The Sources of Probabilistic Thinking in Forensic Science

Motto: *„In mathematics, one does not understand things but gets used to them."*
John von Neumann

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Abstract

The paper provides a historical introduction to the sources of probabilistic thinking including Bayesian Methods in forensic science. Starting form Aristotle and through the ages of Bayes the key figure of founding the contemporary probabilistic methodology used everywhere in different sciences. In forensic science substantial for DNA and fingerprint analysis. The Bayesian Networks will be important to the evidence evaluation and taken into consideration as a tool for the future forensic scientists. Some samples of miscarriage of justice caused by improper usage of probabilistic approach are given providing variety of viewpoints to the readers.

Key words: *Probability, Bayesian methods, Forensic Sciences.*

1. The origins of probabilistic thinking

Making sense of information in probabilistic terms must have originated with the dawn of human cognition. The probability, or in other words the credibility and relevance – or degree of exclusion –, of a special kind of information, criminal evidence, is the basis of legal judgement, the culmination of the criminological process. In this process, the results of the enquiry and the possible consequences of decisions require further decisions to be made, which can be conceived of as a game between the decision maker and the party on the opposite side. The party on the opposite side may be a real entity, such as the defendant, the witness, nature, or a fictive one, such as political interest, for example. It is easy to realize that game theory, which provides a mathematical framework for understanding the dynamics of such processes, is of far greater significance than its name suggests, and it constitutes an important part of a scientifically informed strategy construction in legal decision making. While taking into account multiple uncertain factors simultaneously, strategies in military or criminal investigation aim to provide a course of action for – and subsequently enhance the decision making of – the relevant lead investigator. Experience, quick recognition of connections, and intuition significantly improve the appropriateness of the decision maker's judgement. The degree of success of the decision making process can be enhanced by the application of probabilistic networks, or, in other words, Bayesian networks: the simultaneous utilization of probability theory, combinatorics, game

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theory, decision theory, graph theory and artificial intelligence[2], which may speed up the formation of verdicts substantially. Apart from enabling the kind of fast acting that is required in fresh pursuit, it has the additional advantage of reducing the possibility of error even in the case of an exceptional decision maker. The evolution and intertwining of the contributing disciplines listed above accounts for the current scientifically buttressed basis for sound decision making.

The conceptual framework of probability theory was developed as a response to problems in games of chance. By insisting on proofs as a way of arriving at judgements, human thinking favoured categorical decisions over probabilistic ones, to the extent that the word "perhaps" was frequently subject to scorn.[3] In the darker days of the history of criminal justice, proof – at times acquired even by means of torture – merely served the purpose of supporting the case for the guilty verdict, foreclosing the possibility of exculpation.[4] On Aristotle's account, the fundamental principles of proof include the notion that everything has to be either stated or denied and that "it is impossible for anyone to suppose that the same thing is and is not."[5] "Nor can be any intermediate between contrary statements, but of one thing we must either assert or deny one thing."[6] According to Brakel (1976) and Schneider (1980) Aristotle divided events into three classes: 1) those that are certain to occur, 2) those that occur reliably in most cases, 3) and those that occur occasionally and unpredictably. Regarding the etymology of the term "probability", Cicero is credited with the first use of the Latin word *probabilis*, which subsequently became established in similar forms in English and the neo-Latin languages after the 17th century. Prior to that, the near-synonymous word "chance" had been in use in the English speaking world. The term "likelihood" became widespread in the 20th century, and it took root in Hungarian, as well.

At the dawn of the development of Roman law, the experiences and dilemmas encountered in the evidentiary process of legal disputes led to the emergence of financial-legal categories and principles.[7] The phrases *fecisse videtur* and *fecisse non videtur* ("it seems that") appearing in the sentence constructions of extant Roman judgements suggest that the distinction between the objective truth and the version of the truth that emerges in the course of a lawsuit is not a recent invention.[8] However, the use of the mutual corroborative or weakening force of non-definitive evidence was possible only in private lawsuits and even there, only with certain restrictions. In criminal cases, only the use of definitive evidence was allowed. As the Roman emperor Gratian put it in 382, evidence has to be unequivocal and as clear as day. In Bartolus, some traces of the probabilistic process approach to proof can be discerned in that the judge's initial absolute lack of knowledge (*nesciencia*) is replaced by a conception of the

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[2] The approach according to which artificial intelligence involves all the previous ones is also reasonable.

[3] This is well illustrated by a humorous Hungarian folk saying, according to which the difference between politicians, women and men is that for the latter, the use of the word *talán* ("perhaps") is forbidden, while for the latter two, it is a requirement.

[4] Torture was abolished in Hungary by clause XLII of 1791.

[5] Aristotle, *Met.*, IV 1005b 24.

[6] Aristotle, *Met.*, IV 1011b 25.

[7] A Bessenyő: *Római magánjog I. A római magánjog az európai gondolkodás történetében* [Roman Private Law I. Roman Private Law in the History of European Thought] (Dialóg Campus 2003) 133.

[8] T Nótári: *Római jog* [Roman Law] (Lectum Kiadó 2014) 304.

events open to doubt (*dubitatio*) on the basis of the testimony of the opposing parties. Proof served the purpose of resolving the tension between the unlikely, the uncertain, the probable and the definite. The first effects of proof result in the judge's forming a suspicion (*suspicatio*), which then solidifies into stronger and stronger – if not indubitable – opinion (*opinio*) in the light of stronger and stronger arguments. With the presumption of full-fledged certainty (*perfecta probatio*), the judge arrives at the judgement with a sense of perfect conviction (*perfecta credulitas*).[9] The sense of unease felt in connection with the application of non-definitive evidence is well demonstrated by the *in dubio pro reo* principle that is still in use today. That is why the acquisition of the defendant's confession was deemed so important, because it rendered the decision definitive. Opportunities for the elimination of doubt were seen in oath, torture as well as in the attainment of different sorts of divine evidence.

St Thomas Aquinas drew a threefold distinction between certain knowledge, probabilistic knowledge and chance.[10]

According to Hald, two early conceptions of probability are the objective, statistical or aleatory probability on the one hand, which was held to provide the outcome of experiments or games, and subjective, personal or epistemic probability on the other hand, which is a measure of the degree of belief and is not necessarily based on statistical evidence.[11] Hald's historical overview is primarily concerned with objective probability, which was previously referred to as "chance". As he points out, James Bernoulli was the first to distinguish unambiguously between the two kinds of probability.[12] Hasover and Rabinovich provides Talmudic and rabbinic examples.[13] Ian Hacking gives a clear articulation of the modern dual understanding of probability in his seminal 1975 book, *The Emergence of Probability*.

2. Probability research until the end of the 19th century

Doubt can be understood as a sign indicating a lack of perfect certainty, or, in other words, the presence of uncertainty, which can be rendered measurable most appropriately by the application of mathematical probability. The evaluation of evidence and the subsequent – especially legal – decision provide a basis for the exploration of the mutual relationships between mathematics and the law, which is why the development of the two disciplines will be discussed in tandem.

2.1. From the Pascal-Fermat correspondence to the Bernoullis

Relatively late, in the 17th century, scientific progress began to take off spectacularly partly due to the influence of empiricism and rationalism characterizing the

[9] F Benedek, 'Jogtörténeti adalékok a bizonyosság és valószínűség problémájához' [Addenda from legal history to the problem of certainty and probability] In: L Vargha (ed), *A valószínűség szerepe az igazságszolgáltatásban* [The Role of Probability in Legal Justice] (Conference volume Pécs 1979) 4.

[10] A Hald, *A History of Probability and Statistics and Their Applications before 1750* (Wiley 2003) 30.

[11] *Ibid*. 28–29.

[12] *Ibid*.

[13] AM Hasover, 'Random mechanisms in Talmudic literature' (1967) 54 Biometrika 316; NL Rabinovitch, 'Combinations and probability in rabbinic literature' (1970) 57 Biometrika 203.

Enlightenment. It was around that time that the correspondence between Pascal and Fermat – so frequently quoted in the literature on probability theory – began. Fermat was a lawyer by profession and a mathematics enthusiast.[14] The correspondence concerns a problem in a game of chance originally posed in mediaeval times and rediscovered by Chevalier de Méré. The two scientists reached the solution by 1654, which is also the year to which the birth of probability theory is dated on account of Pascal's letter to the academy in Paris in which he expressed his intention of constructing a mathematics of chance.[15]

The simultaneous treatment of the two seemingly disparate disciplines is not a modern invention as indicated by the title – *De Usu Artis Conjectandi in Jure* – of the doctoral dissertation of Nicolaus Bernoulli, a member of the famous Bernoulli dynasty[16], which he submitted on 14 June 1709 in Basel and concerns the theory of probability.[17] Nicolaus also published a book written by his uncle Jakob after the latter's death titled *Ars Conjectandi* ("The Art of Conjecturing"), which introduces the concept of the law of large numbers. This bears some emphasis because the principles of probability formulated in this work are only valid in cases in which the number of events considered is sufficiently large.

2.2. Thomas Bayes

The Huguenot Abraham de Moivre transported the doctrines from continental Europe to England in 1718 when escaping persecution thanks to the publication his textbook, *The Doctrine of Chances*. Given the similarity of the titles[18], it is reasonable to assume that Thomas Bayes was one those numerous British mathematicians who were influenced by de Moivre's work. The biographical data of Bayes paint an interesting picture. Due to the close relationship between Bayes and the present subject, I believe it is important not to restrict the mention of the main events of his life to a footnote. Thomas Bayes was born in 1702[19] in Hertfordshire. At 18 years of age, he takes up the intriguing combination of Theology and Logic at the University of Edinburgh. He returns to his birthplace three years later to assist his father in tending to the life of the nonconformist congregation of his father. Later, in 1734, he moves to Tunbridge Wells where he holds the position of minister of the Mount Sion chapel. In 1742, he is elected to be a fellow of the Royal Society, but we can only speculate as to the nature of the work warranting his admission. A few years later, he retires from chaplaincy on account of his illness, and in 1761, he passes away. The beginning of the resurrection of his spirit can be dated to 10 November 1763, when Richard Price, a Welsh philosopher of

[14] *Ibid.* 43.

[15] M Sain, *Nincs királyi út! Matematikatörténet* [There is No Royal Path! A History of Mathematics] (Gondolat 1986).

[16] It is rightly regarded as remarkable that the Huguenot Bernoulli family enhanced Basel's reputation by producing eight famous natural scientists. That is the reason why it makes sense to always mention the first name when referencing the work of one of the members of the dynasty.

[17] N Bernoulli, *De Usu Artis Conjectandi in Jure* (Basel 1709). Reprinted in *Die Werke von Jakob Bernoulli, Vol 3* (Birkhiiuser 1975) 287–326. Translated into English by T Drucker (unpublished 1976).

[18] Cf. Bayes's 'An Essay towards solving a Problem in the Doctrine of Chances'.

[19] Due to a lack of birth records, his date of birth is questionable. On the basis of indirect evidence, some date it to 1701, while others to 1702.

considerable influence[20], sends his essay[21] found among his documents to John Canton with the personal recommendation that he regards Bayes' essay as a piece of "experimental philosophy"[22] the "communication" of which to the Royal Society "cannot be improper".[23] The social connections of Price, who was socially considerably active and 20 years the junior of Bayes, made the success of the posthumous publication likely. Bayes' hardly more than twenty page long study stirred Price's imagination, and he regarded it as containing the mathematical proof of God's existence.

In his short essay, Bayes constructed one of the most important theorems of probability theory, the Bayes theorem. By means of his letter of recommendation referred to above, in which he emphasized the importance of the topic, Price made possible the publication of the document that proved to be the foundation of what subsequently became known as Bayesian statistics.

2.3. The treatment of probability after Bayes until the 19th century

Until the 18th century, the theory of probability was referred to as the *doctrine of chances* in the English speaking world, and it remained dormant until as late as the middle of the 19th century. Maxwell motivated the importance of probability theory by pointing out that logic is applicable only in those things that are certain, impossible or entirely equivocal, and (fortunately!) none of those do we have to support with arguments. The logic of the real world, however, requires that the rational thinker take the degree of probability into consideration.[24]

2.4. The influence of the methods of probability theory on science in the 20th century

The importance of chance and uncertain events, and concomitantly, the importance of probability theory became fully recognized in the 20th century. Kolmogorov's tiny book published in 1933 marked the beginning of a new chapter in the history of probability theory with the conception of the foundation of frequentist probability.

Bayesian thinking can be illustrated by its deep and diversified literature, while the primacy of the simple (naïve) approach is better served by the need for acceptance and assimilation.

During World War II, the demand for radar technology in the arms industry prepared the ground for the development of a new theoretical framework. First, the need for calculating the probability of wanted signals, then the need for the probabilistic identification or friend or foe (IFF) created an immense opportunity for the evolution of applied mathematics, and especially to the detailed elaboration of the domain of

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[20] Among his numerous connections, noteworthy are his ties to some of the Founding Fathers, such as Benjamin Franklin, John Adams or Thomas Jefferson (the latter two of whom being the second and the third president of the United States of America, respectively). Honourable mentions are David Hume and Adam Smith, names that will be more than familiar to those with an interest in philosophy or economics.

[21] Subsequently published as '*An Essay towards solving a Problem in the Doctrine of Chances*. By the late Rev. Mr. Bayes, communicated by Mr. Price, in a letter to John Canton, M. A. and F. R. S.'

[22] The theory of probability was treated as the Cinderella of mathematics until as late as the beginning of the 20th century as it was regarded a dubious discipline on the border of mathematics, physics and philosophy. A Rényi, *Ars Matematica* (Typotex 2005) 167.

[23] T Bayes and R Price, 'An Essay towards Solving a Problem in the Doctrine of Chances' (1763) 53 Phil Trans R Soc 370.

[24] ET Jaynes, *Probability Theory: The Logic of Science*, BG Larry (ed) (Cambridge 2010) 3.

credible probability. In the realm of radar signal processing, complex mathematical derivations led to the appropriate interpretation of theoretical problems, which subsequently became one of the invisible pillars of the safe air transport of civilians. Certain concepts took such deep root that the notion of ROC[25] assigned to the decision logic of the radar receiver was adopted without modification in biostatistics, for example.[26] Why did one of the most avid adopter of the methodology happen to be biostatistics? Biological – and especially human biological – research concerns the study of organisms that belong to the same species but whose response characteristics can only be probabilistically described as uniform. This drew the attention of biostatistics researchers to the concept of subjective probability.

A special domain of the practical application of Bayesian subjective probability is that of Bayesian networks, the emergence of which can be derived from Wright's study of hamster reproduction published in 1921[27], and was substantially developed and refined towards the end of the 1970s with the advent of Artificial Intelligence research, to the extent that it is now of accessible benefit in terms of organizational problem solving. At the beginning, the scientist mainly responsible for the study and popularization of Bayesian networks was Judea Pearl.[28] The study and application of Bayesian networks in forensic science and criminalistics was carried out overseas and in the Far East. By way of notable examples, publications by research groups in the United States[29], Brazil[30] or Hong Kong[31] spring to mind. In 1977, Feinstein bemoaned the lack of sufficient support of biostatisticians,[32] but in 2004, David Spiegelhalter and his colleagues welcomed the favourable change that had occurred since then.[33] It is also worth mentioning a sceptical voice in connection with the approach: in criticising Spohn's paper[34], Cartwright questions whether a blanket causal interpretation of Bayesian networks is warranted, and in doing so, she also attacks Spohn's treatment of probabilities.[35]

It is appropriate at this point to mention a few relevant studies, for instance, the work on computer forensics carried out at the University of Hong Kong in which the

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[25] ROC: Receiver Operating Characteristic.

[26] L Lugosi and I Molnár, 'Orvosi diagnosztikus próbák értékelése: Bayes-tétel, ROC-görbe és Kappa-teszt alkalmazása' [The assessment of medical diagnostic trials: The application of Bayes' theorem, the ROC curve and the Kappa test] (2000) 141 *Orvosi Hetilap* 1725.

[27] S Wright, 'Systems of Mating I: The Biometric Relations between Parent and Offspring' (1921) 6 Genetics 111.

[28] J Pearl, 'Reverend Bayes on Inference Engines: a Distributed Hierarchical Approach' (1982) Proceedings, AAAI National Conference on AI, Pittsburgh 133.
http://www.ece.tamu.edu/~bjyoon/ecen689-604-fall10/Pearl_1982.pdf accessed on 20/07/2013.

[29] AB Hepler, 'Improving Forensic Identification Using Bayesian Networks and Relatedness Estimation: Allowing for Population Structure'https://www.ncjrs.gov/pdffiles1/nij/grants/231831.pdf accessed on 20/07/2013.

[30] RN Carvalho, KB Laskey, PCG Costa, M Ladeira, LL Santos, Matsumoto, 'Probabilistic Ontology and Knowledge Fusion for Procurement Fraud Detection in Brazil' http://link.springer.com/chapter/10.1007%2F978-3-642-35975-0_2#page-1 accessed on 20/07/2013.

[31] MYK Kwan, FYW Law, PKY Lai, 'Computer Forensics Using Bayesian Network: A Case Study' http://i.cs.hku.hk/cisc/forensics/papers/BayesianNetwork.pdf accessed on: 20/07/2013.

[32] AR Feinstein, 'Clinical Biostatistics XXXIX: The Haze of Bayes, the Aerial Palaces of Decision Analysis, and the Computerised Ouija Board' (1977) 21 Clinical Pharmacology and Therapeutics 482.

[33] DJ Spiegelhalter, KR Abrams, JP Myles, *Bayesian Approaches to Clinical Trials and Health-Care Evaluation* (John Wiley & Sons 2004) 3.

[34] W Spohn, 'Bayesian Nets are all there is to Causal Dependence' in MC Galavotti, P Suppes and D Costantini (eds) *Stochastic Causality* (CSLI Publications 2001) 157.

[35] N Cartwright 'What Is Wrong With Bayes Nets?' (2001) 84 The Monist 242.

researchers test hypotheses concerning the illegal file sharing (Bit-Torrent) activity of a defendant by means of a Bayesian network.[36] Another study run by Hepler and Dawid illustrates the potential of Bayesian networks in terms of dealing with paternity cases relying on population substructure-based DNA evidence.[37] Prakken and colleagues employ Bayesian networks to model crime scenarios.[38] Hepler, Dawid and Leucari demonstrate the use of Bayesian networks via the analysis of the evidence concerning the Sacco and Vanzetti murder case.[39] Interestingly, Kadane and Schum already provided a detailed Bayesian analysis of the Sacco and Vanzetti case back in 1996.[40]

As an extension of evidence-based medicine[41], an approach rooted in Bayesian philosophy, Sherman lays down the foundations of what he refers to as "evidence-based policy".

It is an indication of the reactionary nature of the judiciary that in spite of the considerable research, in 2010, the Court of Appeal in the United Kingdom ruled in connection with the R v T case that neither the Bayes theorem nor the likelihood ratio may be used for the appraisal of forensic evidence except in the special case of DNA-based investigations.[42] In their paper dedicated to the assessment of the ruling, Fenton and Neil indignantly point out that one need not understand everything about how the circuits of a calculator operate in order to be able to use it fruitfully.[43]

Already in 1982, the American Pearl alluded to the potential usefulness of Bayesian networks in judicial reasoning and referenced Schum and Martin's report concerning their research into the legal application of Bayesian networks.[44]

The method can be applied to the search for forensically interesting documents and verbal expressions on computers used by criminals as well to the continuous observation of the correspondence of monitored individuals. In their work on an information retrieval system mentioned above, de Campos and his colleagues relied on the belief network model of Ribeiro and colleagues.[45]

In many cases, the application of Bayesian networks to criminological research can already be considered a success. Boondao, who is concerned with the risk factor analysis of criminal behaviour, cites a study carried out by WSEAS which provides a Bayesian network-based overview of the nature and situation of breaches of law.[46]

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[36] MYK Kwan, FYW Law, PKY Lai, 'Computer Forensics Using Bayesian Network: A Case Study.'

[37] AB Hepler, AP Dawid, 'Incorporating Population Structure into Forensic Bayesian Networks' https://www.researchgate.net/profile/Alexander_Dawid/publication/242322970_Incorporating_population_structure_into_forensic_Bayesian_networks/links/00b7d5289f828da379000000/Incorporating-population-structure-into-forensic-Bayesian-networks.pdf accessed on 04/12/2014.

[38] H Prakken, C Vlek, B Verheij, BS Renooij, 'Modeling Crime Scenarios in a Bayesian Network' http://www.cs.uu.nl/groups/IS/archive/henry/icail13vlek.pdf accessed on 08/12/2017.

[39] AB Hepler, AP Dawid, V Leucari 'Object-Oriented Graphical Representations of Complex Patterns of Evidence' https://www.ucl.ac.uk/statistics/research/pdfs/rr275.pdf accessed on 07/12/2014

[40] JB Kadane and DA Schum, *A Probabilistic Analysis of the Sacco and Vanzetti Evidence* (John Wiley & Sons 1996).

[41] C Heneghan and D Badenoch, *Evidence-Based Medicine Toolkit* (Blackwell 2006) 81.

[42] http://www.bailii.org/ew/cases/EWCA/Crim/2010/2439.pdf accessed on 08/12/2017.

[43] N Fenton and M Neil 'On Limiting the Use of Bayes in Presenting Forensic Evidence' (2012) http://www.eecs.qmul.ac.uk/~norman/papers/likelihood_ratio.pdf accessed on 08/12/2017.

[44] Pearl, 133.

[45] LMd Campos, JM Fernández-Luna, JF Huete, C Martín and AE Romero, 'An Information Retrieval System for Parliamentary Documents' in O Pourret, P Naim and B Marcot (eds) *Bayesian Networks: A Practical Guide to Applications* (Wiley 2008).

[46] R Boondao, 'Crime risk factor analysis' in O Pourret, P Naim and B Marcot (eds) *Bayesian Networks: A Practical Guide to Applications* (Wiley 2008).

In 2000, Kaye[47] emphasized the beneficial effects of the Bayesian method in terms of decreasing the number of legal mistakes citing Professor Ronald Allen, who had warmly recommended the method to legal professionals as a support tool. The relationship between Bayesian methods and Artificial Intelligence is strong, since Bayesian networks can be improved by means of self-learning mechanisms. I wish to emphasise, however, that in many cases, the application of AI[48] should be understood as providing support rather than replacement in the work of the forensic expert.

The work of Challa and colleagues leads to areas that may prove a rich source of both theoretical and practical knowledge directly applicable in criminalistics and crime-prevention. Although their research focuses on target tracking radar technology, it provides such general, mathematically grounded, visually illustrated object tracking examples that their method, applied to CCTV footage, may be fruitfully utilized in the investigative phase of criminalistics.

2.5. The emergence of probabilistic thinking in Hungary and its relevance to forensic science

One of the first and most interesting examples of Hungarian probabilistic thinking in the 19th century appears in the work of Antrás Fáy, who collected human lifespan-related statistical information in his effort to establish the first Hungarian life insurance company. The first noteworthy Hungarian mathematician who specialised in probability theory may be Károly Jordan on the basis of his paper published in 1921.[49] In a monograph, he criticized those statisticians who intended to ignore probability theory.[50] Names such as György Pólya[51], Alfréd Rényi[52], András Prékopa[53] and László Lovász may also be mentioned. Among the Hungarian representatives of biostatistics, the name of Elek Dinya springs to mind.

In criminal acts, suspicion is related to probability, and degrees of suspicion represent degrees of probability, as was well articulated by Endre Bócz in 1962.[54]

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[47] DH Kaye, 'Bayes, Burdens, and Base Rates' (2000) 4 IJE & P 260.

[48] In my view, the concept of Artificial Intelligence does not satisfy the ordinary expectations (sometimes also reiterated in scientific circles) generated by its name. In comparison, human intelligence is constituted by the brain's – partly learned, partly individual-specific – information related assembly of complex experience manipulating capacities including recognition, recall, association, inference, decision-optimizing and decision-monitoring. Artificial Intelligence is concerned with the computational modelling of some of the listed abilities as well as with producing so-called intelligent devices bestowed with capacities faintly resembling those of humans, such as making human-like decisions or storing and recognizing information, thus producing the semblance of intelligent behaviour. However, such efforts rarely come close to replicating the original capacities. Thus, even mechanisms dedicated to problems trivial to humans such as the spellcheck system of computers can produce endearingly – or annoyingly – inaccurate suggestions, not to mention the lack of text-interpreting abilities or web-based translating tools capable of producing minimally acceptable results.

[49] K Jordan, 'A valószínűség a tudományban és az életben' [Probability in science and life] 53 Magyar Közlöny 775.

[50] K Jordan, *Matematikai statisztika* [Mathematical Statistics] (Athenaeum 1927) 13.

[51] Gy Pólya, *A Gondolkodás iskolája* [The School of Thinking] (Akkord 2000).

[52] A Rényi, *Levelek a valószínűségről* [Letters on Probability] (Akadémiai Kiadó 1969).

[53] A Prékopa, *Valószínűségelmélet műszaki alkalmazásokkal* [Probability Theory with Applications in Engineering] (Műszaki Könyvkiadó 1962) 52–59.

[54] E Bócz, 'Az alapos gyanú a büntetőeljárásban' [Probable cause in criminal action] (1962) 11 Jogtudományi Közlöny 578.

In 1964, Géza Katona authored his keynote paper concerning probabilistic expert opinion in which he suggested the comprehensive application of the probabilistic approach, including expert opinions as well as probabilistic proofs.[55] The mathematicians Mátyás Arató[56] and Imre Kertész published a study in 1966 on handwriting-recognition by means of cybernetic methods[57] in which they examined a writing sample constituting the evidence in a murder by poisoning case via comparative mathematical analysis and probabilistically identified the suspect.[58]

In his 1972 paper, Árpád Erdei summarized the research carried out in 1969 in the National Institute of Criminalistics in which he urged the legal application of cybernetic, mathematical and logical methods.[59] Providing supporting examples from the literature, he recommended thinking in terms of a process approach, which is also indispensable in the case of the application of Bayesian networks. The significance of his work lies partly in the fact that legal experts are often sceptical about the use of mathematical methods in the legal domain.

In his still timely monography, Géza Katona presented multifarious support for the proposition that the role of probabilistic thinking in criminal action is essential.[60] He offered a prescient discussion of the applicability of probability theory and mathematical logic in legal action, and provided examples of the use of biostatistics in Hungary.

The concepts of suspicion (applying to the suspect and representing different degrees of probability), and probable cause (the condition for becoming the defendant) are of crucial significance from the point of view of the commencement and subsequent course of development of criminal investigations. Árpád Erdei talked about a confusion of terms when he pointed out that "the prosecution is against the suspect, not only against the defendant", although he denied that establishing probable cause happens in an arbitrary way.[61]

In 1979, a conference featuring László Vargha was organized in Pécs with the title "The Role of Probability in Criminal Justice".[62] András Vág's discussion offered in his 1983 paper can be regarded as a foreshadowing of what later became known as a

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[55] G Katona, 'Az un. Valószínűségi szakértői vélemények értékeléséről' [Concerning so-called probabilistic expert opinions] J Gödöny and B Popovics (eds) *Kriminalisztikai Tanulmányok III* [Studies in Criminalistics III]. (Közgazdasági és Jogi Könyvkiadó 1964) 75.

[56] It is worth mentioning that Arató published numerous papers on probability theory at different universities, including some on Bayesian-type estimation applications. The Professor Emeritus of the Informatics Department of the University of Debrecen, who passed away in 2015, moved to Moscow in the 1950's with the recommendation of Alfréd Rényi to study under Kolmogorov.

[57] Nowadays, we would refer to these as "computer-based" or "computational" methods.

[58] M Arató and I Kertész, 'Kibernetikai módszerek alkalmazásának lehetőségei a kézírás vizsgálatában' [Possibilities for the application of cybernetic methods in the examination of handwritten texts] (1966) 4 Belügyi Szemle 27.

[59] Á Erdei, 'A kibernetikai, matematikai és logikai módszerek jogi alkalmazásával kapcsolatos néhány problémáról' [On a few problems concerning the application of cybernetic, mathematical and logical methods in law] in J Gödöny (ed) *Kriminológiai és kriminalisztikai tanulmányok IX* [Studies in Forensic Science and Criminalistics IX] (Közgazdasági és Jogi Könyvkiadó 1972) 241.

[60] G Katona, Büntetőítélet a jog határán [Criminal Sentence on the Boundary of Law] (Közgazdasági és Jogi Kiadó 1972) 225–312.

[61] Á Erdei, 'A nyomozás megindításának feltétele' [The condition of commencing the investigation] (1972) 8 Belügyi Szemle 50.

[62] L Vargha, *A valószínűség szerepe az igazságszolgáltatásban* [The Role of Probability in Criminal Justice] (Pécsi Tudományegyetem 1979).

Bayesian network.[63] In his framework, he made use of the correlation coefficient (which may take a positive or a negative value) that is a measure of the relationship – or mutual exclusivity – between events. On the basis of Hagan's Canadian study, he provided a sketch of the entire length of the legal procedure, from its commencement all the way to the judgement. Mueller Othmár wrote approvingly on the use of probabilistic evidence in 1986, but he placed the onus of responsibility on the judge.[64] It is important to highlight legal training in Pécs on account of its relevance to probabilistic thinking, since the University of Pécs has been the first institution in which the philosophy of Bayes is promoted both in textbooks[65] as well as in lectures. In his curriculum, Csaba Fenyvesi incorporates an emphasis on the importance of the theoretical exploration of Bayesian inference and supports the idea of its imminent practical application. He has also repeatedly expressed his views in a number of conferences. As an example of an application of Bayesian inference, the forensic dictionary of the current website of the Hungarian Institute for Forensic Sciences mentions only genetic tests.[66] The likelihood ratio is also listed, and the example used is that of genetic identification.[67]

Summary

The study provides an introduction and an overview to the history and the sources of probabilistic approaches including Bayesian Methods in forensic science from Hungarian viewpoints. Starting form Aristotle and through the ages of Bayes the key figure of the theory founder of the contemporary subjective probabilistic methodology used everywhere in different sciences. The Bayesian subjective provability in forensic science substantial for DNA and fingerprint analysis. The Bayesian Networks will be important to the multiple evidence evaluation and taken into consideration as a tool for the future forensic scientists. Some samples of miscarriage of justice caused by improper usage of probabilistic approach are given providing colorful viewpoints to the readers.

[63] A Vág, 'Matematikai módszerek a kriminológiai kutatásban' [Mathematical methods in research in forensic science] in J Gödöny (ed) *Kriminalisztikai Tanulmányok XX* [Studies in Criminalistics XX] (Közgazdasági és Jogi Könyvkiadó 1983) 253.

[64] O Mueller, 'A szakértői működésre, a szakvélemény hatósági értékelésére, valamint a szakértők díjazására vonatkozó rendelkezések' [Injunctions concerning the functioning of experts, evaluation of expert opinion by the authorities and the remuneration of experts] in Gy Molnár (ed) Az igazságügyi szakértői vizsgálatok kézikönyve [Handbook of Expert Investigation in Criminal Justice] (Közgazdasági és Jogi Kiadó 1986) 121.

[65] F Tremmel, Cs Fenyvesi and Cs Herke, *Kriminalisztika* [Criminalistics] (Dialóg-Campus 2005) 290–294.

[66] "Bayesian inference: the use of the Bayes theorem in probability theory for drawing inferences. On the basis of certain considerations, one assigns prior (a priori) probabilities to events, then, relying on the sample - as well as the Bayes theorem - other (a posteriori) probabilities can be calculated, forming the basis of the statistical inference. The method has numerous advantages, however, in practice, it is rarely possible to establish unambiguous a priori probabilities that are acceptable to all parties concerned. In forensic genetics, it plays a role in testing and interpreting probabilities of identity (*e.g.* paternity probability)." Source: http://bszki.hu/page.php?653 accessed on 28/11/2015.

[67] Source: http://bszki.hu/page.php?674 accessed on 28/11/2015.