Advancing a paradigm shift in evaluation of forensic evidence:

The rise of forensic data science

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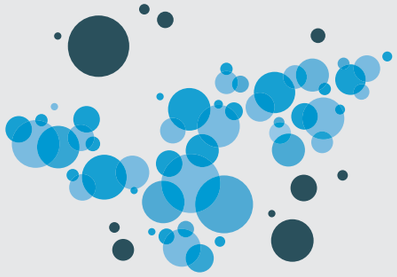

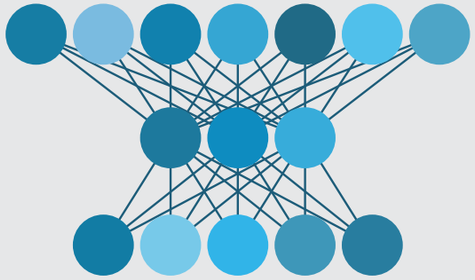

Language

- Sorry, I don’t speak Portuguese.
- This presentation will be in English, with simultaneous interpretation to Portuguese.
- If you want to speak with me later, I’m fluent in English and Spanish.

Acknowledgment

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Disclaimer

- All opinions expressed are those of the presenter and, unless explicitly stated otherwise, should not be construed as representing the policies or positions of any organizations with which the presenter is associated.

Slides and publication

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Advancing a paradigm shift in evaluation of forensic evidence: The rise of forensic data science

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ABSTRACT

Widespread practice across the majority of branches of forensic science uses analytical methods based on human perception, and interpretive methods based on subjective judgement. These methods are non-transparent and are susceptible to cognitive bias, interpretation is often logically flawed, and forensic-evaluation systems are often not empirically validated. I describe a paradigm shift in which existing methods are replaced by methods based on relevant data, quantitative measurements, and statistical models; methods that are transparent and reproducible, are intrinsically resistant to cognitive bias, use the logically correct framework for interpretation of evidence (the likelihood-ratio framework), and are empirically validated under casework conditions.

1. Introduction

The present paper is a written version of a keynote presentation given at the European Academy of Forensic Science 2022 conference. It discusses an ongoing paradigm shift in evaluation of forensic evidence. It describes:

- the current state of affairs (*status quo*)
- the new paradigm (*quo vadis?*)
- obstacles to the advancement of the paradigm shift (*impedimenta*)
- a strategy to advance the paradigm shift (*via progredi*)

2. A paradigm shift in evaluation of forensic evidence

2.1. Status quo

Curran [1]:

> Is forensic science the last bastion of resistance against statistics?
>
> UK House of Lords Science and Technology Select Committee (HoL)

[2]:

> In regard to pattern comparison methods, … "the comparison of fingerprints, toolmarks, footwear, tire marks and ballistics" [are] "spot-the-difference" techniques in which "there is little, if any, robust science involved in the analytical or comparative processes used and as a consequence there have been questions raised around the reproducibility, repeatability, accuracy and error rates of such analysis." (§155)

In forensic science, the process of *evaluation of strength of evidence* consists of: *analysis*, i.e., extraction of information from items of interest (the evidence)[1]; and *interpretation*, i.e., drawing inferences with respect to the meaning of the information extracted by the analysis. Items of interest may be, for example:

- a fingermark of questioned source recovered from a crime scene and a fingerprint collected from a known individual
- a recording of a speaker of questioned identity on an intercepted telephone call and a recording of a police interview with a speaker of known identity

Abbreviations: HoL, House of Lords Science and Technology Select Committee; PCAST, President's Council of Advisors on Science and Technology; EWG, Expert Working Group on Human Factors in Latent Print Analysis; FSR, Forensic Science Regulator for England & Wales; TRL, technology readiness level; UKRI, United Kingdom Research and Innovation.

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[1] In the forensic-inference-and-statistics literature "evidence" is the term commonly used to refer to the items of interest (i.e., the input to the analysis) or to the information output by the analysis (i.e., the input to the interpretation). Usage is somewhat fluid, but, either way, this is evidence from the perspective of the forensic practitioner. From the perspective of the court, evidence is the oral testimony or written submission of the forensic practitioner. In wider forensic-science literature, the term "trace" is often used to refer to items of interest (Roux et al. [3]).

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Contents

Status quo

Status quo

- Curran (2013):

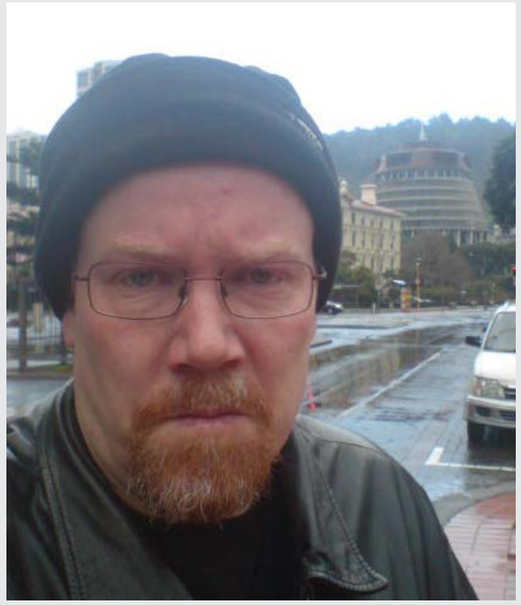
> Is forensic science the last bastion of resistance against statistics?

Status quo

- Curran (2013):

  Is forensic science the last bastion of resistance against statistics?

  Is James still grumpy?



https://www.dropbox.com/s/jnmpuqo668u2i6t/EAFS_curran.pdf?dl=0

Status quo

- UK House of Lords Science and Technology Committee (2019):

  In regard to pattern comparison methods, ...

  “the comparison of fingerprints, toolmarks, footwear, tire marks and ballistics” [are] “spot-the-difference” techniques

  in which “there is little, if any, robust science involved in the analytical or comparative processes used

  and as a consequence there have been questions raised around the reproducibility, repeatability, accuracy and error rates of such analysis.”

Status quo

- The process of **evaluation of strength of forensic evidence** consists of:

  - **analysis**

    extraction of information from items of interest (the evidence)

  - **interpretation**

    drawing inferences with respect to the meaning of the information extracted by the analysis

Status quo

- Items of interest may be, for example:
    - a **fingermark** of questioned source recovered from a crime scene and a **fingerprint** collected from a known individual
    - a **recording of a speaker** of questioned identity on an intercepted telephone call and a recording of a police interview with a speaker of known identity
    - a **fired cartridge case** recovered from a crime scene and cartridge cases fired in a forensic laboratory from a gun found in the possession of a suspected shooter

Status quo

- Forensic practitioners conduct evaluations in order to **assist legal-decision makers to make decisions with respect to questions** of legal concern such as:
  - Do the fingermark and fingerprint originate from the same finger?
  - Is the speaker of questioned identity on the intercepted recording the same as the speaker of known identity?
  - Was the cartridge case recovered from the crime scene fired from the suspect's gun?

Status quo

- Currently, across the majority of branches of forensic science, widespread practice is that:
    - **analysis** is conducted using **human perception**
    - **interpretation** is conducted using **subjective judgement**

Status quo

- Currently, across the majority of branches of forensic science, widespread practice is that:
    - **analysis** is conducted using **human perception**
    - **interpretation** is conducted using **subjective judgement**
- These methods are:
    - **not transparent**
    - **susceptible to cognitive bias**

Status quo

- Even in branches of forensic science in which analysis is conducted using instrumental measurement:

  - interpretation is commonly based on subjective judgement,
    e.g., by eyeballing graphical representations of the measured values.

Status quo

- Across the majority of branches of forensic science,

  even branches of forensic science in which interpretation is conducted using statistical models:

  - interpretation of evidence is often **logically flawed**

  - forensic-evaluation systems (the end-to-end combination of analysis and interpretation methods) are often **not empirically validated** or not adequately empirically validated

Quo vadis?

Quo vadis?

- Saks & Koehler (2005):

> we envision a **paradigm shift** in the traditional forensic identification sciences in which **untested assumptions and semi-informed guesswork** are **replaced by a sound scientific foundation and justifiable protocols**.
>
> Although obstacles exist both inside and outside forensic science, the time is ripe for the traditional forensic sciences to **replace antiquated assumptions of uniqueness and perfection with a more defensible empirical and probabilistic foundation**.

Quo vadis?

- US President's Council of Advisors on Science and Technology (PCAST, 2016):

  > neither experience, nor judgment, nor good professional practice ... can substitute for **actual evidence of foundational validity and reliability**.
  >
  > The frequency with which a particular pattern or set of features will be observed in different samples, which is an essential element in drawing conclusions, is not a matter of "judgment."
  >
  > It is an empirical matter for which **only empirical evidence is relevant**.

Quo vadis?

- US President's Council of Advisors on Science and Technology (PCAST, 2016):

  Objective methods are, in general, preferable to subjective methods.

  Analyses that depend on human judgment (...) are obviously more susceptible to human error, bias, and performance variability across examiners.

  In contrast, objective, quantified methods tend to yield greater accuracy, repeatability and reliability, including reducing variation in results among examiners.

  Subjective methods can evolve into or be replaced by objective methods.

Quo vadis?

- A **paradigm shift** in evaluation of forensic evidence in which methods based on human perception and subjective judgement are replaced by methods based on **relevant data**, **quantitative measurements**, and **statistical models**; methods that:
  - are **transparent and reproducible**;
  - are **intrinsically resistant to cognitive bias**;
  - use the **logically correct framework for interpretation of evidence** (the **likelihood-ratio framework**); and
  - are **empirically calibrated and validated under casework conditions**.

Quo vadis?

- **Transparency and reproducibility:**
    - Methods dependent on human perception and subjective judgement are intrinsically non-transparent and therefore not reproducible by others.
    - **Human introspection is often mistaken**, hence a forensic practitioner's explanation of how they reached their conclusion may not reflect how they actually reached that conclusion.

Quo vadis?

- **Transparency and reproducibility:**
    - In contrast, procedures based on data, quantitative measurement, and statistical models are transparent and reproducible.
    - **Measurement (feature-extraction) and statistical-modelling methods can be described in detail, and data and software tools can potentially be shared with others.**

Quo vadis?

- **Cognitive bias:**
  - Cognitive bias is subconscious bias, it cannot be controlled by strength of will.
  - **Forensic practitioners are susceptible to cognitive bias when making perceptual observations**:
    their degree of belief in the probability that a hypothesis is true can affect their analysis of the evidence and therefore the information that feeds into their interpretation.

Quo vadis?

- **Cognitive bias:**
  - Cognitive bias is subconscious bias, it cannot be controlled by strength of will.
  - **Forensic practitioners are susceptible to cognitive bias when they are making subjective judgements** and are exposed to information that could influence their degree of belief in the probability that a hypothesis is true but that would not logically affect the probability of obtaining the evidence conditional on whether the hypothesis were true.

Quo vadis?

- **Cognitive bias:**
  - Cognitive bias is subconscious bias, it cannot be controlled by strength of will.
  - **Systems in which the strength-of-evidence conclusion is directly the result of subjective judgement are particularly susceptible to cognitive bias.**

Quo vadis?

- **Cognitive bias:**
    - Systems based on quantitative measurements and statistical models require subjective judgements on decisions such as:
        - whether the **data used for training the system** are sufficiently representative of the relevant population for the case and sufficiently reflective of the conditions of the items of interest in the case so that the output of the system will be a meaningful answer to the question posed in the case.

Quo vadis?

- **Cognitive bias:**
    - Systems based on quantitative measurements and statistical models require subjective judgements on decisions such as:
        - whether the **data used for validating the system** are sufficiently representative of the relevant population for the case and sufficiently reflective of the conditions of the items of interest in the case so that the results of the validation will provide a meaningful indication of the performance of the systems under the conditions of the case.

Quo vadis?

- **Cognitive bias:**
  - Systems based on quantitative measurements and statistical models require subjective judgements.
  - These judgements, however, are **made at the beginning of the process** before the practitioner has analyzed the items of interest,
    hence the practitioner cannot know what effect these decisions will have on the strength-of-evidence conclusion.
  - **The remainder of the evaluation process is automated**,
    hence not susceptible to cognitive bias.

Quo vadis?

- **Likelihood-ratio framework:**
  - In current practice, interpretation of evidence is often logically flawed, e.g.:
    - it is based on the **uniqueness** or **individualization fallacy**
    - conclusions are often expressed:
      - **categorically**, e.g., “identification”, “inconclusive”, “exclusion”
      - using an **uncalibrated verbal posterior-probability scale**, e.g., “identification”, “probable identification”, “inconclusive”, “probable exclusion”, “exclusion”

Quo vadis?

- **Likelihood-ratio framework:**
  - In contrast, the likelihood-ratio framework is **advocated as the logically correct framework** for evaluation of evidence **by the vast majority of experts in forensic inference and statistics**, including:
    - Aitken et al. (2011) with 31 authors/supporters
    - Morrison et al. (2017) with 19 authors/supporters
    - Morrison, Enzinger, et al. (2021) with 20 authors/supporters

Quo vadis?

- **Likelihood-ratio framework:**
  - In contrast, the likelihood-ratio framework is **advocated as the logically correct framework** for evaluation of evidence **by key organizations**, including:
    - American Statistical Association (ASA)
    - Association of Forensic Science Providers of the United Kingdom and of the Republic of Ireland (AFSP)
    - European Network of Forensic Science Institutes (ENFSI)
    - Forensic Science Regulator for England & Wales (FSR)
    - National Institute of Forensic Science of the Australia New Zealand Policing Advisory Agency (NIFS)
    - Royal Statistical Society (RSS)

Quo vadis?

- **Likelihood-ratio framework:**
  - The likelihood-ratio framework requires assessment of:
    - **the probability of obtaining the evidence if one hypothesis were true**

      versus

    - **the probability of obtaining the evidence if an alternative hypothesis were true**

Quo vadis?

- **Likelihood-ratio framework:**
  - The two hypotheses must be **mutually exclusive**.
  - One hypothesis should represent the **position of the prosecution** in the case.
  - The other hypothesis should represent the **position of the defence** in the case.

Quo vadis?

- **Likelihood-ratio framework:**
    - Example:
        - The fingermark of questioned origin was deposited by a finger of a particular known individual.

          versus

        - The fingermark of questioned origin was deposited by a finger of some other individual selected at random from the relevant population.

Quo vadis?

- **Likelihood-ratio framework:**
    - In this example:
        - The **numerator** of the likelihood ratio **quantifies the *similarity*** between the mark and the print
        - The **denominator** of the likelihood ratio **quantifies the *typicality*** of the mark **with respect to the relevant population**.

Quo vadis?

- **Empirical validation:**

  - **Empirical validation under conditions reflecting those of the case** to which a forensic-evaluation system is to be applied is the **only way to know how well that system performs under the conditions of the case**.

Quo vadis?

- **Empirical validation:**

  - The need for validation under casework conditions has been emphasized by FSR (2020b), and by PCAST (2016):

    > Without appropriate estimates of accuracy, an examiner's statement that two samples are similar—or even indistinguishable—is scientifically meaningless:
    >
    > it has no probative value, and considerable potential for prejudicial impact.
    >
    > Nothing—not training, personal experience nor professional practices—can substitute for adequate empirical demonstration of accuracy.

Quo vadis?

- **Empirical validation:**
  - Over the last two decades:
    - **protocols** for **calibrating and validating** systems that output likelihood ratios have been developed,
    - including **metrics and graphics** appropriate for representing the results of such validations.
  - Morrison et al. (2021) *Consensus on validation of forensic voice comparison*

Quo vadis?

- **A paradigm shift:**
  - The most famous article heralding a paradigm shift in evaluation of forensic evidence is Saks & Koehler (2005).
  - Saks & Koehler and I describe the same paradigm shift.
  - Shift from a pre-paradigm to a paradigm stage.
  - Saks & Koehler stated that they intended “paradigm shift” as a metaphor, however, ...

REVIEW

The Coming Paradigm Shift in Forensic Identification Science

Michael J. Saks[1] and Jonathan J. Koehler[2]

Converging legal and scientific forces are pushing the traditional forensic identification sciences toward fundamental change. The assumption of discernible uniqueness that resides at the core of these fields is weakened by evidence of errors in proficiency testing and in actual cases. Changes in the law pertaining to the admissibility of expert evidence in court, together with the emergence of DNA typing as a model for a scientifically defensible approach to questions of shared identity, are driving the older forensic sciences toward a new scientific paradigm.

Little more than a decade ago, forensic individualization scientists compared pairs of marks (handwriting, fingerprints, tool marks, hair, tire marks, bite marks, etc.), intuited whether the marks matched, and testified in court that whoever or whatever made one made the other. Courts almost never excluded the testimony. Cross-examination rarely questioned the foundations of the asserted expertise or the basis of the analyst's certainty.

Today, that once-complacent corner of the law and science interface has begun to unravel—or at least to regroup. The news carries reports of erroneous forensic identifications of hair, bullets, handwriting, footprints, bite marks, and even venerated fingerprints. Scientists have begun to question the core assumptions of numerous forensic sciences (*1*–*6*). Federal funding has materialized to support research that examines long-asserted but unproven claims. Courts have started taking challenges to asserted forensic science expertise seriously (*1*). A dispassionate scientist or judge reviewing the current state of the traditional forensic sciences would likely regard their claims as plausible, underresearched, and oversold.

The traditional forensic individualization sciences rest on a central assumption: that two indistinguishable marks must have been produced by a single object. Traditional forensic scientists seek to link crime scene evidence to a single person or object "to the exclusion of all others in the world" (*7*, *8*). They do so by leaning on the assumption of discernible uniqueness. According to this assumption, markings produced by different people or objects are observably different. Thus, when a pair of markings is not observably different, criminalists conclude that the marks were made by the same person or object.

Although lacking theoretical or empirical foundations, the assumption of discernible uniqueness offers important practical benefits to the traditional forensic sciences. It enables forensic scientists to draw bold, definitive conclusions that can make or break cases. It excuses the forensic sciences from developing measures of object attributes, collecting population data on the frequencies of variations in those attributes, testing attribute independence, or calculating and explaining the probability that different objects share a common set of observable attributes. Without the discernible uniqueness assumption, far more scientific work would be needed, and criminalists would need to offer more tempered opinions in court.

Legal and scientific forces are converging to drive an emerging skepticism about the claims of the traditional forensic individualization sciences. As a result, these sciences are moving toward a new scientific paradigm. [We use the notion of paradigm shift not as a literal application of Thomas Kuhn's concept (*9*), but as a metaphor highlighting the transformation involved in moving from a pre-science to an empirically grounded science.] Two such forces are outgrowths of DNA typing: the discovery of erroneous convictions and a model for a scientifically sound identification science. A third force is the momentous change in the legal admissibility standards for expert testimony. A final force grows from studies of error rates across the forensic sciences.

Fig. 1. Factors associated with wrongful conviction in 86 DNA exoneration cases, based on case analysis data provided by the Innocence Project, Cardozo School of Law (New York, NY), and computed by us. Percentages exceed 100% because more than one factor was found in many cases. Red bars indicate factors related to forensic science.

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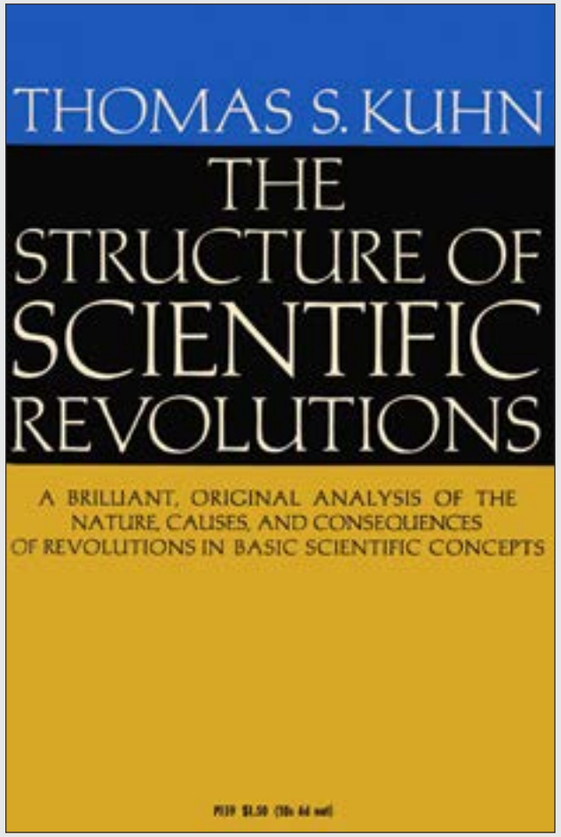
Quo vadis?

- **A paradigm shift:**
  - I view the paradigm shift in evaluation of forensic evidence as a true **Kuhnian paradigm shift** (Kuhn, 1962) that **requires**:
    - **rejection of existing methods** and the **ways of thinking** that underpin them
    - **rejection of the idea that progress can be made by incremental improvements** to existing methods
    - **the wholesale adoption of an entire constellation of new methods and new ways of thinking**



Impedimenta

Impedimenta

- The paradigm shift in evaluation of forensic evidence is ongoing, but progress is slow or stalling for the following reasons:

- **The new paradigm has only been adopted in a few branches of forensic sciences, and only by a minority of researchers and practitioners.**

  - DNA

  - forensic voice comparison

Impedimenta

- **Only some elements of the new paradigm have been adopted as part of incremental change.**
  - Kuhn (1962):

    Just because it is a transition between incommensurables, the transition between competing paradigms cannot be made a step at a time, ...

    Like the gestalt switch, it must occur all at once (...) or not at all.

Impedimenta

- **There is misunderstanding of the new paradigm and resistance to its adoption.**
    - There is misunderstanding among both forensic practitioners and lawyers.
    - There are many examples of legal rulings in which judges have misunderstood the meaning of a likelihood ratio or have not understood empirical validation and its importance.
    - The cultures of some branches of forensic science seem to be especially resistant to the adoption of statistical-model-based methods and of validation.

Impedimenta

- **There is misunderstanding of the new paradigm and resistance to its adoption.**
  - Practitioners in multiple branches of forensic science often:
    - claim that training and experience provide sufficient warrant for their conclusions
    - deny or obfuscate about the need for validation
    - propose lax validation protocols that do not require meaningful demonstration of performance under casework conditions

Impedimenta

- **Research is often not informed by practice and has no impact on practice.**
  - Margot (2011):

    Research in forensic science is sorely needed, but it should address primarily forensic science questions—not questions relating to the application of chemistry, biology, statistics, or psychology.

  - Roux & Weyermann (2021):

    it is critical that researchers and funding bodies understand the importance of conducting research that is informed by practice and can be translated into practical applications

Impedimenta

- **It is difficult to obtain funding for evidential-forensic-science research.**
    - When dedicated forensic-science funding is available, it is most often directed toward:
        - investigative applications
        - high technology readiness

Impedimenta

- **It is difficult to obtain funding for evidential-forensic-science research.**

  - Roux et al. (2021):

    > technology-oriented development ... often overrul[es] the importance of appropriate scientific reasoning to solve actual problems

Impedimenta

- **It is difficult to obtain funding for evidential-forensic-science research.**

  - Bell et al. (2018):

    > The larger scientific community must now come to the aid of our forensic colleagues in advocating both for:
    >
    > (i) the research and financial support that is so clearly needed to advance the field and
    >
    > (ii) the requirement for empirical testing that is so clearly needed to advance the cause of justice.

Impedimenta

- **It is difficult to obtain funding for evidential-forensic-science research.**

  - Bell et al. (2018):

    Forensic scientists have long complained that their work is not always valued by their scientific colleagues because of its applied nature;

    it is time for the scientific community to move beyond that conceit.

Impedimenta

- **It is difficult to obtain funding for evidential-forensic-science research.**

    - House of Lords (2019) recommended that UK Research & Innovation:

        urgently and substantially increase the amount of dedicated funding allocated to forensic science

Impedimenta

- **There are genuine practical impediments to implementing the new paradigm.**
    - Even if practitioners want to adopt the new paradigm, they will be unable to do so unless they are provided with:
        - quantitative-measurement and statistical-modelling/machine-learning tools and case-relevant data necessary for calculating likelihood ratios and for validating system performance
        - training on understanding the new paradigm and on how to implement it in casework

Via progredi

Via progredi

- Kuhn (1962):

> The transfer of allegiance from paradigm to paradigm is a conversion experience that cannot be forced. ...
>
> a generation is sometimes required to effect the change ...
>
> Conversions will occur a few at a time until, after the last holdouts have died, the whole profession will again be practicing under a single, but now a different, paradigm.

Via progredi

- My **strategy** is to **work with researchers and practitioners who want to adopt the new paradigm**, to work with them on **addressing practical impediments** to applying the new paradigm in casework:

  - to provide researchers, practitioners, and lawyers with training leading to understanding of the new paradigm

  - to collaborate with researchers and practitioners on building relevant databases and on developing and validating statistical models / machine-learning algorithms applicable in their particular branches of forensic science

Via progredi

- My **strategy** is to **work with researchers and practitioners who want to adopt the new paradigm**, to work with them on **addressing practical impediments** to applying the new paradigm in casework:

  - to conduct research on how to present likelihood ratios and validation results so as to maximize understanding by individual laypersons and by groups of collaborating laypersons,
    and thereby provide guidance to forensic practitioners on how to communicate forensic-evaluation results to judges and juries

Via progredi

- My **strategy** is to **work with researchers and practitioners who want to adopt the new paradigm**, to work with them on **addressing practical impediments** to applying the new paradigm in casework:
  - build on knowledge gained from the experience of advancing the paradigm shift in forensic voice comparison
  - including transferring and adapting statistical-modelling/machine-learning techniques, and calibration and validation procedures, used in forensic voice comparison

Via progredi

- Research areas:
  - Calibration and validation of forensic-evaluation systems
  - Forensic voice comparison
  - Fired-cartridge-case comparison
  - Forensic anthropology
  - Cell-site analysis
  - Fingerprint examination
  - Forensic comparison of facial images
  - Communication of forensic science

Via progredi

- Recommended reading:

  - Morrison G.S., Enzinger E., Hughes V., Jessen M., Meuwly D., Neumann C., Planting S., Thompson W.C., van der Vloed D., Ypma R.J.F., Zhang C., Anonymous A., Anonymous B. (2021). **Consensus on validation of forensic voice comparison**. *Science & Justice*, 61, 229–309. https://doi.org/10.1016/j.scijus.2021.02.002

  - Weber P., Enzinger E., Labrador B., Lozano-Díez A., Ramos D., González-Rodríguez J., Morrison G.S. (2022). **Validation of the alpha version of the E^3 Forensic Speech Science System (E^{3}FS^3) core software tools**. *Forensic Science International: Synergy*, 4, 100223. https://doi.org/10.1016/j.fsisyn.2022.100223

Via progredi

- Recommended reading:

  - Morrison G.S., Weber P., Basu N., Puch-Solis R., Randolph-Quinney P.S. (2021). **Calculation of likelihood ratios for inference of biological sex from human skeletal remains**. *Forensic Science International: Synergy*, 3, 100202. https://doi.org/10.1016/j.fsisyn.2021.100202

  - Basu N., Bolton-King R.S., Morrison G.S. (2022). **Forensic comparison of fired cartridge cases: Feature-extraction methods for feature-based calculation of likelihood ratios**. *Forensic Science International: Synergy*, 5, 100272. https://doi.org/10.1016/j.fsisyn.2022.100272

Via progredi

- Recommended reading:

  - Swofford H., Champod C. (2021). **Implementation of algorithms in pattern & impression evidence: A responsible and practical roadmap**. *Forensic Science International: Synergy*, 3, 100142. https://doi.org/10.1016/j.fsisyn.2021.100142

  - Kuhn T.S. (1970). ***The Structure of Scientific Revolutions*** (2nd Ed.). Chicago IL: University of Chicago Press.

Conclusion

Conclusion

- A Kuhnian paradigm shift requires:
    - rejection of existing methods and the ways of thinking that underpin them
    - rejection of the idea that progress can be made by incremental improvements to existing methods
    - the wholesale adoption of an entire constellation of new methods and new ways of thinking

Conclusion

- New paradigm:
  - transparent and reproducible
  - intrinsically resistant to cognitive bias
  - logically correct framework for interpretation of evidence,
    the likelihood-ratio framework
  - empirical calibration and validation under casework conditions

Conclusion

- New paradigm methods:
    - relevant data
    - quantitative measurements
    - statistical models / machine-learning algorithms

Conclusion

- Proposed names for the new paradigm:
    - forensic data science
    - forensic science

Thank You