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Mathematics in Forensic Firearm Examination

Erin N. Zalewski
State University of New York, Upstate Medical University, Pediatric Residency Program, Syracuse, New York

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Erin Zalewski
Candidate for Bachelor of
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Honors Capstone Project in Mathematics and Forensic Science

Project Adviser: ______________________________
Matthew Kurimsky
Firearms Examiner, Onondaga County Center for Forensic Sciences
Firearms and Impressions Instructor, Syracuse University

Project Reader: ______________________________
Michael Sponsler
Professor of Chemistry, Syracuse University
Director of Curriculum for Forensic and National Security Sciences Institute

Honors Director: ______________________________
Stephen Kuusisto

Date: May 5, 2015

Abstract

Forensic Science encompasses many disciplines that employ the scientific method to examine, analyze, and interpret physical evidence in the courtroom. The discipline of Forensic Firearm Examination involves the examination and comparison of ballistic evidence components to determine if they came from the same source. In other words, firearm examiners are tasked with determining whether spent cartridge cases or bullets were fired through the same gun. Examination of ballistic evidence can involve the employment of automated matching systems, comparison microscopy, and mathematical analysis. The comparison microscope is the tool of the firearm examiner and allows for the simultaneous view of ballistic components. Through examination and comparison, the examiner determines if the components are an identification or an elimination, or are inconclusive. The use of automated matching systems is often a precursor to an examination and comparison, to determine possible matches with evidence stored in large databases. These systems employ mathematical techniques such as matching algorithms, transforms, and cross-correlation functions. Mathematical analysis involves the application of probabilistic thinking and statistical methods to articulate and support the conclusions of the firearms examiner. There is concern in the court system about the prominent presence of subjectivity in firearm examination. Mathematical methods can help decrease subjectivity, and they are unquestionably valuable for concepts of the discipline, such as consecutively matching striations. However, math does not eliminate the subjectivity of Forensic Firearm Examination and only proves valuable when utilized appropriately. The discipline deals with the comparison of individual characteristics that indicate if markings come from one tool and one tool alone. Fitting this idea into a statistical model is possibly an unsuitable course of action.

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Executive Summary

Courtrooms are witness to countless trials, concerning murder, burglary, assault, arson, grand theft auto, perjury, and so on. Often, the courts will turn to experts in various forensic science disciplines, who harness the power of techniques and training rooted in the scientific method to interpret the physical evidence. Specifically, experts in the field of forensic firearm examination are called upon as needed to test firearm operability, analyze gunshot residue and gun powder identifications, restore serial numbers, complete examinations and comparisons of ballistic evidence, test trigger pulls, and perform shooting reconstructions. In one way or another, these tasks all have foundations in the branches of hard science.

This paper examines different mathematical techniques and methods used in ballistic evidence examination, with the purpose of presenting mathematical methods of forensic firearm examination in concise, easy-to-comprehend language through examples and discussion

The examination of ballistic evidence often begins with automated matching systems. The most prominent system currently utilized by crime laboratories is known as NIBIN, or the National Integrated Ballistic Information Network. An examiner or trained technician enters the components into the system, so that two-dimensional images and three-dimensional topographical information can be obtained using sophisticated microscope cameras and different light sources. It is essential that the images be of the best quality and contrast possible, to allow the process to continue smoothly. This initial aspect of the process relies on imaging techniques such as histogram equalization (which does not fall within the scope of this discussion). From the images obtained, however, the system will consider the topographical patterns of the microscopic markings on the ballistic components. The topographical information encompasses the "peaks and valleys" of the markings, similar to observing elevation changes of a landscape. Using the information obtained, the computer system can determine the direction of the striations and generate a unique "signature." In the simplest terms, the signature resembles a sporadic zig-zag line. Once the signature is constructed, matching algorithms are used to compare it to other signatures stored in the database. The matching algorithms that are utilized by the NIBIN system are considered trade secrets, but a common method of comparison is the employment of the cross-correlation function. This function essentially measures the distances between two signatures. The signatures that possess the highest correlation to the signature in question are compiled into a "hit list" that contains the most likely matches to the evidence. This process, however, is only an investigative step of the examination process; all potential matches must be verified under the comparison microscope by a trained and competent firearms examiner.

The comparison microscope is the tool of the firearm examiner; it allows for the simultaneous view of ballistic components. All forensic evidence has certain characteristics, which are defined as class, subclass, and individual. The term *class characteristics* alludes to a certain group source; *subclass characteristics* alludes to a more restrictive group source; and *individual characteristics* alludes to a particular and unique source. Through an examination and comparison of these characteristics, the examiner determines if the components are an identification or an elimination, or are inconclusive. An elimination is indicated if two components of the ballistic evidence do not share the same source, and this is appropriate when there is disagreement of class characteristics observed. For example, if one bullet has a left twist and another has a right twist, then they were not fired through the same firearm. An identification is indicated when two components of the ballistic evidence share the same source; this is appropriate when there is agreement among all discernible class characteristics, as well as sufficient agreement among individual characteristics. Inconclusive is often reported when there is agreement among all discernible class characteristics, but not enough agreement or disagreement among individual characteristics to arrive at an identification or an elimination, respectively.

Once the examination and comparison have been performed, however, the firearm examiner’s task is not complete. Often, the expert will be called into court to testify and give opinions on their conclusions and interpretations. In the year 2009, the National Academy of Sciences published a report titled *Strengthening Forensic Science in the United States: A Path Forward*, which discussed the shortcomings of the forensic science disciplines. In relation to forensic firearm identification, the report called for more objective foundations and articulations for examination conclusions, perhaps rooted in the mathematical processes of probability and statistics.

Mathematical techniques in probability and statistics are a potential means of supporting evidence evaluations and articulating them in a more objective format. These methods are not without limitations, however. The key to probabilistic considerations begins with the appropriate setting up of propositions. It is beneficial to set up propositions that relate to the arguments of the prosecution and the defense in court. An example of a very basic proposition construction for ballistic evidence, where Proposition 1 represents the prosecution and Proposition 2 represents the defense, would be:

Proposition 1: The evidence bullet was fired through the suspect gun.

Proposition 2: The evidence was fired from a gun other than the suspect gun.

From this format of propositions, different probabilistic values can be considered. Perhaps the most favorable values are given by Baye's Theorem, which allows the probability of a proposition, given known evidence, to be determined by comparing the probability that the evidence given for Proposition 1 is true with the probability that the evidence given for Proposition 2 is true. This theorem allows for adjustment to probabilistic values according to the introduction of new information and evidence. The probability of an event, given evidence, is a conditional probability. All forensic evidence is circumstantial, and therefore, all probabilities considered are conditional. A consequence of Baye's Theorem is the Likelihood Ratio (LR), which measures the value of evidence. The court system is partial to the use of LRs to articulate evidence in the courtroom. However, reporting such statistical values is not always practical; they are also not always as objective as the court may think. While Baye's Theorem and LRs are not complicated formulas, determining which probabilities to "plug in" are not always straightforward. The method of examination that involves counting consecutively matching striations (CMS) observed on evidence is a promising approach that allows for the determination of the needed probabilities, because CMS is constructed in a numerical format. For other markings that are not striated, however, this practice is not beneficial. Therefore, when previous studies do not exist to aid examiners in calculating probabilities, they must draw from their own experience and training. This approach makes the probabilities which are supposed to be objective, subjective. Thus math does not eliminate subjectivity in the discipline. Due to the persistent presence of subjectivity, definitive error rates and confidence intervals are difficult to define.

Introduction

Forensic science encompasses a number of disciplines that employ scientific knowledge and methods for use in the court of law. In particular, the discipline of forensic toolmark examination involves the evaluation of toolmarks through comparative analysis to determine whether they originate from the same tool (National Institute of Justice, 2015). In other words, the discipline focuses on whether a certain "suspect tool" created the "evidentiary toolmark." Firearms are considered to be a specific tool capable of leaving toolmarks on ballistic evidence such as cartridge cases and bullets. Thus, forensic firearm examination represents a smaller subset of forensic toolmark examination which the Association of Firearm and Toolmark Examiners, or AFTE, formally defines as, "a discipline of forensic science which has as its primary concern to determine if a bullet, cartridge case, or other ammunition component was fired by a particular firearm" (NIJ, 2015). However, in addition to examining ballistic evidence, a firearms examiner may be responsible for firearm operability testing, serial number restoration, trigger pull testing, and shooting reconstructions.

Analogous to other fields of forensic science, "the discipline of firearms and tool mark identification is firmly rooted in the scientific method" (Nichols, 2007, p. 586). In fact, the four major branches of science contribute to the field in one way or another. Chemistry techniques are involved in serial number restorations and powder analysis. Physics is used in ballistics and mechanical operations. Knowledge of biology has contributed to the design of ballistic gelatin and is valuable in the evaluation of wound patterns. Finally, mathematics is the backbone of automated matching networks and a critical tool in evidence evaluation.

This paper will discuss significant mathematical techniques involved in the examination of ballistic evidence in the most uncomplicated way possible. For the simpler mathematic techniques, the goal is to gain a sense of familiarity and confidence that can be shared. After all, a critical aspect in all disciplines of forensics is the ability to articulate results and expert opinions to a jury. On the other hand, for the unquestionably complicated mathematical techniques, the objective is not to present complex formulas and algorithms, with pages of algebra, calculus, and theorems. Instead, the goal lies in acquiring a better sense of the ideas and purposes behind the formulas.

History of Firearm Examination

Firearm identification, as a formally defined discipline, is relatively young, with room to expand, evolve, and detail. Informally, however, the discipline can trace its roots back to the Roman era, when it was possible to trace lead bullets thrown by slingers back to their legion of origin, based on the emblems inscribed in the lead (Hatcher, 2006, p. 2). Similarly, fourteenth century archers in England often adorned their arrows with individual markings for identification (Hatcher, 2006, p. 2). When muzzle-loading firearms were commonplace, ammunition was typically homemade, and therefore distinguishable to others (Hatcher, 2006, p. 3). So, while firearm investigation was often undeveloped in procedure, “the juries of that time knew far more of firearms than they do today,” which enabled them to assess the importance of any firearm evidence introduced in court (Hatcher, 2006, p. 3). The courts of the 1870s and the years following accepted expert opinions from sheriffs, police officers, and other individuals who were deemed knowledgeable in the field of firearms (Hatcher, 2006, p. 3). Providing the experts of the time did not stray outside the limits of their knowledge and expertise, their role remained significant (Hatcher, 2006, p. 3). Knowledge that experts possessed, however, was personal knowledge, since, preceding the nineteenth century, there was no scientific literature on the subject of firearm identification (Hatcher, 2006, p. 3). Furthermore, the general public did not deem the practice a science (Hatcher, 2006, p. 3). It was not until the summer of 1900 that Dr. Albert Llewellyn Hall published an article in the *Buffalo Medical Journal* discussing many of the basic principles about firearm wounds and the identification of crime bullets (Hatcher, 2006, pp. 3-4). Nevertheless, the article attracted little attention, and seven years passed before another report relating to the discipline was published (Hatcher, 2006, pp. 4-5). The report discussed the methods of identifying cartridge case evidence with suspect rifles, and like Dr. Hall's article, remained unrenowned (Hatcher, 2006, pp. 5-6). In the year 1912, Professor Balthazard of University of Paris began work to identify a weapon using bullets by photographing the crime bullet and a test bullet fired from the weapon in question and then enlarging the photographs for comparison (Hatcher, 2006, p. 6). This method, while successful, was time-consuming and expensive, and it required an in-depth knowledge of photography (Hatcher, 2006, p. 6). Independent of Professor Balthazard's findings and methodology, others explored a procedure whereby bullets were rolled onto a plastic surface with either lead or carbon paper on top of white paper (Hatcher, 2006, p. 6). This process aimed to transfer and record surface markings from crime and test bullets to another medium, to be used for comparison. However, the results were often insufficient, especially when the bullet was mutilated (Hatcher, 2006, p. 6). Even with advanced equipment, comparisons done with patterns created from the same bullet were sometimes inconclusive (Hatcher, 2006, p. 6). Firearms and ammunition continued to develop as new technologies and techniques were introduced, but society's knowledge in the field did not. Following the introduction of the new "identification methods," "experts" began to take advantage of society's limited knowledge and willingness to blindly accept anything labeled as "scientific" (Hatcher, 2006, pp. 6-7). The absence of qualifications required for an individual to testify as an expert permitted almost anyone to present sweeping opinions based on what the person paying them wanted to hear (Hatcher, 2006, p. 7). Real experts in the field were, unfortunately, scarce, which allowed the majority of the bogus testimonies to go uncontested (Hatcher, 2006, p. 7). Even when testimonies were challenged, valid experts were frequently made to appear unreliable (Hatcher, 2006, p. 7). Ignorance in regard to firearms, and abuse of the justice system, continued to result in inappropriate convictions. Perhaps the most critical contribution to the field of firearm and toolmark identification was the adoption of the comparison microscope which “was obtained and put into service in April of 1925” (Hatcher, 2006, p. 15). Equipped with the capability that the comparison microscope provided, a push was made to educate the general public on the discipline of firearm identification (Hatcher, 2006, p. 15). The two men at the epicenter of this movement, Charles Waite and Calvin Goddard, operated as the Bureau of Forensic Ballistics (Hatcher, 2006, pp. 15-16). Although the Bureau was a private enterprise, it offered expertise to initially hesitant police departments (Hatcher, 2006, p. 16). Eventually, departments acknowledged the valid scientific basis of the Bureau, and testimonies were permitted in the courtroom (Hatcher, 2006, p.16). It was only five years later that courses in the discipline were instituted, first in the Scientific Criminal Investigation Laboratory associated with Northwestern University, and another five years later at the FBI Academy (Hatcher, 2006, p. 17). At the opening of the first programs in the 1930s, “the Science of Firearm Identification was firmly established on a scientific basis” (Hatcher, 2006, p. 18). Ever since its establishment, adjustments to the discipline have focused on “emphasis rather than in basic procedure,” with the goal of simplifying and increasing efficiency in response to a larger workload (Hatcher, 2006, pp.18, 20).

Structure of Evidence Examination

When forensic firearms evidence is submitted to the firearms laboratory, it typically undergoes a process of investigation, comparison, and analysis.

Investigation begins with the cataloging of the evidence into an automated computer network that uses comparison algorithms to “investigate” possible matches in the system. This initial aspect of the examination process involves cutting-edge, and therefore very expensive, technology. As a result, not every laboratory is equipped to execute this phase of examination. Of course the “use of comparison algorithms” alludes to the heavy mathematical influences in this step. Ironically, the math that is encountered first in this discipline is the most complicated. Therefore, rather than jumping straight into the deep end here, these algorithms and techniques are set aside as the last topic of discussion.

Comparison is performed by a trained firearms examiner on a comparison microscope. The examiner examines and compares any possible matches indicated by the investigation to determine whether there is, in fact, a match. This phase of the examination involves the least amount of math and relies heavily on a knowledge of firearms, and experience in microscopic examination and comparison. Since the principles of the forensic firearm examination field itself are contained within this step, this represents a practical first topic of discussion.

Finally, mathematical analysis provides the tools and methods to evaluate, and in some cases, support or confirm, an examiner’s conclusion. Math is heavily influential in this phase of the examination as well, but involves less complicated techniques. The focus is on the statistical evaluation of evidence, which includes likelihood ratios, error rates, and confidence intervals. This step is largely a response to the court’s demand for more quantitative methods and articulations in the field of forensic firearm examination. Therefore, the discussion of this topic will be preceded by a brief discussion concerning the admissibility of forensic evidence in the courtroom.

The format of discussions in this paper does not follow the order of the evidence examination phases, but rather an order in accordance to the mathematical “intensity” within each step. Thus, the field of forensic firearm examination constitutes the first topic of discussion. Following will be a discussion of evidence admissibility in court, and then of the mathematical analysis of evidence. The final topic of discussion, before the concluding remarks, will be investigative tools and automated computer networks.

Forensic Firearm Examination and Identification

Comparison Microscopy

A comparison microscope, as defined by the *Merriam Webster Dictionary*, is “an apparatus consisting essentially of a pair of microscope objective lenses and tubes connected by prisms in such a way that images from both may be viewed side by side through a single ocular lens” (“Comparison Microscope,” 2015). As mentioned earlier, the adoption of the comparison microscopic was critical to the field of firearm identification. Prior to its introduction, forensic firearms examination was a multi-step and often tedious process. First, fired components were examined one at a time with a single compound microscope (National Institute of Justice, 2015, Mod07). Then each component was photographed, and the images were enlarged to show the microscopic details for a side-by-side comparison (NIJ, 2015, Mod07). Finally, an analysis and preparation of exhibits was constructed based on the photographs (NIJ, 2015, Mod07). However, this process only allowed for a sequential microscopic comparison of two objects (NIJ, 2015, Mod07). Simultaneous comparison was only possible with photographs of the objects, which were only two-dimensional representations of the three-dimensional objects (NIJ, 2015, Mod07). When Calvin Goddard and Phillip Gravelle pioneered the idea of the use of the comparison microscope, Charles Waite conferred

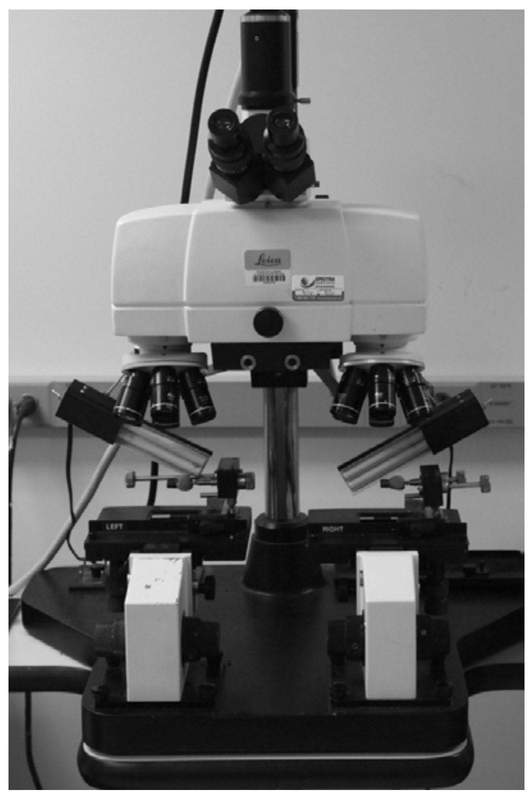

Figure 1

with Remington to construct specialized mounts to accommodate ammunition components (NIJ, 2015, Mod07 and Hatcher, 2006, p. 15). Comparison microscopes are widely implemented in today's forensic laboratories. For the exercises and photographs presented in this paper, a Leica UFM Comparison Microscope with fluorescent lighting, shown in Figure 1, was used.

Characteristics of Evidence

Firearm examination and identification, and in fact, all disciplines in forensic science, distinguish the characteristics of physical evidence according to three categories: class, subclass, and individual. *Class characteristics* are defined as "measurable features of a specimen which indicate a restricted group source, resulting from design factors and therefore are determined prior to manufacture" (National Institute of Justice, 2015, Mod06). Every piece of physical evidence belongs to at least one larger grouping, so any and all physical evidence will have class characteristics (NIJ, 2015, Mod06).

Subclass characteristics are defined as "discernible surface features that are more restrictive than class characteristics such that they relate to a smaller group source or 'subset' of a particular class which are produced incidental to manufacture and are identifiable within a time frame since manufacturing processes change over time" (NIJ, 2015, Mod 06).

Individual characteristics are defined as markings, often microscopic in nature, which are "produced by the random imperfections or irregularities of tool surfaces incidental to manufacture and/or caused by use, corrosion, or damage" (Firearms Definitions, 2015). By definition, these individual characteristics are restricted to one source of origin and differentiate the evidence from any other origin (NIJ, 2015, Mod06). In the discipline of firearm examination, microscopic marks are classified as *impressed* or *striated*. *Impressed* marks are a result of a perpendicular force or pressure, while *striated* marks are a consequence of a shearing and tangential force (Firearms Definitions, 2015).

Theory of Identification

The AFTE Theory of Identification provides a foundation for comparing toolmarks when attempting to determine if they hail from the same origin, or in other words, from the same tool (National Institute of Justice, 2015, Mod09). The theory is characterized by three fundamental principles (NIJ, 2015, Mod09). First, opinions that two toolmarks originate from the same tool are permitted “when the unique surface contours of two toolmarks are in sufficient agreement” (NIJ, 2015, Mod09). Second is *significant agreement*, which refers to a level of consistency that an examiner knows and has come to expect from two items made from the same tool. Furthermore, the agreement should exceed the level of agreement observed from a best known non-match of two items made from different tools (NIJ, 2015, Mod09). “The statement that sufficient agreement exists between two toolmarks means that the likelihood another tool could have made the mark is so remote as to be considered a practical impossibility” (NIJ, 2015, Mod09). Third, while the discipline of firearm examination and identification does have a basis in scientific principles, the practice of examining evidence also relies on the experience and training of the examiner, and interpretations are recognized as subjective (NIJ, 2015, Mod09).

The AFTE Theory of Identification has structured three possible, and acceptable, conclusions of an examination and comparison, which are: elimination, identification, and inconclusive. The first level in an identification process is the examination of class characteristics. At this level, the only appropriate conclusion is an elimination based on a disagreement of class characteristics. An elimination is indicative of the fact that two pieces of projectile evidence did not originate from the same source. The AFTE Glossary defines an elimination as “a significant disagreement of discernible class characteristics and/or individual characteristics” (NIJ, 2015, Mod09).

The second level in the identification process is a microscopic comparison and examination. This is the only level at which arriving at an identification is appropriate. An identification is indicative of the fact that two pieces of projectile evidence originated from the same source. The AFTE Glossary defines an identification as the "agreement of a combination of individual characteristics and all discernible class characteristics where the extent of agreement exceeds that which can occur in the comparison of toolmarks made by different tools and is consistent with the agreement demonstrated by toolmarks known to have been produced by the same tool" (NIJ, 2015, Mod09).

If evidence is lacking in quality and character, such that neither an identification nor an elimination can be made, an appropriate conclusion may be that the comparison is inconclusive. This conclusion typically describes instances in which all discernible class characteristics are in agreement, but (1) there is insufficient agreement of individual characteristics to make an identification; (2) there is some disagreement of individual characteristics, but not enough to make an elimination; or (3) there is no “agreement or disagreement of individual characteristics due to an absence, insufficiency, or lack of reproducibility” (NIJ, 2015, Mod09). *Inconclusive* can also refer to evidence’s being “unsuitable for comparison,” which the AFTE Glossary defines as “[an] outcome [that] is appropriate for fired and mutilated evidence that do not bear microscopic marks of value for comparison purposes such as fired bullet fragments, jacket fragments, lead bullet cores, lead fragments, or metallic fragments that cannot be identified as having been a part of a fired bullet” (NIJ, 2015, Mod09). It should be noted that in the discipline of forensic firearm examination, “more likely that not” is never an appropriate conclusion (Kurimsky, 2014).

Firearm Operations

When the trigger of a firearm is compressed, it releases the firing pin, which strikes the primer of the cartridge case in the chamber (Kurimsky, 2013). The strike detonates the primer, which ignites the gunpowder (Kurimsky, 2013). As the powder burns, turning from a solid state to a gaseous state, it begins to occupy more volume, causing a build-up of pressure in the cartridge (Kurimsky, 2013). Ultimately, the pressure forces the projectile down the barrel of the firearm (Kurimsky, 2013).

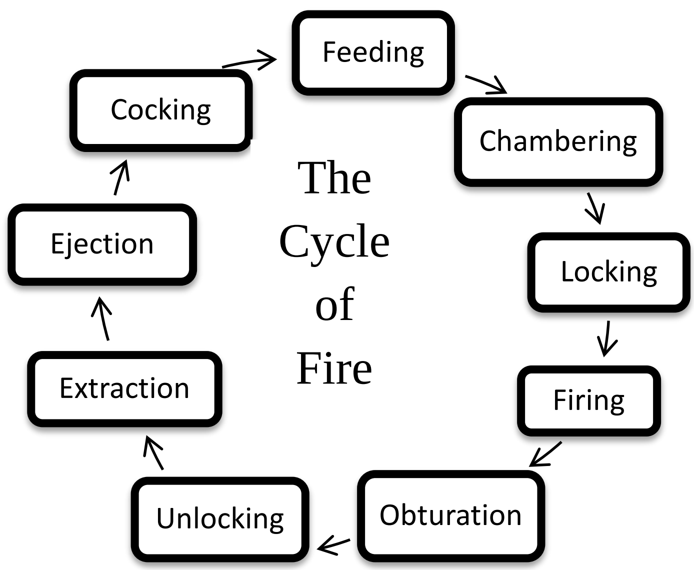

Figure 2

The nine steps of firearm operation, which occur each time a firearm is discharged, are known as the Cycle of Fire, pictured in Figure 2. *Cocking* is the step wherein the firing mechanism is placed under spring tension (Kurimsky, 2013). *Feeding* follows, in which the cartridge is inserted into the chamber, where the breech bolt then pushes it into the final position (Kurimsky, 2013). Next, *chambering*, or the act of inserting a cartridge into the chamber, ensues (Kurimsky, 2013). The cycle continues with *locking*, which refers to the manual or automatic action of supporting the bolt of a firearm immediately prior to firing (Kurimsky, 2013). *Firing* occurs when the breech is fully locked; compression of the trigger mechanically releases the firing pin, so that it can strike the primer of the cartridge (Kurimsky, 2013). The resulting sealing in of gases due to the expansion and/or upset of the bullet base as it travels down the bore is known as *obturation* (Kurimsky, 2013). At this point, the firearm undergoes *unlocking*, which is the reverse of the locking process (Kurimsky, 2013). Often, unlocking occurs in conjunction with *extraction*, or the act of withdrawing a cartridge or cartridge case from the chamber of a firearm (Kurimsky, 2013). *Ejection*, or the act of expelling a cartridge case from a firearm, brings the cycle full circle back to the *cocking* step, so that the steps can repeat each time the trigger is compressed (Kurimsky, 2013 and National Institute of Justice, 2015, Mod08).

Like all machines, firearms do not function perfectly each time they are used. Sometimes, when the trigger is compressed, the cartridge does not fire. This can be a result of mechanical failure within the firearm or defective ammunition (Kurimsky, 2014). In the case of a malfunction whereby the primer does not ignite, the cartridge case is described as being "cycled through" the firearm (Kurimsky, 2014). Even cartridges that are cycled through, however, go through the feeding, chambering, extraction, and ejection steps of the Cycle of Fire (Kurimsky, 2014).

Microscopic Markings

Cartridge Cases

Certain steps in the Cycle of Fire, including feeding, chambering, firing, extraction, and ejection, are responsible for the transference of microscopic markings from the firearm to the cartridge case. Cartridges are classified into two categories, based on the location of their primer:

rimfire and *centerfire*. Rimfire cartridge cases are typically harder to identify from a comparison, as they tend to have fewer and lesser individual markings than centerfire cartridge cases.

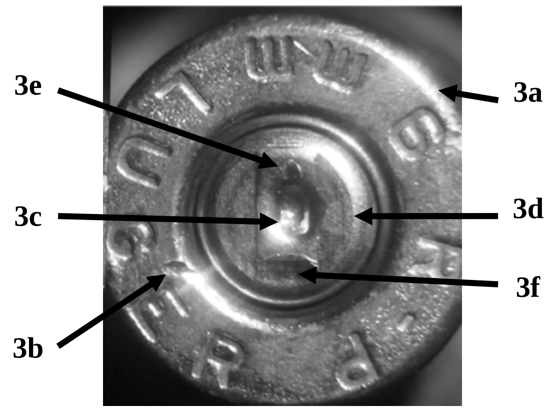

Figure 3

Figure 3 depicts the most common markings found on centerfire cartridge cases. Markings left from extraction (3a) and ejection (3b) are typically found near the base or rim. Firing will result in a firing pin impression mark (3c) and breechface markings (3d), which are typically observed towards the center of the headstamp. In addition, drag marks (3e) and sheer marks (3f) may be present (Kurimsky, 2014).

If a cartridge was fired through a firearm, there will be a firing pin impression. Firing pin shape is a class characteristic (Kurimsky, 2014). Figure 4 depicts a comparison of two firing pin impressions of the same shape. However, the left cartridge case was fired from a Glock 27, while the one on the right was fired from a Glock 19. Both cartridges were fired through semi-automatic Glock pistols, but the impression is not an individual characteristic marking of a particular Glock pistol. A special case of firing pin impressions involves those with concentric circles, which are acknowledged as subclass characteristics (Kurimsky, 2014). Figure 5 shows a comparison of two firing impressions with concentric circles.

Figure 4

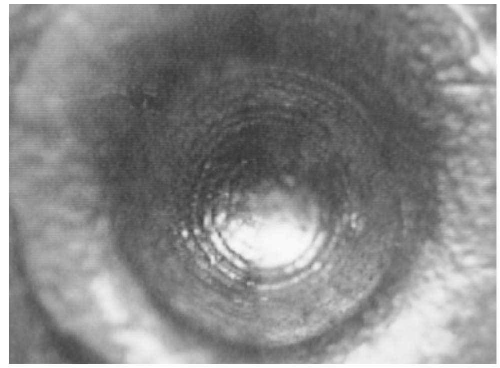

Figure 5

The violent motion that occurs during the discharge of a firearm sometimes results in drag marks on a firing pin impression (Kurimsky, 2014). Drag marks are striated marks resulting from the barrel of the firearm dropping so fast that the firing pin does not have time to completely retract, causing part of the cartridge case to sheer off during extraction and ejection (Kurimsky, 2014). These marks are useful for orienting cases during comparison and are possible sources for making identifications (Kurimsky, 2014). The two cartridge cases shown in Figure 4 exhibit drag marks oriented at twelve o'clock. In addition, Figure 6 shows a comparison of drag mark striations between two cartridge cases fired from the same Glock 19. In this case, the significant agreement of individual characteristics on the drag marks is good for an identification.

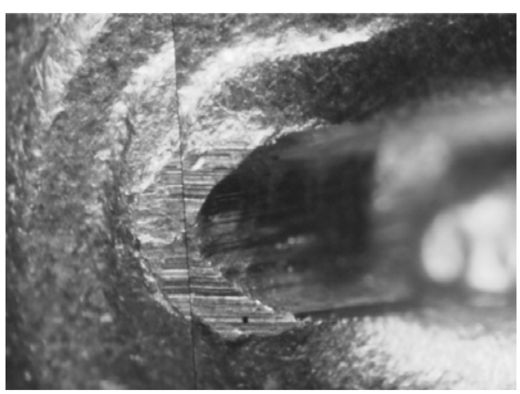

Figure 6

Rimfire cartridge cases that have been fired through a firearm are going to have firing pin impressions as well, but these will be located along the rim of the case (Kurimsky, 2014). Figure 7 depicts a comparison of two .22 Long Rifle (.22LR) rimfire cartridge cases with rectangular firing pin impressions, fired from the same Smith and Wesson 34-1 revolver. In this case, the firing pin impressions have striations that enable an identification to be made. However, in instances where the firing pin impressions are granular, they do not offer a statement of individualization (Kurimsky, 2014). Another comparison of two .22LR rimfire cartridges is seen in Figure 8, where the firing pin impressions are circular. The impressions look very similar, but they are the output of two different firearms. Both guns were Smith and Wesson Rimfire revolvers, but the cartridge on the left was fired through a Model 34-1, while the cartridge on the right was fired through a Model 617. Notice that the cartridge cases seen in Figure 7 and the cartridge case on the left in Figure 8 were both fired through a Smith and Wesson 34-1 revolver, but the firing pin impressions are completely different in shape.

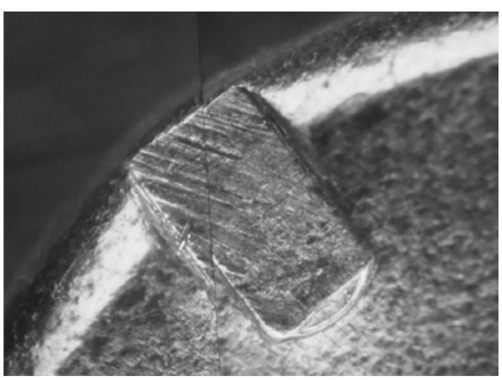

Figure 7

Figure 8

There are select instances where it is possible to observe firing pin impression marks on cartridge cases that have only been cycled through a firearm (Kurimsky, 2014). In pistols and rifles that have floating firing pins, "smaller versions" of the impression can be present

(Kurimsky, 2014). Free-floating firing pins do not experience the same amount of resistance that spring-loaded firing pins do, which allows them to shift forward and occasionally come into contact with a newly chambered cartridge (Kurimsky, 2014). The left cartridge case in Figure 9 was fired through an AR 15 bolt-action rifle, and the cartridge case on the right was cycled through the same firearm. The trigger was not compressed to release the firing pin to fire the cartridge case on the right, but there is still a small impression visible in the center of the headstamp, a consequence of the floating firing pin in the AR 15. Another circumstance that results in a firing pin impression on a cycled-through cartridge case is shown in Figure 10. In particular, the cartridge case in the figure exhibits two firing pin impressions, a consequence of the shooter's pulling the trigger a second time when the first pull did not fire the cartridge (Kurimsky, 2014). Nonetheless, in both figures, breechface impressions are not present on the cycled-through cartridge cases (Kurimsky, 2014).

Figure 9

Figure 10

Breechface markings, like firing pin impressions, can indicate that a cartridge case was fired through a firearm (Kurimsky, 2014). However, these markings are habitually absent from rimfire cartridge cases (Kurimsky, 2014). Breechface marks are "negative impressions found on the head and/or primer of the cartridge case," resulting from the breechface of the firearm ramming into the cartridge (National Institute of Justice, 2015, Mod09; Kurimsky, 2014). There are various breechface impressions, and it is possible to have more than one type on the same gun (Kurimsky, 2014). Striated breechface impressions are good for making identifications, but those that are granular are recognized as class characteristics (Kurimsky, 2014). Figure 11 shows two cartridge cases with striated breechface markings where significant agreement supported an identification. The parallel striations observed on the breechface of a spent cartridge case, however, are actually considered to be impressed toolmarks rather than striated toolmarks (Kurimsky, 2014). Despite their striated appearance, they are a result of pressure rather than motion (Kurimsky, 2014). In Figure 12, two cartridges are shown in comparison, and both have granular breechface impressions. While it was known that both cases were fired through the same Remington 700 bolt-action rifle, claiming an identification based solely on the agreement of breechface impressions is not appropriate. As with firing pin impressions, concentric circles can be recognized as subclass characteristics, as seen in Figure 13, in which both cartridge cases shown were fired through the same Remington 700 bolt-action rifle (Kurimsky, 2014). Notice that while the cartridge cases seen in both Figures 12 and 13 were fired from Remington 700 bolt-action rifles, their breechface impressions differ.

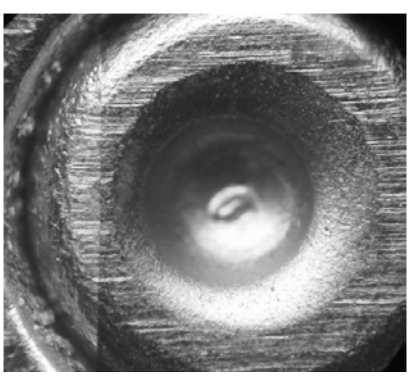

Figure 11

Figure 12

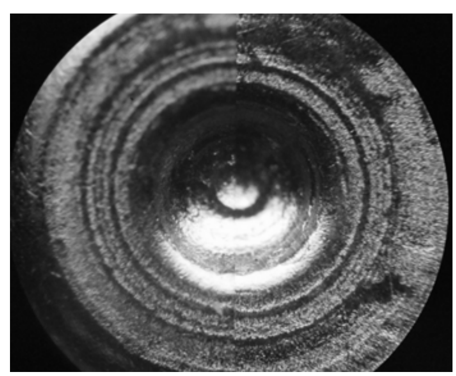

Figure 13

Shear marks occur when the firing pin aperture or breechface moves and shears off part of the moving cartridge case (Kurimsky, 2014). The rough firing pin aperture, or hole, scraping against the priming metal during the unlocking process causes striated shear marks (Kurimsky, 2014). A comparison of two shear marks located near the rims of two cartridges fired through the same AR-15 bolt-action rifle is shown in Figure 14. Significant agreement between corresponding striations allowed an identification to be made. The shear marks depicted in Figure 15 are located on the firing impressions, opposite the drag marks. Again, sufficient agreement of corresponding striations confirmed the identification that both cartridge cases were fired through the same Glock 19 semi-automatic pistol.

Figure 14

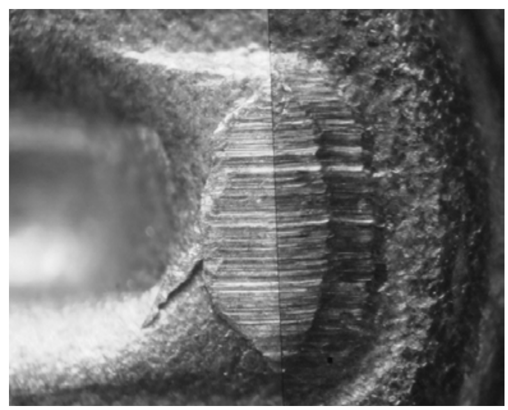

Figure 15

Extractor marks can be observed on cartridge cases that have been fired in a firearm, as well as those that have only been cycled through one (Kurimsky, 2014). The operation of the extractor on the spent cartridge case generates these marks (Kurimsky, 2014). Extractor marks are generally on, or just in front of, the cartridge case rim (Kurimsky, 2014). Occasionally, the marks can be seen on the back of the rim, and/or they extend onto the chamber as a result of violent motion (Kurimsky, 2014). A comparison of striated extractor marks on the rims of two cartridge cases is shown in Figure 16,; it was determined that both cartridge cases had been cycled through the same firearm. On the other hand, Figure 17 shows the rims of two cartridge cases fired though an H&K semi-automatic rifle; in this case, the extractor marks were impressed instead of striated. Arriving at an identification on impressed extractor marks alone is not appropriate.

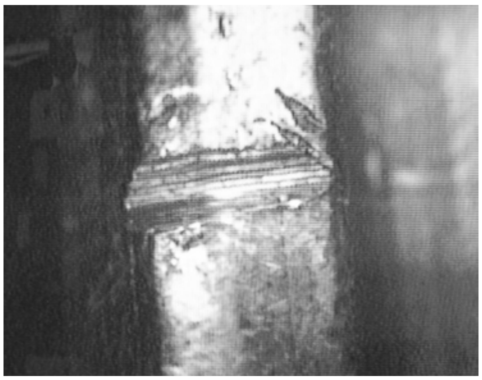

Figure 16

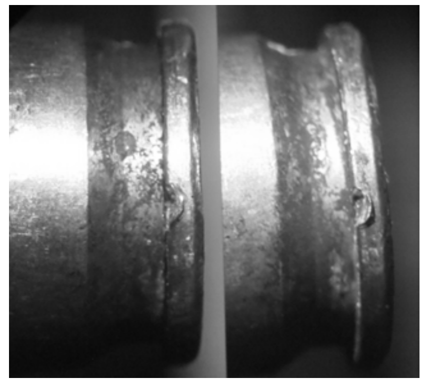

Figure 17

Ejector marks, like extractor marks, can be observed on cartridge cases that have been fired in, as well as those that have only been cycled through, a firearm (Kurimsky, 2014). Generally located on the head of the cartridge case, and roughly opposite the extractor mark, these marks are a result of contact with the ejector of the firearm (Kurimsky, 2014). Two striated ejection marks are shown in comparison in Figure 18, where sufficient agreement between corresponding striations warranted an identification and a conclusion that both cartridge cases were cycled through the same firearm. An ejection port mark can also result from the ejection process, but it occurs at the mouth of the cartridge case, as opposed to the head (Kurimsky, 2014). Ejection port marks are striated and are produced by “hard contact between the ejection port of a firearm and a rapidly moving cartridge case” (NIJ, 2015, Mod09). Figure 19 depicts a comparison of ejection port markings between a cartridge that was fired through a semi-automatic pistol and a cartridge that was cycled through the same firearm. The ejector port mark seen on the left cartridge case, which was fired in the firearm, is significantly wider and larger than the mark seen on the right cartridge, which was cycled through. An individual cannot generate enough speed to simulate the force of firing a weapon just by manually working the slide, so fired cartridge cases have more intense markings (Kurimsky, 2014). Despite these differences, however, significant agreement between corresponding striations is present, permitting an identification.

Figure 18

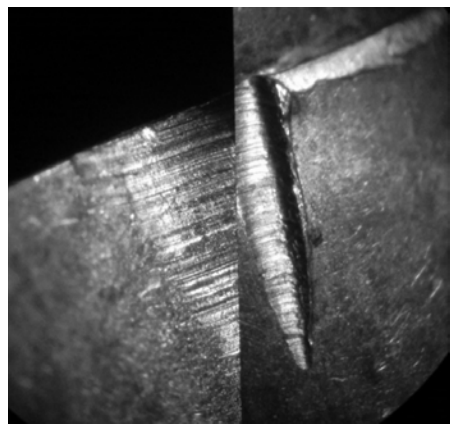

Figure 19

Typically, revolvers are not known to produce extractor and ejector marks. With pistols and rifles, cartridges are fed into the chamber one at a time from the magazine and expelled after they are spent to empty the chamber for the next round; sometimes this results in marks from the extractor and ejector of the firearm (Kurimsky, 2014). In the case of revolvers, however, all of the cartridges are stored in the cylinder, which is designed to rotate after each trigger pull and align a new cartridge with the firing pin (Kurimsky, 2014). All of the spent cartridges remain in the cylinder until the operator manually removes them. With the absence of mechanisms pushing the cartridge cases from the chamber with a violent motion, ejector and extractor markings are not commonly seen (Kurimsky, 2014).

Additional types of marks that can potentially show up on a cartridge case include chamber marks, anvil marks, magazine marks and manufacturing marks (NIJ, 2015, Mod09; Kurimsky, 2014). While it is unlikely that all of these marks will be found on a cartridge case, the possibility always exists.

Bullets

The initial examination of projectile evidence involves the observation of general rifling characteristics. These characteristics, referred to as GRC, are recognized as class characteristics. GRCs encompass a bullet's nominal caliber, or base diameter; the number of land impressions (known as *limps*); the number of groove impressions (known as *gimps*); the width of the limp and gimp impressions; and the twist direction of the bullet, which is determined by the "lean" of the limps and gimps (National Institute of Justice, 2015, Mod10; Kurimsky, 2013). Of the four bullets shown in Figure 20, a right twist is observed on the first two bullets, while a left twist is observed on the last two. The difference in twist direction warrants an elimination of the two leftmost bullets being fired through the same gun as the two rightmost bullets.

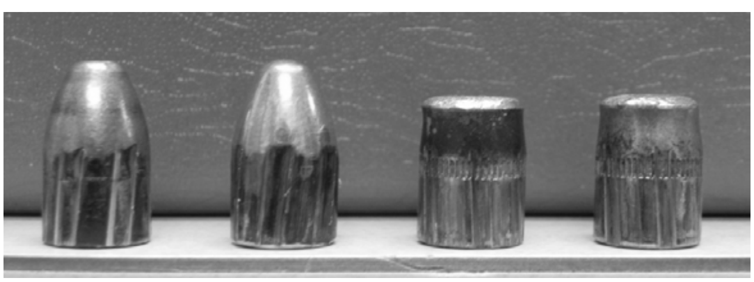

Figure 20

Figure 21

When a bullet is damaged to the point at which the number of limps and gimps cannot be determined, such as the one depicted in Figure 21, basic geometry and algebra come to the rescue. Since a bullet's base is initially circular, its circumference, like any other circle, is given by C = dπ (Step 1). The term *d* represents the diameter of the circle, which in this case is the nominal caliber (Step 2). The term π is given to be 3.14 (Step 3). The circumference of a circle, *C*, is the measurement of the length around the circle. In this case, the circumference is [the limp width times the number of limps] plus [the gimp width times the number of gimps] (Step 4). However, since the number of limps is always equal to the number of gimps, *C* can be written as the sum of the limp and gimp widths times the number of limps and gimps, which is denoted as *x* (Step 5). Use of the Algebraic Property of Distribution helps to simplify the equation (Step 6).

$$C = d\pi$$

$$C = (nominal\ caliber)\pi$$

$$C = (nominal\ caliber)(3.14)$$

$$(limp\ width)(\#\ of\ limps) + (gimp\ width)(\#\ of\ gimps) = C$$

$$(limp\ width)(x) + (gimp\ width)(x) = C$$

$$(x)(limp\ width + gimp\ width) = C$$

Now the original equation $C = d\pi$ can be written as:

$$(x)(limp\ width + gimp\ width) = (nominal\ caliber)(3.14)$$

The term *x*, which represents the number of limps and gimps, is the "unknown" in the equation. Dividing both sides of the equation by $(limp\ width + gimp\ width)$ yields a formula to determine *x* (Kurimsky, 2013).

$$\text{x} = \frac{\text{(3.14)(nominal caliber)}}{\text{(limp width)+(gimp width)}}$$

For purposes of illustration, the equation is used to determine the number of land and groove impressions for the damaged bullet pictured in Figure 21. The nominal caliber of the bullet was measured at 0.346 inches. Of the measureable limps, the average width was 0.078 inches, and of the measurable gimps, the average width was 0.093 inches. Substituting the determined measurements into the equation yields the result that the bullet has six limps and six gimps, as shown below.

$$x = \frac{(3.14)(\text{nominal caliber})}{(\text{limp width})+(\text{gimp width})} = \frac{(3.14)(0.346)}{(0.078) + (0.093)} = \frac{1.08644}{0.171} \approx 6$$

After the GRCs are determined, an examiner will inspect the bullets under the comparison microscope. To make an identification of two bullets, there must be sufficient agreement of striations in two corresponding land impressions (Kurimsky, 2014). Figure 22 shows an identification of two bullets based on this criterion. Striations that exhibit agreement on groove impressions are recognized as subclass characteristics (Kurimsky, 2014).

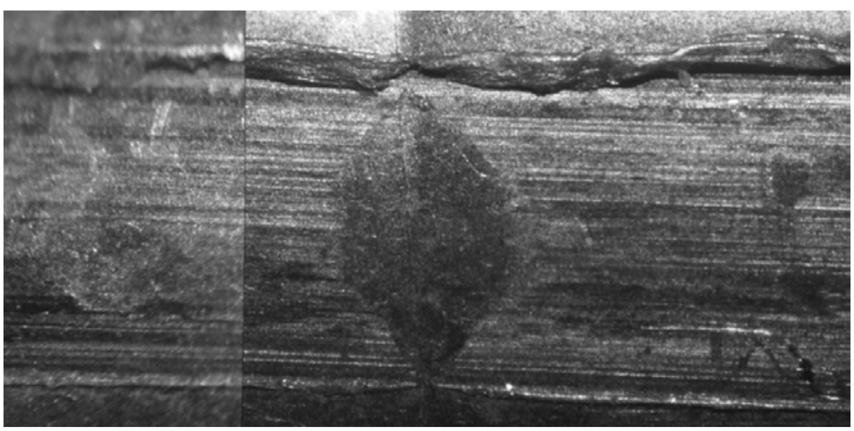

Figure 22

Microscopic Examinations

There are two prominent approaches when examining and comparing firearm evidence under the comparison microscope: pattern matching theory and consecutively matching striae (Kurimsky, 2014). Pattern matching theory refers to “the process of determining whether or not the details of striated marks or impressions on two objects correspond” (National Institute of Justice, 2015, Mod09). This method is valuable, given that it works with both striated and impressed marks, but presents difficulty in communicating how the identification was arrived at (Kurimsky, 2014). “This process has traditionally been more qualitative than quantitative, and therefore difficult to convey to a jury” (NIJ, 2015, Mod09).

The consecutively matching striae (CMS) approach is, to some extent, an “answer” to the need for a more quantitative approach to articulating identifications (NIJ, 2015, Mod09). Al Biasotti studied and analyzed the number of consecutive striae that corresponded in comparisons of known matches and known non-matches (NIJ, 2015, Mod09). Biasotti concluded that in two dimensions, significant agreement is reached when there are either two groups of five matching striae or one group of eight matching striae (Kurimsky, 2014). In three dimensions, significant agreement is reached when there are two groups of three matching striae or one group of six matching striae (Kurimsky, 2014). The analyses that Biasotti employed were statistical and will be discussed more thoroughly in the section titled “Mathematical Analysis.” Important considerations of this method are that (1) striations must occur one after the other to be consecutive; (2) the method can only be applied to striated markings, and (3) “the possibility of sub-class characteristics must be ruled out" (NIJ, 2015, Mod09; Kurimsky 2014). In addition, the CMS approach is not exclusively objective (Kurimsky, 2014). In the discipline of toolmark examination and identification as a whole, “the observations are objective [but] the interpretations of those observations [are] subjective [… which …] well-documented comparison microscopy is extremely effective at minimizing” (Nichols, 2007, p. 589).

Admissibility and the Court of Law

Courtrooms have hosted expert witnesses and listened to expert testimony even before forensic science was formally established. Typically, the testimonies offered were fair and accurate, provided the experts in question did not stray from their expertise. However, without an established set or rules and restrictions, some “experts” began to stray, offering up unfit and unfair testimonies.

Frye and Daubert Standards

Two major court cases, *Frye vs. United States* and *Daubert vs. Merrell Dow Pharmaceuticals*, defined and established the rules for the admissibility of forensic evidence and expert witnesses in the courtroom.

In the 1923 criminal trial of *Frye vs. United States*, the defendant on trial for murder wished to submit the outcome of a lie detector test, in an effort to prove his innocence (National Academy of Sciences, 2009, p. 88). However, the court ruled that the evidence was not permissible in the courtroom, on the grounds that it was unreliable because it lacked “general acceptance in the scientific community” as a legitimate scientific practice (NAS, 2009, p. 88). This ruling constituted the Frye Standard, which stood to ensure that only valid science that was generally accepted by the applicable scientific community was permissible in the courtroom (NAS, 2009, p. 88).

Seventy years later, in the 1993 civil case of *Daubert vs. Merrell Dow Pharmaceuticals,* parents sued the pharmaceutical company for the birth defects of their children, which they claimed to have resulted from the company’s drug, Bendectin, which the mother had been taking during her pregnancy (NAS, 2009, p. 90). Merrell Dow Pharmaceuticals consulted an expert, who assured the court that, after a review of the literature, no association was found that Bendectin was a source of defects in human fetuses (NAS, 2009, p. 90). The plaintiffs brought forth experts of their own, who all declared that, based on animal studies, Bendectin was a source of embryo defects (NAS, 2009, p. 90). The lower courts rejected the evidence the plaintiffs brought forth, "declaring that expert opinion based on a methodology that diverges significantly from the procedures accepted by recognized authorities in the field cannot be shown to be generally accepted as a reliable technique" (NAS, 2009, p. 90). Eventually, the case was granted audience in the Supreme Court, which ruled that the judge is responsible for determining that scientific evidence permitted in the courtroom is both reliable and relevant (NAS, 2009, p. 90). This ruling constituted the Daubert Standard, which established the judge as the "gatekeeper" for the admissibility of scientific evidence and pointed to several factors that the judge should consider (NAS, 2009, p. 90). These include testability, or reproducibility of the technique in question; peer review and publication; knowledge of the technique's potential error rates; the processes and standards that mandate the technique's procedure; and the extent to which the technique is accepted in the applicable scientific community (NAS, 2009, p. 91). The implementation of the cross-examination of expert witnesses is the court's approach to "weeding out" unreliable evidence (NAS, 2009, p. 91).

Each state within the United States of America determines which standard to rule by in conjunction with the statements given in the *Federal Rules of Evidence*.

Federal Rules of Evidence

The *Federal Rules of Evidence* is a compilation of regulations designed to preside over civil and criminal trials in the United State's judicial system. The rules encompass procedures relating to evidence, witnesses, testimonies, competency, and admissibility (*The Federal Rules of Evidence*, 2015). Several rules are pertinent to forensic evidence and the testimony of expert witnesses (*The Federal*, 2015). Specifically, Rules 401 and 402 refer to the admissibility of evidence (*The Federal*, 2015, p. 3). Rule 401 defines relevant evidence as "evidence having any tendency to make the existence of any fact that is of consequence to the determination of the action more probable or less probable than it would be without the evidence" (*The Federal*, 2015, p. 3). Rule 402 dictates that if the evidence in question has been deemed relevant, it is admissible in the court of law, unless declared otherwise by the United States Constitution, Congress, or a ruling of the Supreme Court (*The Federal*, 2015, p. 3). Subsequently, the parameters of expert testimony are outlined in Rule 702 (*The Federal*, 2015, p. 18). A witness is qualified to present expert testimony in the form of an opinion based on their experience, education, knowledge, understanding, and demonstration of skill in the relevant scientific or technical field (*The Federal*, 2015, p. 18). Furthermore, the given testimony must be founded on reasonable data that were the results of reliable standards and methods that the witness employed appropriately (*The Federal,* 2015). In other words, the expert witness is expected to give a fair and accurate representation of the relevant evidence in question.

The NAS Report

The National Academy of Sciences, or NAS, published a report in 2009 titled *Strengthening Forensic Science in the United States: A Path Forward*. In summary, the report discussed the shortcomings of the field of forensics, as well as ideal solutions to certain issues. Issues that were stressed included the absence of an obligatory standardization of terminology and protocols, the certification of experts, the accreditation of laboratories, and ongoing research on statistical methods to determine error rates and confidence intervals (National Academy of Sciences, 2009). The NAS specified the level at which forensic science evidence should be scrutinized in stating:

> The degree of science in a forensic science method may have an important bearing on the reliability of forensic evidence in criminal cases. There are two very important questions that *should* underlie the law's admission of and reliance upon forensic evidence in criminal trials: (1) the extent to which a particular forensic discipline is founded on a reliable scientific methodology that gives it the capacity to accurately analyze evidence and report findings and (2) the extent to which practitioners in a particular forensic discipline rely on human interpretation that could be tainted by error, the threat of bias, or the absence of sound operational procedures and robust performance standards. (NAS, 2009, p. 87)

Concerning the discipline of forensic firearm examination in particular, the issue emphasized in the report was its heavy dependence on subjective conclusions, as opposed to objective analysis (NAS, 2009, p. 155). In order to drive home their notion of the unreliability of the discipline, the NAS cites the case of *United States vs. Green* (NAS, 2009, p. 108), in which the judge declared that the testimony concerning shell casings presented by the prosecution was not reliable in terms of the Daubert Standard, thus barring the expert witness from testifying to the existence of a match (NAS, 2009, p. 108). However, the judge conceded to allow the expert to comment on the similarities seen in the casings, justifying his decision based on the fact that "*every single court post*-*Daubert* has admitted this [type of] testimony" (NAS, 2009, p. 108). The NAS report does recognize the possibility of making an "identification" that two ballistic components were fired through the same firearm, but challenges the field, saying that is inadequate research to verify this claim (NAS, 2009, pp. 153-5). There is, in fact, “no universal agreement as to how much correspondence exceeds the best-known non-matching situation" (Nichols, 2007, p. 589). In response to the allegations of the NAS report, experts in the discipline of forensic firearm examination have stepped up research on more quantitative techniques, which will be discussed in the succeeding section, to articulate their conclusions and methods.

An Aside: The Paradigm of DNA Analysis

Throughout the NAS report, the forensic discipline of DNA analysis is held up and revered as a leading example for other disciplines concerning its objectivity and the presentation of statistical analyses that provide perspective error rates and levels of confidence (NAS, 2009, p. 155). However, it must be established that just because the procedures work great for DNA analysis, this does not mean they will have the same validity when applied to other forensic disciplines (Nichols, 2007, p. 591). To be clear, “the characteristics being compared in DNA profiles are actually subclass characteristics,” whereas the characteristics used to establish identifications in firearm examination are individual characteristics (Nichols, 2007, p. 591). While the level of confidence associated with DNA profiling is ideal, the process is “so different from firearms and tool mark identifications that analogies may be intellectually inappropriate” (Nichols, 2007, p. 591). Thus, despite the increase and expansion of research on more quantitative articulations of ballistic evidence examinations and identifications, there are variables and aspects of forensic firearm examination that may not allow for the complete elimination of subjectivity.

Admissibility of Evidence in the Courtroom

The Frye and Daubert Standards, the Federal Rules of Evidence, and the NAS Report all address the admissibility of forensic evidence in the courtroom. The interpretation and presentation of data and conclusions an expert witness has developed are equally as important as the examinations themselves. If interpretations are not understood by the jury, then there is no point to conducting the examinations in the first place. The NAS Report discusses the significance of writing reports and how "sufficient content should be provided to allow the nonscientist reader to understand what has been done and permit informed, unbiased scrutiny of the conclusion" (National Academy of Sciences, 2009, p. 186). Sufficient content includes; thorough and clear descriptions of the materials and procedures of the method used for evaluation; results, with their associated level of confidence; and conclusions, which should address any sources of uncertainty (NAS, 2009, p. 186). Probability and statistics are sensitive tools that can be utilized to articulate confidence levels and sources of error.

Mathematical Analysis

Mathematical analysis involves the utilization of probability and statistical methods in relation to evidence. These techniques offer valuable tools for determining evidential value and the objective articulation of conclusions. Ideally, these analyses should confirm and support what the forensic scientist has already determined.

Propositions

Before probabilities are considered and statistical analyses calculated, and even before any evidential examinations are conducted, it is imperative to construct an appropriate framework for interpretation. Formulating such a framework involves the establishment of propositions. In fact, "[i]t is a fundamental principle that it is not possible for a scientist to speculate on the truth of a proposition without considering at least one alternative proposition" (Cook, 1998, p. 232). Typically, two propositions are considered; one is representative of the prosecution's claims and the other, the claims of the defense (Cook, 1998, p. 232). Regardless of what the propositions are defined to be, it is crucial that they be mutually exclusive or independent of one another (Cook, 1998, p. 234). In other words, if one proposition is true then the other must not be; there should never be a situation in which both propositions could be true.

Propositions are considered to exist in a hierarchy, at three levels (Cook, 1998, p. 232). Level I, or *source propositions*, are generally aimed at determining the source of origin and involve the examination and analysis of physical evidence (Cook, 1998, p. 233). Level II, or *activity propositions*, address the actual activity that took place, which tends to involve knowledge of circumstantial information, in addition to examination and analysis (Cook, 1998, p. 233). Finally, Level III, or *offense propositions*, address whether or not the activity that occurred was a crime (Cook, 1998, p. 233). Despite the quantity of circumstantial information considered at the three levels, all of the propositions require some degree of background information in order to constitute a logical framework of situations and assumptions (Evett, 2000, p. 5).

To illustrate the proper use and construction of propositions at the three levels, consider the hypothetical homicide of Mr. Victim, who was found shot in his apartment. An autopsy confirmed that the cause of death was a gunshot wound to the head, and bullet X was submitted to the crime lab as evidence. Investigators recovered a suspect gun, Y, in the dumpster behind Mr. Victim's apartment, which was also submitted to the crime lab for examination. Following investigative leads, Mr. Suspect was brought in a week later for questioning. Assuming that rifling impressions were observed on bullet X during examination, it is known that bullet X was fired through a gun. The construction of Level I, or source, propositions can assist in addressing a specific gun that fired bullet X. With the consideration of the suspect gun Y, an appropriate pair of level I propositions would be:

Proposition 1: Bullet X was fired from the suspect gun Y.

Proposition 2: Bullet X was fired from a gun that is not suspect gun Y.

In this framework of propositions, a firearms examiner will perform an examination and microscopic comparison of bullet X and test fire bullets from suspect gun Y. Even if the results of the examination and comparison are inconclusive, in that there are not enough individual characteristic markings to determine an identification or an elimination, the establishment of class characteristics can provide a more precise framework of propositions (Kerkhoff, 2013, p. 287). For instance, if bullet X can neither be eliminated nor identified as having been fired through suspect gun Y based on individual characteristics, but does show agreement for all discernible class characteristics, then appropriate Level I propositions would be:

Proposition 1: Bullet X was fired from suspect gun Y.

Proposition 2: Bullet X was fired from a different gun with the same caliber and class characteristics as suspect gun Y.

If, however, it is determined that bullet X was fired through suspect gun Y, then the investigation can proceed to establish Level II propositions (Cook, 1998, p. 233). With the consideration that Mr. Suspect is a person of interest, an appropriate pair of Level II propositions would be:

Proposition 1: Mr. Suspect is the one who shot the suspected gun Y.

Proposition 2: Mr. Suspect was not present when the suspected gun Y was shot.

Addressing probabilities within the framework of Level II propositions is generally a task for investigators, not firearms examiners. While there may arise instances when an examiner’s expertise is required, much of the Level II proposition framework involves circumstantial knowledge not directly related to the examination of ballistic evidence, such as eye-witness accounts and alibis. Nevertheless, if it is determined that Mr. Suspect did indeed fire the suspect gun Y, then the investigation proceeds towards the establishment of Level III propositions (Cook, 1998, p. 233). Establishing the fact that Mr. Suspect fired the suspect gun Y does not imply that he shot Mr. Victim. There is a possibility that another person, or even Mr. Victim himself, is responsible for the fatal shot that ended his life (Cook, 1998, p. 233). Therefore, an appropriate pair of level III propositions would be:

Proposition 1: Mr. Suspect murdered Mr. Victim.

Proposition 2: Someone other than Mr. Suspect is responsible for the death of Mr. Victim.

Unlike Level I, and sometimes Level II, propositions, Level III propositions "are completely outside the domain of the scientist [... and ...] all of the issues relevant to addressing the higher level propositions must be left to the court" (Cook, 1998, p. 235). Determination of guilt or innocence is never something that a scientist is qualified to address.

Regardless of how the framework of a case is established, the forensic expert is going to be called upon to "address the probability of whatever evidence has been found given each proposition" (Cook, 1998, p. 234). This is articulated through the presentation of a likelihood ratio, which is discussed in more detail after the next two sections. In addition, it must be recognized that a "scientist must always be ready to review the interpretation [of evidence] in light of changing circumstances," so that if at any point "the framework changes then the interpretation must be reviewed" accordingly (Evett, 2000, p. 5; Cook, 1998, p. 238). Most importantly, constructing a proper "framework of circumstances [is what] enable[s] a jury to assign conditional probabilities to chosen propositions" (Evett, 2000, p. 5).

Hypothesis Testing

Hypothesis testing, true to its name, is a statistical process that assesses whether or not a proposed hypothesis is true. The hypotheses are closely related to the proposed propositions described above. Rather than considering probabilities, however, the statistical methods are utilized to evaluate which hypothesis is supported most by the data, or evidence. A court trial is essentially a hypothesis test (Rumsey, 2011). Testing begins with the setting up of two hypotheses. The null hypothesis is the one being tested and is generally set up "so that [it is] believe[d] H_o is true unless [the] evidence [… indicates …] otherwise" (Rumsey, 2011). In the courtroom, the null hypothesis is the verdict "not guilty," since it is presumed the defendant is innocent until proven guilty beyond any reasonable doubt (Rumsey, 2011). The alternate hypothesis is the situation that is true if the null hypothesis is not true. Thus, in the courtroom, the alternate hypothesis would be the verdict “guilty” (Rumsey, 2011). If the jury concludes that the prosecution team has shown sufficient evidence against the null hypothesis of “not guilty,” then the hypothesis is rejected in favor of the alternate hypothesis of “guilty” (Rumsey, 2011). “The burden of proof is on the researcher to show sufficient evidence against [the null hypothesis] before it's rejected” (Rumsey, 2011).

Probability

Probability is defined as “a numerical characteristic expressing the degree to which some given event is likely to occur under certain given conditions which may recur an unlimited number of times” (“Probability,” 2012). The probability that a six will be rolled on a fair-sided die is one-sixth, and the probability that a fair coin will land on heads when tossed are classic examples of probabilistic statements. However, especially in forensic science, probabilities are not as straightforward and simple to discern.

The Laws of Probability

There are three key laws of probability. The first law dictates that a probability can equal zero, one, or any number in between zero and one (Aitken, 2004, p. 23). A probability can never be negative or exceed the value of one (Aitken, 2004, p. 23).

For an event A, where Pr(A) is the probability that event A will occur:

$$0 \leq \Pr(A) \leq 1 \quad .$$

A probability of zero describes an impossible event, while a probability of one describes a certain event (Aitken, 2004, p. 23). Suppose that event A denotes the event that an evidence bullet was fired from a suspect weapon. If, through examination, it is observed that the evidence bullet has class characteristics that are not in agreement with the suspect gun, then Pr(A) = 0 because the bullet is eliminated as having been discharged through the suspect weapon. If, however, all discernible class characteristics are in agreement, as well as a significant number of individual characteristics, an identification can be made, but it does not mean that Pr(A) = 1. In the field of forensic firearm examination, probabilities are never equal to one unless both ballistic components are demonstrated to have been fired from the same firearm. The specifics of this are discussed later in this chapter.

The second law dictates that for two events that are mutually exclusive, the probability of one or the other occurring equals the sum of the individual probabilities of each event (Aitken, 2004, p. 24). As previously mentioned, events are mutually exclusive when the probability of both events occurring is zero (Aitken, 2004, p. 24).

For mutually exclusive events A and B (so Pr(A and B) = 0):

$$\Pr(A\ or\ B) = \Pr(A) + \Pr(B) \quad .$$

The prosecution and defense propositions, as mentioned before, are mutually exclusive. A fired bullet can only travel through one firearm barrel and one alone. The evidence bullet cannot travel down the barrel of the suspect gun and another gun. Therefore, the propositions given by the prosecution and the defense would be:

P1: The evidence bullet was fired from the suspect gun.

P2: The evidence bullet was fired from a different gun with the same caliber and class characteristics the suspect gun.

The probability of both occurring is zero: $\Pr(P_1\ and\ P_2) = 0.$

As an aside, it is important to note that this is not always true for cartridge cases, which can be reloaded and used again. Therefore, the prosecution and defense propositions considering cartridge cases would be:

P1: The evidence cartridge case was fired in the suspect gun.

P2: The evidence cartridge case was fired in a different gun with the same caliber and class characteristics as the suspect gun.

If an examination confirms that the evidence cartridge case was not reloaded and reused, then the events can proceed as mutually exclusive. However, exclusiveness should not be automatically presumed.

Finally, the third law dictates that for two events that are independent, the probability of both occurring is the probability of one event times the probability of the other (Aitken, 2004, pp. 24-25). Events are defined to be independent when "knowledge of the occurrence of one of the two events does not alter the probability of occurrence of the other event" (Aitken, 2004, p. 24).

For independent events A and B:

$$\Pr(A \ and \ B) = \Pr(A) \times \Pr(B) \quad .$$

This third law of probability is not restricted to two events (25). In fact, for any number of events, the probability that all of them will occur is simply the product of the individual probabilities of each event (Aitken, 2004, p. 25).

For *n* events that are independent: A_1, A_2, ... A_n , where *n* can be any positive integer:

(if *n* =4, then there are four independent events: A_1, A_2, A_3, A_4)

$$\Pr(A_1 \ and \ A_2 \ and \ \dots and \ A_n) = \Pr(A_1) \times \Pr(A_2) \times \dots \times \Pr(A_n) \ .$$

In forensic science, however, events are rarely going to exist independently. Events will typically relate to other relative events and evidence in the case and will, therefore, be assessed as conditional probabilities.

Conditional Probability

The third law of probability can also be articulated for *dependent events*. A *dependent event* is one that is affected by some known information (Aitken, 2004, p. 25). The probability of a dependent event is regarded as a conditional probability (Aitken, 2004, p. 25). Thus, for dependent events A and B and known information I, the probability of "A and B given that I is known to be true" is:

$$\Pr(A \text{ } and \text{ } B \mid I) = \Pr(A \mid I) \times \Pr(B \mid A \text{ } and \text{ } I) \quad .$$

(Aitken, 2004, p. 25; Evett, 1998, p. 199)

All forensic evidence is circumstantial and, thus, dependent. Probabilities are "*conditioned* by what [evidence] is known and/or assumed" as the "interpretation of evidence takes place within a framework of circumstances" (Evett, 1998, p. 199). In addition, for any given circumstance with two potential outcomes, it is not guaranteed that both outcomes are equally likely to occur; rather, "[m]any situations have a higher probability of one outcome over the other" (Rumsey, 2011).

The Limitations of Probability

Probability is typically used to describe possible future events rather than ones that have already occurred (Kerkhoff, 2013, p. 285). For instance, declaring that there is a sixty percent chance that a certain gun will fire the chambered cartridge when the trigger is compressed, while indicative of the fact that the gun is very unreliable, is a conceptually sound declaration.

However, saying there is a sixty percent chance the gun will fire the chambered cartridge when the trigger is compressed, *after* the trigger was compressed and the cartridge fired, seems silly and contradictory. Since the event already happened, why is the probability not one hundred percent? It is true that "[c]artridge case and bullet comparison is fundamentally probabilistic in nature" because there is a certain probability that two cartridge cases were discharged through the same firearm or two bullets traveled down different gun barrels; it is just not easy to compute or conceptualize (Kerkhoff, 2013, p. 289). The events that occurred during a crime are generally unknown. Individuals involved in the crime have knowledge of the events, but are not always truthful in recounting them. "Uncertainty is an omnipresent complication in life, and the case of forensic science is no exception" (Taroni, 2010, p. 4). During a trial, an attempt is made to discover what happened, and forensic science plays a key role in telling the story. However, "[k]nowledge about past occurrences is bound to be partially inaccessible," so there are always going to be some instances where certain events remain unknown, even after a case is closed (Taroni, 2010, p. 4).

When reporting a statement of probability, one has to be mindful of what is actually being calculated. Claiming that a bullet was *probably* fired from a certain gun, or that a bullet was *most likely* fired from a certain gun, can be very dangerous and is an inappropriate conclusion, as mentioned in a previous section. These statements are dangerous because they not only suggest that the overall probability was determined for whether the gun fired the bullet, but also that it is more likely than not that the gun fired the bullet based on that overall probability (Kerkhoff, 2013, p. 285). Determining the overall probability of whether the gun fired the bullet lies outside the scope of a firearm examiner's expertise, because it "does not depend on the outcome of a comparison of the marks alone. The chance is always influenced by the circumstantial evidence of the case and has to be [viewed] from a logical perspective" (Kerkhoff, 2013, p. 286). Rather, it is the examiner's task to evaluate "the associative value indicated by the results of the evidence examination only," whereas it is the jury's task to evaluate the overall probability of association (Kerkhoff, 2013, p. 286). Concerning all disciplines within Forensic Science, "it is necessary to ensure that statements which invoke the concept of probability are rooted in logical framework" in order to remain recognizable as scientific (Evett, 1998, p. 199).

Baye's Theorem

Baye's Theorem uses the combination of data with prior known information to provide posterior probabilities for a certain event (Aitken, 2004, p. 72). The reason Baye's Theorem is accredited in relation to forensic science is that it allows modifications when new information, in this case evidence, is introduced (Aitken, 2004, p. 72).

"Bayes's theorem is defined as: The Prior Odds consist of the probability that a hypothesis is true, divided by, or relative to, the probability that the alternative hypothesis is true" (Aitken, 2004, p. 287). Thus, for possible events A and B with presented evidence E, Baye's Theorem is expressed as follows:

$$\Pr(A|E) = \frac{\Pr(E|A)\Pr(A)}{\Pr(E|B)}$$

The formula itself is not particularly complicated. The difficulty in the application of Baye's Theorem lies in determining the conditional probabilities to plug into the formula. For instance, a firearms examiner has to refer to and rely on any previous studies which address the probabilities relating to the quantity of evidence, given a match, Pr(E | A), and the quantity given a non-match, Pr(E | B). The method of CMS, which will be addressed shortly, is a promising approach that examines these values. However, as mentioned before, the CMS approach is applicable only to striated marks. Consequently, when appropriate and applicable studies do not exist, the examiner has to rely on training and experience to consider the probabilistic values, an approach that is often viewed as subjective in nature. Therefore, while presenting a Bayesian probability *may* provide an examiner's interpretations with a higher level of objectivity, subjectivity is not removed completely.

Likelihood Ratios

A likelihood ratio, commonly abbreviated as LR, is a consequence of Baye's Theorem and is utilized to measure evidential value (Aitken, 2004, p. 7). Reporting the value of evidence in the form of a LR is suitable because rather than making a statement about which proposition is more likely than the other, "[i]t expresses how likely the findings are if one [proposition] is true, compared to how likely these findings are if the alternate [proposition] is true" (Kerkhoff, 2013, p. 287). In other words, instead of attempting to determine the overall probability that the prosecution is right compared to the defense, or vice-versa, the spotlight remains on the evidence that was examined. So, while "[t]he court is concerned with questions of the kind 'what is the probability that the defendant committed the crime given the evidence?' … [it is the scientist's job to] address questions of the kind 'what is the probability of the evidence given that the defendant committed the crime?'" (Evett, 1998, p. 200).

For evidence E, known information I, the prosecution's proposition P_1, and the defense's proposition P_2, the likelihood ratio is defined as:

$$LR = \frac{\Pr(E \mid P_1, I)}{\Pr(E \mid P_2, I)}$$

The numerator of the equation addresses the probability of the evidence, given the known information and given that the prosecution's proposition is true (Cook, 1998, p. 234). On the other hand, the denominator of the equation addresses the probability of the evidence, given the known information and given that the defense's proposition is true (Cook, 1998, p. 235).

In addition, the LR, like Bayes' Theorem, can express how odds are altered in relation to any introduction of new evidence (Kerkhoff, 2013, p. 287). In the course of investigations and examinations, however, there are times when, "[i]ronically, a LR [becomes] harder to explain and harder to understand for many people" than other typical jargon that is used (Kerkhoff, 2013, p. 289). Nonetheless, "[r]eporting a LR does not complicate matters, it just shows how complicated matters are" (Kerkhoff, 2013, p. 289).

Statistics

Statistical analysis is a very suitable tool for the evaluation of evidence because, like forensic science, "statistics is really the business of using the scientific method to answer research questions about the world" (Rumsey, 2011). Unlike probability data, statistics are typically generated for past events. Also, rather than examining the value or weight of evidence, as probability theory does, statistics involves collecting evidence to determine how well a technique or process was performed (Rumsey, 2011).

Population

A significant aspect to take note of when performing any kind of statistical analysis is choosing the correct population. For instance, if one wanted to analyze the distribution of gun owners in New York State, it would be absurd to survey the entire population of the United States. Doing so would result in vast amounts of unnecessary and useless data. It would be equally absurd to survey only the population in the state of California, because then all of the data collected would lie outside the parameters of the desired distribution. In the case of comparing ballistic evidence, “when [it has been] established that the caliber and the class characteristics are compatible and [there is] not a convincing degree of agreement or disagreement in the striations, [it is possible to] have just discarded somewhere between 90 and 99.99% of the most relevant population of firearms, depending on the case and the chosen alternate hypothesis” (Kerkhoff, 2013, p. 288). In other words, if an examination of evidence reveals that a cartridge case has a .22 long rifle caliber, then it would be ridiculous to consider firearms of different caliber as the source of origin. An even more ridiculous notion would be considering any centerfire firearm as the source of origin, since a .22 long rifle takes a rimfire cartridge. In forensic firearm identification, simply knowing class characteristics can drastically narrow the population in question.

Limitations of Statistics

The NAS report expressed an inclination to have more quantitative approaches to articulating firearm examination conclusions. While the use of statistical techniques is a step forward, it is critical not to presume that these methods resolve the problem of bias. “*Bias* in statistics is the result of a systematic error that either overestimates or underestimates the true value” (Rumsey, 2011). The presence of bias towards the prosecution or the defense can easily be hidden within numerical data. Statistics can do an excellent job of presenting data in a quantitative format, but just because there are numbers sprinkled into a statement does not mean it should be exempt from scrutiny. “Not all statistics are correct or fair … nothing guarantees that [a] statistic is scientific or legitimate” (Rumsey, 2011). Just as in a laboratory setting, where it is possible for an expert to get inappropriately invested in suspecting guilt or innocence, “[i]n the heat of the moment, because someone feels strongly about a cause and because the numbers don't quite bear out the point that the researcher wants to make, statistics get tweaked, or, more commonly, they get exaggerated" (Rumsey, 2011). For instance, perhaps an examiner strongly believes two bullets are supposed to be a match but is having a difficult time making an identification, so he/she counts a few striations as CMS that in another circumstance they would not have counted. This further illustrates that CMS does not exist as an entirely objective method; it, too, can fall victim to bias. Therefore, it bodes well to be cautious that "[e]ven when the math checks out, the underlying statistics themselves can be misleading" (Rumsey, 2011). Unfortunately, statistical analysis is neither immune to bias nor possesses the capability to measure it; it can only be minimized (Rumsey, 2011).

Error

A firearms examiner, like any forensic expert, is human, and all humans make mistakes. Because of this, expert witnesses must be mindful that their testimonies are not facts (Rumsey, 2011). For as long as uncertainties exist, the existence of error is a certainty. This does not mean that every conclusion made is erroneous, but rather, the presence of possible error can never be excluded completely. Furthermore, errors are not restricted to certain fields or methods and can occur "at any stage in the process of doing research, communicating results, or consuming information ... either unintentionally or by design" (Rumsey, 2011). The NAS report expressed anticipation for defined and established error rates for the field of forensic forearms examination (National Academy of Sciences, 2009).

Margin of Error

The margin of error does not indicate that a mistake was made, but rather, the whole population was not sampled, so the results are expected “to be ‘off’ by a certain amount” (Rumsey, 2011). Presenting a margin of error acknowledges that there is a chance that results could change with subsequent tests and that the test performed is “only accurate within a certain range” (Rumsey, 2011). Expressing a known error rate in the courtroom embodies an ideal situation. The forensic discipline of DNA analysis has well defined methods for providing error rates associated with its results and conclusions. However, as expressed before, the discipline of firearm examination poses different complications. There are two avenues that a margin of error can take. The first considering the error rate associated with identity itself, and the second deals with the firearm examiner’s performance. It is important to note that in the discipline of firearm examination discipline, “the term *identity* must be understood to signify practical and determinable identity only” (Nicholas, 2007, p. 591). The fact is, not every relevant gun is available for comparison, and thus “the use of a different gun cannot be excluded completely as a theoretical possibility” (Kerkhoff, 2013, p. 285). Thus, probabilities in this field cannot take the value one.

As for the second avenue, instituting a strict procedure for calculating and articulating error rates for ballistic evidence comparison may very well be unattainable. The results of DNA analysis are obtained from an orchestration of computer technology and can be articulated in numerical formats. On the other hand, firearm examination is performed by a person, and with the exception of CMS, cannot always be expressed arithmetically. Perhaps, an estimated or projected error rate for the discipline could be considered with the aid of controlled experiments. But “[t]he court is not interested in ‘theoretical error rate’... but [... rather ...] real life potential error rate that is reflective of all human endeavors ... as a means by which to assign weight to the examiner's testimony" (Nichols, 2007, p. 592). Hypothetically, an examiner could conduct numerous blind examinations and comparisons and, depending on how many instances when they reach the wrong conclusion, an error rate could be determined. This proposal, however, is far from practical. First, there are countless firearms, bullets, and cartridge cases in circulation. Would an examiner need a specific error rate for .22 long rifle cartridges fired from a Smith and Wesson 34-1 rimfire revolver and then another specific error rate for 223 REM centerfire cartridges fired from an AR-15 bolt-action rifle? In that case, calculations, comparisons, and frustration would pile up very quickly. In addition, those countless examinations and comparisons would drastically contribute to backlogs that already exist in crime laboratories. Even just considering a general error rate for an examiner poses the dilemma of determining the types of examinations and comparisons to be performed and how many are sufficient. Furthermore, this approach could pressure examiners to report "inconclusive" as a default conclusion. The fact is, "[v]ariation always exists in a data set, regardless of which characteristic you're measuring, because not every individual is going to have the same exact value for every variable" (Rumsey, 2011). Moreover, would examiners need to undergo periodic testing to gauge whether error rates have changed? Obviously, informing the jury on the reliability of a firearm examiner's testimony is critical. Conceivably, standards for the accreditation of laboratory procedures and the certification of firearms examiners could better accomplish this than attempting to assign numerical values to examiners.

When considering the automated systems involved in the discipline of forensic firearm examination, however, establishing values for a margin of error is feasible. Defining error rates for computer processes and algorithms, as opposed to human processes, is significantly more straightforward. Furthermore, if these systems are implemented in the examination process, they must also be proven to produce relevant and reliable results.

Errors of Omission

The common expression that “a half-truth is a whole lie” is still pertinent in the field of statistics. When information is “thrown out” or not reported in a conclusion, then there is an *error of omission* (Rumsey, 2011). The margin of error does not measure bias or mistakes that were made during a procedure (Rumsey, 2011). The value only reflects which result is presented (Rumsey, 2011). So, just as forensic evidence must be scrutinized for reliability, so must statistical analyses. The reliability of a statistic depends a great deal on “the amount of information that went into the statistic,” and further, on the accuracy of the information (Rumsey, 2011). Unfortunately, recognizing when an error of omission has occurred can be difficult (Rumsey, 2011). Like the presentation and interpretation of forensic evidence and forensic methods, statistical analyses should be thoroughly documented. Even so, sometimes, “the best policy is to remember that if something looks too good to be true, it probably is” (Rumsey, 2011). Math and numbers themselves do not lie, but they can be used as a tool for lying (Rumsey, 2011).

Confidence

A confidence interval consists of the statistical result plus or minus the margin of error (Rumsey, 2011). In other words, if the result is denoted as R, and the margin of error is denoted as e, then the confidence interval is $[R – e, R + e]$ (Rumsey, 2011). Thus, the greater the margin of error, the greater the confidence interval will be. A larger confidence interval, however, does not indicate greater confidence. The precise meaning of what a confidence interval represents can be unclear and easily misinterpreted (Rumsey, 2011). A 95% confidence interval does not mean that there is a 95% chance that the statistical result is correct (Rumsey, 2011). Rather, such an interval indicates that if the statistical method is repeated over and over again, then the statistical result will fall into the confidence interval 95% percent of the time (Rumsey, 2011). For example, if a firearms examiner arrives at an identification between two pieces of ballistic evidence, then a 95% confidence interval does not indicate that the examiner is 95% confident of the identification. Instead, the interval signifies that if other firearm examiners continued to examine and compare those same two pieces of ballistic evidence, then 95% of them would declare an identification. Or, if the same examiner performed the comparison over and over again, they would declare an identification 95% of the time. Therefore, if circumstance permit the use of a confidence interval, it is essential that presentations to the jury be clear, concise, and understood. Ideally, "[a] numerical value can be reported that tells others how confident the researcher is about the results and how accurate these results are expected to be" (Rumsey, 2011). However, an obvious problem associated with such an achievement is the difficulty in establishing the appropriate margin of error.

Consecutively Matching Striations

As previously mentioned, CMS are a good "means by which an examiner can describe what he or she is observing in a striated tool mark comparison" (Nichols, 2007, p. 590). Biasotti's work and experiments on CMS utilized the statistical process of a Poisson distribution. This type of distribution is typically employed to "describe the number of events which occur randomly in a specified period of time or space" and is given by the formula below (Aitken, 2004, p. 48).

$$\Pr(X = x) = \frac{(\lambda s)^x}{x!} e^{-\lambda s}$$

In relation to CMS, the components and variables of the distribution can be clarified as follows:

The variable *X*, or the number of events occurring in a certain region of space, is the number of consecutively matching striations observed.

The component Pr(*X* = *x*) is the probability that *X* takes a specific value, denoted as *x*. Thus Pr(*X* = 3) denotes the probability that three consecutively matching striations were observed.

The variable (*s*), or unit of space, represents the number of striations observed on a bullet's land impression.

The variable (*λ*), is the mean (average) number of CMS observed on a land impression.

The component (λs), is the mean number of CMS observed within (*s*) number of striations on a land impression.

The component (*x!*) indicates the "factorial" of *x*, which is calculated by multiplying together all whole numbers from 1 to *x*. For example, if *x* is 5, then:

$$x! = 5! = 1 \times 2 \times 3 \times 4 \times 5 = 120$$

(Aitken, 2004, pp. 48, 223).

Biasotti compared bullets known to have been fired through the same gun, as well as bullets known to have been fired through different guns, and recorded the number of consecutively matching striations for each comparison (Aitken, 2004, p. 223). From there, two data sets were amassed, the first set for comparisons of bullets fired through the same gun (or SG), and the second set for comparisons of bullets fired through different guns (or DG) (Aitken, 2004, p. 223). Afterwards, the comparisons were categorized according to the maximum number of consecutively matching striations observed (Aitken, 2004, p. 223). Then, for each grouping of maximum CMS count, *f*(x | SG), or the probability of the number of striations given that the bullets were a match, was computed. Similarly, *f*(x | DG), or the probabilities for the non-matching bullets were computed (Aitken, 2004, pp. 223-4). With these calculations, likelihood ratios were attained through division: LR = *f*(x | SG) / *f*(x | DG) (Aitken, 2004, p. 224). The calculations made are provided in Table 1.

The attained data allows for the generation of two Poisson distributions, one for SG and another for DG. Beginning with the comparisons from the same gun, the mean, λ_{SG}, is determined by summing the products of x and *f*(x | SG).

$$\lambda_{SG} = \sum_{x=1}^{x=10} (x)(f(x|SG)) = (0)(0.03) + (1)(0.07) + (2)(0.11) + \cdots + (8)(0.02) = 4.01$$

In the same way, the mean, λ_{DG}, was determined by summing the products of x and *f*(x | DG).

$$\lambda_{DG} = \sum_{x=1}^{x=10} (x)(f(x|DG)) = (0)(0.22) + (1)(0.379) + (2)(0.30) + \cdots + (6)(0.001) = 1.325$$

These mean values allow for the Poisson distributions

$$\Pr(X = x \mid SG) = \frac{(\lambda_{SG})^x}{x!} e^{-\lambda_{SG}} \qquad \Pr_{\mathrm{D}}(X = x \mid DG) = \frac{(\lambda_{DG})^x}{x!} e^{-\lambda_{DG}}$$

Where Pr(X=x | SG) is the distribution for the same gun and Pr(X=x | DG) is the distribution for the different gun. The Poisson distribution values for both SG and DG, along with the values for the LRs attained by dividing Pr(X=x | SG) / Pr(X=x | DG), are presented in Table 2 on the following page.

Employing the use of the CMS model is advantageous, but the model has limitations. In fact, "[t]he entire model [relating to CMS] rests on the assumption that the possible patterns which lines can form, are probabilistically independent of each other and identically distributed" (Petraco, 2012). Therefore, the method is only valid for individual characteristic striations and is not for striations that are subclass in nature. In addition, practical studies of CMS typically involve "pristine" sample bullets, which are often chosen based on the well-defined and consistent reproducibility of striations observed on the land impressions (Aitken, 2004, p. 225).

Table 1: CMS Calculations Given from Aitken, 2004, p. 224

Maximum CMS Count (x)	f(x | SG)	f(x | DG)	LR = f(x | SG) / f(x | DG)
0	0.030	0.220	0.136
1	0.070	0.379	0.185
2	0.110	0.300	0.367
3	0.190	0.070	2.71
4	0.220	0.020	11.0
5	0.200	0.010	20.0
6	0.110	0.001	110
7	0.050	-	-
8	0.020	-	-

Sufficient data were not available to determine $f(x \mid \text{DG})$ for seven and eight CMS.

Table 2: CMS Poisson Distributions Given from Aitken, 2004, p. 225

Maximum CMS Count (x)	Pr(X=x |SG)	Pr(X=x |DG)	LR = Pr(X=x |SG) / Pr(X=x |DG)
0	0.020	0.267	0.075
1	0.078	0.353	0.221
2	0.153	0.233	0.657
3	0.200	0.102	1.96
4	0.195	0.034	5.74
5	0.153	0.0089	17.2
6	0.099	0.00196	50.5
7	0.056	0.00037	151
8	0.027	0.000061	443

Automated Matching

Resourceful examination of ballistic evidence begins with automated matching systems and databases. Forensic laboratories might use technology that is similar, but not analogous, to the Automated Fingerprint Identification System (AFIS) to acquire potential matches between the ballistic evidence entered and evidence already collected in the database. Automated matching incorporates the use of imaging and mathematical techniques. Areas of mathematics involved in the process include matching algorithms, topology, wavelet transforms, geometric moments, cross-correlation functions, and statistical analyses. “For use in a forensic laboratory it is important for quality assurance to understand why a certain image is not found in top matching ranks and to have more background in the image matching-engine” (Geradts, 2001, p. 98). In other words, it is valuable to appreciate how the automated matching is facilitated.

NIBIN

The National Integrated Ballistic Information Network, or NIBIN, constitutes the most prominent automated imaging network for ballistic firearm evidence and involves “a combination of specialized computer algorithms, pattern recognition technology, and digital imaging” (National Institute of Justice, 2015, Mod07). The system that NIBIN utilizes is called the Integrated Ballistic Identification System, or IBIS, a technology that is provided by Forensic Technology, Incorporated (FTI) (Technology, 2015). Firearms examiners or trained and competent technicians enter cartridge case evidence or bullet evidence into automated acquisition stations that capture 2-dimensional images and 3-dimensional topographical information (Technology, 2015). The images are converted into an electronic signature, which can be compared to other bullet or cartridge case signatures that are stored in the database (Geradts, 2001, p. 98). Comparison algorithms correlate the signatures obtained against the NIBIN database, to generate a “hit” list composed of the “most likely” evidence matches (Technology, 2015). “IBIS correlation scores are derived as a proprietary estimator in the degree of match between pairs of optical images” (Song, 2006, p. 500). Examiners can view the generated potential matches in the Matchpoint Analysis Station, which allows multiple-angle viewing of ballistic evidence, isolated viewing of specific markings on a cartridge case, score analyses, and 3-dimensional enhancements (Technoolgy, 2015). Despite the sophisticated technology of the system, however, NIBIN is only an investigative tool (Petraco, 2012). Every potential hit must be confirmed through traditional comparison by a trained and competent firearms examiner under the comparison microscope.

Matching Algorithms

The word *algorithm* alone can seem intimidating. However, an algorithm is just a term used to describe “a set of steps that are followed in order to solve a mathematical problem or to complete a computer process” (“Algorithm,” 2015). It should be noted that using the term *algorithm* does not automatically imply difficulty and complexity. While there are many algorithms that are very complicated, there are also some that are simple, and plenty more that fall in between complicated and simple.

The algorithms used in ballistic systems and databases are referred to as *matching algorithms* because they are designed to match the images and signatures of ballistic evidence entered into the system with images and signatures already stored in the system. The matching algorithms used in the NIBIN database are guarded and not publicly accessible. Forensic Technology Incorporated has registered patents on the algorithms and the equipment, which employ a method in which a signature is obtained from an image of the ballistic component, the directions of striations and the signature are evaluated, and then a linear set of values is determined based on the intensity of linear points along the signature (Forensic Technology, 1997). The specifics of these steps, such as how the signatures are obtained and how the striation directions are assessed, are not specified. There are, however, other models of automated matching algorithms utilized for ballistic evidence.

Essentially, the process involves imaging analysis and corrections; topographical measurements, which are used to generate electronic signatures; and cross-correlation, which is used to compare signatures for potential matches (Thompson, 2015).

Imaging

Attaining images of the best possible quality and contrast is critical before any automated comparison can take place (Puente León, 2004, p. 41). The details of imaging techniques extend beyond the scope of this paper, but, essentially, multiple images are taken using sophisticated microscope cameras under different lighting and angles and then fused together (Puente León, 2004, p. 40-3). Additional methods are often applied, such as histogram equalization (explored in Gereradts, 2001) and canny edge detection (explored in Thompson, 2015). An example of the types of images attained, as given by Thompson (2015), is seen below in Figure 23.

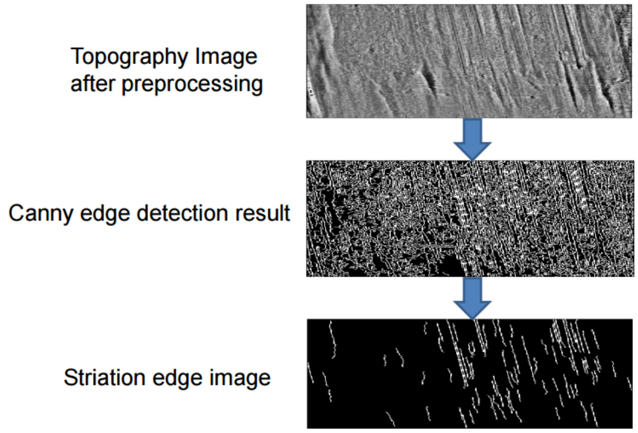

Figure 23

Topography

Once the appropriate images have been obtained, topographical measurements are taken. *Topography*, as defined by the dictionary, is "the physical or natural features of an object or entity and their structural relationships" ("Topography," 2015). Thus, the peaks and valleys that are observed in a toolmark constitute its topography. In fact, toolmarks can be defined as "permanent changes on the topography of a surface created by forced contact with a harder surface (the tool)" (Zheng, 2014, p. 143). The two types of toolmarks seen in firearm examination have different topographical patterns. Striated toolmarks have a topography that looks like parallel lines, while impressed toolmarks have a topography that "mimics a negative copy of the tool surface topography" (Zheng, 2014, p. 143). Topography itself is not a mathematical concept, but the idea is that if two topological images of ballistic evidence are matched through the use of mathematical processes, then the two items of ballistic evidence are a match. In essence, "[i]mpressions and striations made by tools and firearms can be viewed as mathematical patterns composed of peaks, ridges and furrows which [can be] refer[red] to as features" (Petraco, 2012). From the topological data, the computer system can determine the direction of striations and then generate a unique electronic signature for the ballistic evidence component (Thompson, 2015). An example of what a signature could look like, taken from Thompson (2015), is shown below in Figure 24.

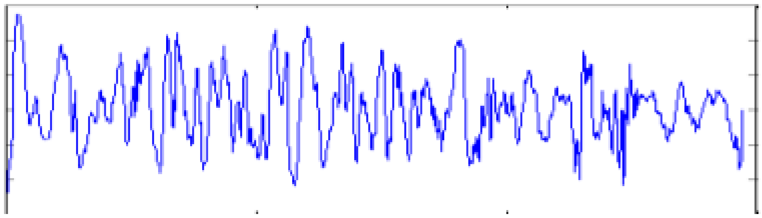

Figure 24

Cross-Correlation Function

Once an electronic signature for the ballistic evidence component is obtained, the system can compare it to other signatures in the database, using the cross-correlation function. The cross-correlation function, given by CCF_{max}, tends to look complicated, but basically just measures the distance between two signatures (Thompson, 2015).

$$CCF_{max} = \frac{\sum_i (x(i) - mx)(y(i-d) - my)}{\sqrt{\sum_i (x(i) - mx)^2}\sqrt{\sum_i (y(i-d) - my)^2}}$$

The variables *x* and *y* represent the two different signatures that are being compared (Bourke, 1996). The terms (*mx*) and (*my*) represent the mean values of signature *x* and signature *y*, respectively (Bourke, 1996). The variable *d* represents the "delay" in the signature (Bourke, 1996). The delays are all of the peaks seen in the electronic signature (Bourke, 1996). Thus, the complicated formula above is just comparing the peaks of the signatures and calculating the distances between them, to attain a value for CCF_{max}. Thompson (2015) illustrates the results that can be obtained through the use of cross-correlation, seen in Figure 25.

After cross-correlation, the computer system will compile a list of the signatures that have the highest correlation to the signature in question (Thompson, 2015). The list represents the most likely potential matches, which a trained and competent firearms examiner can then check. Typically, a CCF_{max} = 100% is what the computer system views as a perfect match. The CCF_{max} values seen in Figure 25 are not quite 100%, but, as discussed in the previous chapter, variation is always going to be present.

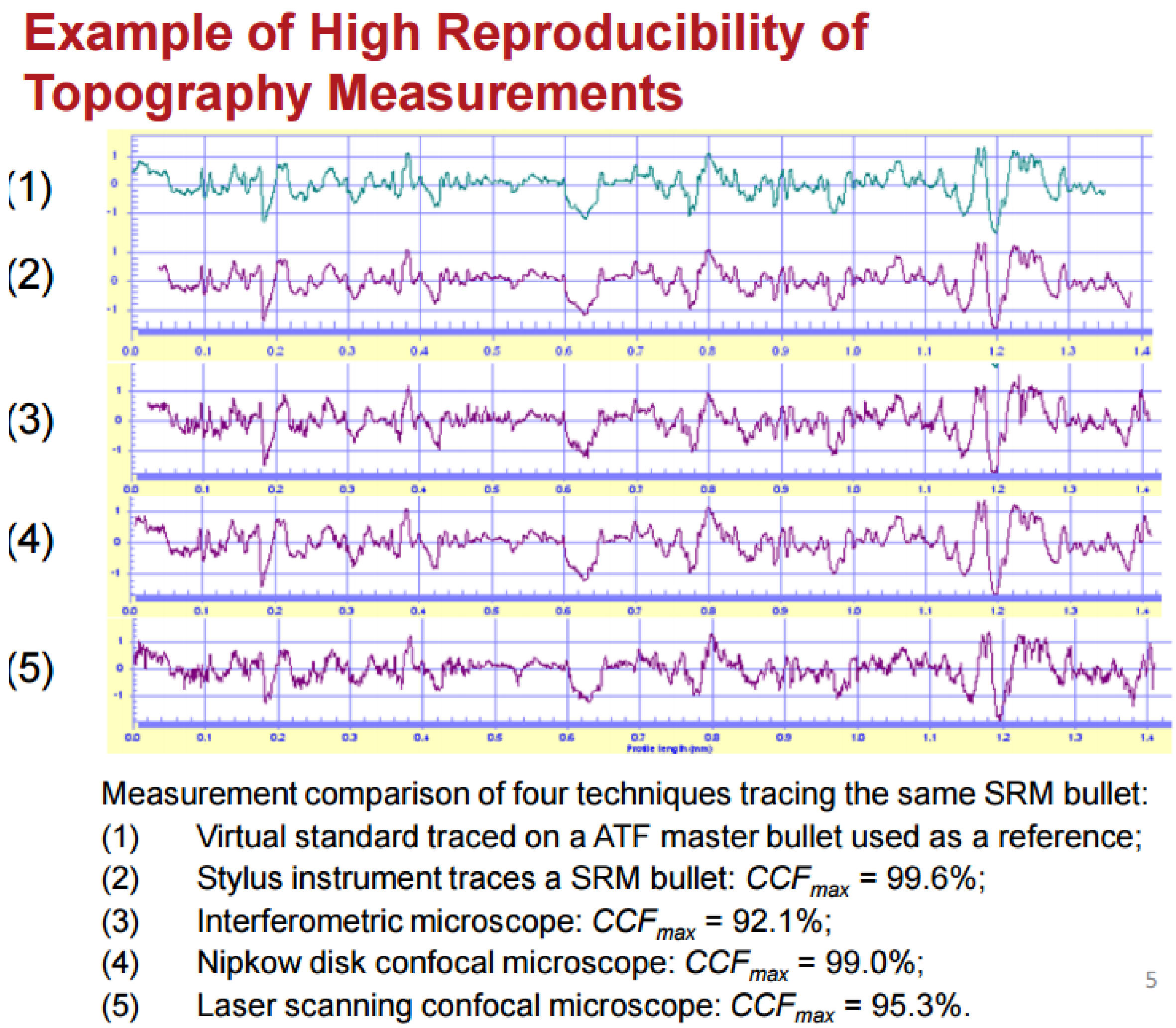

Figure 25

Conclusion

Forensic science, by definition, has a very close relationship with the law. At times, it can be difficult to find the best balance between the two, as observed in the NAS Report:

> [T]here are important differences between the quest for truth in the courtroom and the quest for truth in the laboratory. Scientific conclusions are subject to perpetual revision. Law, on the other hand, must resolve disputes finally and quickly. (National Academy of Sciences, 2009, p. 12)

Regardless of the direction and speed at which the development of forensic firearm identification is projected, however, changes and reform will come. It is understandable that there will be some resistance to change in forensic disciplines, especially concerning experts who have been following certain procedures and protocols for many years. However, the world is not stagnant; it is constantly changing and evolving. The scientific method adapts according to new results and discoveries. Since forensic science applies scientific techniques in courts of law, it has an obligation to adjust to the advances and techniques of society. If a specific technique or procedure has been rigorously tested and found to be more reliable, then adopting it should not be met with a desire to remain in the past.

Continued research and practical experiments involving CMS will continue to bring beneficial insights into articulating matches and non-matches, as well as aid in the reflection of probabilistic values. Future endeavors could include attempting to apply the theory of CMS to striated marks other than those observed on land impressions, such as extractor and ejector marks on cartridge cases. In addition, the focus should also be on the articulation of other markings, to which CMS theory cannot be applied.

On the whole, math is an excellent tool that can be applied to areas of forensic firearm examination, but it is not going to liberate the field from subjectivity. Human nature does not abide by the laws of probability, and thus, trying to fit everything into an equation or formula would be a daunting task. An equation of human nature would have endless variables, to the point at which the equation gives more unknowns then answers. Mathematics and computers do not think for themselves; they cannot make subjective assessments on their own – and they are not supposed to. Concerning the automated portion of the discipline, mathematics is well implemented and practiced. However, it would be unwise to try to "force" math to make subjective leaps. Perhaps it is misguided to completely remove the subjectivity from the field of forensic firearm examination. Instead, determining an appropriate balance of subjectivity and objectivity could prove beneficial.

To conclude, mathematics, when implemented, is never a suitable substitution for an explanation of evidence. Any analysis is going to need a separate explanation of its own. A beneficial mindset to maintain while presenting numerical data is to treat the courtroom like a classroom. A teacher or professor is not going to walk into a classroom, throw a list of equations on the chalkboard, and walk out without a word. If they do, then they are failing to fulfill their role as a teacher. Showing and teaching is not the same thing, but they can be successfully used together. Perhaps it would be beneficial for an expert to show the jury the evidence and resulting conclusions and then teach the jury how the conclusions were reached. If this perspective is to be successful, however, the expert witness, like the teacher, must prepare to teach at the appropriate level for their students—the jury—to learn. If a college professor were to attempt to teach a class of fifth graders in the same manner he/she lectures at the university, the primary accomplishment will be a roomful of frustrated individuals. The duty of the expert witness is to offer testimony concerning their interpretations of the evidence examined. It should be the responsibility of the expert witness to inform and clarify. Good teachers present material well, but great teachers ensure that all of their students understand.

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