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4 What is a medical theory?

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1. INTRODUCTION

Modern medicine has produced many successful theories concerning the causes of diseases. For example, we know that tuberculosis is caused by the bacterium *Mycobacterium tuberculosis*, and that scurvy is caused by a deficiency of vitamin C. This chapter discusses the nature of medical theories from the perspective of the philosophy, history, and psychology of science. I will review prominent philosophical accounts of what constitutes a scientific theory, and develop a new account of medical theories as representations of mechanisms that explain disease.

An account of the nature of medical theories should illuminate many aspects of the development and application of medical knowledge. Most importantly, it should contribute to understanding of medical explanation, both at the general level of causes of diseases and at the individual level of diagnosis of particular cases of a disease. Medical researchers seek to explain the causes of diseases such as tuberculosis, while physicians seek to identify diseases that explain symptoms such as fever. A medical theory such as the bacterial theory of tuberculosis provides good explanations at both the general and individual levels. The primary aim of this chapter is to show how these explanations work. A secondary aim is to show how an account of medical theories can shed light on other aspects of medical research and practice, including the nature of medical discovery, the process of evaluation of competing medical theories, and the ways in which effective treatments of disease depend on the development of good mechanistic theories about diseases.

2. SOME MEDICAL THEORIES

Before examining various accounts of what theories are, it is useful to review some important examples of medical theories. Until the advent of modern scientific medicine in the middle of the nineteenth century, the world's predominant medical theories attributed diseases to various kinds of bodily imbalances. In Europe, the humoral theory of disease originated with Hippocrates around 400 B.C. It held that diseases arise because of imbalances in the body's four humors: blood, phlegm, yellow bile, and black bile. Treatment consisted of attempts to restore the proper balance by ridding the body of excessive quantities of blood, bile, or phlegm by techniques, such as bloodletting and purgatives.

Humoral medicine is no longer practiced, unlike traditional Chinese medicine which is also based on a theory that diseases are caused by imbalances. According to Chinese medicine, which is even older than the Hippocratic theory, everything in the universe including the human body is governed by principles of *yin* and *yang*. Diseases arise when the body has an improper balance of these principles, and they can be treated by herbs and other techniques that restore the proper balance. Thagard and Zhu (2003) describe the conceptual structure and explanation patterns of traditional Chinese medicine.

Traditional Indian medicine is similarly ancient, and also explains diseases as arising from imbalances. Lad (2003) describes the doctrine of Ayurveda as follows:

> According to Ayurveda, health is a state of balance between the body, mind and consciousness. Within the body, Ayurveda recognises the three *doshas*, or bodily humors *vata*, *pitta* and *kapha*; seven *dhatus*, or tissues, plasma, blood, muscle, fat, bone, nerve, and reproductive; three *malas*, or wastes; feces, urine and sweat; and *agni*, the energy of metabolism. Disease is a condition of disharmony in any of these factors. The root cause of imbalance, or disease, is an aggravation of *dosha*, *vata*-*pitta*-*kapha*, caused by a wide variety of internal and external factors.

Thus ancient theories of medicine all attributed diseases to imbalances.

Modern scientific medicine emerged in the 1860s and 1870s, when Louis Pasteur and others originated the germ theory of disease, according to which contagious diseases such as cholera are caused by microorganisms like bacteria. The germ theory is really a class of theories applying to many specific diseases, each of which is associated with a specific infectious agent. These include the bacterium that causes cholera, the virus that causes

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AIDS, the protozoan that cause malaria, the fungus that causes athelete's foot, and the prions that cause spongiform encephalopathies (e.g. mad cow disease).

The twentieth century saw development of additional classes of medical theories. Nutritional diseases, such as scurvy and beriberi are explained by deficiencies in nutrients such as vitamins. Autoimmune diseases such as lupus erythematosus are explained by the immune system becoming overactive and attacking bodily tissues. Genetic diseases such as cystic fibrosis are explained by mutated genes that cause defects in the physiological functioning. Other maladies, such as heart disease and cancer are often caused by combinations of genetic and environmental factors. See Thagard (1999) for a review of the explanation patterns associated with these classes of disease.

All these medical explanations are consistent with the following first attempt to provide an account of the nature of medical theories:

Analysis 1: A medical theory is a hypothesis about the cause or causes of a particular disease.

This account does not go very far, however, because it says nothing about the nature of hypotheses and the causal explanations intended to link diseases with causes. In search of a deeper account, I will now examine the major philosophical views of the nature of scientific theories.

3. PHILOSOPHICAL VIEWS OF THEORIES

Here are the most influential accounts of the nature of theories that philosophers have so far proposed:

- Syntactic: A theory is a collection of universal generalisations in a formal language.
- Model-theoretic: A theory is a set-theoretic structure.
- Paradigm: A theory is a world view based on exemplars.
- Third-world: A theory is an abstract entity in an autonomous, non-physical, non-mental world.
- Cognitive: A theory is a mental representation of mechanisms.

I will explain each of these accounts and assess them with respect to how well they apply to the history of medicine and with respect to how much they shed light on the nature of explanation, evaluation, discovery, and treatment.

In the 1950s and 1960s, the syntactic view was the accepted one in the philosophy of science (see, for example, Hempel, 1965; Nagel, 1961; Suppe, 1977). The logical positivists thought that theories could be represented by universal generalisations in a formal language such as predicate calculus. For example, we might formalise the *Plasmidium* theory of malaria by an expression such as (x)(Px $\rightarrow$ Mx) and (x)(Mx $\rightarrow$ Px), which say that anyone infected by this parasite gets malaria, and that anyone with malaria has been infected by the parasite. There are many problems with this syntactic account that I can mention only briefly. First, relationship between causes and diseases are rarely universal, because there are usually many interacting factors involved, some of them unknown. In contagious diseases, there are usually many more people infected by the relevant microorganism than those that come down with the disease. Second, universal generalisations are inadequate to characterise causality, because they cannot distinguish between cases where a generalisation is true accidentally and ones where it derives from underlying causal structure. Third, the syntactic view of theories assumes that explanation is a matter of logical deduction from universal generalisations, but it is rare outside physics for scientists to be able to generate deductive explanations. In medicine, there is rarely a tight deductive relationship between hypotheses about causes and the diseases they explain. Finally, the syntactic account of theories has nothing to say about how medical hypotheses can be discovered or about how they can be used to suggest treatments of disease.

The model-theoretic (sometimes called the semantic) account of theories was devised to overcome the excessively linguistic nature of the syntactic account (see Suppe, 1977). A model in the relevant sense is a structure consisting of a set of objects that provides an interpretation for sentences in a formal language. On this account, what matters about a theory is not its particular linguistic expression, but rather its specification of a set of models that are intended to include the world. The model-theoretic account is difficult to apply to medical theories because they are rarely susceptible to formalisation. Moreover, this account has nothing to say about the nature of explanation, causality, discovery, and treatment. Hence it is clear that we need a richer conception of medical theories.

In 1962, Thomas Kuhn published *The Structure of Scientific Revolutions*, which introduced the term *paradigm* into the philosophy and history of science. Should we consider a medical theory as a paradigm? Kuhn's use of the term was notoriously vague, but he eventually identified two key senses, as a world view and as a set of exemplars, which are standard examples of problem solutions (Kuhn, 1977). Neither of these senses applies well to medical theories. Even the most general medical theory, the germ theory of disease, does not constitute a world view, and it is not evident what in medical science constitutes an exemplar. Kuhn had some important insights about scientific theories as a part of conceptual systems and about the magnitude of conceptual change in the development of knowledge, but these can be pursued more fruitfully within the cognitive account of theories discussed in the next section.

Karl Popper's (1959) early work in the philosophy of science was similar to the logical positivist's view of theories as syntactic structures. But he later proposed that theories are part of a third world of intelligibles distinct from the first world of physical objects and the second world of mental states. The third world is "the world of possible objects of thought; the world of theories in themselves, and their logical relations; of arguments in themselves; of problem situations in themselves" (Popper, 1972, p. 154). I fail to see, however, what is gained by postulating this mysterious additional world. In accord with contemporary cognitive science, I would deny even the division between Popper's first and second worlds: mental states are physical states of the brain. Moreover, Popper's treatment of theories as abstract entities in an autonomous world sheds no light on questions of evaluation, causality, and discovery, and we have already seen reasons to doubt the deductive view of explanation that Popper assumes. Hence I will now turn to what I think is a more plausible view of medical theories.

4. THE COGNITIVE CONCEPTION OF THEORIES

Cognitive science is the interdisciplinary investigation of mind and intelligence, embracing the fields of psychology, neuroscience, linguistics, philosophy, and artificial intelligence. Since its origins in the 1950s, the central hypothesis of cognitive science has been that thinking is a kind of computational process in which algorithmic procedures operate on mental representations. A mental representation is a structure in the mind/brain that stands for something. This hypothesis has been fertile in generating explanations of many aspects of thinking, such as problem solving, learning, and language use.

From the perspective of cognitive science, it is natural to think of a scientific theory as a complex of mental representations, including concepts, rules, and visual images (see Thagard, 1988, 1992, 1999; and Giere 1988, 1999). Moreover, the main processes involving scientific theories, including discovery, explanation, and evaluation, can be understood computationally. Discovery is an algorithmic process of building new representations, and medical explanation is a process of connecting a representation of a disease with a representation of a relevant cause. Evaluation of competing theories is a computational process that determines which is the best explanation of all the evidence.

The cognitive perspective suggests the following answer to the question of what is a medical theory:

Analysis 2: A medical theory is a mental representation of the cause or causes of a disease.

This analysis is still very general, however, because it neither specify the kinds of mental representations that are involved in the explanation of diseases, nor does it detail the particular kinds of mental procedures that produce discovery, explanation, and evaluation. To show how the cognitive conception can give a rich account of medical theories, I will work through a case history of a novel disease, SARS.

5. CASE STUDY: SARS

Severe acute respiratory syndrome (SARS) was first reported in China in February, 2003, and quickly spread to other countries (CDC, 2004). More than 8,000 people became sick with SARS, of whom more than 900 died. The symptoms of SARS include high fever, headache, discomfort, body aches, dry cough, and the development of pneumonia. SARS is spread by close contact involving respiratory droplets.

The cause of SARS was identified with remarkable speed. In March, 2003, a novel coronavirus, now called SARS-CoV, was discovered in patients with cases of SARS. By April, there was strong evidence that this virus caused the disease (Ksiazek et al., 2003). Moreover, by May, investigators had sequenced the complete genome of SARS-CoV, showing that it is not closely related to previously characterised coronaviruses (Rota et al., 2003). Thus in a matter of months medical researchers managed to discover the plausible cause of the new disease. The medical theory here is: SARS is caused by the virus SARS-CoV. Let us now look at this theory as a kind of mental representation.

First, what is the mental form of the concept of SARS? The traditional view of concepts is that they are defined by necessary and sufficient conditions, so that we would have a definition of the form: person P has SARS if and only if P has the symptoms X, Y, and Z. There is abundant psychological evidence, however that the traditional view does not adequately characterise mental concepts (Murphy, 2002). A prominent alternative theory of concepts is that they consist of prototypes that describe typical rather than universal features of the objects that fall under a concept. Accordingly, we should think of a disease concept as involving the specification of a set of typical features involving symptoms as well as the usual course of the disease. Here is an approximate prototype for SARS, in the form of a structure that artificial intelligence researchers such as Winston (1993) call a frame:

SARS:

A kind of: infectious disease.

Typical symptoms: high fever, dry cough, lung infection.

Typical course: fever, then cough, then pneumonia.

Typical treatment: antiviral drugs, isolation.

Cause: SARS-CoV.

This structure is flexible enough to allow the existence of SARS patients whose symptoms and disease development are not typical.

How are symptoms mentally represented? In some cases, a purely verbal representation is adequate; for example, ‘‘temperature greater than 38 degree Celsius’’. But there is enough evidence that human minds also operate with visual, auditory, and other kinds of representations. A physician’s representation of *dry cough*, for example, may be an auditory and visual prototype based on extensive clinical experience with many patients with dry and wet coughs. Similarly, part of the mental representation of pneumonia may be based on visual images of X-rays that show what pneumonia typically looks like.

Even more obviously visual is the representation of the cause of SARS, the virus SARS-CoV. Pictures and diagrams of this virus and its relatives are available on the web, at such sites as:

- http://www-micro.msb.le.ac.uk/3035/Coronaviruses.html
- http://www.rkm.com.au/VIRUS/CORONAVIRUS/index.html.

Viruses are too small to be photographed through ordinary microscopes, but electron microscopy reveals their basic structure. The term ‘‘coronavirus’’ derives from the crown-like appearance of this class of viruses in images generated by electron microscopes. Hence the mental representation of the SARS virus is multimodal, including both verbal information such as that its genome has 29,727 nucleotides, and visuospatial information about its shape and structure. Diagrams are also very useful for displaying the genome organization and protein structure of the SARS virus (Rota et al., 2003). It is not unusual for human concepts to be grounded in modality-specific systems: Barsalou et al., (2003) reviewed experimental evidence that conceptual processing activates modality-specific brain areas.

Thus it is plausible that the mental representation of both the disease SARS and its cause, the SARS-CoV coronavirus, are multimodal, involving visual as well as verbal representations. Now we get to the hard part: how does the mind represent *cause*? Philosophers have attempted to give verbal reconstructions of the concept of causality, from Hume on constant conjunction to Kant on the causal schema to modern philosophers who have tried to tie causality to probability theory. I suspect that all these attempts have failed to characterise causal knowledge because they neglect the fact that people's understanding of causality is also multimodal. I do not know whether this understanding is innate or learned very early, but people acquire or instantiate the concept of causality through non-verbal perceptual experiences, including ones that are visual, tactile, and kinesthetic (Michotte, 1963). Even infants have strong expectations about what they can expect to see and what they can expect to happen when they interact with the world. Baillargeon, et al. (1995) report that infants as young as 2.5 months expect a stationary object to be displaced when it is hit by a moving object. By around 6 months, infants believe that the distance traveled by the stationary object is proportional to the sise of the moving object. Thus at a very primitive stage of verbal development children seem to have some understanding of causality based on their visual and tactile experiences.

The brain contains regions of the parietal and prefrontal cortices that serve to integrate information from numerous perceptual sources, and I speculate that understanding of causality resides in higher-level non-verbal representations that tie together such visual/tactile/kinesthetic perceptual inputs. Various writers in philosophy and psychology have postulated *causal powers* that go beyond relationships, such as co-occurrence and conditional probability (Cheng, 1997; Harré and Madden, 1975). My multimodal hypothesis suggests how this appreciation of causal powers may operate in the mind. Children know little about logic and probability, but they quickly acquire a sense of what it is for one event to make another happen. Understanding of simple mechanisms such as the lever and even of complex ones such as disease production depends on this preverbal sense of event causation.

In sum, the mental representation of the seemingly straightforward hypothesis that SARS is caused by a newly discovered coronavirus is highly complex and multimodal. Hence from the perspective of the cognitive conception of theories a medical theory is an integrated multimodal representation. Formation of such theories requires building verbal, visual, and other perceptual representations of the disease and its cause. Cognitive science is replete with detailed computational theories of the acquisition of concepts, so the cognitive approach can easily address the problem of understanding how medical theories are discovered. Similarly, there is a well-developed psychological theory and computational model of explanatory coherence that describes how competing theories can be evaluated using artificial neural networks (Thagard, 1992). This leaves the major problem of saying how the cognitive conception of theories can shed light on the nature of medical explanation, which requires attention to the topic of mechanisms. This discussion will also illuminate the relationship between diseases and their causes.

6. MECHANISMS AND EXPLANATIONS

As I have argued elsewhere, modern explanations of disease based on molecular biology are largely concerned with biochemical mechanisms (Thagard, 2003). To understand what biological mechanisms are, it is useful to examine the nature of machines created by people. In general, a machine is an assemblage of parts that transmit forces, motion, and energy to each other in order to accomplish some task. To describe a machine and explain its operation, we need to specify its parts, their properties, and their relation with other parts. Most importantly, we need to describe how changes to the properties and relationships of the parts with respect to force, motion, and energy enable the machine to accomplish its tasks.

Consider the basic lever shown in fig. 1. It consists of only two parts, a stick and a rock. But levers are very powerful and have enabled people to build huge structures such as the Egyptian pyramids. The lever in fig. 1 operates by virtue of the fact that the stick is rigid and is on top of the rock, which is solid. Applying force to the top of the stick (tactile and kinesthetic perception) makes the bottom of the stick to move and lift the block (visual perception), thus accomplishing the machine's task. Similarly, biological mechanisms can be explained by identifying the relevant parts and interactions.

My approach to medical theories is in keeping with the mechanism-based view of explanation espoused by such philosophers of science as

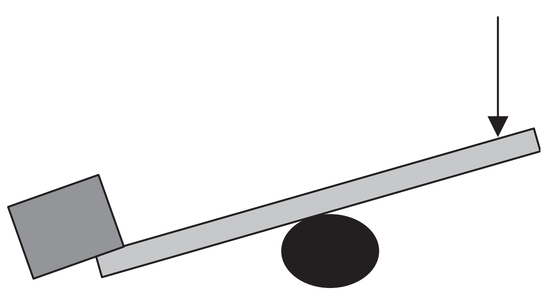

Fig. 1. A simple machine, the lever.

Salmon (1984) and Bechtel and Richardson (1993). Machamer, et al. (2000, p. 3) characterise the mechanisms as ''entities and activities organised such that they are productive of regular changes from start or set-up to finish or termination conditions''. I prefer the term ''part'' to ''entity'' because it indicates that the objects in a mechanism are part of a larger system; and I prefer ''interaction'' and ''change'' to ''activity'' because they sound less anthropomorphic. More importantly, I find the reference to start and finish conditions highly misleading, because the biochemical mechanisms needed to explain biological functioning often involve ongoing feedback processes rather than unidirectional changes. Hence I will simply say that a mechanism consists of a group of parts that have properties and relationship with each other that produce regular changes in those properties and relationships, as well as to the properties and relationships of the whole group.

To apply this to medical explanations, we need to identify for a particular disease the biochemical mechanisms that cause it. The general mechanisms for viral infection and disease causation are well understood (e.g. Freudenrich, 2004). A virus typically has three parts: nucleic acid, consisting of DNA or RNA, which contains genetic instructions; a coat of protein that protects the nucleic acid; and a lipid membrane or envelope that surrounds the coat. For the SARS coronavirus, the envelope carries three glycoproteins, including a spike protein that enables the virus to bind to the cell receptors. Once a virus has attached itself to a cell, it enters it and releases its genetic instructions that recruit the cell's enzymes to make parts for new viruses. The parts are assembled into new viruses, which then break out of the cell and can infect other cells. Schematically, the mechanism is:

$$\text{Attachment} \longrightarrow \text{entry} \longrightarrow \text{assembly} \longrightarrow \text{replication} \longrightarrow \text{release.}$$

Viral replication in itself does not produce disease symptoms, which can arise from two sorts of mechanisms. First, viral release may directly cause cell damage or death, as when the SARS virus infects epithelial cells in the lower respiratory tract. Second, the presence of the virus will prompt an autoimmune response in which the body attempts to defend itself against the invading virus; this response can induce symptoms such as fever that serves to slow down the virus replication. Schematically, these two mechanisms are:

$$\text{Viral infection} \longrightarrow \text{cell damage} \longrightarrow \text{symptoms;}$$
$$\text{Viral infection} \longrightarrow \text{immune response} \longrightarrow \text{symptoms.}$$

Obviously, these mechanisms of disease symptom causation can be broken down much further by specifying the relevant parts, such as the proteins responsible for viral replication and the autoimmune cells that attack viruses, and the relevant processes, such as cell destruction and autoimmune responses. These two kinds of mechanisms, in company with the mechanisms of viral activity, together explain how viruses such as the SARS-CoV cause diseases like SARS.

A similar mechanistic account of medical explanation can be given for many other genetic, nutritional, autoimmune, and cancerous diseases. Hence we can enhance the cognitive conception of the nature of medical theories as follows:

Analysis 3: A medical theory is a mental representation of mechanisms that generate the states and symptoms of a disease.

Note that the parts and changes in biological mechanisms are often represented visually as well as verbally, so for most medical theories the mental representation is multimodal. Disease explanation is a mental process of manipulating representations of mechanisms to link their parts and changes to representations, which may also be multimodal, of states and symptoms of diseases. I use the phrase ‘‘states and symptoms’’ to acknowledge that people may have diseases before they display any symptoms.

Although the word ‘‘cause’’ has been dropped in the enhancement of analysis 2 by analysis 3, I do not mean to suggest that causality can be replaced by mechanism in the explanation of disease. Saying that the parts and interactions of a mechanism *produce* regular changes are equivalent to saying that they cause regular changes, so we need to maintain the unanalysed, multimodal concept of causality that I proposed earlier. Attempts to analyse causality away by means of concepts of universality or probability have been unsuccessful, and my account of medical explanation does not try to eliminate causality from understanding of theories and explanations. Rather, I propose that people’s comprehension of machines and mechanisms presupposes an intuitive notion of causality that derives from non-verbal experience.

Analysis 3 gives a good account of the nature of medical theories as they are currently used by medical researchers and practitioners. Discovery of disease explanations involves formation of hypotheses about mechanisms that link causal factors such as microorganisms with disease states and symptoms. Evaluation of competing theories involves determining the most plausible set of mechanisms for producing a set of symptoms. In the case of SARS, a dominant theory of disease causation was generated with remarkable speed, although many other diseases remain unexplained. However, there is a serious limitation in analysis 3 that I now want to address.

7. DISTRIBUTED COGNITION

Medical theories are representations of biochemical mechanisms, but increasingly such representations are to be found, not in minds or books, but in computer databases. I will briefly describe several such databases and then discuss their implications for understanding the nature of medical knowledge.

Here are six major computer databases of the sort that are becoming increasingly important for understanding the causes of diseases.

1. Metabolic Pathways of Biochememistry
   URL: http://www.gwu.edu/~mpb/
   Function: Graphically represents, in 2D and 3D, all major metabolic pathways, including those important to human biochemistry.
2. ExPASy (**Ex**pert **P**rotein **A**nalysis **Sy**stem) Molecular Biology Server
   URL: http://us.expasy.org/
   Function: Dedicated to the analysis of protein sequences and structures.
3. Biomolecular Interaction Network Database (BIND)
   URL: http://www.bind.ca/index.phtml
   Function: Designed to store full descriptions of interactions, molecular complexes, and pathways.
4. The MetaCyc metabolic pathway database
   URL: http://MetaCyc.org/
   Function: Contains pathways from over 150 different organisms, describing metabolic pathways, reactions, enzymes, and substrate compounds.
5. KEGG: Kyoto Encyclopedia of Genes and Genomes
   URL: http://www.genome.ad.jp/kegg
   Function: A bioinformatics resource for understanding higher order functional meanings and utilities of the cell or the organism from its genome information.
6. Biocarta Pathways Database
   URL: http://www.biocarta.com/
   Function: Uses dynamical graphical models to display how genes interact to determine molecular relationships.

Figure 2 is a vivid example of the kind of pictorial information that is available in these databases. It shows a pathway that is necessary for understanding how defects in regulation of the protein CFTR can lead to cystic fibrosis. With rapid developments in genomics and proteomics, the biochemical bases for a number of diseases are being understood.

The development of these computer databases demonstrates a stark difference between theories in physics and those in biomedicine. A theory in physics such as Newtonian mechanics or relativity can be stated in a small

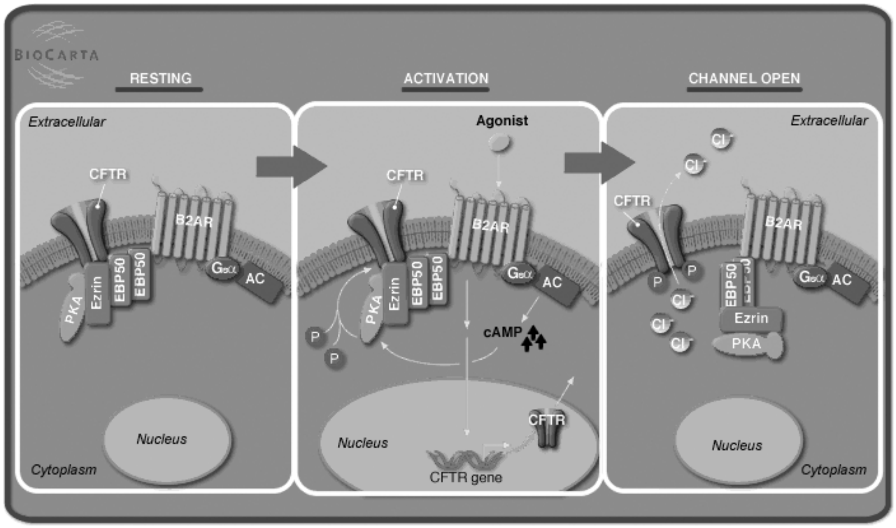

Fig. 2. Depiction of the pathway for CFTR regulation, whose defects are believed to be the major cause for cystic fibrosis. This diagram can be found on the web at http://biocarta.com/pathfiles/h_cftrPathway.asp. Reprinted with permission of BioCarta. See Plate 1 in Colour Plate Section.

number of equations that can be grasped by anyone who has taken the time to learn them. But no single human being has the time, energy, or memory capacity to learn even just the metabolic pathways for a simple organisms such as *E. coli*: the EcoCyc database contains information on 4363 *E. coli* genes, 165 pathways, and 2604 chemical reactions (Karp et al., 2002). Hence the biochemical understanding of any disease by a human scientist needs to be supplemented by access to computer databases that describe genes, proteins, and their interactions. Because biomedical mechanisms are being represented in computer databases, and not minds or books, the representation of the mechanisms for understanding diseases are distributed among various human minds and computers. Giere (2002) reached a similar conclusion about physics, arguing that research in high-energy physics is performed by a complex cognitive system consisting of an accelerator, detectors, computers, and all the people working on an experiment.

AQ: Changed to 'various human minds' OK?

Accordingly, I propose my final analysis of the nature of medical theories:

Analysis 4: A medical theory is a representation, possibly distributed among human minds and computer databases, of mechanisms whose proper and improper functioning generate the states and symptoms of a disease.

Analysis 4 does not contradict any of the previous 3 analyses offered above, but it expands them to allow the increasing role of bioinformatics in medical theorising. I have added the clause about ''proper and improper functioning'' to indicate that explanations of disease presuppose a background of normal biological operation that has broken down.

8. CONCLUSIONS

The extension of my analysis of medical theories to encompass bioinformatics does not undermine any of the criticisms made in section 3 of various philosophical accounts of the nature of theories. The syntactic, model-theoretic, paradigm, and third-world accounts still fail to capture the complexity of medical theories and explanations. In particular, they do not illuminate the ways in which multimodal representations of mechanisms are crucial to the explanation of disease.

Explanations of disease do not always need to go down to the deep biochemical level displayed in fig. 2. Depending on the problem and audience at hand, a medical explanation may operate at a superficial level, for example when physicians tell ordinary patients how they got sick. But explanation is not merely pragmatic: it should draw on established knowledge of mechanisms described at the level of detail appropriate for the task at hand. The most important task in medical research after determining the causes of diseases is developing treatments for them. Whereas drug discovery used to be largely a matter of serendipity or exhaustive search, current pharmaceutical research is based on deep understanding of the molecular bases of disease. Once investigators have identified how defective pathways lead to various diseases, they can search selectively for drugs that correct the defects (Thagard, 2003).

I have defended a cognitive account of medical theories, but there is a great need for further research in cognitive science to describe the mental structures and processes that are used in medical theory and practice. Psychology and the other fields of cognitive science have contributed to powerful theories of mental representation and processing, for example, theories of concepts, rules, images, and neural networks (Thagard, 2005). But here are some difficult unanswered questions that are crucial to further our understanding of how minds do medicine:

1. How do brains represent changes of the sort that mechanisms produce?
2. How do brains operate cooperatively with multimodal representations, for example combining verbal and visual information?
3. How do brains accomplish an innate or learned intuitive understanding of causality that emanates from integrated multimodal representations?
4. What would it take for computers to be able not only to contain information about genes, proteins, and pathways, but also to use that

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information to reason about them in order to generate explanations and treatments?

Thus there is much work to be done to develop the cognitive conception of medical theories from a philosophical account into a full-fledged psychological/computational theory of medical reasoning.

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