The Concept of Disease: Structure and Change

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Abstract

By contrasting Hippocratic and nineteenth century theories of disease, this paper describes important conceptual changes that have taken place in the history of medicine. Disease concepts are presented as causal networks that represent the relations among the symptoms, causes, and treatment of a disease. The transition to the germ theory of disease produced dramatic conceptual changes as the result of a radically new view of disease causation. An analogy between disease and fermentation was important for two of the main developers of the germ theory of disease, Pasteur and Lister. Attention to the development of germ concepts shows the need for a referential account of conceptual change to complement a representational account.

Laypeople are familiar with dozens of diseases such as influenza, chicken pox, and cancer. Medical personnel acquire concepts for thousands of additional diseases, from Alzheimer's to yellow fever. What is the nature of these concepts? Examination of historical and contemporary writings on disease suggests that disease concepts can best be viewed as causal networks that represent relations among the symptoms, causes, and treatment of a disease. Conceptual change concerning disease is primarily driven by changes in causal theories about diseases. To defend these claims, I will review some important developments in the history of medicine and describe the major changes that have taken place in the concept of disease.

I begin with the ancient Greek view of disease displayed in the writings attributed to Hippocrates, whose concepts are closely connected to the humoral theory of the causes of disease. This view dominated European medical thought until the development of the germ theory of disease, which was first hinted at in the sixteenth century but not developed and generally accepted until the nineteenth. Fracastoro, an Italian physician, wrote the first important work on contagion in 1546, but the modern germ theory of disease developed with the research of Pasteur, Lister, Koch, and others in the 1860s and 1870s. Transition from the humoral to the germ theory of disease required a major conceptual revolution,
involving many kinds of conceptual change including a fundamental shift in how diseases are classified. Less radical conceptual changes occurred in the twentieth century with the discovery of genetic, nutritional, and immunological causes of disease.

1. CONCEPTS

On the traditional, purely linguistic view, a concept is given by a definition that specifies necessary and sufficient conditions for its application. On this view, we should be able to provide definitions such as X is a disease if and only if ____, and X is tuberculosis if and only if _____. Like other concepts, however, the concept of disease has not succumbed to this kind of linguistic analysis (Reznek, 1987). Cognitive science has offered a different view of the nature of concepts, understanding them as mental representations; but the nature of conceptual representations has remained controversial. Theorists have variously proposed that concepts are prototypes, sets of exemplars, or distributed representations in neural networks (for reviews see Smith and Medin, 1981; Smith, 1989; Thagard, 1992, ch. 2; Thagard, in press, ch. 4.).

Recently, a growing number of psychologists have emphasized the role of causal connections in understanding the nature of concepts (Carey, 1985; Keil, 1989; Medin, 1989; Murphy and Medin, 1985). The concept of a drunk, for example, is not just a set of prototypical features or typical examples, but also involves causal relations that can be used to apply the concept in an explanatory fashion: if someone falls into a swimming pool fully clothed, we can say that it happened because he or she is a drunk.

Disease concepts are particularly interesting from this theoretical perspective, because they display a rich causal structure schematized in figure 1. Symptoms are the observable manifestations of a disease, which can develop over time in particular ways that constitute the expected course of the disease. The symptoms arise from the cause or causes (etiology) of the disease. Treatment of the disease should affect the symptoms and course of the disease, often by affecting the causal factors that produce the symptoms. For example, tuberculosis has a set of typical symptoms such as coughing and the growth of tubercles (nodules) in the lungs and elsewhere, along with a course that before the twentieth century often included wasting and death. The disorder most commonly affects the lungs, but tuberculosis can also infect many other parts of the body. In 1882, Robert Koch discovered that the cause of tuberculosis is a bacterium, now called , and in 1932, Gerhard Domagk discovered that this microbe can be killed by the drug Prontosil. The drug streptomycin was discovered in 1944 and proved effective in treating the disease. Hence today tuberculosis has a well-understood cause and a kind of treatment that is effective except for the emergence of bacterial strains resistant to antibiotics.
Understanding a disease concept as a causal structure like that shown in figure 1 is consistent with aspects of prototype and exemplar theories of concepts. Patients may have symptoms that approximately match a set of symptoms that typically occur in people with a particular disease. Medical personnel may have in mind particular examples of patients with a particular disease. But a disease concept is not fully captured by a set of typical symptoms or exemplars, because the causal relations are an important part of the conceptual structure, as historical examples will show (1).

2. CONCEPTUAL CHANGE

Thagard (1992) identified 9 degrees of conceptual change summarized in table 1. Conceptual change is not simply a matter of belief revision, since concepts are not simply collections of beliefs. Rather, they are mental structures that are richly organized by means of relations such as kind and part. All the major scientific revolutions in the natural sciences - Copernicus, Newton, Lavoisier, Darwin, Einstein, quantum theory, and plate tectonics - involved major changes in conceptual organization involving kind and/or part relations (Thagard, 1992). Such changes are far more important, both psychologically and epistemologically, than mundane changes such as adding new instances or even adding new concepts. The most radical kind of conceptual change is tree switching, which changes not only the branches of a hierarchy of concepts but also the whole basis on which classifications are made. Such changes are rare, but occurred in the Darwinian revolution when the theory of evolution by natural selection brought with it a new principle of classification. Before Darwin, species were largely classified in terms of similarity, but the theory of evolution added a more fundamental mode of classification in terms of descent. Darwin's trees of kinds of organisms were based on history of descent, not just on similarity. Today, the relatedness of different species can be identified by the degree of similarity of their DNA, providing a genetic, historical basis for classification that sometimes overrules more superficial similarities.

| 1. Adding a new instance of a concept, for example a patient who has tuberculosis. |
| 2. Adding a new weak rule, for example that tuberculosis is common in prisons. |
3. Adding a new strong rule that plays a frequent role in problem solving and explanation, for example that people with tuberculosis have *Mycobacterium tuberculosis*.

4. Adding a new part-relation, for example that diseased lungs contain tubercles.

5. Adding a new kind-relation, for example differentiating between pulmonary and miliary tuberculosis.

6. Adding a new concept, for example *tuberculosis* (which replaced the previous terms *phthisis* and *consumption*) or AIDS.

7. Collapsing part of a kind-hierarchy, abandoning a previous distinction, for example, realizing that phthisis and scrofula are the same disease, tuberculosis.

8. Reorganizing hierarchies by *branch jumping*, that is shifting a concept from one branch of a hierarchical tree to another, for example reclassifying tuberculosis as an infectious disease.

9. *Tree switching*, that is, changing the organizing principle of a hierarchical tree, for example classifying diseases in terms of causal agents rather than symptoms.

Table 1. Degrees of conceptual change, adapted from Thagard (1992), p. 35.

All of these kinds of conceptual change occurred in the development of the concept of disease, particularly during the transition to the germ theory. Accounts of conceptual change by other researchers in the history, philosophy, and psychology of science are reviewed at the end of this paper. With various kinds of conceptual change in mind, particularly branch jumping and tree switching, let us now look at some key developments in the history of the concept of disease.

3. HISTORICAL DEVELOPMENTS

**Hippocrates and the Humoral Theory**

Hippocrates was born on the Greek island of Cos around 460 B.C. We know little concerning what he himself wrote, but between 430 and 330 B.C. a body of medical writing was produced by him and his disciples. The Hippocratic approach to medicine, as interpreted by Galen and others, dominated European medical thought well into the nineteenth century (2).

Hippocrates developed a naturalistic approach to medicine that contrasted sharply with the religious views that preceded him. Figure 2 shows the causal network that the Hippocratics rejected, for example in their discussion of the "sacred disease", epilepsy. On the traditional view, epilepsy was caused by divine visitation, and hence could only be cured by using an appeal to the gods or other magic. Little was said of the existence of a physical disorder responsible for the observable symptoms. The Hippocratics
argued that epilepsy is no more sacred than any other disease, and contended that it is caused by an excess of phlegm, one of the four humors (fluids) that constitute the human body.

Figure 2. Causal structure of religious disease concepts.

The following quotes from Hippocratic treatises concisely summarize the humoral theory:

The human body contains blood, phlegm, yellow bile, and black bile. These are the things that make up its constitution and cause its pains and health. Health is primarily a state in which these constituent substances are in the correct proportion to each other, both in strength and quantity, and are well mixed. (Lloyd, 1978, p. 262)

All human diseases arise from bile and phlegm; the bile and phlegm produce diseases when, inside the body, one of them becomes too moist, too dry, too hot, or too cold; they become this way from foods and drinks, from exertions and wounds, from smell, sound, sight, and venery, and from heat and cold. (Hippocrates, 1988, p. 7).

To modern ears, the humoral theory sounds odd, but contextually it possessed a great deal of conceptual and explanatory coherence. Many of Hippocrates’ contemporaries believed that there are four fundamental elements: earth, air, fire, and water. These possess various combinations of the four qualities of moist, dry, hot, and cold; for example, fire is hot and dry. The four humors also possess these qualities in different degrees, so that bile tends to be hot and phlegm tends to be cold.

Diseases arise because of humoral imbalances. For example, too much bile can produce various fevers, and too much phlegm can cause epilepsy or angina. Imbalances arise from natural causes such as heredity (phlegmatic parents have phlegmatic children), regimen (diet and other behavior), and climate (temperature, wind, and moisture conditions). Different kinds of imbalance produce different diseases with symptoms and development that were acutely observed by the Hippocratics. They described in detail not only the symptoms of patients with a particular disease, but also the ways that the patients tended to develop toward recovery or death. The course of a disease was affected by the development of a particular humor, producing crises that signaled basic changes in patient outcome. Fevers were classified as tertian, quartan, and so on based on the number of days before a crisis occurred.

Treatment of a disease can address either the causes of the humoral imbalance by changing diet and environment, or the humoral balance itself. To rid the body of excess bile or phlegm, methods were used
to induce vomiting or evacuation of the bowels, and veins were opened to let blood. The use of emetics, purgatives, and phlebotomy remained standard medical practice well into the nineteenth century. These techniques make sense within the Hippocratic framework because they are means of changing fluid balances. Figure 3 displays the structure of the causal network underlying the Hippocratic concept of disease.

Figure 3. Causal structure of Hippocratic disease concepts.

The Hippocratics primarily classified diseases by symptoms, particularly in terms of the parts of the body affected by the diseases. The treatise *Affections* classified diseases as shown in table 2. The four seasons played an important role in Hippocratic discussions of diseases, because different seasons brought with them different amounts of the four qualities of heat, cold, moist, and dry, and therefore affected humoral balance.

<table>
<thead>
<tr>
<th>Diseases of the head</th>
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<tbody>
<tr>
<td>Diseases of the cavity</td>
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<tr>
<td>Acute diseases</td>
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</tr>
<tr>
<td>Other winter fevers</td>
<td></td>
</tr>
<tr>
<td>Summer fevers and pains</td>
<td></td>
</tr>
<tr>
<td>Tertian and Quartan fevers</td>
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</tbody>
</table>
Fractatoro and the Contagion Theory

Although some Hippocratics recognized that consumption (tuberculosis) is contagious, contagion played little role in medical explanations of disease until the work of Fracastoro, who was born in Verona about 1478. In 1525 he published a long poem about the newly-recognized disease syphilis, and in 1546 he published his major treatise on contagion.

Fracastoro did not deny the existence of bodily humors such as phlegm, but he contended that there is a large class of diseases caused by contagion rather than humoral imbalance. Persons can contract infections even if their humors are normally balanced. He defined a contagion as a "corruption which develops in the substance of a combination, passes from one thing to another, and is originally caused by infection of the imperceptible particles" (Fracastorius, 1930, p. 5.). He called the particles the seminaria (seeds or seedlets) of contagion. (I translate Fracastoro's "seminaria" as "seeds" rather than the customary but anachronistic "germs".) Fracastoro was unable to say much about the nature of these conjectured particles; bacteria were not observed by van Leeuwenhoek until 1683, and their role in infection was not appreciated until the 1860s. Fracastoro nevertheless discussed the causes and treatment of various contagious diseases.

He described how contagion can occur by direct contact, by indirect contact via clothes and other substances, and by long-distance transmission. In addition, he stated that diseases can arise within an individual spontaneously. His book has chapters for the arrangement of contagious diseases shown in table 3.

Table 2. Hippocratic classification of diseases, from (Hippocrates, 1988, pp. 2-3.).
The differences between diseases are explained by their having different "active principles", i.e. different seeds. Fracastoro distinguished between different kinds of fevers in part on the basis of their being caused by different kinds of contagion. Rather than abandoning the humoral theory, he blended it with his contagion theory, suggesting that seeds for different diseases have different analogies (affinities) for different humors. For example, the principles of syphilis have an affinity with thick phlegm, whereas those of elephantiasis have an affinity with black bile.

<table>
<thead>
<tr>
<th>Contagious fevers</th>
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<tbody>
<tr>
<td>The poxes and measles</td>
</tr>
<tr>
<td>Pestilent fevers</td>
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<tr>
<td>Pestiferous fevers</td>
</tr>
<tr>
<td>Contagious phthisis</td>
</tr>
<tr>
<td>Rabies</td>
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<tr>
<td>Syphilis</td>
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<tr>
<td>Elephantiasis</td>
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<tr>
<td>Leprosy</td>
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<tr>
<td>Scabies</td>
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</tbody>
</table>

Table 3. Fracastoro's classification of contagious diseases, from Fracastorius (1930).

Just as Fracastoro's contagion theory of disease postulates different causes than the humoral theory, it also recommends different treatments. Cure comes not from restoring a bodily imbalance, but from destroying or expelling the seeds of contagion. Remedies that destroy the seeds of contagion include extreme heat and cold, while evacuation of the seeds can be brought about by bowel movements, urination, sweating, blood-letting, and other methods. Methods of treatment thus overlap with those advocated by the Hippocrates, although Fracastoro urged that blood-letting not be used for contagious diseases that arise from without as opposed to those spontaneously generated from within. Figure 4 shows the causal structure of Fracastoro's conception of disease. The seminaria produce an infection that can be treated by destroying or expelling them.
According to Nutton (1990), Fracastoro’s theory of contagion was respectfully received by his contemporaries, although they tended to assimilate his views to the Galenist metaphor of “seeds of disease” which did not, unlike Fracastoro’s view, assume that such seeds are infectious agents transmitted from one person to another. Since no one had observed the seminaria postulated by Fracastoro, his hypothesis had no obvious advantage over Hippocratic assumptions that noxious airs rather than germs are a main source of epidemic diseases. After 1650, Fracastoro had little influence, although interest in his work revived in the nineteenth century when the modern germ theory emerged.

**Pasteur, Lister, Koch and the Germ Theory**

Louis Pasteur was a French chemist who in the 1850s turned his attention to the process of fermentation, including the production of lactic acid in sour milk and the production of alcohol in wine and beer. Many scientists at the time believed that fermentation and putrefaction were the result of spontaneous generation. Liebig, for example, contended in 1839 that fermentation in beer is not caused by yeast, but by the internal development of the beer. Pasteur was able to show that the yeast increased in weight, nitrogen, and carbon content during fermentation, and inferred that yeast is a living organism that is the cause of fermentation in beer and wine. He proceeded in the early 1860s to identify other organisms - bacteria - that produce lactic acid fermentation. To challenge directly the theory of spontaneous generation, he conducted ingenious experiments to show that fermentation does not take place in the absence of contamination by air. Pasteur's work greatly improved the manufacture of vinegar and wine, and he was invited in 1865 to investigate an epidemic of silkworm disease in the south of France, and he also took time to study cholera which had spread to France from Egypt. Naturally, Pasteur applied to silkworms some of the same microscopic techniques that had proven so fertile in his studies of fermentation.

Pasteur (and independently the British surgeon Joseph Lister) made the most important mental leap in the history of medicine, pursuing an analogy between fermentation and disease. They realized that just as fermentation is caused by yeast and bacteria, so diseases may also be caused by microorganisms. In 1878, Pasteur wrote concerning his work on fermentation:
What meditations are induced by those results! It is impossible not to observe that, the further we penetrate into the experimental study of germs, the more we perceive sudden lights and clear ideas on the knowledge of the causes of contagious diseases! Is it not worthy of attention that, in that Arbois vineyard (and it would be true of the million hectares of vineyards of all the countries in the world), there should not have been, at the time I made the aforesaid experiments, one single particle of earth which would not have been capable of provoking fermentation by a grape yeast, and that, on the other hand, the earth of the glass houses I have mentioned should have been powerless to fulfill that office? And why? Because, at the given moment, I covered that earth with some glass. The death, if I may so express it, of a bunch of grapes, thrown at that time on any vineyard, would infallibly have occurred through the saccharomyces parasites of which I speak; that kind of death would have been impossible, on the contrary, on the little space enclosed by my glass houses. Those few cubic yards of air, those few square yards of soil, were there, in the midst of a universal possible contagion, and they were safe from it. .... Is it not permissible to believe, by analogy, that a day will come when easily applied preventive measures will arrest those scourges which suddenly desolate and terrify populations; such as the fearful disease (yellow fever) which has recently invaded Senegal and the valley of the Mississippi, or that other (bubonic plague), yet more terrible perhaps, which has ravaged the banks of the Volga? (translated in Vallery-Radot 1960, pp. 287-289; for the original see Pasteur, 1922, vol. II, p. 547).

From silkworms, Pasteur moved on to diseases such as anthrax and rabies, applying his proverb to "seek the microbe". Some microbes such as the virus that causes rabies are too small to be identified by the microscopes available to Pasteur. The concept of germ underwent substantial changes as microbiology progressed, as I will describe in a later section.

According to Geison (1995, p. 36), "the old and widely accepted analogy between fermentation and disease made any theory of the former immediately relevant to the latter." But Pasteur's breakthrough was more than simple analogical transfer from the domain of fermentation to the domain of disease, for he had to revise the existing analogy. In an 1857 memoir, Pasteur disputed the influential view of Liebig that putrefaction is the cause of both fermentation and contagious diseases (Brock 1961, p. 28). From Liebig's perspective, fermentation and contagion are analogous because they are both caused by putrefaction (rotting). After the establishment of the germ theory of fermentation, Pasteur concluded that disease can be viewed as analogous in that it too is caused by germs. A new analogical mapping supplanted Liebig's. Pasteur seems to have had the revised analogy in mind even before he began work on silkworms in 1865: in his work on problems with wine fermentation in 1864 he wrote of "les maladies des vins", i.e. diseases of wines. See Holyoak and Thagard (1995, ch. 8) for a discussion of scientific analogies.

Pasteur developed the technique of heating milk and wine to prevent development of bacteria, but what is now called pasteurization is no help with diseases of humans (compare Fracastoro' ideas about heat!). Pasteur had no direct way of killing microorganisms, but he discovered how to prevent rabies using vaccination, an ancient technique of exposing people or animals to an attenuated strain of an infectious agent that had been successfully applied by Jenner to smallpox in the late eighteenth century.

The British surgeon Joseph Lister was quick to appreciate the significance of Pasteur's ideas about fermentation, writing in 1867:
Turning now to the question how the atmosphere produces decomposition of organic substances, we find that a flood of light has been thrown upon this most important subject by the philosophic researches of M. Pasteur, who has demonstrated by thoroughly convincing evidence that it is not to its oxygen or to any of its gaseous constituents that the air owes this property, but to the minute particles suspended in it, which are the germs of various low forms of life, long since revealed by the microscope, and regarded as merely accidental concomitants to putrescence, but now shown by Pasteur to be its essential cause, resolving the complex organic compounds into substances of simpler chemical constitution, just as the yeast plant converts sugar into alcohol and carbonic acid. ...

Applying these principles to the treatment of compound fracture, bearing in mind that it is from the vitality of the atmospheric particles that all mischief arises, it appears that all that is requisite is to dress the wound with some material capable of killing those septic germs, provided that any substance can be found reliable for this purpose, yet not too potent as a caustic. (reprinted in Brock , 1961, p. 84).

As a surgeon, Lister had seen many of his patients die from infection, but he realized that Pasteur's finding that germs cause fermentation suggested not only an explanation for why wounds become infected, but also a possible means of preventing infection. Knowing that carbolic acid had been used in Carlisle on sewage to prevent odor and diseases in cattle that fed upon the pastures irrigated from the refuse material, Lister (analogically) began to use carbolic acid to sterilize wounds, dramatically dropping the infection rate.

In the 1870s and 1880s, the German doctor Robert Koch demonstrated that anthrax and tuberculosis are caused by bacteria. Koch realized that there are many different kinds of bacteria, and specific kinds are responsible for specific diseases. By the 1890s, researchers had recognized that microbes much smaller than bacteria are responsible for rabies and many other diseases, and the modern concept of a virus originated. Antibiotic cures for bacterial infections were not developed until the 1930s. But in the latter half of the nineteenth century, sometimes called the golden age of bacteriology, researchers identified the microbial causes of many diseases listed in table 4. Even in recent years, new bacterial infections such as Lyme disease and Legionnaire’s disease have been identified, and evidence is mounting that peptic ulcers have a bacterial origin (see Thagard, forthcoming-a, forthcoming-b).

<table>
<thead>
<tr>
<th>Year</th>
<th>Disease</th>
<th>Organism</th>
<th>Discoverer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1877</td>
<td>Anthrax</td>
<td>Bacillus anthracis</td>
<td>Koch, R.</td>
</tr>
<tr>
<td>1878</td>
<td>Suppuration</td>
<td>Staphylococcus</td>
<td>Koch, R.</td>
</tr>
<tr>
<td>1879</td>
<td>Gonorrhea</td>
<td>Neisseria gonorrhoeae</td>
<td>Neisser, A.L.S.</td>
</tr>
<tr>
<td>1880</td>
<td>Typhoid fever</td>
<td>Salmonella typhi</td>
<td>Eberth, C.J.</td>
</tr>
<tr>
<td>1881</td>
<td>Suppuration</td>
<td>Streptococcus</td>
<td>Ogston, A.</td>
</tr>
<tr>
<td>1882</td>
<td>Tuberculosis</td>
<td>Mycobacterium tuberculosis</td>
<td>Koch, R.</td>
</tr>
<tr>
<td>Year</td>
<td>Disease</td>
<td>Pathogen</td>
<td>Discoverer</td>
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<tr>
<td>------</td>
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</tr>
<tr>
<td>1883</td>
<td>Cholera</td>
<td>Vibrio cholerae</td>
<td>Koch, R.</td>
</tr>
<tr>
<td>1883</td>
<td>Diphtheria</td>
<td>Corynebacterium diphtheriae</td>
<td>Klebs, T.A.E.</td>
</tr>
<tr>
<td>1884</td>
<td>Tetanus</td>
<td>Clostridium tetani</td>
<td>Loeffler, F.</td>
</tr>
<tr>
<td>1885</td>
<td>Diarrhea</td>
<td>Escherichia coli</td>
<td>Escherich, T.</td>
</tr>
<tr>
<td>1886</td>
<td>Pneumonia</td>
<td>Streptococcus pneumoniae</td>
<td>Fraenkel, A.</td>
</tr>
<tr>
<td>1887</td>
<td>Meningitis</td>
<td>Neisseria meningitidis</td>
<td>Weischselbaum, A.</td>
</tr>
<tr>
<td>1888</td>
<td>Food poisoning</td>
<td>Salmonella enteritidis</td>
<td>Gaertner, A.A.H.</td>
</tr>
<tr>
<td>1892</td>
<td>Gas gangrene</td>
<td>Clostridium perfringens</td>
<td>Welch, W.H.</td>
</tr>
<tr>
<td>1894</td>
<td>Plague</td>
<td>Yersinia pestis</td>
<td>Kitasato, S., Yersin, A.J.E.</td>
</tr>
<tr>
<td>1896</td>
<td>Botulism</td>
<td>Clostridium botulinum</td>
<td>van Ermengem, E.M.P.</td>
</tr>
<tr>
<td>1898</td>
<td>Dysentery</td>
<td>Shigella dysenteriae</td>
<td>Shiga, K.</td>
</tr>
<tr>
<td>1900</td>
<td>Paratyphoid</td>
<td>Salmonella paratyphi</td>
<td>Schottmuller, H.</td>
</tr>
<tr>
<td>1903</td>
<td>Syphilis</td>
<td>Treponema pallidum</td>
<td>Schaudinn, F.R., Hoffmann, E.</td>
</tr>
<tr>
<td>1906</td>
<td>Whooping cough</td>
<td>Bordetella pertussis</td>
<td>Bordet, J., and Gengou, O.</td>
</tr>
</tbody>
</table>


The germ theory viewed diseases in terms of a causal network similar to that of Fracastoro, but with much more detail about the nature of germs and possible treatments. Figure 5 displays very schematically the causal relations known to hold for many diseases by the end of the nineteenth century. The Hippocrates were largely confined to a taxonomy of diseases in terms of symptoms, and Fracastoro’s theory allowed only a limited causal classification based on kinds of contagion; but the germ theory of disease made possible a detailed and clinically powerful taxonomy of diseases in terms of their microbial causes. Today, infectious diseases are typically classified as bacterial (e.g. syphilis, tuberculosis), viral
(e.g. AIDS, herpes), protozoal (e.g. malaria), and so on. Knowing what bacteria are responsible for a particular disease indicates what antibiotic treatment to apply. Viruses have proven to be much more resistant to chemical attack.

![Diagram of causal structure of the germ theory of disease.]

**Figure 5.** Causal structure of the germ theory of disease.

Although classification in terms of superficial symptoms such as fever is no longer important, the taxonomy of infectious diseases in terms of microbial agents goes hand in hand with classification in terms of organ system affected. Textbooks are commonly structured in terms of organ systems, so that, for example, respiratory diseases are discussed together. The Hippocratics’ combined an emphasis on humoral imbalances with only a sketchy knowledge of anatomy; the doctrine that diseases have seats in particular bodily organs was developed by Morgagni in the eighteenth century.

**Current Disease Concepts**

Although many diseases are infectious, research in the twentieth century has revealed other kinds of cause of disease: genetic, nutritional, immunological, metabolic, and cytological. The Hippocratics saw some traits such as being phlegmatic as hereditary, but the first demonstration of the genetic basis of a disease was Archibald Garrod's work on alkaptonuria in 1901 (Devor, 1993). Many other kinds of genetic disorders have been identified, and in recent years genetic engineering has offered the possibility of new kinds of treatment for such disorders. Hippocrates placed great emphasis on diet as a factor on disease, and the value of citrus fruits in preventing scurvy was established in 1747, but identification of vitamin C as a nutritional requisite of health occurred only in 1932. Diseases caused by nutritional deficiencies can easily be treated by providing the missing vitamins or other nutrient. Knowledge of the immune system advanced rapidly in the 1950s, making possible the understanding of diseases that arise from attacks by the immune system on the body's own organs, as occurs in diseases such as lupus erythematosus. Metabolic disorders such as diabetes have become increasingly understood as knowledge increases of the physiology of organs such as the pancreas, but causality in such cases is complex, involving an interaction of hereditary and environmental factors. Similarly, although knowledge is developing rapidly...
concerning the nature of the cells and genes involved in the growth of cancers, the causal interactions are enormously complex and hard to identify.

The authoritative *Cecil Textbook of Medicine* is divided into parts that implicitly classify diseases in two complementary respects: organ systems and pathogenesis. Table 5 lists the relevant parts of the textbook. Most of these are organized around physiological systems, such as the cardiovascular and respiratory systems. But there are also parts that group diseases in terms of pathogenetic mechanisms that can affect various organ systems: oncology, metabolic diseases, nutritional diseases, infectious diseases, and so on. Some diseases are naturally discussed in more than one part, as when myocarditis occurs both under cardiovascular diseases and infectious diseases. Modern medical classification thus blends two overlapping taxonomies of disease.

<table>
<thead>
<tr>
<th>Cardiovascular diseases</th>
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<tbody>
<tr>
<td>Respiratory diseases</td>
</tr>
<tr>
<td>Renal diseases</td>
</tr>
<tr>
<td>Gastrointestinal diseases</td>
</tr>
<tr>
<td>Diseases of the liver, gall bladder, and bile ducts</td>
</tr>
<tr>
<td>Hematologic diseases</td>
</tr>
<tr>
<td>Oncology</td>
</tr>
<tr>
<td>Metabolic diseases</td>
</tr>
<tr>
<td>Nutritional diseases</td>
</tr>
<tr>
<td>Endocrine and reproductive diseases</td>
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<tr>
<td>Diseases of the bone and bone mineral metabolism</td>
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<tr>
<td>Diseases of the immune system</td>
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<tr>
<td>Musculoskeletal and connective tissue diseases</td>
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<tr>
<td>Infectious diseases</td>
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<tr>
<td>HIV and associate disorders</td>
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<tr>
<td>Diseases caused by protozoa and metazoa</td>
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The shift from the humoral to the germ theory of disease required a conceptual revolution: the old conceptual and explanatory system was replaced by a radically different one. In contrast, the development in the twentieth century of concepts of genetic, nutritional, immunological, and metabolic diseases were relatively conservative extensions of the nineteenth century ideas: new causes were introduced without denying that the germ theory was right about the causes of diseases to which it had been applied. Let us now look at changes in the concept of disease more systematically.

### 4. CHANGES IN DISEASE CONCEPTS

The development of the concept of disease illustrates all nine kinds of conceptual change that were distinguished in table 1. I will characterize changes as **conservative** if they involve extensions to existing concepts and beliefs, and **nonconservative** if they require rejection of previous concepts and beliefs. The first kinds of conceptual change, adding new instances such as new cases of tuberculosis and empirical generalizations such as about who tends to get tuberculosis, are usually conservative. Adding a new causal rule, however, can drastically alter the concept of a disease by changing the links in the causal network for the disease. When Koch showed that tuberculosis is caused by a bacillus, he developed a very different causal network from that of the Hippocratics: the disease is an infection, not an imbalance, and can be treated by killing the microbes that cause the infection, not by overcoming the imbalance. Adding a new causal rule can be conservative if the rule does not clash with a previously held causal rule, but the replacement of the humoral theory by the germ theory required numerous instances of nonconservative rule addition.

Adding a new part relation is usually a conservative conceptual change in the history of medicine, since finding new parts does not require rejection of previous views about parts. For example, when Schwann proposed in 1839 that animals are composed of cells, his new subdivision did not require rejection of previous views about organs. However, identifying new parts can sometimes lead to nonconservative rule addition if the new parts suggest new causal rules, as when the discovery of new organs made possible novel diagnoses.

Adding a new kind-relation can be conservative when it simply involves subdividing accepted kinds into finer distinctions, as when diabetes mellitus is divided into two kinds, type I or insulin-dependent diabetes and type II or non-insulin dependent diabetes. Sometimes, however, adding kind-relations involves
changing causal rules, as when the germ theory introduced infectious diseases as a new class with
causes very different from those associated with the humoral theory.

Adding a new concept can be conservative when the concept fits with the existing conceptual system.
Adding the classes of genetic and nutritional diseases was conservative with respect to the germ theory,
since the new concepts largely applied to diseases that had not previously been asserted to be infectious.
In contrast, the concept of infectious disease was nonconservative with respect to the humoral theory,
since it required rejecting not only previous beliefs but also previous concepts. Modern concepts of blood,
phlegm, and bile do not play anything like the explanatory and clinical role that they did for the
Hippocratics.

For the germ theory, fever is not itself a disease as it was for Hippocrates and Fracastoro, but only a
symptom of infection. Hence there is no need to include in the taxonomy of diseases a classification of
kinds of fever. Abandonment of the fever branch of the disease taxonomy exemplifies the seventh kind of
conceptual change listed in table 1, collapsing a kind-hierarchy to abandon a previous distinction. This
change is clearly nonconservative, requiring the abandonment of previously accepted concepts and
beliefs.

Branch jumping - reorganizing hierarchies by shifting a concept from one branch of a hierarchical tree to
another branch - is similarly nonconservative. To take a recent example, the new bacterial theory of the
origins of many peptic ulcers requires reclassification of ulcers as an infectious disease, rather than as a
disorder due to excess acidity or as a psychosomatic disease due to stress (Thagard, ULCERS-I).
Similarly, the classification of diseases such as tuberculosis, cholera, rabies, and malaria in terms of their
microbial causes shifts these concepts to a new place in the tree of diseases, abandoning their
classification in terms of kind of fever or superficial symptoms.

Tree switching, changing the basis on which classifications are made, is nonconservative, since it goes
together with the development of new branches that supersede previous classifications. The transition to
the germ theory was a case of tree switching, since it introduced classification of diseases in terms of
their causes, particularly their microbial causes. Modern medicine no longer classifies diseases in terms
of symptoms, but rather in terms of causes and organ systems affected. Symptoms are related to organ
systems, since, for example, a lung disorder has symptoms involving the lungs, but the seat of the
disorder and its causes are more fundamental to classification of diseases than are symptoms. In
contrast, dictionaries of symptoms and other books written for laypeople are still organized in terms of
symptoms rather than organ systems or causes of disease.

In sum, the transition in the nineteenth century from the humoral theory to the germ theory of disease
was highly nonconservative, involving new concepts, new causal rules, and new classifications, as well
as the abandonment of old ones. The transition from the humoral to the germ theory was largely
accomplished by the ability of the latter to provide a superior new account of the causes and treatments
of diseases. In contrast, the twentieth-century expansion of causes of diseases to include nutritional,
immunological, and metabolic considerations was largely conservative with respect to the germ theory.
New causes were introduced, without rejecting the established concepts and beliefs about infectious
diseases. Harvard Medical School now advocates a "biopsychosocial" model of medicine (Tosteson,
Adelstein, and Carver, 1994). The modern trend to multifactorial theories envisioning such diseases as
cancers as the result of complex interactions of genetic, environmental, immunological and other factors is similarly conservative, except with respect to narrow views that attempt to specify a single cause for each particular disease.

5. CHANGES IN GERM CONCEPTS

Accompanying the changes in the concept of disease that were brought about by the germ theory were dramatic changes in concepts describing the infectious agents newly held to be responsible for disease. The development of concepts such as bacteria and viruses involved some of the same kinds of changes so far described for disease concepts.

Historical Development

Microscopic living creatures were first observed in 1674 by Leeuwenhoek. Examining a sample of lake water with a simple microscope, he observed "very many little animalcules"; his descriptions apply to what are now called protozoa (Dobell 1958, p. 110). In 1676, Leeuwenhoek observed many animalcules in water in which pepper had been standing for some weeks, including some "incredibly small" animalcules that were evidently bacteria.

Although we can say that Leeuwenhoek discovered protozoa and bacteria, these concepts did not originate with him, for he wrote only of animalcules differing in their size and parts. Leeuwenhoek never associated the animalcules he observed with the causation of disease. The concept of germ that arose in the nineteenth century was both biological and medical: a germ is a biological organism that can cause disease. Fracastorius concept of seminaria was medical but not biological; Leeuwenhoek's concept of animalcule was biological but not medical. Fracastorius and Leeuwenhoek both introduced new concepts that retrospectively can be seen as ancestors of modern microbiology but were very different from current concepts.

In the twelfth (1767) edition of the Systema Naturae Linnaeus assigned all the animalcules then known to three genera, Volvo, Furia, and Chaos. The entities that Leeuwenhoek had observed were termed "infusoria" in the eighteenth century because they were observed in infusions (solutions) of decaying organic matter. Linnaeus lumped all the infusoria to a single species, Chaos infusorium. (Bullock, 1979, p. 37). The term "bacterium" was introduced by Gottfried in 1829.

Modern microbiology began with the French chemist Pasteur, who in 1857 discovered that lactic acid fermentation is caused by a microorganism, yeast. Previously, fermentation was believed to be result of decomposition of a substance, not the effect of an organism such as yeast. In 1861, Pasteur announced that the ferment which produces butyric acid is an infusorium ("infusoire", Brock, 1961, p. 265). The anaerobic bacteria observed by Pasteur were small cylindrical rods about .002 mm in diameter. This discovery, and subsequent work by Pasteur, Koch, and others on the involvement of microorganisms in disease, led to an explosion of work that resulted, by the end of the nineteenth century, in the
identification of many different kinds of bacteria and protozoa, along with demonstrations that many important diseases such as tuberculosis and malaria are caused by microbes. (The term "microbe" was introduced in 1878 by Sédillot.)

Attempts were made to identify microbes responsible for diseases such as rabies and smallpox, but the agents in these cases were what we now call viruses, which are too small to be seen through an optical microscope. The term "virus" originally meant "poison", and any cause of disease, including Fracastorius's *seminaria*, could be referred to as a virus. In 1884 Chamberland used filtration through a porous vase of porcelain to purify water of microbes, but in 1892 Ivanowski was surprised to find that a filtered extract from diseased tobacco plants could cause disease in previously healthy plant. In 1898 Löffler and Frosch conjectured that hoof and mouth disease is caused by "a previously undiscovered agent of disease, so small as to pass through the pores of a filter retaining the smallest known bacteria." (Lechevalier and Solotorovsky, 1974, pp. 284-285). The conjectured poison became known as a "filterable virus". After 1915, when Twort showed that bacteria can be attacked by filterable viruses, the concept of a virus as an ultramicroscopic organism became established. In 1935, Stanley presented crystallographic evidence that tobacco mosaic virus is a protein. During the 1930s, the electron microscope was developed, and in 1939 Kausch, Pfankuch, and Ruska used it to describe the appearance of the tobacco mosaic virus. Thus use of the term "virus" evolved gradually from concerning any disease-causing poison to concern very small microorganisms detected by electron microscopes.

**Representational Change**

When Leeuwenhoek introduced the term "animalcule", he introduced into his mental apparatus a new concept that differentiated the newly observed entities from larger animals. Concepts need not be formed directly by observation, however, but can be formed as part of the generation of explanatory hypotheses. Fracastorius's concept of *seminaria* did not refer to any entity he had observed, but rather to one he had postulated in order to explain contagion. Similarly, the concept of a filterable virus initially concerned a hypothetical entity, although viruses later were identified by electron microscopy.

After Pasteur, Lister and others showed the medical significance of bacteria in the 1860s, great progress was made in identifying new kinds of bacteria and demonstrating their roles in a host of diseases, including diphtheria, tuberculosis, and cholera. By the end of the 1870s, people no longer spoke of "the" bacteria, but of different bacteria (Bullock, 1979, p. 203). In place of the general concepts of animalcule and infusorium, concepts referring to particular kinds of bacteria and protozoa were developed, and the concept of microbe was introduced to reunify the plethora of newly differentiated concepts. Taxonomy of bacteria was very important for the development of the germ theory of disease: If one bacterium could unpredictably turn into another kind, then it would be difficult to accept the fact that specific disease was caused by a specific bacteria (Brock, 1988, p. 73). Today, more than 2,000 species of bacteria have been identified, along with many species of protozoa.

Proliferation of microbiological concepts did not simply involve extension of existing classification, but often required revision of kind relations. Leeuwenhoek and the eighteenth century taxonomists classified bacteria and other infusoria as animals, but in 1852 Perty contended that some of the infusoria are
"animal-plants", and Cohn argued in 1854 that bacteria of the genus Vibriona are plants analogous to algae. In 1857, the German botanist Nageli proposed that bacteria should be regarded as a class of their own within the vegetable kingdom, for which he coined the term "Schizmocytetes", or "fission fungi" (Collard, 1976, p. 151). Today, in the widely used five kingdom classification, bacteria are no longer classed with fungi, but rather with blue-green algae in the kingdom Monera.

Reclassification of viruses has been even more complex. Originally, "virus" meant "slime" or "poison", but only at the end of the nineteenth century did it start to acquire the meaning of "infectious agent". By the 1940s, the electron microscope made it possible to discern the structure of many kinds of viruses, which are particles consisting only of DNA or RNA (but not both) and a protein shell. Unlike bacteria, which consist of living cells, viruses can not reproduce on their own, but only when they are parasites in living cells. When Pasteur and other early researchers attempted to identify the cause of diseases such as rabies and smallpox, they thought they were looking for a kind of bacteria, but viruses turned out to be a much smaller and simpler kind of entity. Hundreds of kinds of viruses have been identified. By 1950, viruses were soundly differentiated from bacteria, and the field of virology split off from bacteriology. The mental representations of microbiologists reflect these differences, and hundreds of kinds of viruses are now distinguished based on their structure as revealed by electron microscopy. Viruses "cannot logically be placed in either a strictly biochemical or in a strictly biological category; they are too complex to be macromolecules in the ordinary sense and too divergent in their physiology and manner of replication be conventional living organisms" (Hughes, 1977, p. 106). Virologists are wont to say: viruses are viruses.

Reclassification of bacteria first as Schizmocytetes and then Monera, and reclassification of viruses as a unique kind of entity, are examples of branch jumping, the movement of a concept from one branch of a taxonomic tree to another. The development of concepts of bacteria and viruses does not seem to have involved radical change in classificatory practices, although after 1908 pathogenicity was admitted as a taxonomic criterion for bacteria (Collard, 1976, p. 153). The empirical classification is designed to aid the differentiation between medically and industrially important species and others.

In sum, conceptual change in microbiology has involved the formation of many new mental representations corresponding to terms such as "animalcule", "bacteria", and "virus". Concept formation often involved differentiation, as new kinds of entity were distinguished from ones previously known. In addition, the organization of microbiological concepts has changed dramatically over time, as new kinds of infectious agents have been identified and as existing kinds have been reclassified in terms of higher order kinds. The concept of infection has also changed, as the modern meaning of invasion by microorganisms replaced the older, vaguer meaning of infection as staining or pollution. Today, infectious diseases can be differentiated as bacterial infections or viral infections, just as germs can be differentiated as bacteria or viruses. Thus germ concepts and the concept of infection changed in tandem with changes in the concept of disease.

Terminological and mental change has been coupled with changes in ways of fixing the reference of concepts of germs, as the last section of this paper will show. First, I shall compare the preceding account of changes in disease and germ concepts with other recent discussions of conceptual change.
6. OTHER REPRESENTATIONAL ACCOUNTS OF CONCEPTUAL CHANGE

Kuhn

Accounts of conceptual change go back at least as far as the nineteenth-century writings of Hegel and Whewell, but have proliferated since Thomas Kuhn's (1970) work on scientific revolutions. Kuhn (1993, p. 336) now characterizes a scientific revolution in part as "the transition to a new lexical structure, to a revised set of kinds." Terms for kinds "supply the categories prerequisite to description of and generalization about the world. If two communities differ in their conceptual vocabularies, their members will describe the world differently and make different generalizations about it." (Kuhn, 1993, p. 319) The difference is particularly serious if the new set of kind-terms overlaps kind-terms already in place, since there then can be no straightforward translation between the terms in the two theories (see also Hacking, 1993). Buchwald (1992) shows that two competing optical theories in the early nineteenth century worked with taxonomies that cannot be mapped or grafted onto one another.

My discussion of concepts of disease similarly assumes that scientific categories can be thought of as forming a taxonomic tree, although in medicine the tree is tangled because of the intermingling of physiological and pathogenetic taxonomies. I have described several different kinds of changes to the taxonomy of diseases that occurred with the development of the germ theory of disease. It is indeed difficult to translate completely between the humoral and the germ conceptions of disease, because the Hippocratic taxonomy of diseases in terms of bodily locations divides the world up very differently from the classification of diseases in terms of microbial causes. Partial translation is nevertheless possible: we can recognize ancient discussions of diseases like phthisis (tuberculosis) because the symptoms associated with it today are similar to ones identified long ago, even if the etiology and taxonomy of the disease has changed dramatically. Like Kuhn (1993, p. 315), who refers to the lexicon as a "mental module", I take conceptual change to be change in mental representations.

Carey

Carey also takes concepts and beliefs to be mental structures, and lists three types of conceptual change (Carey, 1992, p. 95). The first, differentiation, occurs when a new distinction is drawn. The development of disease concepts has seen many such differentiations, both in distinguishing between particular diseases such as measles and smallpox, and in distinguishing between kinds of diseases such as bacterial infections and viral infections. The second, coalescence, occurs when a distinction is abandoned, as we saw in the abandonment of Hippocratic distinction between kinds of fever and in the scrapping of the distinction between scrofula and phthisis. In Carey's third kind of conceptual change, simple properties are reanalyzed as relations, as when Newton reanalyzed the concept weight as a relation between an object and the earth. Whether there have been medical examples of this kind of conceptual change is unclear.
Chi and her colleagues distinguish between conceptual change within an ontological category and *radical* conceptual change that necessitates a change across ontological categories (Chi, 1992; Slotta, Chi, and Joram, 1996). She argues that physics education requires radical conceptual change, since students must recategorize familiar concepts such as heat, light, force, and current, which their everyday conceptual systems take to be substances, as events defined by relational constraints between several entities. Radical conceptual change cannot occur merely by adapting or extending a previous conceptual scheme, but requires constructing a new set of concepts and shifting to it as a whole.

Is change in the concept of disease radical in Chi's sense? Brock (1961, p. 74) suggests that Fracastor's contagion theory introduced the concept of an infectious disease as a process rather than a thing. But the Hippocrates' extensive discussions of the courses and prognoses of diseases suggest that they also thought of diseases as falling under the ontological category of process. Chi's fundamental ontological categories are matter (kinds and artifacts), events, and abstractions. For the Hippocrates as well as the nineteenth century germ theorists, diseases were complex events, not kinds of things or abstractions. So the transition to the germ theory of disease did not involve radical conceptual change in Chi's sense. Nevertheless, it did require the sort of replacement mechanism that she describes for radical conceptual change in which a whole new conceptual scheme is constructed, not simply produced by piecemeal modification of the previous humoral scheme (3).

Gentner et al. (forthcoming) identified four analogical processes of conceptual change that they conjecture were important in the development of Kepler's work on the solar system: highlighting, projection of candidate inferences, re-representation, and restructuring. As we saw above, the analogy between fermentation and disease was important for Pasteur and Lister who were the central contributors to the germ theory of disease. The analogy between fermentation and disease was already familiar, but Pasteur and Lister created a new mapping between the two processes. This new mapping highlighted the role of microorganisms in fermenting substances and in disease organisms. It also made possible candidate inferences that diseases are caused by germs, just like fermentation. It is not apparent that the new mapping required any re-representation of predicates, but it certainly did require restructuring of causal links in the target domain to include microorganisms as the causal agent of disease. So at least three of the four analogical processes that Gentner et al. discuss in the Kepler case seem to have operated in the development of the germ theory of disease.

Nersessian (1989) discusses several important kinds of conceptual change that occurred with the development of Newtonian physics. Some concepts were added (gravity), some were deleted (e.g. natural motion), and there were many changes in kind hierarchies similar to the ones we have seen in the
development of disease concepts. Nersessian also points out important changes from properties to relations. For example, gravity was reconceived as a force, which is a relation rather than a property. As I mentioned in discussing Carey, this kind of conceptual change may not have occurred in the disease case. Nersessian (1992) describes how analogy, imaging, thought experiments, and limiting case analyses have contributed to conceptual change in the history of physics. Of the mechanisms she discusses, we saw that analogy was very important in the development of the germ theory of diseases by Pasteur and Lister.

7. REFERENTIAL CHANGE

Kitcher (1993) describes conceptual change, not in terms of mental representations, but in terms of *modes of reference*, which are connections between a term and an object that make it the case that the term refers to the object. He describes three types of mode of reference: *descriptive*, when the speaker uses a description to pick out an object that a term is intended to refer to; *baptismal*, when a speaker ostensively applies a term to a particular present object; and *conformist*, when a speaker's usage is parasitic on the usage of others who have established the reference of a term either descriptively or baptismally. A term may have multiple modes of reference, which together comprise its *reference potential*. According to Kitcher (1993, p. 103), conceptual change is change in reference potential.

The germ theory undoubtedly brought with it new modes of reference for disease terms. Tuberculosis could now be described as the disease caused by the tubercle bacillus. Disease concepts did not change completely, however, since, the descriptive modes of reference associated with familiar observable symptoms did not change. Terms for the various microbes that cause disease had baptismal modes of reference that occurred when researchers such as Koch first observed them under the microscope.

When Fracastoro described *seminaria* as the causes of contagion, he used a verbal description that was intended to refer to agents of disease. Microbiologists from Leeuwenhoek on, however, were able to fix reference baptismally by pointing to examples of the new kinds of microorganisms that were being discovered. Their ability to do this depended on the development of a series of technological advances that illustrate the crucial role of instruments in conceptual change in microbiology.

Why was Leeuwenhoek the first to discover the tiny "animalcules" that we now call bacteria? Others in his time were using microscopes to look at previously unobserved phenomena, but Leeuwenhoek developed his own techniques of microscope construction that were unrivaled for decades afterward. He was then able to see numerous sorts of previously unidentified organisms. Here is Leeuwenhoek's own description of the first observation of bacteria, which took place in 1676 as the accidental result of an attempt to discover why pepper is hot to the tongue:

I did now place anew abut 1/3 ounce of whole pepper in water, and set it in my closet, with no other design than to soften the pepper, that I could better study it. ... The pepper having lain about three weeks in the water, ... I saw therein, with great wonder, incredibly many very little animalcules, of divers sorts. ... The fourth sort of little animals, which drifted among the three sorts aforesaid, were incredibly small; nay, so small, in my sight, that I judged that even if 100 of these very wee animals lay stretched out one
against another, they could not reach to the length of a grain of coarse sand (excerpts from Dobell, 1958, pp. 132-133).

Observation of bacteria through a microscope is not easy, both because of the difficulty of producing accurate lenses and because of the need to focus on specimens where bacteria exist. Microscopes that reduced aberration sufficiently to facilitate observation of bacteria were not available until the 1820s. Fixing the reference of concepts referring to different kinds of bacteria depended on these advances in microscopy.

Other experimental techniques were also required for the development of bacteriology (Collard, 1976). Through the 1870s, it was very difficult to obtain pure cultures that contained only one kind of bacterium, since liquid solutions tended to contain many kinds of bacteria. But in 1881 Robert Koch developed a technique of growing bacteria on cut potatoes, and the next year agar was introduced as a solid medium for culturing bacteria. The identification of many medically important bacteria in the next few years used these new techniques.

The transparency of bacteria makes them difficult to observe, but staining techniques have provided powerful ways of determining their presence and structure. Vegetable stains were first applied to bacteria by Hoffman in 1869, and improved techniques including Gram's technique of counter-staining were developed over the next decades. Like culturing in solid media, staining is an important aid to the fixing of reference of terms for new kinds of bacteria. Culturing and staining enabled Robert Koch to discover the bacterium responsible for tuberculosis:

On the basis of my extensive observations, I consider it as proved that in all tuberculous conditions of man and animals there exists a characteristic bacterium which I have designated as the tubercle bacillus, which has specific properties which allow it to be distinguished from all other microorganisms. (Koch, quoted in Brock, 1988, p. 121).

The baptismal mode of reference to the tubercle bacillus thus depended on the development of new experimental techniques.

New techniques were also crucial for the referential development of concepts concerning viruses. Filtration techniques in the 1880s made possible the differentiation of viruses from bacteria, which were too large to pass through the filters. At this point, the only mode of reference for filterable viruses was descriptive: virus was whatever passed through the filters and caused disease. After 1920, centrifuges were increasingly used to isolate viruses and estimate their size based on centrifugation time and force of gravity. A few very large viruses can be identified with optical microscopes, but baptismal fixing of reference of most concepts of viruses requires use of the electron microscope, which also made possible determination of the structure of bacteria. Before 1939, when Kausche, Pfankuch, and Ruska first used the electron microscope for visualization of a virus, the mode of reference was descriptive, as in "the virus of measles". The third type of mode of reference defined by Kitcher (1993) is conformist, when a speaker's usage is parasitic on the usage of others who have established the reference of a term either descriptively or baptismally. For most people, the reference of concepts like bacteria and virus is fixed in this way, since they have neither seen such entities themselves nor been given an accurate description.
How are Kitcher's three modes of reference - descriptive, baptismal, and conformist - related to representational changes involving concept formation, differentiation, and reclassification? Descriptive modes of reference that involve words and verbal descriptions are easily cast in terms of mental representation by supposing that thinkers have (1) mental concepts corresponding to words and (2) proposition-like representations corresponding to descriptions. With respect to description, the mental representation view of conceptual change currently is richer than the referential view, since it pays attention to the kind relations of concepts. But ideas like differentiation and reclassification could be reframed in terms of a verbal lexicon rather than a mental lexicon by taking *kind* as a relation among verbal terms rather than mental structures. Given the theoretical richness of taking concepts as mental representations, there is no reason to prefer discussion of terms as words rather than as concepts.

But the reference-potential view of conceptual change does have an advantage over the mental-representation when it comes to understanding the relation between representations and the world. The baptismal mode of reference operated repeatedly in the history of microbiology, from Leeuwenhoek fixing the reference of "animalcule" to Koch fixing the reference of "tubercle bacillus", to electron microscopists fixing the reference of "tobacco mosaic virus." This mode of reference is best viewed not as a single act, but as a matter of ongoing interaction with the world using instruments and experimental techniques. Koch not only baptized the tubercle bacillus, he photographed and showed how to culture it and transmit it to laboratory animals. This was more than description, and more than baptism: it was development of replicable physical procedures for interacting with the entity referred to by the term (or concept) "tubercle bacillus." Changes in such procedures and attendant new baptismal episodes are aspects of conceptual change not captured by concentration solely on mental representation.

When concepts are formed purely descriptively, for example when seminaria are characterized as the seeds of disease, conceptual change can be viewed in terms of mental structures. But when concepts are formed ostensively as the result of interactions with the world, we have to understand conceptual change in terms of reference as well as representation. Differentiation is not only conceptual: entities can be differentiated into different classes if observation makes them sufficiently distinguishable that they can be dubbed independently.

Although changes in baptismal reference fixation are important to understanding the development of germ concepts, they are not so directly relevant to understanding the development of disease concepts. Diseases involve complexes of symptoms, so there is no entity that one can identify ostensively. Reference to diseases is fixed descriptively in terms of their symptoms or causes, although reference to symptoms and microbial causes can be fixed baptismally.

The mental-representation approach has also tended to neglect the social nature of conceptual change implicit in Kitcher's conformist mode of reference. Even from the perspective of mental representation, conceptual change is a social as well as a psychological phenomenon, but this is not the place to address social aspects of conceptual change in medicine. Thagard (1994) discusses the complementarity of social and psychological explanations of scientific change.

Although representational accounts of conceptual change do not tell the whole story, there remains ample reason to describe conceptual change in part as change in mental representations, especially
kind-relations. Conceptual change is clearly both representational and referential, since the meaning of concepts is a function both of how they relate to each other and how they relate to the world. A full theory of conceptual change must integrate its representational, referential, and social aspects.

8. CONCLUSION

I have described the structure of the concept of disease and the way in which disease and germ concepts have changed. Historical evidence supports three main conclusions:

1. Disease concepts are causal networks that represent the relations among causes, disorders, symptoms, and treatments of diseases.

2. The most important changes in disease concepts occurred because of alterations in beliefs about the causes of disease.

3. The development of germ concepts should be thought of in terms of referential change as well as representational change.

Emphasis on the causal structure of disease concepts does not exclude other cognitive aspects such as sets of prototypical symptoms which are also associated with diseases. But it sees disease as an inherently causal concept, not just a featural one.

Many issues have not been addressed in this paper. What were the cognitive mechanisms by which the concepts and hypotheses of the germ theory of disease were introduced? Analogy, which is clearly at work in the writings of Pasteur and Lister, is one relevant mechanism, but other kinds of concept formation and hypothesis construction may also have been important. Why was the germ theory accepted as superior to the humoral theory? Conceptual changes such as the addition of new concepts, kind-relations, and classifications, in company with abandonment of old humoral ones, show that development of the germ theory was not made by piecemeal revision of the old. Instead, a new conceptual structure had to be put together that supplanted the old one. All the major scientific revolutions in the natural sciences involved replacement of one theory by another on the basis of explanatory coherence (Thagard, 1992), but whether a similar account applies to the adoption of the germ theory of disease remains to be shown.

Recent interest in conceptual change has come as much from developmental and educational psychologists as from historians and philosophers of science. It would be interesting to determine what kinds of conceptual changes must be undergone by medical students training to be physicians or by laypeople attempting to understand and comply with treatment of their illnesses (see Skelton and Coyle, 1991). The structure and change of disease concepts is thus a topic of practical as well as theoretical interest.

ENDNOTES
(1) My account of the structure of disease concepts is consistent with findings by health psychologists that lay theories of illness include the elements of symptoms, consequences, temporal course, cause, and cure; see Skelton and Croyle (1991). Michela and Wood (1986) provide a comprehensive review of causal attributions in health and illness.

(2) The historical and philosophical literature on disease concepts is vast. Useful historical works include Have (1990), Heidel (1941), Hudson (1983), King (1982), Kiple (1993), Magner (1992), Nuland (1988), and Temkin (1973). Philosophical discussions of the nature of disease include Caplan et al. (1981) and Reznik (1987). Also relevant to the germ theory of disease are works on the history of microbiology, such as Brock (1961), Collard (1976), Grafe (1991), and Lechevalier and Solotorovsky (1974).

(3) If laypeople think of diseases as things rather than processes, medical education may require conceptual change across Chi's ontological categories.

REFERENCES


(From: [http://cogsci.uwaterloo.ca/Articles/Pages/Concept.html](http://cogsci.uwaterloo.ca/Articles/Pages/Concept.html))