How Accurate are Probabilistic Odds Claims in Criminal Trials? A "Warranted Skepticism" Approach

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Abstract

Probabilistic odds claims used in criminal trials are often inaccurate due to subjectivity within the methods of forensic science. The potential sources of subjectivity are wide since forensic science is an adversarial process and a full disclosure of assumptions is not required under *Brady*. The prior literature has focused on the limits of Bayesian methods and the potential uniqueness of DNA fingerprints to each person. This paper is unique because it focuses on other sources of subjectivity, such as a lack of disclosure of test results, repeated trials, a presumption of laboratory accuracy, absence of tests, and so on. The infamous *Gilyard* case is helpful as illustration of one common source of subjectivity. The standard approach for DNA analysis was applied to first determine a "match" to Gilyard's DNA to a test sample, and then to estimate the relative frequency of Gilyard's DNA in a reference population at odds of 1-in-18-quadrillion. The odds figure is roughly a million times the number of persons now living or that will ever live and amounts to a strong claim that Gilyard's DNA profile is unique. The "reference population" used to derive the odds claim is hypothetical (or, largely non-existential), just as Karl Popper warned. However, in every criminal case with DNA evidence, there are at least 2 DNA samples that appear to match (in Gilyard, there were 7) not included in the reference population. A significant question is whether the reference population should include the samples at issue in the case. Where the composition of the reference population is merely hypothetical it presumably should be updated to reflect any new evidence as a matter of Bayesian science. Of course, the population is extrapolated from a small dataset, so the existence of 2 or more matching DNA profiles might reduce the odds to a figure perhaps in the thousands, rather than quadrillions. This raises the severe problem that the probabilistic odds calculation depends on the subjective determination of a "match" in the first step. One scholar has suggested that "match" claims are objective because the process has been partly mechanized, even though the interpretation of results has not been standardized. In modern science, however, objectivity refers to replicability by experiment including the interpretation of results. This paper develops many other additional sources of subjectivity in forensic science and suggests: *If subjectivity exists to degree x, then any related or resulting probabilistic odds claim may not exceed x*. As example, if laboratory error is possible at a rate of 1/10,000, then given probabilistic odds should not exceed 1/10,000. The inherent subjectivity of all probabilistic odds claims, as identified by Frank Ramsey, is also explored. The conclusion is that a "warranted skepticism" approach to the use of remote odds claims in criminal cases, such as in *Daubert*, remains appropriate.

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Introduction

Probabilistic odds claims in criminal cases often relate to DNA evidence, such as in the now infamous *Gilyard* case, where probabilistic odds were given as 1-in-18-quadrillion.[1] Rapid technological advances in forensic testing[2] seem to have increased the relative importance and uncertainty[3] over probabilistic odds claims by expert witnesses under the familiar *Daubert* standard.[4] However, probabilistic odds claims given in criminal proceedings may be inaccurate because of subjectivity in the figures.[5] The potential inaccuracy of these claims is largely due to the adversarial methods applied in forensic investigation.[6] Prior literature on this topic has debated the proper use of Bayesian statistical measures

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[1] *Missouri v. Gilyard*, 257 S.W.3d 654 (2008); *see* Gilyard, Statement of Probable Cause ("[The DNA] testing revealed a DNA profile foreign to that of the victim. This DNA profile is the same as the DNA profile developed from the blood standard of LORENZO J. GILYARD, B/M, 05/24/50. The statistical frequency of Lorenzo J. Gilyard's DNA profile in the black population is 1 in 18 quadrillion. One quadrillion is equal to one million billion"). A summary of extremely remote probabilistic odds claims similar to *Gilyard*, and used in other criminal cases was provided in D.H. Kaye, *Trawling DNA Databases for Partial Matches: What is the FBI Afraid Of?* 19 CORNELL J. LAW & PUBLIC POL'Y 145, 148 ("The numbers bandied about in court boggle the mind. Reported match probabilities involve quadrillionths ($1/10^{15}$), quintillionths ($1/10^{18}$), sextillionths ($1/10^{21}$), and even septillionths ($1/10^{24}$)") citing *People v. Nelson*, 48 Cal. Rptr. 3d 399, 404 n.2 (Cal. Ct. App. 2006) aff'd 185 P.3d 49 (Cal. 2008); *United States v. Davis*, 602 F. Supp. 2d 658, 680 n.26 (D.Md. 2009); *see also* Bart Verheij, Floris Bex, Sjoerd T. Timmer, Charlotte S. Vlek, John-Jules Meyer, Silja Renooij & Henry Prakken, *Arguments, Scenarios and Probabilities: Connections between Three Normative Frameworks for Evidential Reasoning*, 15:1 LAW, PROB. & RISK 35 (2016) ("It was estimated that the probability that the DNA profile of a random male matches the DNA profile of that blood trace was about 1 in 1500 billion billion") citing Case: NJFS 2013/155 www.rechtspraak.nl.

[2] The advent of polymerase chain reaction DNA replication technology allowed extremely minute samples of DNA to be replicated to a larger size and then tested using standard DNA testing methodologies. The invention of this technological process occurred in 1980 and resulted in the award of the Nobel Prize to its inventor, Kary Mullis. See https://www.nobelprize.org/prizes/chemistry/1993/mullis/lecture/.

[3] National Research Council, Committee on Identifying the Needs of the Forensic Sciences Community, Strengthening Forensic Science in the United States: A Path Forward, www.nap.edu/catalog/12589.org, at 11 ("Daubert and its progeny have engendered confusion and controversy.").

[4] *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 509 U.S. 579 (1993). *See* David Crump, *The Trouble with Daubert-Kumho: Reconsidering the Supreme Court's Philosophy of Scienc*e, 68 MO. L. REV. 1, 3-5 (2003) ("Having established this policy of 'relaxing' barriers to opinion testimony, however, the Court naturally felt the need to emphasize that there were limits. The first of these limits was that a scientific expert must be, in fact, testifying to 'scientific knowledge.' … This meant that an inference offered in expert testimony 'must be derived by the scientific method' and 'must be supported by appropriate validation.' … 'a key question to be answered in determining whether a theory or technique is scientific knowledge that will assist the trier of fact' would be 'whether it can be (and has been) tested.' The Court then quoted philosopher Karl Popper: 'Scientific methodology... is based on generating hypotheses and testing them to see if they can be falsified; indeed, this methodology is what distinguishes science from other fields of human inquiry.' And the Court added other authorities: '[T]he statements constituting a scientific explanation must be capable of empirical test'; and '[t]he criterion of the scientific status of a theory is its falsifiability, or refutability, or testability.' To this first, 'key' criterion, the Court added three others: peer review and publication, known or potential rate of error, and a concept of general acceptance that mirrored the Frye test but was not to be used as the sole criterion. The Court emphasized that the inquiry was to be 'a flexible one,' and its advisory list of questions was not presumed to be 'definitive.') (citations omitted).

[5] *See infra* Section I. The term "accuracy" has a variety of technical meanings in probability theory. The usage of the term "inaccuracy" here is premised on the idea that extremely remote probabilistic odds claims are "presumptively inaccurate" if there is *any* subjectivity within the forensic analysis. In the context of extremely remote odds claims, the inaccuracy of such a claim can be presumed with the presence of *any* subjectivity.

[6] *See Infra* Part(s) I, II.

generally,[7] especially the use of DNA analyses, which often suggest uniqueness to one individual by an extremely remote probabilistic claim.[8] But, probabilistic odds claims have many potential sources of subjectivity, relating to whether forensic testing is performed in an objective manner and whether it may then be expected to consistently yield accurate and reliable test results.[9] As the National Academies of Science concluded: "[M]ost of the forensic disciplines… rely on subjective assessments of matching characteristics. These disciplines need to develop rigorous protocols to guide these subjective interpretations and pursue equally rigorous research and evaluation programs."[10] Scientific doubt as to accuracy of these subjective claims is not so much "radical skepticism" as it is *warranted skepticism*.[11]

Perhaps the best way to introduce the topic of this paper is to compare the "threshold issue for law" given in the prior literature with how threshold is conceptualized in this article. The distinguished professor, David H. Kaye, wrote that the threshold question for law relates to the potential for uniqueness in forensic testing. He wrote:

> The threshold issue for the law, therefore, is not the impossibility of falsifying universal propositions. It is whether criminalists are warranted in believing, as a practical matter, that certain universals (everyone has different fingerprints, everyone other than identical twins have different genomes, every face is unique, and so on) are true.[12]

The thesis defended in this paper is that the threshold issue for law is slightly different. The threshold is instead whether remote probabilistic odds claims, such as 1-in-18-quadrillion, derived from the adversarial methods of forensic science, are objective enough to be considered accurate.[13] In other words, even if knowledge of "certain universals" is possible, or may someday become possible due to advances in DNA

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[7] *See* David H. Kaye, *What is Bayesianism? A Guide for the Perplexed*, 28 JURIMETRICS 161 (1988) citing Richard O. Lampert, *The New Evidence Scholarship: Analyzing the Process of Proof*, 66 B.U. L. REV. 439 (1986).

[8] *C.g.* David H. Kaye, *Probability, Individualization, and Uniqueness in Forensic Science Evidence: Listening to the Academies*, 75 BROOK. L. REV. 1163; Michael J. Saks & Jonathan J. Koehler, *The Individualization Fallacy in Forensic Science Evidence*, 61 VAND. L. REV. 199 (2008); Jonathan J. Koehler & Michael J. Saks, *Individualization Claims in Forensic Science: Still Unwarranted*, 75 BROOK. L. REV. 1187 (2010); *See* NRC 7 ("Often in criminal prosecutions and civil litigation, forensic evidence is offered to support conclusions about 'individualization' (sometimes referred to as 'matching' a specimen to a particular individual or other source) or about classification of the source of the specimen into one of several categories. With the exception of nuclear DNA analysis, however, no forensic method has been rigorously shown to have the capacity to consistently, and with a high degree of certainty, demonstrate a connection between evidence and a specific individual or source.").

[9] NRC (2009) at 8 ("The simple reality is that the interpretation of forensic evidence is not always based on scientific studies to determine its validity. This is a serious problem. Although research has been done in some disciplines, there is a notable dearth of peer-reviewed, published studies establishing the scientific bases and validity of many forensic methods.") citing J.J. Koehler, *Fingerprint error rates and proficiency tests: What they are and why they matter*, 59 HASTINGS L.J. 1077 (2008); L. Haber and R.N. Haber. *Scientific validation of fingerprint evidence under Daubert,* 7(2) LAW, PROBABILITY & RISK 87 (2008); J.L. Mnookin, *The validity of latent fingerprint identification: Confessions of a fingerprinting moderate*, 7(2) LAW, PROBABILITY & RISK 127 (2008).

[10] NRC (2009) at 8.

[11] *See* DH Kaye (2010) at 1185 ("Radical skepticism of all possible assertions of uniqueness is not justified.").

[12] *Id*. at 1172.

[13] Lindley at 185 ("Another feature of a trial that needs examination in the light of our reasoned analysis is the adversarial system with prosecution and defence lawyers; a system that has spread from the law to politics in its widest sense where we have pressure groups whose statements cannot be believed because they are presenting only one side of the case. After all, there is another method of reaching truth that has arguably been more successful than the dramatic style that the adversarial system encourages. It is called science…").

analysis,[14] this possibility alone does not mean that any forensic scientist who testifies as an expert witness has automatically made a finding in an objective or scientific way. Indeed, other sources of subjectivity within the criminal law are not only theoretically possible, but may even predominate given the adversarial methods of forensic science.

In science, apart from forensic science, an assessment of the methodology used in arriving at a scientific claim is made via a broad disclosure of testing processes, results, alternative theories and so on. Broadly speaking, full disclosure is not performed in criminal law settings pursuant to the *Brady* standard of disclosure. A series of law journal publications have now identified a host of reasons why, or even when, *Brady* disclosures may be made or not made.[15] Professor Kaye likewise seemed to have identified this as a concern when he noted: "Although I am not sure that the law needs to require the expert to express every caveat in direct examination, much would be gained if the legal system or the forensic science profession insisted on written laboratory reports containing all the cautions."[16]

A secondary thesis of this paper is that forensic evidence revealed on direct examination must disclose caveats in probabilistic odds calculations in order to render that claim reliable, or even plausible. The failure to make a disclosure means that a reviewer cannot replicate the calculation. If the reviewer was forced to render a revised probabilistic odds claim taking into account that uncertainty, then that revised claim would necessarily reduce the previously stated odds, at minimum by subtractions from a proposition given as objective in all respects. If possible sources of subjectivity are not disclosed, they are essentially disguised within the adversarial methods of forensic science. Failing to disclose caveats can increase confidence in the probabilistic odds claim and can render alternative explanations extremely remote;[17] skepticism is warranted as to these probabilistic odds claims.[18]

The statement of more remote odds reflects merely a hidden assumption that laboratory error did not occur, for example. If a prosecutor wishes to introduce extremely remote odds on a test result, then these should (or, *must* in scientific terms) contain "cautions" or disclosures of assumptions;[19] alternately, the prosecutor may wish to introduce experimental controls that reduce the risk of laboratory error to

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[14] DH Kaye 1168 (2009/10) A second NAS committee suggested that '[w]ith an increase number of loci available for forensic analysis, we are approaching the time when each person's profile will be unique (except for identical twins and close relatives)." Citing Nat'l Research Council Comm. On DNA Forensic Science, An Update, the Evaluation of DNA Evidence 161 (1996).

[15] *See* D. S. Medwed, (2010). *Brady's Bunch of Flaws*, 67:4 *WASH. & LEE L. REV.* 1533 (2010) ("The Brady doctrine represents an uneasy balance of a prosecutor's role, both to act as an impartial agent of justice and to act as an ardent pursuer of the state's case. Because this is unlikely to work in practice, a possible way to guarantee a defendant receives all exculpatory evidence he or she is entitled to is to simply require prosecutors to turn over all evidence known to them, regardless of whether it is exculpatory or inculpatory."); J. Abel, *Brady's Blind Spot: Impeachment Evidence in Police Personnel Files and the Battle Splitting the Prosecution Team*, 67:4 STAN. L. REV. 743 (2015); M.H. Baer, *Timing Brady, 115* Columbia L. Rev. 1 (2015).

[16] Kaye (2010) at 1179.

[17] The issue of the adversarial nature of forensic investigation has been raised in the prior literature. D.H. Kaye (2010) at 1179 ("The proposals to scale back forensic science testimony reflect the view that an expert testifies not as an advocate, but as the representative of a learned profession, conveying its knowledge, along with its limitations, to the jury… A neutral expert not seeking to overawe the jury would express the important limitations up front.").

[18] *See Infra* Part III.

[19] *See* Alex Biedermann, Joëlle Vuille, Franco Taroni & Christophe Champod, *The Need for Reporting Standards in Forensic Science*, 14 LAW PROB. & RISK 169, 173 (2015) ("If it can be agreed that there is a scientifically rigorous way of reasoning, which represents a safeguard against fallacious conclusions, we see no persuasive reason in principle why it should not be a requirement to follow it and why it could not be retained as a standard.").

near zero. Each of these methods would serve to reduce the inherent subjectivity of the probabilistic odds claim. However, if subjectivity is present, it may be advisable to impose a "ceiling" on probabilistic odds claims derived from numbers incorporating that subjectivity. A suggestion is made here that: *If subjectivity exists to degree x, then any related or resulting probabilistic odds claim may not exceed x.* As example, if laboratory error is possible at a rate of 1/10,000, then given probabilistic odds may not exceed 1/10,000. This approach would be justified where subjectivity was thought to be omnipresent in the adversarial methods of forensic science, such that any and all assumptions leaked into and informed all other assumptions in the case. In that case, the highest degree of subjectivity in any assumption should serve as a ceiling for remote probabilistic odds claims used in the case.

As a last point of introduction, Popper's most well-known standard, the so-called "impossibility of falsifying universal propositions" idea which has been described as "not very helpful" in legal contexts,[20] is not his most relevant point to the discussion here. An even more important point raised by both Popper, and also by the mathematical genius Frank Ramsey, is that probabilistic odds claims comprise subjective beliefs that are not scientific.[21] Popper wrote: "[A] subjective experience, or a feeling of conviction, can never justify a scientific statement, and that within science it can play no part except that of an object of an empirical (a psychological) inquiry."[22] This is important because probabilistic odds claims are beliefs in the form of posited thought experiments and do not actually exist and thus cannot be verified by observation and testing. Simply put, *all* probabilistic odds claims related to the criminal law are subjective statements of belief.[23] In addition, Popper explained how various uses and misuses of hypotheses can give rise to subjectivity in scientific inquiry which may also be important here.[24] This paper will explain that the analysis of hypotheses within the philosophy of science is also increasingly

[20] *See* Popper at 4 ("The problem of induction may also be formulated as the question of the validity or the truth of universal statements which are based on experience, such as the hypotheses and theoretical systems of the empirical sciences. For many people believe that the truth of these universal statements is 'known by experience'.").

[21] Ramsey, supra Note XX; This is true unless a population is fully known, i.e., the number of red balls in a container is known. In Bayesian methods as applied in the criminal context we are generally not concerned with this situation because the DNA profiles of all humans are unknown and determined by sampling and statistical extrapolation.

[22] Karl Popper, The Logic of Scientific Discovery, 24 (2d ed. 2002).

[23] *See* Dennis V. Lindley, *Understanding Uncertainty* (Wiley-Interscience, 2006), 1 ("Statements of uncertainty are personalistic, they belong to the person making them and express a relationship between that person and the real world about which a statement is being made. In particular, they are not objective in the sense that they express a property that is the same for all of us."); Barry Gower, *Scientific Method: An Historical and Philosophical Introduction* (London: Routledge, 1997) at 187 ("For [Frank Ramsey], probabilities as degrees of belief are subjective rather than objective; they represent psychological states. 'There really do not seem to be any such things', Ramsey declared, 'as the probability relations he describes'") citing Frank Ramsey "Truth and Probability" in FP Ramsey *Foundations: Essays in Philosophy, Logic, Mathematics and Economics*, (London: Routledge & Kegan Paul, 1978); Franco Taroni, Silvia Bozza, Alex Biedermann & Colin Aitken, *Dismissal of the Illusion of Uncertainty in the Assessment of a Likelihood Ratio*, 15:1 LAW, PROB. & RISK 6 (2016) ("A corollary of these considerations is that probabilities are not states of nature, but states of mind associated with individuals. One definition of probability is to consider it as a 'measure of belief' in the outcome of an event or the truth of a proposition… Acknowledgement that probabilities are states of mind raises the issue of how to elicit personal probabilities. There are various devices and procedures to do so."). Popper wrote on this point: "A subjective interpretation of probability theory is suggested by the frequent use of expressions with a psychological flavour, like 'mathematical expectation' or, say, 'normal law of error', etc.; in its original form it is psychologistic. It treats the degree of probability as a measure of the feelings of certainty or uncertainty, of belief or doubt, which may be aroused in us by certain assertions or conjectures. In connection with some non-numerical statements, the word 'probable' may be quite satisfactorily translated in this way." Popper at

[24] Popper at 91 ("We choose the theory which best holds its own in competition with other theories; the one which, by natural selection, proves itself the fittest to survive").

relevant to criminal law as it becomes more reliant on forensic science and investigation.[25] Popper's restatement of science as focused on the competition of competing theories rather than independent fact (although modified in various ways by later scholars) is the defining characteristic of modern scientific inquiry and that could also be viewed as his most important contribution to the current debate.[26]

As a final point of introduction and to highlight the practical importance of the foregoing concerns, several sources of subjectivity in probabilistic odds claims in criminal proceedings that might often give rise to a presumption of inaccuracy are as follows:

(i) **Lack of Disclosure of Testing Processes**. The scientific standard of disclosure of testing procedures is strict in comparison to the legal standard under *Brady*,[27] and requires full disclosure of testing processes and results; non-disclosure has the potential to change the given odds upon review (or, render results *entirely* subjective). As an example, full disclosure of the number of trials performed in a DNA testing process prior to obtaining a positive result would be strictly necessary to render any probabilistic result.

(ii) **Error Rate as Ceiling to Remote Odds**. The potential for laboratory testing error (or evidentiary handling error) seems to be excluded almost universally from extremely remote probabilistic odds claims. This result is achieved by switching the subject of the testing process to relate to the person of the criminal defendant, rather than the test sample. For example, compare: (1) "The results indicate a DNA match between the reference sample and *the Defendant*" with (2) "The results indicate a DNA match between the reference sample and *Test Sample A* (taken from the Defendant while in police custody)." A plausible estimate for an unblinded laboratory error-rate might be reasonably estimated in the tens-of-thousands. Thus, it is misleading to first switch the underlying subject of the test from the test sample to the criminal defendant's person, and then to present probabilistic odds of a match that drastically exceeds the laboratory error rate.

Parts I, II and III of this paper describe the significance and sources of subjectivity in forensic investigation. Part I provides the terminology and relation between subjectivity and inaccuracy of probabilistic odds claims. Part II provides a list of sources of subjectivity within forensic science. Part III describes inherent subjectivity within forensic science. Part IV provides a philosophical background distinguishing the prior literature's focus on the "impossibility of falsifying universal propositions" derived from Popper.

I. Presumptive Inaccuracy

Most of the prior literature on the use of probabilistic odds claims in criminal proceedings focuses on the

[25] *Infra*, Part IV.

[26] *See infra* Section IV.

[27] *Brady v. Maryland*, 373 U.S. 83 (1963); *see also United States v. Agurs*, 427 U.S. 97 (1976) (ruling that a specific request for evidence is not required); *Kyles v. Whitley*, 514 U.S. 419 (1995) (holding that the rule applies to evidence known only to the police and not the prosecutor); *see generally* Baer at 12 ("Brady does not demand the disclosure of every piece of potentially exculpatory evidence, but instead focuses only on 'evidence' that is 'material' to the defendant's case. In the first instance, the prosecutor decides whether a given piece of evidence meets Brady's definition. The Supreme Court has elaborated that evidence is material if it 'undermines confidence in the verdict' and there exists 'a reasonable probability that had the evidence been disclosed to the defense, the result of the proceeding would have been different.'") (citations omitted).

idea of accuracy as trueness,[28] meaning whether or not Bayesian probabilities are accurate enough to be considered true.[29] An illustration of this problem would be a debate over determining whether it is true that an arrow has struck a bullseye while blindfolded (i.e., without being able to observe the target). Bayesian statistics essentially allow scientists to make blindfolded claims of striking the bullseye when the result cannot be verified by observation.

This article is unique in the literature because it is not so much concerned with whether any accurate blindfolded propositions can be made at all. Instead, for purposes of this article, what I mean by "presumptive inaccuracy" is that in any specific situation the course of the arrow is affected by many ballistic factors, or what I will refer to as "context". For shooting an arrow, the ballistic factors might include windage, humidity, temperature, and so forth. If any of these conditions are not ideal, then accuracy is *presumptively* reduced from ideal conditions (such as that would comprise a statistical *proposition* as it is often given in the context of forensic science). If the archer does not say that she has checked for wind, rain and cold, then I would conclude that she has not taken these factors into account, rendering the claim of having struck the bullseye under the assumption of ideal conditions as "presumptively inaccurate".

Furthermore, if the archer is an adversary in the context of a criminal proceeding, and says that conditions are ideal for archery as a broad proposition (i.e., calm, dry, temperate, and so on), then I would say these claims are potential sources of subjectivity that must be checked. If the archer then claims to be exceedingly confident she has made a bullseye shot, this can only be true if her claim as to perfect archery conditions is itself verifiable. Any humidity on the bowstring, for example, means that the exceeding confidence about the bullseye shot must be reduced upon review. A presumption of perfect conditions might be given by an expert witness in a variety of ways, such as explicitly by footnote, or even perhaps implicitly with a mental note, that might be revealed solely on cross-examination.

Any review of the accuracy of probabilistic odds claims actually requires a determination of whether the level of subjectivity in the analysis might also be greater than initially reported. This could mean that the probabilistic odds claim is presumptively inaccurate because the report was given at a higher level of precision than was warranted. For example, imagine in the *Gilyard* case that it was possible that evidentiary handling error could have resulted in the test sample being contaminated with Gilyard's blood that was taken during the initial investigations and held by the police department for several decades. If that is *possible*, albeit extremely unlikely, at odds of 1-in-10,000 hypothetically, then a related probabilistic odds claims should have been given at the lower end of 1-in-10,000 rather than 1-in-18-quadrillion. And, I wish to assert here that this is true even though the "match" claim and the odds of uniqueness claim were presented separately by the forensic scientist in the *Gilyard* case and might be presented separately as standard methodology in all criminal cases.

1. Subjectivity Silos

[28] Lindley at 12 ("Thus an event is uncertain for you if you do not know whether it is true or not."); Taroni, Bozza, Biedermann & Aitken at 5 ("For the individual at hand, it is not known whether a given proposition (e.g. the suspect is at the origin of the trace), or a given event (e.g. a random person from a relevant population has a given DNA sequence) is true or not. Given the partial knowledge of the individual, the value p expresses the degree to which the proposition or event of interest is taken to be true. Probability provides a very close description of the problem faced by any person contemplating an uncertain event or proposition.").

[29] The term "accuracy" can also refer to precision and margin-of-error. In the arrow illustration, "precision" could refer to the groupings of arrows around or within the bullseye, and "margin-of-error" could refer to determining whether an arrow which is positioned on the line is considered within the bullseye.

In my view, the formal separation of subjective claims makes little or no difference because both claims are subjective and the information is relevant to and informs the other subjective belief. Subjective information should be presumed to leak in the course of a police investigation and not to be held in subjectivity silos. I find no concept of subjective "siloing" in probability theory either. This means that in applying Bayesian science, all of the available information should be assessed in making Bayesian calculations. Under this approach, if the odds of evidentiary contamination are subjectively thought to be 1-in-10,000, then it is unreasonable and potentially prejudicial,[30] to propose odds of uniqueness at 1-in-18-quadrillion. This separation implies that the probabilistic odds claim is held in a separate subjective silo, and I find that assumption unreasonable, as I subjectively believe that in most cases the forensic examiner would be aware of all other results in deriving the latter claim.

Moreover, these extremely remote odds are misleading when the "match" event was determined at a lower level of confidence that was used in actually deriving the probabilistic odds claim. Again, Prof. Kaye appears to have correctly identified this problem and described it as follows:

> Because the prevailing method of agarose gel electrophoresis for measuring the lengths of the VNTR fragments is not sensitive enough to distinguish between fragments that are extremely close in size, laboratories declare a match when two conditions are met. First the examiner must feel that the crime sample fragments and the suspect's fragments have migrated the same distance on the gel. Second, computerized measurements must confirm that the difference in migration distances is less than plus-or-minus three (or some other number of) standard deviations of a set of independent, duplicate measurements.[31]

However, that does not describe an "objective" procedure. In science, objectivity refers to the replicability of results. The footnotes to this statement reveal that the results are not replicable in many cases, and this lack of replicability is resolved by testing many lengths against a posited distribution.[32] This is not objective because the posited distribution is non-existential, and also because the interpretation of results is not standardized. In addition, "computers" do not make optical measurements.[33] This reflects a hidden problem with the Bayesian methods where statistical calculation of probability is confused with objectivity in the taking or analysis of a measurement, as if these were the same. For example, a computer can also be used to calculate the results of a polygraph examination, but we would not therefore say that the polygraph has been computerized and the results are therefore "objective".

The infamous *Gilyard* case is helpful to illustration the practical significance of the foregoing. The standard approach for DNA analysis was applied to determine a "match" to Gilyard's DNA to a test sample, and then to estimate the relative frequency of Gilyard's DNA segment in a reference population at odds of 1-in-18-quadrillion.[34] The "reference population" is posited without any subjective assumptions,

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[30] *See infra*, Sections I and II. For an alternative view *see* D.H. Kaye (2010) 1179 ("Thus, even though there is some risk of prejudice, this risk seems worth running with most forms of trace evidence, at least when compared with the alternative of entirely depriving the jury of a fair description of a relevant scientific finding.").

[31] David H. Kaye, *DNA Evidence: Probability, Population Genetics, and the Courts*, 7 HARV. J.L. & TECH. 101 (1993).

[32] Kaye (1993) Footnotes 43 to 48.

[33] References to modern technology as a characteristic objective "science" often reflect a view of Baconian science from the late 17th century where science was thought of as the use of new technology, such as telescopes.

[34] Note that probability theorists avoid the discussion here by position a known proportion of people with a given genotype even though this is not known in actual practice. *See* Lindley at 88 ("Consider a specific form of evidence. Suppose the crime is one of breaking and entering and that the criminal has left DNA evidence at the scene, made

which is to say the reference population is not real (non-existential), just as Karl Popper warned.[35] In addition, the figure given in *Gilyard* is roughly a million times the number of persons now living or that will ever live; it amounts to a strong claim that Gilyard's DNA profile is unique. The significant question is whether the "reference population" should include the samples at issue in the case. That is, in every case, there are at least 2 DNA samples that appear to be the same (in *Gilyard*, there were 7). If the samples are not presumed to "match", then we have potentially 2 separate data points that are the same. If the reference population existed in the world, then 1 or more of the samples should clearly *not* be included in the population, but here the composition of the reference population is hypothetical (i.e., non-existential) and should be updated as a matter of Bayesian methods for the new evidence.[36] The issue is extremely important since the odds claim is extrapolated from a small dataset, so if both samples were incorporated into the Bayesian analysis (and not presumed to be from the same source) that might reduce the odds to a figure in the thousands and not the quadrillions.

The severe problem is that the odds claim therefore seems to be subjective at it depends in part on the confidence in the subjective "match" claim.[37] Kaye thus proposes that "match" claims are "objective" because the "matching" process has been partly mechanized using computers, although the interpretation of results has not been standardized. However, in modern science, the term "objectivity" refers to replicability by experiment. The interpretation of results is included within that definition, so if one DNA laboratory uses a variance standard of 3, and another 4, standard deviations, in order to determine a "match", this difference alone means the test results are not objective. The possibility of obtaining different results from different laboratories seems to be well-known amongst criminal law practitioners, I take it to be an occurrence on the order of magnitude in the hundreds, rather than in the millions. If this is true, it raises potential problems relating to "laboratory shopping" where prosecutors might select laboratories based on the propensity to find a "match" between samples based on prior experience with the laboratory, as illustration. Furthermore, nearly all of the subjective aspects of forensic science as developed in Part I, could apply to render a result not replicable, even where an optical device connected to a computer was used to record and evaluate measurements.

Upon review, *any* probabilistic odds claim should be adjusted if the forensic examiner fails to disclose, or fails to collect, details about the testing procedure used to generate the result. This is because scientists generally do *not* presume a full validity of test results in the absence of full disclosure of the evidentiary and testing processes. In the specific context of Bayesian probabilistic calculations, each trial or test result cannot be taken as independent of other tests performed on the same evidence; that is, each inconclusive trial or discarded test result on evidence must constitute at the very least a subtraction from a calculated probability to a specific event. By analogy, we are concerned with the shooting conditions

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when he broke the window to gain access. A forensic scientist has examined this evidence and found that the DNA is of a genotype that occurs in a proportion F of people. Furthermore, the defendant is of the same genotype. The evidence E thus consists of two parts; the match between the DNA of the defendant and the DNA at the scene, and the proportion of people with this genotype.").

[35] This is reflected in several sections of *The Logic of Scientific Discovery*, including Parts I-V and XIII.

[36] Christian Dahlman, Frank Zenker & Farhan Sarwar, *Miss Rate Neglect in Legal Evidence*, 15:4 LAW, PROB. & RISK, 240 (2016) ("A decision-maker who is presented with additional evidence (E) for some hypothesis (H), must reassess the probability of H and calculate the probability of the hypotheses given the new evidence, $P(H|E)$. How evidence affects this probability is generally captured by 'Bayes Rule'… In a legal case, where the hypothesis states that the defendant is guilty and the evidence consists in the testimony of an eyewitness, $P(H)$ is the probability that the defendant is guilty before the testimony has been taken into account. The ratio of the relevant prior probabilities, $P(H)/P(\sim H)$, is referred to as the 'prior odds', i.e. the odds that the hypothesis is true before the evidence has been considered.").

[37] Kaye (1993) at 112 ("When a sample from a defendant matches both objectively and subjectively, the defendant can hardly complain that the laboratory should not have bothered with the subjective phase of the procedure.").

on that one specific point in time when the arrow was released and not the likelihood of accuracy under perfect shooting conditions generally. So, if we have data about other archery shots at that point in time, that information is highly relevant to the Bayesian conclusion related to that particular event. In statistical terminology, this is to say any given odds comprise a subjective assessment of the likelihood of one discreet event which either did or did not occur (e.g., the DNA profile matched or did not match).[38] All *context* is relevant to that subjective determination, whereas context would not be relevant in fixed population "frequency" analyses.[39]

2. Context

Context is relevant to Bayesian probabilistic odds claims. Statisticians sometimes refer to some types of context as "parameters".[40] This is to say that Bayesian subjectivity relates both to the rendering of odds in perfect shooting conditions and also to specific factors that affect odds in the particular situation under examination. A simple illustration of what I mean by "context" is where multiple tests are run on the same DNA evidence; if the repeated test is run on the same evidentiary sample, then the repeated tests would affect a Bayesian probabilistic odds calculation to some degree. This is true regardless of the actual results of the repeated test. The actual results are indeed always relevant because any positive, negative, or inconclusive results would each be informative in various ways.[41] In fields other than forensic science, repeated tests are often used to confirm initial test results. The repeated test has the effect of increasing the confidence level from a single test and could actually increase confidence in a probabilistic odds calculation. In forensic science however, re-tests on positive results appear to be relatively rare, so the existence of multiple tests are likely to constitute subtractions to given probabilistic odds. The simple rule of context then is that any testing on the same evidence must affect to some degree the overall calculation; any reasonable scientist would adjust subjective assessment of probabilistic odds to reflect repeated tests on the same evidentiary sample.

a. Posterior Probability in Context.

Baye's Rule refers to the formula used in calculating probability for an event.[42] The odds can be updated to take into account new evidence and the result is referred to as "posterior probability".[43] This is often

[38] To say that a probabilistic odds claim is "subjective" is also to say that it is either presumptively inaccurate, or at minimum, unverifiable. Lindley at 194 ("[U]ncertainty, and therefore probability, is personal.")

[39] Popper referred to "Objective Probability". *See* Popper at 137 ("According to this view, numerical probability statements are only admissible if we can give a frequency interpretation of them. Those probability statements for which a frequency interpretation cannot be given, and especially the non-numerical probability statements, are usually shunned by the frequency theorists."); Taroni, Bozza, Biedermann & Aitken at 7 ("There is also a 'frequency-based' interpretation of probability, where probability is interpreted using the concept of frequency rather than beliefs. As an illustration of the connection between frequency and probability, consider an urn containing a certain number of balls, indistinguishable except by their colour, which is either white or black, and the number of balls of each colour being known.").

[40] O'Hagan at 133 ("[B]ayesian inference does make probability statements about parameters. It can do so because the epistemic uncertainty in parameters can be quantified using the personal probability.")

[41] Lindley at 185 ("[D]ata, or evidence, is always expected to be of value, in the sense that your expected value of the information provided by evidence is always positive.").

[42] Lindley at 82

[43] Taroni, Bozza, Biedermann & Aitken at 241 ("'[P]osterior probability' [is] the probability of the hypothesis after the evidence has been considered.")

discussed in the context of forensic science.[44] The trouble with this approach is as explained in Part IV: "The Trial Lawyer's Insistence on a Theory of the Case" occurs if only the prosecution can propose a theory of the case. Then the defendant is precluded from the introduction of outside facts that would explain events using an alternate theory. Taroni, Bozza, Biedermann & Aitken explain further as follows:

> When the competing propositions of interest Hp and Hd are 'simple', that is there is only one main proposition and one alternative, the BF reduces to the well-known likelihood ratio (LR), and depends only on the observed data. When 'composite' propositions are considered (e.g. when at least one of the compared propositions covers several possibilities), the BF does not reduce to the likelihood ratio.[45]

The more difficult question of "context" then is under what circumstances it becomes necessary to subtract from a Bayesian calculation of probabilistic odds when other separate forensic evidence exists, especially DNA evidence, with a comparable confidence level to the test results. As illustration, this would be when multiple DNA tests are run on separate samples, each purporting to be from the defendant (e.g., Blood sample A; Saliva Sample B), yield different DNA test results, with one matching and one not matching a reference sample. The point is that assessment of the results requires a subjective comparison. The forensic examiner would in that case be forced to make a determination whether to make a subtraction from a Bayesian calculation to account for the different test results. Importantly, such a subjective determination might not constitute exculpatory evidence under the *Brady* standard, so the defense may have no idea that the other test result even exists.[46]

Next, an even more difficult question arises when non-forensic evidence of some sort comes up in the trial where such evidence may not have a comparable level of confidence to DNA evidence, but may relate to a Bayesian probabilistic odds claim derived from DNA evidence.[47] As illustration, imagine several eye-witnesses place the defendant in another state at the time of the crime.[48] The forensic examiner might in that case make a determination to subtract from a Bayesian calculation to take this separate evidence into account. As Lindley explained: "[T]he original odds on guilt being multiplied by the likelihood ratio for guilt, given the new evidence, to provide the final odds on guilt given the new evidence."[49] As a practical matter, this is usually done by forensic scientists only indirectly, presumably upon instruction from the police investigators. After the discovery of inconsistent evidence, for example, DNA testing process may be expanded to close relatives or other suspects, to potentially account for the anomaly by identifying a separate source of the DNA match.

Furthermore, a formal paradox arises in the case of "dueling" probabilistic odds claims. A defendant might offer competing *forensic evidence* in support of an alternative "Theory of the Case".[50] For

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[44] Taroni, Bozza, Biedermann & Aitken at 3 Notice that to compute the likelihood ratio in a particular application, such as the evaluation of findings in forensic science, two ingredients are necessary: the probability distribution of the outcomes if hypothesis H_p is true, and the probability distribution of those outcomes if hypothesis H_d is true.

[45] Taroni, Bozza, Biedermann & Aitken at 3

[46] The line of relevant publications on the application of the *Brady* rule are provided above. *See supra* Note XX.

[47] *See* Verheij, Bex, Timmer, Vlek, Meyer, Renooij & Prakken at 40 ("Non-probabilistic information used in the case was for instance based on the suspect's confession that contained specific details about the crime's circumstances, and on physical traces such as the victim's body found in the meadow.").

[48] Lindley describes a similar situation of updating Bayes events in a criminal trial for new evidence. Lindley at 183.

[49] Lindley at 182.

[50] Taroni, Bozza, Biedermann & Aitken at 12 To approach this topic, scientists may consider related questions, that are more readily tractable, in particular: 'How often may a forensic scientist obtain such a likelihood ratio for observations and findings that actually come from a population characterizing the prosecution's case, H p (e.g. when

example, he was somewhere else at the time of the crime and cites solid DNA "match" evidence to support that claim.[51] A clever defense team might gather its own DNA evidence that could be probative to the same degree as other forensic DNA evidence. As a matter of Bayesian theory, this evidence could paradoxically reduce, by some subjective degree, the probabilistic odds calculated from other *completely separate* forensic evidence relating to the specific claim made in the case.

Context is indeed overwhelming important to the use of forensic evidence in criminal cases because of the very broad manner in which DNA evidence is typically introduced in criminal proceedings. That is, forensic results are often presented very broadly as relating to the specific defendant, and not to a test sample supposedly taken from the defendant. The context likewise becomes very broad when evidence is introduced in this manner. For example, if the forensic expert limited trial testimony merely to describe the test sample itself, then a probabilistic odds claim could be derived on a relatively clean mathematical basis regarding the sample. But, as is nearly always the case, when the forensic expert makes the leap of faith to associate the test sample to the specific defendant, he or she incorporates all of the subjective context that would be necessary to complete the leap, such as laboratory error or intentional error in processing or handling of evidence. If that context is not disclosed, then the probabilistic odds claim derived from that evidence is *presumptively inaccurate*.

Therefore, as a practical matter, nearly all of the context of the criminal trial has the potential to affect the subjective (Bayesian) probabilistic odds claim given in respect to a particular event. A clean mathematical calculation is unrealistic and presumes there is no context that might affect that Bayesian calculation. Of course, a subtraction might be nominal in some cases depending on the circumstances. Yet it is likely that a severe reduction to the stated probabilistic odds would be required in many cases, especially with extremely remote probabilistic odds, such as the 1-in-18-quadrillion figure given in the *Gilyard* case. A review of the forensics literature indicates, however, that probabilistic odds claims are often described both in theory and practice as independent mathematical events. This is error; Bayesian probabilistic odds claims used in criminal cases are always stuck down in the fog and uncertainty of context.[52] If or when a forensic scientist derives an odds claim as a clean mathematical calculation, this is subject to footnotes or other disclosure that must at times swamp the calculation.[53] The list of subjective aspects of forensic science developed in this paper provide illustrations of how or when the footnotes might raise skepticism about the calculation. Furthermore, it follows that the calculation of extremely remote probabilistic odds (e.g., 1-in-100-million) might be considered implausible in all cases when details of the DNA testing procedure are unknown due to a lack of disclosure.

3. Adversarial Disclosure, *Brady*

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items from the same source are analysed and compared)?', 'How often may a forensic scientist obtain such a likelihood ratio for observations and findings in a situation as specified by the alternative proposition assumed by the defence case, H d (e.g. when the compared materials come from different sources)?'. Note that the answers to these questions are not of particular relevance for the evaluation of evidence in a particular case.

[51] Furthermore, in any criminal case the "hypothesis of guilt" at issue in the trial derives from the prosecution; but, that hypothesis is not the only possible hypothesis. Criminal defense lawyers often seek to advance an alternative "Theory of the Case".

[52] Taroni, Bozza, Biedermann & Aitken at 5 ("Arguably, probability is 'conditional' on available information and there is no problem in principle with two persons having different probabilities for the same event (Lindley, 2000). This emphasis on conditionality leads to a second important point, namely that probability is personal. It is personal in the sense that it refers to the subject who holds a particular probability, hence the alternative designation 'subjective probability'. Here, the term 'subjective' refers to the opinion of the person of interest, and not to a suggestion of arbitrariness.") citing Dennis Lindley, *The Philosophy of Statistics*. STATISTICIAN, 293 – 337 (2000).

[53] Add cite.

Disclosure in criminal cases is premised on the minimum standards for the disclosure of exculpatory evidence, referred to in the United States when violated as "*Brady* violations".[54] A convergence seems to be presumed between the minimum standards of disclosure in a purportedly "scientific" project and the legal standard of disclosure under *Brady*. The presumed convergence means that when the state meets the minimum *Brady* standard for legal disclosure, it is presumed that it also meets a scientific standard of disclosure pursuant to *Brady* (and for purposes of *Daubert* and progeny). Any details about the forensic investigation that are not exculpatory, or in other words do not explicitly falsify the core hypothesis of guilt, have the potential not to be disclosed to opposing counsel in the course of the criminal trial.[55] However, even a cursory review of any scientific journal in nearly any field concerned with science, such as biology, physics, astronomy, and so on (apart from econometrics) should reveal that this is not the scientific standard, and the respective standards of science are *higher* than that provided by the legal standard of *Brady*. Scientists, in their respective publications, disclose every failed trial, explain every test not performed, and discuss every possible theory both for and against the hypothesis to which they are concerned.

The objective methods of modern science mean in part that information should be fully available to all parties, such that a causal hypothesis can be tested using all available information. The lack of robust disclosure has potentially major implications for the use of probabilistic odds claims based on DNA testing in criminal trials. For example, when multiple trials are run on evidence with inconclusive results prior to a positive DNA test result, the probabilistic odds claim must be reduced by the prior inconclusive test results. On the other hand, scientists *do* take into account the entire context and process of testing. Even the simple absence of a test or procedure may diminish the meaningfulness of stated results. In adversarial proceedings, the reliability of evidence may be diminished from a scientific standard where full disclosure is not required under the *Daubert* standard. The use of probabilistic odds claims derived from DNA evidence in criminal trials illustrates this potential problem. For example, the scientific basis of probabilistic odds claims is affected when the experimenter who conducts DNA tests fails to disclose either (i) the number of trials performed before a supposedly positive "match" was obtained, or (ii) the existence of other inconclusive test results. Even in cases of extremely remote probabilities, the odds may change though the failure to disclose may not be at the level of exculpatory evidence.

II. "Onion Layers" of Subjectivity in Forensic Science

To fully consider the probabilistic odds claim of forensic science requires peeling back several sources of subjectivity, much like peeling back the layers of an onion. Eight layers of the onion are detailed below.

1. Repeated Trials

The first and most obvious problem with the use of probabilistic odds claims in the criminal context relates to repeated trials. Under the *Brady* standard, the prosecution is generally not required to turn over to the defense counsel the number of inconclusive tests that may have occurred before a positive result was obtained. The prosecution is therefore essentially free to run an unlimited number of tests, unbenounced to the defense, unless an exculpatory result arises, and perhaps not even then, depending of course, on how the prosecutor interprets the *Brady* standard.[56] Take for instance when multiple tests are run on a DNA sample, and one is positive and others inconclusive. If such inconsistent tests have

[54] Add Cite
[55] Add Cite
[56] *Supra* note xx.

even the potential to change the expectation in the mind of the experimenter or reviewer, then the given probability of the outcome is perhaps much less. If the probabilistic claim given at trial is extremely remote, such as 1-in-100-million, then any inconclusiveness in the procedure whatsoever is likely to greatly reduce the given probabilistic odds to a much lesser figure.

2. Absence of Tests

In order to even imagine a scientific type of criminal process, the first prerequisite would be an independent type of investigation that would not set out to gather evidence solely to advance a theory of guilt. This type of investigation would require some degree of independence for the examiner to both gather and to examine evidence that might support other hypotheses. Unlike an independent investigation, lack of testing of any hypotheses other than that of a defendant's guilt would be more aptly described as the process of "confirmation" of beliefs held by an investigator rather than "science" or scientific inquiry.[57] In a criminal trial, presenting the forensic investigator as a "scientist" or "expert" to the jury may at times give the impression of the existence of an independent examination.

Yet, a possible lack of testing is not limited to merely pursuing one theory of guilt and not others. It also potentially includes a situation where the forensic investigator fails to perform a follow-up check on an initial positive result. This may occur in the criminal investigation when the first result is thought to be sufficient for a conviction and the forensic investigator decides to stop further testing once the initial positive result is obtained. This approach is possible in criminal investigations because a follow-up test is not perceived as examining a competing hypothesis. Simply put, since forensic "science" is not proceeding on the basis of falsification of competing hypotheses, it is *not* seen as strictly necessary to check an initial "confirmation" of the first hypothesis. In other fields of science, the absence of a test that could have been performed and was not performed, is seen as evidence that other hypotheses have not been sufficiently falsified;[58] in some contexts, scientists may apply a severe skepticism to the positive result and presume that the simple test likely would have shown a negative result had it been performed. This type of severe skepticism is indicative of scientific inquiry. In scientific fields other than forensic science,[59] an initial positive test result might be disregarded entirely if a simple check could have been performed that might have falsified the initial positive result.

3. Tests Designed Solely to "Confirm" Suspicion

The history of criminal law going back to King James VI of Scotland has shown that the type of beliefs[60] held by the criminal investigator are extremely broad and range from a belief in the existence of witches,

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[57] *See also* Taroni, Bozza, Biedermann & Aitken at 6 This interpretation of probability is more typically known as the 'belief type' interpretation of probability. It is a very common and, for various reasons, appropriate interpretation of the theory. It considers all probabilities as subjective, in the sense of personal expressions of degree of belief held by an individual. There are other interpretations of probability, though they run rather quickly into conceptual difficulties and may exhibit drawbacks in practice, in particular in forensic and legal contexts citing Lindsey 2006; de Finetti, *Theory of Probability, A critical introductory treatment, Volume 1* (John Wiley & Sons, London, 1974).

[58] Other scholars have reached the same point by logical reasoning. *See* D.H. Kaye (2010) 1177 ("The take-home message would be, "we have a match, but we cannot say how many other people or things would match.").

[59] The absence of trace evidence has even been proposed as "evidence of absence" in the field of forensic science. *See* William C. Thompson & Nicholas Scurich, *When does absence of evidence constitute evidence of absence?* 291 FORENSIC SCIENCE INT'L e18 (2018).

[60] Lindley at 12 Belief does not reside entirely with you because it refers to the world external to you. Belief is not a property of that world because your degree of belief may reasonably be different from mine. Rather belief expresses a relationship between you and the world, in particular between you and an event in that world.

to the more mundane.[61] This overlap between witchcraft and science is partly why scientific inquiry after the Reformation does not so much "confirm" a given theory as it does rule out competing theories. The reason Popperian science does not proceed by a "confirmation" method is because some type of evidence always exists to confirm almost anything.

The problem is that superstition is difficult to distinguish from scientific inquiry when applying a "confirmation" method. For example, imagine I believe that the black crow outside my window controls the weather. I then begin to gather entirely accurate empirical evidence that shows each time the crow jumps twice and calls out with a "caw" immediately thereafter, it rains. How do we distinguish these accurate empirical observations of bird signs from scientific inquiry? Popper addressed this problem and proposed that scientific inquiry should proceed by falsification rather than confirmation to rule out superstition. For this reason, in modern science, one should not say that a DNA test "confirmed" the hypothesis of an investigator, for example.[62]

This issue leads into modern debates in the philosophy of science as to when empirical tests should be used to confirm hypotheses, a topic for which many modern scholars distinguish Popper.[63] It is true that some hypothesis held as scientific and are not subject to falsification, and there are also universal laws that do not meet Popper's definition.[64] However, as will be explained further in Part IV, the key issue from criminal law and forensic investigation, and for econometrics and taxation for that matter, relates to the broader issue that Popper set out to resolve.[65]

4. Lack of Controls

Forensic science generally does not proceed with blind tests or controls of any kind. The lack of blind tests or controls within forensic investigation make it plausible that error could occur at a relatively high rate compared to other types of scientific testing. Blind tests or controls are used in other areas of both scientific and criminal testing. Perhaps the quintessential example of such controls is the testing of pharmaceutical drugs, where the experimenter would test both a test and control group, often without knowledge of which group constitutes the control. In forensic investigation there is no control. The investigator always knows which sample is the test.

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[61] Kelsee Shearer, *King James' Daemonologie and Scottish Witchcraft Trials*, All Master's Theses, Central Wash. Univ. Paper 378 at 13 (2016) citing Brian Levack, *The Witch-Hunt in Early Modern Europe* (Harlow: Pearson Education Limited, 2006) ("Eager to prove his intellect and find acceptance in the budding science community that was steadily building on the Continent, James took his firsthand experiences with witchcraft and enthusiastically wrote his own witchcraft treatise, Daemonologie, that would rival the Malleus Maleficarum in terms of detail and scope.").

[62] Popper at 4-8.

[63] *See* DH Kaye (2005) at 474 ("Rejecting 'verificationism,' [Popper] maintained that corroboration must be understood in terms of a process akin to natural selection, in which theories that survive the most severe tests, emerge as highly 'corroborated.' This general view is congenial to many working scientists, but most philosophers of science do not accept Popper's specific views on the appropriate measure of confirmation or corroboration.")

[64] D.H. Kaye (2010) 1171 But this difficulty with a direct empirical proof is not tantamount to Popper's realization that universal laws cannot be proved to a logical certainty by simple induction. Modern science is full of universal laws. The laws of electromagnetism, for instance, remain unproven and unprovable in Popper's logical sense. The only universal propositions that can be proven to a certainty are deductively valid ones, such as the theorem that all whole numbers that end in an even digit are divisible by two. No experimentation is required to test this law. In contrast, no matter how many times scientists observe that a change in the magnetic flux in a coil or wire induces a voltage, they cannot be certain that it will happen the next time. In principle, a single experiment with no change in voltage would disprove Faraday's Law. (citations omitted)

[65] Add cite

One advantage of forensic evidence to prosecutors in obtaining a conviction appears to be the lack of controls. That is, even with an eyewitness identification the criminal law in each jurisdiction has identified standards by which the eyewitness lineup should be performed.[66] Of course, these standards make it more difficult to use eyewitness evidence. The degree of standards for probabilistic odds varies by jurisdiction, of course; however, in many cases they are relatively light, and may comprise merely professional standards of competence for forensic investigators rather than legal standards of evidence admissibility. One of the primary recommendations of the National Research Council Committee was to establish protocols in the field of forensic science.[67]

5. Causal Theory Derived from Test Results (Reversal of Scientific Method)

Similar to econometrics, the research method for forensic "science" can be easily reversed from the scientific method if the theory arises from the dataset itself. Thus, where a broad DNA search from a public database reveals a "match",[68] this does not reflect the true scientific method where the theory should be tested by data and not drawn directly from the data; accordingly, any criminal suspicion based solely on DNA profile "mining" needs to be augmented with additional evidence. Since every dataset will contain patterns, not all observed patters within a dataset will be meaningful.[69] In the context of forensic science, this means that a match from an evidentiary kit and a public DNA profile does not necessarily entail criminal culpability. Another way to think about this is that by rummaging through hundreds of thousands of public DNA profiles, the odds of finding a coincidental match greatly increase.

6. Lack of Independence Between Tester and Theory Maker

Another major concern with forensic investigation arises insofar as law enforcement officers serve as both the evidence-gatherer and theory-maker. In a criminal case, the core hypothesis at issue is that the defendant committed the crime.[70] Some attempt to collect evidence which might be exculpatory to a defendant is actually required in order to refer to the investigation as forensic "science". As Verheij, et. al, explained in a discussion of the various normative methods in probability theory: "In scenario approaches, it is necessary to consider all possible scenarios, lest we run the risk of the so-called 'tunnel-

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[66] *See* Christian Sheehan, *Making the Jurors the "Experts": The Case for Eyewitness Identification Jury Instruction*, 52 BC L. REV. 651, 653-4 (2011) (discussing evidentiary and procedural means by which the legal system addresses the potential for errors in eyewitness identification).

[67] NRC report at 24-5 ("Recommendation 6… to establish protocols for forensic examinations, methods, and practices. Standards should reflect best practices and serve as accreditation tools for laboratories and as guides for the education, training, and certification of professionals.").

[68] *Golden State Killer caught through GEDmatch search* (2018). *Forensic Magazine*; D.E. O'Leary, DNA mining and genealogical information systems: Not just for finding family ethnicity. *25*(4) *Intelligent Sys. Accounting, Finance and Management,* 190 (2018).

[69] Lindley at 132 ("The main lesson to be learnt from the material in this chapter is that the relationship between two uncertain events is not always what it appears to be because there may be a third event that influences them both and distorts the apparent connection. Thus the connection between treatment and recovery of the patients may be completely changed by consideration of the patient's sex; or the apparent dependence of crime on race can be destroyed by the inclusion of unemployment.").

[70] Lindley at 90 ("The example of the DNA evidence… illustrates the general point of needing to look at alternatives. If guilty, the evidence is sure to match, but if innocent, the match is less certain, how certain depending on the frequency of the genotype.").

vision': focusing on one or a few scenarios and thus neglecting other—possibly true—scenarios."[71]

The foremost goal of forensic science as proper "science" is an attempt by *both* the prosecution and defense to falsify the core theory of guilt advanced by the prosecution. And, in a situation when the defendant appears to be guilty, the investigators find that they are unable to falsify that theory using all the evidence at their disposal. This process, in fact, should regularly occur when initial suspects are "cleared" at the outset of an investigation.[72] The "clearing" of suspects is a process of ruling out lots and lots of culpability hypotheses in short order and itself is an illustration of scientific inquiry. But, true forensic "science" would require that even after the prosecution of a particular defendant begins, the state is still attempting to "clear" the defendant by falsifying its own core theory of guilt, but finds it is unable to do so. In the trial itself, the defense then might also overtly attempt to "clear" the defendant perhaps using forensic evidence of its own. At the end of the day, when the defendant is not cleared, forensic "science" would then be able to conclude only that none of the evidence available falsified the hypothesis that the defendant committed the crime. However, this sort of fanciful scientific approach is obviously very different than the adversarial process of criminal law as it now stands when the prosecutor levies a theory of guilt against the accused and then brings the full weight of the state to find evidence to support its theory.

7. Difficulty of Cross Examination on Witness's Subjective Beliefs

The adversarial method is usually described as a truth-seeking process where cross-examination is one of the key methods applied to arrive at truth. In *Daubert,* the Court referenced the adversarial process as one key element to evaluating evidence.[73] Thus, a severe deficiency in probabilistic odds claims is that since these claims are merely personal beliefs, such claims cannot be falsified on cross-examination, except in the rare case of a mathematical error or an admission by the expert witness that his beliefs were not genuinely held. The expert testifies only as to her expectations or beliefs about the probabilistic odds in relation to forensic evidence; a counter-expert called by the defense can argue that the given level of probabilities expressed are unreasonable expectations or beliefs, or perhaps are not genuinely held by the witness.[74] And, if any experiment generates results inconsistent with the prediction, they can always be attributed to random chance. Popper wrote on this point: "Probability hypotheses do not rule out anything observable; probability estimates cannot contradict, or be contradicted by, a basic statement; nor can they be contradicted by a conjunction of any finite number of basic statements; and accordingly not by any finite number of observations either."[75]

Thus, a genuine belief about the level of probability in any probabilistic odds claim cannot typically be falsified outright including by cross-examination. The actual impossibility of the endeavor partly explains why a challenge to probabilistic odds claims is so rarely attempted by defense counsel in criminal cases. Furthermore, if probabilistic odds claims are so difficult to falsify, then we should not expect inaccuracies

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[71] Verheij, Bex, Timmer, Vlek, Meyer, Renooij & Prakken at 37. As Lindley wrote: "The central lesson [of this section] is that you must consider the uncertainty of any evidence on the basis of all hypotheses that might explain it."

[72] *See generally* Lindley at 102 ("Similarly, at the commencement of a police investigation with N suspects, the police might reasonably regard all equally probable of being guilty. In neither case is it ignorance, but merely a sensible position describing uncertainty.").

[73] "The Court expressed confidence in the adversarial system, noting that '[v]igorous cross-examination, presentation of contrary evidence, and careful instruction on the burden of proof are the traditional and appropriate means of attacking shaky but admissible evidence.' NRC (2009) at 10 citing *Daubert*, 509 US at 596.

[74] Of course, mathematical or tabulatory error is possible in the formulation of a subjective belief.

[75] Popper at 181.

to have been documented in prior legal proceedings, notwithstanding such claims are now ubiquitous.

8. Low Quality of Data

Forensic expectations of the distribution of DNA profiles are determined by statistical surveys, sampling, and analysis. Statistical claims about the distribution of DNA in the human population depend on very small numbers of DNA samples taken from a few human beings and extrapolated to the larger population. These extrapolations render predictions about the distribution of genetic DNA markers.[76] Probabilistic odds claims can then be derived statistically, such as in the *Gilyard* case where the "frequency of Gilyard's DNA profile in the Black population" was determined to be 1-in-18-quadrillion.[77] The 1-in-18-quadrillion prediction is unusual because of the remoteness of its probabilistic odds, reflecting roughly *a million times* the number of human subjects (of all shapes and colors) that have ever lived. A broad concern about very remote claims has been raised extensively in the prior literature,[78] and in various court cases.[79]

The "mining" of DNA profiles from public databases belies a significant problem with the calculation of probabilistic odds generally, which is that the distribution of DNA profiles throughout a population is not actually known.[80] Any calculation of probabilistic odds depends on the statistical confidence in the ability to make predictions using the existing sample. The significant issue broached in the prior literature is that testimony given in the courtroom by a forensic "expert" is distilled to a probabilistic odds claim even though the figure itself is uncertain as all Bayesian claims are uncertain;[81] and furthermore, this type of statistical uncertainty due to data quality may not be understandable to a lay jury who have no means to determine the quality of statistical sampling in respect to DNA tests.[82]

III. Inherent Limits

In scientific contexts outside of the courtroom, scientists are generally reluctant to distill results to a probabilistic odds claims. Scientists do not generally attach probabilistic odds claims to scientific results even when this approach is plausible and apropos to the experiment. The general reluctance to use such odds claims is also likely due to their inherent subjectivity, which renders the claims unreliable.[83] Other scientists may also prefer to make their own assessment of the meaningfulness of experimental results and simply do not care very much about the mental state of the experimenter and how he or she assesses the "odds" of his or her own scientific conclusion.

1. Intervention of Human Forces

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[76] D.H. Kaye (2010) 1181 For concreteness, suppose that the sample consists of 7000 sequences. When a defendant's sequence is not in the database (which is the usual situation), one could say that so far it has been encountered one out of 7001 times. There is ample room to argue that this number should not be taken too seriously. It does not come from a random sample, and it might not be representative of the population in the vicinity of the crime."

[77] Gilyard, *supra* Note 1.

[78] Add cite

[79] Add cite

[80] Add cite

[81] D.H. Kaye (2010) 1171 ("The flaw is not with the logic. It is with the data.").

[82] Add cite.

[83] Tony O´Hagan, *Dicing with the Unknown*, Significance (Sept/2004), 133 ("The degree-of-belief interpretation of probability is sometimes referred to as a personal probability or subjective probability because, as noted already, different people may have different degrees of uncertainty about a proposition. It is 'subjectivity' of this approach to probability that is most objected to by followers of the frequentist theory.").

Another reason for the reluctance of scientists to distill beliefs to probabilistic odds in the social sciences is that the intervention of human forces renders what are thought to be extremely remote events much more plausible, and at times, even likely. Hence, there are risks which insurance companies will not insure or may set out to exclude from insurance policies, such as terrorist attacks, even though the risk is well-known statistically and thought to be extremely remote.

Perhaps the most well-known illustration of this problem of the occurrence of unexpected events due to human forces relates to the now infamous investment fund: *Long-Term Capital Management*. The managers of the fund had excellent data and analytics on the historical occurrence of unlikely events in the bond and derivative markets. The fund set out to make very broad but very large leveraged bets in against the occurrence of rare market events. But, amazingly, the rare events which the managers identified, in fact shortly after the fund made its investment in the market the "unthinkable began to occur".[84] Nearly all the invested capital of *Long-Term Capital Management* was lost. The lesson has been incorporated into investment theory on Wall Street, especially building awareness that an unlikely event can be caused when other investors place countervailing bets against another investor's position.

(a) "Black Swan" Events

Examples of "black swan" events in the criminal law are readily available.[85] However, the occurrence of presumed "black swan" events may also occur when the forensic expert does not take into account factors that would significantly reduce the probabilistic odds claim. For example, family members, even ethnic groups, often live close together and share some degree of genetic background.[86] Any possibility of a common genetic background would significantly reduce probabilistic odds claims. The very existence of *any* documented "black swan" events in the relatively short time frame for which records have been kept, implies that the probability of fingerprints or DNA wrongly identifying a suspect are dramatically higher than would be calculated using background data about trait distribution in the general population.

2. Bona-Fide Mistakes

The possibility of a bona-fide "mistake" on DNA evidence, such as mislabeling, might also be considered significant enough to discount any situation when forensic evidence is presented with a probabilistic odds claim that is extremely remote, such as 1-in-100-million. The possibility of a technical error in the gathering of evidence by a technician or crime laboratory is presumptively more likely than the given extremely remote probabilistic odds often given in criminal cases. One illustration of possible laboratory mistake is evidence labeling error. The presumption in the field of forensic "science" seems to be that mistakes would be severable from the probabilistic odds claim itself. The forensic examiner might then not taken into account the potential for making errors in performing the statistical calculation. However,

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[84] Franklin R. Edwards, *Hedge Funds and the Collapse of Long Term Capital Management*, 13:2 J. ECON. PERSPECTIVES 189, 199 (Spring 1999) ("By spring 1998, however, the unthinkable began to occur. The Asian financial collapse festered on, and concerns arose that similar problems could spread to other emerging market countries.").

[85] See e.g. Case surrounding Brandon Mayfield, Press Release, Federal Bureau of Investigation*, Statement on Brandon Mayfield Case, (May 24, 2004*) cited in Simon A Cole*, More than Zero: Accounting for Error in Latent Fingerprint Identification,* 95 J. Crim. L. & Criminology 985, 986 (2004-2005) ("Mayfield's print was in the database because of a 1984 arrest for burglary and because of his military service. The government's affidavit stated that Green 'considers the match to be a 100% identification' of Mayfield.").

[86] See David H. Kaye, *'False But Highly Persuasive:' How Wrong Were The Probability Estimates in McDaniel v. Brown?* 108 MICH. L. REV. FIRST IMPRESSIONS 1, 2 (Sep, 2009) ("Close relatives tend to share more DNA features ('alleles') than do unrelated individuals.").

by Bayesian standards, the probabilistic odd claim as part of forensic testimony in a courtroom should, of course, take into account all factors including a bone-fide mistake in collection.

Given the possibility of laboratory or collection error, we should expect to, and actually do, observe reports of extremely unlikely results arising from time-to-time and much more often then predicted as a statistical matter.[87] This is because the probabilistic odds claim given in court does *not* take into account the potential for a bona-fide mistake. Furthermore, when the rate of error is unknown or unknowable but thought to be significant, then it is also conceivable that the probabilistic odds claim should not be calculated at all.

3. Intentional Error

Extremely remote probabilistic odds claims are also potentially flawed because of the likelihood of intentional error in forensic collection or analysis. This is most often thought of as "planting" evidence by the police. Perhaps the most documented illustration in the context of DNA evidence has been developed by criminal defense attorney Katherine Zellner related to the second Steven Avery case.[88] The suggestion of intentional error by one policy officer in the Avery case has given rise to a lawsuit by this police officer against Netflix.[89]

In the post-conviction motion in the Avery case, according to Zellner, her forensic expert used a scanning electron microscope and found that the bullet fragment linked by DNA to the murder victim appeared to be imbued with wood and covered with an unknown wax-like substance. And, the case records indicated that prior to the discovery of the bullet fragment in Avery's garage, a Chapstick lip balm vial used by the victim was indeed taken from the victim's residence by the police as a DNA reference sample. The implication is that the DNA reference sample of Chapstick lip balm may have been used to contaminate the actual testing sample. The imbued wood on the sample suggested the bullet fragment likely came from the round striking the garage wall rather than the murder victim. The property owner subsequently disclosed to Zellner he had fired 1,500 to 2,000 similar .22 caliber rounds in the vicinity of the garage. The implication is that the Wisconsin crime lab technician may have either failed to examine the key piece of forensic evidence in the case with a scanning electronic microscope, or chose to remain silent about both the wax coating and imbued wood on the bullet fragment that was used to convict Avery in the second case. In a scientific method of forensic inquiry, these tests should have been performed or the details should have been disclosed at trial *even by the prosecution* to test (presumptively, to even falsify) the hypothesis that the bullet fragment was the cause of death in the case.

III. Philosophical Background

In legal proceedings, the measure of "science" appropriate for expert testimony is essentially undefined under the *Daubert* gatekeeper standard.[90] Probabilistic odds claims and other forensic testimony are, thus, often referred to as forensic "science" under a very loose understanding of that term.[91] However, the term "science" has been defined differently in various historical eras. Insofar as probabilistic claims

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[87] Notably, the XXX case was billed as a coincidence, but this may be an illustration of a filing error in the FBI fingerprinting system which was not publicly disclosed in a failed attempt to avoid civil liability.

[88] Add cite

[89] Add cite

[90] *See* Henry F. Fradella, Lauren O'Neill & Adam Fogarty, *The Impact of Daubert on Forensic Science*, 31 PEPP. L. REV. 2 (2004).

[91] Add cite with explanation.

are considered "science" within the field of "forensic science under a Bayesian version of science", this is because the belief expressed by the "expert" is considered *reasonable* by other experts. For example, other experts might agree that the odds of rolling a 1 on a 6-sided unweighted die are 1 in 6. The implicit definition of "science" within "forensic science" is a collection of reasonable beliefs or expectations held by experts in the field. As D. H. Kaye wrote: "[S]cientists speak of many propositions that are merely highly likely as if they have been proved. They are practicing rather than evading science when they round off in this fashion."[92] This is an accurate statement of Bayesian science. The underlying numerical calculations of probability with the odds claim are then the means to confirm the beliefs are "reasonably" held when presented to the jury; if the mathematics are done correctly, the probabilistic odds are generally presumed to be reasonable.

As explained further below, the Bayesian version of science described in the prior paragraph works as long as the beliefs (or, hypotheses) under investigation are subject to falsification. Bayesian science does not function in respect to debates over the existence of guardian angels, for example. Modern "science" is rather thought of more as the evaluation of competing falsifiable hypotheses about causation. The purpose of scientific experimentation is to falsify hypotheses of causation; those hypotheses that withstand scrutiny are held by scientists as the best causal explanations available, at least until the hypothesis can be revised and updated.

1. Probabilistic Odds Comprise Beliefs or Mental States

As observed by the mathematical genius Frank Ramsey, probabilistic odds claims always comprise merely expectations held in the mind of the experimenter, and are therefore not falsifiable via observation and testing.[93] The potential for falsification by testing is the hallmark of scientific inquiry.[94] Probabilistic odds claims comprise expectations (or mental states) held by the experimenter. Absent the possibility of scientific testing, probabilistic odds claims regarding the distribution of genetic markers in the human population can only be evaluated based on the quality of the underlying data and statistical methodology. Probabilistic beliefs cannot be *disproven* by observation and are thus not strictly falsifiable in scientific terms (i.e., I cannot *disprove* by experiment that the probability of rolling a 1 on a six-sided die is not 1/6, no matter how many times I roll the die).[95] As Dennis Lindley wrote:

> This change comes about with the acquisition of new data and the consequent updating by Bayes rule. If the original statement was well supported, then the change will usually be small, but if, as with BSE, the data are slight, then a substantial shift in scientific opinion is reasonable. It is people

[92] D.H. Kaye (2010) at 1176.

[93] *See, supra* Section III.2. Popper, Logic of Scientific Discovery at 70 ("We can say of a theory, provided it is falsifiable, that it rules out, or prohibits, not merely one occurrence, but always at least one event… Then we can illustrate the postulate of falsifiability by the requirement that for every empirical theory there must be at least one radius (or very narrow sector) in our diagram which the theory forbids.".

[94] D.H. Kaye (2005) at 474 ("Ordinarily, a key question to be answered in determining whether a theory or technique is scientific knowledge that will assist the trier of fact will be whether it can be (and has been) tested. 'Scientific methodology today is based on generating hypotheses and testing them to see if they can be falsified; indeed, this methodology is what distinguishes science from other fields of human inquiry.'") (citations omitted).

[95] Professor D.H. Kaye linked this issue to Popper. D.H. Kaye (2010) at 1166. He wrote: ("As Karl Popper famously explained, it is logically impossible to prove a hypothesis by accumulating positive instances. The hypothesis, 'all swans are white,' remains unproven, even after a large number of sightings of white swans, because the sighting of a single black swan would disprove it. Similarly, the hypothesis that no two objects are indistinguishably alike cannot be proven true from an accumulation of observations in which different object sources produce distinctive markings.").

with rigid views who are dangerous, not those who can change coherently with extra data.[96]

The best one can hope for is to update beliefs about probabilistic odds by providing new evidence to the experimenter that might explain unexpected results (i.e., the dice must be weighted, or, the distribution of DNA characteristics in the population must be different than we thought). For example, if I roll a 6-sided die 100 times and never roll a 1, the expectations regarding the probability of rolling a 1 with that die might need to be updated.

2. Problems in the Prior Literature

The prior literature on the topic of probabilistic odds unfortunately states that "philosophy of science", specifically referring to Karl Popper's work on the potential for falsification, is not very helpful to scientific inquiry in the legal context.[97] Kaye wrote: "The basic idea of falsifiability as a criterion for separating science from metaphysics surely is accessible to judges. The problem, as we shall see, is that this notion is not terribly useful in evaluating most scientific evidence."[98] To illustrate the Bayesian version of science reflected in this view, in probabilistic odds claims, one cannot say that such a hypothesis is false, as a "probabilistic" result is, by definition, uncertain, and acknowledges the possibility of an unexpected result.[99] In Bayesian science generally, scientists are always subjectively evaluating hypotheses about a scientific topic; the collective assessment is taken to constitute the field of science. Unfortunately, the claim that Popperian science is not relevant to evidence is wrong; Popperian science remains relevant in the legal context for several reasons.[100]

(a) "Non-Existential" Methods of Forensic Science (and Econometrics).

The reason that claims of Leiter and D. H. Kaye is wrong is that in *some specific contexts,* it is possible to say that a probabilistic odds claim is not subject to falsification other than merely because it is inherently uncertain. And, those specific contexts where falsification is impossible always include the issues under debate of probabilistic odds claims in the criminal law. That is because the methodology to be applied begins with a definition that actually says the results are not subject to falsification because they apply a "non-existential" methodology. The term "non-existential" here refers to the positing of a hypothetical model or dataset as methodology. This is to say, the most obvious means to render a claim not subject to falsification is to actually define it as not being subject to falsification. And, this method of defining a

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[96] Lindley at 194.

[97] Brian Leiter, *The Epistemology of Admissibility: Why Even Good Philosophy of Science Would Not Make for Good Philosophy of Evidence*, 1997 B.Y.U. L. REV. 803.

[98] D.H. Kaye, *On "Falsification" and "Falsifiability": The First Daubert Factor and the Philosophy of Science,* 45 JURIMETRICS 474 (Summer 2005), 476. Kaye's defense of Bayesian approaches to DNA testing can be seen as a defense of "conventionalism". S*ee* Popper at 61 (""Thus, according to the conventionalist view, it is not possible to divide systems of theories into falsifiable and non-falsifiable ones; or rather, such a distinction will be ambiguous. As a consequence, our criterion of falsifiability must turn out to be useless as a criterion of demarcation.").

[99] Popper at 189 ("For since probability statements are not falsifiable, it must always be possible in this way to 'explain', by probability estimates, any regularity we please.").For example, even if the DNA marker was identified in multiple persons other than Gilyard this still could not falsify outright the 1 in 18 quadrillion expectation given in the *Gilyard* case. D.H. Kaye (2010) 1183 ("As long as there is a nonzero probability of duplication or another swan to consider-as there always will be-such testimony apparently fails Fallacy's exacting standard for statistical proof. As we have seen, however, this austere standard does not comport with normal scientific practice. In the DNA field, scientists have indicated that opinions of general uniqueness' or uniqueness of a particular DNA type within some smaller region are or will soon become scientifically acceptable.'").

[100] *See supra* Sections III and IV.

separate universe (or model)[101] apart from the actual universe turns out to be the standard *modus operandi* of both forensic science, and economics in respect of tax policy, as illustrative.[102]

Rule: When the scientist begins by positing an alternative universe to be the subject of scientific inquiry, then the non-existential claim is not subject to falsification. The comparison of conditions between the real and hypothetical universe is an inductive process, and not a deductive process, *even if a*ll the analysis within the alternative universe is scientifically (and statistically) valid.

Citation: Popper, Realism and the Aim of Science, xix xxi (W. Bartley Iii ed., 1983)

> (4) Purely existential statements are not falsifiable… 'There is a ceremony whose exact performance forces the devil to appear.' Such statements are not falsifiable. (They are, in principle, verifiable: it is logically possible to find a ceremony whose performance leads to the appearance of a human-like form with horns and hooves. And if a repetition of the ceremony fails to achieve the same result, that would be no falsification, for perhaps an unnoticed yet essential aspect of the correct ceremony was omitted.)

Under Bayesian (and econometric) methods, existential statements are made in relation to a dataset which cannot be observed because the experiment relates to a hypothetical universe (dataset, or model). The Bayesian or econometrician says that an alternative universe exists which is analogous to this universe. This reflects a broad existential claim, just as described by Popper. However, this is only *potentially* helpful if the conditions of the alternate universes are analogous to the actual world and that determination is not subject to observation and testing.

Bayesian probabilistic odds claims are accordingly not falsifiable *for several reasons* under Popper's definition, with the most important reason relating to the initial positing of an alternative universe comprised in the model or data set. In the non-existential methodology of forensic science and econometrics, the "scientist" typically begins by saying they have constructed either a (i) "model"[103] or (ii) "dataset" that will be used as a proxy for the real world. This is considered helpful or advantageous to economists or forensic scientists because the alternative universe can be studied either deductively or by Bayesian methods. Nearly all tax policy is formed on the basis of such models, such as the "small open economy" model.[104] I have already written on this topic extensively as it relates to taxation and policy recommendations on tax policy.[105] Popperian "science" is admittedly not very helpful in evaluating whether existential Bayesian claims are viable based on the strength of the underlying dataset. However, Popperian science is useful in distinguishing scientific claims from superstition reflected in models where the model lacks empirical support. Probabilistic odds claims are a category of superstition because they are purely existential statements that constitute mental states which are not subject to falsification and may or may not relate to the actual world.

(a) The significance of Kelvin's Dictum

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[101] Lindley at 200 ("One way of appreciating the distinction between a theory and a model is to recognize that a theory incorporates an explanation for many phenomena, whereas a model does not and is specific.").

[102] *See e.g.,* Arnold Harberger, *The Incidence of the Corporation Income Tax*, 70 J. POL. ECON. 215-240 (1962).

[103] Lindley at 200 ("Scientists have found models so useful as a way of thinking about data that they have been extensively used even without a theory."

[104] Harberger *supra* Note XX.

[105] Bret Bogenschneider, *Tax Incidence and Scientific Inquiry*, 7:2 J. PHIL. INT'L L. 26 (2017).

The reference to "superstition" present within the methods of forensic science is effectively the unquestioned belief in Kelvin's Dictum ("When you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind").[106] The idea is that all beliefs expressed in the form of probabilities are superior to qualitative beliefs. This is not true in situations where we have reasons to doubt the objectivity of the numbers given. Some numbers, in particular, extremely remote probabilistic odds claims, can be misleading and represent an inferior means of knowing where we have reason to believe the given numbers are subjective. Indeed, many of the respected sources of probability theory seem to contain what amount to recruiting statements for group adherence to Kelvin's Dictum.[107]

3. Illustrations of the "Existential Test" of non-Falsifiability

Popper wrote at a time when Viennese scholars were struggling with how to distinguish superstition from scientific inquiry. The mistake in concluding that Popper's version of "philosophy of science" is not very helpful to law is in the presumption that superstition has been largely eliminated from law and related disciplines. However, superstition has not been eliminated, with one key difference. The difference between modern day superstition and superstition in the 17th-century is that superstition is no longer hidden within a belief system. When scholars or, especially, statisticians or econometricians use superstition in its modern form, they usually say so explicitly. For example, economists will tell you they are using a "model" (meaning formal deductive superstition) and statisticians will tell you they are using a "sample" (meaning inductive superstition).

This can be best illustrated with examples, as follows:

Example 1 (17th-century science): King James VI of Scotland sets out to determine if a woman is a witch. There is no empirical way to verify if a woman is a witch. Therefore, the King proceeds methodologically as follows:

> Step 1: Posit a world where witches exert negative influences on human beings.
>
> Step 2: Carefully evaluate the woman subjectively for evidence of witchcraft based on the criteria from the prior step. Ask the woman if she is a witch. Subject her to advanced scientific tests to determine if she is a witch.

Methodological problem (with Step 1): The hypothetical world of witchcraft might also constitute superstition hidden within a predominant belief system. For example, everyone including all the witch doctors at the time, believe it to be science.

Example 2 (corporate tax theory, modern day): An economist sets out to show that corporate tax cuts cause economic growth.[108] There is no empirical data to show a correlation between tax cuts and

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[106] William Thomson (Lord Kelvin) Popular Lectures and Addresses (Macmillan and Co, London, 1889) vol 1 at 73.

[107] *See e.g.* Taroni, Bozza, Biedermann & Aitken at 2 ("[I]t appears reasonable to say that the number of scientists or lawyers who still are sceptical about the metric called Bayes factor (BF), in the context often referred to as the likelihood ratio, has reduced considerably. This development is favoured and supported by the fact that operational standards and recommendations in different forensic disciplines substantially support the use of this metric of probative value.").

[108] *See e.g.* HM Revenue & Customs, Analysis of the Dynamic Effects of Corporate Tax Reductions (2013) www.gov.uk/government/uploads/system/uploads/attachment_data/file/263560/4069_CT_Dynamic_effects_paper_20130312_IW_v2.pdf

economic growth. Therefore, the economist proceeds methodologically as follows:

Step 1: Build a hypothetical "model" of the economy using variables (represented by Greek letters) that is implicitly taken to describe the real economy.[109]

Step 2: Propose a change in the hypothetical model whereby a decrease in the tax rate variable (Greek letter, *t*) is taken to increase GDP growth. Logically prove by deduction that in the model if *t* variable decreases, economic growth increases.[110]

Methodological problem: The hypothetical model of the economy might not correspond to the actual economy.

Example 3 (criminal law): A prosecutor wishes to match a DNA sample taken from a crime scene to a defendant.

Step 1: Build a reference database of DNA profiles that is believed to a high degree of confidence to reflect the real distribution of DNA profiles in the human population.

Step 2: Take a test sample of DNA from the defendant, and compare it to the reference sample, using the reference database that was constructed in Step 1.

Methodological problem: The reference database might not correspond to actual DNA distributions.

4. The Modern View of "Science"

The modern view of "science" or scientific inquiry arose in part with the writing of Karl Popper with the publication of *The Origins of Scientific Discovery*.[111] The modern view of science is relevant to law because forensic science often applies an earlier understanding of science, what I refer to as "Baconian science".[112] Scholars that argue philosophy of science is not helpful to expert testimony in legal trials do not appear to have grasped the historical progression of science or scientific inquiry. This creates a potential for error arises in reverting back to older historical ideas of science, which were rejected for good reasons. Popper rejected the idea that scientific inquiry entailed simply making and recording observations of the empirical world. He instead premised scientific inquiry on the evaluation of competing theories or hypotheses. Although modified and adapted by later scholars,[113] Popper's key

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[109] Harberger, *supra* note XX.

[110] *Id.*

[111] *See* Popper at 74 ("The doctrine that the empirical sciences are reducible to senseperceptions, and thus to our experiences, is one which many accept as obvious beyond all question. However, this doctrine stands or falls with inductive logic, and is here rejected along with it. I do not wish to deny that there is a grain of truth in the view that mathematics and logic are based on thinking, and the factual sciences on sense-perceptions.").

[112] *See* Sir Frances Bacon, *Novum Organum* 50 (Joseph Devey ed., 1902) ("There are and can be only two ways of searching into and discovering truth. The one flies from the senses and particulars to the most general axioms, and from these principles, the truth of which it takes for settled and immoveable, proceeds to judgment and to the discovery of middle axioms. And this way is now in fashion. The other derives axioms from the senses and particulars, rising by gradual and unbroken ascent, so that it arrives at the most general axioms last of all. This is the true way, but as yet untried."); Francis Bacon, Thoughts and Conclusions on the Interpretation of Nature or a Science Productive of Works, in THE PHILOSOPHY OF FRANCIS BACON 73, 89 (Benjamin Farrington tr., 1653) (Liverpool U. Press, 1964).

[113] *See* Carl G. Hempel, *Philosophy of Natural Science* (Prentice Hall, 1966).

insight emphasizing the role of *theory* in scientific inquiry has continued in various iterations to the present day.

Before Popper, a pre-modern of science was followed when science was thought of as experiments (always performed by scientists) that proved ideas to be right and wrong based on empirical observations. This knowledge was then gathered together in books, essentially a codex, specifying what was known about science and the physical world. Popper's inclusion of the word "discovery" in the title is accordingly a key aspect of his work. That one word, *discovery*, makes all the difference. After Popper, "science" meant not only a codex of knowledge passed down through generations of scientists with experimental "proof", but an active process of the evaluation of hypotheses. Such evaluation results in *discovery* as old hypotheses are necessarily falsified in some respect and updated. Popperian science allowed for empirical science of the time to be updated without saying that something that had previously been "proven" to be correct turned out to be wrong, such as the belief that the earth is flat. Of course, that hypothesis was eventually replaced by a new and better scientific theory. For example, the hypothesis that the earth is flat came into conflict with the hypothesis that the earth is round, which itself eventually came into conflict with the hypothesis that the earth is slightly oval, and so on. Science thereby became a flexible system based on method, not the holding of certain beliefs that had been "proven" to be true.[114] This process of scientific *discovery* keeps science from getting stuck, occurs continuously, and will never end; scientific theories are thus always given as tentative.[115] Scientific inquiry in Popperian terms means the ongoing process of the testing and falsification of hypotheses in this manner.

Popper also wrote in response to a line of skeptical thought arising from the Vienna Circle at the time in relation to superstition; Viennese scholars began to realize it was both possible and valid (based on the scientific methodology of the day) to present empirical evidence of wild claims for which empirical evidence was available, such as the origins of mysterious creaks and groans in old buildings. This was at the time an extraordinarily serious challenge to empirical science. A more recent example is the report by a former first family that the White House is haunted. That is, when we hear creaks and groans in an old wooden house, this comprises empirical evidence of ghosts; in the lack of any other *theory*, we attribute this to ghosts. A necessary feature of science is, thus, to both say what it includes, and what it excludes. Popper resolved this problem by the focus on the potential for falsification of hypotheses rather than the confirmation of hypothesis. In general terms, superstition can be distinguished from science in that the results cannot be replicated by other scientists who observe the ghosts.[116] This is not to say the initial creaks and groans did not occur in a suspicious manner; rather, the point is merely that the observations are not replicable and, thus, not predictive or useful to others in describing causation.

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[114] Lindley at 186 ("The central idea in our understanding of science, and one that affects our whole attitude to the subject, is that The unity of all science consists alone in its method, not in its material."

[115] Popper at 25 ("Whatever may be our eventual answer to the question of the empirical basis, one thing must be clear: if we adhere to our demand that scientific statements must be objective, then those statements which belong to the empirical basis of science must also be objective, i.e. inter-subjectively testable. Yet inter-subjective testability always implies that, from the statements which are to be tested, other testable statements can be deduced. Thus if the basic statements in their turn are to be inter-subjectively testable, there can be no ultimate statements in science.").

[116] Lindley at 197 ("Bearing in mind the distinction between probability and likelihood, what is wanted are data that are highly likely when the theory is true, and unlikely when false. A good theory cries out with good testing possibilities. There are theories that lack possible tests. For example, reincarnation, which asserts that the soul, on the death of one animal, passes into the birth of another. I cannot think of any way of testing this, even if we remove the notion of soul and think of one animal becoming another. The question that we have met before, 'How do you know that?', becomes relevant again.").

The extraordinary problem is that forensic science seems to be premised on a different conception of scientific inquiry than that described by Popper. Forensic science is largely an empirical approach. It usually corresponds to the Baconian view of science taken from the seventeenth and eighteenth century and can be understood as a creature of that earlier time period. Under this approach, scientific hypotheses are thought to arise through observations alone. The role of theory in science is thus minimized. Since scientific observations are made exclusively by scientists, the role of the scientist is also to mediate science to the general public.[117] This mediation process looks like what an expert witness does in the course of a criminal trial. Likewise, description of "science" within leading probability theory texts seem to describe a Baconian version of science, where theory arises from observation, rather than a modern version of science where observation arises from theory.[118]

In many cases, the differences in scientific methodology between the centuries should not be expected to have any practical effect.[119] At the margin, however, the differences between seventeenth or eighteenth and twentieth century "science" does matter, and the differences can be significant, especially as to legal proceedings. The use of remote probabilistic claims derived from DNA evidence is an example where an eighteenth-century scientist could reach a different conclusion than a twentieth century scientist. Under a more modernized understanding, forensic "science" could be understood as the attempt to falsify a series of hypotheses and counter-hypotheses at issue in the case. Forensic "science" would then not mean "science" as it was understood in historical periods, namely the gathering and systemization of empirical observations to comprise observable "facts" derived from forensic science. Facts are understood in Popperian science as a function of theory and not independent from theory. Accordingly, forensic science would entail the use of forensic investigation to (i) generate a hypothesis of causation (such as a timeline of events surrounding the crime), and/or to (ii) challenge or falsify the hypothesis of causation advanced by the opposing party.

5. The Trial Lawyer's Insistence on a "Theory of the Case"

A primary factor distinguishing pre-modern versions of science from modern science, is the preeminence of theory in practice. This preeminence of theory constitutes the second reason the distinguished Professor Leiter is wrong in concluding that Popper and the philosophy of science is not relevant to expert

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[117] An intriguing explanation for the growing interest in forensic "science" reflected in television programs and documentaries on the topic is a lay understanding of science as simply the use of advanced technology to solve crimes. This understanding perhaps relates all the way back to the Sherlock Holmes novels of Ian Fleming. And, since juries are comprised of laypersons, it is potentially important to understand how laypersons understand science or scientific inquiry. The best historical examples in the context of forensic science are of course fingerprinting and the invention of DNA replication technology. The idea of science as technology reflects a view of science taken from the eighteenth century, when for example, telescopes were state-of-the-art and only available to scientists.

[118] *See e.g.* Lindley at 189 ("A simplified version of the scientific method notes three phases. First, the accumulation of data either in the field or in the laboratory; second, the development of theories based on the data; and third, use of the theories to predict and control features of our world."); *Id.* at 193 ("Next, by a process that need not concern us here because it hardly has anything to do with uncertainty, a theory is developed, not by experimentation or observation, but by thought. In this process, the scientist considers the data, tries to find patterns in it, sorts it into groups, discarding some, accepting others; generally manipulating data so that some order becomes apparent from the chaos. This is the ''Eureka!'' phase where bright ideas are born out of a flash of inspiration, Most flashes turn out, next day, to be wrong and the idea has to be abandoned but a few persist, often undergoing substantial modification and ultimately emerge as a theory that works for the original set of data. This theory goes out into the world and is tested against further data.").

[119] Lindley at 196 ("In practice, the distinction between logical truth and scientific truth does not matter, only occasionally, as with Mercury, does it become significant.")

testimony in legal proceedings. The practice of forensic science is thought to produce independent "fact", rather than "facts" relating to an underlying scientific theory. That is, in Baconian or pre-modern science, scientists set out to essentially discover or reveal "facts" about the world. Popper argued that "facts" were a function of theory. So, in order for a scientist to gather "facts," there must be a "theory" to which those "facts" are somehow relevant to or relate.

The practice of criminal law itself does resemble scientific inquiry in this crucial aspect of Popper's writing - the preeminence of theory in practice.[120] For example, the post-conviction lawyer, Kathleen Zellner, in her now famous post-conviction defense of the convicted murderer Steven Avery, said the following:

> I need to do two things. First, I need to challenge the theory of the prosecution. Then, I need to create an alternate theory of the case.[121]

Popper made a similar point in respect of scientific inquiry. Popper wrote:

> [T]he theoretician must long before [experimentation] have done his work, or at least what is the most important part of his work: he must have formulated his question as sharply as possible. Thus it is he who shows the experimenter the way. But even the experimenter is not in the main engaged in making exact observations; his work, too, is largely of a theoretical kind. Theory dominates the experimental work from its initial planning up to the finishing touches in the laboratory.[122]

The key aspect of criminal law practice, especially in an era of forensic science, seems to be the evaluation of competing *theories*. Thus, it is not merely the introduction of "facts" created by forensic scientists that comprises the practice of criminal law. Criminal lawyers are advancing theories using facts to support those theories. Interestingly, the reference to "facts" was given by the prosecuting attorney Kenneth Kratz in the Steven Avery murder case directly in response to Zellner.[123] Kratz holds that "facts" can be used to establish Avery's guilt, reflecting a pre-modern view of scientific inquiry; Zellner holds that the relevance of "facts" change depending on the theory one holds about the case, reflecting a modern view of scientific inquiry consistent with Popper. The Zellner/Kratz interaction illustrates the key relevance of the theory of science to the actual *practice* of criminal law.

The importance of the philosophy of science based on competing theories to criminal law is increasingly emphasized as methods of forensic investigation have expanded. To a forensic scientist applying a Baconian method of science, a "theory of the case" might be seen as unnecessary because facts are taken as independent of theory. Therefore, it is very possible to imagine criminal law as merely the evaluation of forensic evidence derived solely from forensic scientists, perhaps without lawyers. The idea might be to exclude lawyers from the process of the introduction of facts premised on forensic evidence in criminal cases. Of course, this will not work in actual practice for the reasons described by Popper, and that is because lawyers mediate the evidence by advancing alternate "theories of the case" just as Zellner

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[120] Scientists often disagree in a manner similar to legal contexts. See Lindley at 9 "The repeatability aspect of science, with its consequent removal of almost all uncertainty, often leads people to think that all science is objective, as it virtually is after there has been a lot of confirmatory repetition, but active science is full of uncertainty, as healthy disagreement between scientists testifies.").

[121] Making a Murderer, Episode 3, Minute 7:37.

[122] Popper at 90.

[123] Making a Murderer, Episode 10, Minute 39.55 ("[S]peculation, conjecture are not going to decide this case, facts will decide the case.").

described.[124]

c. Non-Forensics-Based Probabilistic Odds

Bayesian statistical methods as now applied as part of forensic analyses criminal proceedings are also subject to criticism because they "prove" too much. That is, Bayesian methods could be used much more broadly in criminal cases. This is to say that probabilistic odds claim can be distilled about the likelihood of the random occurrence of two events in many situations. If I am at all correct that probabilistic odds claims are subjective, then it would be possible to prove almost anything using this method.

Probabilistic odds claims currently originate almost exclusively with forensic investigation. However, other types of non-forensic evidence could be used to generate probabilistic odds claims with similar degrees of reliability to forensic evidence. As an illustration, in the infamous second murder trial of Steven Avery, Avery was convicted of murder with the use of forensic DNA evidence.[125] However, *non*-forensic evidence was also introduced at trial that Avery had purchased handcuffs and chains not long after his exoneration for the first rape conviction and subsequent release from prison after serving 20 years.[126] Avery's alleged murder victim, Theresa Halbach, then disappeared (and her cell phone went silent) minutes after meeting with Avery at his residence.[127] The handcuffs and chains were subsequently recovered in Avery's residence. A confession was obtained from a minor that handcuffs were used to restrain Halbach prior to her murder (although that confession was subsequently challenged and was not offered as evidence in Avery's trial).[128] The relevance of the Avery example is that the purchase of handcuffs and chains followed shortly thereafter by the disappearance of a murder victim at the defendant's residence is an *extraordinary* anomaly that could be treated statistically.[129]

The likelihood of the random occurrence of the two events in the Avery murder case as described in the prior paragraph could also be distilled to a probabilistic odds claim. This calculation would involve gathering statistics for the locality including the number of handcuffs sold, the number of persons, the number of missing murder victims, and an estimate of the number of meetings between persons over a period of time. The remoteness of the handcuff and murder victim meeting anomaly in the Avery case, when reduced to a probabilistic odds claim, is presumptively so unusual that it is similar by degree to the possibility of a random "match" between DNA samples taken from two different persons.

Furthermore, when such non-forensic testimony is introduced as evidence and *not* distilled to a probabilistic odds claim, the jury is left to make an uninformed guess as to whether random events might explain otherwise seemingly incriminatory coincidences; of course, the proper use of this sort of evidence is the justification given for testimony by expert witnesses generally.[130] There are many situations where

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[124] Zellner then goes on to describe evidentiary disputes in criminal law practice citing the potential for "negative evidence". Making a Murderer, Episode 3, 39:33

[125] Notably, much of that forensic evidence has been cast into serious doubt on post-conviction motions. Zellner's post-conviction motions suggest that blood evidence and the victim's car may have been planted by the police on the Avery property.

[126] Add Cite

[127] Add Cite

[128] Add Cite

[129] The resulting figure would not be certain due to a secondary inference as described above, and since other explanations could of course be gathered to explain the perceived anomaly. But these problems also exist in similar calculation even in respect of DNA "matches" ubiquitous to the criminal law.

[130] *See* Scott Brewer, *Scientific Expert Testimony and Intellectual Due Process*, 107 YALE L.J. 1535, 1564 (1998) ("[M]y chief concerns in this Article, those of institutional competence and justified epistemic deference-whether courts,

the jury members might disagree about the probative value of this type of evidence, such as a defendant's purchase of handcuffs and chains. Some jury members may find handcuffs and chains innocuous in daily life, others not, and Bayesian inferences may be helpful in these types of matters.

In order to maintain a trial system by laypersons, there must be inherit limits, albeit arbitrary limits, within the legal system as to when an expert witness can give testimony about his or her beliefs.[131] It is possible to imagine a future legal system where lay jurors are replaced by experts, or even computers. For the reasons stated in this article, this ideal would require a less subjective (or even non-adversarial) approach to criminal investigation, however.

Conclusion

Forensic investigation follows an adversarial legal process and not an objective process more characteristic of scientific inquiry. In scientific papers, as opposed to courtrooms, probability odds claims are rarely advanced. When probabilistic odds claims are advanced, such claims are viewed with extreme skepticism by other scientists. Perhaps the quintessential example of such skepticism occurred with econometric modeling, where the Federal Reserve has found the results of nearly all published econometric studies are not replicable.[132] As a matter of Bayesian science, statistical *propositions* relating to a non-existential universe, dataset, or model, are always subjective, and do not become objective by presenting them separately an odds claim distinct from a "match" claim.[133] Subjectivity can often be reduced in probabilistic odds claims with disclosure.[134]

In the situation where a forensic expert remains silent about the subjectivity in the results on direct examination, then the results are not replicable and may appear implausible to others on review, and may actually be implausible in some cases. A comprehensive disclosure of all possible sources of subjectivity in forensic analysis, such as repeated trials, inconclusive results, alternative theories, and so on, should be considered mandatory in any situation where a probabilistic odds claim is presented in the course of a criminal proceeding. The *Brady* standard of disclosure only of exculpatory evidence does not correspond to the scientific standard of disclosure. Because cross-examination of non-existential beliefs, such as probabilistic odds claims, is extremely difficult, implicit discounting by an expert witness without disclosure to the opposing party also does not seem like a workable methodology in legal proceedings. If a discount to a probabilistic odds claim is applied by an expert witness due to subjectivity, this should be disclosed. The potential of including explicit footnoting caveats, which Prof. Kaye referred to as "cautions",[135] in a written report of the forensic testimony seems more possible, as cross examination could then be focused directly on the footnotes. However, in criminal contexts, written reports of expert witnesses are not currently required so there is nothing to footnote.

As a final point, in criminal law proceedings, the jury is often encouraged to take the word "science" to mean that the evidence provided by the scientist is objective. However, since non-existential

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using rules of evidence, procedure, and other institutional and doctrinal devices, are competent to effect a transfer of experts' justified beliefs to judges or juries in a way that is sufficiently legitimate for legal decisionmaking.").

[131] See Federal Rules of Evidence 702.

[132] Richard G Anderson and William G Dewald "Replication and Scientific Standards in Applied Economics a Decade After the Journal of Money, Credit and Banking Project" 76(6) *Federal Reserve Bank of St Louis Review* 79, 81 (1994).

[133] *See supra*, Part I.

[134] Disclosure allows the reviewer (or opposing counsel) to understand whether assumptions were made as part of the analysis and how these were taken into account in any forensic analysis.

[135] Kaye (2010) at 1179.

probabilistic odds claims are not objective[136] and the presentation of that type of evidence should reflect that it comprises a belief of the witness and not a description of empirical fact. At minimum, probabilistic odds claims should be presented in a criminal trial as a belief statement by the expert witness such as "I believe the odds are 1-in-100-million" as opposed to "The odds were found to be 1 in-100-million using scientific methods".

[136] *Supra* Part(s) I, IV.