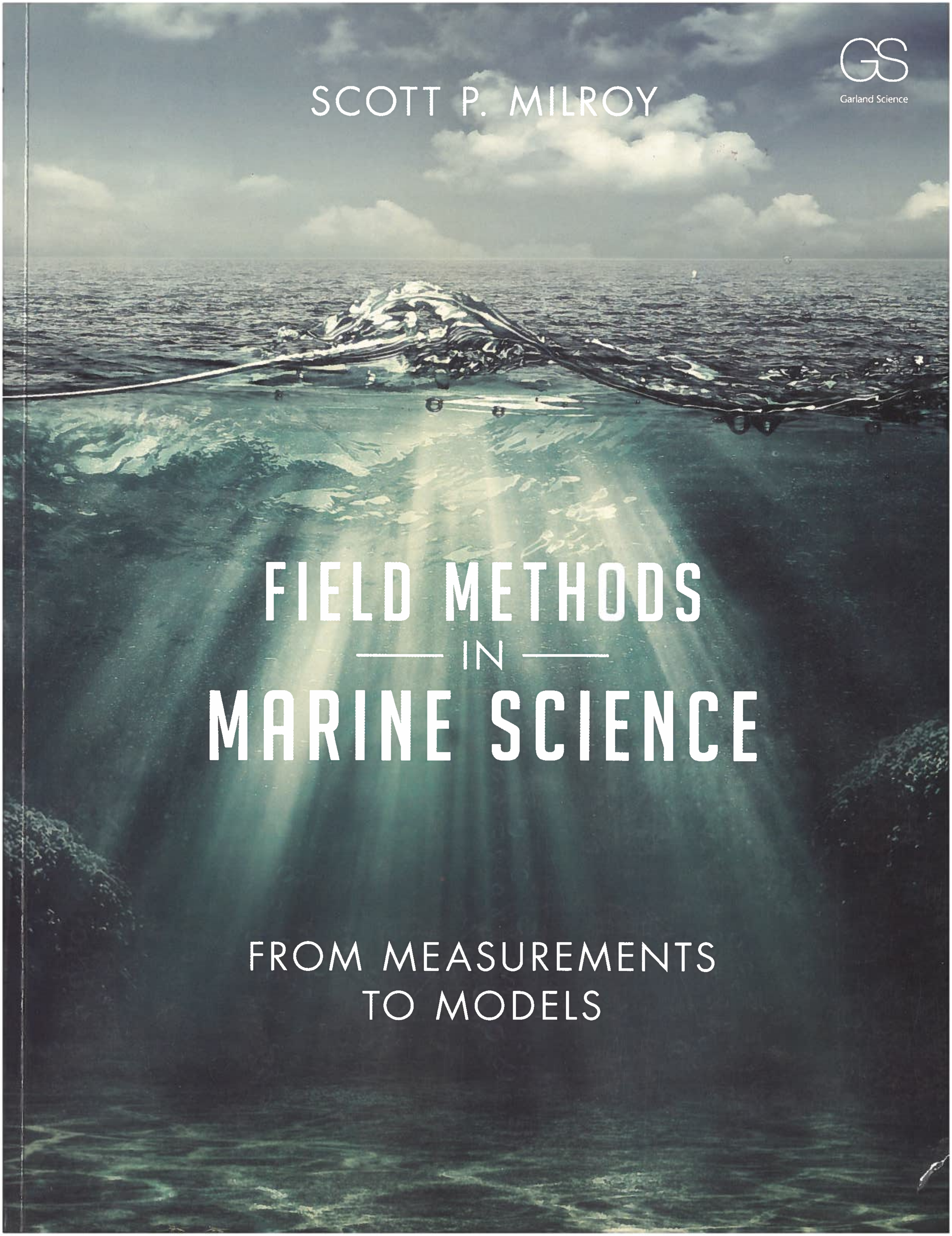

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Garland Science

# FIELD METHODS IN MARINE SCIENCE

## FROM MEASUREMENTS TO MODELS

# Unit 1
# First Principles

## Contents

Chapter 1

# The Foundations of Scientific Inquiry

*"There can be no doubt that all our knowledge begins with experience."* – Immanuel Kant

It may seem an overly simplistic question, but very few take the time to really consider: What is science? How does the knowledge gained through scientific inquiry differ from other modes of learning, and is it appropriate to afford greater respect to the sciences? Of course, those are judgments we must each make for ourselves, but it is certainly worth our time to consider such questions honestly.

The foundations of scientific inquiry were laid by ancient mathematicians, logicians, and naturalists stretching back to the dawn of human intelligence and curiosity. Since science is, at its core, a process of learning through trial and error, it is not surprising that a rudimentary understanding of the natural world could be gleaned from evidence acquired by the ancients, using very little technology. Even today, the performance of science is not predicated by the use of expensive, highly technical equipment—good science can be performed using one's own senses and acute intellect. But with each new discovery, scientists were able to draw upon the wisdom and experience of their predecessors to form a deeper understanding of the natural world, and use that information to guide the direction of new inquiries. But what was so critically important to learning was the very process of science itself.

## Key Concepts

- Science relies upon the philosophy of empiricism, which states that neither fact nor truth can be known; we must rely instead on evidence.
- All scientific endeavors must be performed according to a strict set of rules, called the scientific method.
- The scientific method does not guarantee accuracy or provide proof; it simply provides an ordered framework for scientific inquiry.
- In order for knowledge to be gained through scientific inquiry, it must be testable through experimentation.
- Experiments are not self-determining—they merely provide evidence that must be analyzed for significance and meaning.

**Figure 1.1** René Descartes (1596–1650). One of the most influential philosophers, whose works helped to establish the philosophical underpinnings of the scientific method.

## The Difference Between Evidence and Truth

Truth. The concept, at its face, seems simple enough for our minds to grasp, and so we speak of it casually, as if we could demonstrate our mastery of it by being so dismissive of its real significance. But "truth" (as we so flippantly regard it) is a concept that should bring us all to our knees as we consider the awesome enormity of what that word represents. In its grandest sense, truth is represented by the sum total of the universe's facts: integrated, unchanging, and eternal.

Long and laboriously have philosophers struggled with the problem of truth. As it turns out, the problem is humankind's fundamental (in)ability to learn certain truths about the universe we occupy, simply because our method of inquiry—via intellect and experience—is inherently flawed. Interestingly enough, it is not the human intellect that harbors the origin of error—it is instead the knowledge gained through experience that cannot be trusted.

The most persuasive philosophical arguments for this were offered by René Descartes, a seventeenth-century French mathematician and philosopher (**Figure 1.1**). In his *Meditations on First Philosophy*, Descartes offered,

> *"Whatever, up to the present, I have accepted as possessed of the highest truth and certainty I have learned either from the senses or through the senses. Now these senses I have sometimes found to be deceptive; and it is only prudent never to place complete confidence in that by which we have even once been deceived."*

In other words, any evidence gained through the use of our imperfect senses must be considered suspect and never afforded absolute confidence. This philosophical axiom would at first seem to be a fatal blow to all learning. After all, if human knowledge is borne from experience, but these experiences can never be fully trusted, how then are we expected to learn anything? Is it possible to know anything prior to first experiencing it with or through our senses?

Although Descartes would have us questioning everything we can see, hear, touch, taste, and smell, he was also able to demonstrate that there is knowable truth in our universe—truth that is independent of our senses. In an oft-quoted passage from his *Meditations*, Descartes offers what is probably his most famous contribution to philosophy:

> *"If I am persuading myself of something, in so doing I assuredly exist. But what if, unknown to me, there be some deceiver, very powerful and very cunning, who is constantly employing his ingenuity in deceiving me? Again, as before, without doubt, if he is deceiving me, I exist....Ego sum, ego existo."*

Though often mistranslated as "I think therefore I am" (rather than "I am, I exist"), the meanings are essentially the same: regardless of whether we are perceiving our universe rightly or wrongly, the mere fact that we are perceiving the universe at all requires that we exist in the first place.

This is a critically important philosophical point to make, because it establishes the human ability to know truth *a priori*; that is, from the beginning (without experience). Hence, if humankind is capable of knowing this truth, perhaps there are more truths that are knowable and that these truths can be used to make ourselves more perfect instruments of learning.

### Immanuel Kant's *Critique of Pure Reason* Picks Up Where Descartes Leaves Off

Although Descartes had firmly established that existence is a necessary prerequisite for all sentient beings in the universe, it wasn't until the late eighteenth century that a Prussian philosopher named Immanuel Kant (**Figure 1.2**) first published his *Critique of Pure Reason* and solidified the philosophical foundations necessary for scientific endeavor. The first of Kant's critical assertions was the *a priori* truth of space:

> *"Space is a necessary a priori representation, which underlies all outer intuitions. We can never represent to ourselves the absence of space, though we can quite well think it as empty of objects. It must therefore be regarded as the condition of the possibility of appearances, and not as a determination dependent upon them."*

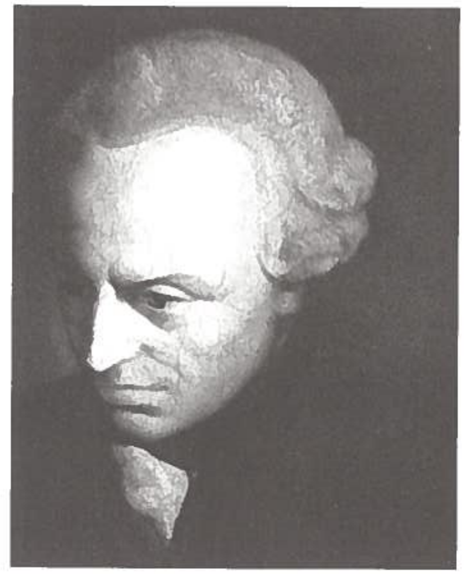

**Figure 1.2** Immanuel Kant (1724–1804). A pioneer in philosophical thought, particularly as it relates to the empirical sciences.

Thus, Kant posits that space must exist before any observation can be made, whether that observation is made truly or falsely. Between Descartes and Kant, the necessity of existence begs the *a priori* representation of space (wherein all things that exist must be found).

But the true value of Kant's work, with regard to what is knowable in the context of science, is revealed in his treatment of time and causality. In his *Critique*, Kant asserts,

> *"All appearances are in time; and in it alone ... can either coexistence or succession be represented. Now time cannot by itself be perceived. Consequently, there must be found in the objects of perception ... the substratum which represents time ... and all change or coexistence must be perceived in this substratum, and through relation of the appearances to it."*

So, regardless of whether our observations are false, the mere ability for humankind to perceive of them as being either coexistent or successive would require that time be an additional *a priori* truth within our universe. Beyond the obvious implications of time as an *a priori* truth, this notion of succession, in very logical terms, sets the stage for causality (that is, cause and effect).

But causality implies something else that is absolutely critical to the sciences, something that Kant argues must also be an *a priori* truth of our universe: the truth that order exists. Kant offers the following thought experiment, meant to provide his proof:

> *"Let us suppose that there is nothing antecedent to an event ... All succession of perception would then be ... merely subjective, and would never enable us to determine objectively which perceptions are those that really precede and which are those that follow."*

In other words, were it not for an ordered universe, our perceptions would never allow us to determine consistent causality. In a universe plagued with chaos, it would be impossible for humankind to learn anything because this notion of "cause and effect" would be utterly meaningless. But in our universe, we do not perceive chaos—we perceive order, even though the "truth" of our perceptions should be vigorously questioned (as Descartes would remind us). And so it is the order in our universe that affords us humans the possibility to describe it through our imperfect perception and intellect. That is where science comes in.

## Empiricism and the Scientific Method

As we have discussed, the process by which nearly all human knowledge is gained is through experience. But the employment of our intellect requires that we first gather the appropriate evidence through the flawed filter of our senses. This is the practice of **empiricism**, a school of philosophy that attempts to understand universal truths through the acquisition and analysis of evidence. Thus, it seems a straightforward proposition to claim that all true science is empirical. But it should be equally obvious that in the pursuit of truth, science is inherently weakened by the limitations of empiricism. Weakened, yes—powerless, no.

After all, if our ultimate goal is to describe the order within our universe, we need not be perfect—just consistent. Regardless of how badly we bungle our attempts to describe our surroundings, the truth of the universe remains unchanging and eternal. Eventually, if we are consistent in our efforts and refinements, we may eventually converge upon the truth (provided that we ourselves do not create chaos where none previously existed).

To that end, the scientific method was developed to provide a uniform process by which the philosophy of empiricism can be employed in a prescriptive manner, designed to maximize the power of analysis and to constrain error. Again, it is important to remember that error can never be completely eliminated from our scientific pursuits. But if we conduct our imperfect science according to some very strict rules, there is hope that we can reveal the consistency of our error, and therefore remove it (or at least account for its presence). To guarantee that kind of consistency, the scientific method must be followed as a very logical, stepwise procedure (**Figure 1.3**).

### Observation

What would at first seem to be the simplest aspect of the scientific method can also be the most significant; after all, observation is the first step on the long road to discovery! And since we can use any combination of our senses (sight, smell, sound, taste, and touch) to make an observation about the world around us, there is no shortage of information streaming into our brains at any given moment. The difficulty actually comes when we try to limit our sensory input to only those perceptions that are pertinent to the phenomenon we wish to investigate.

As a very simple example, let us assume we've gone swimming a number of times, but this is our first time to the beach to swim in the ocean. After the first wave hits us square in the face, we taste for the first time the saltiness of ocean water, which is very different from the taste of water from the swimming pool back home. Regardless of this new salty sensation, your first experience in the ocean is providing you with several other sensations you have never witnessed before in your pool back home: the waves crashing over your head, the sand squishing between your toes, and so on. But if the saltiness of the ocean is truly what has piqued your interest, the scientific method requires that you focus your attention only on those senses, and those bits of sensory information that are relevant to the investigation at hand.

Thanks to Immanuel Kant, we can feel confident that all phenomena within the natural world that are observable must also be ordered—they must fundamentally possess some kind of pattern of "cause and effect." So regardless of whether we have correctly perceived something, causality must exist in all our observations. In other words, there must be something causing our perception of salty ocean water. Explaining that causality—that order—is the very point of science, and it is the goal of the inquisitive scientist. And what do inquisitive scientists do? They ask questions.

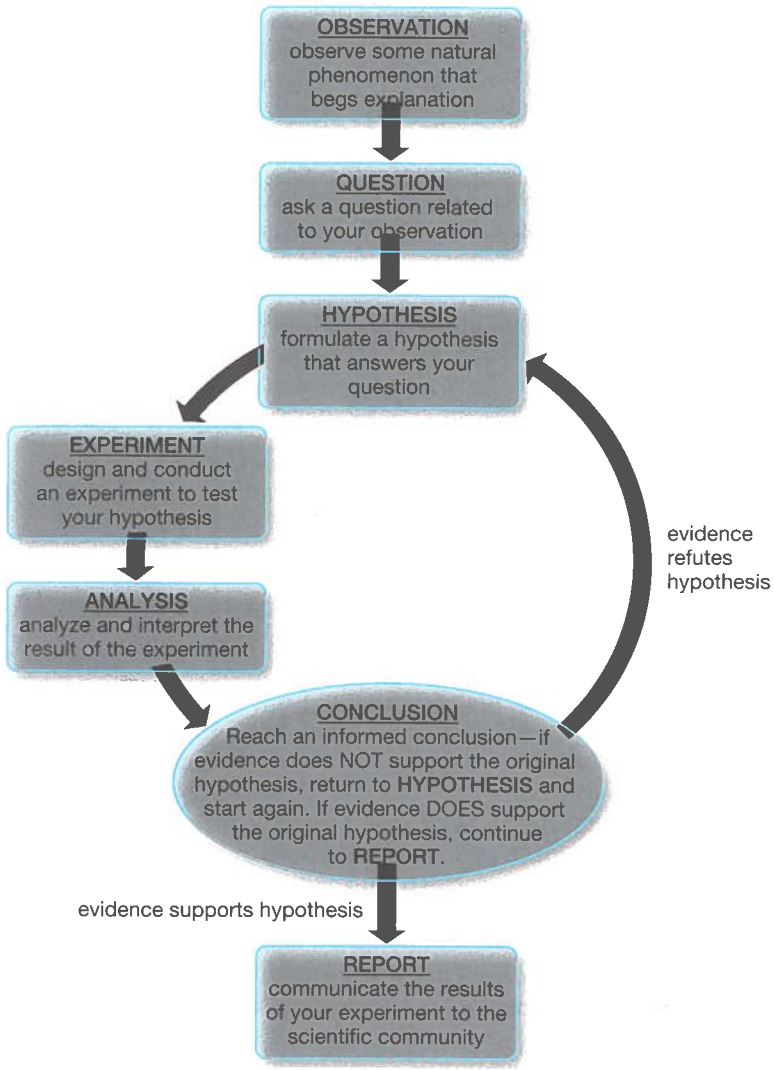


**Figure 1.3** The scientific method involves a prescribed technique for investigating natural phenomena, acquiring new knowledge through the use of empirical evidence, and incorporating those discoveries into the body of human knowledge.

## Question

It is human nature for us to perceive something unusual or interesting and then immediately ask what, when, which, where, how, and why. In the context of science, we ask questions to explore what is knowable about the world around us. Within the scientific method, it is critical that we ask the right question: it must be a question that is relevant to the observation(s) we just made, and it must be answerable with data. In other words, it must be a question for which we can gather evidence in our attempt to answer it.

Ideally, you should try to construct a question that can be answered in the strictest binary terms: yes or no, positive or negative, black or white. If the phenomenon you wish to explore is far too complex to be explained with a single "yes or no" question, you should try to construct a logical series of binary questions that will allow you to deduce the answer, based on the results of each question answered within the series.

Let us return to our earlier example of experiencing the salty taste of ocean water for the first time. There can be any number of questions we might ask about our observation. Do the waves smacking us in the face (or that sand between our toes) have something to do with the saltiness of the ocean? What about the color of our bathing suit, or the sound of children laughing

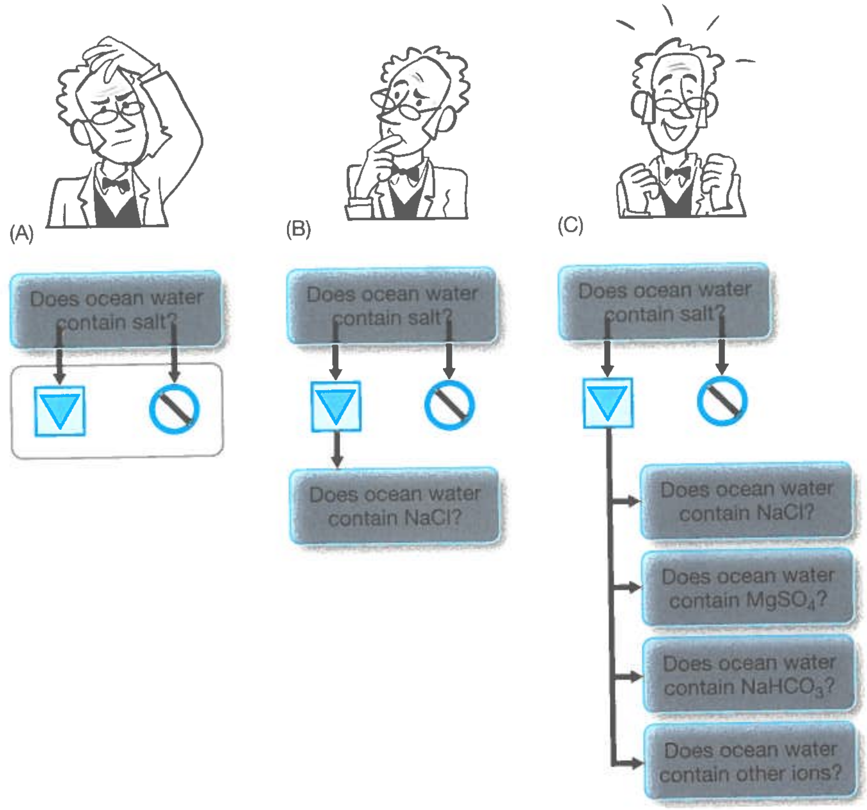


**Figure 1.4** Within the context of the scientific method, a series of well-designed questions will allow a clever investigator to use one answer as the logical basis to ask further, more in-depth questions. As simple as it may seem, the answer to our first question (A) of whether the ocean tastes salty or not will establish whether the "saltiness" phenomenon even exists and whether it is necessary for us to continue our line of inquiry. If the answer to our first question is "yes," perhaps we can follow up with a question seeking to ascribe that phenomenon to a particular salt like sodium chloride, or NaCl (B). Of course, NaCl is only one kind of salt; other questions may be necessary to explore all of the other salty possibilities (C).

while playing in the sand? Forget about whether any these are truly relevant to the saltiness of the ocean—we have not tested any of them yet, so we can't say for sure. It's more important to consider the usefulness of the questions. The best advice is to "be specific" when asking a scientific question.

It would be more useful (and more logical) to construct a series of very specific, binary questions so that the answer to a preceding question will determine the relevance of subsequent questions (**Figure 1.4**). The simplest (and most relevant) question to ask is simply "Does ocean water contain salt?" If the answer to that question will satisfy our curiosity, regardless of whether it's a "yes" or "no," there would be no reason to continue this line of investigation. If the answer is "yes," we may wish to inquire as to whether the salt in the ocean is sodium chloride (NaCl). If we had a sophisticated understanding of the diversity of salts that occur naturally in seawater, we might wish to expand the question to investigate the presence of many different salts in the ocean, like magnesium sulfate ($MgSO_4$) or sodium bicarbonate ($NaHCO_3$). Of course, if the answer to our original question is "no," we would not need to waste our time exploring the variety of salts in the ocean: that is the value of a wisely ordered series of specific questions.

## Hypothesis

Once an observation has been made and a question has been asked, it is our nature to find the answer and attempt an explanation. Even if we know the answer to our question, we still want to know why that is the answer. So, during our application of the scientific method, we as the observers are compelled to consider all the information at our disposal (like our formal education, readings, television shows, personal experiences) in order to make an educated guess, a **hypothesis**, which provides an answer to the original question and therefore explains the observation. Keep in mind that it is not necessary that an initial hypothesis be correct, only that the hypothesis is testable by experimentation. As long as a hypothesis can be tested, any failings in the hypothesis will be revealed in the experimentation and analysis phases of scientific inquiry. It is also important to note that hypotheses that cannot be tested are not invalid or worthless; in fact, they may well be true. But if such hypotheses cannot be tested, they are simply "unscientific."

Within the scientific method, you must have a separate hypothesis for each and every question you have asked. Each hypothesis must also provide an unequivocal answer to the question being asked. For example, your hypothesis for the question "Does ocean water contain salt?" can be either

- Hypothesis 1: Ocean water contains salt.

or

- Hypothesis 2: Ocean water does not contain salt.

Either hypothesis is perfectly valid. What's more important is that they are specific, unequivocal statements: ocean water either contains salt or it doesn't. Of course, we won't know which hypothesis is correct until we perform the experiment and evaluate the data. But if you have crafted an unequivocal hypothesis, the data will provide the evidence to support (or refute) it.

The testability of your hypothesis is of critical importance. Since you will be required to collect data to establish the validity of your hypothesis, you will have to "think ahead" as to what sort of experimental methods and equipment you will have at your disposal, and what sort of data (measurements) will be most useful to you. After all, how could you test the hypothesis "Ocean water contains salt" if you have no means to collect ocean water, or have no equipment to analyze its salt content?

Since most scientific hypotheses will be tested using numerical (that is, quantitative) data, it is often preferable to state your hypothesis as a mathematical statement. This will allow you to use your data as a means to test the mathematical validity of the hypothesis. For instance, the hypothesis "Ocean water contains salt" can be written mathematically as

$$[salt]_{seawater} > 0$$

or as

$$[salt]_{seawater} \neq 0$$

where the concentration of salt in seawater (written as $[salt]_{seawater}$) will always be a positive, nonzero number if any salt is present. Either of these mathematic expressions would be valid; regardless of which hypothesis we chose, the answer to one is simultaneously the answer to the other. If we decided to use the alternate hypothesis instead, that is, "Ocean water does not contain salt,"

$$[salt]_{seawater} = 0$$

this too would be a perfectly valid mathematical expression. Remember that our hypothesis is just an educated guess; we still have no data to support (or refute) any of these hypotheses. But a well-crafted hypothesis should be both testable and answerable, pending the outcome of our experiment (whatever that outcome may be).

## Experiment

The proper design and execution of the experiment is perhaps the most difficult aspect of the scientific method. The critical goals of any experiment are twofold: (1) to provide evidence that can be used to affirmatively test the validity of the hypothesis; and (2) to reduce all sources of error introduced by those conducting the experiment (sometimes called experimental **artifacts**). Our challenge as scientists is to design a customized experiment for each and every hypothesis we wish to test, and to conduct such experiments as perfectly as humanly possible.

We know that the natural world is a very complicated place, so it is always in our interest to simplify things as much as we possibly can. In the context of the experiment, we should always take great care to eliminate all conceivable sources of variability in our experiment except for those variables we are specifically testing. As a general rule, this is accomplished by setting up an **experimental group**, where the variable being tested is present and changed (in an orderly fashion) from experiment to experiment. It is also necessary to have a **control group**, where the variable being tested is either absent or is unchanged from experiment to experiment. In this way, comparisons can be made between the experimental group and the control group, based on the measurable differences between the two.

Since we want to limit all sources of variability within our experiment (except for those specifically under investigation), it is often a good idea to create a list of variables that could potentially affect the outcome of the experiment. This step should be taken very carefully and methodically, because variables must first be identified before they can be taken into consideration and controlled within an experiment. Keep in mind that it is not just the natural world that is variable; our chosen experimental method, the equipment being employed to collect and analyze data, and even the inconstant behavior of your research staff can introduce variability if you are not careful.

If we were interested in testing our "Ocean water contains salt" hypothesis, we would need to make a list of every possible variable in our experimental method, which might look something like this:

- Time of collection
- Collection device or method
- Analytical device or method
- Researcher performing collection or analysis
- Water temperature at time of collection
- Water depth at time of collection
- Geographic location of sample

For some of these, we could make a very persuasive argument that they should have no bearing on whether the water being collected and tested actually contains salt, and can therefore be ignored (for example, time of sample collection, water temperature, and/or depth). Others may not directly affect the salt content of the water, but they may affect our ability to confidently perform those measurements (such as the equipment, the methodology, and/or the researcher).

Because human and instrument error are always a factor, they can never be ignored; instead, they must be managed by adhering to a strict collection and analytical methodology. For example, a strict cleaning regimen would be necessary to ensure the collection device (and analytical instrument) do not become contaminated with salt. Likewise, it may be necessary to calibrate the equipment with known concentrations of salt to make sure the instrument is functioning properly, prior to the analysis of field samples. Using the same research staff, or at least having your staff identify which samples they collected and/or analyzed, would also be a useful way to ensure consistency throughout the experiment.

Ultimately, you should control each and every source of variability except for the one variable you wish to test: the salt content of various water samples. In this particular case, you could collect water samples from a variety of different geographic locations to test the hypothesis "Ocean water contains salt." Since our hypothesis presumes that ocean water contains salt, our experimental group would be those samples collected from various locations in the ocean, and our control group would be those samples collected from various locations anywhere except the ocean. In this way, we will have our control group (the water samples not collected from the ocean) to serve as the baseline, against which we can compare the results of our experimental group (that is, our ocean water samples) for salt content.

## Analysis

Ultimately, the performance of any experiment will yield data, but what those data mean will still require analysis. Although error can enter the scientific method at any stage, this step in the process is perhaps the most susceptible to **bias** simply because it requires **subjective** (rather than **objective**) analysis of the evidence. During the analysis phase, the investigator is compelled to review all of the experimental data and determine whether the bulk of the evidence either supports or refutes the original hypothesis. Keep in mind that the investigator performing this analysis has also been responsible for the primary observation, the authorship of the initial hypothesis, and both the design and execution of the experimental method—hardly an impartial contributor to the process. This is why it is preferable to phrase the original hypothesis as a mathematical expression. Mathematical equations are inherently objective, as are quantitative data. If the collected data are consistent with the logic of the hypothesis, an objective analysis will naturally follow (and in so doing, we better protect ourselves from unintentional bias).

Regardless of the strength of your hypothesis or the veracity of your data, as human beings we are always prone to making errors in our analyses. In the context of science, this almost always occurs because we have some preconceived notion of how our experiments should turn out, and if our data seem to support our original hypothesis, it is difficult to step back from all of our hard work and look at the results with a truly cynical eye. Results can be easily misinterpreted unless you are very careful to devise an experiment where the results can only be construed in one way.

For example, let us assume we had collected various ocean water samples, meticulously filtered each sample to remove any suspended particles, and then measured the density ($\rho$) of those samples and compared those results to a sample of ultrapure fresh water ($\rho$ = 1.00 g cm$^{-3}$). In every sample of ocean water, $\rho$ > 1.00 g cm$^{-3}$, providing our evidence that there must be dissolved salt in ocean water, since it is more dense than fresh water: that is our analysis. Although it is perfectly reasonable to assume that the increased density of seawater is caused by dissolved salt, we did not specifically analyze seawater for salt. It is still possible, but implausible, that any other dissolved substance (such as sugars, dissolved free amino acids, pesticides from coastal run-off, etc.) could account for the increased density of seawater.

Unless we analyze specifically for salt ions, we cannot definitively attribute the high density of seawater to dissolved salt.

### Conclusion

Although it is often difficult to arrive at a perfectly objective conclusion, this is not to say that scientists cannot be trusted to perform these analyses. In fact, a good scientist should always employ somewhat of an alter ego at this stage, in an attempt to use the data to argue against the initial hypothesis. The mark of a true scientist is to "go where the data take you," without regard to any of your preconceived notions or agendas.

If the data do not support your initial hypothesis, that's perfectly acceptable—you are still practicing good science. Just because your first guess was wrong doesn't mean you should give up; on the contrary, you now have one more piece of the puzzle, which also means you're one step closer to the real solution! To that end, the scientific method will require that you (1) question your initial observations; (2) revise the hypothesis; (3) design and execute new, more revelatory experiments; (4) perform alternative analyses; and (5) repeat as necessary, until the evidence supports your latest hypothesis. That is the beauty of the scientific method: your "failures" are not failures at all—they are used to build the foundation for better hypotheses.

So what happens if we get it right the first time—if our initial hypothesis was carefully crafted and is indeed supported by the evidence? Be careful to remember that there is no such thing as a scientific "fact," nor can a scientific hypothesis ever be "proven." Science (and the scientific method) rely upon the preponderance of evidence in pursuit of the truth, but can a single scientist ever lay claim to discovering the truth? Let's assume for the sake of argument that the truth, through the practice of science, is indeed knowable. It would then stand to reason that our conclusions would stand firm in the face of rugged scrutiny. After all, the truth is the truth, and the truth is never wrong—not one little bit. So let's invite the scrutiny and see how well our scientific conclusions hold up.

### Report

Even after all this careful and meticulous work, investigators can never be fully trusted to analyze their own data without bias. Thus, the profession demands that scientists publish their complete research, from observation to conclusion, without omission. This additional scrutiny, performed by the scientific community at large, is the most reliable guarantee of quality assurance and quality control (QA/QC), and will most definitely reveal any mistakes made or biases undisclosed. In this manner, the weakest link in the scientific method (that is, our subjective analyses) is strengthened by the critical review of many, many scholars.

**Figure 1.5** Shoal grass (*Halodule wrightii*) is a common species of seagrass, found worldwide in shallow coastal waters with soft (sand or mud) substrates and moderate water clarity. Dense seagrass meadows offer food and protection to a wide variety of marine species, including the microalgae that grow upon the surface of the leaves, giving the mature grass blades a "fuzzy" appearance. ((c) of Hans Hillewaert / CC-BY-SA-4.0.)

## An Example of the Scientific Method in Action

### Observation

Sea grasses represent important intertidal and subtidal habitats, providing both food and shelter for a wide variety of marine species, while stabilizing sediments against erosion. Shoal grass (*Halodule wrightii*) is a particularly important species, because it has a global distribution in tropical to subtropical climates, and succeeds in coastal waters of widely variable temperature and salinities (**Figure 1.5**). Shoal grass can even withstand extended periods of exposure during low tide. Although shoal grass can be found at depths of up to 12 m throughout the Gulf of Mexico, its growth within northern Gulf of Mexico waters is conspicuously sparse.

So an otherwise widespread and highly competitive species does not seem to grow in northern Gulf of Mexico waters—that is an interesting pattern or phenomenon that begs explanation. Perhaps if we could discover why shoal grass does not grow very well in these waters, there may be some action we could take to improve growth conditions and restore coastal seagrass habitats.

## Question

Why does the growth of shoal grass (*Halodule wrightii*) seem to be inhibited in northern Gulf of Mexico waters?

That is the fundamental question, but the scientific method will require us to pose that question in a way that can be tested as a hypothesis (or series of hypotheses). Since shoal grass seems to do quite well in the rest of the Gulf of Mexico, there must be some kind of local stressor—a condition unique to the northern Gulf of Mexico—that adversely affects the growth of shoal grass. Time to make an educated guess as to what that might be.

## Hypothesis

$H_1$—Suspended sediment from river effluent adversely affects the growth of shoal grass.

Based on our research of this particular topic, the Mississippi River (and several other rivers) has a profound impact on several environmental features within coastal waters of the northern Gulf of Mexico. Since shoal grass can survive in wide salinity ranges, the fresh water effluent is not likely to be a factor, but perhaps the sediment load is. Of course, our hypothesis could be completely wrong, but this is a well-reasoned educated guess.

Note that Hypothesis 1 ($H_1$) is unequivocal—as written, the hypothesis can be easily tested and can have only two possible answers (yes or no). But $H_1$ only seeks to answer "if" the suspended sediment has an adverse effect on the growth of shoal grass; if our evidence suggests that the sediment does indeed have an effect, $H_1$ will not be able to answer the "how" or "why." For that, we may need to add a few follow-on hypotheses:

$H_2$—The deposition of sediment adversely affects the growth of shoal grass.

$H_3$—The turbidity (that is, the lack of water clarity) caused by suspended sediment adversely affects the growth of shoal grass.

Excellent—we now have three hypotheses to test. If our data support $H_1$, we will have just cause to explore $H_2$ and $H_3$. Note that $H_2$ and $H_3$ each will provide further information as to the mode of inhibition: whether it's caused by the actual deposition of sediment upon the shoal grass, whether it's caused by the reduced availability of light, or both!

## Experiment

To provide data to test our hypotheses, we might first conduct a survey of several coastal sites throughout the northern Gulf of Mexico (**Figure 1.6**) to measure:

1. The total area of coverage of shoal grass at each site
2. The distance of river outfalls from the Gulf of Mexico
3. The average annual discharge for each of these rivers
4. The average sediment load for each of these rivers
5. A water sample collected from each site
6. The turbidity at each site

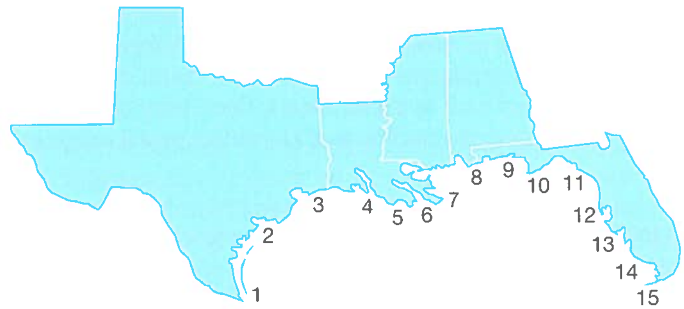


**Figure 1.6** In order to provide adequate assessment of shoal grass habitat along the northern Gulf of Mexico, we might wish to establish 15 coastal research stations from which we will conduct measurements of (1) live coverage of shoal grass, (2) station distance to nearby river(s), (3) average river discharge, (4) average sediment load, (5) sediment characteristics, and (6) water clarity.

Data collected from items 1–4 of this survey would enable us to establish a quantitative relationship between shoal grass and the potential influence of river effluent; specifically, the amount of suspended sediment in the effluent. If there is an obvious trend between shoal grass coverage and the total sediment load of nearby rivers, our analysis may be able to confirm $H_1$.

Data provided from item 5 of this survey would enable us to test $H_2$. Water samples collected from each site could be returned to the lab to measure the particle sizes and settlement rates of the suspended sediment. This would provide additional information as to whether there is a trend between shoal grass coverage and sediment deposition, either as a rate of deposition or as a rate of sediment accumulation.

Data collected from item 6 of this survey would enable us to test $H_3$. By measuring the turbidity (or water clarity) at each site, we would be able to easily estimate the amount of available light reaching the bottom. This would provide additional information as to whether there is a trend between shoal grass coverage and water clarity.

Note that using previously published data and/or taking measurements at our chosen sites may provide sufficient data to test our hypotheses, without the need for direct experimentation. If such data were available, we would essentially be conducting a survey (or census) of data relevant to our hypotheses and not specifically conducting our own experiment(s).

If we were dissatisfied with the simplicity of one of our hypotheses, we would be required to design our own experiment. This would allow us to perturb the system and monitor the changes in response to that perturbation (using different experimental groups), relative to some baseline condition that serves as the control.

Let's assume our initial survey results strongly supported $H_3$. If we wanted to know more than just "if" water clarity had an adverse effect on the growth of shoal grass, we could easily design an experiment to actually quantify the growth response of shoal grass to varying light levels (as turbidity).

First, we would need to list all of the experimental parameters that may have unwanted effects on our experimental results. If we had decided that water clarity (turbidity) should be our variable to be tested, everything else has to be controlled:

| | |
|---|---|
| Test subject: | Sprigs of shoal grass (preferably clones, or at least sections from the same cultivar, to minimize genetic differences in the test subjects) |
| Static conditions: | Sterile, artificial (or filtered) seawater<br>f/2 growth media (nutrients and minerals) |

| | |
|---|---|
| | Sterile quartz sand (as substrate) |
| | 5 L opaque black aquaculture vessels |
| | Fixed temperature (25°C) |
| | Fixed photoperiod (14 h light:10 h dark) |
| | Flow-through system (chemo/thermostat) |
| Variable conditions: | Photosynthetically active radiation (PAR): |
| | $25\ \mu mol\ m^{-2} s^{-1}$ |
| | $50\ \mu mol\ m^{-2} s^{-1}$ |
| | $100\ \mu mol\ m^{-2} s^{-1}$ |
| | $250\ \mu mol\ m^{-2} s^{-1}$ |
| | $500\ \mu mol\ m^{-2} s^{-1}$ |
| | $1000\ \mu mol\ m^{-2} s^{-1}$ |
| | $1500\ \mu mol\ m^{-2} s^{-1}$ |
| Control: | Mean solar light intensity ($\mu mol\ m^{-2} s^{-1}$ PAR) at sea level, for mean latitude of the entire study area |
| Measures: | PAR |
| | Rate of new shoot production |
| | Leaf dimensions (length, width) |
| | Aboveground biomass (ash-free dry weight) per unit area |
| | Belowground biomass (ash-free dry weight) per unit area |
| | Chlorophyll content of leaf tissue (µg chl *a*/µg C) |

An experiment like this would allow us to measure a number of different growth parameters for shoal grass, relative to variable intensities of PAR (**Figure 1.7**). Then, not only could we use the quantitative data from our experiment to verify the simple hypothesis as stated in $H_3$, we could also use that same data to determine the complex growth dynamics of shoal grass as a function of PAR intensity (to include optimal light conditions for maximal growth, minimum light thresholds for survival, etc.). Hence, true experimentation (rather than simple surveys of data) will allow a much more powerful application of the scientific method.

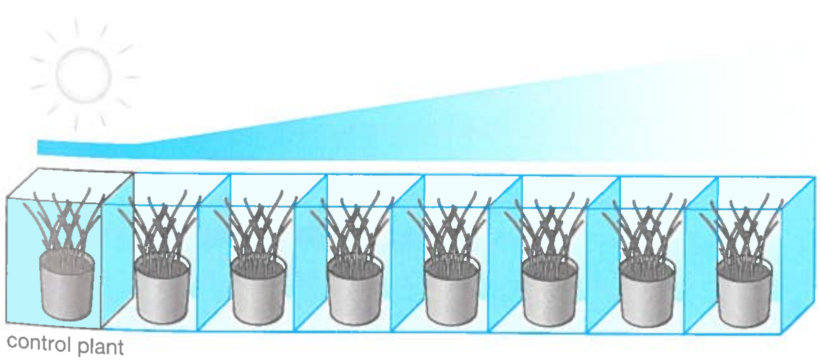


**Figure 1.7** A conceptual design for an experiment to test the effects of increasing light intensity (to represent increasing water clarity) on the growth of shoal grass, *Halodule wrightii*. Although there are many potential factors that could influence the growth of seagrass, the scientific method requires that all other factors be removed, so that our experimental groups are only exposed to changes in one variable: the different intensities of light (25–1500 µmol $m^{-2} s^{-1}$). Within the control, a fixed light intensity is used to represent the baseline (or "normal") condition, against which all other results will be compared.

## Forward in Science, Forward in Truth

If you boil it all down, science is simply defined by the ordered process we use to test hypotheses. And because our hypotheses are little more than educated guesses, we cannot fairly expect our hypotheses to be 100% correct. Thus, true science is about "trial and error." It is about learning—and the learning never ends.

To that end, the most challenging aspect to the scientific method lies in the custom design of an experiment, uniquely fashioned to test our equally unique hypotheses. Obviously, there is no grand experiment that can be applied evenly to all conceivable hypotheses. Instead, we must rely upon the firm conceptual framework of the scientific method and seek inspiration from those scientists who came before us, providing their own well-tested methodologies from which we may borrow. That is the essential goal of this text—to provide you with that guidance, that is, the initial springboard from which you may develop your own ideas and methods.

But remember always the lessons of history's great philosophers, particularly those of Descartes and Kant: truth cannot be found in the sciences. The evidence we glean from the natural world are bread crumbs along the trail of understanding, but these crumbs are mere points of data, not facts (and certainly not truth).

## References

Descartes R (1984) Meditations on first philosophy. In The Philosophical Writings of Descartes, Vol. I-II (Cottingham J, Stoothoff R, & Murdoch D, trans), pp 12–23. Cambridge University Press.

Kant I (1965) Critique of Pure Reason. (Smith NK, trans). St. Martin's Press.

## Further Reading

Bacon F (2011) Novum Organum Scientiarum (New Instrument of Science). (Spedding J, Ellis RL, & Heath DD, eds). Cambridge University Press.

Cohen MR & Nagel E (2002) An Introduction to Logic and the Scientific Method. Simon Publications.

Gauch Jr. HG (2002) Scientific Method in Practice. Cambridge University Press.

Hume D (1978) A Treatise of Human Nature. (Nidditch PH & Selby-Bigge LA, eds). Oxford University Press.

Locke J (1979) An Essay Concerning Human Understanding. (Nidditch PH, ed). Oxford University Press.