Medical Analogies: Why and How

Paul Thagard
Philosophy Department
University of Waterloo
Waterloo, Ontario, N2L 3G1, Canada
pthagard@watarts.uwaterloo.ca

Abstract

This paper describes the purposes served by medical analogies (why they are used) and the different cognitive processes that support those purposes (how they are used). Historical and contemporary examples illustrate the theoretical, experimental, diagnostic, therapeutic, technological, and educational value of medical analogies. Four models of analogical transfer illuminate how analogies are used in these cases.

Models of Analogical Transfer

The widespread use of analogies in cognition, including scientific reasoning, has been well documented (e.g. Biela, 1991; Holyoak and Thagard, 1995; Leatherdale, 1974). But there has been no systematic discussion of analogical thinking in medicine. This paper describes six uses of medical analogies that illustrate different kinds of analogical transfer.

Analogical transfer, in which people use a source problem to provide a solution to a target problem, can take place in at least four different ways. The model of analogical transfer most commonly discussed in cognitive science works as follows. First, someone attempts to solve a target problem, and then remembers or is given a similar source problem for which a solution is known. Then the target problem is solved by adapting the solution to the source problem to provide a solution to the target. Many psychological experiments have followed this pattern (e.g. Gick and Holyoak, 1980). And many computational models of analogical problem solving, including most work on case-based reasoning, also fit this pattern (e.g. Kolodner, 1993). Accordingly, I will use the term *standard model* for this pattern of retrieving a source to solve a target problem.

There are, however, other ways in which people use analogies to solve problems. In the standard model, the target problem serves as a direct retrieval cue for the source problem, but retrieval can also take place more indirectly using a schema that is abstracted from the target problem. According to the *schema model,* an attempt to solve a target problem produces an abstract schema that then serves as a powerful retrieval cue for finding a source problem that provides a solution to the target problem. Although the abstraction may directly suggest a solution to the target problem, it may less directly suggest a solution by producing recall of a particular case that is sufficiently similar to the target to serve as the source of a solution. Darden (1983) discusses analogies in terms of shared abstractions.

In both the standard and schema models, the thinker starts with a target problem and retrieves a sources, but there are important cases where reminding works in the opposite direction. These cases are ones where an attempt to solve a target problem has failed, and the problem solver leaves it aside. Later, however, the problem solver serendipitously encounters a solved problem that can serve as a potential source, and this new source prompts recall of the unsolved target problem. Instead of the target providing a retrieval cue for the source, the source provides a retrieval cue for the target. The *serendipity model* refers to a pattern of analogical transfer in which a target problem is recalled and solved using a source accidentally encountered after initial solutions fail (cf. Langley and Jones, 1988). Darwin's discovery of the theory of evolution by natural selection fits well the serendipity model: Darwin had long wondered about how biological evolution occurs, and only found a solution when he read Malthus and realized that Malthus's ideas about human population growth could be adapted to provide an explanation of species evolution in terms of the struggle for existence.

In all three models so far described, the source problem exists independently of the target problem. But there are rich analogies in which the source problem is constructed in order to provide a solution to the target problem. Nersessian (1992) describes how Maxwell generated a theoretical explanation of electromagnetism by constructing a mechanical analog. He did not understand electromagnetism in terms of any known mechanical system, but instead concocted a new mechanical system that suggested the equations that he was then able to apply to electromagnetism. I will use the term *generation model* for analogical transfer that takes place when a target problem is solved by analogy with a source problem that is specially constructed. The process of generation of a source analogy is roughly this:

1. Start with a target problem.
2. Retrieve or encounter a very approximate analog.

3. Fill out the approximate analog by looking at the target and identifying aspects of the constructed analog that need identification. Fill these in.

4. Transfer from the newly constructed source to target.

The standard, schema, serendipity, and generation models are complementary accounts of analogical transfer rather than competitors (see figure 1). Different episodes of human analogical problem solving employ all four of the reasoning strategies that the models describe. In particular, there are important medical analogies that instantiate each of these models.

Theoretical Analogies

Theoretical analogies are ones that are important in the development and justification of explanatory hypotheses. Important theoretical analogies in physics include comparison of sound with water waves and of light waves with sound waves. Biology has also employed analogies that contributed to theoretical development, such as Darwin's analogy between natural and artificial selection. Theoretical analogies have been equally important in the history of medicine, from the Hippocratics to the development of the germ theory of disease and beyond. The ancient Greeks explained health in terms of a balance of the various qualities constituting the body, using a term for balance "isonomia" that also connoted equality of political rights (Temkin 1977, p. 272). The great seventeenth century physician, Thomas Sydenham, conceived of diseases as akin to biological species, maintaining that just as characteristics of a plant species are extended to every individual, so the characteristics of a disease apply to every individual who has it (Bynum 1993, p. 341).

The most important theoretical analogy in the history of medicine was used by Pasteur and Lister in the development of the germ theory of disease. In the 1850s and 1860s, they realized that just as fermentation is caused by yeast and bacteria, so diseases may also be caused by microorganisms. Pasteur's ideas about infection moved from using microorganisms to explain why milk, beer and wine ferment, to proposing similar explanations of diseases in silkworms, to explaining human diseases such as rabies in terms of germs. 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).

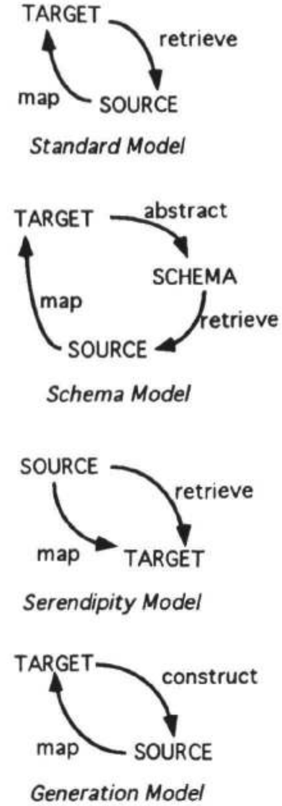

Figure 1. Models of analogical transfer.

Pasteur's theoretical analogy had the following structure :

Fermentation is caused by germs.
Disease is like fermentation.
So, disease may also be caused by germs.

As far as one can tell from the historical record, the development of Pasteur's ideas appears to fit with the standard model of analogical transfer. In working on silkworms, he was able to draw on his previous work on fermentation, and in working on human diseases, he drew on the ideas and techniques that had been useful with silkworms. The previously understood problems of fermentation and silkworm diseases provided sources for analogical solution of the subsequent target problem of human disease.

A similar theoretical analogy was also important in the development of modern surgery. Before the 1860s, many surgical patients suffered serious infections, which were not explained until the British surgeon Joseph Lister realized the significance of Pasteur's ideas about fermentation, and recognized that germs in the air can cause infection of wounds, just as they cause fermentation (Brock, 1961, p. 84).

The structure of Lister's reasoning was:

> Fermentation is caused by germs.
> Putrefaction (infection) following surgery is like fermentation.
> So, putrefaction may be caused by germs.

This analogical transfer does not fit the standard model, since Lister must have worried about the problem of wound infection for many years before reading Pasteur's work on fermentation, which reminded him of the pre-existing wound target problem. In this case the source problem (fermentation) prompted the target problem (infection), so it best fits the serendipity model of analogical transfer.

The analogy between fermentation and infection was a remote one, since on the face of it there is little apparent similarity between grapes becoming alcoholic and wounds becoming infected. Closer analogies are ubiquitous in medical research which relies heavily on the use of animal models to determine the causes of disease. For example, Robert Koch determined that tuberculosis is caused by a bacterium by doing experiments with guinea pigs. He showed that injecting guinea pigs with bacteria taken from other guinea pigs with tuberculosis induced tuberculosis in them. Obviously it would be unethical to induce tuberculosis in humans in this way, making it impossible to do a controlled experiment of tuberculosis in humans. Koch used animals to *generate* an analog to human disease (Brock, 1988). This is not a case of analogical transfer by reminding or serendipity, but rather of constructing an animal analog that can then be used to make inferences about human diseases. The structure of the analogical transfer in these cases is roughly:

> We want to know the causes of a disease in humans.
> Animals (e.g. guinea pigs) have the same (or similar) disease.
> In animals, the disease is caused by X.
> So the human disease may also be caused by something like X.

The constructive nature of animal analogies is even more evident when new animal strains are created to provide models for human diseases. For example, biologists have used genetic engineering to create a strain of mouse that gets Alzheimer's disease. Because the mouse develops the types of plaques on the brain found in humans with Alzheimer's and suffers memory problems, it can be used in experiments aimed at determining the causes of and possible treatments for Alzheimer's. Analogies based on animal models are also important for therapeutic purposes (see below). Sometimes, animal models are arrived at serendipitously, as when researchers who set out to genetically engineer rats as a model of human arthritis discovered that they had created a model of ulcerative colitis.

Critics of animal experimentation have raised doubts about the ability of such models to provide explanations of human diseases (LaFollette and Shanks, 1995). Animal models often break down because of physiological differences between humans and the animals used, which lead to differences in causality and treatment effectiveness. Treatments that are effective in animals or in the test tube often do not work on humans. Analogical reasoning is often a risky kind of inference, but Holyoak and Thagard (1995) describe various steps that can be taken to improve the quality of analogical reasoning. We urge analogists to use *system mappings,* ones based on deep similarities of causal relations rather than superficial similarities. When animal experimentation uses animals whose physical processes are known to be similar to humans, there can be a system mapping based on the existence of similar causal mechanisms. We also urge analogists to use multiple analogies, that is to consider the relevance of various possible source analogs for the case at hand. Well-informed medical researchers look at various possible animal models for a human disease, and base their experimental conclusions on deep causal similarities between the animals and humans. Under these conditions, animal models provide generated theoretical analogies that are at least suggestive about the causes of diseases in humans.

Medical thinking about some human diseases has also been aided by analogies with similar diseases. Researchers on tuberculosis made comparisons with similar infectious diseases such as smallpox and syphilis, and researchers on yellow fever made comparisons with malaria. These analogies are relatively close ones and generally fit the standard model of analogical transfer. Hadlow (1959) noticed similarities between the sheep disease scrapie and the New Guinea disease kuru and suggested experiments to determine if the latter was also transmissible. Research on these brain diseases led to Prusiner's (1982) hypothesis concerning a novel infectious agent called prions, which he analogically suggested might also be responsible for other diseases such as Alzheimer's.

I have included in this section only analogies that are important in the development and justification of explanatory hypotheses. Explanatory analogies whose function is primarily expository are discussed in the section on educational analogies.

Experimental Analogies

In order to establish a medical hypothesis, controlled experiments are needed to distinguish causation from mere correlations. Epidemiologists have established numerous standards for designing experiments that address the causes of diseases. Because of the complexity of experimentation, however, it is unlikely that medical researchers design their experiments from scratch. Experimental design can be done by an application of the standard model of analogical transfer, when a researcher remembers a previous experiment that suggests how to do the desired new experiment. Dunbar (1995) describes the frequent use of analogies in the design of experiments in molecular biology, and Kettler and Darden (1993) describe a program that uses analogy to help design protein sequencing experiments.

Experimental analogies have the following structure:

We need to do an experiment to accomplish X.
A previous experiment accomplished Y, a task similar to X.
So, we can do a modification of the previous experiment.

It is also possible that analogical transfer in experimental design could fit the serendipity model. We could imagine a researcher wondering how to design an experiment to test a hypothesis and then encountering a paper describing an experimental procedure that tests a similar hypothesis. The researcher could then design a similar experiment.

Diagnostic Analogies

Medical research aims at discovering the causes of diseases, but the reasoning task facing most physicians consists of diagnosing the presence of disease in individual patients. The physician needs to decide what disease or complex of diseases provides the best explanation of the patient's symptoms. This task often does not involve analogy. In straightforward cases, it can be almost deductive: If the patient has symptoms S1, S2, and S3, then it is almost certain that the patient has the disease D. In more complex cases, the reasoning is abductive, with the physician having to pick from a variety of diseases that would explain the patient's symptoms a diagnosis that fits best with what is known.

Sometimes, however, a diagnosis problem does not admit of a simple deductive or abductive solution, and analogies may then be useful. The general structure of diagnostic analogies is:

The patient P has the unusual set of symptoms S1, S2, and S3.
Another patient with similar symptoms had a disease D.
So maybe P has the disease D also.

Koton (1988) describes a case-based-reasoning program that produces causal explanations of a heart patient's symptoms by retrieving examples of similar patients.

Therapeutic Analogies

In addition to the task of diagnosis, medical reasoners want to be able to treat patients in ways that cure their diseases or at least reduce their symptoms. Berlinger (1996) describes a dramatic case of a baby born with a cystic cygroma that made it very difficult for him to breathe. When the baby stopped breathing, it became crucial to insert a tube in the baby's airway, but a bunch of yellow cysts hid the airway so it was not clear where to insert the tube. Dr. Berlinger fortunately remembered a previous case where an emergency technician had inserted a breathing tube to save the life of a snowmobiler with a severed windpipe by sticking the tube where bloody bubbles indicated the airway. Analogously, Berlinger pushed down on the baby's chest to push air out through the cysts, generating saliva bubbles that he could use as a guide for insertion of the breathing tube. This therapeutic analogy fits the standard model of analogical transfer, with the doctor retrieving a source problem (the snowmobiler) to solve the target problem (the baby). There are undoubtedly more prosaic cases in which physicians prescribe treatments because they worked previously with the same or similar patients.

Therapeutic analogies can also be based on similarities between diseases. Greenberg and Root (1995) describe a case where a physician was unable to diagnose a particular disease or diseases in a patient with a very complex set of symptoms. However, because the patient's symptoms were similar to those of patients with identified diseases who had been successfully treated, the physician recommended a similar treatment. This case fits the standard model of analogical transfer.

At a more general level, therapeutic analogies can be drawn from animal models used in experiments to determine the effectiveness of treatments for diseases. The general structure of these analogies is:

We want to know the medical effects of a treatment in humans.
Animals (e.g. guinea pigs) are similar to humans.
So we can try the treatment first in animals.
We can then transfer the conclusions (positive or negative) back to humans.

As with the animal model analogies described above in the section on theoretical analogies, these analogies fit the generative model of transfer, and the value of the animal therapeutic analogies will depend on the relational similarity of the relevant causal processes in animals and humans.

Finally, here is an analogy used to suggest early and aggressive treatment of HIV infections (Ho et al., 1995, p. 126):

> The CD4 lymphocyte depletion seen in advanced HIV-1 infection may be likened to a sink containing a low water level, with the tap and drain both equally wide open. As the regenerative capacity of the immune system is not infinite, it is not difficult to see why the sink eventually empties. It is also evident from this analogy that our primary strategy to reverse the immunodeficiency ought to be to target virally mediated destruction (plug the drain) rather than to emphasize lymphocyte reconstitution (put in a second tap).

Technological Analogies

Medicine requires many technologies for the diagnosis, treatment, and prevention of disease. A technological analogy is one in which transfer produces a new medical tool. I will discuss three examples: Lister's treatment of wounds, the invention of the stethoscope, and the invention of polymerase chain reaction.

Lister's analogy between fermentation and putrefaction suggested a possible means of preventing infection. He recalled 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; he accordingly began to use carbolic acid to sterilize wounds, dramatically dropping the infection rate. This analogical transfer fits the standard model. Having inferred from Pasteur's work that germs from the air might cause putrefaction, he generated a new solution to the target problem of how to prevent germs from infecting wounds. This problem reminded him of the Carlisle use of carbolic acid, which he then applied successfully (if not pleasantly) to surgery.

Earlier in the nineteenth century, a French physician had used analogy in the invention of the most widely used piece of medical technology, the stethoscope. There are two different historical accounts of this discovery, alternatively fitting the schema and serendipity models of analogical transfer. Here is Laennec's (1962, pp. 284-285) own description in 1819 of how he invented the stethoscope:

> In 1816, I was consulted by a young woman labouring under general symptoms of diseased heart, and in whose case percussion and the application of the hand were of little avail on account of the great degree of fatness. The other method just mentioned [application of the ear to the chest] being rendered inadmissible by the age and sex of the patient, I happened to recollect a simple and well-known fact in acoustics, and fancied, at the same time, that it might be turned to some use on the present occasion. The fact I allude to is the augmented impression of sound when conveyed through certain solid bodies, - as when we hear the scratch of a pin at one end of a piece of wood, on applying our ear to the other. Immediately, on this suggestion, I rolled a quire of paper into a sort of cylinder and applied it to one end of the region of the heart and the other to my ear, and was not a little surprised and pleased, to find that I could thereby perceive the action of the heart in a manner much more clear and distinct than I had ever been able to do by the immediate application of the ear.

This account fits with the schema model of analogical transfer: Laennec solved the target problem of how to listen to the woman's heart by abstracting it into a general acoustic problem that reminded him of pin scratching a piece of wood. The wood then served as a source to suggest rolling up a piece of paper to use to listen to the woman's heart. On Laennec's account, a general acoustic fact provided the retrieval cue for finding a source problem that could be used to produce a solution to the target problem.

A different account has, however, found its way into the historical record, due to Laennec's friend Lejumeau de Kergaradac:

> Ainsi que l'auteur me l'a raconté lui-même, il dut au hasard la grande découverte qui a immortalisé son nom. Dison-le tout de suite, ces hasards-là ne se rencontrent que sous le pas d'un homme de génie. Traversant un jour la cour de Louvre, il aperçu des enfants, qui l'oreille collée aux deux extrémités de longues pièces de bois, se transmettaient le bruit de petits coup d'épingles frappés à l'extrémité opposée. Cette expérience vulgaire d'acoustique fut pour lui comme une révélation. Il conçut sur le champ la pensée de l'appliquer à l'étude des maladies du coeur. Dès le lendemain, à sa clinique de l'hôpital Necker, il prit le cahier de visite, le roula sur lui-même, et le ficela bien serré, tout en y ménageant un canal central, puis le posa sur un coeur malade. Ce fut le premier stéthoscope. (quoted by Grmek, 1981, p. 113).

Whereas Laennec described himself as using acoustic principles to think of the wooden source analogy, his friend's account described Laennec as serendipitously encountering children listening to a pin scratch wood. The children's game provided a fortuitous source analog that reminded him of his ongoing target problem of effectively listening to patients' chests. In accord with the serendipity model of analogical transfer, the encountered source provided a retrieval cue for the target problem rather than vice versa. The historical record is not adequate to establish which of these accounts of Laennec's is correct, although an authority leans toward Laennec's own story (Grmek 1981). Nevertheless, the two versions of the story are useful for distinguishing between the schema and serendipity models of analogical transfer, and Laennec's discovery under either description qualifies as a technological analogy of great medical importance.

In 1983, Kary Mullis, a biologist at Cetus Corporation in California invented polymerase chain reaction (PCR), a technology that now has many applications in molecular medicine. PCR is a method in which an enzyme called a polymerase is used to act along a strand of DNA to produce unlimited quantities of selected genetic material for further investigation. The idea for PCR came to him on a drive to his cabin in Mendocino County. He had been looking for a general procedure for identifying a single nucleotide at a given position in a DNA molecule. According to Rabinow (1996, p. 96) the discovery came about because Mullis had been experimenting with fractals and other computational procedures involving iteration and exponential amplification:

> This was the breakthrough moment. His tinkering with fractals and other computer programs had habituated him to the idea of iterative processes. This looping, back and back again, as boring and time consuming as it might be on the level of physical practice, was nearly effortless on the computer. Mullis made the connection between the two realms and saw that the doubling process was a huge advantage because it was exponential.

This discovery appears to fit the standard model of analogical transfer. Wondering about how to solve the target problem of producing large quantities of genetic principle led Mullis to think of a kind of computational problem with which he was familiar. The iterative processes of fractals then provided a source problem that suggested a solution to the target problem. Thus technological analogies exemplify the standard as well as the schema and serendipity models of analogical transfer.

Educational Analogies

All the analogies I have discussed so far are highly creative ones in which new solutions were suggested for important theoretical, experimental, diagnostic, therapeutic, and technological problems. Much more common, however, are more prosaic educational analogies which function to enable someone who has already figured out something about the nature of disease to convey that information to someone else. For example, Zamir (1996) explains why regular exercise is important for healthy hearts by using an extended financial analogy that compares coronary output to bank deposits. Strachan and Read (1996, p. 458) provide an analogy that helps to distinguish the roles of different cancer-causing genes: "By analogy with a bus, one can picture the oncogenes as the accelerator and the TS [tumor suppressor] genes as the brake. Jamming the accelerator on (a dominant gain-of-function mutation in an oncogene) or having all the brakes fail (a recessive-loss-of function mutation in a TS gene) will make the bus run out of control." Medical researchers and practitioners can also use analogies to explain new ideas about disease causality to others. Analogies can also be used to give practical advice, as with the following anonymous comparison inspired by Mad Cow Disease. Safe eating is like safe sex: You may be eating whatever it was that what you're eating ate before you ate it.

Conclusion

I have described how analogies are useful in medicine for theoretical, experimental, diagnostic, therapeutic, technological, and educational purposes. The processes of analogical reasoning are not, however, always the same, and different cases of medical analogizing fit different models of analogical transfer, although the standard model in which source analogs are remembered and applied to solve a target problem is probably the most common. Additional examination of historical cases and ongoing medical practice will undoubtedly provide more illustrations of different ways in which analogical transfer can contribute to medical thinking.

Acknowledgments

This research is funded by the Natural Sciences and Engineering Research Council of Canada.

References

Berlinger, N. T. (1996). The breath of life. *Discover*(March), 102-104.

Biela, A. (1991). *Analogy in science*. Frankfurt: Peter Lang.

Brock, T. D. (Ed.). (1961). *Milestones in microbiology*. Englewood Cliffs, NJ: Prentice-Hall.

Brock, T. D. (1988). *Robert Koch: A life in medicine and bacteriology*. Madison, WI: Science Tech Publishers.

Bynum, W. F. (1993). Nosology. In W. F. Bynum & R. Porter (Eds.), *Companion encyclopedia of the history of medicine* (pp. 335-356). London: Routledge.

Darden, L. (1983). Artificial intelligence and philosophy of science: Reasoning by analogy in theory construction. In P. Asquith & T. Nickles (Eds.), *PSA 1982* (pp. 147-165). East Lansing:

Dunbar, K. (1995). How scientists really reason: Scientific reasoning in real-world laboratories. In R. J. Sternberg & J. Davidson (Eds.), *Mechanisms of insight* (pp. 365-395). Cambridge, MA: MIT Press.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology*, *12*, 306-355.

Greenberg, D. L., & Root, R. K. (1995). Decision making by analogy. *New England Journal of Medicine*, *332*, 592-596.

Grmek, M. D. (1981). L'invention de l'auscultation médiate. *Revue du palais de la découverte*(22), 107-116.

Hadlow, W. J. (1959). Scrapie and kuru. *Lancet*, *2*, 289-290.

Ho, D. D., Neumann, A. U., Perelson, A. S., Chen, W., Leonard, J. M., & Markowitz, M. (1995). Rapid turnover of plasma virions and CD4 lymphocytes in HIV-1 infection. *Science*, *373*, 123-126.

Holyoak, K. J., & Thagard, P. (1995). *Mental leaps: Analogy in creative thought*. Cambridge, MA: MIT Press/Bradford Books.

Kettler, B., & Darden, L. (1993). Protein sequencing experiment planning using analogy. In L. Hunter (Eds.), *Proceedings of the First International Conference on intelligent systems for molecular biology* (pp. 216-224). Menlo Park, CA: AAAI Press.

Kolodner, J. (1993). *Case-based reasoning*. San Mateo, CA: Morgan Kaufmann.

Koton, P. (1988). Reasoning about evidence in causal explanations. In *Proceedings of the Seventh National Conference on Artificial Intelligence* (pp. 256-261). Cambridge, MA: MIT Press.

Laennec, R. (1962). *A treatise on the diseases of the chest* (Forbes, J., Trans.). New York: Hafner.

LaFollette, H., & Shanks, N. (1995). Two models of models in biomedical research. *Philosophical Quarterly*, *45*, 141-160.

Langley, P., & Jones, R. (1988). A computational model of scientific insight. In R. Sternberg (Eds.), *The nature of creativity: Contemporary psychological perspectives*. (pp. 177-201). Cambridge: Cambridge University Press.

Leatherdale, W. H. (1974). *The role of analogy, model, and metaphor in science*. Amsterdam: North-Holland.

Nersessian, N. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In R. Giere (Eds.), *Cognitive Models of Science* (pp. 3-44). Minneapolis: University of Minnesota Press.

Pasteur, L. (1922). *Oeuvres*. Paris: Masson.

Prusiner, S. B. (1982). Novel proteinaceous infectious particles cause scrapie. *Science*, *216*, 136-144.

Rabinow, P. (1996). *Making PCR*. Chicago: University of Chicago Press.

Strachan, T., & Read, A. P. (1996). *Human molecular genetics*. New York: BIOS Scientific.

Temkin, O. (1977). *The double face of Janus*. Baltimore, MD: Johns Hopkins University Press.

Vallery-Radot, R. (1926). *The life of Pasteur* (Devonshire, R. L., Trans.). Garden City, NY: Doubleday.

Zamir, M. (1996). Secrets of the heart. *The Sciences*(September/October), 26-31.