Perspectives

Determinism or Probability—or Teaching Students How to Ask Questions

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My mother just found out she is pregnant. Will she have a child with Down's Syndrome? Why did my dad die of lung cancer? Exactly what side effects will I experience when I take birth control pills? As teachers of biology, we are all familiar with such questions posed by students who are concerned about their own health or that of family members. These questions, as they have been phrased, demand simple answers or explanations which imply a cause-and-effect (deterministic) response. Students may be disappointed or may not understand when we are unable to give simple, straightforward answers. For example, "Will my mother have a child with Down's Syndrome?" asks for a yes or no answer. But of course no one can answer that before the fact. Knowing only the age of the woman, one can reply that she has a 1 in 180 chance or a 1 in 25 chance, etc., of having a child with Down's. So one must answer the question with a statement of probability, even though the student has asked the question in a way that demands a deterministic answer.

I believe that students demand a cause-and-effect answer because our culture and our education have taught us to expect deterministic explanations in science. This inappropriate belief that deterministic explanations are always to be expected in science has led to much misunderstanding, between physician and patient, ecologists and the public, etc. Unresolved misunderstandings have led to numerous lawsuits, much litigation, and great unhappiness. It is time for us as teachers of science to make it our business to explain to students that there are two major ways of developing scientific explanations, the deterministic and the probabilistic, and that there are situations in which each is appropriate or inappropriate. And because most students not interested in science as a career choose biology as their high school or college science elective, a larger burden of teaching these important differences falls to biology teachers.

Determinism and Probability

Determinism or a deterministic explanation suggests that an event or effect can be explained by a cause. Cause and effect are expected to be repeatable, a given cause always leading to the same effect. Phenomena which can be explained in this way are repeatable; any observer, given the same set of conditions, will obtain the same results. This realization was a remarkable development in the history of human thinking. Belief in cause and effect with its emphasis on the naturalness of phenomena was and is important in freeing all people, not just scientists, from their fears and superstitions; once events are perceived to recur in regular or predictable ways and can be explained naturally, fears can be reduced. No chaos, no capriciousness. At heart, nature is understandable. Much of our teaching in science, particularly in secondary schools and in the early college years, stresses the deterministic nature of science.

Though extremely useful, determinism does not go far enough, for there are many natural events which cannot be explained deterministically, yet show regular patterns of occurrence. For these events, the notion of probability provides an explanatory system. Probability is the likelihood of occurrence of a particular event, or an estimated ratio of the particular form of an event and the number of ways in which the event can occur. One cannot make simple cause-and-effect statements about the occurrence of an event, but only statistical predictions.

Some say that probabilistic and deterministic explanations represent opposing and discrete ways of understanding a phenomenon, while others suggest that they are the extremes of a continuous spectrum of explanations. Although this is an intriguing philosophical question, no attempt will be made to address this issue here. The goal of this essay is to explore some of the practical aspects of when each kind of explanation is appropriate.

Considerations of Appropriateness

Level of Hierarchy—The gas laws are often used as an example of cause and effect in nature. For example, expressed mathematically, the pressure generated by a given volume of gas can be accurately predicted if one knows the temperature; to generalize, if one knows any two variables, the third can be predicted. This "law of nature" works very well at the macroscopic level at which we humans live and work. However, if we look at the phenomenon at a molecular level, the deterministic explanation fails and a probabilistic one is more appropriate: pressure is the result of random collisions of molecules with the side of the container, and no prediction about which molecule will hit where and when can be made. Thus, the so-called gas laws are deterministic at the macroscopic level which in turn is the result of a probabilistic process operating at the molecular level. Therefore, the level at which an explanation is demanded may determine the appropriate mode of explanation.

Perspective.—Deterministic explanations regarding the germ theory of disease have been successful in biology. For example, infections in the body by the bacterium *Treponema pallidum* cause the development of a series of symptoms called syphilis. However, another perspective on *T. pallidum* and syphilis demands a probabilistic explanation. In a population of 1,000 people exposed to active cases of syphilis, 80% will be expected to contract the disease. We cannot predict who will develop the disease, but can give an estimate expressed as a probability. Thus the perspective of the question automatically implies the level or kind of explanation that is appropriate.

Incomplete Knowledge—Some events first explained probabilistically may eventually be understood in terms of cause and effect. The relationship between cigarette smoking and lung cancer is an example. Early studies suggested that there was a statistical correlation between smoking and cancer. The question remained, why some heavy smokers did not develop lung cancer while others, even some light smokers, did. Recent studies suggest that certain people have enzymes that transform elements of tobacco smoke into compounds which result in cancer. Those people who lack this enzyme will not develop lung cancer. (This is not to advocate cigarette smoking, since lung cancer is only one of a number of problems associated with smoking.) Therefore, once we have full knowledge we may be able to describe an event as a result of two (or more) interacting causes.

Interacting Factors—Some events turn out to have a cause-and-effect explanation with two causative factors acting together or in sequence to produce a specific effect, as discussed above. There are some phenomena which we explain probabilistically that perhaps could be explained deterministically if we knew more of the complex of interacting factors. An example of this is tuberculosis, a bacterial disease which requires specific genetic susceptibility for the disease to develop. More complex is the prediction of specific side effects for a particular individual when taking a medically prescribed drug. For drugs, we know that there are many variables which affect the action of the drug, for example, the age and sex of the person. The genetic makeup of the individual may have an effect; the time of day at which the drug is taken; whether or not the drug was ingested or injected; the time of food intake relative to drug ingestion; the emotional state of the person; what the person has been told regarding the expected effect of the drug; synergistic effects with other drugs, etc. If we knew and could precisely define each of these in relation to a particular drug, then perhaps we could make cause-and-effect predictions or explanations for a particular individual and a particular drug. However, the multiple and complex interacting factors suggest that there are some phenomena which cannot ever be explained deterministically because of the practical impossibility of knowing everything. Teratogenic effects of certain environmental pollutants may also be in this category in which practicality demands that we not seek deterministic answers.

Obligatory Probabilistic Explanations—These previous examples suggest that once we have complete knowledge, then deterministic explanations will be possible. There are, however, situations in which there is reason to believe that one can never predict a specific effect before the event has occurred, but can only predict probabilistically. In this category is the prediction of the number of deaths from automobile accidents over a holiday weekend. Predictions of this sort can be made with amazing accuracy based on past history and a few assumptions (e.g., the weather and the price of gas). However, the predictions are about the phenomenon regarding the population in general and can say nothing about which particular individuals will be killed or involved in the accidents. After the fact, individual collisions can be analyzed for cause, but these individual analyses of cause and effect do not aid in predicting which individuals will be affected the next holiday weekend. There are other events in nature which may also fall into this category of obligatory probabilistic explanations. Many applications of biomedical theory fall into this category. For example, a genetic prediction gives this: 1) if both members of a couple are heterozygous for the gene for phenylketonuria (PKU), the probability of a child with PKU is 1 in 4, and 2) for each separate conception that probability remains the same. The analysis of the disease as caused by the dual, defective genes does not permit us to predict that this or that particular conception will result in a child with PKU.

Discussion and Summary

It is important to teach our students when to seek deterministic explanations and when to seek probabilistic ones. It is important for our society to recognize that our understanding of diseases caused by exposure to pollution is probabilistic, that most desirable effects and especially the unwanted side effects of new drugs, vaccines, and other biomedical technologies require probabilistic explanation. Indeed, there are cases where a physician may simply be ignorant or incompetent or careless, or the technology for diagnosis may not yet exist. However, in other instances, the circumstances preclude any deterministic explanation; no physician can be faulted for failure to predict precisely for a specific patient the consequences from a given action. To continue demanding deterministic explanations in such situations is inappropriate, and even harmful. When things go wrong with inappropriate explanations, as they surely will, our simplistic faith in determinism cannot be upheld; disappointment and disillusionment follow. Not far behind come lawsuits. Large awards to plaintiffs by sympathetic juries lead to rising expectations by the public and more stringent demands on manufacturers, drug companies, and the Food and Drug Administration and other regulatory agencies. This, of course, hampers research; it creates a climate of distrust between patients and physicians. We demand cause-and-effect explanations when perhaps a scientist or physician can only respond with a statement of risk. Patients are upset when they fail to get a definitive explanation from their physician. Some then seek aid from those with absolute answers, often charlatans. The problem of laetrile and its advocacy by some for cancer therapy is an example of this. Citizens are upset when scientists are unable to give definitive answers to environmental questions. The recent uproar over whether the chemical dumps at Love Canal caused birth defects is a case in point.

If we can teach our students the difference between deterministic and probabilistic explanations, and if we can help them know which mode is appropriate in a given circumstance, perhaps we can help develop a society not confused by these two ways of explaining. If we can get a student to ask "What is the risk of my death from lung cancer if I work in the asbestos factory?" not "Will asbestos cause my death by lung cancer if I work in the factory?" and yet know that *Treponema pallidum* causes syphilis, perhaps that will be the measure of our success.

Acknowledgment—Thanks to my colleagues Drs. Harry Stevens and Helen Hiscoe for their help in developing the ideas in this essay.

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