Jose de Leon[1,2]

Teaching Medical Students How To Think: Narrative, Mechanistic and Mathematical Thinking

[1]Mental Health Research Center at Eastern State Hospital, Lexington, KY, USA
[2]Psychiatry and Neurosciences Research Group (CTS-549), Institute of Neurosciences, University of Granada, Granada, Spain, and Biomedical Research Centre in Mental Health Net (CIBERSAM), Santiago Apóstol Hospital, University of the Basque Country, Vitoria, Spain

Computers are becoming better than physicians in some activities. To survive, 21st century physicians need to become better thinkers. The most unique human cognitive skill is the ability to understand other human minds by creating stories about oneself and others (narrative thinking). Narrative thinking is at the core of the art of medicine, and dominated medicine until the 19th century when two types of scientific thinking (mechanistic and mathematical thinking) started to become influential. Mechanistic thinking uses mechanisms (abstract concepts which cannot be demonstrated in experiments but are needed for making hypotheses and interpreting observations from the experiments). In the 19th and 20th centuries, physicians grouped symptoms and signs into syndromes with the hope of separating each syndrome into various diseases based on etiopathological and/or physiopathological mechanisms. The 21st century brought mechanisms based on molecular genetics. Mathematical medical thinking expanded in the 20th century with the tools developed by statisticians. Now data mining and/or machine learning is threatening statisticians.

The traditional teaching of medical students based on the example of a clinician mentor who does not engage in reflective thought may no longer be enough. The three types of medical thinking, narrative, mechanistic and mathematical, need to be incorporated by the 21st century physician, whose thought process should also consider the biopsychosocial model of disease and its center, which is the patient. Computers will never substitute for a self-reflective medical expert who is aware of the strengths and limitations of human beings and of an environment characterized by information overload.

Keywords: Data mining, Education, Education/medical, History, 19th century, 20th century, History of medicine, Machine learning, Mathematics, Psychiatry/history, Thinking, Science, Statistics as topic, Systems theory

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Correspondence:
Jose de Leon, M.D.
Mental Health Research Center at Eastern State Hospital
1350 Bull Lea Road, Lexington
KY 40511, USA
Tel.: 1 859 846 8440
Fax: 1 859 846 8446
E-mail: jdeleon@uky.edu

Enseñando a Pensar a los Estudiantes de Medicina: El Pensamiento Narrativo, Mecanístico y Matemático

Los ordenadores están empezando a ser mejores que los médicos para algunas actividades médicas. Para poder sobrevivir estos avances los médicos del siglo XXI necesitan aprender a ser mejores pensadores. La habilidad cognitiva más propiamente única de los humanos es la habilidad para entender otras mentes humanas creando historias sobre uno mismo y sobre los otros (el pensamiento narrativo). El pensamiento narrativo es el núcleo central del arte de la medicina y dominó la medicina hasta el siglo XIX en el que empezaron a tener peso dos tipos de pensamiento científico: el pensamiento mecanístico y el pensamiento matemático. El pensamiento mecanístico se basa en mecanismos (conceptos abstractos que no se pueden demostrar en experimentos, pero se necesitan para formular hipótesis e interpretar las observaciones de los experimentos). En los siglos XIX y XX, los médicos agruparon los síntomas y los signos en síndromes con la esperanza de separar los síndromes en enfermedades gracias a los mecanismos etiopatogénicos y/o los mecanismos fisiopatológicos. El siglo XXI ha traído los mecanismos basados en la genética molecular. El pensamiento médico matemático se desarrolló en el siglo XX gracias a las herramientas desarrolladas por los estadísticos. El desarrollo de la minería de datos y el aprendizaje de máquinas está empezando a amenazar a los estadísticos.

El aprendizaje tradicional en medicina en los que los estudiantes aprenden de unos tutores que son clínicos experimentados, pero no son capaces de desarrollar un pensamiento auto-reflexivo, quizá ya no sea suficiente. Los tres tipos de pensamiento (el narrativo, el mecanístico y el matemático) deben ser asimilados por el médico del siglo XXI e incorporados en un modelo biopsicosocial en el que el paciente es el centro. Las computadoras nunca podrán sustituir a expertos médicos auto-reflexivos que son conscientes de: 1) las limitaciones de los seres humanos y 2) una realidad caracterizada por la sobrecarga de la información.

Palabras clave: Minería de datos, Educación, Educación/médica; Historia, Siglo XIX, Siglo XX, Historia de la medicina, Aprendizaje automático, Matemáticas, Psiquiatría/historia, Pensamiento, Ciencia, Estadística, Teoría de sistemas

"Hannah Arendt, one of the foremost political philosophers of the twentieth century, has argued that it is the responsibility of educators not to leave children in their own world but instead to bring them into the adult world so that, as adults, they can carry civilization forward to whatever challenges it will face by bringing to bear the learning of the past. In the same collection of essays, she discusses the recognition by modern science that Nature is inconceivable in terms of ordinary human conceptual categories - as she writes, 'unthinkable in terms of pure reason'." E.R. Dougherty[1]

Medicine, or rather, Western medicine was born 2500 years ago in Greece. It is not possible to understand the limitations of medical education in the 21st century without understanding the history of medical education in Western civilization. Table 1 tries the almost impossible task of summarizing in one page 2,500 years of medical education[2-8] as medical science developed[3] and was influenced by developments in scientific thinking[9-16]. The reader may want to read the table again after reading the whole article. For most of the past 2,500 years, mentoring by an experienced physician has been the crucial part of medical education. Table 1 describes 3 phases of mentoring[2]. its onset in Greece, academic mentoring when universities developed in Europe[3] and scientific mentoring when universities progressively incorporated modern science in their teaching. By the end of the 20th century, physician mentoring was challenged by evidence-based medicine (EBM), which proposed that physicians should educate themselves by completing systematic reviews and meta-analyses. In the 21st century, physician mentoring has been challenged by advances in the cognitive sciences[4-6], which described the biases of human cognition and their impact on medicine, explaining that the traditional physician mentor did not explain his thinking process[7,8]. Physicians are not scientists but practical reasoners[17] as Aristotle (384–322 BC), the ancient Greek philosopher, emphasized. On the other hand, having a good grasp of the history of scientific thinking will help any physician improve his/her thinking immensely. Table 1 very briefly summarizes the scientific advances[9-16] and how they apply to 2,500 years of medicine[3]. For those readers interested in better understanding the history of science, this author recommends books by a psychologist[13] and by an engineer who is also a medical researcher knowledgeable in the philosophy of science[14].

This article attempts to explain medical thinking in a way that can be mastered and incorporated by medical students into their own thinking. It has three major sections: 1) the challenges of medical thinking in the 21st century; 2) narrative, mechanistic and mathematical thinking in medicine[18]; and 3) the context of the physician thinker. The three major sections have subsections. The section on the challenges of medical thinking in the 21st century includes 3 subsections: 1) how doctors think, 2) 21st century doctors versus computers, and 3) 21st century doctors versus their problematic patients and problematic colleagues. The section on narrative, mechanistic and mathematical thinking in medicine[18] includes 5 subsections: 1) the battle among three Western traditions over medical thinking in 19th century France, 2) the late 19th century confluence of scientific medical thinking, 3) 20th century developments in medical narrative thinking, 4) 20th century developments in medical mechanistic thinking, and 5) 20th century developments in medical mathematical thinking. The section on the context of the physician thinker includes 3 subsections: 1) the biopsychosocial model of disease, 2) the patient as the center, and 3) the physician as an expert.

THE CHALLENGES OF MEDICAL THINKING IN THE 21ST CENTURY

How Do Doctors Think?

Until recently, how doctors think has not been a subject of interest for practicing physicians or physician educators but in the first decade of the 21st century, two books[7,8] titled *How Doctors Think* have been published. In spite of their very different backgrounds and approaches to answering the question, both authors agree that current medical education appears to develop a physician who learns to think by practicing, and does not know how to verbalize the limitations in thinking of his/her mentors and, worse yet, his/her own biases. This is hardly a new idea. This pattern of not-easily-verbalized thinking based on learning by example from a mentor was called "tacit knowledge"[19] by Michael Polanyi (1891-1976). Polanyi[20] was a Hungarian physician who emigrated to Germany where he became a researcher in the physico-chemistry field and then moved to the United Kingdom where he "settled" for becoming a philosopher of science[21], so well-recognized that he was able to publish an important article on mechanistic science in the journal *Science*[12]. Geliwick proposed that Polanyi never stopped thinking as a physician and "became a physician of culture and philosopher to help medicine today[22]".

Table 1 **Phases of medical education reflecting advances in mechanistic and mathematical science throughout history**

Time	Phases of Medical Education	Advances in			
		Mechanistic Science		Mathematical Science	
		In general	In medicine	In general	In medicine
-500 BC	Mentoring[a]		*Humoral Theory*[k]	Geometry[u]	
-300 BC		Aristotelian Biology[f]			
1100	Academic Mentoring[b]				
1500	Scientific Mentoring[c]		Modern Anatomy[l]		
1600		Empirical Method[g]	Modern Physiology[m] Sydenham Nosology[n]	Modern Science[v]	
1700		Linnean Taxonomy[h]	Anatomic Pathology[o]	Modern Chemistry[w]	
1800					Louis' study[x]
		Experimental Biology[i]	Anatomoclinic[p] Physiopathologic[q] Etiopathogenic[r]		
1900			Boom of Medicine[s]	Statistics[y]	RCTs[z]
		Article on Mechanistic Science[j]			
1980s	EBM[d]		Molecular Genetics[t]		
2000	Unawareness of thinking[e]				

EBM; evidence-based medicine. RCT; randomized clinical trial (or randomized controlled trial).

[a]Greek medicine gave great relevance to mentoring by a trained physician who, according to the Hippocratic Oath, had to be treated as a father by his medical trainees. The training physician had to treat his trainees as his children. Other physicians needed to be respected as colleagues[3].

[b]In the 1100s three universities developed (Bologna, Paris and Montpellier)[3] in Europe. Universities extended to other areas of Europe allowing the teaching of medicine in the context of an academic environment where other academic disciplines were also developing. A prior medical school had started one century before, the Schola Medica Salernitana, in the South of Italy[3].

[c]Scientific mentoring was progressively incorporated into academic medical schools starting with basic medical sciences, such as anatomy, and then with clinical sciences, such as nosology[3].

[d]EBM is a definitive departure from the prior 2,500 years of medical education[2]. Before the EBM model, education was based on mentorship with a more experienced physician. Therefore, the older, more-experienced physicians were the "experts". With EBM, the expert is one who can master the technique of systematic reviews and meta-analyses. EBM[2] was mainly developed in the 1980s at McMaster University in Canada by Gordan Guyatt (1953-present), an internist and David Sackett (1934-2015), a physician and epidemiologist.

[e]Cognitive science has ignored the role of unconscious biases in human decisions for almost 100 years due to the disturbing role of Freud, which led to scientists discontinuing studies on unconscious motivations[4,5]. The progressive recognition that human biases are very important in understanding the behavior of individuals and their economic decisions[6] has slowly infiltrated medical thinking and led to the publication of two textbooks with the title *How Doctors Think* in 2005[7] and 2007[8] which emphasize that physicians are unaware of their thinking.

[f]There is general agreement that Aristotle (384–322 BC) was not only a philosopher but a scientist using empirical observation to advance knowledge. He certainly did research on the natural history of Lesbos, and the surrounding seas. His writings contain some observations and interpretations, along with myths and mistakes. His methods included dissection and observation, so he is considered the founder of biology[9].

[g]Francis Bacon, an English philosopher (1561-1626), published *New Organon* in 1620 where he defended the need for the empirical method for advancing scientific research[13,14].

[h]Carl Linnaeus (1707-1778) was a Swedish biologist who is considered the father of modern taxonomy. He developed a classification of animals and plants described in a book first published in 1735, called the *System of Nature*. This classification was very influential in medical nosology[3].

[i]Claude Bernard was a French physiologist (1813-1878). Biological research was not fully developed[10] until Bernard completely developed the empirical method in his book *An Introduction to the Study of Experimental Medicine*[11] first published in 1865.

[j]Michael Polanyi, a Hungarian-born physician who became a philosopher of science in the United Kingdom (1891-1976), published an important article[12] describing the relevance of mechanisms in science.

[k]The Hippocratic theory of the 4 humors (blood, yellow bile, black bile and phlegm) is so primitive and has such limited observation to support it that it appears more narrative thinking (a story) than mechanistic thinking (a scientific theory with a mechanism tested after repeated observation). To reflect its dubious classification as a mechanistic theory, it is in italic font. In Roman times, Claudius Galenus (approximately 130–200), known as Galen of Pergamum, further elaborated the humoral theory[3].

Table 1 Continuation

[l]Andreas Vesalius (1514-1564), a Flemish physician and anatomist, published *On the Fabric of the Human Body in Seven Books* in 1543[3].
[m]William Harvey (1578-1657), an English physician, published *On the Motion of the Heart and Blood in Animals* in 1628, describing the major circulatory system. It was one of the first major steps in the development of modern physiology[3].
[n]Thomas Sydenham (1624-1689), an English physician, is considered the founder of modern nosology[3]. His last book, *The Process of Healing*, was published in 1692.
[o]Giovanni Battista Morgagni (1682-1771), an Italian physician, is usually considered the father of modern anatomical pathology. He focused on organ pathology. In 1761, he published *Of the Seats and Causes of Diseases Investigated Through Anatomy*[3].
[p]Anatomoclinical thinking, mainly developed in France, led to collecting subjective symptoms and objective signs and relating them to organs, the method by which syndromes were developed.[3] The original idea was proposed by Marie François Xavier Bichat (1771-1802) in a book called *General Anatomy* published in 1801, but it was implemented in the clinical environment by Jean-Nicolas Corvisart (1755-1821), Gaspard Laurent Bayle (1774-1816) and René-Théophile-Hyacinthe Laennec (1781-1826) who invented the stethoscope[3].
[q]Physiopathological thinking was a product of advances in physiology and pathology[3]. Physiological thinking was mainly developed by Claude Bernard while Rudolf Ludwig Carl Virchow (1821-1902) developed anatomic pathology to the level of the cell.
[r]Etiopathological thinking, a product of advances in microbiology and immunology, allowed medical researchers to differentiate diseases from within syndromes[3]. Microbiology was developed mainly by the work of the French investigator Louis Pasteur (1822-1895) and the German physician Robert Koch (1843-1910). Immunology was developed through the combination of laboratory research and the application of serum in clinical practice.
[s]In the 20th century the combination of anatomoclinical, physiopathological and etiopathogenic thinking led to a boom in medicine with the development of various medical specialties[3].
[t]The contribution of molecular genetics to the redefinition of syndromes in the late 20th century is described in Table 2.
[u]Greek mathematics focused on geometry. Euclid of Alexandria (lived in the 4th and 3rd centuries BC) is usually considered the founder of geometry with his book *Elements*[13,14].
[v]Galileo Galilei (1564-1642), an Italian scientist, wrote *The Assayer* in 1623 where he defended the concept that the universe "is written in the language of mathematics". This statement is usually considered the birth of modern science[13,14].
[w]Antoine Lavoisier (1743-1794) is usually considered the founder of modern chemistry, with the transformation of this science from a qualitative to a quantitative one[13,14].
[y]Ronald A. Fisher (1890-1962), an English statistician, developed the frequentist approach to statistics, which was crucial for the application of statistics in medicine[2].
[x]Pierre Charles Alexandre Louis (1787-1872), a French physician, used the observational method and numerical calculations ("numerical method"). Moreover, he proposed that medicine must become a numerical science[2].
[z]Austin Bradford Hill (1897-1991), an English epidemiologist and statistician, published an article in 1948 describing the first modern RCT[2].

21st Century Doctors versus Computers

You are a 21st century physician or medical student, so you think you do not need to worry about the ideas of a physician born in the 19th century; then you happen to read a 2016 book *"The Industries of the Future"*[23], or listen to the news and you may start to seriously worry. Computers are becoming better diagnosticians than radiologists[24], pathologists[24] and dermatologists[25]. Recognition of visual patterns is a type of tacit knowledge for which the human brain is not as sophisticated as a 21st century computer, which can learn from millions of images. Radiologists, dermatologists and pathologists are on their way out, just as dinosaurs. Next in line for extinction are the surgeons; robots are developing better motor skills than surgeons. Motor skills are another type of implicit skill learned by working with a physician mentor.

To survive, 21st century physicians need to be better at exchanging information with patients than computers could be. More importantly, they need to be better thinkers than their artificial competitors. Is there any area of knowledge in which human brains are better than computers? Yes, there is a most unique human trait that is beyond the reach of computers, according to evolutionary psychologists[26] and other thinkers[27]. The human brain has an unmatched ability to understand other human minds and what the evolutionary psychologist Dubin[26] calls their "level of intentionality", in which people describe the intentions of other human beings by using stories, including those stories inside other stories (Peter believes that Jane thinks…). "Narrative thinking" is the basis for understanding other human minds, as people create stories about themselves and others, and then try to overlap and compare them. Most human beings are good at using stories to understand other human beings, although people with Asperger syndrome are not[28]. The brain structures needed for automatic processing of empathy are not well developed in people with Asperger traits. Asperger traits are not rare in medical students and most of the students who have them gravitate to medical specialties with less human contact and more procedures, or to research[13,28].

21st Century Doctors versus Their Problematic Patients and Problematic Colleagues

If you are a medical student, you need to be aware that some individuals are better narrative thinkers than the majority of physicians, and their skills can become quite problematic for the patient-physician relationship. Labelling is a typical activity in narrative thinking, and these people can be labeled as having "dark personalities" by a psychologist[29] or personality disorders by a psychiatrist[30]. Although there are no adequate studies that definitively establish their frequency[31], a United States (US) medical student should expect that at least 5%, or 1/20, of his/her patients have the potential for becoming problematic and can probably outmaneuver him/her, unless he/she becomes an expert in narrative thinking. This scenario may become even more complex, since a 5% prevalence may also apply to health professionals, including physicians, who are problematic[30] and yet employed as the medical student's current or future colleagues. To manage these problematic and manipulative patients (and colleagues), physicians need to master two types of narrative thinking; they have been described as thinking "existentially" and thinking "dirty[32]". Freudenreich and co-workers[32] defined "thinking dirty" as understanding that patients and physicians sometimes work toward different goals and "thinking existentially" as understanding in what life circumstance this disease met that specific patient.

21st Century Doctors and Learning to Think

This "uplifting" article proposes the following "narrative" for 21st century medical students, assuming that they survive the challenge of being displaced by computers; they are going to have the opportunity to enjoy taking care of most of their patients, while at the same time watching out for the 5% who are problematic patients and the 5% who are problematic colleagues. It sounds like great fun. Even so, the author believes that medicine can be great "fun", as long as practicing physicians are aware of their limitations and biases as described[7,8], and more importantly, if when they are medical students, they learn to think better than their predecessors in this noble profession.

Those who are interested in learning more about how to correct their own biases should read books on how cognitive psychologists are starting to explore human biases[6] since physicians are as biased as any other human beings, as the classic book "Follies and Fallacies in Medicine[33]" demonstrates.

NARRATIVE, MECHANISTIC AND MATHEMATICAL THINKING IN MEDICINE

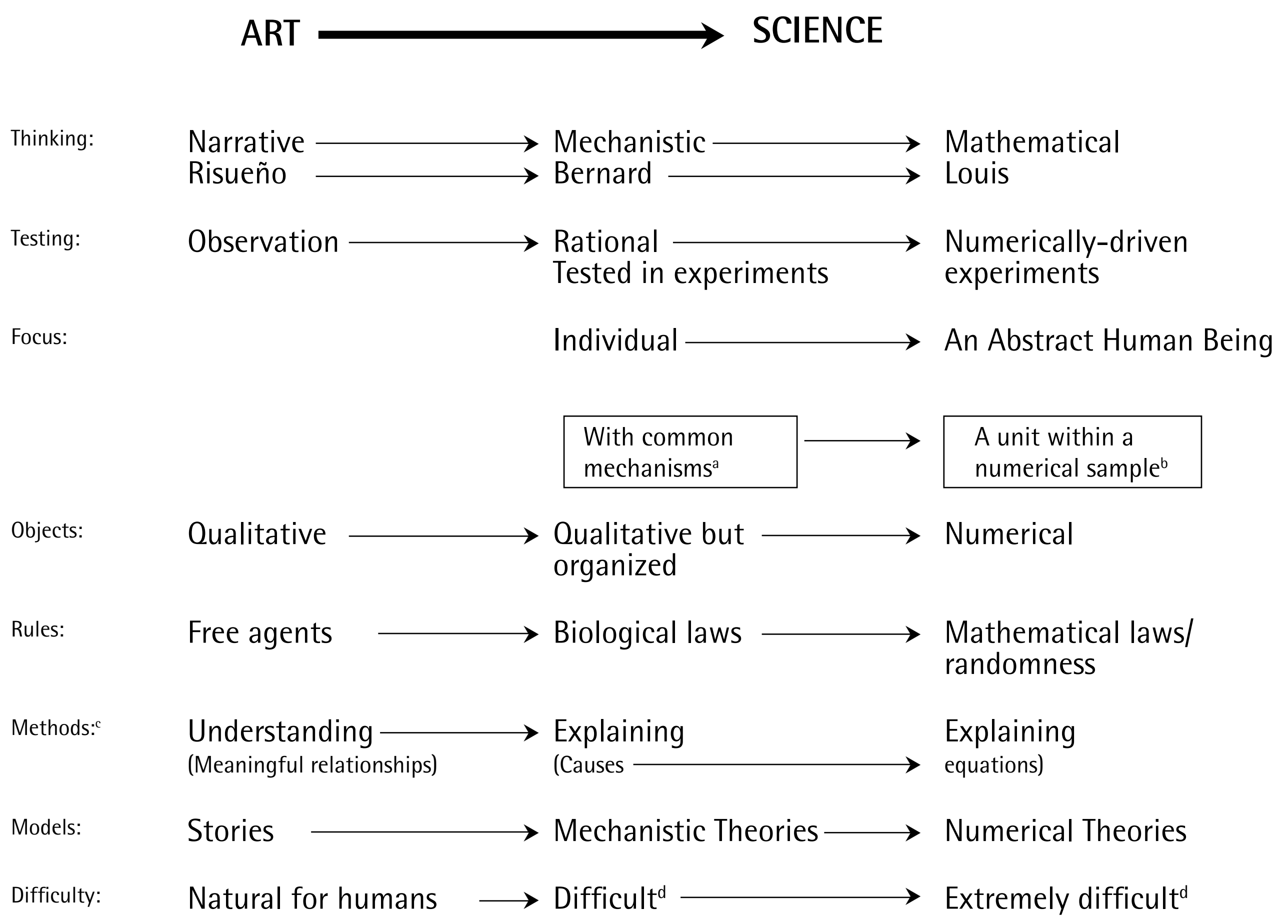
Battle among three Western traditions over medical thinking in 19th century France

The recipe for improving medical thinking comes from an old story, a 19th century battle in France about the art and science that influences medical thinking[18]. The art of medicine is mainly reflected in narrative thinking. Narrative thinking is the normal way that humans pass along knowledge, so it is as old as humanity, and has dominated Western medicine from its birth in Greece 2,500 years ago through the 19th century; it led to the belief that medicine was mainly an art.

Scientific thinking developed in Western civilization through the combination of Hebraic (also called Jewish or Jerusalem) and Hellenic (Greek or Athens) traditions[34,35]. After 2,500 years, the development of quantum physics makes it clear that scientific thinking has developed to a point that science has become unreasonable for untrained normal human beings.[1] In that sense, the 20th century Spanish philosopher Ortega y Gasset (1883-1953) stressed that "experimental science is one of the most unlikely products of history[36]." Furthermore, some argue[15,28] that the purest scientific disciplines, such as mathematics and physics, are more attractive for people with Asperger traits. Figure 1[4-6] stresses how medicine as an art focuses on individual human beings, which is how humans typically think, while science focuses on abstract human beings. In mechanistic science, the individual becomes an abstract human being with common mechanisms explained by our common evolutionary history. In mathematical science, the individual becomes an abstraction of a human being represented by a number; each individual is a unit within a numerical sample. The "extreme unnaturalness" of mathematical science is demonstrated by the fact that even scientists trained in probabilities tend to be biased when automatically interpreting the use of probabilities in real world situations[6].

In this endeavor to simplify the complex reality of science (Figure 1), the science of medicine is considered a combination of mechanistic and mathematical thinking applied to medicine (Table 1). Mechanistic thinking may have been born when Aristotle established the basis for biology 2,500 years ago[9]. Mechanisms are abstract concepts which cannot be demonstrated in experiments but are needed for making hypotheses and interpreting the observations made during experiments[18]. Modern scientific thinking including mathematical thinking is usually considered to have originated in the 17th century when Galileo Galilei proposed that the universe is written in the language of mathematics[15,16].

Pierre Charles Alexandre Louis (1787-1872) crusaded against the use of bloodletting in pulmonary infections in Paris during the 1830s and 1840s, trying to demonstrate that bloodletting was not the panacea that most physicians pretended it was[37,38]. Louis used the observational method and numerical calculations, leading to the birth of clinical epidemiology[38] and EBM[39] according to recent articles. Louis's proposal that medicine must become a numerical science was too much for Benigno Risueño de Amador (1802-1849), who wrote a report attacking the use of the numerical ap-



[a]Mechanisms are determined by evolution and most of them are very similar in most human beings.
In mechanistic science, the individual becomes an abstract human being with common mechanisms explained by our common evolutionary history.
[b]In mathematical science, the individual becomes an abstraction of a human being represented by a number; each individual is a unit within a numerical sample.
[c]German philosophers such as Dilthey distinguished between understanding and explaining. Understanding is fundamental for human sciences while explaining is the method used by the natural sciences. Jaspers applied these concepts to psychiatry[4,5].
[d]Nature is inconceivable in terms of ordinary human conceptual categories, according to Arendt; it is "unthinkable in terms of pure reason[1]". Science is not easy for human beings. Mathematical scientific thinking is even more challenging, even for trained scientists[6].

Figure 1 *Gradients in the methods of thinking in medicine*

proach in medicine[40,41]. Risueño was a professor at Montpellier Medical School, one of the oldest medical schools in Europe. He believed that medicine is an art and cannot be represented by numbers. He embodied the non-quantitative, qualitative narrative tradition in Western thinking. Conversely, Louis represented the most quantitative side of the scientific approach, stressing that unproven theories delayed the development of medicine and that medicine needed to follow a numerical approach.

Claude Bernard (1813-1878) represented mechanistic science, the third school of thinking fighting for control of medicine. He was one of the major physiologists of the 19th century[42], helping to establish physiopathological thinking[3] to the point that the medical historian Pedro Lain Entralgo (1908-2001) considered biological research not fully developed[10] until Bernard wrote his book *An Introduction to the Study of Experimental Medicine*[11]. Bernard's position on medical thinking can probably be described as intermediate between Risueño and Louis[43,44]; he posited that clinical medicine had to be guided by probabilistic evidence as long as physiological mechanisms remained unknown, but numeric approaches interfered with Bernard's model of experimental medicine, which did not need statistics to prove that physiological mechanisms were present; they were demonstrated by physiological experiments which use an experimental design rather than statistical tests to get answers[43,44].

In summary, Risueño, Louis and Bernard represented the struggle among the three Western traditions for the right to dominate 19th century medical thinking. Risueño stressed that each individual is different so numeric approaches do not work in medicine, that medicine is an art, and that qualitative approaches are crucial[40,41]. Louis despised the unproven narrative theories that had dominated medicine for centuries. His approach was scientific and quantitative, leading in the 20th century, after the development of statistics, to a mathematical model of science in medicine[38,39]. Bernard believed that physiological theories are fundamental to the advancement of medicine, but acknowledged that in the absence of known mechanisms a probabilistic interpretation of experiments can aid this advancement[43,44]. Bernard developed the pathophysiological approach[3] to medicine, demonstrating that mechanistic theories are crucial to the evolution of medicine despite being considered "philosophical" by defenders of empirical research. In this view, there is a progressive gradient from Risueño's to Bernard's to Louis's ways of thinking (Figure 1).

Late 19th Century Developments in Scientific Medical Thinking

Lain Entralgo[3] proposed that the triumph of 20th century medicine was supported by the development in the 19th century of three new ways of thinking; he called them anatomoclinical, physiopathological and etiopathological thinking, which are essentially mechanistic thinking (Table 1). Nineteenth-century physicians started using anatomoclinical thinking to collect subjective symptoms and objective signs and relate them to organs, the method by which syndromes were developed. Physiopathological thinking (a product of advances in physiology and pathology) and etiopathological thinking (a product of advances in microbiology and immunology) allowed them to differentiate diseases within the syndromes. Thus, this process of identifying diseases within a syndrome requires finding causes for a lesion (etiopathological thinking) or at least a clearly abnormal physiological mechanism (physiopathological thinking)[3].

In summary, physicians group symptoms and signs into syndromes with the hope of separating, within the syndrome, various diseases by gaining new knowledge of etiopathological or physiopathological mechanisms[4]. The better the mechanisms are understood, the more specific the treatment can be.

20th Century Developments in Medical Narrative Thinking

The best known and most influential narrative thinking in medicine is psychoanalysis, developed by the Viennese physician, Sigmund Freud (1856-1939). Karl Popper (1902-1944) was another Viennese who become a highly regarded philosopher of science and who defined psychoanalysis as a *pseudoscience*, a theory that cannot be falsified[45]. In spite of young Freud's self-designation as a scientist[46] there is general agreement by thinkers from all kinds of backgrounds that Freud was a novelist[47-49], an expert in narrative thinking, rather than a scientist.

Freud's language and terms are extraordinarily complex but are clearly summarized in a book[50] very appropriately called *A Narrative Textbook of Psychoanalysis.* Freud and his disciples developed a circular method of thinking in which all their observations were contaminated by their theories[5]. Karl Jaspers (1883-1969) was a German psychiatrist who later become an internationally known philosopher[51]; he proposed that psychiatry[52,53] is a hybrid discipline requiring two methods, *explaining* from the natural sciences and *understanding* from the social sciences, which respectively provide an explanation of illness that follows the medical model and an understanding of psychiatric abnormalities that are variations of human living. Psychoanalysis relies only on understanding by establishing associations using meaning, essentially by using narrative thinking.

20th Century Developments in Medical Mechanistic Thinking

During the last half of the 20th century, Alvan Feinstein (1925-2001), a US physician, stressed the importance of "pathophysiological and etiologic mechanisms" in the basic medical sciences, which make them similar to experiments, while ordinary clinical practice is characterized by unplanned "experiments[54-58]". He proposed a new approach, clinimetrics[58], to measure the clinical and personal phenomena required for patient care.

The Human Genome Project has led some to observe that "genetic anatomy" is the main contribution of 20th century medicine[59]. This is obviously a simplification of the very complex process that modified mechanistic medicine in the 20th century, based on mechanisms at the molecular level, to the point of providing a new way of defining diseases in the 21st century. The idea of "molecular pathology" was first described by a 19th century German physician and began to be applied using chemical discoveries in early 20th century medicine[3]. However, the development of what is called in English-speaking countries[3] molecular biology[60] and its progressive development in the last half of the 20th century made it possible for 21st century molecular genetics to redefine diseases. In the 19th and 20th centuries, physicians combined anatomoclinical, etiopathological and physiopathological thinking to delineate syndromes/diseases, while in the 21st century, molecular genetic thinking is redefining syndromes such as the Di George[61] and Lynch[62] syndromes (Table 2).

20th Century Developments in Medical Mathematical Thinking

Mathematical thinking in medicine was not fully established until statistical thinking was developed by an English statistician, Ronald A. Fisher (1890-1962). He applied the method of testing for significance, which is usually called the frequentist approach to statistics in medicine[63].

After that, randomized controlled trials (RCTs) were introduced in medicine and meta-analysis was developed to summarize RCTs by quantifying average results for an average patient[2]. EBM, by focusing on "average" ideal results for an ideal patient, became the culmination of numerical scientific thinking in medicine. EBM originated in a Canadian university but, due to shrewd and effective marketing, has become part of the language of most practicing Western physicians[2]. Unfortunately, in most cases, these clinicians bringing EBM to the discussion are unable to speak coherently about the definitions of EBM, RCT and meta-analysis, and their strengths and limitations. Ioannidis has become one of the most influential medical scientists in medicine by insisting that medicine is plagued with false results due to: 1) financial and other conflicts of interest and 2) biases associated with the quest for statistical significance[64]. He has recently criticized EBM[65].

Contemporary statisticians, with great horror, have begun to see how they could be replaced by data mining or machine learning[66], developed by engineers and computer scientists to manage what is now called "big data[67]". Data mining and machine learning were developed in the later years of the 20th century, when the defense agencies of the US government, along with large corporations including credit card companies, were faced with huge quantities of data. They started to "mine" this data by using computer programs which can "learn" from that specific data[66]. The data is divided in half and the computer, using complex programs, develops statistical models fitting the first half of the data that can be applied to the second half of the sample by adjusting these statistical models. Unfortunately, these models developed by data mining/machine learning are "black box" models. The computer learns that, by combining an X number of variables you can classify the data almost perfectly, but the computer does not provide an exact description of how to combine these variables. The "learned" model is usually based on extremely complex mathematical combinations. In a second complex step, called forensic analysis, once a model is developed, the classificatory properties of the model can be examined by studying specificity, sensitivity and accuracy[68]. The relationship between classically-trained statisticians and the bioinformaticians and engineers with expertise in data mining was originally antagonistic[66]. As data mining became more widespread and then won the battle, and statisticians and data miners started to

Table 2	Redefinition of Syndromes by Molecular Genetics
DI GEORGE SYNDROME	
Using 19th century mechanistic thinking, 20th century physicians described the Di George syndrome and the velocardiofacial syndrome. Then, 21st century discoveries in molecular genetics allowed medical science to better reconsider these two apparently different but somewhat overlapping syndromes and reclassify them as the 22q11.21 deletion syndrome. The location and size of the chromosome deletion in each individual patient explains the extension of the syndrome's signs and symptoms[61].	
LYNCH SYNDROME	
In the middle of the 20th century, Lynch described a familial form of colon cancer that was different from familial adenomatous polyposis; later it was called Lynch syndrome. Then recently some gene variations in genes relevant for repairing DNA were identified and associated with an autosomal dominant transmission. These gene variations confer risk not only for colon cancer but other cancers. So the current definition of Lynch syndrome is based on molecular genetics. This disorder can manifest in multiple types of cancers outside of the colon, although early and familial forms of colon cancer are the most frequent presentations of the syndrome[62].	

contemporize[69]. Pioneers in data mining such as Edward R. Dougherty, a US engineer, criticized data mining in the biological sciences such as genomics, which he said is degenerating into non-scientific approaches because it is not paying attention to the basic principles of science, such as the need for experimental design or operational definitions[70].

In summary, statistical methods try to establish whether the reality found in medicine fits these mathematical models, but statisticians are beginning to realize that, in the process of finding significant results in a specific study, they have developed mathematical models that fit the data to that specific study too well. Statisticians call this "overfitting". Therefore, overfitting is not only a major problem in complex traditional statistical models; it is also a major threat in new data mining techniques which, due to their exploratory nature, are particularly prone to overfitting[71]. For medical research to move forward, these statistical models need to 1) move from the emphasis on a model that fits a specific study well to the reproducibility of results across multiple studies, and 2) balance the average results of a group with the need to focus on unusual individuals who may not be represented by the average[2].

THE CONTEXT OF THE PHYSICIAN THINKER

The Biopsychosocial Model of Disease

George Engel (1913-1999) was an internist who trained in psychoanalysis and worked at the University of Rochester in New York. In 1977, he published a very influential article in the journal *Science* comparing the biopsychosocial model of disease with the biomedical model[72]. The biopsychosocial model was further extended in a 1980 article[73]. Engel's biopsychosocial model was very influential, particularly in US psychiatry, whose two antagonistic sides (biological psychiatry and psychoanalysis) settled on an artificial truce as a result[4]. McLaren[74] has criticized Engel for not defining his model; he just provided a description of how it might function. Ghaemi[75] has provided a more comprehensive critique of Engel's model while Fava has recently defended it[76]. Many 21st century authors[77-79] with different approaches and backgrounds agree that Engel's biopsychosocial approach has degenerated into a bio-bio-bio approach in psychiatry which is contaminated by an extreme form of biological reductionism. In the view of this author, the biopsychosocial approach in medicine and psychiatry can be more specifically applied by using narrative, mechanistic and mathematical thinking and knowing when to apply each of these types of thinking. Psychiatry is a unique medical specialty 1) that has many more narrative components than other medical specialties, and 2) in which mechanistic thinking is 150 years behind[5,80] because the specialty's organ, the brain, is too complex to develop good mechanistic thinking. Moreover, some argue that mathematical thinking may be particularly difficult as a means of managing psychological symptoms[81,82]. As a matter of fact, a recent landmark study has demonstrated that many psychological findings previously considered to be well-established could not be replicated[83].

The Patient as the Center

Human beings are very complex individuals. Medical education should emphasize that each patient is an individual and medical activity should focus on the patient. Even medical scientists stress that medical research needs to be patient-centered in order to be useful[84,85]. The patient also has to be at the core of a proper application of the biopsychosocial model, according to Schwartz and co-workers[86] and Saraga and co-workers[87].

Unfortunately, recent proposals describing the patient as center use multiple overlapping terms (personalized medicine[88], precision medicine[89], stratified medicine[90] and person-centered medicine[91]) that mean different things for different authors[92].

The Physician as an Expert

As medicine is becoming more complex and more health professionals serve as physician extenders, it is clear physicians need to become "experts[93]" so that they cannot be replaced by advances in computers and artificial intelligence. Unfortunately, the scientific approach has not been particularly successful in studying and explaining some of the more complex concepts of human life, such as expertise, but researchers from different areas including educational sciences[94] are trying to define what an "expert" is. In the view of the author[2], physician educators become experts when medical students and residents select them for their teaching. Similarly, the best proof that a physician has become an expert clinician is when multiple physicians around him or her decide to recommend him/her to their family members and friends.

It is interesting that some of these experts in education[94,95] are starting to realize that understanding some of the most complex concepts of learning and expertise requires consideration of some of the complex concepts about education that classic thinkers such as Aristotle developed, including what he called virtues[96,97]. The idea of teaching about virtues is reaching medical education[98]. Furthermore, some new psychological theories are trying to incorporate some of these very complex but important concepts about human persons including the self-determination theory[99], which focuses on autonomy, competence, and relatedness.

This theory has been incorporated in medical education[100]. Moreover, when we teach patients, which is called psychotherapy, it needs to be centered on what the patient thinks is important[101]. Physicians must also consider the concept of self-leader which includes the needs for achievement, self-regulation and self-efficacy. Self-leaders can be good leaders for others[102]. In summary, computers can never replace a self-reflective medical expert who is aware of his/her own strengths and limitations, as well as the strengths and limitations of his/her patients. It is not clear that artificial intelligence can imitate the creative thinking that is needed to develop new important advances in medicine. However, current medical education does not appear to the author to be able to provide an appropriate environment for developing new physician scientists who can integrate and master the art of medicine, scientific mechanistic thinking and scientific mathematical thinking. In an environment dominated by "big data" and information overload[23], physicians need to develop better thinking approaches in order to navigate an environment overloaded with confusing information which is dominated by the melding of corporate capitalism and communication technologies[103]. At this time, it may be important to remember the words of the poet T.S. Elliot "Where is the wisdom we have lost in knowledge? / Where is the knowledge we have lost in information[104]?"

To face 21st century challenges, medical education needs to move from implicit to explicit thinking and teach that medical thinking is not scientific thinking, although it should be supported by scientific thinking. Physicians are not scientists; they are practitioners who combine narrative, mechanistic and mathematical thinking in their practice. A prior article[18] provides an example of how to combine narrative, mechanistic and mathematical thinking in psychopharmacology.

CONCLUSION

Medical education has 2,500 of history (Table 1). This article tries to contribute to medical education by classifying medical thinking into three types: narrative, mechanistic and mathematical thinking. Narrative thinking has dominated Western medicine since its birth in Greece 2500 years ago until the 19th century and has led to the belief that medicine is mainly an art. The science of medicine should combine mechanistic and mathematical thinking. Mechanistic thinking was definitively established in medicine in the 19th century by Bernard[11]. Mathematical thinking was introduced in medicine by Louis[37-39] in the 19th century in his crusade against the use of bloodletting.

In the 19th and 20th centuries, physicians grouped symptoms and signs into syndromes with the hope of separating each syndrome into various diseases based on etiopathological and/or physiopathological mechanisms[3,18], as their knowledge grew. In the 20th century, 1) narrative medicine took a non-scientific turn with Freud[5]; 2) mechanistic thinking led to clinimetrics[58] and set the stage for the application of mechanistic genetics in 21st century medicine, which defines disease using molecular genetics; and 3) mathematical thinking led to the application of the frequentist approach and the development of RCTs and meta-analysis, which led to the collision between EBM and personalized medicine[2]. In the 21st century, data mining or machine learning[66] is substituting for statisticians in the management of big data.

If 21st century physicians do not want to be replaced by computers they need to abandon the teaching by example that only provides "tacit knowledge[19]", which has dominated medicine for 2500 years. They must make explicit the strengths and weaknesses of their thinking. This article proposes that the three types of medical thinking, narrative, mechanistic and mathematical, need to be incorporated within the context of the physician thinker, whose expertise should include a biopsychosocial orientation with the patient as its center. Computers will never displace a self-reflective medical expert who is aware of his/her strengths and limitations on three levels: 1) self level, 2) patient level and 3) environmental level, where information is dominated by the melding of corporate capitalism and communication technologies[103]. Twenty-first century physicians need to become better thinkers if they want to serve their patients well, survive automatization, and contribute to advances in medicine. They need to value knowledge more than information and aspire to wisdom.

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CONFLICTS OF INTEREST

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Mathematical thinking, by contrast, is a specific way of thinking about things in the world. It does not have to be about mathematics at all, though I would argue that certain parts of mathematics provide the ideal contexts for learning how to think that way, and in this book I will concentrate my attention on those areas. Mathematicians, scientists, and engineers need to â€œdo math.â€Â (Though once you have learned how to think mathematically, getting the right answer becomes a lot easier than when you were just following procedural recipes.) If you want to know if you have got something rightâ€”and we all doâ€” you should seek out someone who knows. Deciding whether a piece of mathematical reasoning is correct is a value judgment that requires expertise. This chapter focuses on the ideas of narrative thinking and storytelling in school science education. In distinguishing between narrative and paradigmatic (or logico-mathematical) thinking, the...Â Kieran Egan, in Teaching as Storytelling, p. 5. A first insight into modern narrative theory regards the fact that every good story has a consistent plot.