensic analysts can reach very different conclusions about whether or not someone's DNA matches a profile from a crime scene. This week we show how, even when analysts agree that someone could be a match for a piece of DNA evidence, the statistical weight assigned to that match can vary enormously.

In an inset, 'When lawyers question DNA' (on p. 9 in Geddes, 2010) in the special report on DNA evidence in the second issue, Scottish forensic scientist Alan Jamieson, who at scholars' conferences is often a wise and sobering voice about expert testimony, pointed out that defence lawyers can obtain the prosecution's statistical data concerning DNA samples, provided they are only permitted to use them in order to dispute them in the case at hand, and not for the purposes of other investigations and trials; and that moreover, if the case does not reach court, the refutations put forth by the defence would never reach to public domain.

The *New Scientist* report by Geddes (2010), 'What are the chances?', was subheadlined: "In the second part of our investigation, Linda Geddes shows that *the odds attached to a piece of DNA evidence can vary enormously*" (added emphasis). The article began with a case of conviction then still being appealed in California: "Charles Richard Smith has learned the hard way that you can prove almost anything with statistics. In 2009 a disputed statistic provided by a DNA analyst landed him with a twenty-five-year jail sentence". This was for sexual assault at a parking lot in Sacramento, CA, in January 2006, when a woman was forced into oral sex with the perpetrator. A swab of cells from Smith's penis showed his own DNA and that of another person, and indicated that he had been sexually intimate with an unknown person. The DNA analyst as "Smith's trial said the chances of the DNA coming from someone other than [the victim] were 1 in 15,000. But both the prosecution and the analyst's supervisor said the odds were more like 1 in 47", and a later review reduced this to 1 in 13, "while a different statistical method said the chance

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[153] Criticism also comes from critics of the application of probability theory to juridical proof in general, such as Ron Allen: even though one would have thought that DNA evidence would be a "safer" domain for statisticians, it is not quite so. Allen and Pardo (2007a) offered a critique, in terms of the *reference-class problem* (see Section 2.4 above) of how probability theory was applied to juridical proof concerning DNA random-match evidence in Nance and Morris (2002, 2005).

of seeing this evidence if the DNA came from [the victim] is only twice that of the chance of seeing it come from someone else." Geddes (2010, p. 8) further remarked:

> "Usually DNA evidence is pretty strong", says David Balding, a statistical geneticist at University College London, whose calculation puts the lowest probability on the link between Smith and [the victim]. "My point is that the number juries are provided with often overstates the evidence. It should be a smaller number".

On 15 May 1997, Odd O. Aalen from Norway posted a question, in an e-list about statistics in legal evidence[154]: "Does anybody on this list know about criminal court cases where purely statistical evidence has been the sole or major evidence, and where the defendant has been convicted on this basis? I am thinking here of purely numerical evidence as opposed to substantive proof and statistical calculations related to this". On that very day, a reply came from Robert Lempert, a well-known scholar from the University of Michigan: "There have by now been a couple of DNA cases like this". Arguably, this shows how important the debate on statistics is.

Another posting on the same day provided more detail. It was by Bernard Robertson, editor of *The New Zealand Law Journal*, and definitely a "Bayesian enthusiast" in the controversy about Bayesianism in law. He stated: "The case of Adams provides an interesting example as the only prosecution evidence was DNA while the defence produced some more conventional evidence which tended to point the other way and also produced Professor Donelly to explain how to use Bayes Theorem to reduce the posterior odds below 'beyond reasonable doubt'." Robertson pointed out that this generated publications in the legal literature in England.

In an article by mathematicians from Queen Mary and Westfield College, London – Balding and Donnelly (1995) – a contribution was made to clarify the role of the modes of statistical inference, in the controversy over the interpretation of DNA profile evidence in forensic identification. They claimed that this controversy can be attributed in part to confusion over which such mode of inference is appropriate. They also remark that whereas some questions in the debate were ill-posed or inappropriate, some issues were neglected, which can have important consequences. They propose their own framework for assessing DNA evidence,

> in which, for example, the roles both of the population genetics issues and of the non-scientific evidence in a case are incorporated. Our analysis highlights several widely held misconceptions in the DNA profiling debate. For example, the profile frequency is not directly relevant to forensic inference. Further, very small match probabilities may in some settings be consistent with acquittal.

Besides, there is also another kind of risk with DNA evidence. "Even in DNA cases, there is always the possibility of lab error or planted evidence" (Allen, 2008a, p. 328, note 1). The presence of DNA or of fingerprints from a given person at the scene of a crime does not necessarily mean that the person they identify was involved at the crime. In England in 2011, a retired teacher was arrested, demonised by the media,

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[154] bayesian-evidence@vuw.ac.nz

and then released in connection with the kidnapping murder of a young woman architect, as there was evidence indicating his presence where she lived, but he was the landowner. He may have had other opportunities of losing hair or leaving fingerprints at the place. Besides, DNA evidence may be mislabelled inside a laboratory. Or then, perpetrators may leave on purpose DNA evidence, perhaps hair, but even blood from a person they want to implicate.

There is even the risk of fake DNA. based on a paper by an Israeli team of scientists led by Dan Frumkin that had appeared in the journal *Forensic Science International: Genetics*, an unsigned item the British periodical *Criminal Law & Justice Weely*, Vol. 173, No. 34 (August 22, 2009) reported on p. 531, under the headline ‘Fake DNA’, that Frumkin’s team had taken DNA from human hair was taken and multiplied many times, and that an enhanced sample of that DNA “was then inserted into blood cells that had been purged of their previous DNA. Dr Frumkin suggested that, in theory, criminals could use the technique to plant samples of blood or saliva at crime scenes to cover their tracks and implicate another party.” One would not expect to find a sample of saliva at a crime scene other than by the victim or the perpetrator if they were alone and in some isolated place, but if DNA from hair could be planted inside saliva, then the very expectations about how saliva could occur at a crime scene means that perpetrators could frame somebody. “The researchers said that the use of DNA is often the key to proving the guilt or innocence of suspects and that by using the technique they had developed, genetic profiles could easily be synthesized” (ibid.), even though this is currently beyond the ability of your usual perpetrator.

8.7.2.3 Human Fingerprints

Let us turn to *human fingerprints*,[155] which as usually found in investigative contexts are of the hand palm, and in particular, of the tips of the fingers.[156] Steps involving identification by fingerprints are as follows:

- A particular person (suspect X) handles an object (an exhibit).
- That exhibit is exposed to the environment.
- The exhibit is eventually recovered and treated, revealing fingerprints.

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[155] See, e.g., Jain and Maltoni (2003) and Champod, Lennard, Margot, and Stilovic (2004). Also see the discussion in, e.g., Stoney (1997), Cole (2001, 2004, 2005, 2006a, 2006b), Cole et al. (2008), Balding (2005), Saks and Koehler (2008).

[156] Sometimes, the terms *fingerprint* and *fingerprinting* are used metaphorically. We have already come across *soil fingerprinting techniques* in a project in forensic geology that resorts to a decision support system, at the end of Section 8.5.1. In Section 8.5.6, we considered *chemical fingerprints*, identifying an individual component in a mixture (taken to be a multivariate, mixed chemical system). Another metaphorical use of the term *fingerprint* is found in *digital steganography*, a discipline we dealt with in Section 6.2.1.5 (which itself spans more, thematically). One sometimes talks about fingerprints, and a fingerprint vault scheme, in *digital steganography:* see

- The developed fingerprints are imaged.[157]
- The images of the fingerprints are transferred to a database.
- The images of fingerprints are compared, and if this is done automatically, then a pattern matching algorithm is used.
- Suspect X is identified.

The introduction to the Wikipedia entry for "Fingerprint" states[158]:

> A *fingerprint* is an impression of the friction ridges of all or any part of the finger. A friction ridge is a raised portion of the epidermis [skin] on the palmar (palm and fingers) or plantar (sole and toes) skin, consisting of one or more connected ridge units of friction ridge skin. These ridges are sometimes known as "dermal ridges" or "dermal papillae".
>
> Fingerprints may be deposited in natural secretions from the eccrine glands present in friction ridge skin (secretions consisting primarily of water) or they may be made by ink or other contaminants transferred from the peaks of friction skin ridges to a relatively smooth surface such as a fingerprint card. The term fingerprint normally refers to impressions transferred from the pad on the last joint of fingers and thumbs, though fingerprint cards also typically record portions of lower joint areas of the fingers (which are also used to make identifications).

Fingerprint identification, based on traces left by the skin of some persons' finger tips, is much debated in the literature, and until the end of the twentieth century its accuracy was hardly questioned, once it had come to be accepted by the beginning of that century. As we are going to see, the probative value of fingerprint evidence is no longer as secure as it used to be, and we are going to come back to that. Itiel Dror and colleagues' paper "When emotions get the better of us: The effect of contextual top-down processing on matching fingerprints" (Dror, Péron, Hind, &

Li et al. (2005). In *forensic ballistics*, one speaks of *ballistic fingeprinting*. Also in intrusion detection within computer security, metaphorically one speaks of *fingerprints* and *fingeprinting* (Section 6.2.1.12), in relation to attempts to identify an intruder.

One sometimes speaks of fingerprinting for the identification of an individual rhinoceros. Amin, Bramer, and Emslie (2003) described experiments with "rhino horn fingerprint identification", i.e., "the identification of the species and origin of illegally traded or confiscated African rhino horn", using techniques of intelligent data analysis. Rhino horns are akin to compacted hair and fingernails, and their chemical composition refelcts what the animal has been eating throughout its life. In turn, the chemistry of the food is affected by climate and geology. The so-called *fingerprint* of a rhino horn is a combination of variable values. In the project reported about by Amin et al. (ibid.), *Discriminant Function Analysis* was the principal technique of data analysis used, the prediction of the category in which a given case belongs is obtained by deriving mathematical functions that provide the greatest possible discrimination among categories. The same paper discussed a further stage, at which it was intended to use artificial neural nets for classification, or the automatic induction of classification trees (for the latter, cf. Quinlan, 1986; Kothari & Dong, 2002; Siroky, 2009; Chen et al., 2011). Contrast the task in the rhino project, to the task of identifying an individual, which is the case of techniques for the recognition of cattle based on characteristics of the animal's back skin that are akin to fingerprints.

[157] A discussion of fingerprint development and imaging, with the chemistry involved in the development explained in clear detail, can be found in an excellent PowerPoint presentation posted online, and authored by Steve Bleay of Britain's Home Office Scientific Development Branch (Bleay, 2009).

[158] http://en.wikipedia.org/wiki/Fingerprint.

Charlton, 2005) is a paper in cognitive psychology, applied to how experts perform at matching fingerprints. Dror and Charlton (2006) and Dror et al. (2006) tried to identify the causes of why experts make identification errors. Dror and Rosenthal (2008) tried to meta-analytically quantify the *reliability* and *biasability* of forensic experts.

"On the palmar surface of the hands and feet are raised surfaces called friction ridges. The scientific basis behind friction ridge analysis is the fact that friction ridges are persistent and unique" (from the Wikipedia entry for 'Fingerprint'). The Wikipedia entry, which as accessed in late 2007, was detailed and engaging (our present readers are encouraged to access it), states:

> Fingerprint identification (sometimes referred to as *dactyloscopy)* or palmprint identification is the process of comparing questioned and known friction skin ridge impressions (see *Minutiae*)[159] from fingers or palms to determine if the impressions are from the same finger or palm. The flexibility of friction ridge skin means that no two finger or palm prints are ever exactly alike (never identical in every detail), even two impressions recorded immediately after each other. Fingerprint identification (also referred to as individualization) occurs when an expert (or an *expert computer system* operating under *threshold scoring* rules) determines that two friction ridge impressions originated from the same finger or palm (or toe, sole) to the exclusion of all others.
>
> A *known print* is the intentional recording of the friction ridges, usually with black printer's ink rolled across a contrasting white background, typically a white card. Friction ridges can also be recorded digitally using a technique called *Live-Scan.* A *latent print* is the chance reproduction of the friction ridges deposited on the surface of an item. Latent prints are often fragmentary and may require chemical methods, powder, or alternative light sources in order to be visualized.

Computerisation brought about major changes in the *modus operandi* of fingerprint identification. The following is quoted from the Wikipedia entry[160]:

> Before computerization replaced manual filing systems in large fingerprint operations, manual fingerprint classification systems were used to categorize fingerprints based on general ridge formations (such as the presence or absence of circular patterns in various fingers), thus permitting filing and retrieval of paper records in large collections based on friction ridge patterns independent of name, birth date and other biographic data that persons may misrepresent. The most popular ten print classification systems include the Roscher system, the Vucetich system, and the *Henry Classification System* [. . .]
>
> In the Henry system of classification,[161] there are three basic fingerprint patterns: Arch, Loop and Whorl. There are also more complex classification systems that further break down patterns to plain arches or tented arches. [. . .]

An explanation of fingerprint appearance is provided by Bistarelli, Santini, and Vaccarelli (2006, pp. 360–361, section 2.1):

> The most evident structural characteristic of a fingerprint is the pattern of interleaved ridges and valleys that often run in parallel. Ridges vary in width from 100 to 300 lm and the period of a ridge/valley cycle is typically about 500 lm. If analyzed at global level, almost

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[159] http://en.wikipedia.org/wiki/Minutiae.

[160] http://en.wikipedia.org/wiki/Fingerprint.

[161] On which, see http://en.wikipedia.org/wiki/Henry_Classification_System.

> all of the patterns exhibit one or more regions characterized by a distinctive shape and called *singular regions.* These regions can be classified into three typologies according to their shape: loop, delta, and whorl are characterized respectively by a ⌒, **Δ**, and ***O*** shape. A particular presence of these singular regions defines the whole fingerprint class: the five classes in Henry's scheme [(Jain & Maltoni, 2003)] are *arch, tented arch, right loop, left loop, and whorl.*
>
> At local level, other important features called minutiae refer to ridge discontinuities. Minutiae ar sometimes called "Galton details",[162] in honor of the first person who categorized them and observed that they remain unchanged over the individual's entire life [(Lee & Gaensslen, 1991, 2nd edn. 2001)].[163] Most frequently, the minutiae types can be identified by terminations, where a ridge line ends, and bifurcations, where a ridge bifurcates forming a "Y" [. . .], even if several types have been observed, described by their shape (dot, island, hook, lake, ridge crossing and multiple bifurcations).
>
> Another important point in the image, which can be used also to align the fingerprint images, is the "core point", corresponding to the center of the north most loop type singular region. In fingers without loop or whorl regions, the core is associated with the point of maximum ridge line curvature. The most important minutiae characteristics are the location coordinates inside the image, their form type (e.g. termination, bifurcation, island, etc.) and the orientation of the ridge (in degree) on which the minutia is found.

Advances in research make it possible to avoid having to develop the prints first, in order to examine fingerprints[164]:

> Within the Materials Research Centre, University of Swansea, UK, University of Swansea, UK, Professor Neil McMurray and Dr Geraint Williams have developed a technique that enables fingerprints to be visualised on metallic and electrically conductive surfaces without the need to develop the prints first. The technique involves the use of an instrument called a scanning Kelvin probe (SKP), which measures the voltage, or electrical potential, at preset intervals over the surface of an object on which a fingerprint may have been deposited. These measurements can then be mapped to produce an image of the fingerprint. [. . .]
>
> Currently, in crime scene investigations, a decision has to be made at an early stage whether to attempt to retrieve fingerprints through the use of developers or whether to swab surfaces in an attempt to salvage material for DNA fingerprinting. The two processes are mutually incompatible, as fingerprint developers destroy material that could potentially be used for DNA analysis, and swabbing is likely to make fingerprint identification impossible.
>
> The application of the new SKP fingerprinting technique, which is non-contact and does not require the use of developers, has the potential to allow fingerprints to be retrieved while still leaving intact any material that could subsequently be subjected to DNA analysis. [. . .]

In the United States (ibid.):

> The FBI manages a fingerprint identification system and database called IAFIS, which currently holds the fingerprints and criminal records of over fifty-one million criminal record subjects, and over 1.5 million civil (non-criminal) fingerprint records. U.S. Visit currently holds a repository of over 50 million persons, primarily in the form of two-finger records (by 2008, U.S. Visit is transforming to a system recording FBI-standard tenprint records).

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[162] Psychologist and anthropologist Francis Galton (1821–1911), Charles Darwin's cousin.

[163] Allegedly, the first edition was a bestseller of Lee and Gaensslen's (1991) *Handbook of Fingerprint Recognition.* The second edition, of 2001, is a major revision. A more recent handbook is *Handbook of Fingerprint Recognition* by Davide Maltoni, Dario Maio, Anil K. Jain, and Salil Prabhakar (2003, 2nd edn. 2009).

[164] http://en.wikipedia.org/wiki/Fingerprint.

> Most American law enforcement agencies use Wavelet Scalar Quantization (WSQ), a wavelet-based system[165] for efficient storage of compressed fingerprint images at 500 pixels per inch (ppi). [. . .] For fingerprints recorded at 1000 ppi spatial resolution. law enforcement (including the FBI) uses JPEG 2000 instead of WSQ. [. . .]

8.7.2.4 Fingerprints from Dead Bodies

Sometimes forensic fingerprinting specialists are faced not with the task of pinpointing a live suspect criminal from the fingerprints he or she left, but rather with trying to achieve identification for a dead body, based on the skin of the finger tips. Take the case of mummified bodies. "The identification of mummified bodies places high demands on the skills of a forensic fingerprinting specialist. From a variety of methods, he must be able to choose the most appropriate one to reproduce the skin ridges from fingers, which are often shrunk and deformed", as stated in the English abstract of a paper by Ineichen and Neukom (1995), of the Zurich cantonal police: their "article introduces and discusses a method for indirect fingerprinting. In this method, a negative cast of the mummified fingertip is first produced with a silicon mass. This 3-dimensional negative is then filled with several layers of a white glue/talc mixture, until a skin-thick positive is attained. Using this artificial skin it is possible to reproduce, in a relatively short time, a fingerprint which is free of disturbing skin wrinkles and deformities" (ibid.).

The problem with using fingerprints from dead bodies is that deformation can be expected to be much worse that the elastic deformation that normally affects fingeprints from living persons. Bear in mind that fingers are in three dimensions, whereas fingerprints appear on a surface. Computer methods for fingerprint matching (the fingerprints having been left by persons while alive) have to cope with the problem of elastic deformation. In dead bodies, the deformation caused by decay is plastic, not just elastic. That is to say, the shape that the fingertip has taken will not revert to the previous shape the way that the finger tip of a living person, when pressed against a surface, is going to go back to its previous shape when not pressed.

8.7.2.5 The Problem of Assessing Fingerprint Sufficient Similarity

Are fingerprints really reliable? The courts in the United States and elsewhere have usually been rather unresponsive to challenges to identification accuracy. But there is another problem with the use of *latent prints*, i.e., of such fingerprints that were found at a crime scene (Cole, Welling, Dioso-Villa, & Carpenter, 2008, p. 167):

> [A]side from being unresponsive to the question of accuracy, the individuality issue is problematic in its own right (Saks & Koehler, 2008). It is commonly said that the 'individuality' or 'uniqueness' of friction ridge skin is one of the 'fundamental premises' of latent print individualization (Moenssens, 1999).[166] Such discussions generally treat this premise as

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[165] See http://en.wikipedia.org/wiki/Wavelet_Scalar_Quantization

[166] Cf. Moenssens (2003).

> one that has been satisfied – i.e. the ‘individuality’ of friction ridge skin is ‘known’ or ‘proven’. By this, it would appear that fingerprint proponents mean that the exact duplication of any area of friction ridge skin is extremely unlikely. But such an assertion has little meaning without knowing the conditions under which extreme similarity would be considered ‘duplication’, what scale of area of friction ridge skin is being discussed and at what level of resolution friction ridge skin is observed. Assertions of ‘uniqueness’ or ‘individuality’ could, for all we know, mean nothing more than that, when analysed at the level of molecules, no two areas of friction ridge skin will duplicate exactly. Such a statement is undoubtedly true not only of friction ridge skin, as well as many other objects in the world, but also of little value in measuring how accurately source attributions can be made from those objects by human experts using visual analysis.

For practical legal purposes, mere non-duplication is not what really matters. Rather (ibid.):

> Obviously, what is wanted is not the mere assertion of non-duplication, but, rather, measurements of the variability of different areas of friction ridge skin and, crucially, multiple images derived from the same areas of friction ridge skin. In short, the issue is not so much the individuality of an area of friction ridge skin itself, but rather the range of variability of legible impressions that can be produced by a given area of friction ridge skin relative to the range of impressions that could be produced by analogous areas of friction ridge skin from different individuals.
>
> Perhaps most importantly, it makes little sense to discuss the ‘individuality’, or even the ‘variability’, of ‘fingerprints’ as if it were a quality that inhered in friction ridge skin. These qualities can only exist in conjunction with some sort of perceptual system, whether human or mechanical.

Let us consider the common task of identifying suspect perpetrators, based on prints left by their fingers, in the British context. In the words of a scholar based in London, Mike Redmayne (2002, p. 25):

> Fingerprint experts have no statistics on which to base their conclusions. There is a large degree of consensus that individual fingerprints are unique, and that a certain number of similarities between two prints proves identity beyond almost any doubt. But there are no figures on which to base these judgments: no way of quantifying the cut-off point at which sufficient similarity proves identity. David Stoney has written perceptively about the process of fingerprint identification. He suggests that, on perceiving enough points of identity, the expert makes a ‘leap of faith’ and becomes ‘subjectively certain’ of identity. In many countries there is a convention that a particular number of points is required before a match is announced. In England and Wales, the magic number was long sixteen. Latterly, few people saw much logic in the ‘sixteen points’ rule, and it was abandoned in 2001. But the convention helps to explain why, when the expert in *Charles* went to court on just twelve points, his evidence was vulnerable to a *Doheny*-style challenge.

The *Doheny* case is one in which identification revolved on the DNA evidence. Also from England and Wales, it was judged in 1997 by the Court of Appeal, “which after agonising over” the risks of misconceptions on the part of jurors of what DNA evidence stands for (Redmayne, 2002, p. 20),

> hit upon an ingenious solution. Rather than explaining the subtle but important distinction between the probability of guilt given the DNA evidence and the probability of the DNA evidence given guilt in semantic terms, it would provide a simple illustration to convey the key issues [. . .]. Its sample jury instructions for DNA cases proceeds as follows:

> Members of the jury, if you accept the scientific evidence called by the Crown, this indicates that there are probably only four or five white males in the United Kingdom from whom that semen could have come. The defendant is one of them. If that is the position, the decision you have to reach, on all the evidence, is whether you are sure that is was the defendant who left that stain or whether it is possible that it was one of the other small number of men who share the same DNA characteristics.

The quotation, previously given, about fingerprints, as taken from Redmayne (2002, p. 25), is about the case of Neil Charles, convicted of robbery and false imprisonment, and the principal evidence about whom was a fingerprint; moreover, "[t]here was circumstantial evidence to link him to the crime scene – he had been seen acting suspiciously nearby earlier in the day, and [closed-circuit TV] cameras caught him in the area later on" (p. 25). "The defence strategy was simple: to get the expert think of his testimony in *Doheny* terms, so as to draw out an admission that Charles was just one of *n* men who might have left the print" (p. 25). "But the Court of Appeal would not allow two experts to explore these issues further because they had not been called at trial. In any case, it did not think the *Doheny* analogy apt because 'the Crown's case did not rest on any random occurrence ratio [sc. match probability]'." (ibid., p. 25, Redmayne's brackets).

Redmayne remarks that fingerprint identification is such powerful evidence that perhaps "really there is no room for a *Doheny* argument. The expert makes the leap of faith, leaving no quantifiable gap over which the jury must jump [. . .]. But as the match threshold moves down from 16 points, there is less room for complacency" (ibid., p. 26). There has been contention about the admissibility of fingerprint evidence. Yvette Tinsley, from the Victoria University of Wellington, New Zealand, discussed a possible reform of identification procedures (Tinsley, 2001).

Scotland's Fingerprint Inquiry[167] is likely to have repercussions also outside Scotland, in the long term. The Inquiry Report was expected in 2011. Oral hearings took place in the summer and autumn of 2009. On 14 March 2008, Scotland's Cabinet Secretary for Justice, Kenny MacAskill, announced a public judicial inquiry (set up by Scottish ministers under the Inquiries Act 2005). Its remit has been to investigate the steps taken to verify the fingerprints associated with the case of *H.M. Advocate* v. *McKie* in 1999, and related matters.

The background is as follows. Charged for the murder of Marion Ross, David Asbury was convicted in May 1997, and the prosecution case against him included fingerprint evidence. During the investigation into the murder, a fingerprint was found on the doorframe of the bathroom in Marion Ross's home. That fingerprint (which became known as "Y7"), was identified as belonging to Shirley McKie, a serving police officer involved in the murder investigation. During Asbury's trial, McKie denied that the fingerprint was hers. After the murder trial, she was prosecuted for perjury: the charge was that she had lied while giving evidence on oath, because of what she had said in her evidence at David Asbury's trial. The evidence before the jury at McKie's trial

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[167] http://www.thefingerprintinquiryscotland.org.uk

> included evidence from defence fingerprint experts that Y7 was not her fingerprint. The jury, unanimously, found Shirley McKie not guilty of perjury. The identification of Y7 was made, originally, by officers of the Scottish Criminal Record Office. Various fingerprint experts have expressed differing views as to whether Y7 is the fingerprint of Shirley McKie. In August 2000 David Asbury was granted interim liberation pending an appeal against his conviction for murder. His conviction was quashed in August 2002. The Crown did not oppose his appeal. Shirley McKie raised an action for damages arising from the identification of Y7 as her fingerprint. It was settled out of court by the Scottish Ministers, without admission of liability, in February 2006.[168]

The Scottish government set up the Fingerprint Inquiry to fulfil its commitment to hold an independent, public, judicial inquiry into the circumstances surrounding the Shirley McKie case. The Fingerprint Inquiry's[169] terms of reference, as agreed by the Scottish Ministers, are as follows:

- To inquire into the steps that were taken to identify and verify the fingerprints associated with, and leading up to, the case of HM Advocate v. McKie in 1999
- to determine, in relation to the fingerprint designated Y7, the consequences of the steps taken, or not taken, and
- to report findings of fact and make recommendations as to what measures might now be introduced, beyond those that have already been introduced since 1999, to ensure that any shortcomings are avoided in the future.

An editorial (Koehler, 2008) in a special issue of the journal *Law, Probability and Risk*, by Jonathan Koehler from Arizona State University in Tempe, began by noting:

> Ten years ago, the notion that a top academic journal should publish an exchange on the scientific validation of fingerprint evidence would have been a non-starter. Until then, all but a few self-interested defendants and defence attorneys believed that when a fingerprint examiner matched a crime scene print (a latent print) to a suspect's reference print, the evidence was absolute and irrefutable. A fingerprint match proved identity if not guilt. Today, however, scientists, attorneys and others are taking a hard look at the forensic sciences in general and fingerprint evidence in particular. The oft-repeated claims that fingerprints are unique and that the source of fingerprint fragments can be identified with certainty have received special attention.[170]

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[168] The quotation is from the webpage "About the Inquiry: Background" at the site of the inquiry itself, at http://www.thefingerprintinquiryscotland.org.uk/inquiry/23.html

[169] Set up under the Inquiries Act 2005, it is one of the first inquiries under that Act to use the Inquiries (Scotland) Rules 2007.

[170] The uniqueness claim was rejected by Balding (2005), Cole (2004) and Saks and Koehler (2008). Koehler noted (2008, p. 85): "Kaye (2003) points out the serious flaws in a study that some rely on as proof of fingerprint uniqueness. As for the certainty of fingerprint identifications, the data (not surprisingly) show that fingerprint examiners are fallible. Many commit false-positive and false-negative errors in proficiency tests and in casework (Cole, 2005, 2006a, 2006b). Indeed, some critics argue that there is no scientific reason to believe that fingerprint examiners can make reliable identifications at all (Epstein, 2002)." A bibliography of legal scholarship rejecting the validity of fingerprint identification can be found in the long very last footnote of Cole (2009), and it should be looked up there.

In an article from the United States cautious about the reliability of fingerprint evidence, Cole et al. (2008) began by pointing out: “Efforts to harness computer fingerprint databases to perform studies relevant to fingerprint identification have tended to focus on 10-print, rather than latent print, identification or on the inherent individuality of fingerprint images.” (ibid., p. 165). That is to say (ibid., p. 166):

> Latent print individualization is a forensic technique that endeavours to attribute a ‘mark’ (a crime scene or ‘latent’ print) to the ‘friction ridge skin’ (the corrugated skin that covers human fingers, palms and soles) of an individual. Such attributions are currently achieved through a visual comparison of the mark with an exemplar ‘print’ whose origin is known. These attributions are made by human latent print examiners (LPEs). Computer algorithms (Automated Fingerprint Identification Systems or AFIS) are often used to search large databases for ‘candidate’ prints to present to the examiner, but there is neither an agency or a jurisdiction that currently allows a computer system to make *latent* print attributions nor an algorithm that claims an ability to make such attributions. This is not the case for 10-print attributions, in which the source of a set of 10 ‘inked’, or intentionally recorded, prints is attributed. Such attributions are sometimes made by computer algorithms (Cherry & Imwinkelried, 2006).
>
> Professional LPEs are restricted to three conclusions: individualization, inconclusive and exclusion (Scientific Working Group on Friction Ridge Analysis Study and Technology, 2003).[171] Thus, the only ‘inclusionary’ conclusion – i.e. the only conclusion that implicates a suspect – is the conclusion of ‘individualization’. ‘Individualization’, in turn, is defined as the claim that a particular area of friction ridge skin is the only possible source of a particular mark (Scientific Working Group on Friction Ridge Analysis Study and Technology, 2003). In other words, all other possible sources have been eliminated as possible sources of the mark.

Cole et al. (2008) questioned *accuracy*, i.e., how often it is that individualisations based on latent prints are correct: “Does the accuracy vary predictably in response to particular variables, such as, say, the amount of information contained in the mark or the skill level of the examiner?” (ibid., p. 166). They also questioned *sufficiency:* “How much consistent friction ridge detail is it necessary to find, in order to support a conclusion of individualization?” (ibid.). Their third question concerned *individuality:* “How rare are the various friction ridge features used in latent print analysis within various populations? How rare are various combinations of friction ridge features? How similar are the most similar areas of friction ridge skin, of some specified size?” (ibid.). Cole et al. (2008, pp. 166–167):

> There have been essentially no empirical studies addressing the accuracy questions (Haber & Haber, 2003, 2008), although some preliminary studies are now beginning to be undertaken (Wertheim et al., 2006; Langenburg, 2004; Haber & Haber, 2006). Purported answers to the sufficiency question are known to have been legislated rather than derived from empirical data (Champod, 1995; Evett & Williams, 1996; Cole, 1999). Current professional guidelines developed in the United States mandate an essentially circular definition of ‘sufficiency’: ‘Sufficiency is the examiner’s determination that adequate unique details of the friction skin source area are revealed in the impression’ (Scientific Working Group

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[171] Tthe Scientific Working Group on Friction Ridge Analysis, Study and Technology (SWGFAST) was established in 1995, and its mission is to establish consensus guidelines and standards for the forensic examination of friction ridges. See http://www.swgfast.org/ Several resports are posted at that site.

> on Friction Ridge Analysis Study and Technology, 2002, section 1.5). The most sustained scholarly attention has been devoted to individuality, but much of it has focused on demonstrating or asserting the mere fact of the absolute non-duplication of complete fingertip-sized areas of friction ridge skin, rather than on measuring the degree of variability. This is true of both of the two major strands of fingerprint research. Statistical research focused on estimating the probability that exact duplicate areas of friction ridge skin (usually complete fingertips) exist (Pankanti et al., 2002; Stoney, 2001). Anatomical research focused on detailing the formation of friction ridge skin, while occasionally commenting that this process was sufficiently complex to support an assumption of non-duplication as a 'working principle' (Cummins & Midlo, 1943; Wilder & Wentworth, 1918; Wertheim & Maceo, 2002).
>
> Nonetheless, defenders of latent print individualization have tended to seek to shift the debate to individuality when pressed concerning accuracy, a tendency that one of us has elsewhere called 'the fingerprint examiner's fallacy', the argument that the accuracy of a source attribution technique may be inferred from the uniqueness or variability of the target object (Cole, 2004, 2006b). [. . .]

What Cole et al. (2008) themselves did, was to carry out experiments measuring how accurate an automated fingerprint matching system was at identifying the source of *simulated latent* print (i.e., fingerprints taken, as though, from a crime scene, while actually having been obtained for the purposes of the experiment). The computer system carried out the task of a human latent print examiner fairly weel, except in that it (like presumably the human expert) tended to produce false positives (ibid., p. 165): "there are non-mate images that scored very highly on the AFIS's[172] similarity measure. These images would be susceptible to erroneous conclusions that would be given with a very high degree of confidence. Not surprisingly, the same was also true of the simulated latents which contained less information." They claimed that this is useful for assessing human experts, too: "We suggest that measuring the accuracy and potential for erroneous conclusions for AFISs might provide a basis for comparison between human examiners and automated systems at performing various identification tasks" (ibid.).[173]

8.7.3 Computational Techniques for Fingerprint Recognition

8.7.3.1 General Considerations

Research in *biometrics* within computer science has found various applications,[174] and in particular, identification by means of fingerprints is no longer confined to use by the police. In the words of Bistarelli et al. (2006, pp. 359–360):

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[172] *AFIS* stands for "automated fingerpint identification system".

[173] Incidentally, note that Srihari, Srinivasan, and Beal (2008) discussed the discriminability of the fingerprints of twins. Sargur Srihari's team at the University of Buffalo is active in both computer-assisted handwriting recognition, and computer-assisted fingerprint recognition.

[174] For example, see fn. 177 in Chapter 6.

> The term "biometrics" is commonly used today to refer to the authentication of a person by analyzing his/her physical characteristics (like fingerprints) or behavioral characteristics (like voice or gait). Since these characteristics are unique to an individual, their measurement provides a more reliable system of authentication than ID cards, keys, passwords, or other traditional systems while accessing restricted areas in office buildings and factories, or controlling the security of computer networks, electronic commerce, and banking transactions. The reason is that all these secret keys can be easily stolen or cloned to steal the personal identity, or they can also be forgotten by the owner preventing the whole identification process. Biometric characteristics are, instead, generally more difficult to duplicate and they naturally always "follow" the owner. Moreover, an advantage of biometrics is that they cannot be lent (like a physical key), and thus, they [guarantee the owner's] on-site presence.
>
> The most common biometric techniques are signature verification, retinal analysis, facial analysis, fingerprint verification, hand geometry, and voice verification. These technologies are comparable by the aid of several indicators, such as permanence (measurement should be invariant with time), uniqueness (different values for different persons), universality (everyone should have this trait), acceptability (if people are willing to accept this technology), performance (the recognition accuracy and system requirements) and circumvention (how [easy it is] to fool the system). Fingerprint matching is one of the most diffused biometric techniques used in automatic personal identification, because of its strong reliability and its low implementation cost; moreover, it is also the most mature and explored technology of all [biometric techniques].

Computational fingerprint recognition techniques – examining the pattern of ridges and furrows in fingerprints, and their *minutiae points*, that is to say, *ridge ending* and *ridge bifurcation* – are an active area within image processing. Na, Yoon, Kim, and Hwang (2005) discussed the shortcoming of such techniques. Brislawn, Bradley, Onyshczak, & Hopper (1996) described the FBI compression standard for digitised fingerprint images. Criminal investigation is just one of the area in which fingerprints are used for identification. "The fingerprint sensors are becoming smaller and cheaper, and automatic identification based on fingerprints is becoming an attractive alternative/complement to the traditional methods of identification" (Khuwaja, 2006, p. 25), not only in criminal investigation, but, along with other so-called *biometric* methods employed in *personal authentication systems*, and based on an individual person's body or sometimes behavioural features, also in e-banking, e-commerce, smart cards, and access to sensitive databases, and sometimes for access into premises with security requirements. The procedure is not without problems. Khuwaja remarks (ibid., pp. 24–25):

> The quality of the finger image is the most significant factor in a reliable process (Emiroglu and Akhan, 1997; Jiang et al., 2001). One aspect of fingerprint identification systems, which largely has been overlooked, is the need for a determination on a pixel-by-pixel basis of the reliability of the information. In an image, one region might be highly reliable, while another is not. Sets of information must be extracted from an image by the system, a process known as encoding. This process is made difficult by the fact that different prints of the same finger may be substantially different due to effects such as (a) pressure; increased pressure leads to ridge joining and decreased pressure leads to ridge breaking. (b) dirt and moisture; this can cause phantom joints; (c) elasticity of the skin; the whole image can become sheared and distorted; (d) background; the latent may be taken from a complex background, both in relif and pattern; (e) inking; the amount of ink used to take finger impressions significantly affects the images; and (f) smudging; often regions of the print image are smudged.

Moreover, when fingerprints are scanned, there may be imperfections in the images (ibid., p. 25). Such imperfect images “require some preprocessing before the features on them can be extracted. The imperfections in the images manifest themselves in the form of noncontinuous regions and noncontinuous ridges (Costello, Gunawardena, & Nadiadi, 1994). These areas need either to be enhanced or ignored for valid recognition of the fingerprint” (Khuwaja, ibid.)

Automatic fingerprint identification systems are widely used, and there exist several pattern matching techniques applied to matching fingerprints, but the matching is time-consuming. There exists a series of Fingerprint Verification Competitions (FVC), in which the systems entered by competitors are tested on databases, and the performance is in terms of authentication reliability and speed.

Apart from the time it takes to match fingerprints, another problem is deformation. Hao, Tan, and Wang (2002, section 1) explain this as follows:

> In most [automatic fingerprint identification systems], the representation of fingerprints is based on minutiae such as ridge ending and ridge bifurcation, with each minutia being characterized by its locations and orientation. With this representation, the matching problem is reduced to a point pattern matching problem. In the ideal case described by Jain et al. (1997), the matching can be accomplished by simply counting the number of spatially overlapping minutiae. But in practice, the sensing system maps the three-dimensional finger on to two-dimensional images. Once the location, pressure and direction of impression change, the mapping will change accordingly, which inevitably leads to nonlinear deformation of fingerprint images. Two fingerprint images may have translation, rotation or even nonlinear deformation between them. If the time span between two impressions is long, the images may also change due to cuts on finger or skin disease.
>
> In most systems, fingerprint is represented with a set of minutiae which is called template. The representation itself may be noisy due to presence of spurious minutiae and absence of genuine minutiae. Also, the properties of minutiae such as the location and orientation may be inaccurately estimated due to image degradation and imperfect preprocessing.
>
> Considering all these situations, a good fingerprint matching algorithm should meet the following two criteria:
>
> - Be robust to all kinds of possible deformation which are commonly observed in fingerprints and are hard to model.
> - Be robust to small perturbation on minutiae and minutiae properties.

Terje Kristensen (2010) reported about a computer application to fingerprint identification, intended to reduce the matching time. To carry out classification a Support Vector Machine (SVM) algorithm[175] was resorted to. “The given fingerprint database is decomposed into four different subclasses and a SVM algorithm is used to train the system to do correct classification. The classification rate has been estimated to about 87.0% of unseen fingerprints. The average matching time is decreased with a factor of about 3.5 compared to brute force search applied” (ibid.).

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[175] Support vector machines or vector support machines are the subject of Section 6.1.9.3. Moreover, we have said something about support vector machines at the end of Section 6.1.2.3.

A variety of approaches is encountered in the scholarly literature of automated fingerprint matching. For example, Chen and Kuo (1991) applied *tree matching*. Isenor and Zaky (1986) resorted to *graph matching* in order to solve the problem of *elastic deformation*. The matching is based on *euclidean distance* in Jain, Prabhakar, Hong, and Pankanti (2000) as well as Lee and Wang (1999), who represented the fingerprint with texture information extracted by *Gabor filters*.

> In image processing, a *Gabor filter*, named after Dennis Gabor, is a linear filter used for edge detection. Frequency and orientation representations of Gabor filters are similar to those of the human visual system, and they have been found to be particularly appropriate for texture representation and discrimination. In the spatial domain, a 2D Gabor filter is a Gaussian kernel function modulated by a sinusoidal plane wave. The Gabor filters are self-similar: all filters can be generated from one mother wavelet by dilation and rotation.[176]

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[176] From Wikipedia (http://en.wikipedia.org/wiki/Gabor_filter). The impulse response of a Gabor filter "is defined by a harmonic function multiplied by a Gaussian function. Because of the multiplication-convolution property (Convolution theorem), the Fourier transform of a Gabor filter's impulse response is the convolution of the Fourier transform of the harmonic function and the Fourier transform of the Gaussian function. The filter has a real and an imaginary component representing orthogonal directions. The two components may be formed into a complex number or used individually" (ibid.). With the convention that "λ represents the wavelength of the sinusoidal factor, θ represents the orientation of the normal to the parallel stripes of a Gabor function, ψ is the phase offset, σ is the sigma of the Gaussian envelope and γ is the spatial aspect ratio, and specifies the ellipticity of the support of the Gabor function" (ibid.), the Gabor filter is given by the following formulae. As a complex number:

$$g(x,y;\lambda,\theta,\psi,\sigma,\gamma) = \exp\left(-\frac{x'^2+\gamma^2 y'^2}{2\sigma^2}\right)\exp\left(i\left(2\pi\frac{x'}{\lambda}+\psi\right)\right)$$

The real component is:

$$g(x,y;\lambda,\theta,\psi,\sigma,\gamma) = \exp\left(-\frac{x'^2+\gamma^2 y'^2}{2\sigma^2}\right)\cos\left(2\pi\frac{x'}{\lambda}+\psi\right)$$

The imaginary component is:

$$g(x,y;\lambda,\theta,\psi,\sigma,\gamma) = \exp\left(-\frac{x'^2+\gamma^2 y'^2}{2\sigma^2}\right)\sin\left(2\pi\frac{x'}{\lambda}+\psi\right)$$

where

$$x' = x\cos\theta + y\sin\theta$$

and

$$y' = -x\sin\theta + y\cos\theta$$

Fasel, Bartlett, and Movellan (2002) compared Gabor filter methods for another problem in pattern-matching that is relevant for biometrics, namely, the *automatic detection of facial landmarks.*[177]

Jain, Ross, and Prabhakar (2001) combined texture features and minutiae features, while being specifically interested in solid-state fingerprint sensors: in fact, these only provide a small contact area "for the fingertip, and, therefore, sense only a limited portion of the fingerprint. Thus multiple impressions of the same fingerprint may have only a small region of overlap. Minutiae-based matching algorithms, which consider ridge activity only in the vicinity of minutiae points, are not likely to perform well on these images due to the insufficient number of corresponding points in the input and template images. We present a hybrid matching algorithm that uses both minutiae (point) information and texture (region) information for matching the fingerprints" (ibid., from the abstract).

Kovács-Vajna (2000) combined triangular matching and dynamic time warping to tolerate nonlinear deformation of fingerprints.[178] Tan and Bhanu (2006) applied genetic algorithms[179] to fingerprint matching. The genetic algorithm "tries to find the optimal transformation between two different fingerprints. In order to deal with low-quality fingerprint images, which introduce significant occlusion and clutter of minutiae features, we design a fitness function based on the local properties of each triplet of minutiae" (ibid., from the abstract). They found that their approach compares favourably with an approach based on mean-squared error estimation.

Ito, Nakajima, Kobayashi, Aoki, and Higuchi (2004) proposed an algorithm for fingerprint matching, which resorts to the *Phase-Only Correlation* function. It uses phase spectra of fingerprint images, and we are going to devote to it a special subsection (see Section 8.7.3.3). Kong, Zhang, and Kamel (2006) were concerned with *palmprint identification*, and for that purpose, they resorted to *feature-level fusion;* as they explained in the abstract:

> Multiple elliptical Gabor filters with different orientations are employed to extract the phase information on a palmprint image, which is then merged according to a fusion rule to produce a single feature called the Fusion Code. The similarity of two Fusion Codes is measured by their normalized hamming distance. A dynamic threshold is used for the final decisions. A database containing 9599 palmprint images from 488 different palms is used to validate the performance of the proposed method.

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[177] The article by Fasel et al. (2002) "presents a systematic analysis of Gabor filter banks for detection of facial landmarks (pupils and philtrum). Sensitivity is assessed using [. . .] a non-parametric estimate of sensitivity independent of bias commonly used in the psychophysical literature. We find that current Gabor filter bank systems are overly complex. Performance can be greatly improved by reducing the number of frequency and orientation components in these systems. With a single frequency band, we obtained performances significantly better than those achievable with current systems that use multiple frequency bands. [. . .]" (ibid., from the abstract).

[178] Cf. Kovács-Vajna, Rovatti, and Frazzoni (2000); Farina, Kovács-Vajna, and Leone (1999); and cf. Zs. Kovács-Vajna, "Method and Device for Identifying Fingerprints", U.S.A. Patent No. US6,236,741, filing date: 19.02.1997, issued: 22.05.2001; Zs. Kovács-Vajna, "Method and Device for Identifying Fingerprints Using an Analog Flash Memory", U.S.A. Patent No. US6,330,347, filing date: 28.07.1998, issued: 11.12.2001.

[179] Genetic algorithms are the subject of Section 6.1.16.1 in this book.

Ying Hao, Tieniu Tan, and Yunhong Wang, from the National Lab of Pattern Recognition at the Institute of Automation of the Chinese Academy of Sciences in Beijing, proposed an algorithm for fingerprint matching that is based on error propagation (Hao et al., 2002). They remarked that traditional methods treat fingerprint matching "as point pattern matching, which is essentially an intractable problem due to the various nonlinear deformations commonly observed in fingerprint images" (ibid., from the abstract). According to their own method (ibid.):

> Firstly, ridge information and Hough transformation are adopted to find several pairs of matching minutiae, the initial correspondences, which are used to estimate the common region of two fingerprints and the alignment parameters. Then a MatchedSet which includes the correspondence and its surrounding matched minutiae pairs is established. The subsequent matching process is guided by the concept of error propagation: the matching errors of each unmatched minutiae are estimated according to those of its most relevant neighbor minutiae. In order to prevent the process from being misguided by mismatched minutiae pairs, we adopt a flexible propagation scheme.

The matching algorithm they proposed comprises three steps (ibid., section 2). In the first step, each and every minutia "in the reference template is matched with each minutiae in the input template and all resulting potential correspondences are used to find several most reliable one, the initial correspondences, using Hough transformation" (ibid.). In the second step, "all minutiae surrounding the correspondence are matched and those minutiae pairs whose matching error are less than certain thresholds are added to the MatchedSet" (ibid.). In the third step, the algorithm adjusts "the matching error of each unmatched minutia according to the information provided by the MatchedSet recursively until the number of elements in MatchedSet stops increasing. A conformation process which checks the consistency of the matching errors of elements in the MatchedSet is made to label and remove the mismatched minutiae after each iteration" (ibid.). The MatchedSet is initialised after the two templates have been aligned and the common region estimated. Error threshold are chosen with care, so that only reliable pairs are added to the initial MatchedSet (ibid., section 2.3).

Arun Abraham Ross (2003) developed, under Anil Jain's supervision, a "hybrid fingerprint system that utilizes both minutiae points and ridge feature maps to represent and match fingerprint images" (from the abstract of the thesis). For image filtering, Ross used Gabor filters (Ross, 2003, section 2.3). Filtered images were underwent *tessellation* (i.e., mosaicking), for ridge feature mapping (ibid., section 2.4 and chapter 3). A deformable model was resrted to, in order to account for the elasticity of fingertips. Ross explained (ibid., in the abstract of the thesis):

> The hybrid matcher is shown to perform significantly better than a traditional minutiae-based matcher. The ridge feature maps extracted by this technique have also been used to align and register fingerprint image pairs via a correlation process, thereby obviating the need to rely on minutiae points for image registration. To address the problem of partial prints obtained from small-sized sensors, a fingerprint mosaicking scheme has been developed. The proposed technique constructs a composite fingerprint template from two partial fingerprint impressions by using the iterative control point (ICP) algorithm that determines the transformation parameters relating the two impressions. To mitigate the e_ect of non-linear distortions in fingerprint images on the matching process, an average deformation

> model has been proposed. The model is developed by comparing a fingerprint impression with several other impressions of the same finger and observing the common ridge points that occur in them. An index of deformation has been suggested in this context to aid in the selection of an 'optimal' fingerprint impression from a set of impressions. Finally, techniques to combine fingerprint information with the other biometric traits of a subject (viz., face and hand geometry) are presented.

The mosaicking is because of the following problem (Ross, 2003, pp. 55–56):

> [T]he average number of minutiae points extracted from a Digital Biometrics optical sensor (500 × 500 image at 500 dpi) is 45 compared to 25 minutiae obtained from a Veridicom sensor image (300 × 300 image at 500 dpi). This loss of information affects the matching performance of the veriffcation system – the relatively small overlap between the template and query impressions results in fewer corresponding points and therefore, results in higher false rejects and/or higher false accepts.

The remedy is as follows (Ross, 2003, pp. 56–57):

> To deal with this problem, we have developed a fingerprint mosaicking scheme that constructs a composite fingerprint template using evidence accumulated from multiple impressions. A composite template reduces storage, decreases matching time and alleviates the quandary of selecting the "optimal" fingerprint template from a given set of impressions. In the proposed algorithm, two impressions (templates) of a finger are initially aligned using the corresponding minutiae points. This alignment is used by a modified version of the well-known iterative closest point algorithm (ICP) to compute a transformation matrix that defines the spatial relationship between the two impressions. The resulting transformation matrix is used in two ways: (a) the two template images are stitched together to generate a composite image. Minutiae points are then detected in this composite image; (b) the minutia sets obtained from each of the individual impressions are integrated to create a composite minutia set.

8.7.3.2 Bistarelli, Santini, and Vaccarelli's Algorithm, Suiting the Hardware Constraints of a Smartcard Architecture

A team from Pisa and Pescara, Italy, comprising Stefano Bistarelli et al., proposed (2006) what they called "a light-weight fingerprint matching algorithm that can be executed inside the devices with a limited computational power" (ibid., p. 359). Their implementation is on a smartcard, and is support by the Java Card$^{\text{TM}}$ platform.[180] In devising their algorithm, they based in on "on the minutiae local structures (the "neighborhoods"), that are invariant with respect to global transformations like translation and rotation" (ibid.). Such local structure information

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[180] On which, see http://www.javacardforum.org/ See Chen (2000b) about the architecture of Java Card. "Performing a biometric verification inside a smartcard is notoriously difficult, since the processing capabilities of standard smartcard processors are limited for such a complex task. With *Match-on-Card* (MoC) technology, the fingerprint template is stored inside the card, unavailable to the external applications and the outside world. In addition, the matching decision is securely authenticated by the smartcard itself, in this way, the card has only to trust in itself for eventually unblocking stored sensitive information, such as digital certificates or private keys for digital signature. Our verification MoC algorithm was developed to work in this very strictly bounded environment" (Bistarelli et al., 2006, p. 359).

about the minutiae characteristics, i.e., ridge pattern micro-characteristics, spares the system the need to pre-align the processing fingerprint templates, "which would be a difficult task to implement inside a smartcard" (ibid., p. 360). The CPU (i.e., the central processing unit) of a smartcard pose limitations: "matching on smartcard environment is bounded by the hardware simplicity (CPU limitations first of all), and thus waiting for a complete minutiae match could lead to a waiting time which is too long for the user. In our algorithm we solve this problem by stopping the computation as soon as it is possible to assert, with satisfactory confidence, that the considered templates belong to the same fingerprint" (ibid., p. 367).

"The main characteristic of the algorithm is to have an asymmetric behavior, in respect to the execution time, between correct positive and negative matches" (ibid., p. 359). Correct positive martches are when the same fingerprint is recognised. Correct negative matches are when two different fingers left the prints. The asymmetric execution time "is because the match procedure stops immediately when few minutiae pairs result in a positive match. If this check does not succeed, for example if the two fingers are different, or if the two acquisitions of the same finger are very disturbed, the procedure is fully executed (lasting longer) and the match decision is taken only at its end" (ibid., p. 360). Bistarelli et al. explained (2006, p. 367):

> Our proposed matching algorithm computes how much the neighborhood of a minutia in the candidate template is similar to the neighborhood of each minutia in the reference template. At the end of this scan step, the two most similar minutiae (those whose "similarity value" is the lowest) are matched and then discarded from subsequent scan phases concerning other different minutiae of the candidate template. All these similarity measures are summed together during the process and, at the end, the algorithm can decide if the two templates match by applying a threshold on this global score.

The problem with smartcard hardware limitations is solved "by stopping the computation as soon as it is possible to assert, with satisfactory confidence, that the considered templates belong to the same fingerprint" (ibid.). In fact, the "algorithm stops as soon as it finds some minutiae pairs (i.e. a number between 2 and 5) matching with a very good average similarity value, or even immediately when only the last examined minutiae pair has a matching value lower than a very rigourous threshold. Otherwise, if these two conditions are not true, the algorithm explores all the minutiae pairings space" (ibid.).

We translate into text the flowchart in Bistarelli et al. (2006, p. 367, figure 6). The input of the algorithm is the candidate minutia *C* from a candidate template. *C* is taken to be matched. The reference template is also taken as input, and each of its minutiae is called *R* (where "the minutia information exactly corresponds to its neighborhood features: the terms 'minutia' and 'neighborhood' can be used as synonyms, since to match a minutia we need to match its neighborhood", ibid.).[181]

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[181] "The algorithm scans sequentially the minutiae of the reference template until a good match for the input minutia is found. Both candidate and reference minutiae lists are stored according to the increasing minutia reliability value: in this way we try to stop the procedure more quickly by scanning a reduced portion of the template minutiae lists. In fact, a minutia with a high reliability in a given template, when not cut away by partial overlapping, will probably have a high reliability

Step 1. Initially, minutia *R* in the reference template is taken, and *MinutiaDissimilarity* is initialised to zero.

Step 2. Take neighbour *I* or *R*.

Step 3. Take neighbour *J* of *C*.

Step 4. Is *J* matched? If yes, increment *J* by one and go to Step 3. If no, go to **Step 5.**

Step 5. Find *NeighDissimilarity* between *I* and *J*. This corresponds to these four substeps (Bistrarelli et al., 2006, p. 368), where (ibid., p. 366) *Ed* stands for "euclidean distance" (between the central minutia and its neighbour), *Dra* stands for "distance relative angle" (this is the angle between a segment which joins two minutiae points,[182] and the central minutia ridge direction), *Oda* stands for "orientation difference angle" (this is the difference angle between the central minutia orientation angle and the neighbour ridge orientation angle),[183] and *Rc* stands for "ridge count" between the central minutia and its neighbour (See Fig. 8.7.3.2.1):

1. To find the difference in absolute value between corresponding features:

$$\begin{aligned} EdDiff &= |Ed_1 - Ed_2|\,, \\ rcDiff &= |Rc_1 - Rc_2|\,, \\ draDiff &= |Dra_1 - Dra_2| \end{aligned}$$

and

$$odDiff = |Oda_1 - Oda_2|\,.$$

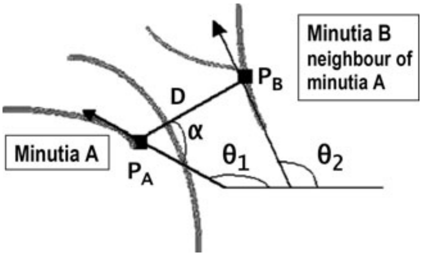

Fig. 8.7.3.2.1 Features of the minutiae. Redrawn from figure 5 of (Bistarelli et al., 2006)

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also in other templates obtained from the same finger. Thus, the stopping conditions can be met earlier than in a casual disposition of the minutiae in the list. Moreover, it is obviously better to prematurely stop the procedure with few but 'good' minutiae than with low quality ones. The minutia of the reference template matched in this way, is then marked as 'already matched' and is not considered in the successive iterations." (Bistarelli et al., 2006, p. 368).

[182] Such as the ending of one ridge, and a bifurcation point of two other ridges close by.

[183] The orientation difference angle is the difference between two angles, which are each an angle between a horizontal straight line, and the straight line that is tangent to the respective ridge (thus being the central minutia ridge direction) at the given minutia point (such as the ending of the ridge, or a bifurcation point). It is the minutia point being one of the two ends of the segment we mentioned concerning the distance relative angle.

2. To check that every feature difference value is below the corresponding acceptance threshold; if only one difference value exceeds the relative threshold, the two neighbors cannot correspond inthe two respective neighborhoods (*edDiff* must not be greater than the limit set by *edDiffThr, rcDiff* than *rcThr*, *edDiff* than *draThr* and *odDiff* than *odThr*). The set of the four feature difference thresholds can be globally defined as the features *bounding box*, which makes the algorithm tolerant to small non-linear distortions.
3. To multiply each feature difference for the corresponding eight value: thus,

$$
\begin{aligned}
&edWghtDiff = edDiff \times edWght,\\
&rcWghDiff = rcDiff \times rcWght,\\
&odWghtDiff = odDiff \times odWght
\end{aligned}
$$

and

$$draWghtDiff = draDiff \times draWght.$$

The different weight alues are necessary to attribute more importance to the features that match better such as, in our test experience, the euclidean distance. Before multiplying for the weight value, we have normalized the feature differences with respect to the bounding box thresholds (to have homogenous values).

4. To sum together all the four weighted differences to represent the global dissimilarity between the two neighbors:

$$
\begin{aligned}
NeightDissimilarity = {} & edWghtDiff\\
&+rcWghtDiff\\
&+draWghtDiff\\
&+odWghtDiff.
\end{aligned}
$$

Step 6. Is BBox, i.e. the bounding box, OK? If yes, go to **Step 7.** If no, discard *NeighDissimilarity*, then increment *J* by one and go to **Step 3.**

Step 7. Is *J=LastNeigh* verified? If yes, go to Step 8. If no, increment *J* by one and go to **Step 3.**

Step 8. Match *I* and *J* with best *NeighDissimilarity:*

> the algorithm finds for the first neighbor of the reference minutia, the most similar neighbor in the input minutia among those satisfying the bounding box checks; the most similar is the one for which the algorithm finds the lowest *NeighDissimilarity* value" (ibid., p. 368). "The chosen most similar neighbor in the reference minutia is then marked and not considered while matching other neighbors" (ibid.).

> "The obtained *NeighDissimilarity* value is then added to the global similarity score between the minutiae, *MinDissimilarity*" (ibid., p. 368)

$$MinutiaeDiss+ = NeighDissimilarity$$

Moreover:

Increment by one the value of *NM*, that is the number of neighbours matched.

Step 9. Is the *NM*=*N* verified? That is to say: has the required minimum number *N* of neighbours been matched?

Step 10. Match *R* and *C*. (*MatchCost* is a temporary average.)

$$\begin{aligned}&MatchCost = MinutiaeDiss/NM\\&MinutiaeMatched++\end{aligned}$$

That is to say:

> "if the neighborhoods of the two *R* and *C* minutiae have been matched [. . .], the *MinDissimilarity* score between *M* and *N* is finally divided by the number of matched neighbor pairs and then added to the global dissimilarity value between the candidate and reference templates: the *MatchCost*. The number of matched minutiae *MinutiaeMatched* is then incremented" (ibid., p. 368).

Step 11. Are stop conditions verified? If yes, return a successful match. If no, repeat this procedure with the next candidate minutia *C*.

Step 12. Is *I*=*LastNeigh* verified? That is to say:

> "at the end of the two neighborhoods scanning and if the procedure has found less than *N* matching neighbor pairs between the two minutiae ("Yes" case [to the test *I*=*LastNeigh*]), these two minutiae can not be considered as matching because their neighborhoods agree on too few points of evidence to be a reliable pair, even if their *MinDissimilarity* value is very low. Thus, the following minutia *R* in reference template has to be checked ("No" case in [the test of **Step 13**]), but if there are no more minutiae *R* to be examined, the entire procedure [. . .] is repeated for the next minutia *C* in the decreasing reliability order of the candidate template." (ibid., p. 368).

If yes, go to **Step 13.** If no, increment *J* by one and go to **Step 3.** That is to say: if no, the procedure is repeated for all the other neighbours in the minutia of the reference template, excluding the ones already marked.

Step 13. Is *R*=*LastMin* verified? If yes, repeat this procedure with the next candidate minutia C. If no, increment R by one and go to **Step 1.**

8.7.3.3 The Tohoku Algorithm for Fingerprint Matching Based on Band-Limited Phase-Only Correlation

Tatsuo Higuchi's team at Tohoku University and Tohoku Institute of Technology published (Ito et al., 2004) an algorithm for fingerprint matching, which resorts to the *phase-only correlation* (*POC*) function.[184] It uses phase spectra of fingerprint images. The algorithm was claimed to be "highly robust against fingerprint image degradation due to inadequate fingertip conditions" (ibid., p. 682). It was also claimed that it "exhibits efficient identification performance even for difficult fingerprint images that could not be identified by the conventional matching algorithms" (ibid.). They experimented with the technique they developed, and carried out comparisons to other techniques, by using a prototype (from Yamatake Corporation) of a fingerprint verification system with a pressure-sensitive sensor; the fingerprint database was with fingerprints from employees of the 700-strong staff of Yamatake Corporation.

Given two $N_1 \times N_2$ images (such as two fingerprints to be compared), $f(n_1, n_2)$ and $g(n_1, n_2)$, let their index ranges be:

$$n_1 = -M_1 \ldots M_1 \qquad \text{(where } M_1 > 0\text{)}$$

$$n_2 = -M_2 \ldots M_2 \qquad \text{(where } M_2 > 0\text{)}$$

Let us consider those two functions' respective two-dimensional *discrete Fourier transforms*, $F(k_1, k_2)$ and $G(k_1, k_2)$:

$$\begin{aligned} F(k_1, k_2) &= \sum_{n_1, n_2} f(n_1, n_2) W_{N_1}^{k_1 n_1} W_{N_2}^{k_2 n_2} \\ &= A_F(k_1, k_2) e^{j\theta_F(k_1, k_2)}, \end{aligned}$$

and

$$\begin{aligned} G(k_1, k_2) &= \sum_{n_1, n_2} g(n_1, n_2) W_{N_1}^{k_1 n_1} W_{N_2}^{k_2 n_2} \\ &= A_G(k_1, k_2) e^{j\theta_G(k_1, k_2)}, \end{aligned}$$

where the ranks of k_1 and k_2 are defined as:

$$k_1 = -M_1 \ldots M_1 \qquad \text{(where } M_1 > 0\text{)}$$

$$k_2 = -M_2 \ldots M_2 \qquad \text{(where } M_2 > 0\text{)}$$

and where

$$\begin{aligned} W_{N_1} &= e^{-j\frac{2\pi}{N_1}} \\ W_{N_2} &= e^{-j\frac{2\pi}{N_2}} \end{aligned}$$

---

[184] The concept was used earlier by e.g. Kuglin and Hines (1975), and Kenji, Aoki, Sasaki, Higuchi, and Kobayashi (2003).

Moreover, the operator

$$\sum_{n_1,n_2}$$

stands for

$$\sum_{n_1=-M_1}^{M_1} \sum_{n_2=-M_2}^{M_2}.$$

$A_F(k_1,k_2)$ and $A_G(k_1,k_2)$ are *amplitude components.* By contrast,

$$e^{j\theta_F(k_1,k_2)}$$

and

$$e^{j\theta_G(k_1,k_2)}$$

are *phase components.* The following formula gives the *cross spectrum*, *RFG*(k_1,k_2), of the two two-dimensional discrete Fourier transforms, $F(k_1,k_2)$ and $G(k_1,k_2)$:

$$\begin{aligned} R_{FG}(k_1,k_2) &= F(k_1,k_2)\overline{G(k_1,k_2)} \\ &= A_F(k_1,k_2)A_G(k_1,k_2)e^{j\theta(k_1,k_2)} \end{aligned}$$

In the latter formula, $\overline{G(k_1,k_2)}$ stands for the complex conjugate of $G(k_1,k_2)$. By definition, we denoted in that same formula the phase difference as follows:

$$\theta\ (k_1,k_2) = \theta_F\ (k_1,k_2) - \theta_\mathrm{G}\ (k_1,k_2)$$

Moreover, the operator

$$\sum_{k_1 k_2}$$

stand for

$$\sum_{k_1=-M_1}^{M_1} \sum_{k_2=-M_2}^{M_2}.$$

The ordinary $r_{fg}(n_1,n_2)$ is the correlation function

$$r_{fg}(n_1,n_2) = \frac{1}{N_1 N_2} \sum_{k_1,k_2} R_{FG}(n_1,n_2) W_{N_1}^{-k_1 n_1} W_{N_2}^{-k_2 n_2}$$

and is the two-dimensional *inverse discrete Fourier transform.* The *normalised cross-phase spectrum*, also called the *normalised cross-spectrum*, is given by definition by the following formula:

$$\begin{aligned} \hat{R}_{FG}(k_1,k_2) &= \frac{F(k_1,k_2)\overline{G(k_1,k_2)}}{|F(k_1,k_2)\overline{G(k_1,k_2)}|} \\ &= e^{j\theta(k_1,k_2)}. \end{aligned}$$

The phase-only correlation function is given by the formula:

$$\begin{aligned}\hat{r}_{ff}(n_1,n_2) &= \frac{1}{N_1N_2}\sum_{k_1,k_2} W_{N_1}^{-k_1n_1} W_{N_2}^{-k_2n_2} \\ &= \delta(n_1,n_2) \\ &= \begin{cases} 1 & \text{if } n_1 = n_2 = 0 \\ 0 & \text{otherwise.} \end{cases}\end{aligned}$$

As a particular case, if the two images are identical, if follows from the latter formula that their phase-only correlation function is the *Kronecker delta function*, $\delta(n_1, n_2)$. In the application at hand, it is two fingerprints that are compared. Ito et al. (2004) found it advantageous to resort for that purpose to the phase-only correlation function, as opposed to the ordinary correlation function, because of how accurate the phase-only correlation function is in image matching: it exhibits a much higher discrimination capability. In fact, when it is plotted as a surface in three dimension, the phase-only correlation function gives a distinct sharp peak when the two images being compared are similar to each other, whereas the peak drops significantly if the two images are not similar. Also with ordinary correlation, there is a peak if the two images are similar or identical, and the peak is not there is the two images are not similar, but with the phase-only correlation the difference is much sharper. "Other important properties of the POC function used for fingerpint matching is that it is not influenced by image shift and brightness change, and it is highly robust against noise" (Ito et al., 2004, p. 683).

In section 3 of Ito et al. (2004), the definition of phase-only correlation function was modified into a *band-limited POC function*, one that is dedicated to fingerprint matching tasks. Meaningless high-frequency components in the calculation of the cross-phase spectrum were eliminated from the new definition. Depending on the fingerprint image, if the ranges of the *inherent frequency band* are given by

$$k_1 = -K_1 \dots K_1 \qquad (\text{where } 0 \leq K_1 \leq M_1)$$

$$k_2 = -K_2 \dots K_2 \qquad (\text{where } 0 \leq K_2 \leq M_2)$$

– where the parameters K_1 and K_2 can be automatically detected by image processing – the effective size of the *frequency spectrum* is given by the formulae

$$L_1 = 2K_1 + 1$$

$$L_2 = 2K_2 + 1.$$

The *band-limited phase-only correlation function* was defined as follows:

$$\begin{aligned}\hat{r}_{fg}^{K_1K_2}(n_1,n_2) = \frac{1}{L_1L_2}\sum_{k_1=-K_1}^{K_1}\sum_{k_2=-K_2}^{K_2} \hat{R}_{FG}(k_1,k_2) \\ \times W_{L_1}^{-k_1n_1} W_{L_2}^{-k_2n_2},\end{aligned}$$

where

$$n_1 = -K_1 \ldots K_1$$

$$n_2 = -K_2 \ldots K_2.$$

Ito et al. remarked (2004, p. 684):

> Note that the maximum value of the correlation peak of the band-limited POC function is always normalized to 1 and is not depending on the frequency band size L_1 and L_2. The shape of the band-limited POC function for the two identical images is always the Kronecker's delta function $\delta(n_1,n_2)$. Also, note that the original POC function can be represented as
>
> $$\hat{r}_{fg}(n_1, n_2) = \hat{r}_{fg}^{M_1 M_2}(n_1, n_2).$$

As an alternative method for defining a frequency-selective POC function, had the Tohoku team adopted instead some adequate *low-pass filter* to the cross-phase spectrum, this would have resulted in the shape and height of the correlation peak depending on the type of the low-pass filter (Ito et al., 2004, pp. 684–685, citing Kenji et al., 2003), and what is more, this would have required fitting a model peak function to the correlation array, in order to evaluate the similarity between images, whereas with the band-limited POC function this is not required (Ito et al., 2004, p. 685).

Ito et al. (2004, p. 685, figure 5) give an example in which the original POC function would give a false negative, that is to say, when a registered fingerprint was matched to an impostor's fingerprint, the original POC limited gave a peak. By contrast, the band-limited POC function, for the same input pair of fingerprint, gave no peak. Therefore, the band-limited POC function is more reliable – it discriminates much better – than the original POC function, for the purposes of fingerprint matching.

The algorithm for fingerprint matching using the band-limited POC function takes an input $f(n_1, n_2)$, i.e. the registered fingerprint image, and $g(n_1, n_2)$, i.e. the fingerprint image to be verified. The output is a matching score between $f(n_1, n_2)$ and $g(n_1, n_2)$. The steps of the algorithm are as follows (Ito et al., 2004, p. 686):

Step 1. Store in advance a set of rotated images$f_\theta(n_1, n_2)$ of $f\,(n_1, n_2)$ over the angular range

$$-\theta_{\max} \le \theta \le \theta_{\max}.$$

with an angle spacing 1°.

Step 2. Calculate the POC function

$$\hat{r}_{f\theta g}^{M_1 M_2}(n_1, n_2)$$

between $f_\theta\,(n_1, n_2)$ and $g\,(n_1, n_2)$.

Step 3. Calculate the rotation angle

$$\Theta = \arg\max_{\theta}\{S_1^{M_1 M_2}[f_\theta, g]\}$$

by evaluating the similarity between $f_\theta\,(n_1, n_2)$ and $g\,(n_1, n_2)$, in order to select the rotation-normalised image $f_\Theta\,(n_1, n_2)$.

Step 4. Estimate image displacements (τ_1, τ_2) between $f_\Theta\,(n_1, n_2)$ and $g\,(n_1, n_2)$ from the peak location of

$$\hat{r}_{f_\Theta g}^{M_1 M_2}(n_1, n_2)$$

Step 5. Extend the size of $f_\Theta(n_1, n_2)$ and $g(n_1, n_2)$ by τ_1 and τ_2 pixels for n_1 and n_2 directions, to obtain $f'(n_1, n_2)$ and $g'(n_1, n_2)$.

Step 6. Extract the effective fingerprint regions $f''(n_1, n_2)$ and $g''(n_1, n_2)$ from $f'(n_1, n_2)$ and $g'(n_1, n_2)$.

Step 7. Detect the inherent frequency band (K_1, K_2) from the two-dimensional discrete Fourier transforms of $f''\,(n_1, n_2)$.

Step 8. Calculate the band-limited POC function

$$\hat{r}_{f'' g''}^{K_1 K_2}(n_1, n_2)$$

Step 9. Compute the *matching score*

$$S_P^{K_1 K_2}[f'', g'']$$

(by summing the highest peaks of the band-limited POC function: there may be several peaks, because elastic deformation causes them to be produced: see below), and then give the matching score as output, and terminate the execution of the algorithm.

In their experiments, Ito et al. explain (2004, p. 686), they used $\theta_{\max} = 20°$. They also explained (ibid.):

> In many cases, the band-limited POC function has multiple peaks, which is caused by elastic fingerprint deformation. The fingerprint image can expand or contract when a fingertip contacts with the sensor surface. Each portion of the fingerprint image will be shifted independently, which means several sub-domains in the image are moving individually. In this case, the POC function produces several peaks corresponding to the multiple translated sub-domains. The height of every correlation peak reflects the matched area of each sub-domain. Hence, we decide to employ the sum of these peaks as an evaluation criterion in order to make the proposed matching algorithm robust against elastic deformation.

8.8 Bloodstain Pattern Analysis, and the Use of Software for Determining the Angle of Impact of Blood Drops

8.8.1 The Basics

Do not confuse *DNA profiling* and *bloodstain pattern analysis* (*BPA*).[185] In order to carry out the latter (which some prefer to call *blood spatter analysis*), the analyst (or examiner) has to consider, for each blood pattern, factors including the number of blood patterns in the environment (e.g., on the floor and the walls inside a room), dispersion, shape, size, volume, orientation, and location. What is reconstructed (if reconstruction is successful, but not always this is feasible) is the events that occurred during the criminal incident. The analyst has to classify the bloodstain pattern, and then to associate that pattern back to a source event, that is conjectured to have unfolded at the crime scene. Concerning BPA, the Wikipedia entry[186] provides this usefully concise information:

> Bloodstain pattern analysis (BPA) is one of several specialties in the field of forensic science. The use of bloodstains as evidence is not new, however the application of modern science has brought it to a higher level. New technologies, especially advances in DNA analysis, are available for detectives and criminologists to use in solving crimes and apprehending offenders. The science of bloodstain pattern analysis applies scientific knowledge from other fields to solve practical problems. Bloodstain pattern analysis draws on biology, chemistry, maths, and physics among scientific disciplines. As long as an analyst follows a scientific process, this applied science can produce strong, solid evidence, making it an effective tool for investigators.

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[185] Bloodstain pattern analysis is the subject of a valuable short introduction by Louis Akin (2005), of books by Tom Bevel and Ross Gardner (2008), and by Stuart James and William Eckert (1999), whereas the book by James et al. (2005a) is more recent (whereas their James et al., 2005b is an overview article about the recognition of bloodstain patterns). MacDonell (1993) is still cited sometimes, in the 2000s, in such studies that also cite more recent literature. Cf. MacDonell and Bialousz (1979). Stuart James also edited a paper collection on the subject (James, 1999). With respect to the second edition of 2002, the third edition of Bevel and Gardner's book (2008) includes new chapters that "detail a true taxonomic classification system, with a supporting decision map to aid analysts in the field; a specific methodology based on scientific method; conducting experiments in support of bloodstain pattern analysis; anatomical issues associated to bloodstain pattern analysis; issues surrounding the examination of clothing in bloodstain pattern analysis; as well as a chapter detailing the various presumptive testing and enhancement techniques for bloodstains" (ibid., from the summary). The contents of the third edition include: Bloodstain pattern analysis: its function and a historical perspective – Bloodstain pattern terminology – Bloodstain classification – A methodology for bloodstain pattern analysis – The medium of blood – Anatomical considerations in bloodstain pattern analysis – Determining motion and directionality – Determining the point of convergence and the area of origin – Evaluating impact spatter bloodstains – Understanding and applying characteristic patterns of blood – Bloodstained clothing issues – Presumptive testing and enhancement of blood – Documenting bloodstains – An introduction to crime scene reconstruction and analysis [this is also the subject of a book by those same authors: Gardner and Bevel (2009)] – Presenting evidence – Experimentation in bloodstain pattern analysis – Dealing with the risk of bloodborne pathogens – Appendix A weight/measurement conversion table – Appendix B: Trigonometric functions and their application in bloodstain pattern analysis.

[186] http://en.wikipedia.org/wiki/Bloodstain_pattern_analysis.

Bloodstain pattern categories include: *passive bloodstains, projected bloodstains*, and *transfer/contact bloodstains.* The same Wikipedia entry explains: “The definitions used below are from the suggested IABPA terminology list”. In particular: “Passive bloodstains are those stains created by the force of gravity”. *Passive drops* are “Bloodstain drop(s) created or formed by the force of gravity acting alone”. *Drip pattern* denotes “A bloodstain pattern which results from blood dripping into blood”. *Flow pattern* is “A change in the shape and direction of a bloodstain due to the influence of gravity or movement of the object”. *Pool pattern* is “A bloodstain pattern formed when a source of blood is stationary for a period of time”.

“A projected stain occurs when some form of energy has been transferred to a blood source”. The respective terminology includes:

> *Low Velocity Impact Spatter* (*LVIS*) – A bloodstain pattern that is caused by a low velocity impact/force to a blood source.
>
> *Medium Velocity Impact* Spatter (*MVIS*) – A bloodstain pattern caused by a medium velocity impact/force to a blood source. A beating typically causes this type of spatter.
>
> *High Velocity Impact Spatter* (*HVIS*) – A bloodstain pattern caused by a high velocity impact/force to a blood source such as that produced by gunshot or high-speed machinery.
>
> *Cast-Off Pattern* – A bloodstain pattern created when blood is released or thrown from a blood-bearing object in motion.
>
> *Arterial Spurting* (or *Gushing*) *Pattern* – Bloodstain pattern(s) resulting from blood exiting the body under pressure from a breached artery.
>
> *Back Spatter* – Blood directed back towards the source of energy or force that caused the spatter.
>
> *Expiratory Blood* – Blood that is blown out of the nose, mouth, or a wound as a result of air pressure and/or air flow which is the propelling force.

“A transfer or contact stain is produced when an object with blood comes in contact with an object or surface that does not have blood. It may be possible to discern the object that left the blood impression.” The respective terminology includes: *wipe pattern*, this being “A bloodstain pattern created when an object moves through an existing stain, removing and/or altering its appearance”; and *swipe pattern*, this being “The transfer of blood from a moving source onto an unstained surface. Direction of travel may be determined by the feathered edge.”

> As indicated above, there are other terms currently used in BPA and different ways of classifying bloodstain patterns. For example there is a debate over the misnomer of the LVIS, MVIS, and HVIS as it relates to the physical term ‘velocity’. A sub-committee of the SWGSTAIN [i.e., the Scientific Working Group on Bloodstain Pattern Analysis] has been tasked with addressing the terminology issues and develop a taxonomy for bloodstain patterns.

When it comes to *velocity impact stains*, the same entry explains:

> Contrary to what the name states, the terms low-, medium-, and high-velocity impact spatter do not describe the velocity of the blood droplets as they fly through the air. The variation in the ‘velocity’ is meant to describe the amount of energy transferred to a blood source in order to create the stains. Velocity is a speed (m/s) with a direction. Often the terms force and energy are quoted in conjunction with the unit ft/s or m/s which is an incorrect. Force is related to velocity and mass (N or 1 kg ·m·s−2). Energy (work) is related to the force exerted on an object (J or N·m or kg·m2·s−2).

Physical considerations apply: “Once blood has left the body it behaves as a fluid and all physical laws apply”. In particular, *gravity* “is acting on blood (without the body’s influence) as soon as it exits the body. Given the right circumstances blood can act according to ballistic theory.” *Viscosity* “is the amount of internal friction in the fluid. It describes the resistance of a liquid to flow”. *Surface tension* “is the force that gives the ability to blood to maintain its shape”.

Blood spatter flight characteristics do matter: “Experiments with blood have shown that a drop of blood tends to form into a sphere in flight rather than the artistic teardrop shape. This is what one would expect of a fluid in freefall. The formation of the sphere is a result of surface tension that binds the molecules together. This spherical shape of blood in flight is important for the calculation of the angle of impact (incidence) of blood spatter when it hits a surface. That angle will be used to determine the point from which the blood originated which is called the Point of Origin or more appropriately the Area of Origin.[187] A single spatter of blood is not enough to determine the Area of Origin at a crime scene. The determination of the angles of impact and placement of the Area of Origin should be based on the consideration of a number of stains and preferably stains from opposite sides of the pattern to create the means to triangulate.”

It is important to determine *angles of impact.*

> As mentioned earlier a blood droplet in freefall has the shape of a sphere. Should the droplet strike a surface and a well-formed stain is produced, an analyst can determine the angle at which this droplet struck the surface. This is based on the relationship between the length of the major axis, minor axis, and the angle of impact. A well-formed stain is in the shape of an ellipse [See Fig. 8.8.1.1]. Dr. Victor Balthazard, and later Dr. Herbert Leon MacDonell,[188] realized the relationship of the length-width ratio of the ellipse was the function of the sine of the impact angle. Accurately measuring the stain will easily result in the calculation the impact angle. [. . .] Because of the three-dimensional aspect of trajectories there are three angles of impact, α, β, and γ. The easiest angle to calculate is *gamma* (γ). Gamma is simply the angle of the bloodstain path measured from the true vertical (plumb)[189] of the surface [. . .] The next angle that can be quite easily calculated is *alpha* (α). Alpha is the impact angle of the bloodstain path moving out from the surface (see [Fig. 8.8.1.2] with alpha at the top by the stain). The third angle to be calculated is *beta* (β). Beta is the angle of the bloodstain path pivoting about the vertical (z) axis [. . .] All three angles are related through the equation quoted below.

Let L be the length of the ellipse, that is to say, its major axis. Let W be the width of the ellipse, that is its minor axis. Let α be the angle of impact. Those variable are related by the equation

$$\sin\alpha = W/L$$

---

[187] The *point of origin* is also called the *point of hemorrhage*. Louis Akin “prefers to use the term *point of hemorrhage* to distinguish the area from which the blood was disgorged from other *points of origin*, the latter phrase being a widely used term in blood spatter, ballistics, crime, and accident scene investigation and reconstruction. Although most experts use the word *point*, the word *area* is a more conservative one to use” (Akin, 2005, p. 7).

[188] The author of MacDonell (1993).

[189] The plumb line is parallel to the z axis, in a Euclidean space in three dimensions.

Fig. 8.8.1.1 Upward moving bloodstain showing proper ellipse placement[190]

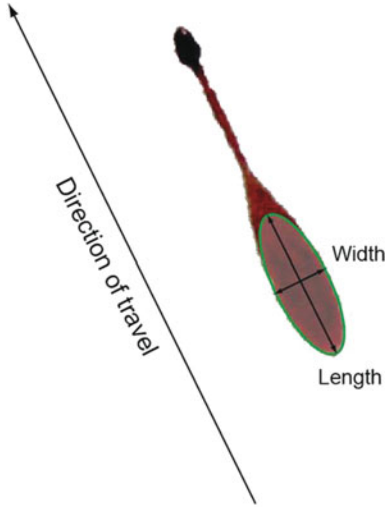
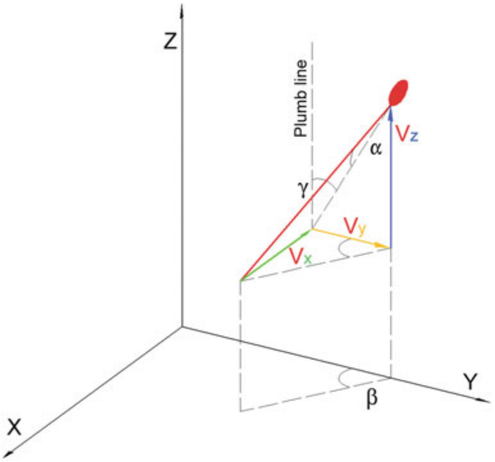


Fig. 8.8.1.2 Angles of impact[191]



Therefore,

$$\alpha = \arcsin{(W/L)}$$

The three angles α, β, and γ are related by this equation:

$$\tan\beta = (\tan\alpha)\,/\,(\tan\gamma)$$

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[190] In the public domain; http://en.wikipedia.org/wiki/File:BPA_ellipse_example.png Image made by Kevin Maloney.

[191] In the public domain; http://en.wikipedia.org/wiki/File:BPA_AOI.png Image made by Kevin Maloney.http://upload.wikimedia.org/wikipedia/en/9/91/BPA_AOI.png is the full resolution version.

Measurements need be carried out with diligence and accuracy by the bloostain pattern examiner (analyst). “In the past analysts have used a variety of instruments. Methods currently used include:

- Viewing loop with an embedded scale in 0.2 mm increments or better that is placed over the stain. The analyst then uses a scientific calculator or spreadsheet to complete the angle calculations.
- Bloodstain Pattern Analysis (BPA) software that superimposes an ellipse over a scaled close-up image of an individual bloodstain. The programs then automatically calculates the angles of impact” (from the Wikipedia entry).

8.8.2 Software

There exists *bloodstain analysis software* for calculating the angles of impact, in bloodstain pattern analysis:

> Accurately measuring the stain and calculating the angle of impact requires due diligence of the analyst. In the past analysts have used a variety of instruments. Methods currently used include:
>
> > Viewing loop with an embedded scale in 0.2 mm increments or better that is placed over the stain. The analyst then uses a scientific calculator or spreadsheet to complete the angle calculations.
> >
> > Bloodstain Pattern Analysis (BPA) software that superimposes an ellipse over a scaled close-up image of an individual bloodstain. The programs then automatically calculates the angles of impact.

Using software produces a very accurate result that is measurable and reproducible. One software product for bloodstain pattern analysis is the *Crime Scene Command* program,[192] produced by On Scene Forensics in Austin, Texas, and which is claimed to be easy to use. The originator of Crime Scene Command is Louis L. Akin. There is an *On Scene Blood Spatter Calculator*, for use on homicide scenes. A testimonial by a forensic instructor, Thomas Hanratty, from Milwaukee, Wisconsin, found at the producer’s website, for *Crime Scene Command*, claims: “An officer, either a first responder[193] or a detective, merely plugs in a few measurements and the dreaded math calculations are performed for him/her. Best of all, a record is generated of a

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[192] See http://www.onsceneforensics.com/Crime_Scene_Command.htm

[193] Concerning *first responding officers*, also called *first responders* (which strictly speaking is a broader category, as sometimes the earliest responders are members of the public), Miller (2003) writes: “The first responders at a crime scene are usually police officers, fire department personnel or emergency medical personnel. They are the only people who view the crime scene in its original condition. Their actions at the crime scene provide the basis for the successful or unsuccessful resolution of the investigation. They must perform their duties and remember that they begin the process that links victims to suspects to crime scenes and must never destroy the links” (ibid., p. 118).

wealth of materials, if the entire program is used; including witnesses, suspects, an evidence log, photo log and bloodstains. And it's all in one complete report."

The key benefits claimed by On Scene Forensics for *Crime Scene Command* are as follows.[194] The software

- Makes a record of the case information as a number one report.
- Serves as a scene personnel log showing the name, agency, badge number, time in and out, of each person who enters the scene.
- Makes a detailed record of the circumstances surrounding the death of the victim:
  - Weather conditions
  - Environmental conditions
  - Position of victim
- Performs all bloodstain computations instantly including:
  - Angle of impact in degrees
  - Point of origin
  - Transfer stain description and location
- Performs all bullet trajectory computations from a bullet hole in a solid surface including:
  - Gives caliber of bullet
  - Angles of impact in degrees
  - Trajectory path
- Suspect page records all information on the suspect.
- Records evidence found at the scene in a printable log.
- Records photographs taken at the scene in a printable log.
- Records witness statements, res gestae statements, and officers' notes on scene.
- Easy to read permanent record can be stored as a word document on hard drive or disk, and printed, faxed, or emailed.
- Can be used as notes when testifying.

8.8.3 Point or Area of Origin

The description at the end of the previous subsection refers, among the other things, to to *point-of-origin calculations.* Apart from the angles of impact, another thing that needs to be calculated is the *area of origin* indeed. The IABPA definition is: "Point (Area) of Origin – The common point (area) in three-dimensional space to which the trajectories of several blood drops can be retraced." The *area of origin* is shown in Fig. 8.8.3.1. "The area of origin can give a general location [(Bevel & Gardner, 2008, p. 195)] or relative posture [(James et al., 2005a, p. 219)] of a bleeding victim

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[194] Also see Sections 8.8.4 and 8.8.5.

who has received a blow. In the literature, there are several limits used for area-of-origin calculations. These include a tennis ball, a grapefruit, a soccer ball, and a basketball" (Maloney, Killeen, & Maloney, 2009, p. 518).

The Wikipedia entry for "Bloodstain Pattern Analysis" explains:

> The *area of origin* is the area in three-dimensional space where the blood source was located at the time of the bloodletting incident. The area of origin includes the area of convergence with a third dimension in the z direction. Since the z-axis is perpendicular to the floor, the area of origin has three dimensions and is a volume.
>
> The term *point of origin* has also been accepted to mean the same thing. However it has been argued, there are problems associated to this term. First, a blood source is not a point source. To produce a point source the mechanism would have to be fixed in three-dimensional space and have an aperture where only a single blood droplet is released at a time, with enough energy to create a pattern. This does not seem likely. Second, bodies are dynamic. Aside from the victim physically moving, skin is elastic and bones break.

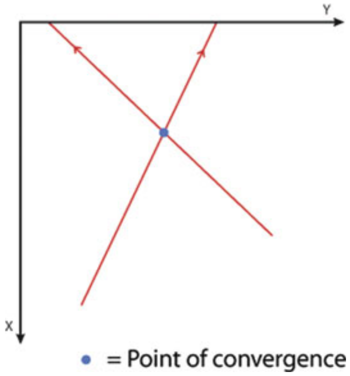

Fig. 8.8.3.1 Area of origin.[195] The *blue area* represents a volume in three-dimensional space. The area of origin is the area in that space to which the trajectories of several blood drops can be traced

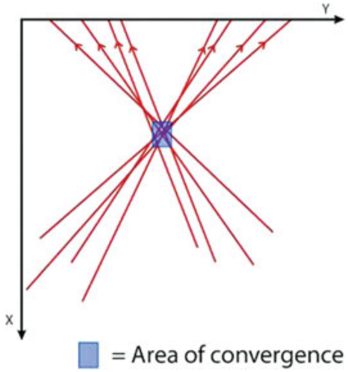

Fig. 8.8.3.2 Point of convergence[196]

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[195] In the public domain; http://en.wikipedia.org/wiki/File:BPA_Origin.gif (animation). Image made by Kevin Maloney in 2005.

[196] In the public domain; http://en.wikipedia.org/wiki/File:BPA_POC.png Image made by Kevin Maloney.

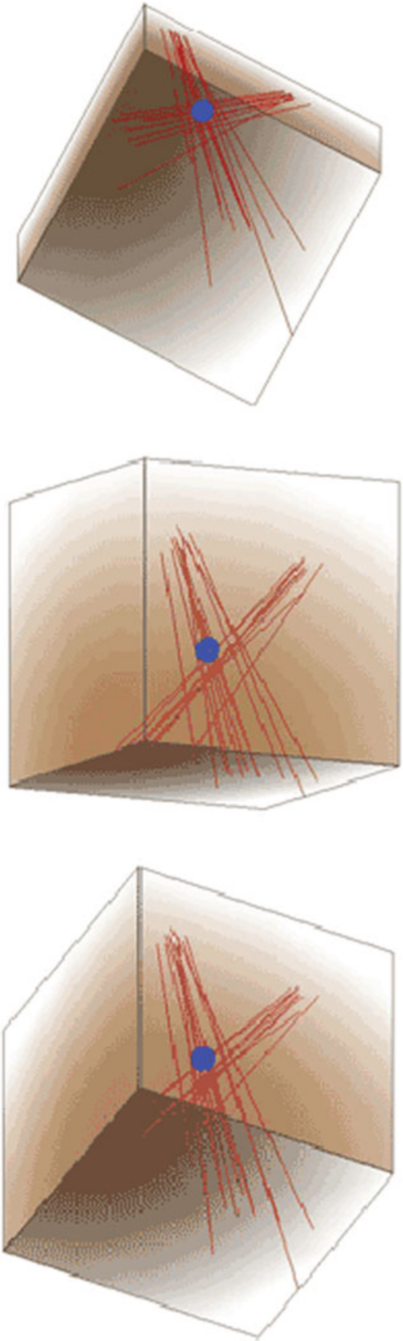

Fig. 8.8.3.3 Area of convergence[197]

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[197] In the public domain; http://en.wikipedia.org/wiki/File:BPA_AOC.png Image made by Kevin Maloney.

> Once a force is applied to the body there will be an equal and opposite reaction to the force applied by the aggressor (Newton's third law of motion). Part of the force will move the blood source, even a millimetre, and change the origin while it is still producing blood. So the source becomes contained in a three-dimensional volume, or region. As with the area of convergence, the area of origin is easily calculated by using BPA software. There are other longer, mathematical methods of determining the area or origin, one of which is the tangential method.

Other important concepts are the *point of convergence* and the *area of conve1rgence.* "The point of convergence is the intersection of two bloodstain paths, where the stains come from opposite sides of the impact pattern" (from the Wikipedia entry). See Fig. 8.8.3.2. "The area of convergence is the box formed by the intersection of several stains from opposite sides of the impact pattern" (ibid.). See Fig. 8.8.3.3. "To determine the point/area of convergence an analyst has to determine the path the blood droplets travelled. The tangential flight path of individual droplets can be determined by using the angle of impact and the offset angle of the resulting bloodstain. 'Stringing' stains is a method of visualising this. For the purpose of the point of convergence, only the top view of the flight paths is required. Note that this is a two-dimensional (2D) and not a three-dimensional (3D) intersection" (ibid.). "In the past, some analysts have drawn lines along the major axes of the stains and brought them to an area of convergence on the wall. Instead of using a top-down view, they used a front view. This provides a false point/area of convergence" (ibid.).

8.8.4 More Concerning Software

On Scene Forensics provides for *Crime Scene Command*[198] this description of the program at a glance:

> This user friendly program installs in seconds and is easy to use without having to attend special classes. The program does all the trigonometric calculations necessary to determine the angle of impact and point of origin for blood spatter, the angle of impact and trajectory for bullet holes, and to estimate the time of death at a homicide scene. There is a crime scene log to enter the name, identification, agency, and purpose for everyone who enters the crime scene. There are separate pages for witnesses, victims, the scene environment, as well as death information for the pathologist. The program will estimate the time of death within four hours for the 18 hours after death.
>
> Photographs of the crime scene, the individual bloodstains, and bullet holes, and items of evidence can be stored with each stain or pattern. The entire program and all the reports it generates can be printed with a single click of a mouse.
>
> The software makes a permanent record of the crime scene that can be stored to hard drive printed as a Word document, faxed, or emailed. The printed reports can be used as bench notes and used on the stand to refresh memory and they satisfy the requirement for a scientific record of crime scene reconstruction.

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[198] See Sections 8.8.2 and 8.8.5.

> The Crime Scene Command program also includes screens for recording witness statements and making notes at the scene.
>
> Crime Scene Command is meant to be used at the crime scene and is best installed on a laptop computer so that it can be taken to the scene. It is designed to be user friendly to patrol officers and not just to specially trained technicians. The program can be used at any crime scene, not only homicide scenes.

We have referred (in Section 8.8.2) to software products of On Scene Forensics. Another software product for bloodstain pattern analysis is *HemoSpat*, from a Canadian firm, FORident Software Inc.[199] Its owener and lead developer is Andy Maloney. He developed the software, whereas his brother Kevin Maloney is the firm's expert in bloodstain pattern analysis (but neither a co-owner, nor an employee; he is affiliated with the Forensic Identification Section of the Ottawa Police Service). At its website for *HemoSpat*, the firm claims that it is more efficient than the competing *BackTrack* software, because the latter "forces the analyst to follow specific steps which kaes it difficult and time consuming to correct mistakes or allow others to review your work. BackTrack does not allow you to use angled surfaces and has problems with current digital image sizes". By contrast, "*HemoSpat* maintans the analytical data from each project making peer review and verification possible." Like *Crime Scene Command*, that tool, too, is claimed to be easy to use. Version 1.3 of *HemoSpat* was released in September 2009, and version 1.4.1. was released in January 2011. The firm's website also states: "The March/April 2011 issue of the *Journal of Forensic Identification* contains an article titled 'One-Sided Impact Spatter and Area-of-Origin Calculations'. This is the result of a combined effort of FORident Software, L'Institut de Recherche Criminelle de la Gendarmerie Nationale in Paris, France, and the Forensic Identification Section of the Ottawa Police Service in Ottawa, Canada." To say it with the abstract of Maloney, Nicloux, Maloney, and Heron (2011):

> It is common practice when calculating area of origin from impact spatter to use stains from both "sides" of the pattern – stains to the left and to the right of the blood source. Impact spatter at crime scenes, however, often provides the analyst with bloodstain patterns that are not as pristine as those created in a controlled environment. One situation that may arise is impact spatter consisting of stains from only one side of the pattern because of the removal of an object after the impact, such as a door or a person, or because the stains from one side are not on a planar surface. This study looks at a method of calculating the area of origin using stains from only one side of the pattern and shows that these partial patterns may still provide usable calculations to determine the area of origin.

Maloney et al. (2011, p. 132) explain how the practical need arises:

> Bloodstain analysts must work with the data they are presented with at the crime scene, regardless of quantity or quality. Sometimes this means eliminating partial impact patterns because too few stains may be found for a regular analysis. This study demonstrates that at least some incomplete impact patterns – "one-sided" patterns – need not be eliminated from the analysis of the scene because they can still provide an acceptable calculation of the area of origin.

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[199] See http://hemospat.com/index.php FORident Software Canada, Inc., 132-207 Bank St., Ottawa, Ontario, Canada K2P 2N2. Their email address is inf@hemospat.com

Some articles published by the Maloney brothers in the *Journal of Forensic Identification* can be downloaded from Andy Maloney firm's website. Maloney et al. (2011) is one of these. Another paper is 'The Use of Hemospat to Include Bloodstains Located on Nonorthogonal Surfaces in Area-of-Origin Calculations' (Maloney et al., 2009), abstracted as follows:

> Determining the origin of impact patterns at crime scenes can be a challenge when there is limited or less-than-ideal information. This is made even more difficult if the analyst cannot incorporate data from nonorthogonal and orthogonal surfaces in the same analysis. Using HemoSpat software for impact pattern analysis allows analysts to remove several limitations, maximize the use of this information, and produce precise and reliable results.

By contrast (Maloney et al., 2009, p. 514):

> Historically, bloodstain pattern analysts using forensic software for area-of-origin calculations had to exclude nonorthogonal (angled) surfaces from their calculations. Analysts could not incorporate orthogonal and nonorthogonal surfaces at the same time in their analyses [(Eckert & James, 1993, pp. 152–154; Carter, 2001b)].

Maloney et al. pointed out (2009, p. 523):

> The task of analyzing bloodstains on nonorthogonal surfaces is made easier by using the HemoSpat software. This allows the analyst to remove objects from the scene, analyse them in a controlled and safe environment, and incorporate the data in an area-of-origin calculation.

From the same website, one can also download a white paper (FORident Software, 2009) about the validation of HemoSpat. The goal was "to validate the accuracy of the HemoSpat bloodstain analysis software against an accepted standard and to examine the reproducibility of the results." This was done in collaboration with the Royal Canadian Mounted Police (RCMP). A comparison was made with the *BackTrack* computer program for bloodstain pattern analysis. Kevin Maloney had earlier participated in the validation of BackTrack (Carter et al., 2005). Maloney, Carter, Jory, and Yamashita (2005) is concerned with the representation in three dimensions of bloodstain pattern analysis. Both BackTrack and HemoSpat use the *tangent method* outlined by Carter (2001a). Carter (2001b) is an electronic book on the computer-assisted directional analysis of bloodstain patterns, and is provided with the BackTrack Suite. "The users have more direct control over the ellipse in HemoSpat using the mouse, whereas BackTrack requires the user to enter numbers to adjust the ellipse" (FORident Software, 2009, p. 3).

8.8.5 Effects of Velocity on Blood Drops and Blood Spatter

Louis L. Akin

8.8.5.1 Introduction

The software Crime Scene Command (CSC)[200] by On Scene Forensics was created in response to complaints by law enforcement officials that blood pattern software

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[200] See Sections 8.8.2, 8.8.4, and 8.8.5.

programs were difficult to learn and required classroom instruction. CSC is intended to be user friendly enough for a person with only a basic knowledge of blood patterns to use. It automatically calculates the angle of impact and area of origin and averages the area of origin for several impact stains. The program has additional features such as a scene personnel log, evidence collection log, and separate tabs for information on victims, suspects and witnesses including statements. It also calculates bullet trajectories. Its only drawback is that it does not produce a 3-dimensional diagram like the others do, but that complexity is what requires classroom instruction or a nerd to operate the programs and was left out to produce a fast, reliable, easy to learn and user friendly program.

Through a variety of schools, classes, and seminars, homicide detectives and crime scene technicians or criminalists are garnering a level of expertise that has not previously existed in law enforcement. New technologies, sciences, and applied sciences are available for detectives and criminalists to use in solving crimes and apprehending offenders. Blood pattern analysis may require special schooling and expertise. However, blood pattern evidence collection is an example of an applied science that a homicide detective or first responding police officer can learn to use at a scene without having to become an expert in the field.

Blood spatter interpretation or analysis itself may be compared to tracking. It may take considerable training to reach the level of a tracker who can say that a footprint was made two days before by a pigeon-towed 180 male who has bunions. It does not require that level of training or expertise to be able to look at a footprint and determine which way the person was going. Just pick out the heel and toe.

Likewise, although an expert may be able to see things in the blood pattern that the first responding officer at a crime scene doesn't, a responder can preserve the evidence and take the measurements of the stains in a pattern just as he does at an accident scene. He or she could even learn to determine generally where a victim was positioned by looking at the blood spatter the same way he could tell which way a footprint is going.

A basic understanding of blood spatter analysis will also allow the first responding officer to assist in correctly collecting and preserving blood stain data at the scene. Fortunately, the principles and procedures to learn are not complicated, and while it is easier to use software to make the calculations, the basic principles can be learned from a source as brief as this article and applied by using a hand held calculator. Some critical determinations, such as establishing the point of convergence that shows where the victim was standing can be done without use of a calculator at all.

This basic understanding is important, because the interpretation of blood spatter patterns and other evidence at crime scenes may reveal critically important information such as:

- The positions of the victim, assailant, and objects at the scene during the attack.
- The type of weapon that was used to cause the spatter.
- The number of blows, shots, stabs, etc. that occurred.

- The movement and direction of victim and assailant, after bloodshed began.
- It may support or contradict statements given by witnesses (James & Eckert, 1999, pp. 10–11).

The investigator may use blood spatter interpretation to determine:

- What events occurred.
- When and in what sequence they occurred.
- Who was, or was not, there.
- What did *not* occur.

The lists of precisely what information can be learned by the interpretation of blood stain patterns are similar for Bevel and Gardner (2002), James and Eckert (1999), Hueske (1999), Akin (2004), and Sutton (1998).

8.8.5.2 Photography, and Traditional Determination of Velocities of Blood Spatter

Without a doubt, the most important thing to at a crime scene in regard to blood spatter analysis is to photograph the scene and the blood spatter. The photographs should all be made at a 90 degree angle from the surface on which the blood stains are found and a scale should always be in the photograph so the viewer can tell the size of the drops in the pictures.

The velocity of the blood spatter when it strikes a surface is a reasonably reliable indicator of the speed of the force that set the blood in motion in the first place. The velocity is that of the force causing the blood to move rather than of the speed of the blood itself and it is measured in feet per second (fps); high velocity blood, for instance, *may* be caused by a bullet moving at 900 fps, medium velocity blood spatter may be caused by a spurting artery or by a blunt instrument striking the already bloody head or limb of a victim.

Low velocity stains are produced by normal gravity and the stains are generally 3 mm or larger. It is usually the result of blood dripping from a person who is still, walking, or running, or from a bloody weapon. Dripping blood falls at a 90° angle and forms a 360° circumference stain when it hits a flat surface, depending, of course, on the texture of the surface. See Fig. 8.8.5.2.1 for an example of low velocity spatter.

Medium blood spatter is produced by an external force of greater than 5 fps and less than 25 fps. The stains generally measure 1–3 mm in size. Blood stains this size are often caused by blunt or sharp force trauma, that is, knives, hatchets, clubs, fists, and arterial spurts. They might also result from blood being cast off a weapon or other bloody object.

Most medium velocity blood found at crime scenes will be created by blood flying from a body as a result of blunt or sharp force or the body colliding with blunt or sharp surfaces. It may be the result of a punch, a stab, or a series of blows. A void space may be created by anything that blocks the blood from falling on the

Fig. 8.8.5.2.1 An example of low velocity blood spatter

surface where it would have normally landed. The object creating the void may be either the victim or the attacker's body or a piece of furniture that was moved. See Fig. 8.8.5.2.2 for an example of medium velocity spatter.

High velocity blood spatter is produced by an external force greater than 100 fps and the stains tend to be less than 1 mm. The pattern is sometimes referred to as a mist. High velocity patterns are usually created by gunshots or explosives, but may also be caused by industrial machinery or even expired air, coughing, or sneezing. In any case, the spatter tends to be tiny drops propelled into the air by an explosive force. High velocity droplets travel the least far because of the resistance of the air against their small mass. See Fig. 8.8.5.2.3 as an example of high velocity spatter.

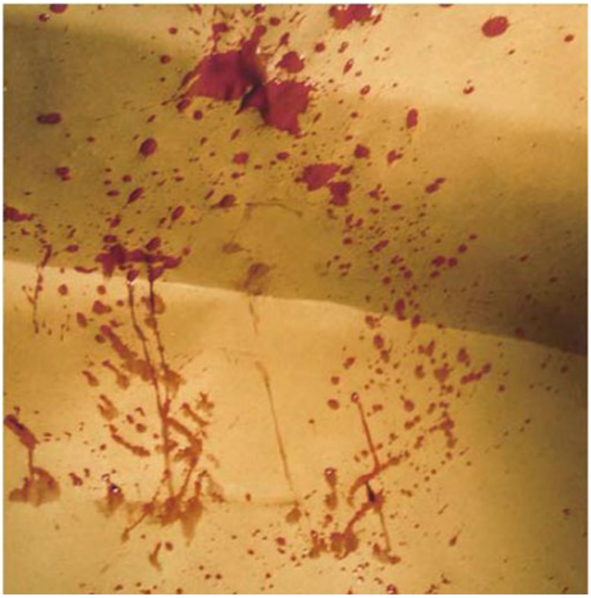

Fig. 8.8.5.2.2 An example of medium velocity blood spatter

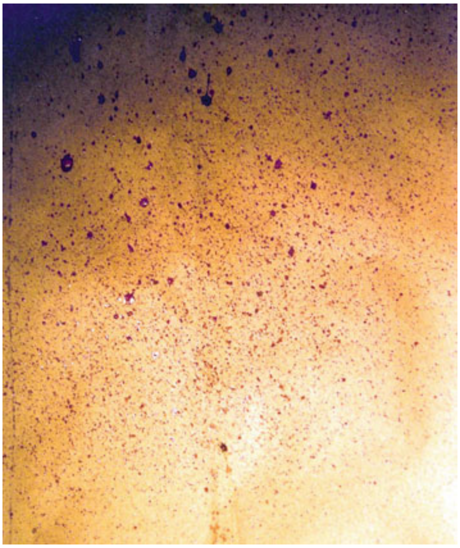

Fig. 8.8.5.2.3 An example of high velocity blood spatter

8.8.5.3 Blood Spatter Flight Characteristics

Experiments with blood have shown that a drop of blood tends to form into a sphere rather than a teardrop shape when in flight. The formation of the sphere is a result of surface tension that binds the molecules together.

Fresh blood is slightly more viscous than water, and like water it tends to hold the spherical shape in flight rather than a tear drop shape as seen in cartoons.

This spherical shape of a liquid in flight is important for the calculation of the angle of impact (incidence) of blood spatter when it hits a surface. That angle will

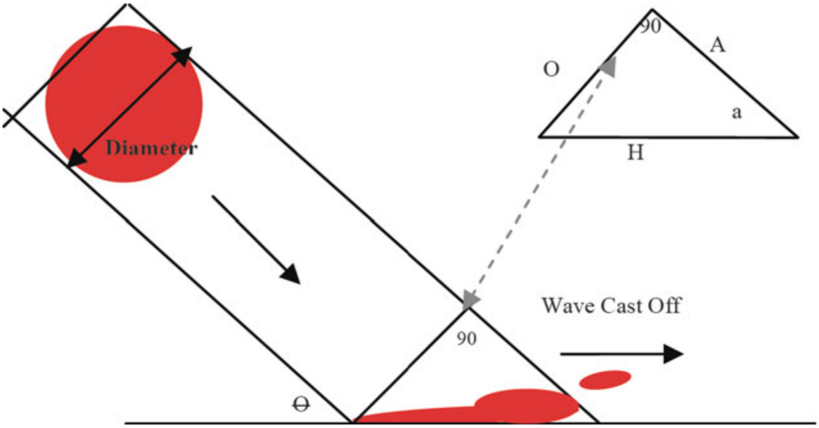

Fig. 8.8.5.3.1 Side view of blood drop in air, and then striking a flat surface

be used to determine the point from which the blood originated which is called the Point of Origin or as this author prefers, the Point of Origin (PO).

Generally, a single spatter of blood is not enough to determine the Point of Origin at a crime scene. The determination of the Angle of Impact and placement of the PO should be based on the consideration of a number of spatters and preferably spatters that will provide an arc of reference points in order to create a triangulation effect.

The process for determining the Angle of Impact is not complicated. When a drop of blood strikes a flat surface the diameter of the drop in flight will be equivalent to the width of the spatter on the surface as seen in Fig. 8.8.5.3.1. The length of the spatter will be longer, depending on the angle at which the drop hit. The following diagram will help the reader to understand this concept.

8.8.5.4 Point of Convergence (POC)

For purposes of instruction, we will consider a case in which a fan shape blood pattern is found on a floor as the result of a gun shot wound to the head. When blood disperses in various directions from a wound the blood drops will tend to fan out. As the drops strike the floor, they will elongate into oval shapes. An imaginary line drawn through the middle of the oval shape lengthwise will run back to the area where the blood came from.

If lines are drawn through several of the blood spatters as in Fig. 8.8.5.4.1 the lines will cross at the point where the person was standing. That point is called the Point of Convergence and will be flat on the floor (if that is where the spatter is located). Somewhere above that point is where the blood originated. If the victim was shot in the head, it may be 4–6 feet (roughly the height of an average person) above that point. Where the blood left the person's body is called the Point of Origin

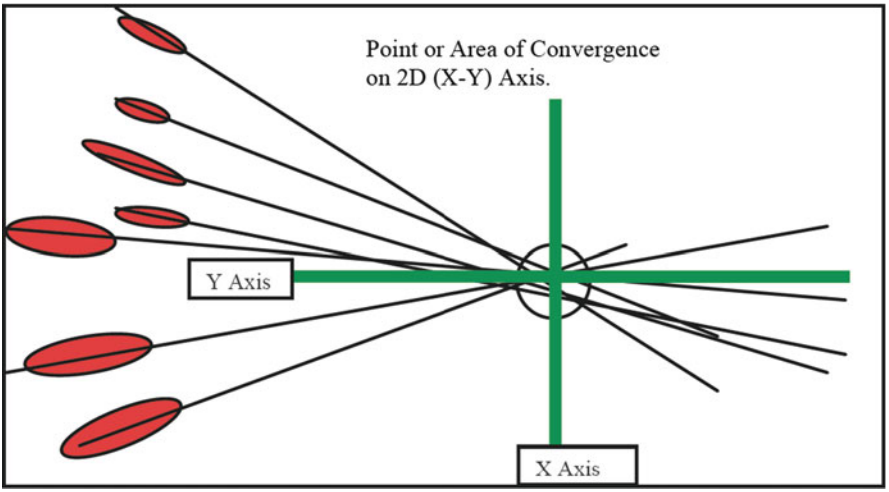

Fig. 8.8.5.4.1 Lines through the central axes of the spatter cross at the Point of Convergence

as previously mentioned. To find the Point of Origin (PO), first determine the two-dimensional Point of Convergence (POC) on the floor as seen in Fig. 8.8.5.4.1.

8.8.5.5 Determining the Angle of Impact (AOI), and the Point of Origin

The next step in the process is to determine the Angle of Impact (AOI) for representative bloodstains. Specialized blood spatter calculator software that performs all the calculations automatically is available from online vendors, but for those who do not mind doing the trigonometry all the calculations can be done on an ordinary hand held scientific calculator or even by the use of printed copies of arc sine tables.

The Angle of Impact is the angle at which the blood drop hit the floor. It can be determined by taking the inverse arc sin of the width divided by the length ratio of an individual blood spatter.

If using software just enter the width and length into the table on the screen and the calculation will be done automatically. If using a hand held calculator, divide the length of the drop into its width, then take the arc sinee which is the second function on a hand held calculator (or just look on a trigonometric functions table) to get the degrees of the AOI.

For example, if a drop measures 0.5 mm wide and 1.0 mm long, dividing 1.0 into 0.5 would give a ratio of 0.5. The arc sin of 0.5 is 30 degrees. Find that by using the cosecant function on the calculator, or by looking at an arc sinee table. This calculation determines that the blood drop hit the ground at 30 degrees and it is already known that it came from the Point of Convergence.

Measure the distance from the individual drop to the Point of Convergence and multiply that number by the *tangent* (TAN) of the Angle of Impact. This calculation (by the Theorem of Pythagoras) will tell how high up the spatter originated from. The following paragraph explains this more thoroughly.

The *Point of Origin* (PO) is located above the Point of Convergence (POC) on the perpendicular axis. In this case that would be 90 degrees perpendicular to the floor. It is the point from where the blood was disgorged from the body. To determine where that point is located first measure the distance from each blood stain along its central axis to the POC. Then take the TAN of the degrees AOI. Third, multiply the TAN of the AOI by the distance. Measure that distance from the floor up the perpendicular axis and you will arrive at the Point of Origin.

In conclusion, *blood pattern analysis experts* can develop vast amounts of information from the patterns of blood at a crime scene. First responding officers and homicide detectives will be more aware of the value of blood spatter evidence if they understand the fundamentals of pattern analysis. Additionally, *first responding officers* and *detectives* can glean a great deal of information themselves at the scene without becoming experts and they can assist the experts later with the data that they gathered at the scene. If the blood spatter evidence is properly photographed and if accurate measurements are taken of the length and width of the individual spatters and the distance from each spatter to the Point of Convergence, the analyst can later make the necessary calculations based on that data and draw conclusions from them. If the measurements and photographs are not taken, critical information may be lost forever.