1 How to plan research

> The great tragedy of Science – the slaying of a beautiful hypothesis by an ugly fact.
>
> Thomas Henry Huxley (1825–95)

Success in science, as in most complex endeavors, depends partly on preparedness and planning. The three Persian princes of Serendip notwithstanding, a great truth is found in the aphorism that chance favors the prepared mind. No mere chapter could constitute a complete guide to planning research. This one attempts to cover the main points common to most projects. We begin with a background sketch of epistemology: how science as a whole works and the roles of individual investigators. That introduction provides a framework for discussing specific issues of planning research. Subsequent chapters deal with some of the major steps of doing science (e.g. how to write a grant proposal and how to communicate the results of research) that ensue after good planning.

SCIENTIFIC EPISTEMOLOGY

In order to plan research effectively, the investigator should understand how his or her activities fit into the endeavor of science as a whole. Some explanations of the ''scientific method'' confound epistemology – how we accumulate knowledge and understanding through science – with specific research activities of the individual investigator. This section attempts to disentangle the two by sketching the ''big picture'' first and then showing where the practicing scientist fits in.

Science as process and product

One can conceive of science as a cycle of activities and results based on procedures that are often referred to as the ''hypothetico-deductive method.'' This method evaluates a hypothesis (more generally, a model) of how the world might work and deduces consequences that must be true if the world does actually work in the way posited. One can then check the real world to see whether these predicted consequences are verifiably true. The process is cyclical because if

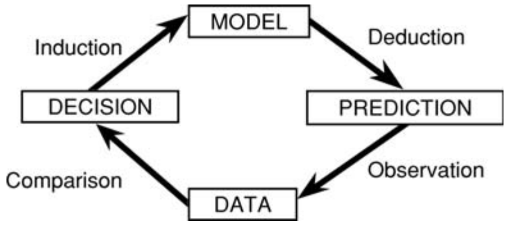

FIGURE 1.1 A schematic representation of the epistemological cycle

the consequences cannot be verified, then a new hypothesis (model) must be tried. Even if the predicted consequences can be verified, however, that result might be coincidence. Therefore, one strives to deduce new predictions from the same hypothesis and test these as well. The cycle, which we call here the epistemological cycle, can be represented schematically as in Figure 1.1.

Figure 1.1 uses some simple conventions of illustration. Boxes, which are labeled in FULL CAPS, represent statements that can be written down: products of the processes. Arrows, which are labeled in lower case, represent processes that yield the statements in the boxes to which they point. Furthermore, each arrow originates at a statement and points to another statement, so as to show the sequence of steps in the process of science. As the diagram represents a cycle, we can scrutinize its parts beginning at any arbitrary place and then return to that place by completing the cycle. The practicing scientist, however, usually enters the cycle at one of two places: creating (or revising) a model from data at hand, or drawing testable predictions from an existing model. We begin discussion at the latter point, assuming that a model of some natural phenomenon already exists.

Deduction and prediction

Deduction is a type of reasoning that in logic leads from a set of premises to a conclusion. In science, the logical premises constitute the model, which is a speculation of how things might work in nature, and the logical conclusion is a specific prediction that is testable by observation. One could also say that a deduction is the result of the process of deducing, but that use would give two meanings to the same word, so we restrict ''deduction'' to the process itself.

Some writers encapsulate the deductive process as reasoning from generalities to particulars, but we think of it as a rearrangement of knowledge. In the terminology of logic, deductive reasoning extracts from a set of premises (the MODEL of Figure 1.1) one or more conclusions (the PREDICTION of Figure 1.1). No new knowledge appears in the prediction: everything in the prediction is already inherent in the model. The deductive process simply isolates part of the model or isolates several parts and then combines them. Consider a simple example:

> MODEL: the earth rotates on its axis, spinning counterclockwise when viewed from above the North Pole.

From this model, one can deduce the prediction that the sun (and the other stars, for that matter) should rise above the eastern horizon, travel across the sky, and set in the west. The model of course embeds some hidden assumptions, such as all these celestial bodies being fixed in space relative to the earth. Almost all models have implicit assumptions, and failing to recognize them could lead to problems in reasoning. The prediction deduced can be written down and checked empirically, which means that one uses the process of observation, including formal measurement, to see whether the predictions match reality as we view it.

Deduction is at heart a stipulated set of rules for assuring this relationship between model and prediction: *if the model is true, then the prediction deduced from it must also be true*. The rules take many forms, the oldest of which is the Aristotelian syllogism. In its commonest form, the syllogism produces a conclusion (prediction of scientific epistemology) from two premises (together making the model in epistemological terms). For example:

PREMISE 1 (part of model):	If only Jack drives the van
PREMISE 2 (part of model):	And if the van is on a field trip
CONCLUSION (prediction):	Then Jack is on a field trip

Of course, science does not depend upon syllogistic reasoning, which is full of pitfalls because of the inherent imprecision of language. For example, consider this syllogism: unicorns all have horns (premise 1), and this animal has a horn (premise 2); therefore, this animal must be a unicorn (conclusion). The logical error in that syllogism is termed a fallacy of affirmation and is common in reasoning with language; just because A implies B (if it is a unicorn, it has horns) does not necessarily mean that B implies A (if it has horns, it is a unicorn). The error leads to apparent substantiation that unicorns exist. Anyone can see through the problem in a simple syllogism like this one, but much reasoning from scientific models is similarly linguistic in nature and so entails all the dangers of language itself.

Linguistic reasoning does not have to be in syllogistic form, as was demonstrated by Bertrand Russell. For example, it is possible to draw a conclusion from only one premise:

PREMISE: If a horse is an animal
CONCLUSION: Then a horse's head is an animal's head

Most scientific deduction is basically mathematical in nature, and, conversely, most mathematics taught in secondary schools is deductive in nature – Euclidian geometry and algebra, for example. Simple algebraic deduction can even be written in syllogistic form:

PREMISE 1: If $x + y = 6$
PREMISE 2: And if $y = 4$
CONCLUSION: Then $x = 2$

The deductive logic underlying the earlier example concerning the rotation of the earth on its axis was geometric.

The bridge between linguistic reasoning and mathematics is symbolic logic. Many such logic systems have been devised from different starting points, and in most cases different systems are easily shown to be equivalent. That is, given the same set of premises (together, the model of Figure 1.1), deduction by the rules of any given system leads validly to the same conclusion (the prediction of Figure

1.1). Boolean algebra is a form of symbolic logic that stands sort of midway between linguistic reasoning and traditional mathematics. The Boolean system uses the linguistic-like operators *and*, *or*, *not*, *if*, *then*, and *except* to relate variables such as propositions. Formal set theory is even more mathematical-like, using symbols for operators. All systems of deduction have in common the key property: if the premises (model) are true, then the conclusion (prediction) deduced from them is true, assuming that the deductive process scrupulously followed the rules of the system.

Observation and data

Observation in Figure 1.1 is the process that leads to data. ''Observation'' might seem a restrictive term, connoting merely noting visually what an animal is doing or some other aspect of the world. Nevertheless, we use ''observation'' as a general term to include all ways in which human senses are extended by instruments to record data. Ultimately, the investigator observes: for example, observes a dial or digital display on an instrument, or observes sound spectrograms made from tape recordings. Thus, observation in Figure 1.1 means any sensing and recording process that leads to data that can be written down or otherwise represented in hard copy.

The term ''observation'' might also be applied to the data produced by observing. In order to avoid confusion, we restrict our use of ''observation'' to the process and use ''data'' to describe the results of that process.

You might already have considered the question of why the arrow representing the observation process in Figure 1.1 points from PREDICTION, it being obvious why it points to DATA. The arrow originates at PREDICTION because the prediction specifies what kinds of data need to be observed. The prediction states what *must* be the case if the model is true, and the data show whether or not the prediction is upheld in the real world. Data that have nothing to do with the prediction might be an informative sidelight to a particular investigator's activities, but they have no direct bearing on the empirical test of the model. Nevertheless, observation with no particular model in mind can produce data that ultimately lead to a hypothesis. We have said that the investigator *usually* enters the epistemological cycle with a model to be tested or with data (often from the literature) for generating or revising hypotheses, so entering the scientific cycle through simple observation without starting predictions is an exception.

The word ''experiment'' does not appear in Figure 1.1. We have avoided that term because it tends to connote a carefully controlled laboratory environment in which every attempt is made to control extraneous variables that could influence the data. Some of biology – and especially the behavioral ecology practiced by the authors – involves mainly field studies. In some cases field studies also involve formal experiments, but in many cases they do not.

No fundamental difference exists, in terms of epistemology, between a laboratory experiment and field observations. Each approach to gathering data relevant to a prediction has its advantages and disadvantages. Laboratory experiments usually provide considerable control over extraneous variables that could influence the results, but the laboratory environment may produce artifacts. Field studies may be more natural and realistic, but generally they exercise little control over extraneous variables that could influence results. Both laboratory experiments and field observations play a role in research and can provide a particularly powerful approach when used in concert.

Comparison and decision

Sometimes, explanations of scientific epistemology fail to be explicit about the process of comparing the data observed with the prediction deduced from the model. This step is crucial to the workings of science, however, because it is not always evident whether the data are in agreement with a prediction. Extraneous factors *always* act upon any aspect of biology under observation, even in carefully controlled laboratory experiments.

As with deduction and observation, the term ''comparison'' could be applied to both the process and the results of that process. In order to avoid confusion, we use the word ''comparison'' to refer only to the process. The results of the process constitute the ''decision'' (regardless of whether the results fit the prediction).

The process of comparison commonly uses statistical methods for comparing data with predicted results. For example, a model might predict that older animals of some species tend to dominate younger animals. The data could show that this predicted relationship is an imperfect one, so the question becomes whether dominance structure is unrelated to age or is influenced by age as predicted or by some other age-associated traits. The investigator would probably employ some appropriate statistical test to see whether dominance relations were random or non-random with respect to age.

The comparison between data observed and the prediction deduced from the model yields a DECISION. Ideally, the decision is simply whether the data fit the prediction, but things do not always turn out so nicely. One may decide that it is impossible to tell whether a match exists. A common outcome of the process of comparison is that some expected difference is not statistically reliable, and yet a trend in the predicted direction is noticeable. Therefore, the difference could be real but not established by the data, either because extraneous variables unduly influenced the data (as commonly occurs in field studies) or because the sample size was insufficient to provide statistical reliability. In such cases, the main recourse is to gather better data, either with improved control over extraneous variables or with larger samples.

Yet another way in which comparison between predictions and data can fail to yield an unambiguous decision about the model is when some predictions are supported and others are not. Any validly deduced prediction that is rejected by empirical data falsifies the model, but when the deductive chain is not tight and other predictions are consistent with data, researchers sometimes refer to ''partial confirmation'' of the model. This situation usually suggests that the model is not quite right but has merit that could be improved by modifications based on careful scrutiny, without having to ''go back to the drawing board.''

Induction and model

The decision resulting from comparison between data observed and the prediction deduced from the model dictate the next step in doing science. As noted earlier, three kinds of decisions are possible: (1) the data do not resolve the question because they are inadequate or conflicting, (2) the data do not match the prediction, or (3) the data confirm the prediction. In the first case, if the data are not sufficient, then nothing can be done except to go back and gather data adequate to the task. On the other hand, if the results testing different predictions conflict, then the model is probably not quite right and needs to be modified.

Suppose the data show unambiguously that the prediction cannot be correct: the data are simply not as predicted if the model is true. Only one explanation of this situation exists: the model is false. We say in science that the data reject the model (because they do not match the prediction deduced from the model). In this case, if one is to explain the phenomenon under investigation, it is necessary to produce a new model, or at least revise the old one, and then proceed with making and testing new predictions.

The creative process of proposing how nature works involves induction. Induction is sometimes characterized as reasoning from particulars to generalities, but that catchphrase seems vague and in any case may not always apply. We prefer to think of induction as a cluster of very complicated creative processes in which the thinker identifies possible patterns from available facts and proposes causal relationships that might explain the patterns.

No rules for creative induction exist, and the many books written on the subject seem to agree that induction is not one but many complex mental processes that find a pattern where none was recognized previously. Most of the famous models of science have come from people who reflected on disparate empirical data and somehow united them into a coherent framework. For example, Charles Darwin realized that the traits of parents and their offspring tend to be similar (genetic inheritance was not yet understood), that more offspring are born than survive to reproduce themselves, and that survival probably depends at least partly on the traits of the individual. From these empirically verifiable facts, Darwin reasoned correctly that if the survival traits are heritable, then evolution must occur: his model of natural selection. To recount another famous example, Danish physicist Niels Bohr mused over the emission spectra of elements. When one burns a substance, it emits light of specific wavelengths, the combination of wavelengths being unique to every different element. From a vast storehouse of emission spectra accumulated by empirical scientists, Bohr conceived of his atomic model of a positively charged nucleus surrounded by negatively charged electrons of different energy levels.

The examples from Darwin and Bohr are what historian of science Thomas Kuhn has called ''paradigm shifts'' or ''revolutions'': whole reorganizations of thinking in a given area of science. Kuhn first believed that progress in scientific understanding was completely dependent upon such revolutions but later came to realize that stepwise revision of models also moved science forward (see Kuhn 1996). An entire spectrum exists from minor honing of models through substantial revisions and generalizations to major shifts in paradigms, and all have their place in the progress of science. Few practicing scientists will bring forth revolutionary new ways of viewing some natural phenomenon, but each scientist should strive to keep an open mind and induce new, viable ways of uniting disparate facts through induction.

Uniqueness of models

Because induction is a type of creativity, scientific models that result from it are unique to their creators. This assertion is controversial, but most apparent exceptions to the asserted uniqueness turn out not