Department of Chemistry

An Investigation into the Foundational Principles of Forensic Science

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Declaration:

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

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Abstract

This thesis lays the groundwork for a philosophy of forensic science. Forensic science is a historical science, much like archaeology and geology, which operates by the analysis and understanding of the physical remnants of past criminal activity. Native and non-native principles guide forensic science's operation, application, and interpretations. The production history of mass-produced goods is embedded in the finished product, called the supply chain. The supply chain solidifies much of the specificity and resolution of the evidentiary significance of that product. Forensic science has not had an over-arching view of this production history integrated into its methods or instruction. This thesis offers provenance as the dominant factor for much of the inherent significance of mass-produced goods that become evidence.

Presentations and Publications

Some ideas and concepts in this thesis appeared in the following presentations and publications:

“Forensic Science is History,” 2004 Combined Meeting of the Southern, Midwestern, Mid Atlantic Associations of Forensic Scientists and the Canadian Society of Forensic Scientists, Orlando, FL, September.

“Crime Scene Investigation,” NASA Goddard Engineering Colloquium, Goddard Space Flight Center, Greenbelt, MD, November 2005

“A supply chain approach to evidentiary significance,” 2008 Australia New Zealand Forensic Science Society, Melbourne.

“Locard's Exchange...Principle? Theory? Law? An exploration of forensic science's foundational principle,” Houck, M. and Crispino, F. 2008 Australia New Zealand Forensic Science Society, Melbourne.

Houck, MM. "Trace Evidence" in *Forensic Science Handbook*, James Fraser and Robin Williams, eds. Willan Publishing, Devon, UK, 2009.

Houck, M.M. and Siegel, J.A. *Fundamentals of Forensic Science*, 2nd edition. Academic Press, San Diego. 2010.

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Reflecting on the ideas presented in this work, I realize I have been thinking of them in one way or another my entire academic and professional career. I could not have attained any of my goals or assisted others in the way I have without the support of my parents, Max and Janet Houck. With unwavering sacrifice and the strongest support, they gave me opportunities I would never have had otherwise. Somewhere, somehow, they know of this particular goal and rejoice--this work is dedicated to them.

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Chapter 1: Introduction

> "I have for example distinguished things, which inertly exist or just lie there from facts, which are the propositions of things in relationship, in much the same spirit that Flaubert…discovered how things were brought to life in his fiction by having them interact with other things. A wheel is a thing, not a fact, and a parking stone is a thing, not a fact, but if the wheel rolls over the paving stone, they both come to life as a fact. Even if it is a fact solely in his own mind. Sun is just a noun, but if the sun shines through the window, together they are joined into propositional life."
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> —E.L. Doctorow, *The City of God*

> "If you were a detective engaged in tracing a murder, would you expect to find that the murderer had left his photograph behind at the place of the crime, with his address attached? Or would you not necessarily have to be satisfied with comparatively slight and obscure traces of the person you were in search of?"
>
> —Sigmund Freud

Introduction

This thesis intends to lay the groundwork for a philosophy of forensic science. What is being offered here is not to be considered "the" philosophy of forensic science, but "a" philosophical underpinning for the forensic sciences. The overall argument is as follows: forensic science is historical in nature, working off of the physical remnants of past criminal activity, and, thus, has certain native and non-native principles that guide its operation, application, and interpretations. One of the implicit precepts in this view of forensic science is that the production history of mass-produced goods is embedded in the finished product. This production history, the result of what is called the supply chain, sets in large part the specificity and resolution of the evidentiary significance of that item. Forensic science historically has not had an over-arching view of this production history inculcated into its education, training, and application. In part, this is due to forensic science lacking a philosophical umbrella under which this supply-chain view could be housed; some of the reasons for this philosophical vacancy will also be discussed in this thesis. Provenance, therefore, dominates as the basis for much of the innate significance of mass-produced goods that become evidence.

A Beginning

The philosopher William Barrett makes the distinction between technicians and scientists [6]. A technician is someone who knows what to do given a method. A scientist, however, knows what to do if something goes wrong with a method--that is, they understand the process behind the method. This understanding requires not merely the mechanistic appreciation of a step-by-step protocol but a deeper realization of the fundamentals underlying the method: The philosophy, the theory, the integrated matrix of data, nuance, and experience.

Behind each method, regardless of the discipline, is the accumulated knowledge of successful discoveries, failed attempts, and the eventual establishment of solid theories or even laws. Information is that which reduces uncertainty and methods are designed to be reproducible ways to reduce uncertainty [7]. Inherent in each method, then, are the implicit and explicit supporting knowledge--as distinct from mere information--that make the method work. Succinctly put by the physicist P.W. Bridgman, “the concept is synonymous with the corresponding set of operations” ([8], page 14). More prosaically, as Renfrew and Bahn note, “It could be argued that the whole philosophy of archaeology is implied in the questions we ask and the form in which we ask them” ([9], page 16).

Packed tightly into each method is the philosophy and principles that make it work. An example may help better explain this compacted idea. If length is measured to distinguish between two otherwise similar objects, intrinsic in the measurement of their length is the ability to make that distinction--otherwise, why use length and not mass or volume? Further, the way in which length is quantized delimits the utility of the method. As Coates [10] explains (see Figure 1),

> Ruler A, divided into twelve 1-inch increments, cannot reduce the uncertainty about the dimension in question entirely because no hash mark coincides exactly with the rectangle’s edge. I am reduced to guessing the rectangle’s width, but I am

> quite certain it lies between 3 1/2 and 3 3/4 inches. If I want to reduce my uncertainty further I need a ruler with hash marks that are closer together. Ruler B, which has marks that are just 1/2-inch apart, does this. However, it presents a higher level of uncertainty than does Ruler A because there is only one possibility in 24 (instead of 12) that the object being measured will fall between any two hash marks. This is equivalent to increasing the amount of information the ruler can convey by one bit. The interesting thing is that my own uncertainty decreases as the ruler's uncertainty increases...Each time a ruler is subdivided by doubling the number of hash marks, as shown in Rulers C, D, and E, it gains another bit of information and I grow more certain of exactly how wide the rectangle is--up to a point. (pages 133-134).

The ability of a method to resolve differences between two otherwise similar objects is key to its utility in forensic science. Each method has a resolution to it, a limit of specificity [6]. In fact, the basis of the forensic sciences is "their diagnosticity: [their] ability to assign traces of [evidence] objects to their correct source with a certain degree of specificity under certain parameters of detection and under certain rules governing such assignments ([11], page 246). For example, testing for blood groups using only the ABO system, the greatest specificity that can be achieved is Type AB (4% of the US population); adding the Rh Factor to the testing regime improves the specificity to as little as 0.6% (Type AB Negative)[1]. The resolution of each evidence type is elucidated more or less depending on the particular method used to analyze it. For example, although examination of a cotton fiber and a rayon fiber with a polarized light microscope can easily distinguish the two based on morphology and optical properties, an infrared spectrometer would determine both to be "cellulosic" [12].

The idea of resolution thus is not unknown to forensic science but it can be poorly understood (as with the specificity of hairs or serology; see [13]). Nevertheless, it has a tremendous importance to the proper understanding of what constitutes "interpretation" of any forensic evidence. In many

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[1] Stanford School of Medicine, http://bloodcenter.stanford.edu, referenced April 2009.

regards, this is what Saks and Koehler rail against in their *Science* article (that, other than DNA, the forensic sciences have no basis for statistical interpretation and must rely on uniqueness) and what Cole supports when he eschews uniqueness as the panacea for forensic meaning

> What matters is whether we have analytical tools necessary to discern the characteristics that *distinguish* one object from all others or, in the forensic context, distinguish *traces* made by each object from traces made by every other object… Every object is presumably unique at the scale of manufacture. The question is whether objects are distinguishable at the scale of detection ([11], pages 242-243).

The real answer thus lies in detangling the complexity of natural and material items that become evidence within one or more models that reflect their structure, specificity, and prevalence. As will be demonstrated in the current work, the complex and dynamic nature of supply chains make predictive modeling of populations of manufactured items nearly impossible. What constitutes a significant difference between two otherwise analytically similar objects depends on, among other things:

- The raw materials, their proportions, and content,
- The intermediate processes and their affect on the raw materials and finished goods,
- The quality control and assurance levels utilized at various points along the supply chain,
- And the methods used to analyze the items

To predict that two Nike AirJordan sneakers, for example, from two separate production lots will or will not accord in all physical and chemical parameters is untenable. The chemistry of the polymers—including the fabrics—in the shoes' components may differ, the colors of the various components may not be the same, and the outsoles may differ in small details (as the molds for the tread and outsole portion are carved individually by one or more tradesmen) [14]. These distinctions suggest that it becomes possible to classify the object more closely than simply its manufacturer but provenance—in the forensic sense—then becomes possible. However, in retrospect, it is a relatively easy matter to test the various components in series and determine if any of them differ through the methods used (chemistry, microscopy, spectroscopy, visual examination).

The knowledge embedded in a method comes from scientists experimenting, correcting, understanding, and refining information. A method is successful and useable by a technician--who may not fully understand what lays behind it--because of this tuned contextual and compacted knowledge built into the process. Forensic science has been labeled as an “applied” science, in that it is perceived to be not a scientific discipline unto itself but rather the mere application of physical, chemical, and biological methods to legal issues. For those who hold this view, including some practitioners as well as academics, forensic science would be reduced to either technicians performing routine analyses day-in and day-out without regard for the practice as a larger profession or scientists performing methods created for non-forensic purposes bent to the solution of criminal acts. Neither state, from a professional development point of view, is entirely palatable. Although some forensic methods originated wholly within the forensic system, patterned evidence and questioned documents are examples, altering non-forensic methods to meet forensic philosophical and procedural requirements (as arguably happened with DNA analysis) may be the bulk of the work waiting to be done.

For forensic science to truly become a separate discipline to stand next to its sibling sciences, it must unpack the theories and principles from its methods and make its foundations explicit [15]. A deeper understanding of the intellectual infrastructure of forensic science can only improve its procedures, its appreciation by other scientific professions, its efficacy, and the criminal justice system. This dissertation is an attempt to offer a view of the forensic science infrastructure.

Forensic scientists are Knowledge Workers

“Knowledge worker” is a term coined by Peter Drucker in 1959 to describe the then-rising group of workers whose jobs required extensive education, the application of theoretical and analytical knowledge, and continuous learning [16]. Knowledge work, as defined by Drucker, “is not experience-based as all manual work has always been. It is learning-based.” ([16], page 227). Knowledge work has high entry costs:

> Knowledge work and most of services work, in their work characteristics, are nontraditional. Displaced industrial workers thus cannot simply move into knowledge work or services work the way displaced farmers and displaced domestic workers moved into industrial work. At the very least they have to make a major change in their basic attitudes, values, and beliefs. ([16], page 227)

Specialization, not generalization, is what makes knowledge useful and the more specialized knowledge is, the more useful it becomes. Increased specialization does not imply that the knowledge will become more “applied”, however, as many knowledge workers with highly specialized knowledge conduct very basic research, as with high-energy particle physics. With specialization comes two concomitant features of knowledge workers: They operate in teams and they have to have access to an organization. Teams balance out the necessary specialization for knowledge to be applied properly and the organization provides the basic continuity that allows the knowledge workers specialization to be converted into performance [16]. For forensic scientists, the coterie of investigators, laboratory colleagues, and the larger organization constitutes one or more participatory teams.

In this context, forensic scientists use their specialized knowledge to convert items of evidence into reports and testimony. Knowledge of evidence is thus the fount of forensic knowledge and, in part, sets the limits of its interpretation. An academic base is required for forensic science to mature as a science and profession [17]. The “formal” aspect of academic education, however, can run afoul of those who see the formalities as being at least as and sometimes more important than the knowledge itself. Formal education can also “fall prey to overvaluing immediately useable, “‘practical’ knowledge, and underrate the importance of fundamentals, and of wisdom altogether” ([16], page 235). Drucker’s comments are echoed in the perceived friction between basic and applied sciences [18, 19] and the historical estrangement between academia and forensic science [15]; the traditional divide between basic and applied sciences only aggravates this situation [19-21].

Evidence is the basis for forensic knowledge

Evidence is converted into reports by forensic scientists and this makes evidence the foundation for what can be thought of as “forensic knowledge.” The goal of a forensic analysis, according to Kirk, is to individualize evidence [22]. The concept of individualization is familiar enough: things in a person’s environment are recognized as being their property, such as when a valet attendant retrieves an owner’s car correctly from the parking lot [23]. In practice, however, individualization is not provable [24]. The very basis of statistics is the testing of samples because the populations of interest are either pragmatically or actually too large to test in their entirety [25]. Even in forensic DNA analysis the result is a statistical random-match probability. Granted, the specificity of a 13-loci association results in a random-match probability of 1 in 4.8 quintillion [26]; this begs the question of “identity.” Some laboratories set a threshold for reporting individualization to “a reasonable degree of scientific certainty” but that is a policy decision for reporting purposes, not a purely scientific one. All things of interest through the world cannot be tested practically--regardless of the fineness of a method’s resolution, forensic science is relegated, therefore, to statistical characterization of interpretive results.

For the sake of argument, assume all evidence is class level evidence. Thus, it is in the best interests of forensic scientists to be as specific as possible about the putative source of any given item of evidence, that is, identify the item so that it is classified in the smallest set (with the fewest members) as possible. Therefore, the level of specificity is dependent on the scientist's ability to resolve and meaningfully distinguish ever-finer class memberships. To do this, the forensic scientist must know as much as possible about the manufacturing process of the evidence type in question. Distinguishing Spectra® from other polyolefin fibers requires knowledge of the extreme drawing these fibers undergo to produce a final product that, although made from roughly the same material as milk jugs, can stop bullets [27]. Simply approaching a suspected fiber as polyolefin using methods blind to its specific properties [28] will preclude a more accurate identification of Spectra®.

Forensic Science is a Historical Science

Developed by Edmund Locard, one of the central tenets of forensic science posits that an exchange of information occurs when two items come into contact, even if the results are not identifiable or are too small to be found [29]. The results of such a transfer would not be the transfer itself, but the remnants of that transaction, what paleoclimatologists call proxy data [30]. Proxy data that is collected and analyzed, forensically speaking, is evidence; if it is not collected or analyzed, it can hardly help to make a proposition more or less likely.

Based as it is on the analysis of material goods, forensic science has much in common with archaeology, another historical science. However, several aspects of forensic science set it apart from other historical sciences, mainly its exceedingly shallow (by comparison) time-depth and focus on the individual. These differences necessitate that forensic science should have principles that allow it to act as a separate science. The principles that are used in forensic science fall into two categories: native and non-native. The native principles represent concepts or tropes that were either generated by forensic scientists or are so ingrained in the process and procedures of forensic science that they can be considered original to the discipline. The non-native fundamental principles largely come from geology and relate to issues of order, time, and placement [31]. Principles from chemistry and biology obtain, of course, but not at the same fundamental level: Time, order, and placement obtain as primary concepts because forensic science is historical and, thus, reconstructive like geology [32].

Forensic Science is a Separate Science

Unlike other historical sciences, forensic science has not achieved acceptance as a “real” science, either by academic or legal critics [33]. Obstacles to this acceptance include the temporal depth of study (very shallow), the principle of uniqueness (unproven), the dichotomy of basic and applied science (artificial), and the pace of change in modern material culture (inescapable). These obstacles can be countered, some easily, some very slowly. Forensic science has native and non-native principles in place, tacitly or explicitly, that provide a basis for establishing it as a “real” science and, doing so, gain greater acceptance among its sibling disciplines.

Supply Chains as a Basis for Significance

Finished products represent an encoded item, the details of its manufacturing history imbedded in its composition, component parts, design, and intended end use [34, 35]. Many factors contribute to a product’s final history, not the least of which is its intended end use. In Rivoli’s book, *The Travels of a T-Shirt in the Global Economy*, the questions begin at the base level of construction of the garment--the fibers:

> What is the best tradeoff between strength and fineness? Should the cotton fiber be combed or not? Should the cotton be twisted to the right or the left? How much twist should be put into the yarns? And finally, because a pound of cotton can be transformed into anywhere between 800 and 2,500 yards of yarn, what yarn “count” should be produced, and with which grades of cotton? ([36], page 68)

In this era of “green economies,” forensic scientists worldwide should exercise additional care in studying materials through not only their first life but also their second (or perhaps third):

> ...used T-shirts are contained in, for example, automobile doors and roofs, carpet pads, mattresses, cushions, insulation, and caskets. And finally, in a fascinating full-circle story, high-quality cotton shoddy can be spun back into low-grade yarn and turned into cheap clothing again…old cotton sweaters will go to Pakistan to be turned into new sweaters. Shoddy will go to factories everywhere and also to India, where it is transformed into cheap blankets that are passed out to refugees. Italy is a customer for old wool, where an industry is built on recycling fine cashmere. ([36], page 187)

Working backwards from the finished product to tease out the manufacturing history can be variously successful--details may be clear and closely narrow a manufacturing source (see, for example, [37-39]), while others may be traceable but obscured or unintelligible at a “forensic level” of relevant distinction (5,300 pounds of cotton, for example, could produce about 13,500 t-shirts [36]). Thus, to identify sourcing features and elucidate the manufacturing history to narrow or identify a source, a first principles approach is necessary, going forward through the manufacturing process to learn what forensically-useful traits are sustained and available in the finished product, as well as which ones are analytically accurate.

A supply chain (more properly called a logistics network, but the former phrase has stuck) is the system of organizations, people, suppliers, intermediate processors, activities, and resources involved in moving a product or service from supplier to customer (Figure 2). Supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to an end customer. From an economist’s point of view, supply chains link value chains (the processes that a product passes through, gaining value at each step) [40].

Supply chains may also be internal to a company, such as a manufacturing process but unless the company produces everything they need for producing their product, an external network of suppliers must exist. Cumulatively, the exchanges throughout a supply chain will be between variously aligned companies, each seeking maximum profits based on those things they can control. Ironically, from a forensic point of view, each company may have little or no knowledge or interest in the company's up- or down-stream in the supply chain [41]. This complicates the forensic scientist job in trying to source any one item of evidence – the relevant and required documentation may not exist with the producer. Contingent and incidental characteristics can aggregate in a matrix of otherwise intended mid-to-end results. Supply chains, even for the simplest of products, can therefore become quite complex, interrelated webs of raw materials, processes, machinery, human activity, and quality control. This complexity is illustrated with a commonly available, seemingly simple product: Aspirin.

A manufacturing example of an internal supply chain: Aspirin[2]

Standard aspirin tablets are made by adding corn starch and water to acetylsalicylic acid (active ingredient) along with a lubricant (such as hydrogenated vegetable oil, stearic acid, talc, or aluminum stearate) to keep the mixture from sticking to the machinery. The corn starch and water act as binding agents and filler; binding agents hold the tablet together while fillers (also called diluents) increase the bulk of the tablet to achieve a desired size. Various other diluents, such as mannitol, lactose, sorbitol, sucrose, and inositol, are added to chewable aspirin tablets, giving the tablet a pleasing taste and speed up dissolution. Either type of tablet may be colored; the United States has approved FD&C Yellow No. 5, FD&C Yellow No. 6, FD&C Red No.3, FD&C Red No. 40, FD&C Blue No. 1, FD&C Blue No. 2, FD&C Green No. 3, a limited number of D&C colorants, and iron oxides, among others.

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[2] This section developed from *An Introduction to Pharmaceutical Formulation*, 1965; Mann, 1991; Draper, 1992; and Weissman, 1992.

The shape of an aspirin tablet varies with manufacturer to help identify their brand(s). The surfaces of the tablets can have a range of shapes and styles, such as flat, round, concave, or convex. The dosage of the tablet will, in part, determine the weight, size, thickness, and hardness. The upper and/or lower surfaces of the tablets may be scored with a shallow groove to facilitate breaking the tablet in half. Symbols, names, or letters may be stamped or engraved on the surface to identify the brand or the manufacturer.

Aspirin tablets are manufactured through a process called dry granulation (or slugging). The size of any one batch is dependent upon the scale of manufacture, the dosage, and the type of machinery used. The tablets are made in batches of the same dosage (amount of active ingredient) by the following processes. The ingredients are weighed separately in sterile canisters and mixed multiple times to blend the components as well as expel air.

The ingredients are then compressed into units generally from 7/8 to 1 inches (2.22 to 2.54 centimeters) in size called slugs. The slugs are pushed through a mesh screen to further mix the ingredients; smaller batches are worked by hand with a stainless steel spatula, while larger batches are filtered mechanically with a Fitzpatrick mill. Additional lubricant is added with a rotary granulator and sifter.

The aspirin tablets are created by compression in a machine called a punch and the process in often therefore called punching. Small batches are made in a single-punch and larger ones in a rotary tablet machine. On either machine, the process is similar, although the single punch machine is simpler in concept. On single-punch machines, the aspirin mixture is fed into a single tablet mold, called a dye cavity. The excess mixture is scraped away from the cavity. A punch—a short steel rod the same shape and size of the dye cavity—drops into the dye cavity and compresses the mixture between it and another, lower punch. The upper punch retracts and the lower punch rises and pushes the tablet out of the dye cavity. The machine resets and more mixture is fed into the dye cavity (Figure 3).

Rotary tablet machines work on the same principle except multiple punches work in a series and a number of dye cavities revolve as the mixture is dispensed. The upper and lower punches operate in sequence with the rotation of the dye cavities. Even a simple rotary tablet machine can easily produce upwards of 2 million tablets per year[3].

The finished tablets are moved in bulk to an automated bottling assembly line. The tablets are fed into polyethylene or polypropylene plastic bottles or glass bottles. The bottles, in turn, are packed with cotton, sealed with a sheer aluminum top, and then sealed with a plastic and rubber child-proof lid. A taper-resistant round plastic band is then to the lid. The bottles are individually labeled, stamped with an expiration date, and packaged into shipping containers, typically cardboard boxes. The packages are then placed in larger cardboard boxes or palletized for shipping and distribution.

Even a simple, common product like an aspirin tablet has many dozens, if not hundreds, of steps that can add to the complexity of the material. A change, substitution, or variation in any one of the following may create a discernible difference between otherwise similar batches (not an exhaustive list):

Ingredients	**Manufacturing**
corn starch	dosage
water	weight
acetylsalicylic acid	upper surface shape
hydrogenated vegetable oil	lower surface shape
acetylsalicylic acid	scoring
talc	thickness
aluminum stearate	diameter
mannitol	punch type

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[3] Dr. Ed Franzosa, Drug Enforcement Administration, personal communication, 2006.

lactose
sorbitol
sucrose
inositol
colorants

pressures
bottling process
mixing
screening

This variety has direct and significant implications for forensic work should an aspirin tablet or tablets come under investigation for poisoning or tampering, as in the Tylenol poisoning case [42] or in other types of combinatorial calculations from suitably-sized databases (for example, see [2]).

This extended discussion on a fairly simple commodity is offered as an example of the complex matrix of goods, processes, and variability inherent in each manufactured product. The extension of the forensic mindset to include supply chain information could greatly enhance the resolution of classification for evidentiary items. Incumbent upon this enhancement, however, is laying the foundation for forensic science's place as a separate science that is historical in nature.

Focus of the Present Work

Section 1 presents a set of philosophical underpinnings considered necessary for the functioning of forensic science in this work. Chapter 2 addresses the basis of establishing forensic science as a historical science and what implications this has for its procedures, relevance, and foundational philosophy. Chapter 3 provides an argument as to why forensic science is a separate scientific discipline and not scientific methods "merely applied" to issues of legal concern. Section 2 offers the bulk of the rationale for the necessity of supply chain information in forensic science. Chapter 4 details supply chains and their "links", providing the infrastructure necessary to detail distinctions between otherwise similar classes of evidence and how to refine them. Chapter 5 debunks the concept that population frequency statistics are the only approach to take with forensic evidence. A closer look is taken at aspects of supply chains for textile fibers, glass, and pharmaceutical tablets, giving the necessary examples to support the central thesis that evidentiary significance is rooted in supply chains. These supply chains are dynamically linked to the design and economics of the products manufactured and cannot be subsumed under a population frequency rubric. Finally, Chapter 6 will offer a combinatorial example using tablet data to demonstrate one approach to expressing the significance of tablet evidence at the class level.

An extension of the supply chain argument could conceivably be extended to naturally occurring items, such as hairs, soil, or other biologicals (see, for example, [43] or [44]) but is complicated by the scope of this work as a thesis and the inherent complexity of living things over manufactured ones [45]. Thus, only manufactured items, considered emblematic of human intelligence and activity [46], will be considered in this thesis.

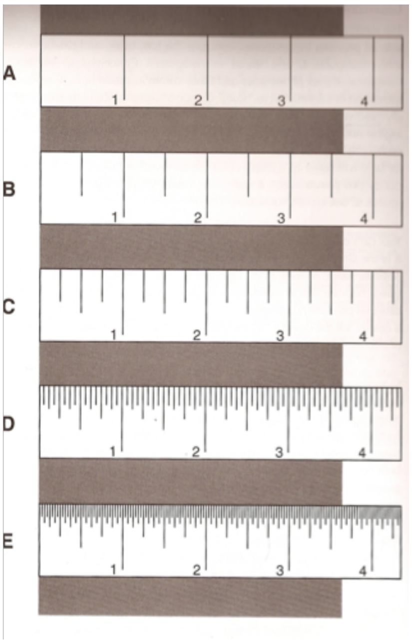
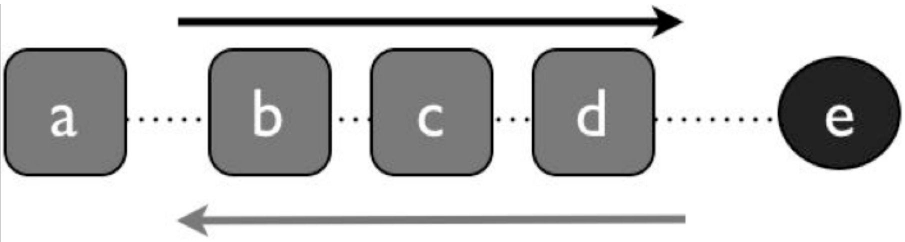


Figure 1.The precision of a measurement reduces uncertainty (from Coates, 2003).



A diagram of a suggested supply chain. The black arrow represents the flow of materials and information and the gray arrow represents the flow of information and feedback. The elements are (a) the initial supplier, (b) a subsidiary supplier, (c) a manufacturer, (d) an intermediate process, (e) the final customer.

Figure 2. A diagram of a supply chain.

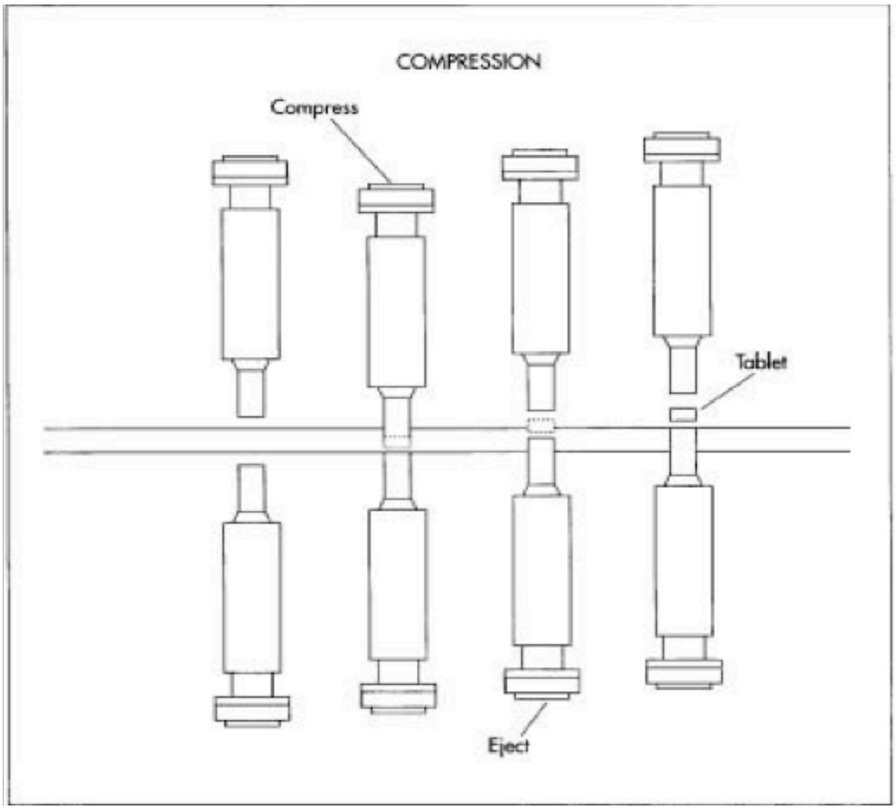


Figure 3. This drawing illustrates the principle of compression in a single-punch machine. First, the aspirin mixture is fed into a dye cavity. Then, a steel punch descends into the cavity and compresses the mixture into a tablet. As the punch retracts, another punch below the cavity rises to eject the tablet.

Section 1

Chapter 2: Forensic Science is a historical science

> “Narrative is a sequencing of something for somebody.” [47]

> “The ashes of an oak in the chimney, are no epitaph of that oak, to tell me how high or how large that was; It tells me not what flocks it sheltered while it stood, nor what men it hurt when it fell.” (as quoted in [48], page 58)

Introduction

Curiously, the trope of following a historical trail being a type of “detective” or “forensic” work appears in many disciplines, including history [49, 50], geology [32], and even photography [48], but is not a truism in forensic science. Forensic science is manifestly a historical science, in that it attempts to reveal and explain past criminal events through the analysis of physical evidence. While the historical nature of forensic science has been assumed (take, for example, the title of one forensic text, *Crime Reconstruction* [51]), the philosophical basis for this assumption has not been explicated. This section defines forensic science as a historical science, offers support for its theoretical basis within itself and the related sciences, and suggests the fundamental ontology for a philosophy of forensic science as a historical science.

Time’s Arrow

Time presents itself as a dichotomy. First, history is seen as a *sequence* of events, each unique in its characteristics, unrepeatable, and in series. Reassembling the events in the proper order creates the narrative of history seemingly moving in one direction. Gould calls this “time’s cycle” [52]. The other side of time is that it has no real *direction*, its

> “(f)undamental states are immanent in time, always present and never changing. Apparent motions are parts of repeating cycles, and differences of the past will be realities of the future.” ([52], page 11).

This has been called, somewhat misleadingly, “time’s arrow” [49]. Although time has no predetermined direction, in retrospect it seems so; Davies offers the example of an egg being broken:

> …an egg dropped on the floor will smash into pieces, whereas the reverse process—a broken egg spontaneously assembling itself into an intact egg—is never witnessed. This is an example of the second law of thermodynamics, which states that the entropy of a closed system—roughly defined as how disordered it is—will tend to rise with time. An intact egg has lower entropy than a shattered one. Because nature abounds with irreversible physical processes, the second law of thermodynamics plays a key role in imprinting on the world a conspicuous asymmetry between past and future directions along the time axis. ([53], page 40)

Thus, time does not “flow,” *per se* but is a series of events that form an irreversible unidirectional sequence. The arrow of time is said to point to the future but this is no more accurate than saying, because a compass’ needle *points* north*,* it is *traveling* north [53]. As Davies notes, the arrow of time demonstrates that the world is asymmetrical *in* time and not that time *itself* moves in any one direction. The event-nature of time is exemplified in a video of any event, like the egg breaking. Run backwards, any viewer would recognize the sequence for what it is. Cut up into individual frames and shuffled, however, the video could be re-arranged into a proper timeline sequence. Even mixed, the stack of images retains the asymmetry of time, revealing it as a property of the stochastic world and not a property of time in and of itself. The sorting of stochastic events in time is an integral part of the forensic mindset, as made clear in this quote from Edward Heinrich, a pioneer of forensic science,

> It is a matter of understanding the scientific aspects of ordinary phenomena. Rarely are other than ordinary phenomena involved in the commission of a crime. One is confronted with scrambled effects, all parts of which separately are attributed to causes. The tracing of the relationship between isolated points of fact, the completion of the chain of circumstances between cause and effect, are the highest functions of reason--to which must be added the creative imagination of the scientist (as quoted in [54], page 44).

Gaddis discusses the present as a singularity “through which the future has got to pass in order to become the past” ([49], page 30). In his view, the present fastens together relationships between patterns that extend across time (what he calls continuities) and phenomena that do not form patterns (contingencies) and thus acts as a bottleneck or gateway to the past. The contingencies are those phenomena that are sensitive to initial conditions. In a forensic context, these would be things that happen at or near the time of the criminal activity; for example, the orientation of a firearm when discharged, where a minor change in angle could result in a significant alteration of events. Continuities, in Gaddis' terms, are not laws or theories but phenomena that happen repeatedly and often enough to be perceived as a pattern or regularity (as opposed to the notion of a *singu*larity). A forensic example might be the way blood pools and dries (as distinct from other liquids), the succession of insects on a corpse, or the transfer of fibers. As continuities and contingencies converge in the present, they are inextricably bound together into events. The confluence of continuities and contingencies ultimately result in the activities that leave physical remnants at a crime scene that become forensic evidence. This idea was noted by Eco regarding the question of who is guilty for a crime: "To know the answer (to think you know) you have to conjecture that the facts possess a logic - the logic that the guilty party has imposed on them" [55]. The combination of the product(s) as evidence being a physical manifestation of its production history (supply chain) and its use in the commission of a crime imply that logical base which forensic scientists attempt to reveal.

The sheer number of possibly involved and potentially relevant contingencies and continuities become Heinrich's "scrambled effects" and complicate crime scene and laboratory interpretation. Not everything at a crime scene relates to the crime and not all evidence at a crime scene is collected. Environmental effects and degradation can also obscure or eliminate evidence. Processing a crime scene involves decisions about relevance of evidence based upon one or more hypothesized scenarios of the criminal activities. All of these factors preclude not only a complete reconstruction of a crime scene but also a reconstruction that utilizes every scrap of evidence [51, 56]. Therefore, the forensic investigation process parallels that of historical investigation in three main ways [49]. First is *selectivity*, which couples with the notion of sampling either at the crime scene or in the laboratory, insofar as the investigator must decide what is relevant and how much weight to give to it. The historian E.H. Carr pointed out that millions of people have crossed the Rubicon but historians decide which ones to write about [57]. The second is *simultaneity*, the ability to be in multiple places or times at once; forensically, this is the ability to reflect on the scene or items of evidence as the scientist views actual or subsidiary (derivative) evidence. Gaddis emphasizes that it is "only by standing apart from the events they describe…that historians can understand and, more significantly, *compare* events" ([49], page 25, original emphasis), such as the comparison between questioned and known items [58]. By being outside of the temporal flow that they study, by being "out of time," so to speak, historians can compare otherwise incomparable, temporally separated events, such as the Roman Empire and World War II. The third and final is *scale*, shifting back and forth from macro to micro, "to see processes at work that are visible to us now but were not then" ([49], page 26). For the forensic scientist, this would be relating trace evidence to the source item (fibers to a textile, for example) or one scene to multiple other scenes (such as in the DC Sniper case [59]). These three abilities of the forensic investigator help to select, organize, and compare evidence from one or more events to best effect.

Methodologically, historical scientists are obligated to this type of manipulation of space, time, and scale because they represent a "departure from literal representation". A literal representation—the events and entities involved themselves—would be impractical. Moreover, as Fischer notes, this would necessitate a historical scientist knowing *everything* before they could know *anything* [60]. Historical evidence is of necessity incomplete and the scientist's perspective limited. And, importantly for forensic purposes, the event itself is "a vast expanding universe of particular events, about which an infinite number of facts or true statements can be discovered"

([49], page 27). A distillation of facts—representation rather than replication—is required to make past events intelligible and communicable.

The reason historical scientists cannot use all of the available evidence in their investigations because time is asymmetrical. This same asymmetry, ironically, provides much more evidence than is necessary to make a determination about past events; that is, localized events tend to be overdetermined [32, 61]. Cleland offers this example,

> …the eruption of a volcano has many different effects (e.g., ash, pumice, masses of basalt, clouds of gases), but only a small fraction of this material is required in order to infer that it occurred; put dramatically, one doesn't need every minute particle of ash ([32], page 989).

Any of a number of these effects, or even sub-collections of them, would suffice to support the determination of volcanic activity. An important implication of the overdetermination of the past is that it is harder to predict future events (such as a volcanic eruption) than it is to infer that one has happened [61]. Another example would be a baseball thrown through a window into a living room; not every piece of glass would be needed to conclude that the window was broken. Notwithstanding the baseball on the floor, many other types of evidence also could lead to that conclusion, such as sounds, moisture (rain, for example), and odors. Interestingly, another example from Cleland's paper about geology is that of a crime:

> Perhaps the best way to appreciate the extent of the asymmetry of overdetermination is to consider the difficulty of committing a perfect crime; i.e., footprints, fingerprints, particles of skin, disturbed dust, light waves radiating outward into space must be eliminated. It isn't enough to eliminate just a few of them; anything missed might be discovered by a Sherlock Holmes and used to convict you. Moreover, each trace must be independently undone. You cannot remove a footprint by eliminating a particle of skin or, for that matter, another footprint. In contrast, and this is the other side of the asymmetry of overdetermination, erasing all traces of a crime *before* it occurs is remarkably easy, usually only requiring only a single intervention: don't fire the gun ([32], page 989).

The future, by contrast, is underdetermined. Many factors go into a crime, for example, but any could have prevented it (not firing the gun, in Cleland's example). The ultimate causal factor cannot be predicted due to an extreme number of potentially-critical variables (the victim not being in the "right" place at the "right" time, for one) [53], Gaddis' contingencies unresolved. The asymmetry of time means that the results must be obtained for the accuracy of a prediction to be ascertained. Experimental science, wedded to the future as it is, works with minimal "clues" to determine a future effect while reducing the controlled-for variables (contingencies) to indicate better which one of them may have caused the final effect. Historical sciences, by comparison, work with too many effects ("clues"), some of which are obscuring or irrelevant, to determine a past cause.

Because of the limitations imposed on them by the asymmetry of time, historical sciences can not be as "certain" as other disciplines, such as physics or mathematics. Nevertheless, these diachronic sciences that piece together fragments of past events and processes would become the perennial well from which forensic scientists would draw again and again.

Origins of the forensic mindset

Humans and their kind have a several-million-year prehistory of hunting prey [62]. Over the millennia, humans learned to reconstruct the shapes and traces of the unseen animals from tracks, broken branches, spoors, odors, and other indicators or clues [63]. The ability to hunt and track is often cited as the basis for what could be termed a forensic mindset [63-65]. Ginzburg suggests it is "what may be the oldest act in the intellectual history of the human race: the hunter squatting on the ground, studying the tracks of his quarry" ([63], page 105). Even a forensic eminence such as Locard noted the antiquity of a forensic mindset: "Searching for traces is not, as much as one could believe it, an innovation of modern criminal jurists. It is an occupation probably as old as humanity" ([66], as translated in [51], page 7).

The idea that traces or clues are inherently historical is also seen in ancient narratives that contribute to modern definitions. In the myth of of Theseus, the King of Crete, Minos, demanded that Theseus be sacrificed to the Minotaur, a creature that lived in a maze. The maze, a labyrinth designed by Daedelus, was intended to keep prisoners from escaping until the half-man, half-bull monster killed them. Minos' daughter, Ariadne, loved Theseus and secretly gave him a sword to kill the Minotaur and a ball of thread. Theseus played out the thread behind him as a trail. After killing the monster, Theseus retraced his path, following the thread, out of the labyrinth to safety [67]. Thus, the Oxford English Dictionary gives as the first definition of the word *clue*: 'A ball of yarn or thread' [68].

The first modern document demonstrating a forensic mindset is Voltaire's novel, *Zadig ou la Destinee* (*Zadig, or the The Book of Fate*, 1747), the story of a Babylonian philosopher, the eponymous Zadig, who challenges religious and political orthodoxies of Voltaire's own day through thinly-veiled tales woven into one narrative. Zadig's accumulated powers of observation lead him into trouble when members of the royal household approach him in a panic. Zadig says that they must be searching for a dog and a horse, both of which Zadig describes perfectly although he claims never to have seen either. He details the method of his seemingly supernatural knowledge:

> [the tracks] were those of a small dog. Long, shallow grooves drawn across tiny heaps of sand between the paw-marks told me that it was a bitch whose teats were hanging down, which meant that she had whelped a few days previously. Other traces going in a different direction, and apparently made by something brushing constantly over the surface of the sand beside the front paws, told me that she had very long ears. And as I noticed that the sand was always less indented by one paw than by the other three, I realized that the bitch [had] a slight limp ([69], pages 132-133).

Zadig goes on to describe the King's missing horse in a similar manner. The retainers decide that Zadig himself must have stolen the animals and take him to the King, with further adventures ensuing. The character of Voltaire's novel stands as the conceptual predecessor of nearly every detective and forensic scientist, fictional or real.

Trifles, Traces, and Clues

Perhaps the original scientist-as-detective, Georges Cuvier (1769-1832), the founder of comparative anatomy and paleontology, used scattered, fractured bits of information to reconstruct the prehistory of the Earth and its animals [70]. In a 1798 paper, Cuvier wrote on his realization of the form and function of bones as it relates to the overall identifiable anatomy of an animal, leading to the recognition of the creature from which the bone originated:

> This assertion will not seem at all astonishing if one recalls that in the living state all the bones are assembled in a kind of framework; that the place occupied by each is easy to recognize; and that by the number and position of their articulating facets one can judge the number and direction of the bones that were attached to them. This is because the number, direction, and shape of the bones that compose each part of an animal's body are always in a necessary relation to all the other parts, in such a way that--up to a point--one can infer the whole from any one of them, and vice versa ([71], page 36).

This has been called 'Cuvier's principle of correlation of parts' and is a central tenant in biology and paleontology. Rudwick notes that Cuvier claimed to be able to *identify* an animal taxonomically from a single bone, not completely *reconstruct* it, as the above quote might imply. The reconstruction would only be possible with a sufficient number of bones representing the animal in question.

The same clue-based method was employed in an unlikely venue: Art. In an attempt to make attributions of Italian artists' works more accurate and less susceptible to false identifications, an art connoisseur and politician, Giovanni Morelli, published essays on a novel method, for the art world. From 1874 to 1876, under the pseudonym Ivan Lermolieff, Morelli outlined a method for identifying artists based on what he considered to be incidental, unintentional indicators of the artist in the work itself. As Vakkari notes, “[o]n the basis of [Morelli’s] observations, he concluded that every artist tends to repeat certain forms and shades in the same way” and these forms “were not influenced by school or tradition” ([72], page 46). The forms were indicators of the artist’s unconscious additions to the art, exclusive of their formal education and training. Morelli focused on unintentional details such as hands, ears, and shading (Figure 4).

In modern parlance, these would be clues to the artist’s identity. Morelli’s method, which he called *metodo sperimentale* (“experimental method”), entailed detailed, systematic perception of elements of the work with comparison to known artwork. The reference to known works was a central tenet of the method; without authenticated references, the inference of identity may be wrong. In forensic terms, this would lead to an incorrect classification or the resolution of an item of evidence into too large a class (perhaps leading to a Type II error). Having a reference collection of known materials presupposes that the provenance of those items is well-characterized, accurate, and traceable. Reference collections therefore stand as explicit object-based examples of the inherent supply-chain that produced it.

Although Morelli called it “experimental,” the method was not what would now be recognized as a scientific experiment [7, 73]. The method was a rubric, a device to systematically and more objectively assess the identity of an artist; less rigorous or structured methods, in Morelli’s opinion, had led to many works being misattributed through incompetence of the critic or outright fraud by a painter copying a master’s style. Morelli’s work caused a stir in the art world during his life and for several years after because of his re-attribution of hundreds of works hanging in famous European museums; over half of his reassignments were correct [72].

Poe may have been influenced by Voltaire's story of Zadig for the character of Auguste Dupin [74], widely regarded as the first detective in modern fiction [75]. Morelli's method has been linked as a formative basis for Freud's analytical psychoanalysis [76] and, more importantly for this work, to Doyle's detective character, Sherlock Holmes [77, 78]. Another intriguing link to Morelli's method is offered by Anderson ([79], as noted in [72]), who asserts Cuvier's comparative anatomy is the basis for Morelli's "connoisseurship." As noted by Essig [80], the basis for the method of the fictional detective Sherlock Holmes (the first story was published in 1887) was the historical sciences, particularly the example of Cuvier's foundational work in paleontology, and the medical sciences, especially Doyle's medical school professor, Joseph Bell. Holmes, despite being a fictional character, influenced Bertillon ("I would like to see Sherlock Holmes' methods of reasoning adopted by all professional police.") and Locard ("Sherlock Holmes was the first to realize the importance of dust. I merely copied his methods.") (as quoted in [81], pages 447 and 448, respectively). To bring the relationships full circle, there is some evidence that Doyle was inspired by early editions of Hans Gross' ground-breaking treatise, *Criminal Investigation* (1893) [82]. One early reference ([83], as noted in [72]) links Morelli, Freud, and Doyle through their medical education and training: Morelli studied medicine and Freud was a physician, as was Doyle before he became famous for his fiction. Vakkari states Ginzburg saw the use of "medical semiotics--a discipline that is used when diagnosing an internal illness" as the lynchpin: "The conclusions are drawn from external, and from a layman's point of view, from sometimes irrelevant, signs" ([72], page 49). Interestingly, this medical connection between Morelli, Freud, and Doyle was denied by Morelli himself ([72]).

The clues of Zadig, Cuvier, Dupin, and Holmes are minor things ("trifles", in Holmes' terms) that reveal the larger truth of the investigation. As has been posited elsewhere [58, 84], the fossil of the paleontologist, the specimen of the anatomist, and the artifact of the archaeologist is what a forensic scientist would call evidence, Freud's "slight and obscure traces." Detection, like archaeology and other historical investigations, is by definition illuminating, an uncanny act "which reveals that which should have remained invisible" ([85], page 12) thereby making the absent present [86]. Huxley was the first in science to tie what he called "Zadig's Method" to real science and scientists, notably Cuvier [87]. This modality of small clues revealing a larger truth has been touted as a medical or diagnostic paradigm, common to geology, paleontology, archaeology [63], psychoanalysis, art connoisseurship, and—of course—forensic science [65]. This convergence of the diagnostic methods in multiple disciplines at roughly the same time (the end of the nineteenth century) may have been influenced by the *zeitgeist* of the state gaining control over a growing urban populace of increasing diversity, leading to new forms of criminality, increased prosecutorial powers, and concomitant needs for identification [88, 89]. This perception reached its tipping point with police agencies adopting Bertillion's and Galton's methods of personal identification [63, 90-92], both of which used small measurements or features to identify an individual (see Figure 6).

Evidence is Proxy Data

Criminal events under investigation are, by definition, history. The events themselves were not seen and are inaccessible to present-day investigators. Historical scientists are, as Bloch noted, "in the predicament of a police magistrate who strives to reconstruct a crime he has not seen" and, thus, "never arrives until after the experiment has been concluded" ([93], page 35). If one is lucky, in Bloch's words, the experiment leaves behind "residues" that allow a reconstruction of those inaccessible events. Residual evidence represents a more-accessible kind of information, in that one need not be literate to decode an item's provenance. As Prown sagely notes, "[o]bjects created in the past are the only historical occurrences that continue to exist in the present" ([46], page 3). Gaddis comments that time and space provide the field in which history occurs but it is structure and process that are the mechanism by which that reconstruction take place:

> It’s here that the methods of historians and scientists—at least those scientists for whom reproducibility cannot take place in the laboratory—roughly coincide. For historians too start with surviving structures, whether they be archives, artifacts, or even memories. They then deduce the processes that produced them. Like geologists and paleontologists, they must allow for the fact that most sources from the past don’t survive, and that most daily events don’t even generate a survivable record in the first place ([49], page 41).

The kind, sequence, and magnitude of the events must be reconstructed from the physical remnants (Bloch’s “residues”) of past criminal events. The concept of physical remnants—what forensic science would now call ‘traces’—is common among historical sciences but goes by different terminology (“fossils”, “artifacts”, “symptoms”, “clues”). A more descriptive and encompassing term, used in paleoclimatology, is “proxy data”. Surface temperature records are only available for approximately the past hundred years; therefore, indirect or “proxy” indicators, such as geological patterns, flora and faunal remains, and shorelines, must be used to reconstruct earlier climatic variability [94]. Proxy data acts as the components for a complex reality that cannot be experienced directly; invariably, the data are organized to relate the reconstruction in a narrative structure [63]. Historical scientists, like historians, “are not much interested in things or their thingness for their own sake, but as routes to past experience” ([95], page 7). Multiple validated proxies are useful for periods of temporal overlap and no one proxy by itself is enough to reconstruct larger events [94, 96]; this is also the case in forensic science, where one item of evidence rarely “makes the case” [97, 98]. Bradley [99] delineates that each proxy material differs according to:

- Its spatial coverage
- The period to which it pertains
- Its ability to resolve events accurately in time

Bradley further notes that the choice of proxy record—in forensic science, the choice of relevant evidence—is highly dependent upon what physical mechanism is being investigated. Forensically-speaking, evidence therefore differs in its spatial coverage (soil, as an example, comes to mind), the period to which it pertains (the criminal act, not the para-criminal activities), and its resolution in time (a hair could be a day or a decade old [100], whereas its persistence as transferred evidence is more ephemeral [101]).

By definition, proxy data all contain a signal, a meaning, a forensic significance on two levels. First, the meaning of the material in its original context: A handgun, a rock, a carpet. Prown notes this as the item's intrinsic value: "intrinsic in the fabric of an object itself…established by the rarity of the materials used" ([46], page 3). At this first level of meaning, forensic science typically deals in class level evidence [102] and leads to a sourcing of the material at some level of resolution. The second level of meaning is an added layer which the criminal activity has contributed to the item: The handgun used to shoot the victim, the rock used to break the store window, the carpet where the sexual assault took place. This level of meaning is "more transient or variable" ([46], page 3) as well as interpretive:

> The material the archaeologist finds does not tell us directly what to think…tell us nothing directly in themselves…The archaeologist has to develop a picture of the past, just as the scientist has to develop a coherent view of the natural world. It is not found ready made ([9], page 12).

In relation to material culture as mass-produced products, the use of "ready made" here means the *contextual* meaning, the *interpretive* meaning of the object is not patent but must be revealed through the recognition and interpretation by the expert. Renfrew and Bahn note, "we can only understand the archaeological record—that is to say, what we find—if we understand in more greater detail how it came about, how it was formed" ([9], page 13); this is certainly true also in forensic science. Bound within the second level of meaning would be the intention of Kirk's notion that forensic science is the science of individualization [22], although Kirk used this term in a statistical sense[4]. The signal, at either level, may be weak or obscured

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[4] It is interesting to note, however, that Kirk also said, "On the witness stand, the criminalist must be willing to admit that absolute identity is impossible to establish. ... The inept or biased witness may readily testify to an identity, or to a type of identity, that does not actually exist. This can

in background “noise” [29]. In any event, proxy data fix Gaddis’ contingencies and continuities to that event and create a record to be discovered, decoded, and analyzed [99].

A working forensic (as opposed to a legal) definition for evidence, then, is proxy data that is identified, collected, and analyzed for a legal process (civil or criminal). With this understanding of the basic unit of forensic science, the method of history now pertains more directly to a better understanding of forensic methodology.

History as Method

At the most basic level, as outlined by Stanford ([103], pages 64-65) and Prown (for material artifacts) ([46], pages 6-10), using evidence in historical analysis requires three steps. First, examine the item, describing it morphologically and compositionally, that is, classification in the forensic sense [58]. Second, assess the item in context, in relation to its use, its use history, any changes it may have undergone; for forensic science, this could be read as the proximate history or association to the scene and putative sources. Finally, Stanford tells us to consider the item’s origins, “how and why it was produced, by whom and with what intention, in what context, and in what circumstances” or as Prown puts it, the scientist develops “a program for validation, that is, a plan for scholarly investigation of questions posed by the material evidence.” Arguably, this could be considered assessing the item’s ultimate history, its significance, its supply chain.

Beyond Stanford’s three steps, Fisher offers a set of “rules” for historical scientists ([60], page 63). Interestingly, Prown notes some similar “rules” that must be adhered to in order to make sense of the object’s description (the second step described above):

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come about because of his confusion as to the nature of identity, his inability to evaluate the results of his observations, or because his general technical deficiencies preclude meaningful results.” (Kirk, *Crime Investigation*, 1963; page 10).

> **The Rule of Relevance**: “Historical evidence must be a direct answer to the question asked and not to some other question.”
>
> **The Rule of Immediacy**: The “best relevant evidence, all things being equal, is evidence which is most nearly immediate to the event itself.”
>
> **The Rule of Affirmation**: Evidence “must always be affirmative. Negative evidence is a contradiction in terms—it is no evidence at all. The nonexistence of an object is established not by nonexistent evidence but by affirmative evidence of the fact that it did not, or could not exist…”
>
> **The Rule of Responsibility**: “The burden of proof, for any historical assertion, always rests upon its author. Not his critics, not his readers…not the next generation.”
>
> **The Rule of Probability**: All “inferences from empirical evidence are probabilistic.”
>
> **The Rule of Context**: The “meaning of any empirical statement depends upon the context from which it is taken. No historical statement-in-evidence floats freely outside of time and space. None applies abstractly and universally.”
>
> **The Rule of Precision**: An “empirical statement must not be more precise than its evidence warrants. And degrees of precision, of course, vary greatly from one piece of evidence to another.”

The Rules of Relevance, Immediacy, and Affirmation are a mental construct of triage of an item’s description and meaning. Relevance is the focus, Immediacy relates directly to the notion of the “best evidence rule” in the law [104], and Affirmation is pithily summed in the well-known phrase, “Absence of evidence is not evidence of absence” [105]. Greater personal accountability and systematic oversight for one’s work product may have prevented some of the more painful scandals in forensic science, such as the work of Fred Zain or Michael West [106]. Only recently has ethics become a topic of genuine research in forensic science [107]. More will be said later about the issue of probability in forensic science but, necessarily, this is one area where research could have provided greater support for forensic science's role as a proper science were some of its challenges not so thorny [23]. Although the issue of contextual bias in forensic science has cropped up in recent research literature (for example, see [108-110]), context nevertheless is critical in sampling and interpreting evidence and crime scenes. Where the environments of the victim and suspect overlap at the scene of the crime, the most probative evidence is to be found. Context, however, may trump the inherent value of an item of evidence. For example, in a stranger-on-stranger sexual assault that occurs in a location neither person frequent, a very different coterie of evidence will be collected than in the instance of the same type of sexual assault that occurs between cohabitating spouses who have sexual contact (Figure 5).

Resolution, or here Precision, is a key concept historically overlooked in forensic science, perhaps because of the primacy of the conceit of uniqueness [11, 22]. A deeper understanding of an object's production history, its supply chain, can potentially enhance resolution or at least validate the current level of precision for an item of evidence. This is the central thesis of the current work.

Forensic science as modern material culture

Forensic science can be thought of as "short-term archaeology" in that it reconstructs a prior event from proxy data of a material nature [111]. Although the time depths are much shorter in forensic science, methodologically this should not matter too much, according to Buchli and Lucas [86] because what archaeologists actually do is analyze material culture. They do note, however, that other disciplines interested in twentieth-century material culture rarely do as well as archaeologists at "making the invisible visible" (page 15); forensic science is not mentioned in their work. The very nature of forensic science is the revealing of the unseen. Having started, scientifically, with the analysis of poisons—the ultimate unseen evidence—forensic science needed to branch out, expanding to encompass whatever sciences were necessary to elucidate the causes of a crime and the sources of evidence:

> The scene of a crime could be nearly anywhere; the traces could involve nearly anything. To comprehend those traces, Holmes' science needed to embrace not simply the body, but the whole of the physical world. It involved using any and all possible sciences—and even creating new ones—in order to better interpret circumstantial evidence ([80], page 243).

Methodologically, however, this was more difficult than simple chemistry, biology, or toxicology: Forensic science focused on the individual human actor, culturally bound, bobbing in a sea of background “noise” of materials science, cultural artifacts, and psychological purpose. Humans are the most difficult of topics [112, 113].

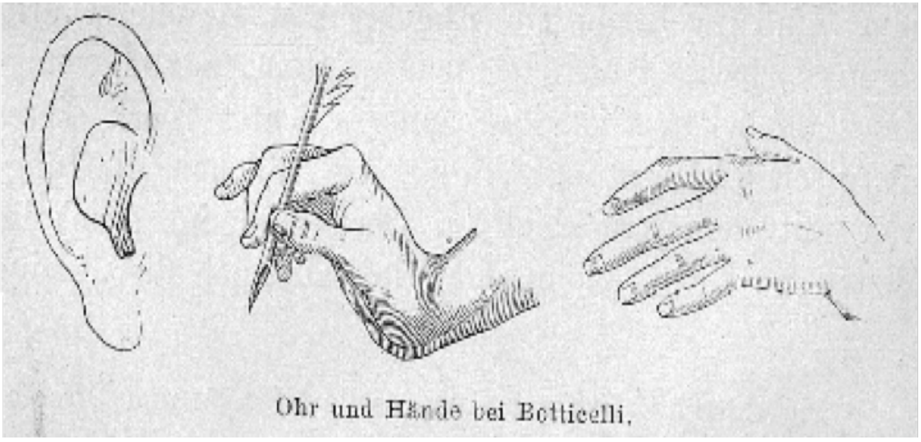
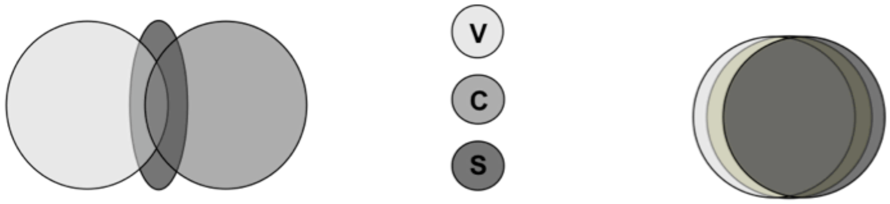


Figure 4. Morelli's diagram describing hands and ears from Botticelli, in Kunskritische Studien uber italienische Malerei. Die Galerien Borghese und Doria Panfili in Rom, Leipzig, 1890, p.105, as used in Vakkari, 2001, page 47.



Victim and **Criminal** only interact at a **Crime Scene** unfamiliar to both
Ex. Sexual assault in an alley

Victim and **Criminal** interact at a **Crime Scene** familiar to both
Ex. Spouse kills co-habitating spouse

Victim and **Criminal** interact at a **Crime Scene** familiar only to the **Criminal**
*Ex. Kidnapping and assault in **Criminal**’s house*

Victim and **Criminal** interact at a **Crime Scene** familiar only to the **Victim**
Ex. Home invasion

Figure 5. Context matters in the meaning of evidence.

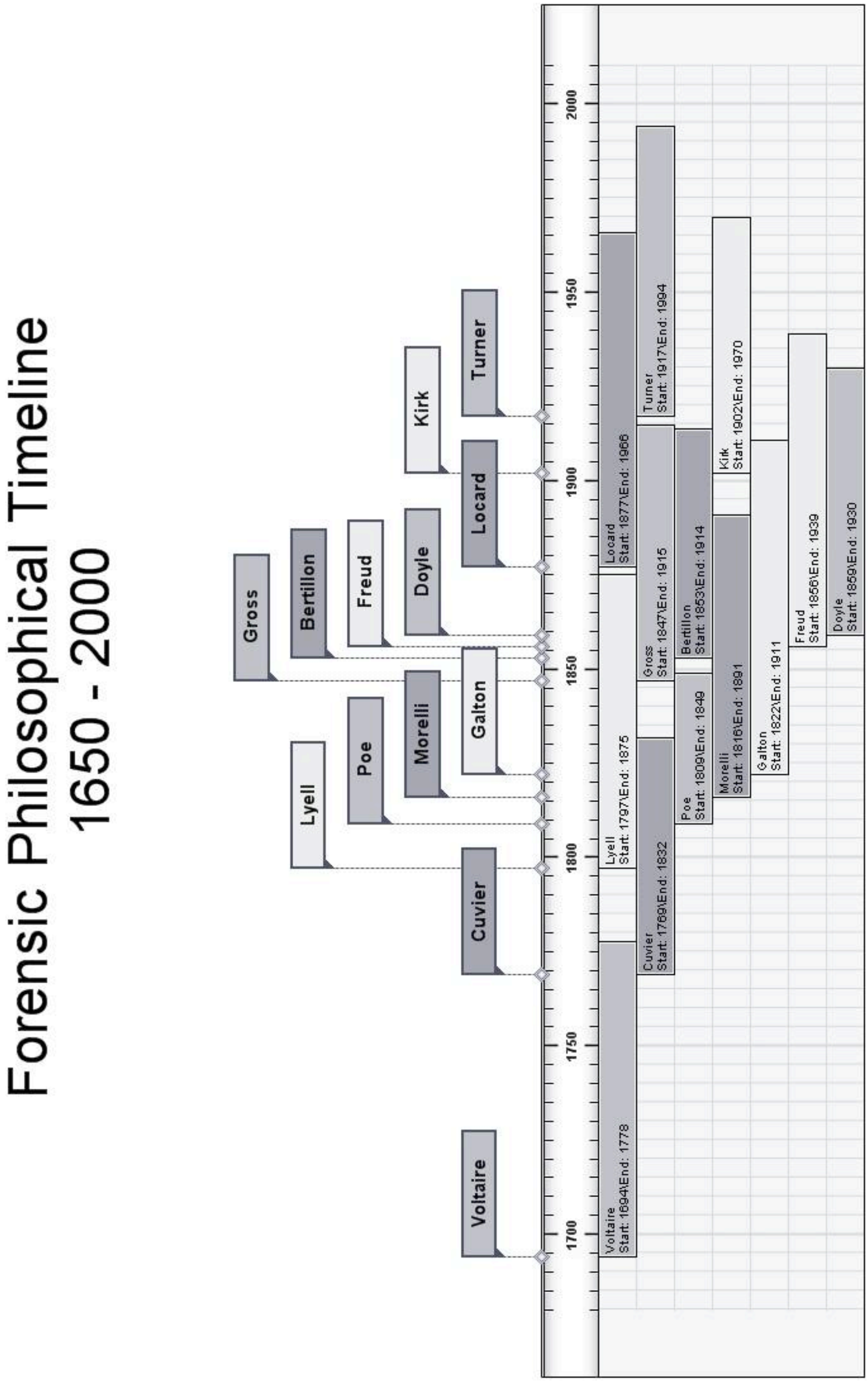


Figure 6. A timeline of relevant individuals who influenced the forensic mindset.

Chapter 3: Forensic science is a separate science

> “Methodological innocence leads to methodological vulnerability.” ([49], page 51)
>
> "Adso," William said, "Solving a mystery is not the same as deducing from of first principles. Nor does it amount simply to collecting a number of particular data from which to infer a general law. It means, rather, facing one or two or three particular data apparently with nothing in common, and is trying to imagine whether they could represent so many instances of a general law you don't yet know, and which perhaps has never been pronounced.” ([64], page 365)

Introduction

As was offered in the previous chapter, forensic science is a historical science in that the focus of its study is past criminal events. Unlike many other historical sciences, however, forensic science has not achieved the universal status of being a “real” science, either by academics [13, 114] or legal critics [115, 116]. Obstacles to this acceptance include the temporal depth of study, the principle of individualization, the dichotomy of basic and applied science, and the pace of change in modern material culture. This chapter describes these obstacles and the notional principles in place, tacitly or explicitly, that counter or may lead to countering the obstacles. With this basis, forensic science should be able to operate as a science and, doing so, gain greater acceptance among its sibling disciplines.

Of the historical sciences, forensic science is most similar to archaeology for a variety of reasons, significantly its shorter temporal depth, its analysis of material culture, and the analysis of mass-produced proxy data [117-121] (Table 1)[5]. The relatedness between forensic science and archaeology has been discussed elsewhere but largely through field methods (crime scene reconstruction and excavations) [122].

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[5] As a reminder, consideration of natural items—and the application of supply chain logistics—that become evidence are outside the scope of the current work.

	Forensic Science	**Archaeology**	**Geology**	**Astronomy**
Time Frame	Hours, days, years	Decades to millennia	Millions of years	Billions of years
Activity Level	Personal; Individual	Social; Populations	Global	Universal
Proxy Data	Natural and mass-produced	Natural and manufactured	Natural	Light

Table 1. Forensic science is an historical science because it reconstructs past events from the physical remnants ('proxy data') of those events. In this way, forensic science is similar to other historical sciences such as astronomy, geology, paleontology, and archaeology but is most similar to the latter.

One of the key concepts that has defined forensic science nearly from the outset is individualization, the assignment of an item of evidence to one and only one source [22]. This concept has been asserted with a certainty that defies scientific convention [24, 115, 116, 123], although that position has weakened in some quarters through a discussion in the literature [11, 116] with the recognition of statistics being an integral part of forensic interpretations [24, 124]. The defiant nature of the strong form of individuality—which may have its origins in the legal requirements of the forensic disciplines [106]—has helped retard the scientific acceptance and progress of forensic science as a separate science [11]. Additionally, the concept of basic vs. applied sciences, as originally outlined by Vannevar Bush [21], may have kept forensic science marginalized from academic sciences, as it has tinged others with a perception of "science light" [125].

A Science of Modern Material Culture

Crime is considered a cultural activity. Archaeologists discern past cultural activities through remnant material objects they call artifacts [126]; historians, although not to the same extent, perform similar analyses with objects [127]. The material culture is central to the analysis of past cultural practices. In this sense, forensic science is very similar to archaeology. The main difference, of course, is the time-depth: Forensic science deals with modern materials while archaeology studies material culture from the origin of human culture to the early 20th century. From the beginnings of trade, material culture is presupposed by consumerism, the complex of "technologies, organizations, and ideologies that facilitate the mass production, mass distribution, and mass consumption of goods" ([118], page 28). Consumer societies are arranged around and oriented to providing its citizens with the vast array of products that serve various utilitarian and abstract functions [117, 119-121]. Majewski and Schiffer offer these "methodological commitments" to a material-consumerist archaeology (emphasis added):

> 1. A concern to describe and explain the *time-space parameters of events and processes, such as manufacture and use*, in the life histories of artifacts and artifact types;
>
> 2. an appreciation for the *involvement of people in the entire suite of activities* making up the life history of an artifact or artifact type;
>
> 3. the recognition that artifacts carry out *diverse utilitarian and symbolic functions*;
>
> 4. employment of a *comparative perspective*, both diachronic and cross-cultural, but one that also acknowledges contingent, contextual factors in specific cases;
>
> 5. a *commitment to achieving an understanding of the operating principles of technologies and artifacts and then using that knowledge when constructing explanations of variability*; and
>
> 6. use of a hands-on approach for recording the formal, spatial, quantitative, and *relational properties of artifacts themselves*.

Majewski and Schiffer suggest that these foundations provide archaeologists with the ability to compare evidence about the consumption of material goods across a great time depth; the accumulated data over these spans of time can be used to explore rarely tested hypotheses. Forensic science faces a challenge in this regard, in that the time depth it studies is so brief and the material culture so ephemeral [46], yet complex by comparison with some archaeological artifacts, that data bases of modern materials are difficult to maintain and populate. Materials are improved, diversified, and discarded at a rapid pace because of consumerism, fashion, marketing, design, and utility [35, 128, 129]. Entire classes (in the forensic sense) are lost in the march of progress; for example, the idea of ‘dead fibers’, those that appeared at a price-utility horizon but were later discontinued and replaced by fibers with lower cost, better performance, or both [130].

The rapidity of change of modern material culture creates one of the greatest challenges to forensic science. A historical archaeologist (one who studies human culture from the origin of writing, roughly AD 1500 forward [131, 132]) is able to compare ceramic composition and design across decades, whereas the loss-horizon of modern materials can be less than a year [35]. Keeping abreast of new materials creates an enormous burden on forensic scientists, especially those who are responsible for analyzing multiple material types, such as trace analysts [97]. The pace of development is breathtaking not only for new products but for variants of existing products:

> For every rotary-phone model available in 1970, consumers have their choice of two dozen wireless models today; for every option package available for the 1985 Dodge Charger, there are several hundred option configurations offered for the 2006 Dodge Charger. And while endeavoring to “give the people what they want,” companies have created unprecedented levels of complexity ([133], page 4).

Although journal articles on specific material types help (for example, see [134]), the pace of market change can easily outstrip a scientific journal’s backlog of submitted articles. Products make it to market faster than ever; for example, Zara takes a clothing design to a retail product in only 5 weeks [135]. Long-term training post-employment for forensic scientists is a stop-gap; manufacturing must be incorporated into forensic educational programs. Ironically, this high-speed turnover also provides forensic science with increased resolution of products, provided they can be discerned from each other and the forensic scientist has the knowledge and ability to do so.

Another impediment is what could be called “material taphonomy,” the changes in goods over time under a variety of difficult-to-reproduce environments (for example, see [136]). Majewski and Schiffer recommend foundational studies of two types, those that reveal “basic parameters of an artifact type or types--that is, when, where, and by whom it was manufactured” and those that investigate “specific inferences about behavioral processes in the life history of artifacts” ([118], pages 28-29), and, here, for forensic science, read ‘evidence’ for ‘artifacts’. The history of design prioritizes the study of design *per se* rather than the consumption, use, or degradation of the product [86], recyclable products notwithstanding, which have their grave in the cradle-to-grave cycle preconfigured [137]. Forensic science can be said to dabble in both kinds of study on a case-by-case basis: the former are often called “manufacturer inquiries”, such as [138], and the latter are called “target studies”, such as [139]. The ad hoc nature of this research has left forensic science open to criticism and lacking an internally-consistent, coherent theory-laden philosophy [115, 140]. Although useful in and of themselves, “one-off” studies build little in terms of a unified, deep conception of forensic science’s foundations. Fundamental research into the nature of transfer and persistence has been published (the canonical Pounds and Smalldon papers [141-144], for example, and more recently that of Walbridge [145]) but more is needed to fully understand the underlying mechanisms and properties; not just *that* transfer occurs but *how* and *to what extent*.

Science and the Individual

Another obstacle to traditional scientific research in forensic science is its focus of activity on the individual or personal level. Archaeology focuses on the social, by comparison, and the unit is usually the family or household [118]; geology has a global-to-local orientation on natural processes [146, 147]. Forensic science's focus on the individual creates additional complexities unknown to other sciences. Like archaeology, forensic science goes beyond mere acquisition of goods and "subsumes the cultural relationship between humans and consumer goods and services, including behaviors, institutions, and ideas" ([118], page 31); unlike archaeology, forensic science works at the level of the individual, and must take personal—as opposed to social or institutional—behaviors into account [22, 122]. An archaeologist would, for example, analyze all porcelain ceramics or porcelains from the St. James' factory in order to make a larger statement about the materials or designs but a forensic scientist would analyze *this specific* porcelain object as an object and its relation to a *specific* crime. Law enforcement surely recognized the technical utility of the "perverse exercise" that was forensic science [80] and this utility, as was mentioned earlier, kept forensic science at a technician level (in Barrett's sense of the word [6], knowing what to do but not why that method works) during what could be considered its journeyman days:

> "...Not for an instant do we presume to disparage the sacred importance of the scientific evidence, but we can only hope that it will be remembered that it is not *science only*, but the *application of science to a particular question*, which is required" (*Illustrated Times* 2 , 17 May 1856, page 338; emphasis in original, as quoted in [148]).

Ironically, the demand of an individual-activity focus, predicated on the needs of the criminal justice system [92, 149, 150], may have kept forensic science from reaching the status of other sciences envisioned by forensic pioneers [22, 54, 151-153].

The Gallileian paradigm of science, one of detailed observation and experimental methodology, is considered to work only for some sciences; psychoanalysis, for example, was considered non-scientific by Popper because it could not provide falsifiable predictions [154]. This notion of predictive power as a hallmark of science operates particularly well for some physical sciences, such as physics, and some historical sciences, such as astronomy (predicting a planet's future position, for example) [155]; however, it does not apply to other established sciences as well, such as biology and geology [32]. Controlled (predictive) experiments are the *sine qua non* of science and other (non)scientific disciplines do not "measure up" because they,

> …cannot perform the controlled experiments of chemists or biologists because they cannot easily control other important factors. Like astronomers or meteorologists, they generally must be content largely to observe ([156], page 8).

A lack of predictive experimentation, by most accounts, has not lessened the acceptance of those historical disciplines deemed "sciences" although some have expanded their range through constructing new experimental methods [157]. Biology for many years suffered the same struggle to define itself as an autonomous science [45, 158]. Nevertheless, the academic distinction between those disciplines that experiment and those that do not persists: Hypotheses about the remote past "can never be tested by experiment, and so they are unscientific…No science can ever be historical" ([125], pages 5 and 8). Instances of "real" sciences using forensic methods, however, can easily be found [159, 160].

A notional lack of prediction is only one aspect, however, of why certain historical sciences have not been anointed as "real" sciences. The other, as noted by Ginzburg, is the individual nature of some sciences, including medicine [63]:

> …the real obstacle to the application of the Galileian paradigm was the centrality (or the lack of it) of the individual element…The more that individual traits were considered pertinent, the more the possibility of attaining exact scientific knowledge diminished (page 111).

In Ginzburg's view, sciences that deal with individual cases, situations, documents, or people are inherently qualitative for two reasons. First, using a medical example, an organized catalog of individual diseases is not enough because each disease manifests itself differently in each patient, reducing the analysis to *this* disease in *this* person. Although some of the traits are sufficiently uniform to accurately diagnose the disease, a subjective level of variance and tolerance for expression has to be learned through experience. This is seen in many forensic sciences, where, although one can learn the basic-through-advanced concepts by rote, experience is critical in the accurate interpretation of evidence (hairs being an excellent example; see [100, 161, 162], for instance). Second, the physician's knowledge of the disease was always remote, removed as he was from the patient's first-hand knowledge of the symptoms and effects. The doctor was always distant from the patient's condition (not being the patient himself), much in the way that the forensic scientist is distant from the crime or the source of the evidence [63]. In forensic science, as in medicine, the accumulation of experience is central, because

> [t]hese are essentially mute forms of knowledge in the sense that their precepts do not lend themselves to being either formalized or spoken. No one learns to be a connoisseur or diagnostician by restricting himself to practicing only preexistent rules ([63], page 125),

and, this is precisely one of the main criticisms leveled at forensic science: It is too subjective, too "experienced-based" to be good science [114, 115]. The core of the forensic mindset—the revealing of larger truths through the decoding of apparently unrelated indicators—is not only is strength but also being a weakness.

Regardless of any perceived methodological deficiencies, medicine nevertheless gained social and scientific prestige; other sciences were not so fortunate. This leads to a third obstacle, one not offered by Ginzburg: The objects of study in many of the "individual sciences" were familiar everyday items, deemed unworthy of "real" scientific investigation. Thus, "[a]s a staple of historical training, material culture has generally been absent from most university history programmes" ([95], page 1). Because the items were homely and "common," their analysis required the “almost…perverse exercise in making familiar categorizations and spatial perceptions unfamiliar--a translation from an everyday perceptual language... making the familiar unfamiliar” ([86], page 9). Add that anything can become evidence and forensic science seemed almost doomed from its onset to the margins of mainstream science; after all, who else would study pubic hairs [163], air bags [138], blow flies in Cleveland [164],and automotive-door blunt force trauma [165] as a coherent science?

The concept of the individual runs counter to most philosophies of science, as noted by Medawar, when he said, “In all sciences we are being progressively relieved of the burden of singular instances, the tyranny of the particular” ([166], page 29). The limitation of the study of the individual as a science led the sciences to follow one of two paths: “Sacrifice knowledge of the individual” ([63], page 112) and deal in mathematically-pliant (and, assumedly, more objective) generalizations or develop a new paradigm, a “science of the individual,” founded on an as-yet undefined body of knowledge. The natural sciences, broadly defined, took the first path [167]; forensic science has only recently tried to follow that uncharted second way [82, 122, 168-170]. Other sciences similarly have wrestled with the process of fundamental philosophical development and professional identity, notably archaeology [171], statistics [172], biology [20, 45, 173], and—for the current study, most importantly—chemistry [174-176], which will be discussed later.

How Forensics Co-opted Science

In 1910 Edmund Locard established the first forensic laboratory in the world in Lausanne, Switzerland; it would be another 13 years before the first forensic laboratory would be created in the US by the Los Angeles Police Department. In 1930, the Federal Bureau of Investigation (FBI) established its Bureau of Identification, followed two years later with the creation of its own forensic laboratory (November 24, 1932). Other types of operational forensic science laboratories were instituted in the US after this and later expanded due to funding from the Office of Law Enforcement Assistance and its successor, the US Law Enforcement Assistance Administration (LEAA) to improve law enforcement's access to forensic testing in the 1960s and 1970s [177, 178]. This created an expansion of forensic science educational programs, generally, over the years, reflecting the growth of formal education Kirk spoke of (Figure 7). The origination of the curriculum in what was then "police science" and later was coined "criminalistics" by Kirk [22] was oriented around teachings in law and medicine [179, 180].

The translation of the forensic laboratory from Europe to the US (most likely through emulation of Scotland Yard's facilities) resulted in the laboratory functions shifting from an independent university setting (as with Locard) to a subservient administrative section within a law enforcement agency [181-183]: The laboratory literally served law enforcement. The autonomy of the university, particularly in the US with the notion of academic freedom [184], was largely gone and the purpose of the scientist was now to respond to the investigator's needs:

> Without a doubt, the laboratory, as it exists in the United States, is an appendage of a quasi-military operation of an enforcement agency. As in the military, the laboratory technician in the quasi-military operation is subordinate to the administration, which is usually not technically trained. The technician, therefore, does not have the freedom of decision nor the opportunity for research that would exist if he were a dedicated, well-trained scientist acting as a civilian in the proper framework ([183], pages 99-100).

The forensic laboratory, from its inception, was seen as desirable, "cutting edge" science used to enhance older investigative methods (the "needle in the haystack" method of human intelligence and shoe leather [185]). Ironically, the breadth and utility of forensic science may have been a hindrance to its development, much as in statistics [186]. The desirability of having a laboratory, aggravated by its media status as a new method of catching criminals (for an instance of *plus ca change plus a la meme chose*; see [187]), resulted in many laboratories being hastily conceived and brought into being, resulting in numerous problems, such as the professional roles and independence of scientists, salary differentials between scientists and officers, oversight of scientists by sworn personnel, and a misunderstanding of technicians vs. scientists [181]. The proliferation of new laboratories stressed the resources of police agencies along with the increased demands, administrative as well as financial, that science entailed: Capital equipment, training, and personnel. These pressures further subsumed the scientists' work under that of the investigator who now had to juggle not only his own cases but manage the scientists and their increasingly complex scientific techniques [149].

Despite the modernity of "scientific detection" and any perceived benefits accrued, the laboratory was also an "incomprehensible" [181] novelty to the non-scientific police:

> Some of these [law enforcement] agencies which are so eager to have a laboratory have demonstrated to the author's satisfaction that they don't even know what a laboratory is for. Even worse, they have little or no conception of the proper use of a laboratory ([183], page 100).

For example, in 1942, one police science text noted that,

> In general, American detectives do not place much weight upon the application of scientific principles to the solution of the crimes which they are called upon to investigate. There is a reason for this. they place more stress on their lines of information and their acquaintance with criminals and criminal methods (page 39)…"What help," they say, "will science be in catching pick-pockets, bunco men, swindlers, and other types of criminal offenders?" ([188]pages 39-40).

The conservative nature of the law has a different flavor than the conservative approach science takes. The external influences and pressures of the law's goals and requirements tinted forensic science's perspective and retarded what might have otherwise been a more fruitful area of academic endeavor:

> The forensic scientist is conservative in his outlook, partly because over the years he has had to acquire his methods slowly and painfully: I have deliberately used the word painfully because the acquisition has been accomplished against the background of growing work load, shortage of

> money for equipment, and in the face of some skepticism of the value of scientific evidence from the legal profession. …However, the process has not been made easy by the tactics of some lawyers who have relied on emotive rather than rational criticism ([189], page127).

Science is open-ended and questioning [190] while the law needs a specific answer in a limited amount of time [191]. The differences between legal and scientific professionals has been detailed elsewhere [192] but, suffice it to say, the legal profession has driven forensic science before it and left it, in the opinions of some, nearly empty, barely able to stand as a science or even a collection of methodologies [13, 115, 116, 193]. As previously suggested, this is a more emotive than rational—or even realistic—criticism and yet it has effected forensic science just the same.

Forensic laboratories popped up at the local, state, and national level, each with individual mandates, political structures, and jurisdictional requirements. The result is the uncoordinated patchwork that exists today [13], one which historically abandoned the concept of "consistency". If forensic scientists accept their science as "merely applied", why should anyone else think differently? The expansion of forensic science into academia creates additional tensions—with limited resources, academics "in established departments…want to preserve what they viewed as the traditional core of their disciplines" ([194], page 1). Forensic science's treatment as applied often subordinated it within existing biology or chemistry academic departments; as was the case with paleontology, a related historical science, this prevented the discipline from having the opportunity to establish itself as a separate science within academia [195]. The recent growth of forensic science programs is encouraging but possibly signals only the beginning of forensic science being incorporated into academia:

> "Emerging fields of knowledge become new scientific disciplines only after they have found a secure place in universities…New scientific ideas emerge in a variety of

> settings, but they become the common heritage of humanity only when processed by an institution for advanced instruction like the modern university" ([196], page 73).

Although forensic science programs have existed in the US since 1947, they are only now beginning the struggle for academic acceptance [197].

Basic or Applied?

American universities have always had a utilitarian basis to them, reflecting the pioneering, entrepreneurial spirit of the New World [184]. American universities are governed by laypeople—in direct contradiction to European academic traditions—and this has reinforced what Hofstadter said was a universal respect for a "man of intelligence" but not intellectuals [198]. This philosophical strain between Europe and America, between knowledge and practice, has festered within the academy and become aggravated by the rise of the US as a major world power [167]. Physics, for example, was at one time considered, in part, to be a lowly science for the very reason that it was premised on practical, *physical* experiments; "the physical manipulation of objects was seen as not belonging to the scholarly tradition, in which a clear distinction between doing and knowing still predominated" ([167], page 60). The battle continued into the 19th century until state-sponsored industry and military needs spurred funding for and political support of physical research; academia's hand was forced into accepting physics as a science [199]. The two traditions, practical experimenters and bookish scholars, came together as a single community each with its own epistemological standing [200]. That comparative standing was unequal and those sciences that "discover" (natural) were thought of more highly (by tradition) than those that "invented" (human-built); the difference between these two terms was made distinct only in the 19th century [200, 201].

The flow of ideas in science is typically described as "from basic to applied", that is, fundamental discoveries about the world lead linearly to direct useful applications [202, 203]. Although this certainly does happen, there are many, many examples of unexpected discoveries in applied science leading to basic knowledge about the world, such as radio astronomy, pulsars, computers, lasers [203], and microfluidics [202]. As was noted by the Nobel Laureate (Chemistry), George Porter, "Thermodynamics owes more to the steam engine than the steam engine owes to science.” Numerous well-known scientists, for example Carl Gauss, Lord Kelvin, Pierre Gilles de Gennes, and Charles Townes, have all worked in both “pure” and “applied” research; Quake’s point is that the line between the two is artificial and impedes science overall [202].

Chemistry is a good example of an applied or experiential science becoming accepted as a basic one [175, 176, 204]. Chemistry originated as diverse methods applied in numerous industries, like mining and metallurgy, and eventually (early 18th century) began to explore topics outside of the standard academic areas [175]. Early chemists pushed for their studies to be considered an autonomous science, apart from physics. Chemistry eventually married the “intellectual understanding of nature” and “the practical conquest of nature” ([204], page 39) into one discipline. And acceptance was not immediate—Cambridge had a chair of chemistry only in 1702, 80 years behind other sciences [176]. Its dual nature is still a struggle for some: Librarians classify chemistry books differently from applied-chemistry books (the 500s, “natural sciences and mathematics” for the former and the 600s “technology (applied science)” for the latter [205]).

One of the major motivators in coalescing chemical methods into the science of chemistry was the development of organic chemistry and the rise of the synthetic dye industry [175, 176, 204]. By incorporating chemical theory into chemical formulae, chemists could now organize reactions (main, side, and successive) and the composition of chemical compounds by quantitative units. Using Comte’s hierarchy of sciences as a basis, Ostwald stated that chemistry had achieved the first two stages of a science, that of determining the facts and classifying them in an orderly way. Only physics, in his opinion, achieved the third level: Determining general laws that describe phenomena [206, 207]. Despite any contentions one may have with Ostwald's assessment of chemistry's level of science, it must be recognized that the formulation of general laws is considered the highest mark of a science [208].

How would forensic science fare with Comte's levels of science? Forensic science surely can determine the facts. The organization of these facts may be more or less orderly, more so for some disciplines (DNA) than for others (pattern evidence, for example). No accepted scheme has been developed for the organization of forensic science's facts, that is, no coherent foundational philosophy. Rowlinson offered chemists four errors committed by "would-be chemical philosophers" in their attempts to distinguish chemistry from physics ([176], page 7) that "forensic philosophers" would do well to heed:

1. "Citing the views of past distinguished chemists" when those views have been "overtaken by events" more recent and perhaps more relevant,
2. "Not distinguishing history from philosophy",
3. Considering the failure of a modern method to explain experimental results as a "failure of the essential correctness of the theories", and
4. Taking "an excessively legalistic approach to the points under discussion," that is, to answer questions only factually and not creating a new philosophy every time a solution to a problem is offered.

Taking Rowlinson's errors into consideration, can forensic science overcome its history by, like chemistry, codifying basic and general principles borrowed from other disciplines including those made specific to its needs into a coherent organizational framework? As a starting point, has forensic science posited any principles or laws unique to itself?

A Scheme of Forensic Science Philosophy

Evidence is the basic conceptual unit of forensic science. Haq and co-authors provide a definition of physical evidence as "any change in physical environment (as space-energy-matter) that is brought about or associated with human criminal activity" ([209], page 214). Evidence also has been described as people, places, and things involved in, associated with, or altered in relation to an alleged criminal act [58]. These objects, in combination with the criminal activity, become joined into propositional life, through the convergence of Gaddis' contingencies and continuities.

Every piece of forensic evidence carries two fundamental levels of information. The first is class information, grouping items by shared characteristics. All Philips-head screwdrivers, for instance, constitute a class: They all are hand tools with “plus-shaped” tips. Classes are contextual. An orange, a grape, and a bowling ball could be grouped in the class “round objects”; they could also be segregated into “round organic” and “round inorganic.” Classes have multiple members and it may not be possible to distinguish--other than by enumeration--between members within a class: a rack of black bowling balls, a bunch of grapes, or a sack of oranges, for example. Therefore, it may be possible to describe a piece of evidence from a crime scene, such as a pubic hair, only as being indistinguishable in all tested characteristics from a known sample, the pubic hairs of the suspect. For other types of evidence, a very high level of resolution may be possible; DNA short tandem repeat (STR) analysis is a primary example [26].

Forensic science has three native principles that form a philosophical, if not theoretical, basis; other principles or concepts, borrowed from related historical disciplines, fill in necessary working modes. The three native principles are classification, individualization, and the exchange principle. The non-native principles include the principles of correlation of parts, uniformitarianism, superposition, lateral continuity, and chronology.

Native Principles: Classification

Any collection of objects, real or imagined, is a set; set theory is the branch of mathematics that studies these collections. Basic set theory involves categorization and organization of the objects, sometimes using Venn diagrams, and involves elementary operations such as set union and set intersection. Advanced topics, including cardinality, are standard in undergraduate mathematics courses. For purposes of this thesis, only elementary set theory is necessary to convey the notion of classification as a native forensic principle.

The notion of set is undefined; the objects described as constituting a set create the definition. The objects in a set are called the members or elements of that set.[6] Objects belong to a set; sets consist of their members. The members of a set may be real or imagined; they do not need to be present to be a member of that set. Membership criteria for a set should be definite and accountable. The set, “All people in this room over 5’5” tall,” is a well-defined, if currently unknown set—the height of the people in the room would have to be measured to accurately populate the set. If the definition is vague then that collection may not be considered a set. For example, is “q” the same as “Q”? If the set is “The 26 letters of the English alphabet,” then they are the same member; if the set is, “The 52 upper-case and lower-case letters of the English alphabet,” then they are two separate members.

Sets may be finite or infinite; a set with only one member is called a singleton or a singleton set. Two sets are identical if and only if they have exactly the same members. The cardinality of a set is the number of members within it, written |A| for set A. A set X is a **subset** of set Y if and only if every member of X is also a member of Y; for example, the set of all Philips head screwdrivers is a subset of the set of all screwdrivers. Forensic scientists would term this a “subclass” [210] but that is a terminological and not a conceptual difference. Two more concepts are required for the remainder of our discussion. The **union** of X and Y is a set whose members are only the members of X, Y, or both. Thus, if X were (1, 2, 3) and Y were (2, 3, 4) then the union of X and Y, written $X \cup Y$, would contain (1, 2, 3, 4).

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[6] Because of the potential confusion of element, a member of a set, and element, a primary kind of material (for example, magnesium or iron), the term “member” will be used in this discussion.

Finally the **intersection** of two sets contains only the members of both *X* and *Y*. In the previous example, the intersection of *X* and *Y* would be (2, 3), written $X \cap Y$ [211, 212].

The distinction between class and individual evidence is central to forensic science [210]. Little has been done in the way of research or refinement of the bulk notion of "class"; the work of Thornton [210] is an overlooked but notable exception. Thornton noted that variance in class characteristics in one set of handguns was "nonchalance in the manufacturing method" (page 502). This "nonchalance" is part of the variance in the supply chain that has been mentioned in this thesis. Set theory may provide fertile ground for advanced research in the latent epistemology of forensic science.

Taxonomy, the practice and science of classification, refers to a formalized system for ordering and grouping things, typically living things using the Linnean method . Given that the taxa (the units of a taxonomic system) are sufficiently fixed so as to provide a structure for classification, the utility of taxonomy to forensic science is questionable. Evidence is initially categorized much like the real world; that is, based on the in-house or market-specific taxonomy created by one or more manufacturers. Forensic science alters and enhances this taxonomy to further clarify the meaning of evidence relevant to the goals and procedures of the discipline [213]. Forensic science's taxonomies, while based—at least initially—on the manufacturers' taxonomies, is nevertheless different from them. Manufacturing of economic goods, for example, creates its taxonomy through analytical methods. Set methods ensure a quality product fit for purpose and sale. The taxonomy is based on the markets involved, the orientation of the company production methods, and the supply chain. Explicit rules exist on categories recognized by manufacturers and consumers, either as models or brands [35, 214]. Forensic analytical methods create different classifications because the science uses different sets of methods because forensic scientists have different goals. Their classifications are based on manufactured traits, but also aftermarket qualities, intended end use but also “as used”. The “as used” traits are those imparted to the item after purchase either through normal use or criminal use. Forensic science has developed a set of rules through which the taxonomies are explicated. For example, forensic scientists are interested in the size, shape, and distribution of delustrants, microscopic grains of rutile titanium dioxide incorporated into a fiber to reduce its luster [215, 216]. The manufacturer has included delustrant in the fiber at a certain rate and percentage with no concern for shape or distribution (but size may be relevant). The forensic science classification is based on a manufacturing taxonomy but is extended by incidental characteristics that help us to distinguish otherwise similar objects. The methods may vary and, therefore, the classifications (Figure 8). Both production and forensic taxonomies lead to evidentiary significance because they break the world down into intelligible classes of objects related to criminal acts. Forensic science has developed an enhanced appreciation for discernment between otherwise similar objects but has yet to explicate these hierarchies to its benefit. Thus, although classification is an inextricable part of forensic science, forensic science does not necessarily deal in fixed taxonomies.

Native Principles: Individualization

The second level of information is the concept of uniqueness of evidence. Kirk cites individualization as the central concept in criminalistics (nee forensic science) [22]. Individualization is the sourcing of something to one and only one origin, that is, a unique source or a set with one and only one member. Individualization comes with assumptions that affect the resolution of analyses [217]. The first assumption is that all things are unique in space and, thus, their properties are non-overlapping. The second assumption is that properties are constant with time (see the later discussion on Uniformitarianism). Without these assumptions, statements such as, “Yes, that is a Philips head screwdriver and it is mine,” could not be properly understood. While the screwdriver in question meets the requirements for class membership in the set of “all Philips head screwdrivers,” it also possess some traits that allow for a unique identification as one's personal screwdriver (Figure 9).

The assumption of uniqueness of space is considered axiomatic and, therefore, an inherently non-provable proposition [11, 115] for numerous reasons, only some of which are germane here. The population size of "all things that might be evidence" is simply too large to account. Additionally, conclusive evidence is not readily available in typical forensic investigations. Because of this, as Schum notes, statistics are required:

> Such evidence, if it existed, would make necessary a particular hypothesis or possible conclusion being entertained. In lieu of such perfection we often make use of masses of inconclusive evidence having additional properties: The evidence is incomplete on matters relevant to our conclusions, and it comes to us from sources (including our own observations) that are, for various reasons, not completely credible. Thus inferences from such evidence can only be probabilistic in nature ([218], page 2).

A statistical analysis is therefore warranted when uncertainty, either of accounting or veracity, must exist. If an absolutely certain answer to a problem could be reached, statistical methods would not be required. In the research laboratory, the choice of the sample is more or less under the control of the scientist. In the forensic laboratory, however, the choice of evidence recognized, collected, and received largely is uncontrolled. It could be argued that the crime scene personnel have a form of control over this process but not in the basic sense of who was involved in the crime, the setting of the crime, the materials at hand and those used in the commission of the crime—the myriad ancillary details that constitute the signal and noise of a scene. Each crime is committed only once; therefore, it may seem that the study of a long series of events may be of little use. Most evidence exists at the class level and although each item involved in a crime is considered unique, it still belongs to a larger class. In reality, the majority of forensic science works at a class-level of resolution. Indeed, even DNA, the argued "gold standard" of forensic science, operates with classes and statistics [26]. Because forensic science deals with the ultimate uncertainties of the real world of criminal activities with physical items, the diaspora between the real world and the controlled environment of the research laboratory is significant. The ultimate causes or answers in casework are unknown, the evidence involved has not been compared with the evidence in a significant number of other cases, and the proper interobserver checks and balances were not in place. In other words, casework is not research, uncertainty abounds, and statistics must be used [24].

In a recent paper by Cole [11], the author argues convincingly that the concept of uniqueness is “necessary but not sufficient to support claims of individualization” (page 246) and suggests that the concept does more harm than good for forensic science. If it is accepted that uniqueness is axiomatic [219] and, thus, in Wittgenstein’s view, meaningless [220], then

> What matters is whether we have analytical tools necessary to discern the characteristics that *distinguish* one object from all others or, in the forensic context, distinguish *traces* made by each object from traces made by every other object…Every object is presumably unique at the scale of manufacture. The question is whether objects are distinguishable at the scale of detection. Since all objects in the universe are in some respects ‘the same’ and in other respects ‘different’ from all other objects in the universe, according to Wittgenstein, what really matters is not uniqueness but rather what rules we articulate by which we will make determinations of ‘sameness’ and ‘difference’ ([11], pages 242-243).

Although things may be numerically unique at the point of production (a la Kwan [217]), this does not help to distinguish between otherwise similar objects at the point of detection. New rules, or a refinement or at least a reification of existing ones, is required for forensic science to move forward as a separate discipline.

Native Principles: Exchange

The third native principle that guides forensic science is the exchange principle, developed by Edmund Locard [29, 66, 221]. The principle posits that when two items come into contact, information may be exchanged; the results of such a transfer would be proxy data. This exchange may occur even if the results are not identifiable or are too small to be found. Because forensic science demonstrates associations between people, places, and things through the analysis of proxy data, essentially all evidence is transfer evidence (Table 2).

Item	Transferred From (source)	Transferred To (target/location)
Drugs	Geographic locale of plant	Dealer
	Dealer	Buyer's pocket or car
Blood stains	Victim's body	Bedroom wall
Alcohol	Bottle	Drunk driver's blood stream
Semen	Assailant	Victim
Ink	Writer's pen	Stolen check
Handwriting	Writer's hand	Falsified document
Fibers	Kidnapper's car	Victim's jacket
Paint chips	Vehicle	Hit-and-run victim
Bullet	Shooter's gun	Victim's body
Striations	Barrel of shooter's gun	Discharged bullet
Imperfections	Barrel-cutting tool	Shooter's gun's barrel

Table 2. Essentially, all evidence is transfer evidence, as is suggested by these examples. Note that in many cases, as with bullets, there are multiple layers of the transfers that build to the proximate source of meaning for evidence. These layers often are integral parts of the supply chain of the product.

Each evidence example offered in the Table has multiple layers that build up, some hierarchically, to create the specificity and meaningfulness of the evidence. Note that many of these layers explicitly involve the supply chain of the product but extend past the traditional notion of its end point (consumer), as with the bullet example. This highlights the concept that forensic science adds meaning to mass-produced items and creates additional taxonomic levels to the existing ones used by manufacturing [4].

What is known as “Locard's Exchange Principle” was never postulated as such by its author, although he offered many practical examples in support of its workings[7]. The original work states:

> The truth is that none can act with the intensity induced by criminal activities without leaving multiple traces of his passing. [...] The clues I want to speak of here are of two kinds: Sometimes the criminal leaves traces at a scene by his actions; sometimes, alternatively, he picked up on his clothes or his body traces of his location or presence ([221], page 139, translated by Frank Crispino).

Locard is speaking, in modern professional parlance, of one-way transfer and cross-transfer. Commonly—and erroneously—the Locard Exchange Principle is often paraphrased as, “Every contract leaves a trace.” This phrasing sounds less like a *principle* (a general or inclusive statement about an aspect of the natural world that has numerous special applications or is applicable in a wide variety of cases [68]) and more like a *law* (deduced from particular facts, applicable to a defined group or class of phenomena, and expressible by the statement that a particular phenomenon *always* occurs if certain conditions be present [68]). Locard's own words sound definitive (“none can act...without”) and the Exchange Principle stands unchallenged in forensic science and is considered axiomatic [170]. This standing, however, begs the question: Is the Exchange Principle truly a principle, or is it a theory or even a law of nature? More importantly, if untested or unproven, is it even scientific?

A law of nature is a scientific generalization based on empirical observations of physical behavior through repeated scientific experiments. Laws are accepted universally; the accumulation of a summary description of the world through laws of nature is a central goal of science. Physical laws are:

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[7] Portions of this section were presented at the 2007 ANZFSS Symposium and were co-authored with Frank Crispino.

True, at least within their regime of validity; stable, and omnipotent (effect all things)

- Universal, simple, and absolute ([222], pages 82-83)
- Generally conservative of quantity, often expressions of existing homogeneities (symmetries) of space and time, and typically theoretically reversible in time, although time itself is irreversible ([223], page 59).

Physical laws are, by their nature, simpler than theories, which have many component parts. Therefore, theories are more malleable in the face of new information while laws, being an umbrella for a set of strictly empirical results, remain unchanging (the law of gravity cannot be repealed). Theories account for observations by explaining and relating them to other observations. A foundation is then laid for testable predictions (experimentations) based upon those theories. Laws state *that* something happens, theories explain *why* something happens.

If left at the dogmatic phrasing of “every contact leaves a trace”, the Exchange Principle is manifestly not a law of nature: A steel ball-bearing touching a steel plate would result in a millisecond trace of kinetic energy and perhaps a few molecules of steel, hardly evidence of a useful type but evidence nonetheless—a transfer *did* occur but currently there is no way to analyze it. This is what led Thornton to state:

> It should be recognized that Locard’s doctrine is, and always has been, an assumption—not an immutable law drawn after a systematic study or experimentation…[it] may be modified to state, “If a contact leaves a trace, it is up to us to detect it.” ([224], page 210).

The set of variables in any scenario that even remotely resembles the real world becomes difficult to account for in a law-like fashion (Pounds and Smalldon's fiber transfer work comes to mind [141-144]); nominally, only those few controlled variables would hold and may not resemble “the real world”. The Exchange Principle is therefore fundamentally a statement that combines materials science, criminology, and psychology; hence, it is probabilistic, concerning a set of inductive observations that are poorly to moderately understood in terms of their complexity, universality, and application [145]. The Exchange Principle fits the definition of a principle far better than its colloquial phrasing might suggest. This could confer to the Exchange Principle an epistemologically recognized qualification of a 'bridge principle' [225], one that establishes relations between a proposed process and the observed data, in the case of forensic science, criminal activity and the traces left behind by it. More basic research is necessary to better understand the Exchange Principle and its function as a central tenet of forensic science (for example, see [145].

Non-native principles: Uniformitarianism and others

Numerous guiding principles from other sciences apply centrally to forensic science, several of which come from geology. The first, and in many ways the most central, of the external principles is that of Uniformitarianism. The principle was proposed by James Hutton, popularized by Charles Lyell, and the word was coined by William Whewell and states that natural phenomena do not change in scope, intensity, or effect with time [146]. Paraphrased as “the present is the key to the past,” the principle implies that a volcano that erupts today acts in the same way as volcanoes did 200 or 200 million years ago and, thus, allows geologists to interpret proxy data from past events through current effects. Likewise, in forensic science, bullets test-fired in the laboratory today do not change in scope, intensity, or effect from bullets fired during the commission of a crime two days, two weeks, or two years previously. The same is true of any analysis in forensic science that requires a replication or reconstruction of processes in play during the crime’s commission. An analogous process occurs in forensic science’s sister discipline, archaeology, when ethnographic data, such as the tool-making processes of modern native peoples, is studied to discern and reveal past cultural practices [126]. Uniformitarianism offers a level of objectivity to historical sciences [226] by “positing relationships of a general nature and then by deriving predictions or tests of each relationship with respect to particular...cases” ([86], page 4). Thus, as with Edmund

Halley predicted the return of “his” comet in 1758 before his death in 1742, “the scientist makes no distinction between old and new data, because he believes that the nature of the phenomenon has not changed in the interval” ([103], page 146).

To the list of non-native principles should be added Cuvier’s Principle of Correlation of Parts (recall from Chapter 2), without which little could be done having Locard’s Principle firmly in hand. Cuvier’s principle is what allowed him to identify anatomical elements and their parent organism from miniscule fossil bones or even parts of them.

Gardner and Bevel [122] outline three additional principles from geology that they hold as applicable to crime scene reconstruction[8], those of superposition (in a physical distribution, older materials are below younger materials unless a subsequent action alters this arrangement), lateral continuity (disassociated but similar strata (layers) can be assumed to be from the same depositional period), and chronology, (the notion of absolute dates in a quantitative mode and relative dates in a relational mode, that is, older or younger) [146]. These three principles are attributed to Nicolaus Steno [227] but were also formalized and applied by William “Strata” Smith [228]. A forensic example of the principle of superposition would be the packing of different soils in a tire tread, the most recent being the outermost [229]. A good case of lateral continuity would be the cross-transfer of fibers in an assault, given that the chances of independent transfer and persistence prior to the time of the incident would be improbable [230, 231]. An example of absolute chronology in forensic science would be the simple example of a purchase receipt from a retail store with a time-date stamp on it. Examples of relative chronology abound but could range from the

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[8] There is some intent in their article that crime scene reconstruction is its own science, that is, separate from or at least within what might be called criminalistics or forensic science: “Crime scene reconstruction (CSR) is a distinct forensic discipline and faces the same issues [as] “every discipline in forensics” (page 891).

terminus post quem of a product no longer made, such as a rope [232], to a cold beer can where none should be [231].

Chapter Summary

Combining the native and non-native principles offered here in forensic science provides a platform for further developing a philosophy of forensic science. Some abstractions have been discussed, the philosophy offered here is mainly practical in the sense that it allows forensic science to operate on a daily basis. Furthermore, instituting the rules offered by Fisher for historical sciences should further flesh out the ontological skeleton of forensic science. On this platform, forensic science should be able to move forward and be recognized as a separate science.

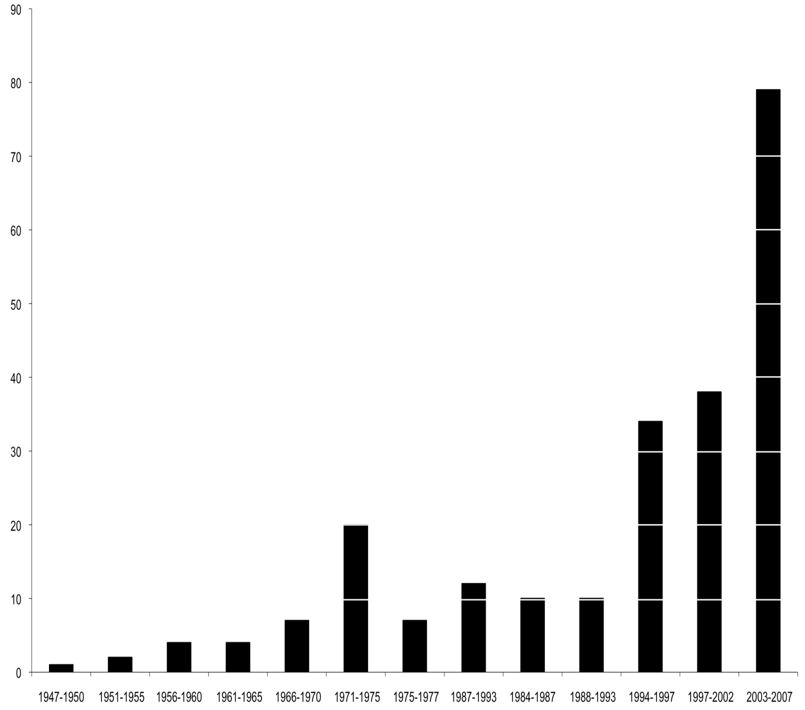

Figure 7. Cumulative number of "forensic science" programs in the US, undergraduate and graduate, 1947-2007. Sources: 1947-1975 [3]; 1975-2007 [5]. The “jump” between 1977 and 1987 represents the end point of the first article’s survey and the start of the second’s.

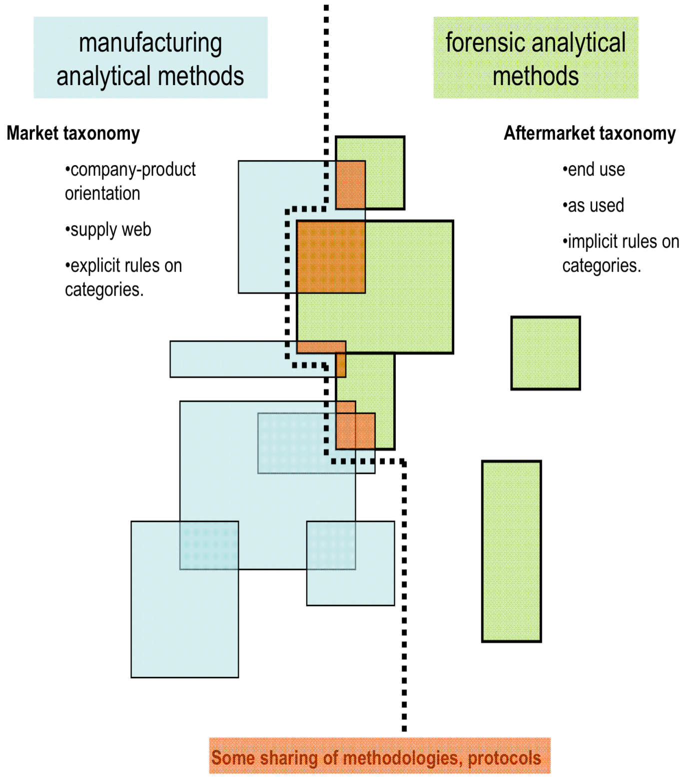

Figure 8. Manufacturers and forensic scientists create taxonomies that share taxa based on analytical methods yet may differ based on other analyses. From [4].

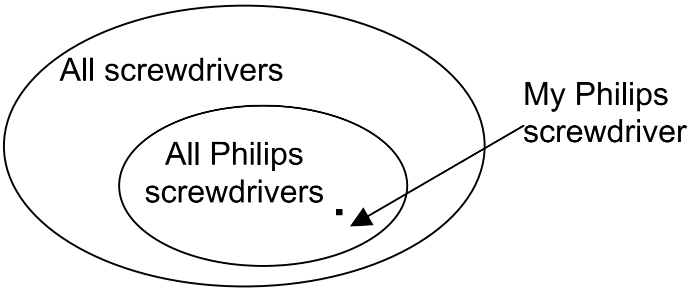

Figure 9. Venn diagrams of various classes of screwdrivers, including a unique instance (my Philips screwdriver).

Section 2

Chapter 4. Supply Chains as a Basis for Significance

> "I think it's because no one understands the axiom of criminal economics."
>
> "What on earth is that?" Kenzo said.
>
> "Well, suppose a murderer carries a torso away from the scene of the crime. What does he do with the leftover bones and internal organs once he's stripped off the skin? Actually I must confess that has only just occurred to me now that this sort of problem—the efficient management of crime-related waste—might be called 'criminal economics.' [233]

> In real life a man rarely finds that he leaves any traces behind, at least unless he is a criminal with the police on his trail. The lives of the atomized masses and of the collectivized individuals of our times vanish without trace. ([234], page 208)

Introduction

Recall from Chapter 2 the notion of continuities and contingencies converging in the crime; as they bind together, the physical manifestations of the evidence's manufacturing history become intertwined with the actions of the people involved in the crime. The physical remnants (Locard's traces, that is, evidence) have thus imposed upon them a logic, a meaning that must be used to explicate the criminal events. Part of this logic is the design and manufacturing of the physical products that become evidence.

The complexity of modern design and production methods belies the typically straight-forward methods used in forensic laboratories. Many evidence types are analyzed with little regard to the product's origins or production history. This may lead the scientist to conclusions and interpretations that under- or over-represent the true significance of the evidence. Supply chains create the myriad variations encountered in mass-produced items and, therefore, lay the foundation for the potential significance of those items encountered as evidence in forensic investigations and casework. This notion of supply chains and the complexity of manufacture is rarely incorporated into education, training, or laboratory methods, to include interpretation, in the forensic sciences. Given that non-biological materials constitute the bulk of forensic evidence [235], a greater emphasis should be placed on supply chains and their influence on the specificity of forensic interpretations.

For the discipline, this demands changes to the way that forensic science is taught in educational programs and in training workshops: Manufacturing processes must be used as the baseline for evidence analysis and interpretation. For the forensic scientist, understanding supply chains will lead to more accurate analyses in the short term and clearer foundations for interpretations in the long term. Ultimately, this view of forensic evidence could lead to a new way of treating mass-produced products that become evidence that makes forensic science more accurate, more precise, and more reliable.

Supply Chains

A supply chain is the system of organizations, people, suppliers, intermediate processors, activities, and resources involved in moving a product or service from supplier to customer. Chopra and Meindl define it as:

> all stages involved, directly or indirectly, in fulfilling a customer request. Supply chain that only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers themselves [236].

The complexity of supply chains suggests they should be called logistics networks, but the former phrase has stuck. Supply chain activities transform natural resources, raw materials, and components into a finished product that is delivered to an end customer. From an economist's point of view, supply chains link value chains (the processes that a product passes through, gaining value at each step) [40].

The management of supply chains, including production, location, and transportation, is intended to make the process responsive and efficient for the particular market in question; the company's identity is shaped, in turn, by the market and the supply chain solutions it employs. Most supply chain decisions result in a trade-off between responsiveness and efficiency. Different supply chain requirements may independently conflict with other separate requirements [10, 237]. The following attributes help to clarify requirements for the customers served:

- quantity of the product needed in each lot
- response time the customers are willing to tolerate
- the variety of products needed
- the service level required
- the price of the product
- the desired rate of innovation in the product

Thus, a company has to make decisions about its supply chains individually and collectively in five areas:

- production,
- inventory,
- location,
- transportation, and
- information.

Production is the conversion of one supply chain component into another, such as raw materials into processed goods or those into finished goods. Inventory is everything from raw materials to processed goods to finished goods held throughout the supply chain by manufacturers, distributors, and retailers. Location is the geographical placement of nodes of activities in the supply chain. Transportation is the movement of elements within the supply chain between different facilities or suppliers. Information is what drives supply chain decisions.

Companies historically have owned much or all of their supply chain. This vertical integration, as it was called, was intended to maximize control and efficiency in the more predictable economy of the early 1900s. With increasing market size, customers had more choices and became more selective of what products they bought. Vertical integration was slow to respond and cumbersome to adjust with customer demand. Greater competition, a faster pace, and a global market drove companies to seek not just optimized internal processes but also external ones. This network of inter-dependence, with each company doing what it did best, defined virtual integration.

> Say we get an order from a European retailer to produce 10,000 garments. It's not a simple matter of our Korean office sourcing Korean products or our Indonesian office sourcing Indonesian products. This customer we might decide to buy yarn from a Korean producer but have it woven and dyed in Taiwan. So we picked the yarn and ship it to Taiwan. The Japanese have the best zippers and buttons, but they manufacture them mostly in China. Okay, so we go to YKK, a big Japanese zipper manufacturer, and we order the right zippers from their Chinese plants. Then we determine that, because of quotas and labor conditions, the best place to make the garments is Thailand. So we ship everything there. And because the customer needs quick delivery, we may divide the order across five factories in Thailand… Five weeks after we have received the order, 10,000 garments arrive on the shelves in Europe… ([238], page 36).

Virtual integration vastly complicates product tracking and sourcing because of the increased number of individual companies involved in each product rather than one company completing all the tasks for a final product. On the plus side for forensic science, this complexity means that variability and diversity will be high for most products, assisting with segregating otherwise similar items of evidence (for example, see [239]).

Design Configures the Product

Most people wear a wristwatch. What does the watch do, however? Although the simple answer is, "It tells time," that is not the complete answer because a watch, or any product for that matter, means a great deal more than merely what is perceived as its primary function. As the noted designer Del Coates has said, "It is impossible, in fact, to design a watch that tells *only* time." The watch's appearance

> says different things--about itself, its designer, its manufacturer, its era, and the person who wears it. Knowing nothing more, the design of a watch alone--or of any other

> product--can suggest assumptions about the age, gender, and outlook of the person who wears it. It also conveys implications about its quality, performance, and worth. It suggests as well what the manufacturer deems important. ([10], pages 1-2)

Another way to think about this concept, suggests Coates, is that “[e]ven as we watch TV, we watch a TV set.” ([10], page 12). Everything made by humans contains in its form moral and cultural statements that demonstrate, or at least reflects, its creators and audience. In this way, artists, archaeologists, and historians interpret and understand material cultures past and present through their objects (artifacts).

Since the 1990s, design has become a larger and larger part of the production process and, thus, the selection of components directly affect the supply chain necessary to produce the item. The cost of design can exceed 50% of the product’s cost [237]. The emphasis on supply chain management is to reduce costs and create efficiencies; therefore the supply chain necessary to create and support a product is created in large part by the product’s design. Product design defines the shape of the supply-chain and has a great impact on the cost and availability of the product. The complexity of a supply chain increases immeasurably if several different products or models are to be made at one production line or facility. The product will—of necessity—be produced temporarily and then swapped for the other product for some period of time and then back. The efficiencies of the factory can easily impinge on the complexity of the finished product.

Even when the manufacturing process is followed properly step-by-step, a production lot may not conform to the stated specifications; “adjusting a batch to meet specifications can be something of a guessing game” and some parameters may be difficult or impossible to adjust, like viscosity ([240], quote from page 230). Some components may be tightly controlled while others are not. For example, in shotgun pellets, the amount of Pb and Sb are strictly controlled (Pb = 95-99%; Sb = 1-5%) while the amount of trace impurities (such as Cu, As, and Ag) demonstrates wide variation between batches [241]. If these batches are mixed during production or assembly into the shells (batches A, B, and C are poured into one large hopper and then dispensed into the shells on a production line), these pellets are far less useful forensically. Other types of variation are less fluid but no less important for distinguishing between otherwise indistinguishable products like shoe soles [242].

A product must be designed in restrictive terms that define the constraints under which the designer must work. The terms, called parameters, correspond to some property, attribute, or characteristic that define or constrain the product's final form. The parameters may be fixed (10 pounds), fuzzy (8-10 pounds), qualitative (heavier), or open (unspecified). The design process becomes more complicated with each additional constraint. Parameters are prioritized and set down as specifications for production. These specifications, in turn, become the arbiters for questions, re-prioritizing, trade-offs, and economics: the choice of steel over platinum, for example, to hit a desired retail price [10]. "Thus, it is easier to design a good drinking glass, made in a single piece from a single material, than an automobile" ([10], page 45). Yet, as Yafa notes, the challenges with a material as deceptively simple as cotton fabric could be daunting; pre-industrial dyers faced many constraints:

> To cheat nature, dyers had to create a bridge between substances that naturally repelled one another. The first step perfected by the Indians along the eastern Coromandel coast—the center of chintz dyeing—was to repeatedly soak cotton in solutions that broke down its waxy structure. Bleaching with lemon juice or sour milk helped convert the grayish raw crop to white fibers, but that was only a beginning…dyers learned to then "animalize" their cotton fiber [with] buffalo milk, goat urine, and camel dung, and sometimes blood and albumen. The proteins in the animal excretions did the bulk of the work in making the fiber receptive to the dyes. Next came the mordants…faintly colored metallic salts obtained from natural sources, most commonly alum and iron…The mordant reacted with the dye to form a "lake" that permeated the animalized fiber's

> core…The only important exception was the popular blue indigo, a pigment that chemically fixes to cotton fiber around its core and needs no chemical catalyst ([243], page 28).

And these constraints persist or change as a product develops over time. “Denim,” a corruption of a French material called *serge de Nimes* (a twill common to the town Nimes) that was created in the 16th century, was a cheap strong cloth used in the overalls of sailors (the nickname “jeans” comes from Genoan sailors who wore the fabric) and workmen [244]. By the 18th century, denim jeans were made exclusively of cotton. The application of indigo dye, a colorant commonly found in the Americas, was not just a chemical decision but also an economic one—the cloth and the indigo dye were inexpensive; plant-based dyes, such as indigo, are typically less expensive to produce and apply [243, 245]. In more modern times, the combination of inexpensive components and fit-for-purpose qualities (indigo’s affinity for cotton; fading was not a concern) placed denim at a long-standing appropriate price point; its flexibility and counter-culture flair contributed to its popularity as a fashion garment although price and durability were denim’s original attraction [243, 244].

Seemingly simple products can be deceiving. The simple notion of “more = more” is not a linear relationship between design and information. More detail, more embellishment in a finished product would suggest more front-end, pre-production intent to include more information. However, more design does not necessarily mean more information—“each product comes with the fullest possible compliment of design” ([10], page 50). Leaving something out of a product entails just as much “design” as including it; the single button on an iPod is a good example. This accords with Shannon’s notion of information that it be sufficient in all relevant respects and not optimal [246] and, indeed, the notion of “optimal” flies in the face of continual improvement towards quality [247]. Information is that which reduces uncertainty [246] and only so much certainty is needed for a product to meet production and customer requirements. Design choices lead to consumer choices (and, in truth, this is a feedback system) and, despite the moniker “mass-produced”, choices mean there must be differences between products within a class: “Clearly, there must be a difference in [pencil] sharpeners, else why would there be so many choices?” ([248], page 173). Society pushes the market to provide what is desired and this helps to delineate products by quality, price, utility, and value [35, 248]. As Ted Levitt, the marketing and management expert, noted,

> “There is no such thing as a commodity. All goods and services are differentiable. … In the marketplace, differentiation is everywhere. Everybody—producer, fabricator, seller, broker, agent, merchant—tries constantly to distinguish his or her offering from all others. This is true even of those who produce and deal in primary metals, grains, chemicals, plastics, and money” ([249], page 100).

A finished product always provides what Coates’ calls “discretionary information”, even in what may seem to be trivial information, such as decorative elements. “Design” decisions involve more than discretionary issues, however, and some are integral to the product.

Lipstick offers an interesting combination of necessary and discretionary information. First offered in push-up cases in 1915, lipsticks even then were dyed with natural colorants, such as carmine made from the cochineal bug (*Dactylopus coccus*) found on a particular species of Mexican cactus [250]. Lipsticks were not indelible (that is, they would transfer their color to any surface they touched) until about 1925. Colorants that dyed the skin red were introduced then and sold well until the 1960s when make-up in general was eschewed by females, particularly in the US [251, 252]. The design requirements for lipstick are, by any standard, demanding. The lipstick should [240, 251, 252]:

- Produce the desired color and surface (matte, frosted, glossy, etc.),
- Cover the lips evenly and go on smoothly,
- Not feel greasy but must have a neutral taste,
- Last in coverage and color and be indelible,

- Be resistant to environmental effects (heat, cold, moisture, etc.),
- Retain its shape in its container, and
- Be non-toxic and anti-bacterial.

Modern lipsticks might have the following basic composition [251, 252]:

Dye	5%
Titanium dioxide	10%
Oil	40%
Wax and modifiers	20%
Emollient	25%
Other	Trace[9]

The composition depends on whether the lipstick is matte, gloss, or pearlescent, for example. Barel, et al. list 11 different types of waxes and 9 different emollients [251] used in "classic lipstick". A simplified process is described as follows ([251], page 671):

> "1. Pigments are premilled in either one of the emollients (e.g., castor oil) or the complete emollent phase either by a 3-roller mill, stone mill, or a type of ball mill. 2. Grind phase is added to complete emollient phase and waxes, heated and mixed until uniform (approx. 90-105°C). 3. Pearls and fillers are added to above phases and mixed with shear (if necessary) until homogenous. 4. Add actives, preservatives, fragrance and antioxidants and mix until uniform. 5. Maintain a temperature just above the initial set point of the waxes and fill as appropriate."

All this chemistry, design, and process in a product roughly 2.5" long. It is important to note that supply chains are forward in orientation having a finished product as their goal. Forensic science, being historical in the primary sense, must tease out the particular parameters of any one product to learn how (or if) it can be differentiated from other similar products. If, as Philip Nobel says, design is the art that is hidden in plain sight [253], then it is fitting that forensic science is that which makes the invisible seen (see Chapter 2). Products encoded with their manufacturing information lay

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[9] Including odorants, preservatives, vitamin E, sunscreen, and occasionally flavoring agents.

waiting for forensic scientists to unravel a history that otherwise would stay hidden.

Post-supply chain transformations

In archaeological theory, artifacts are considered to go through either cultural transformations (c-transforms) or natural transformations (n-transforms) [254]. A c-transform would be a human activity that alters or augments the artifact's shape or content, such as abrading a piece of fabric, grinding a serial number from a gun frame, or tableting methamphetamine, among other forensic examples. An n-transform, however, is part of a natural process and would involve the chemical break down of the fiber, the rusting of a metal part, or the dissolution of a tablet in water, to continue with the previous examples. C- and n-transforms are part of the full articulation of production and consumption "through the synthesis and construction of raw materials into artifacts and their subsequent breaking down and decay back into the natural system." ([254], page 23).

Crimes scenes are mixtures of relevant and irrelevant (from an investigative point of view) objects which have undergone c- and n-transforms. The relevancy is determined by the object's involvement in the criminal activity, regardless of the transform: A bullet hole in a wall from a firearm discharged at a victim (c-transform) may be as useful to an investigation as the decomposing body of the victim that yields a post-mortem interval (n-transform). It is important to distinguish between transforms for the sake of clarity and accuracy. For example, fly specks, the small spots left behind when a fly has fed on a bloody surface, must be distinguished from aerosoled blood spatter [255]. The focus in forensic science has been on peri- and post-crime transforms; one of the tenets of the present work is that much of what is termed "significance" from an evidentiary standpoint actually is in place and fixed *prior* to the crime. In this sense, the fixture of the supply chain in the final product echoes Gaddis' distinction between contingencies and continuities. A product is the culmination of the contingencies (nodes in the supply chain) and continuities (production methods) of its manufacture, a modern artifact of that particular design, manufacture, and distribution stream.

Globalization and localization have led some investigators to adopt a forensic mindset. Food, tied to the concept of *terroir* (the special characteristics that geography bestows upon particular varieties of consumables, such as wine or coffee [68]) and the processing required to render it edible, is a particularly fertile product for supply chain sourcing. Some analyses produce inexact results. One study used multicollector-inductively coupled plasma mass spectrometry (MC-ICPMS) and thermal ionization mass spectrometry (TIMS) to link food commodities to production locales in Europe. The researchers found that correlations between soil locales and various elements in products (Ba, Ca, Na, Rb, and $^{87}Sr/^{86}Sr$ ratios) existed but should be interpreted with caution [256]; median values of $^{87}Sr/^{86}Sr$ at the 95% confidence level were 0.7091, 0.7098, and 0.7056 for three wheat samples, for example, leading to a high potential for false positives. The researchers recommend “as many parameters as possible should be combined to obtain optimal spatial discrimination”.

Wine and associated products offer a more specific palette of media to identify sources. Not only can wines be easily distinguished by the continent from which the oak for the ageing barrels originated [257, 258] but also to the forest where the trees were grown [259] regardless of the variability involved in the barrel production or cooperage [260]. This discrimination is possible because of the natural complexity of wine, the wine-barrel interactions, and the methods employed, typically a form of high-resolution mass-spectrometry, providing “an instantaneous metabolite picture of a complex logical system, which encompasses all of…[the] genetic factors modulated by constantly evolving environmental factors” ([260], page 9175).

As food becomes more processed, however, the supply chain becomes more complicated and sourcing potentially more difficult. One study on fast food used carbon and nitrogen stable isotopes to interpret sources for feed to animals, the fat used to cook potatoes, and the confinement that comes with modern animal production [261]. The authors found the extent of confinement similar for chickens and cattle and that heavily-fertilized corn constituted between 93% and 100% of the food for the animals. Additionally, the analysis of ^{13}C indicated that different fast food chains used different methods for cooking their French fries, which differed from the ingredients listed by those businesses. Food and related comestibles are consumed and incorporated into living organisms. Such as example, one with a forensic application, is the oxygen isotope ratios in human skeletons, specifically ^{18}O [1]. The levels of ^{18}O vary due to landscape development, locale, and geography (for example, ^{18}O is lower in mountains and on the lee-side of ranges). The level of ^{18}O taken up in humans is determined by drinking water and using an average value based on local precipitation (Figure 1) produces a distribution across the landscape. Differences in background relate to differences in available isotopes. This method was used to investigate the identity of a female murder victim in Mammoth Lakes, California, tracing her living locales from her early life in Oaxaca, Mexico to her later years most likely in southern Mexico or northern Guatemala until her demise in southern California.

Impediments to traceability

Despite these instances of tantalizing success, supply chains are, in reality, “much messier” because “[r]elationships change frequently and may be combative, loosely aligned, cooperative or collaborative…such turmoil creates inefficiencies” ([262], page 1). Record-keeping is crucial for tracking products through the supply chain. For example, in a study of traceability of foodstuffs, the US Office of Inspector General found that a lack of lot-specific record-keeping, incorrect or missing labeling, and the mixing of products from a variety of sources contributed to the Office’s inability to trace products through each stage of the food supply chain [263]. In that study, only 5 of the 40 products could be traced through each stage of the food supply chain, nearly 60% of the food facilities kept inadequate records about their sources, recipients, and transporters, and managers of those facilities often were not aware of the US Food and Drug Administration's record-keeping requirements (Figure 11). Record-keeping, so central to forensic science and law enforcement, is important to manufacturing only insofar as it relates to legal requirements for such paperwork, quality assurance, and supplier/purchaser contracts [264]. Traceability through paperwork may represent the greatest potential obstacle to sourcing items as evidence.

Conclusions

Supply chains are central to the resolution of two otherwise similar products. By their nature, supply chains cast forward towards a finished product; forensic science, on the other hand, must lurch backwards to unravel the supply chain of that item of evidence. The complexity of product design and supply chains helps and hinders resolution—increased complexity means more intentional or incidental variation but also creates more information which must be sorted and parsed. As will be discussed in the next chapter, the centrality and complexity of supply chains leads to a potentially confounding question in the interpretation of forensic evidence. If DNA is the "gold standard" in forensic science [13], then why are the other forensic sciences not following its lead on interpretation and using population frequencies?

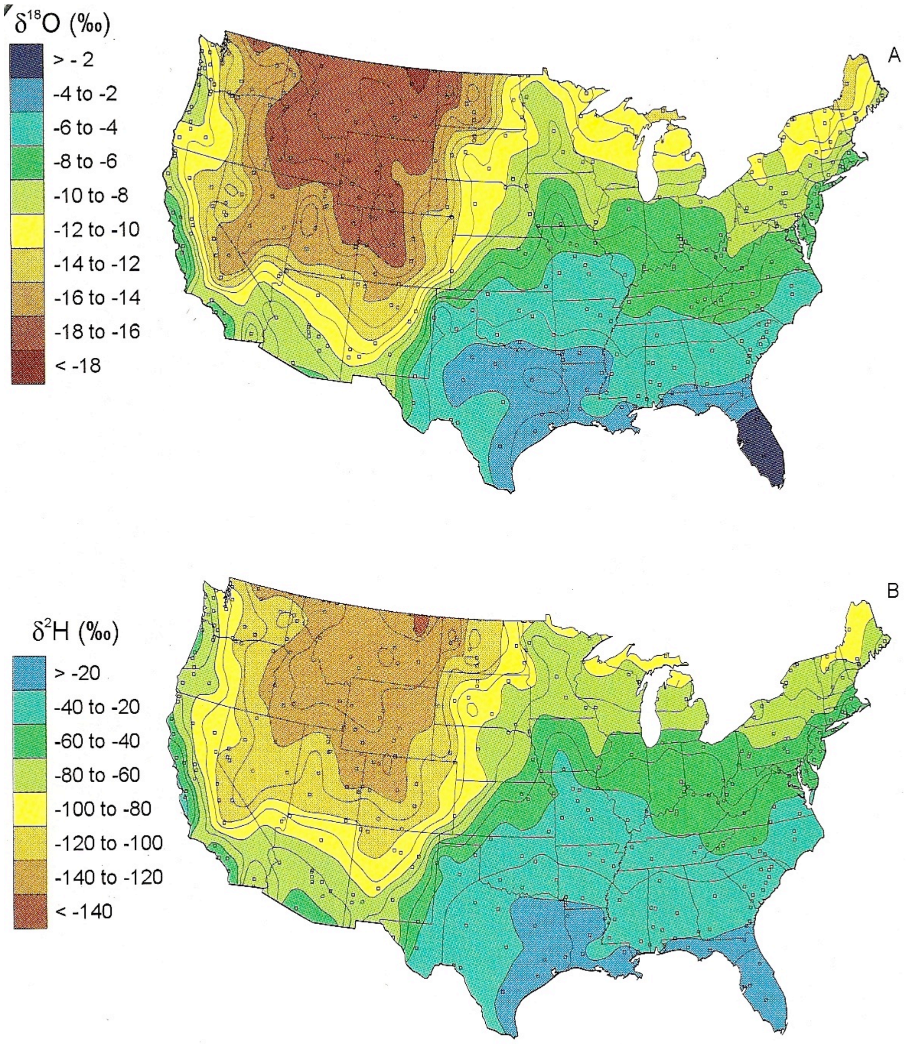

Figure 10. Oxygen isotope map of North America. Brown to yellow colors denote regions in which $^{18}\text{O}/^{16}\text{O}$ is low, green to blue where $^{18}\text{O}/^{16}\text{O}$ is higher. From [1], page 30.

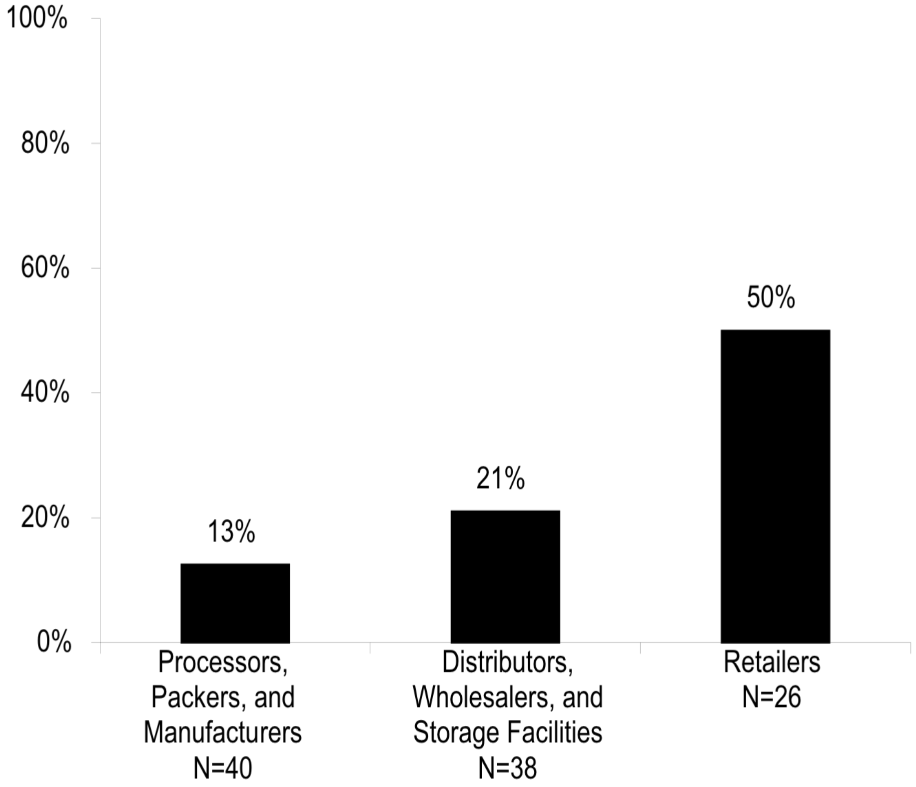

Figure 11. Percentage of managers who reported not being aware of FDA records requirements. *Source*: US OIG analysis of food facility responses, 2008; based on 104 of the 118 facilities that responded to this question.

Chapter 5. Why DNA cannot be the only interpretative model

> "Forensic biologists always go on about how wonderful DNA is. You only have to worry about one molecule; we chemists have to worry about all the other molecules."
>
> --Joe Buckle, Royal Canadian Mounted Police, personal communication

> The factual errors which academic historians make today are rarely deliberate. The real danger is not that a scholar will delude his readers, but that he will delude himself. [265]

Introduction

Manufactured products are multi-component materials with diverse production histories. DNA is, by comparison, a simple molecule and the current forensic methods exploit the human genome in a way that manufactured materials cannot be. DNA, therefore, is the "odd method out" in forensic science and its success is a matter of the simplicity of the molecule, the historical timing of the method's development, and the design of the method for forensic purposes. Forensic DNA analysis, while it is unarguably an excellent and well-founded technique, cannot be held as the "gold standard" for all forensic methods. This chapter argues that the value of forensic DNA analysis lies in the process of its acceptance rather than as a model for all evidentiary interpretations.

The DNA model

The impact of DNA analysis on the criminal justice system and particularly forensic science can hardly be overstated. From its first use in the United Kingdom in the exoneration of Richard Buckland and the conviction of Colin Pitchfork [266], forensic DNA analysis has left an indelible and permanent imprint on forensic science. Perhaps the pinnacle of the forensic DNA phenomenon is the following quote from the 2009 National Academy of Sciences report on forensic science,

> “With the exception of nuclear DNA analysis, however, no forensic method has been rigorously shown to have the capacity to consistently, and with a high degree of certainty, demonstrate a connection between evidence and a specific individual or source.” ([13], page 7)

The success of DNA, in part, has come from its specificity to source a biological stain to an individual. Although not uniqueness, the current method employed in forensic DNA analysis can estimate random match probabilities to 1 in 1 quintillion or higher [26]. The development of the forensic DNA method has not been without its rough patches (aka, “The DNA Wars” [267]) but the tussles between academia and applied forensic science resulted in a more robust method [268]. As non-DNA methods develop and progress, similar disputes can be expected and may often turn on the expectation of specificity currently rendered by DNA.

The DNA molecule is, chemically-speaking, simple. The molecule is made up of two polymers constructed of units, called nucleotides, supported on a backbone of sugar and phosphate groups connected by ester bonds . One of four types of molecules, called bases, is attached to each sugar and the two polymer chains are connected by pairing the bases. The series of bases provide the coding for proteins through a sequence of amino acids. Currently, forensic DNA analysis (also called DNA profiling) utilizes the polymerase chain reaction (PCR) and short tandem repeats (STR) on highly polymorphic regions with short repeated sequences (3, 4, or 5). The highly polymorphic regions readily discriminate between unrelated people, the premise being that unrelated people will have different numbers of repeat units in these regions. The DNA fragments are amplified using the polymerase chain reaction (PCR), separated and analyzed by electrophoresis. The discrimination power of current DNA analysis lies in the 13 loci (a locus is the specific location of a gene on a chromosome) chosen for use in forensic DNA databasing. These loci are considered to be independently assorted and, thus, may be multiplied together to produce the enormous random match probabilities previously quoted [269, 270]; that is, the product rule may be applied [26, 271, 272]. The product rule states that events A and B are independent if and only if the probability of A given the probability of B is equal to the probability of A multiplied by the probability of B. Independence is an assumption, although it is an "extremely convenient assumption" ([272], page 61). The forensic loci, therefore, are *sufficiently* independent—with corrections—to apply to questions of forensic sourcing [273].

DNA profiles are the product of genetics and evolutionary histories which have inherent and imposed dependencies; these dependencies have been statistically corrected for to allow predictions (for random match probabilities) [274]. Part natural selection, part non-random mating, part chemical structure of the DNA molecule, the human genome cannot be considered to be "designed" in the sense that has been used in the current work for mass produced products [45]. Therefore, the question remains, to what extent can the purported "gold standard" of DNA interpretation be applied to non-biological products? A detailing of three types of products which are encountered as evidence—glass, textiles, and pharmaceutical tablets—will help to provide the answer to this question.

Glass

Although the origin of glass in human history is uncertain, it has nevertheless had a profound effect on civilization and particularly science: A review of 20 major science discoveries that changed the world revealed that 15 could not have happened without glass tools [275]. Glass, in its various forms, is now a ubiquitous material in our modern world; this "commonness", however, does not mean it is homogenous. The heterogeneity of glass is based upon its manufacturing supply chain and the specificity of it end use products.

Glass is an inorganic fusion product which has cooled to a rigid condition without crystallization [276]; glass lacks long-range atomic symmetry and exists in a vitreous state [277]. The main component of glass is silica. Glass is also made with glass former, an oxide that easily forms a glass with silica [278]; although pure silica (SiO_2) can be made into a glass (its “glass melting point” is 2300°C/4200°F) it is hard to work with. Formers also make glass a more complex material, compositionally. Sodium carbonate (Na_2CO_3) in soda-lime glass reduces the melting point to 1500°C/2700°F but renders the material water soluble; adding calcium oxide (CaO), magnesium oxide (MgO), and aluminum oxide (Al_2O_3) make the material more durable and chemically stable [278, 279]. Other additives, such as lead, boron, barium, thorium oxide, lanthanum oxide, and cerium (IV) oxide, result in specialized glasses for aesthetic purposes and scientific or optical applications. Cullet (recycled glass) and calumite (an iron industry by-product) may also be included for energy and cost savings. Sodium sulfate, sodium chloride, antimony oxide, and synthetic soda ash (Na_2CO_3) may be added to refine the glass and reduce bubbles [280]. The method by which the recipe for an accurate and successful raw material mixture is derived is called glass batch calculation [278, 279, 281].

Once the raw material components are prepared and mixed, they are melted in a furnace. The type of furnace used is dependent upon the kind and amount of product to be made. Modern glass production is an automated process that can produce several hundred tons of glass per day [281]. Raw materials are continually fed into the production line and the furnace can accumulate and bleed out glass from concatenated batches over several weeks, leading to glasses with intermediate compositions between batch loads [282]. Smaller pot furnaces, electric melters, or day tanks are used for specialty glasses with lower production levels, from one to five tons daily [281, 283]. Once the glass if formed, controlled cooling take places in an annealing oven called a lehr. Tempering, laminating, and other surface finishing processes are completed at this point to improve durability, strength, or optical properties [278, 281, 283].

Despite the industrialization and automation of glass production, it is a highly variable material:

> Each of the raw materials used to produce glass contains impurities that are uncontrolled by the manufacturers and consequently vary in amount and composition over time. The mixing of raw materials during batching is incomplete, and the batch will unmix during transport and delivery to the furnace. Some mixing occurs as the molten glass flows through the furnace, but it is not sufficient to make an absolutely uniform product. The refractory materials lining the glass furnace are gradually eroded into the glass melt over the lifetime of the furnace ([284]).

As noted by Bottrell, in her work as a co-author with Koons and others [285], glass products have “small but measureable variations in their chemical, optical, and physical properties both within and between production runs” [284] despite the industry’s efforts at prediction and quality control [286, 287]. Forensic scientists exploit these variations to discriminate between glass samples encountered as evidence [2, 285, 288-293]. It is important to remember that the industry’s quality assurance procedures and production parameters may not take into account the traits forensic scientists use to discern between samples (that is, manufacturing and forensic taxonomies differ). Additionally, while these variances have been useful to forensic scientists, they are essentially ad hoc analyses because of the extraordinary number of potential variables involved in the production process [2].

Fibers

Manufactured fibers are the various families of fibers produced from fiber-forming substances, which may be synthesized polymers, modified or transformed natural polymers, or glass. Synthetic fibers are those manufactured fibers which are synthesized from by-products of petroleum and natural gas (e.g., nylon, polyester). Therefore, all synthetic fibers are manufactured, but not all manufactured fibers are synthetic. Fibers are the basic unit of textile science [294] and are most often the basic unit of forensic analysis [295]; therefore, fiber manufacturing will be discussed here to demonstrate the principles regarding supply chain and manufacturing complexity. Construction of fabrics and, especially, dyeing expand the complexity of textile production enormously [239, 296, 297]; a complete treatment of these factors is outside the scope of the current work.

Manufactured fibers are formed by converting solid polymer into a viscous material called spinning dope. The spinning dope is created by rendering solid monomeric material into a liquid or semi-liquid form with a solvent or heat; the method of conversion depends on the type of polymer to be spun into fibers. Nylons, for example, are semicrystalline and have a specific melt point while acrylics are amorphous solids and are more easily rendered into a liquid; thus different methods are required to process the main polymers for processing. The spinning dope is pumped through a shower head-like device called a spinneret. The extruded fibers are initially rubbery but soon are solidified through one of several methods, depending on the type of fiber produced and its desired end-product parameters [298-300]. Fibers must have certain properties to be useful and not all polymers can be spun into fibers (Table 3).

	Textile	**Industrial**
Tensile strength	5 g/denier	7-8 g/denier
Initial modulus	30-60 g/denier	50-80 g/denier
Elongation at break	not less than 10%	8-15%
Creep temperature	215°C	250°C

Table 3. Characteristics for textile and industrial uses of fibers. Data from [299].

Four main methods of spinning fibers are currently used in the textile industry: wet, dry, melt, and gel. In wet spinning, the spinneret is submerged in chemical bath that precipitates the extruded fiber and eventually solidifies it. Wet spinning is used on acrylic, rayon, aramid, modacrylic, and spandex fibers. Dry spinning starts with a similar method as wet spinning for rendering the raw polymer into spinning dope—solvents—but the extruded fiber solidifies through the evaporation of the solvent. Air is blown over the fibers in a chimney-like area to speed drying and solidification. Acetate, triacetate, acrylic, modacrylic, PBI, spandex, and vinyon fibers are made by dry spinning. Polymers that must be melted for extrusion are spun by melt spinning; the melt-spin method and the nature of these thermopolymers allow for a wider variety of cross-sectional shapes to be produced than with wet or dry spinning. Nylon, polyester, and olefin fibers are made this way. Gel spinning operates much like melt spinning except that the original polymeric material is kept in a gel-state, which keeps the polymer chains more bound throughout the spinning process. The extruded fiber is run through air first then a liquid bath, providing for extreme tensile strength; gel spinning is sometimes referred to as wet-dry spinning. Polyethylene and aramid fibers are produced by gel spinning. Once extruded, the fibers are taken up on bobbin or spool which then passes the fibers on to other finishing operations to reach its desired final form for sale, either to a producer or dyer [294, 299, 301, 302].

The fiber forming process at the pre- through post-spinneret phase is key to a fiber's final properties. Very little is known about how the preextrusion region influences the final fiber properties because of the fluid nature of the material, the production process, and the microscopic and molecular activity of the material. The elastic nature of the melt, polymer "memory", and molecular orientation may play a role [299]. One example of this sensitivity to initial conditions can be seen in the phenomenon of die swell, a response to compression entering a nozzle or die and its recovery or "swell" upon exiting (Figure 12). The longer the polymer is in the pre-extrusion area, the more mixing and disorientation of the crystallinity that can occur [299, 303]; just how much disorientation, however, is unknown and is complicated by preextrusion sheer history, molecular entanglement, and the relative magnitude of stress and response. Orientation due to velocity fields and disorientation from thermal (Brownian) motion are competing forces, resulting in an exchange of influences as the fiber orients and cools down post-extrusion. This competition, along with time-temperature experiences, orientation by the force and pull of the take-up bobbin, spinning rate, fiber diameter, the polymer nature, and stress history, sets the fine lattice structure of the fiber and, thus, its final properties [299, 300].

The results of the die swell phenomenon and the effect-history of the previously mentioned factors sets the stage for all further work done on the fiber, including yarn spinning, fabric production, and, in particular, dyeing. Color is the most important aspect of any garment [304] and color consistency and matching are significant criteria, creating a struggle for the textile industry [305, 306]. Dye-fiber combinations are crucial to a good color match, along with other desired properties, such as color fastness, crock fastness, and bleeding [294]. As the substrate, the fiber and its fine structure are key to achieving a desired color and color properties. Fibers are often drawn post-extrusion to increase orientation for durability and strength [299]; crystallinity is set more or less once the fiber cools completely on or before the bobbin. Crystallinity affects dye absorption and orientation affects dyeing rates and even small differences in fine structure result in dye absorption that exceed commercially-accepted values, in some cases by up to 163% [307]. Dyeing factors, such as pH, temporary ionic processes, salt activity, and pre-activation, can also affect uptake and final color [296, 308].

At the buyer’s end of the textile supply chain, an additional method may confound the forensic scientist’s attempts to derive source attribution from fiber evidence. Shade sorting is identifying fabrics of the same color and piecing them together to produce a uniformly-colored textile [304]. A color’s shade may vary from “lot to lot or from bolt to bolt, or even within a bolt from end to and/or from side to side to center to side” ([304], page 186). Instrumental analysis is typically employed for consistency and reproducibility. Much like the shotgun pellet example offered in Chapter 1, shade sorting can confound any sourcing that a forensic scientist may wish to perform—any lot to lot variance may now be obscured by the demands for uniform color and the actions of the manufacturer to meet those demands.

Given that shade and dye differences are detectable in the forensic laboratory [309-311] and may have an influence on the interpretation of case evidence [39, 311], it is incumbent on the forensic scientist to use the most discriminating methods possible, including statistical analysis [312], to sort as-found fiber evidence.

Tablets

The production of tablets was previously discussed, using aspirin as an example (see Chapter 1), and will not be repeated here. Design elements in the description of the tablets themselves will be discussed using manufacturing terminology for licit tablets and forensic terminology for illicit tablets[10] [313-315].

Tablets consist of powdered active substances and excipients compressed into a solid form. The excipients include binders (for example, methyl cellulose or gelatin), glidants (magnesium stearate), disintegrants (starch or cellulose), sweeteners, flavoring, and pigments. The tablet may be coated for ease of swallowing and longer shelf life.

Tablet morphology varies with manufacturer and the surfaces of the tablets can have a range of shapes and styles. The upper and/or lower surfaces of the tablets may be decorated with a shallow groove, symbols, names, or letters to identify the brand or the manufacturer (Figure 13).

Tablets may be scored on the upper or lower surface and may contain a single or double scoring line. The monogram, if present, may be debossed (formed as a groove or indentation), imprinted, or embossed (protruding

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[10] http://www.justice.gov/dea/programs/forensicsci/microgram/index.html

above the surface), and this may occur on the upper side, lower side, or both sides. The potential range of tablet colors is vast but standardized terminology helps in the categorization of shades [316]. The coloring itself may be uniform, mottled (small aggregates), blotchy (large aggregates), patterned, or the tablet may be bi-colored, where one half or one surface is a different color than the opposite half or surface. Tablets come in a wide variety of shapes, typically round, oval, oblong, and other, usually polygonal, shapes. The profile of the tablet may be flat, convex, or concave; each of these may occur with a bevel (to prevent chipping and erosion of the tablet's edge) or without. The surfaces of the tablet may be smooth, roughened, or damaged from chipping, breaking, or picking (tableting material that adheres to the press during manufacture resulting in an avulsion of powder from the tablet). The thickness of a tablet is limited by the dosage and delivery method but is typically measured to the nearest 0.1mm. Weight, likewise, varies and is measured to within the nearest mg per tablet. Multiple punch sets may be used per tablet, for example, differing logos on the upper and lower sides. The origin of the tablet can be considered for classification purposes as authentic, counterfeit, illicit or undetermined. None of these characteristics, however, take into account any chemistry of the active ingredients, binders, diluents, etc.; these have an extensive effect on a tablet's construction and classification [314, 317, 318].

Can the DNA model fit non-biological evidence?

Design characteristics of mass-produced products are not independent; neither is their frequency in populations, logistical or economic distribution, or occurrence as evidence strictly independent of other possibly relevant parameters [10, 34, 35, 129, 319]:

> For most, if not all, nonbiological items of trace evidence, it is not possible to appropriately sample or otherwise determine a frequency distribution for each variable in the population relevant to a given crime scene or subject. Therefore, valid probability calculations cannot be made. ([2], page 502)

Even an assumption of independence may not be warranted—corrections may be necessary to adjust for even weakly correlated parameters, as in [2] where bin size (12σ) was used to correct for a weak correlation (0.601) between Al and Mn (Figure 14).

Other methods may be used, however, that do not require independence and these may be used on other types of non-biological evidence. For example, Koons and Buscaglia used data from an FBI database of glass composition and refractive indices to calculate the total number of distinguishable element combinations, arriving at a random match probability of between 10^{-5} and 10^{-13} [2]. It must be stressed that these values bear no necessary relation to the population of glass parameters but are the total number of distinguishable element combinations.

Population frequencies are simply not a viable method of assessing the significance of non-biological evidence. Given the complexities of manufacturing and forensic histories, interpretative models of non-biological (that is, mass-produced) products encountered as evidence must:

- be based on the morphology and chemistry of the product,
- take the product's economic and logistical distribution frequency into account, and
- realistically reflect the product's supply chain

An example based on tablet data will be discussed in the next and final chapter.

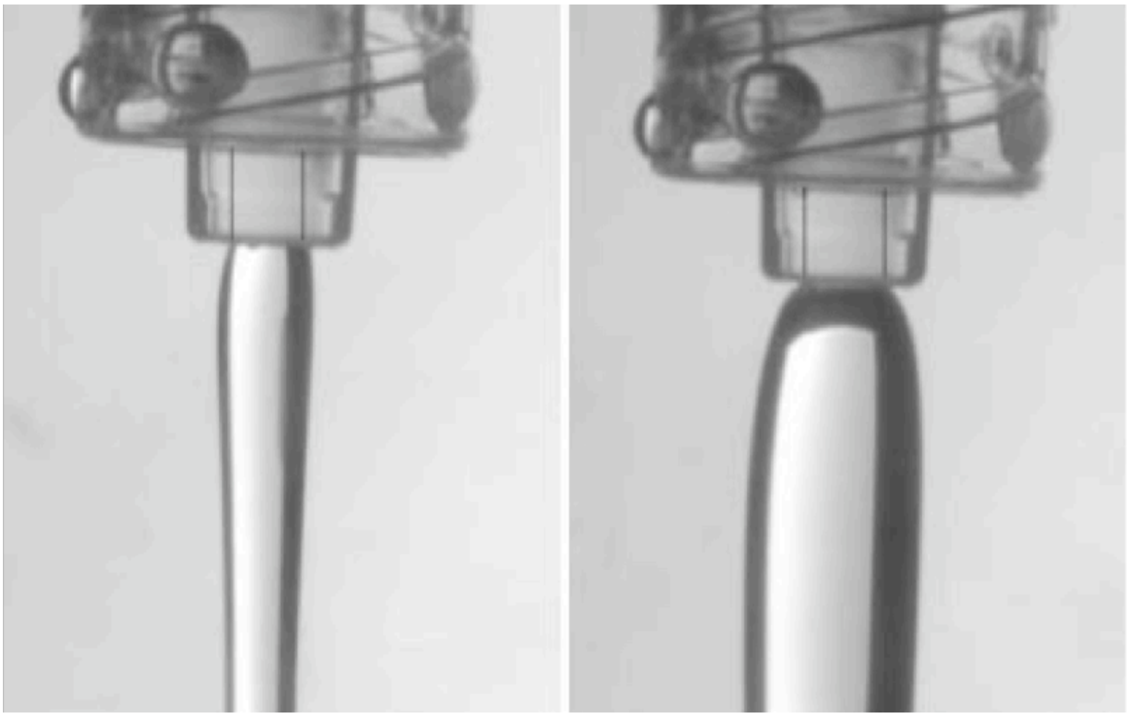

Figure 12. Die swell, a necking down of material after extrusion. From web.mit.edu/nnf/research/phenomena.

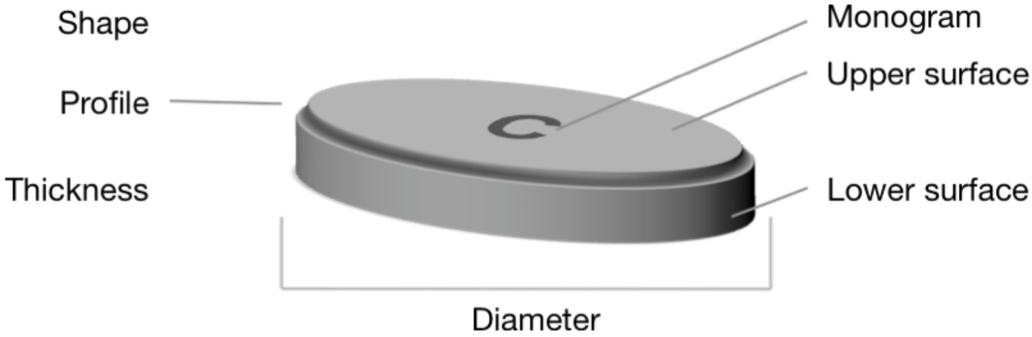

Figure 13. Diagram of the basic morphology of a tablet.

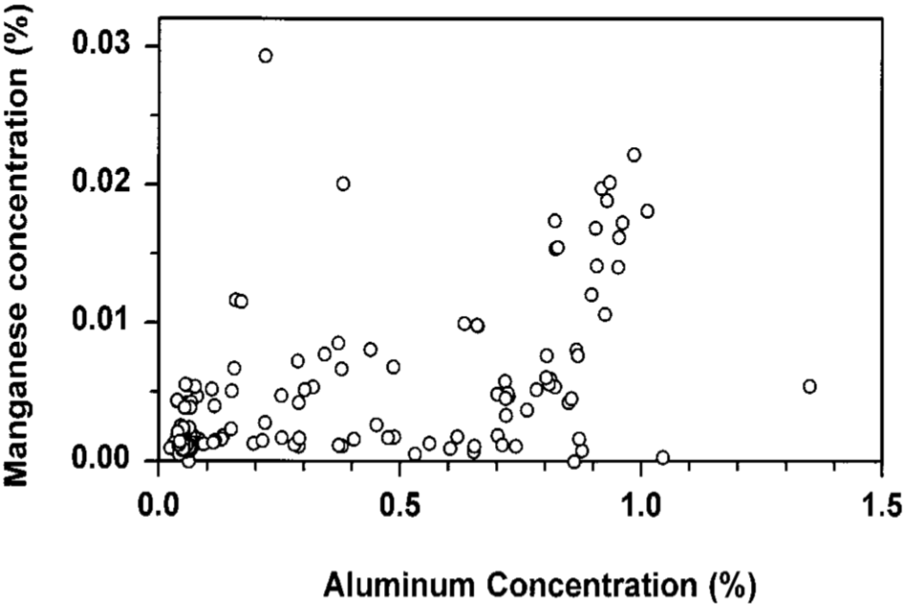

Figure 14. Distribution of glass specimens among Al and Mn bins. From [2].

Chapter 6: A Combinatorial Example

> "The boys with their feet on the desks know that the easiest murder case in the world to break is the one somebody tried to get very cute with; the one that really bothers them is the murder somebody thought of only two minutes before he pulled it off."
> --Raymond Chandler, *The Simple Art of Murder*

Introduction

As detailed in the last chapter, the complex of information imbedded in manufacturing histories requires interpretative models that are sensitive to the morphology, chemistry, and supply chain of the product. An example utilizing pharmaceutical tablet morphology is offered.

Tablets as a Combinatorial Example

Following the example of Koons and Buscaglia [289], a combinatorial example is offered in this study utilizing pharmaceutical tablet morphology. The basic descriptive information for tablets has been broken down into a taxonomy suitable for combinatorial processing. Each taxon may have multiple sub-taxa; for example, *Scoring* has 9 possible states:

	Upper-none	**Upper-single**	**Upper-double**
Lower-none	UN-LN	US-LN	UD-LN
Lower-single	UN-LS	US-LS	UD-LS
Lower-double	UN-LD	US-LD	UD-LD

The structure used in the study is as follows (the numbers in parentheses for each main taxon relates to the number of sub-taxa in that group):

Scoring (9)
- Upper—none
- Upper—single
- Upper—double
- Lower—none
- Lower—single
- Lower—double

Monogram (16)
- Upper—none
- Upper—debossed
- Upper—imprinted
- Upper—embossed

Lower—none
Lower—debossed
Lower—imprinted
Lower—embossed

Tablet colors (27) (Color terms based on [316])

Light brown
Brown
Dark brown
Light red
Red
Dark red
Light orange
Orange
Dark orange
Light yellow
Yellow
Dark yellow
Light green
Green
Dark Green
Light blue
Blue
Dark blue
Light purple
Purple
Dark purple
White
Off-white
Light gray
Gray
Dark gray
Black

Coloring (5)[11]

Uniform
Mottled
Bi-color[12]
Patterned
Blotchy

Shape (4, not counting quantitative traits; see later discussion)

- Round
  - Diameter to nearest 0.1mm
  - Land width to nearest 0.1mm
- Oval
  - Long diameter to nearest 0.1mm
  - Short diameter to nearest 0.1mm
  - Land width to nearest 0.1mm
- Oblong
  - Long diameter to nearest 0.1mm
  - Short diameter to nearest 0.1mm
  - Land width to nearest 0.1mm
- Other
  - X diameter to nearest 0.1mm
  - Y diameter to nearest 0.1mm
  - Land width to nearest 0.1mm

Profile (6)

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[11] Coloring characteristics for bi-color tablets are assumed to be independent of side for purposes of this study; that is, a bi-color tablet could be uniform on Side 1 and mottled on Side 2, for example.

[12] The two colors used in a bi-color tablet are assumed to be independent of each other for purposes of this study.

Flat with bevel
Flat with no bevel
Convex with bevel
Convex with no bevel
Concave with bevel
Concave with no bevel

Surface (6)
Smooth
Rough
Chipped
Broken
Picking/sticking
Other

Thickness (see later discussion)
Range for n tablets to nearest 0.1mm

Average Weight (see later discussion)
To nearest mg per tablet

Multiple Punch Set (conclusion, not statistical)
Yes
No
Undetermined

Origin (conclusion, not statistical)
Authentic
Counterfeit
Illicit
Undetermined

This taxonomy of classes yields the following numbers of sets, *absent quantitative traits* (diameter, weight, etc.):

Combinations for *single color* tablets

Trait	Number of subclasses	Cumulative sets
Scoring	9	9
Monogram	16	144
Tablet colors	27	3,888
Coloring	5	19,440
Shape	4	77,760
Profile	6	466,560
Surface	6	2,799,360

Combinations for *bi-color* tablets

Trait	Number of subclasses	Cumulative sets
Scoring	9	9
Monogram	16	144
Tablet color	27	3,888
Coloring	5	19,440
Tablet color	27	524,880
Coloring[13]	4	2,099,520
Shape	4	8,398,080
Profile	6	50,388,480
Surface	6	302,330,880

With the addition of quantitative values (diameter, weight, thickness, etc.), these combinations increase significantly. Conceptually, each increment of quantitative measure would add one more subclass to the total. For example, using a round tablet for simplicity, if tablet diameter were measured to the nearest 1mm and tablets ranged from 5mm to 30mm, this would add 25 new subclasses to the subclass “Shape Round” (5mm, 6mm, 7mm, etc.). Working out the normal ranges for measurements of diameter(s), land thickness[14], and weight would add significantly to the matrix of combinations. Again, for a single color round tablet, assuming 25 new incremental subclasses for diameter, land thickness, and weight, this would lead to a total of 43,740,000,000 possible combinations (2,799,360 x 25 x 25 x 25). Some of these possible combinations, however, may not be achievable given manufacturing and material constraints (a 5mm diameter, 25mm land thickness, 5mg tablet may not be realizable). Further statistical analysis of what constitutes the parameters of licit and illicit tablets is warranted before utilizing quantitative traits such as those discussed here.

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[13] The trait “bi-color” is removed from the second calculation as it is duplicative of the first tablet side's assessment as “bi-color”. Therefore, only 4 categories exist for Coloring on Side 2 of a bi-color tablet.

[14] Much like firearm barrels and bullets, tablets may have raised structures called lands.

An Example Using Tablet Data

Data provided by the US Drug Enforcement Administration contained 3,929 records with data for the following data variables: Weight, Diameter, Color, and Shape; the original data for this study has been redacted for law enforcement purposes. The values for color and shape were condensed to a systematic list of names [316] and these names were then converted to numbers for statistical treatment. The descriptive statistics for weight and diameter are shown in Figures 15 and 16, as well as frequency histograms for all variables.

Independence and frequency calculations

The frequency of an event *i* is the number n_i of times the event occurred. Absolute frequencies are the counts n_i themselves (7 in 126 events, for example) whereas relative frequencies are when those are normalized by the total number of events (1 in 20 [7/126 = 0.55%]). To say that two events are independent means that the occurrence of one event makes it neither more nor less probable that the other occurs. As an example, if a die is rolled and a six is the result, the odds of getting a six on the next roll are unaffected by the previous roll; they are independent. If a die is rolled twice, and the first die is a six, however, the chance that the total of the two numbers equals eight is dependent on the first and second rolls. Another example is if one card is drawn from a deck, replaced, and a second card is drawn; the chance that both cards are red is independent of either draw. By contrast, if two cards are drawn *without replacement* from the deck, the chance of drawing a red card the first time and that of drawing a red card the second time are dependent. In statistics, two variables are independent if the conditional probability distribution of either given the observed value of the other is the same as if the other's value had not been observed [320].

The tablet data set in this study has thousands of entries with millions combinations of class traits; accordingly, the traditional statistical test for independence, the X_2 test, is not applicable [320]. Understanding the more complex relationship between the variables requires a calculation of correlation. A correlation matrix and table appear below for Pearson's product-moment correlation of the tablet data; a correlation (Z-value) of 1.00 indicates perfect positive correlation [320].

With a null hypothesis that a positive, directional relationship exists between variables—that is, a correlation—a *r* value greater than or equal to 0.026 rejects the null hypothesis at the 0.05 level of significance. Therefore, the following variables are independent of each other:

- Color : Weight
- Color : Diameter
- Color : Shape

These would be the only pair-wise variables from the tablet data that could be used in a computation of a random match probability (that is, color x weight *or* color x diameter *or* color x shape). Random match calculations will depend upon the specificity and range of either weight or diameter as measured.

Assuming for purposes of this report that weight and diameter are listed in their respective units, this would provide 3,534 and 23 (rounding up) units of discrimination, respectively. The large range of weight results from a few outliers of large value (78 records, or 2% of the total records, of 1,000 and above); removing these values changes the range to 970 (995 - 25). Again, assuming that each unit represents one discriminating difference, this adds greatly to the diversity of tablet classes. Because of dependence on other variables and for purposes of producing a conservative result, the variable diameter will be dropped from further calculations. Adding the variable weight (with 27 subclasses) but removing the variable shape due to its dependence on other variables, the number of classes and cumulative sets changes as follows:

Trait	Number of subclasses	Cumulative sets
Scoring	9	9
Monogram	16	144
Tablet colors	27	3,888
Coloring	5	19,440
Profile	6	116,640
Weight	27	3,149,280

The remaining traits—scoring, monogramming, coloring, and profile—would need to be tested for statistical independence prior to their use in any practical calculations.

For application to a hypothetical case, assume the following traits:

	Questioned Tablets	Known Tablets
Scoring	Upper-none:Lower-none	Upper-none:Lower-none
Monogram	Upper-imprint:Lower-none	Upper-imprint:Lower-none
Color	White	White
Coloring	Uniform	Uniform
Profile	Flat no-bevel	Flat no-bevel
Weight	200	200
Surface	Smooth	Smooth
Thickness	4	4
Shape	*Round*	*Round*
Diameter	*20*	*20*
Logo design	*Smiley face*	*Smiley face*
Active ingredient	*Same*	*Same*
Other ingredients	*Same*	*Same*

At the class-level of information—even though most of these traits are the most common or are near the average values—the combination of traits above the line is estimated to be one of 3,149,280 possible configurations[15]. It must be stressed that this is not a *frequency*, which implies a measurement of the number of occurrences within a fixed time interval divided by the length of the time interval. The number of configurations is estimated from the available data which is not a representative sampling of

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[15] Shape and diameter are removed from this calculation for reasons discussed earlier.

tablets; therefore, the entries do not represent the appearance of any one kind of tablet over any specific period of time.

Adding chemistry to this type of assessment would significantly increase the value of the evidence, particularly for illicit tablets which have lower quality assurance tolerances than professionally-produced ones (Figure 17) [321]. These variations in composition, constituents, shape, and consistency would all lead to exclusion in a comparison examination scheme. Although B, D, and E are round tablets, differences in their manufacturing parameters—essentially quality control—lead to distinct differences that are easily seen. Therefore, the manufacturing supply chain and production processes provide the basis for differentiation. This example offers counterfeit prescription tablets but “genuine” illicit tablets, such as ecstasy, could also be differentiated because of their manufacturing characteristics.

The information imbedded in design and production histories of products requires interpretative models that are sensitive to the discriminating parameters of that product, such as morphology, chemistry, and design elements. This chapter offered a combinatorial example utilizing pharmaceutical tablet morphology; the chemistry of the varied tablets was not considered and would have significantly increased the combinations of outcomes. A thorough understanding of design and manufacturing is essential for a proper interpretation of forensic evidence. Clearly, establishing that a given seized tablet shares all of the morphological parameters of a sample from a cache of seized tablets from another location has forensic and investigative importance. Being able to state, for example, that the tablets share the same morphology out of a possible 3,149,280 possible configurations places the evidence’s significance in clearer context and relieves the expert from the burden of supporting an *ipse dixit* type of testimony [322-324]. This offers a departure from current forensic practice but an advancement towards a sounder basis for forensic science interpretations.

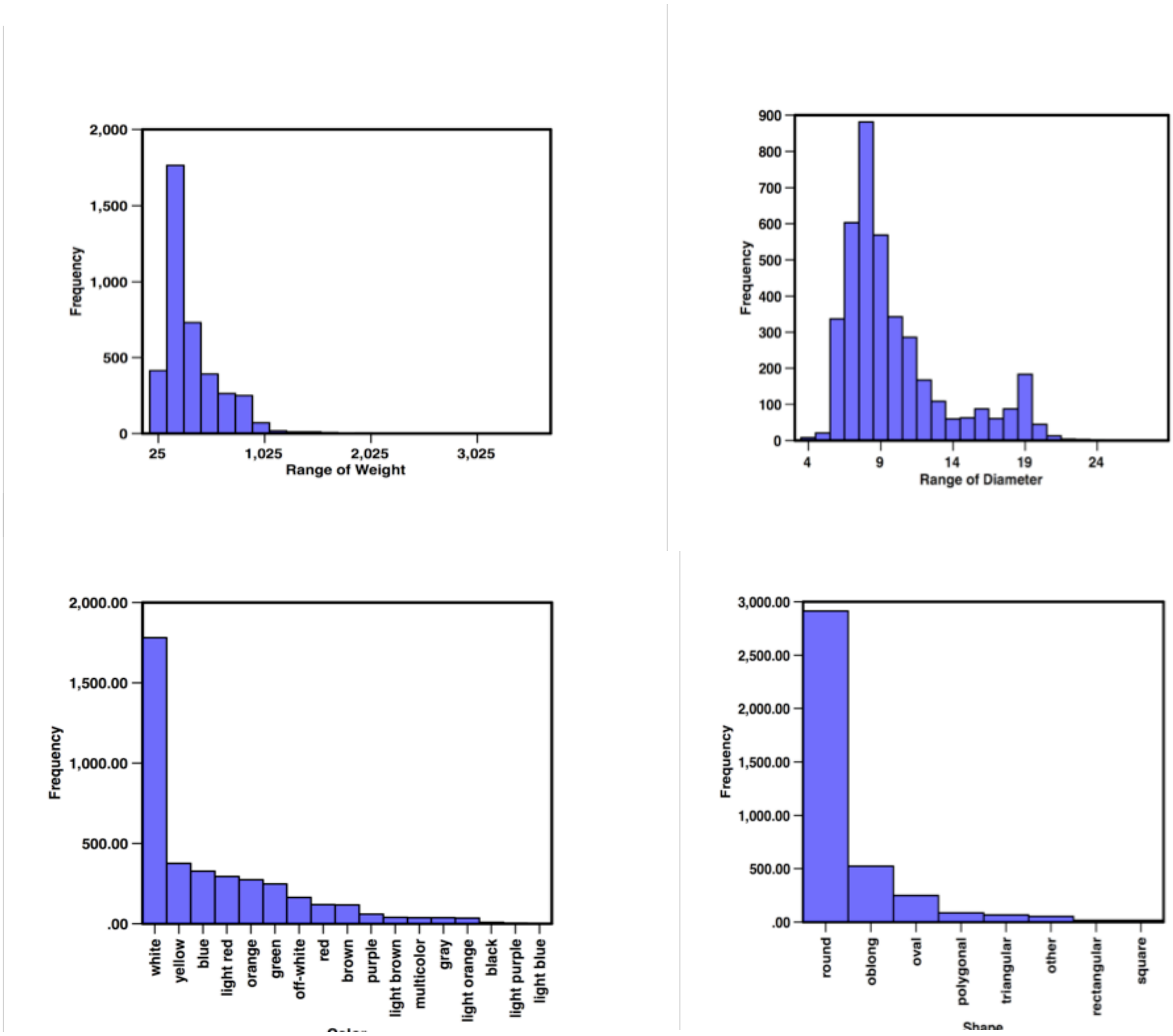
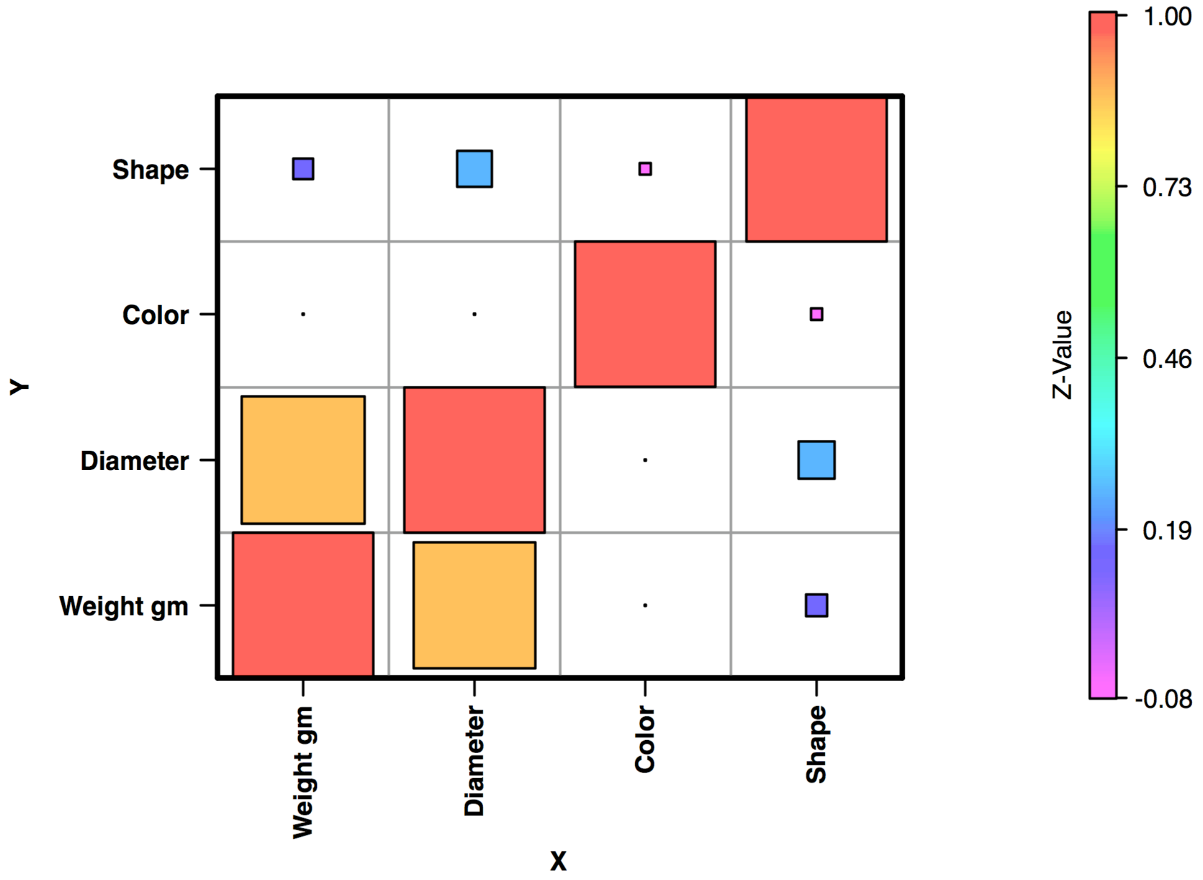


Figure 15. Histograms of tablet frequency data. (A) Range of weight; (B) Range of diameter; (C) Colors; and (D) Shape.

	Weight (mg)	**Diameter (mm)**
Minimum	25	4
Maximum	3,570.00	27.6
Mean	334.7	10
Median	245	8.7
Variance	73,764.20	13.78
Std Dev	271.6	3.71



	Weight	Diameter	Color	Shape
Shape	0.146	0.249	-0.075	1
Color	0.008	0.005	1	
Diameter	0.869	1		
Weight	1			
degrees of freedom:	3,927			
r(one-tailed) 0.05:	0.026			
r(one-tailed) 0.01:	0.037			

Figure 16. Correlation values of selected tablet parameters.

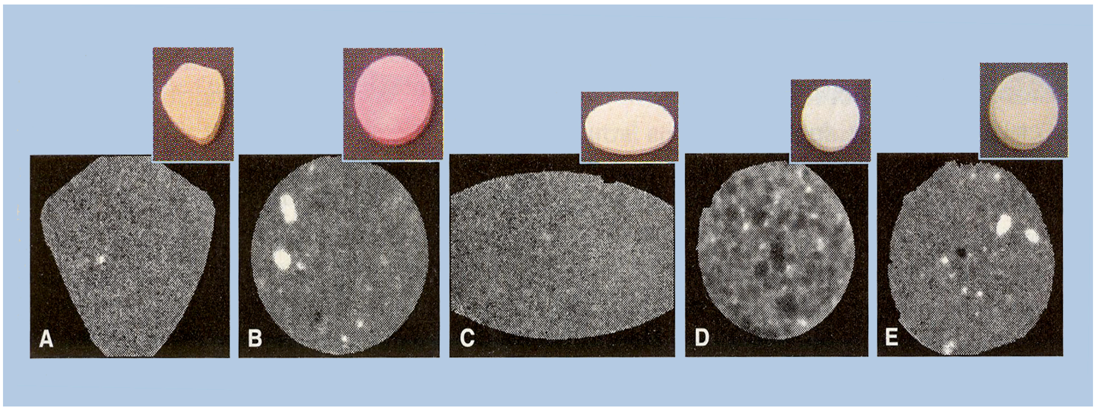


Figure 17. Simvastatin tablets imported to the US via the Internet. (A) Merck & Co, USA, (B) Mexico, (C)Thailand, (D), India, and (E) Brazil. Top photographic images; bottom NIR images with bright spots showing active ingredients. From [321].

Chapter 7: Conclusions

> "Forensic science is, in many ways, an untidy, scruffy sort of discipline." ([325], page 3)

This thesis has asserted that forensic science has a philosophical foundation based on forensic scientists being knowledge workers and forensic science being an historical science. This philosophy frames the discipline and a deeper understanding of its practice. Changing philosophical perspectives provides opportunities to apply previously unrelated models to analysis and, especially, interpretation. It is hoped that multidisciplinary interpretive models may translate to forensic evidence and assist with its interpretation.

Forensic science is historical in nature with certain native and non-native principles that guide it. The native principles represent concepts both created by forensic scientists and those deeply ingrained in the procedures of forensic science. These concepts are considered axiomatic and have not been thoroughly tested or in some cases validated. The phenomena and mechanisms of transfer and persistence, for example, are only partially understood; forensic science lacks an overarching philosophical structure against which to test these principles. As Thornton and Peterson have noted,

> Forensic science has historically been troubled by a serious deficiency in that a heterogeneous assemblage of technical procedures, a pastiche of sorts, however effective or virtuous they may be in their own right, has frequently been substituted for basic theory and principles. ([325], page 3)

The non-native principles relate to order, time, and placement. Other principles borrowed from chemistry and biology are useful but do not work at the same fundamental level. The production taxonomies of manufactured goods and their supply chains from manufacturing, wholesale, retail, and reclamation have been offered in this thesis as the foundation of evidential significance. As Cole noted, forensic scientists need to “distinguish *traces* made by each object from traces made by every other object” ([11], page 243). This thesis has posited that the real answer thus lies in detangling the complexity of natural and material items that become evidence within one or more models that reflect their structure, specificity, and prevalence. The complex and dynamic nature of supply chains make predictive modeling of populations of manufactured items nearly impossible. What constitutes a significant difference between two otherwise analytically similar objects depends on a forensic understanding supply chains.

To date, studies of forensic significance typically have been oriented to the product level of information (Figure 18). It may not be sufficient to base forensic interpretations on *product* information; *production* information—the supply chain—can have a direct effect on the kind, quality, and accuracy of written or oral (testimony) results. This production information may be physical (morphological) or chemical in nature. These taxonomies of production with the supply chain—writ large—constitute the basis for evidential significance. The proposed expansion of forensic science to embrace design and production information offers a platform to solidify forensic science’s role in both the sciences and the legal system. The discussion of glass, fibers, and tablets demonstrates the potential complexity of these materials and how design and production parameters can influence interpretation. The extended example using tablet morphology data provided insights to how combinatorial approaches may be used for evaluating forensic evidence.

Beyond forensic methodologies for analysis and interpretation, the philosophical perspective offered in this thesis has implications for education and research. In forensic education, manufacturing processes must be integrated into textbooks, lectures, and curricula. If the supply chain forms the basis of evidentiary significance, as has been argued herein, then a clearer understanding of its processes, variances, and economics must be brought into the classroom from the beginning. Additionally, training must also inculcate this information in workshops, seminars, and short courses. Research solicitations in forensic science must also reflect this change in perspective. Exploratory proposals using new and existing data sets must be encouraged to seek out and test plausible analogous models or new ones.

For forensic science to truly become a separate discipline to stand next to its sibling sciences, it must unpack the theories and principles from its methods and make its foundations explicit [15]. Barrett's distinction between technicians, who know what to do, and scientists, who know what to do when something goes wrong, is central to the notion of forensic science being regarded as a separate discipline. A deeper understanding of the intellectual infrastructure of forensic science can only improve its procedures, its appreciation by other scientific professions, its efficacy, and the criminal justice system.

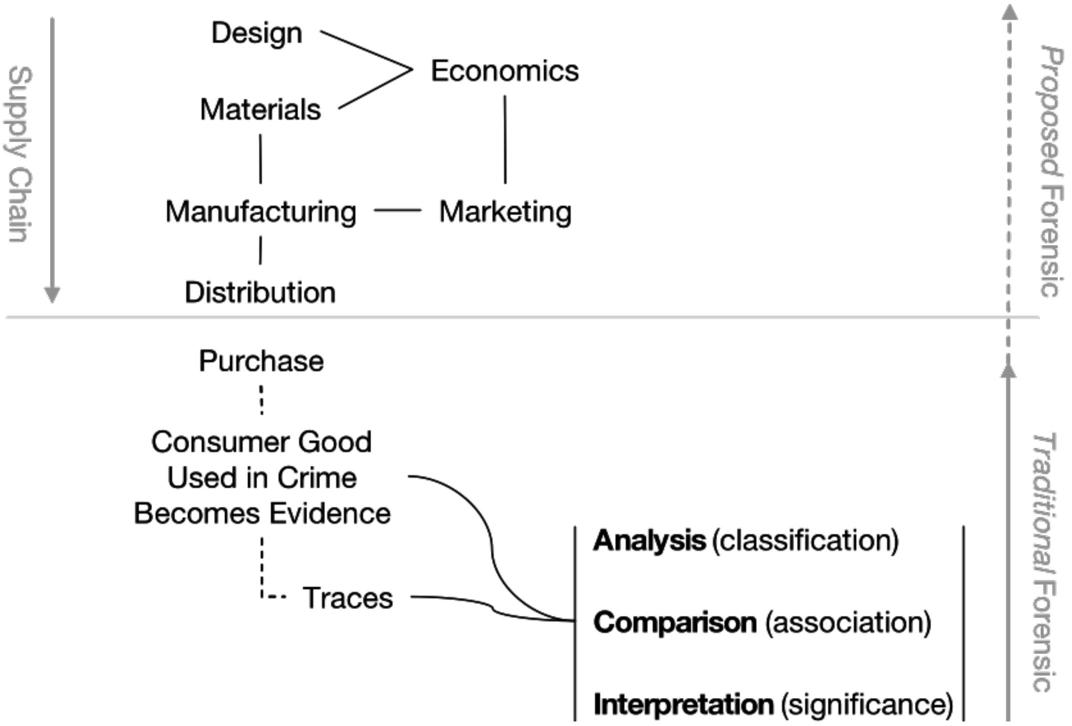


Figure 18. Traditional forensic analysis begins at the point of evidence and only works backwards to the point of ownership at the time of purchase; this provides a limited support of association between the evidence items and their purported sources. The proposed forensic scheme would require at least a knowledge of the product/item back to the design phase, if not an actual source of knowledge about the cumulative processes—the supply chain—that result in the item and its ultimate forensic significance.

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