The Science of Medical Decision-Making

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Principles, Algorithms, and Practice

By

Olivier Cussenot and John Reynard

Cambridge Scholars Publishing

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This book first published 2026

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-6351-9
ISBN (Ebook): 978-1-0364-6352-6

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PREFACE

When Olivier Cussenot told me that he wished to publish a new book in English on Artificial Intelligence (AI) and Prostate Cancer, I had two reactions: first, I knew nothing about AI – which is not strictly true as we all use AI regularly without even noticing that we do - and second, I could not think of a better partner for the book than my longstanding colleague at Oxford John Reynard. And I was right. The book is a masterpiece of information that brings AI all the way to the uninitiated, in language easy to read, and will be of interest to every single health professional who cares about patients.

Using the exemplar of Prostate Cancer is perfect, and not just because we are urologists. There is no other disease which causes more controversies in its management than prostate cancer, which is paradoxically the most commonly diagnosed malignancy in men in the Western hemisphere.

And yet the evidence that has driven screening for prostate cancer and its management has been plagued by poor evidence or lack of evidence for many decades. Randomised clinical trials are challenging, expensive, difficult to complete and even the successful few that have delivered evidence have not necessarily changed global practice. Should a healthy 50-year-old man get screened by prostate specific antigen testing? Should he receive a biopsy of the prostate, and if found to have cancer, should he be treated and how?

There is an increasing pressure on health providers to open up the floodgates of screening in many countries. It is inescapable that if this is allowed, it will lead to unacceptable levels of over-detection and over-treatment, and harm will exceed benefit.

My passion in prostate cancer is of course to provide evidence through well conducted clinical research and bridge the gap between the bench and the bedside. But most importantly, it is to find the prostate cancer ‘black box’.

Let me explain. Every time an airplane crashes, the first effort after trying to rescue survivors is to look for the flight recorder, otherwise known as the black box. This box – which incidentally I found out recently is usually not black but red! – contains critical information about the causes and circumstances of the crash, from which one can learn, and help to prevent future disasters. It is the same with prostate cancer. Every time a man dies of the disease, he has a little invisible ‘black box’ in his cancerous tissue, genes and biomaterial such as blood products. It is this very ‘black box’ which will teach us about the lethality of prostate cancer, and how we can predict it before diagnosis, allowing us to target screening to individuals at risk, and in the post-diagnostic space to understand what treatment if at all is required to prevent the disease from causing harm to the patient and his family. And every time a researcher discovers in the laboratory new knowledge, a fissure is made in that black box from where some new information leaks, as best described by the French neurologist Jean-Marie Charcot (1825-1893): “Disease is old and nothing about it has changed. It is we who change as we learn to recognise what was formerly imperceptible”.

That is the magic link that Olivier and John describe so elegantly between accumulation of knowledge, big data and the immense capabilities of AI, much beyond what we can imagine. This sophisticated tool has the potential to facilitate breaking the codes which will help us to decipher the causality which leads to aggressive disease and death, rather than the simple association of information with prostate cancer lethality. AI has the power, but as elaborated by the authors we must not lose the perception that we are health professionals who need to build compassion in our interactions with the patient, understand priorities, fears and hopes. Even with the best algorithms and information in the world, we must not dehumanise medicine, as cited by the French mathematician and philosopher René Descartes (1596-1650): “Science without conscience is but ruin of the soul”.

Freddie C. Hamdy
Oxford, March 2025

PROFESSOR DENIS KESSLER: IN MEMORIAM

Medical decision-making is about making choices – choices for the prevention, diagnosis, or treatment of diseases. It is a complex process at least partly because of the complexity of the function and afflictions of the human body, but also for two other fundamental reasons. The first is that the medical decision is, inherently, always made in *uncertainty*, because one cannot infallibly predict the course of a disease in a patient, or the consequences of the different diagnostic or therapeutic options offered to him or her. The second is that the medical decision has a marked personal character: its assessment is not absolute but intrinsically relative, varying from one patient to another. What is the objective function that we are going to set for ourselves? To allow a relative improvement in the patient's situation? To do so in the short-term or over the long-term? To minimize the adverse effects of a given treatment? To implement a reversible or permanent treatment?

From this point of view, making an "optimal" medical decision requires the doctor to attempt to define the benefits and risks of different interventions in probabalistic terms (the probability of success and failure, and how success and failure might be defined), and to do so in the context of the patient's subjective preferences, which will reflect that patient's risk aversion, and the absolute and relative importance that patient may or may not attach to this or that capacity or disability.

Using the jargon of the theory of decision-making in a risky environment that was developed by John von Neumann and Oskar Morgenstern[1] and that was encapsulated in the concept of "utility", since personal preferences are subjective, a medical decision must [1]*ultimately* aim to choose the intervention that maximizes *the expectation of utility* of the patient. In this sense, medical decision-making is multidimensional: the biosciences that constitute its substrate must necessarily be integrated into a more holistic approach in which not only mathematics (probability) plays a role, but also the human, social and behavioral sciences in the broad sense are fundamental.

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[1] In their work *Theory of Games and Economic Behavior* (1944)

The authors aim to show in this book the instruments that exist in the current decision-making toolbox, and which must be used in a context of uncertainty, using the case of prostate cancer as an example.

The choices are often binary and the doctor must make recommendations to the patient with the obvious risk of being wrong. This is the noble but anxiety-provoking role of the therapist and it lies at the heart of the responsibility that comes with decision-making. The authors consider in this book that faced with a difficult problem, with risks associated with each of the therapeutic alternatives, rationality leads to a strategy called "minimax regret" – a strategy that minimises maximum regret. Choosing a therapy aimed at maximizing what the patient regards as useful, while minimizing the subsequent possibility of regret ("given the negative effects of the therapy finally chosen, I wish I had made another choice"). It is therefore necessary to integrate all the available statistics and data, to consider in uncertainty all the therapies, and *ultimately* to choose the one that we are least likely to regret having implemented, if that choice ultimately ends in failure.

However, the implementation of this theoretical approach faces its pitfalls. Assessing the probabilities of success and failure as well as the consequences of an intervention on a given individual by statistics, which by their very nature are based on collective data, is a challenge. Unlike a roll of the dice whose production conditions are perfectly known and infinitely reproducible, the "frequentist" approach is not fully applicable in medical matters, for two main reasons. On the one hand, since everyone is *unique*, the assumption that knowledge of what has been observed in other patients makes it possible to infer their probabilities of success and failure on the patient under consideration is strong and always involves some uncertainty. On the other hand, even if we disregard this first limitation, we only have a limited history and finite data series. Information is necessarily incomplete, and often evolving. This is especially true for rare diseases. The theoretical probability distribution of the consequences attached to a diagnostic or therapeutic choice for a given patient – assuming that it exists and can be inferred by observation of the past – can therefore only be evaluated in an imperfect way. Statistics-based medicine has a major limitation: by construction, it does not allow the doctor or patient to consider a "first time", i.e. something that has never happened before – or at least that has never been recorded – in another patient. Even in the case of personalized mechanical medicine, which is based on knowledge of the genetic, biological or pharmacological mechanisms specific to the patient in order to justify diagnostic or therapeutic choices, the assessment of risks and benefits is necessarily based on the observation of the past. Nor can we exclude the possibility that the case of the patient being treated is singular in this respect. The doctor and his patient are thus faced with the problem of ambiguity that is structurally impossible to completely remove. A given case may correspond to a point belonging to two different probability distributions without being able to determine accurately, which one is the more relevant. In addition to this intrinsic uncertainty, there are various factors that can influence and alter decision-making on both the physician's and the patient's side. These include errors in reasoning, cognitive biases or even the fact that our knowledge as well as our ability to understand and abstract remain limited. Thus, even assuming that the probabilities of success and failure of the various interventions as well as their respective consequences on the patient have been perfectly objectified and are known with certainty – chimerical hypothesis! – many human factors can still cause significant dysfunction in the medical decision-making process.

Under these conditions, it is easy to understand the potential usefulness of algorithmic medicine based on Artificial Intelligence (AI) techniques in supporting and facilitating medical decision-making.

AI research was born in the 1950s and is therefore not new. The fantasy of AI is even less so, since artificial entities endowed with intelligence or consciousness have appeared in fiction for more than two hundred years, as evidenced by the surreal creation of Frankenstein's monster by Mary Shelley in 1818. However, a real turning point has taken place over the last twenty years, thanks to advances in computing, the advent of "super-connectivity", but also advances in theoretical understanding and underlying mathematical tools. Algorithms and learning methods have thus become an extremely fruitful field of research, and AI is now omnipresent in our lives, sometimes without us even noticing.

As with other sectors and disciplines, medicine must integrate this burgeoning development in AI to increase its explanatory and predictive capabilities. In the age of data profusion – "*Big Data*" – information is accessible in large quantities from multiple sources and almost in real time, so that the main challenge now is to extract the "substantive marrow". AI appears to be the right technological response to deal with the abundance of these data flows, which are set to increase exponentially. By allowing us to analyze this tremendous amount of information and extract knowledge from it, AI gives us a glimpse of a world in which predictive (*ex-ante*) and control (*ex-post*) capabilities will change the way diseases are diagnosed and treated. In addition, AI could prove useful in objectifying the patient's "utility function" and thus integrating their personal preferences into the medical decision-making process in order to choose between the different diagnostic and therapeutic options corresponding to their situation.

For these different reasons, AI is in many ways a quantum leap for the medical world. For the latter, taking advantage of this revolution requires ownership and adoption of the technologies associated with it, both in terms of tools and in terms of skills and human capital. Physicians in particular need to learn to work alongside AI and to have a basic understanding of the underlying theory and methods of AI.

AI will inevitably affect how healthcare professionals are trained, and how they perform their tasks, but it is not about man versus machine – it is about man with machine. Judgement, innovation, creativity, intuition, but also and above all responsibility, require and will require a human dimension for a long time to come. In other words, AI will not replace the doctor's opinion or the patient's decision but will complement the toolbox they can use, upon which to base an informed decision.

Through a rigorous work of synthesis and analysis, the authors bring a welcome light on the complex subject of medical decision-making, which is at the confluence of science, psychology, sociology and philosophy. This book allows the reader to grasp the main concepts and foundations of medical decision-making, to understand the related difficulties, and to discern the advantages and limitations of AI-based medical decision support systems. In doing so, it illustrates forcefully and brilliantly how medicine is both a science and an art.

Olivier Cussenot and John Reynard, Oxford April 2025

PROLOGUE

Since ancient times, the principles of decision-making have been laid down by Aristotle and medical decision-making has evolved within a moral and ethical framework originally defined by Hippocrates.

Recently, the space in which medical decision-making is placed has also been constrained by societal changes – specifically a move away from deference to the decisions made by the doctor towards shared decision-making, enshrined in the concept of autonomy, a patient's fundamental right to make decisions about their health.

Philosophy and mathematics have taken an important place in the standardization of the reasoning process that is involved in decision-making. Since the 50s, the advent of artificial intelligence has taken over this field of research by wanting to mimic or even mitigate cognitive bias linked to human reasoning process. Today, neuropsychological theories and mathematical algorithms compete to mimic the functioning of the human brain.

The 'actors' involved in medical decision-making have also evolved so that now medical decisions are no longer solely the domain of the medical profession, but are shared between the doctor and the patient. This is a reflection of a fundamental principle, that of autonomy - the power of self-determination in the making of medical decisions that affect an individual.

A crucial facet of the patient's ability to make informed decisions is the giving of information by the doctor in an understandable and impartial form.

Faced with a new condition or disease, patients are often ill prepared to make decisions. For those patients who do not have the experience of a chronic disease (where the patient may become very well informed about treatment options) the 'novice' patient must turn to his entourage, sometimes medicalized, or his attending doctor or the jungle of search engines on the Web.

The patient may be offered the option of a second medical opinion with a specialist, but this may add complexity to decision-making, since the second opinion may to be divergent from the first (the problem with a second opinion may be that it can be a second i.e. *different* opinion). The patient is then confronted with the tyranny of choice – https://www.scientificamerican.com/article/the-tyranny-of-choice/.

Here there may be some role for artificial intelligence providing the option of a third opinion, free of any affect or conflict of interest, such decision support systems allowing patients to better understand the options being proposed by the doctor and allowing the patient to challenge the benefits and risks of those options.

At present these support systems remain mostly in the sphere of education, or case simulation, because of the high development costs related to the constraints on the accreditation of these systems as medical devices and the Law on the Protection of Individual Data (GDPR).

In a language accessible to the non-specialist, we will address the human processes and their artificial *alter ego* that underpin the stages of medical decision-making: from knowledge, through reasoning, to the concretization of decisions compatible with individual affective values and societal constraints. To illustrate our remarks, we will refer to the different individual or collective problems and unfortunate choices encountered during our clinical experience in the management of prostate cancer. The main concepts, inherent in machine learning and expert systems, are approached from an educational point of view and as a cultural introduction to algorithmic medicine. We also report some conversation with ChatGPT (2023; OpenAI) about ethical decisions to which doctors are exposed when dealing with their patients. We will also discuss the pitfalls inherent in different modes of reasoning and heuristic dysfunctions that can lead to a regrettable or harmful decision for patients.

CHAPTER 1

INTRODUCTION

Artificial intelligence aims to create cognitive processes comparable to those of humans. It emerged as an autonomous scientific discipline in 1956, under the impetus of the Artificial Intelligence Group of the Massachusetts Institute of Technology (MIT) founded by Marvin Lee Minsky (1927-2016) and John McCarthy (1927-2011) at a conference in the United States (*Dartmouth Summer Research Project on Artificial Intelligence 1956*). In his report, published in March 2018, "Giving meaning to artificial intelligence", the French deputy and mathematician (Fields Medal 2010) Cédric Villani (1973) wrote*: "Artificial intelligence in health ... can contribute to improving citizens' access to care, through medical pre-diagnosis devices or guidance assistance in the care pathway*".

In November of the same year, the French National Consultative Committee on Ethics for Life Sciences and Health (CCNE) also published a report entitled: "Digital and health, what ethical issues for which regulation?". This report proposed 2 major ethical pitfalls to be the subject of regulatory devices as a preamble to the deployment of medicine based on artificial intelligence algorithms - "*On the one hand the risk of depriving the patient of a large part of his ability to participate in the construction of his management process in the face of the proposals for decisions provided by an algorithm and on the other hand the danger of a reduction in the consideration of individual situations in the context of a systematization of reasoning based on models whose limits may be linked to their ability to take into account the whole characteristics and preferences of each patient*".

These two assertions analysed by the AI language model ChatGPT 2023 report that "*the use of artificial intelligence in medicine can certainly present some risks and challenges. One of the concerns raised in your statement is that AI could potentially limit patient involvement in their own care. This could happen if patients feel that the algorithm's recommendations are given more weight than their own input or preferences. Another concern is that AI systems might oversimplify complex medical situations and fail to* *take into account individual differences between patients. AI models are based on data and statistical analysis, which can be limited by the quality and quantity of the data used to train them. Thus, AI models may not always capture the nuances of each patient's unique situation or preferences, leading to a "one size fits all" approach. It is important to note, however, that the potential risks associated with AI in medicine are not unique to this field. The use of any technology or system in healthcare requires careful consideration of the benefits and risks, as well as appropriate safeguards to ensure that patient autonomy and individuality are respected. In summary, while AI has the potential to revolutionize medical care, it is crucial to ensure that patients remain at the center of the decision-making process and that the limitations of AI models are recognized and addressed".*

From our human doctor point of view the two ethical issues provided by the French National Consultative Committee on Ethics for Life Sciences and Health testify to a certain technocracy on the part of the commission because they do not correspond to the reality on the ground and often go against the problems requested by the patient community.

Medicine based on artificial intelligence algorithms "does not deprive", but rather increases the patient's abilities to participate in their care. Patients must be able to choose their medical care after being informed about the different diagnostic or therapeutic options that correspond to their situation. It is the patient who *ultimately* decides on their care, with full knowledge of the facts, which implies that the patient has been provided with all the information necessary in order to make a choice.

In France the Public Health Code states that seeking a second medical opinion is a right. Article R4127-60 specifies that "The doctor must propose the consultation of a colleague as soon as the circumstances require it or accept that requested by the patient or his entourage".

In England this concept has been enshrined in Martha's Rule. Martha Mills died from sepsis aged 13 in 2021, due to a failure to escalate her to intensive care and after her family's concerns about her worsening condition were not responded to. NHS England states that Martha's Rule will allow "patients, families, carers and staff … round-the-clock access to a rapid review from a separate care team if they are worried about a person's condition" [https://www.england.nhs. uk/patient-safety/marthas-rule/]

Decision support tools are above all there to help the patient in their choice by providing them with a third opinion that has the objectivity and precision of mathematical calculation and to facilitate the dialogue with the doctor on the possible options of care. In England, the regulatory body NICE (the National Institute for Health and Care Excellence) has fully understood this need and recommends that patients use expert tools, for example for prostate and breast cancer. Thus, patients can carry out their consultation with their doctor by relying on an expert artificial intelligence system and thus perfect their information on the benefits and risks of the different treatment options offered to them.

Moreover, NICE has recognized the potential benefits of AI in healthcare and have been involved in initiatives related to AI implementation. In February 2021, NICE published a rapid guideline on the management of COVID-19, which included a section on the use of AI and machine learning in the diagnosis and treatment of the disease. The guideline recommended that healthcare providers consider using AI and machine learning tools as part of a multi-faceted approach to the management of COVID-19.

Decision support tools make it possible to integrate personalized patient profiles, thus contributing to a better understanding and individual estimation of the benefits and risks of the different management options. As we shall see so-called evidence-based medicine that has imposed itself on doctors via institutional recommendations (such as that of the High Authority for Health) is essentially empirical, based on statistics that often ignore the consideration of individual situations and the evolution towards personalized scientific medicine.

The field of artificial intelligence is vast, with very numerous and diverse methods. In medical research, machine learning and deep learning techniques have and continue to contribute massively to the discovery of new biological factors to understand diseases or predictors of response or resistance to treatments. Diagnostic or treatment tools based on artificial intelligence have shown their great effectiveness for the automatic analysis of "real augmented reality" images or sounds, in support of the human machine: couple sense organs/brain for perception or brain/hand for action.

These new tools are already there to assist radiologists or emergency physicians in the reading of CT and MRI scans, in the interpretation of electrocardiograms or heart sounds on echocardiograms, for dermatologists in the examination of skin lesions, ophthalmologists for the inspection of the retina and for pathologists in their histopathological interpretation of tumours. Artificial intelligence systems are also employed in planning in interventional radiology, or in the control of radiotherapy or of surgical robotics.

More and more these new technologies are involved in our daily lives in the form, for example, of brake assist systems and obstacle detection in the automotive industry or wrist worn devices that monitor our physical activity, heart rate and sleep.

These successes of artificial intelligence are ultimately a refinement of observation tools as were, in their time, the advent of the stethoscope or microscope that made it possible to see "the invisible" or hear "the inaudible".

The current challenge goes beyond these technologies to address the process of reasoning, placing the medical reasoning of today and tomorrow in front of or in accordance with artificial intelligence. One of our research concerns has been to "encode" medical knowledge to provide an architecture to the reasoning process. A bit like road mapping is integrated into a GPS, an essential basis for proposing the most relevant route according to the user's wishes, but also in accordance with pre-established rules: road topography, traffic directions or traffic flow.

This first approach integrating human knowledge of context, has often been neglected in artificial intelligence systems developed by "data scientists", when based on machine learning from medical data in natural language or scientific publications have been, despite a considerable mass of data, quickly limited in relevance as was found for the IBM Watson Heath program (How IBM overpromised and underdelivered on AI health care DOI:10.1109/MSPEC.2019.8678513). It is this prerequisite that has been at the centre of J Pearl's reflection (Turing Prize 2011) on the limits of so-called intelligent learning systems.

However, the development of generative artificial intelligence in various fields can aid in medical diagnosis by generating the synthetic patient which can then be used to simulate medical scenarios in the training of healthcare professionals. But there are also concerns regarding the ethical and legal implications of using AI in medicine, and it is important to ensure that any AI applications are used in a responsible and ethical manner.

Because of our surgical specialty, we will illustrate and dissect throughout this book concrete situations, encountered in our practice and which support the pitfalls inherent in the medical decision.

It is a matter of regret that in 2025, and despite the complexity of modern technical medicine, we still see frequent decision-making wanderings or false certainties based on simple reasoning biases. This was seen in the COVID-19 pandemic. We will see that in our specialty of urology in the management of prostate cancer that medical and institutional positions and expert opinion can also harm patients both collectively (in the context, for example, of the necessity or otherwise of prevention or screening), and at the individual level in the context of diagnostic or therapeutic decision-making for the individual patient.

CHAPTER 2

PROSTATE CANCER AS A COMMON THREAD AND CASE STUDY

In order to illustrate our remarks, we will use as a common thread, different decision-making issues encountered for prostate cancer (*In the turmoil of the prostate 2020*). Prostate cancer is a disease that usually affects men over 50 years old. In 2020 there were approximately 450,000 new cases of prostate cancer and 100,000 deaths from the disease in Europe. However, prostate cancer is a heterogeneous entity because it has schematically two evolutionary modes: cancers with slow or very slow evolution, representing the most frequent form of prostate cancer and cancers whose evolution towards metastases (migration of prostate cancer cells to other organs such as lymph nodes, bones or viscera: lung, liver, brain) will lead to complications and death.

Prostate cancers can be diagnosed early through screening, conventionally by testing the blood for a protein called prostate-specific antigen (PSA). However, the increase in PSA levels in the blood may be due to other causes such as age-related benign prostatic enlargement, so that the diagnosis must be confirmed in the presence of a high PSA level by prostate imaging and prostate biopsies.

Because of the different forms of behaviour of prostate cancer, the variable significance of a high PSA level and the variable evolution of diagnosed cancers, the management of prostate cancer has been the subject of controversy over the last 20 years, on the one hand regarding the benefit of a screening strategy based on PSA level (the majority of cancers diagnosed early, even untreated, will not have an impact on quality of life or the risk of premature death) and on the other hand on the risk of overly aggressive treatments, which can cause urinary incontinence and sexual dysfunction (loss of erections).

While it is now certain that heritable, familial or ethno-geographical genetic factors have an important part to play in the genesis of prostate cancer, environmental or behavioral hypotheses have been put forward without consistent evidence or with contradictory evidence. As with the COVID-19 pandemic, controversies and scientifically questionable results are disseminated, without filter or reservation, in the media or on social networks, on the simple argument of making the "buzz". Throughout this book, we will consider the difficulties inherent in decisions in medicine as illustrated by the modern history of prostate cancer management. We will see how the deciphering of human reasoning and its encoding thanks to artificial intelligence tools can normalize decision-making processes and debunk certain certainties.

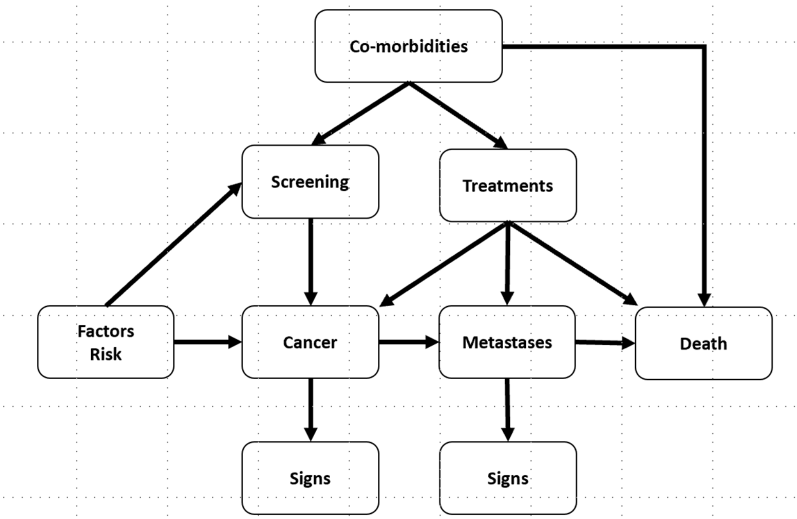

Figure 1: Modelling the natural history of prostate cancer

CHAPTER 3

MEDICAL DECISION-MAKING AND THE ART OF MEDICINE

a. The 'actors' in the medical decision

The medical decision today responds (or should respond) to the patient's right of self-determination. In this "shared medical decision" process, the patient is the one who makes the final decision on medical matters concerning him or her. The physician must provide the patient with complete, fair and intelligible information on the advantages and disadvantages of the recommendable options for their medical care. In this sense, the development of decision support tools can find all its meaning. The French High Authority for Health (HAS) rightly states that: "*Decision aids for patients are tools that help patients and health professionals in their shared decision-making on an individual health issue. They do not advise one option over another, nor do they replace consultation with a practitioner. They are designed as a complement to accompany, not replace, the advice of a health professional. They prepare the patient to make informed decisions with the health professional based on his values. Their current forms are heterogeneous (paper document, video, interactive multimedia tool) and can be used before or during a medical consultation. Their content aims to: make explicit the decision to be taken and the reasons that require it to be taken; guide the patient to prioritize the options available according to their preferences based on the benefits and risks that are valuable, important to them, and certainty about their preferences. explain the steps of the decision-making process and communication with the other people involved in the decision (doctor, family, relatives)*". Thus, the patient must be able to "challenge" the doctor's proposals - what motivates them, what supports them (scientific evidence and uncertainty), what makes it possible to implement them (technical means).

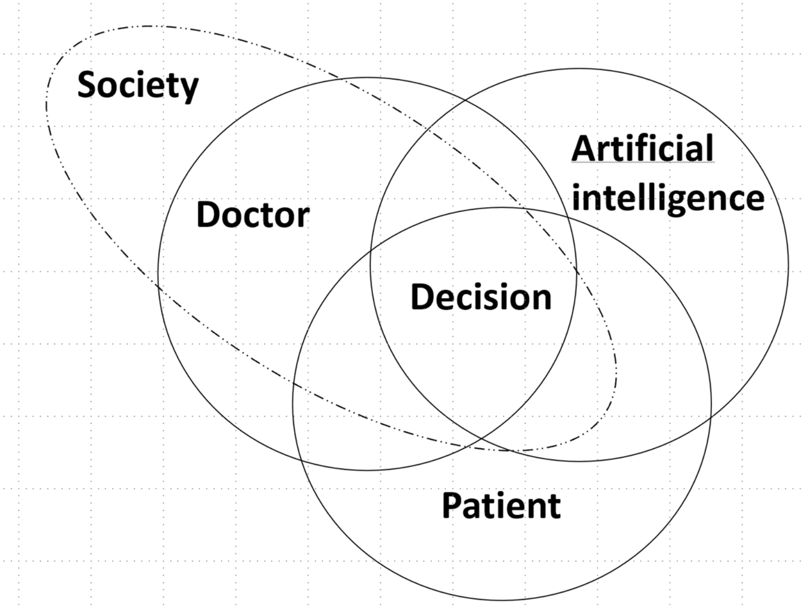

Figure 2: The actors of medical decision-making and the place of systems based on artificial intelligence

b. Medical reasoning (inference)

i. Evolution of concepts

In epistemology, Aristotle (384-322), a disciple of Plato (428-427), is recognized as one of the first to have brought out a true theory of decision-making.

Figure 3: The 3 stages of the syllogism according to Aristotle

Decision-making is the path of thought between knowledge (premises) and conclusion, through reasoning. The intellectual process of reasoning consists of inferences. In artificial intelligence we also speak of inference engine between system inputs: knowledge bases (made of databases or documentaries) between system inputs: knowledge bases (made of databases or documentaries) and listed in a thesaurus or dictionary and system outputs: prediction and decision. For human reasoning, schematically two major currents of thought co-exist. One, carried by René Descartes (1596-1650) or Immanuel Kant (1724-1804), is centered on rationalism, essentially based on logic, and the other refers to behaviorism based on instinct and human values (affect). But as Blaise Pascal (1623-1662) said: "Reason and instinct, marks of two natures", as we will see, this dualism does not mean an opposition between these marks - rather as Henri Bergson (1859-1941) and Konrad Lorenz (1903-1989) suggest, they represent two natural evolutions. Reasoning involves an initial mental representation (called according to the context: belief, prejudice, object, stereotype, premise, credence) of a set of basic ideas (inputs), on another set of target ideas (output) that underpin the decision. Recently, the hypothesis has been advanced that our brain, from an early age infers, from our perceptual inputs, predictions and generates a signal of surprise or error when these predictions are disturbed by unexpected outputs.

Our experience (history of the frequencies of events according to the situation) leads us to simplify the architecture and processing of data, allowing us to compress information. This approach, in the neurobiological context, is consistent with the hypothesis of epigenesis by selective stabilization of brain development espoused by Jean Pierre Changeux in 1998 in "The neuronal man" and in 2003 in "The man of truth". A fully connected and redundant neural biological network will select the iteratively stimulated connections to establish a stable functional architecture of the network. Stanislas Dehaene in his cognitive psychology course at the “Collège de France”, describes the statistical or "Bayesian" brain, comparing this ability to that of sound or image compression systems. For him "*our brain may not need to represent itself or transmit what it already knows how to predict, only the error of prediction counts for it*".

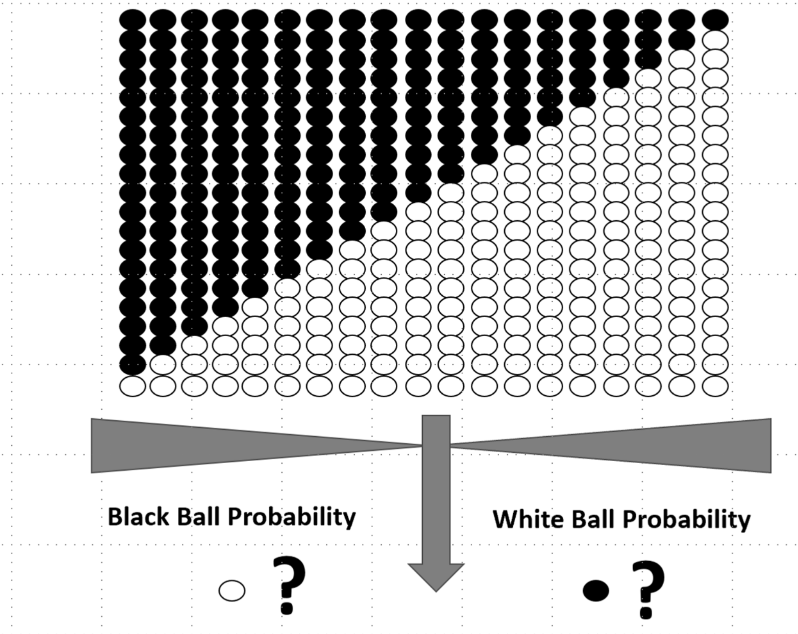

Figure 4: When drawing lots for a ball within a set of black and white balls, our experience from early childhood of such games is that we are naturally surprised if the colour of the ball drawn at random does not correspond to the colour of the most represented balls

More recently research in cognitive psychology has suggested that in the decision-making process our brain can function using quantum probability – the "Quantum Brain" (Emmanuel Haven and Andrei Khrennikov, co-authors of Quantum Social Science, Cambridge University Press, 2013).

This conception can be consistent with the theories in psychology of Amos Tversky (1937-1966) and Daniel Kahneman (1934). In their view individuals decide by a sequential process of anchoring (first opinion) followed by adjustments. In this model individuals can modify their judgment according to the occurrence of successive information. The order in which the information influences the estimates of final probability and consequently the decision, results in an order effect. Conversely, the order in which the information appears may not influence the estimates made by individuals. When subjects have the opportunity to actively select information, novice individuals will tend to seek more information to confirm their beliefs, while expert individuals will mostly look for conflicting evidence. Faced with a difficult decision between two choices of equal value in terms of initial probability, we use a dynamic evaluation system that changes our preferences as we think until we have decided.

A decision in medicine will be based on knowledge and rational reasoning (inferences) but also on the psychological context of the doctor and the patient. Whether the inference is human or robotic, from the data collected comes the interpretation and decision phase. The result, intuitive for the doctor, or programmed by the robot, is in the form of a "prediction" – based on probability (with its reliability being derived from performance). It is possible in a mathematical, logical model to set and program the decision rules beforehand, from prediction thresholds, to automate the expert system. If, as suggested by "the principle of sufficient reason" enunciated by Gottfried Wilhelm Leibniz (1646-1716), decision-making becomes a largely automatable task where every choice made is the result of predetermined factors, then the human psychological part would be solely responsible for our own uncertainties. This subjective (instinctive) part with his personal values (affective, psychological, societal) remains for some the guardian of self-determination by the one who makes the decision. According to the aphorism of Blaise Pascal (1623-1662): "The heart has its reasons that reason does not know". We will see later how neuropsychologists show that our brain chooses between a fast intuitive reasoning (short circuit), approximate or even fallacious, and a more complex logical reasoning (long circuit) but more accurate according to our emotions or our education.

In his or her reasoning, the doctor establishes, from his or her knowledge (anchoring) of the reported symptoms an intuitive classification based on his or her knowledge of the causes, according to their probabilities of association with the symptoms observed and according to the context (prevalence or *probability a priori* of the disease according to age, sex, geographical origin, risk factors).

Apart from relatively rare cases where a symptom is pathognomonic of (highly specific for) a disease, the doctor will look for additional information by for example examination, and the weight placed on those findings (that weight being determined by their positive or negative predictive value and according to their risks for the patient), will invalidate or support the diagnostic hypothesis (this is the process of adjustment). In the same way, the choice of a treatment or therapeutic sequence is based on the analysis of prognostic factors (signs) that are associated with the general condition of the patient (context), the evolution of the disease or the positive or negative response to possible treatments.

One of the visual algorithmic approaches, often proposed in medicine, is to define decision trees that integrate and synthesize the different arguments of reasoning that lead to the diagnostic or therapeutic decision. These decision trees, developed by experts, are mind maps and, as we will see later(highly specific) must be distinguished from the decision trees generated in machine learning from data.

ii. Typology of modes of reasoning

Global reasoning by analogy

This is probably the most common mode of reasoning. It is based on universal, automatic, metaphorical and stereotyped learning. We could call it "paleo-reasoning", evoking a phylogenic hierarchy of neurostructures in the brain. Its base is our primary knowledge on which logical reasoning will draw its beliefs (also called: anchoring, prejudice, credence, premise, a priori). It consists in transferring knowledge of particular cases to other special cases that resemble them. In this sense it responds to the principle of "uniformity" where the frequent repetition of identical events suggests the rule as long as the exceptions to the rule are not known.

The human brain preferentially works by analogy. Analogy is the common process of learning about our environment through our five senses. For Humberto Maturama (1928-2021) "we access knowledge with the help of our sensory organs through a process of projection (mapping) of the objective external reality on our nervous system and we adjust our behavior to the structure of the world that this projection gives us". From a perception, a mental object is stored and evolves as a concept (mental object, graph or stereotype) without the sensory component. It is assigned a "label" (name), allowing for a system of taxonomy and natural cladistics (cladistics is an approach to biological classification in which organisms are categorized in groups based on hypotheses of most recent common ancestry) [Figure 6].

This process of pruning the sensory component is enriched by the different combinations in the iteration of mental objects. The Nobel Prize winner Bertrand Russell (1872-1970, Nobel Prize for Literature 1950) described an atomic model ("The philosophy of logical atomism") for describing the conjunction between mental objects - done by sharing groups of neurons like electrons pooled between 2 atoms in a chemical bond. Thus, a neuron can participate in several graphs of different mental objects. When a new object is observed (perceived), it is confronted (resonance or dissonance) with the concept. It follows from this confrontation with reality (perception) whether or not the new object will be associated with the concept. This ability to learn according to an intuitive non-explicit scheme, by approximate similarity, is comparable to that used in artificial intelligence in deep machine learning models (Deep-Learning) using neural networks.

This "paleo-reasoning" is shared with animal species, as we have seen in our experience of dogs being able to detect prostate cancers. Dogs can recognize a unique individual by that individual's smell, but also can establish, after learning, categories (cancer or absence of cancer) from different individual odours.

In medicine, reasoning by analogy is based on the comparison of observations (clinical cases) and their similarities. It is this mode of reasoning that forges the experience of the doctor - the "know-how" of the doctor being based on the recognition and classification into normal or pathological groups based on observations of made during clinical examination of textures, sounds (auscultation), odours or palpation of the body for example. More explicitly, it is the "theoretical knowledge" of the doctor, by associating signs or symptoms by their preferential combination in different nosological contexts learned during day-to-day exposure to patients.

The principle of parsimony, enunciated by William of Ockham (1285-1347) and popularized today under the term "Ockman's Razor: *one must never multiply beings without necessity*" applies here by retaining only the most relevant conditions (rejection of useless entities). For example, the association "man over 50 years of age, abnormal PSA level, prostate cancer" is common. The knowledge of 2 of these conditions intuitively evokes to a doctor the third – the man is aged over 50, he has an abnormal PSA, therefore he has prostate cancer. There is no causal link here between the conditions, just an association of ideas.

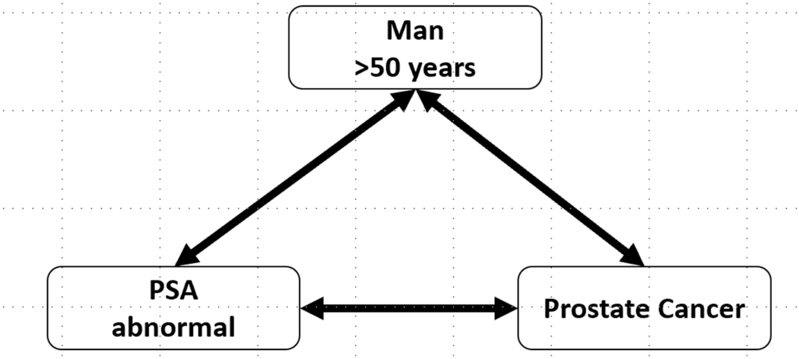

Figure 5: Two of these Three observations suggest to the doctor the third by analog learning

This learning, called "unsupervised" in artificial intelligence ("Machine Learning"), groups into classes (clusters) the variables from the strength of their statistical association. Here too, machine learning algorithms apply the principle of Ockham's razor in order to eliminate irrelevant variables (background noise) and thus avoid what we will call overfitting when we develop machine learning techniques. Reasoning by analogy testifies to the ability of the animal brain to associate by classes conditions occurring simultaneously or sequentially. It is the basis of the rules (knowledge base, anchoring) that prevail over the other modes of reasoning called "logical" that we will call "neo-reasoning" because associated with the development of the pre-frontal cortex of the brain and seeming specific to man and probably to large primates.

Directed, syntactic reasoning

It is the "logical" reasoning that responds to a triptych: a rule (theory, belief, prejudice, *a priori*), an observation and a conclusion. This "neo-reasoning" with its logical syntactics was formalized by Aristotle in his 2 fundamental modes: deductive and inductive.

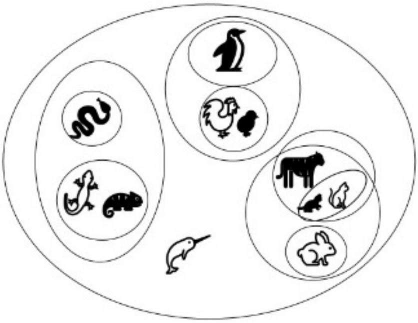

Figure 6: Analog association between animals of different groups, bases of taxonomy

Deductive reasoning

From a general rule held to be true and a particular observation one can deduce a conclusion. This is the syllogism if the conclusion is valid. Opposite to this is the paralogism: false reasoning that appears valid, especially to its author (the reasoner believes to be logical). The hierarchy between observation and conclusion is facilitated by our knowledge of the temporality where causes precede effects. Applying this reasoning to our example whose rule has been established by experience (by analogy) we would have:

(1) Rule held to be true: men over 50 years of age and who have prostate cancer have an abnormal PSA level in 90% of cases.

(2) Observation: This man over 50 years of age has prostate cancer

(3) Conclusion: This man over 50 years old will, in 90% of cases, have an abnormal PSA level

This reasoning is empirical because the probability stated in (1) is considered a learned rule and commonly accepted by knowledge and it is deterministic because it fixes the probability stated in (3)