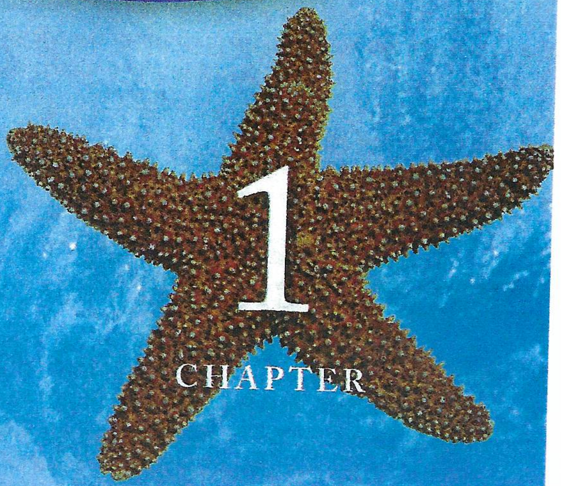
A diver measures light penetration through sea ice in the Arctic Ocean.

Part One
Principles of Marine Science



1
CHAPTER

The Science of Marine Biology

Marine biology is the scientific study of life in the sea. The ocean is vast, home to countless strange and wonderful creatures. It is often the beauty, mystery, and variety of life in the sea that attract students to a course in marine biology. Even professional marine biologists feel a sense of adventure and wonder in their studies.

There are also many practical reasons to study marine biology. Life on Earth probably originated in the sea, so the study of marine organisms teaches us much about all life on Earth, not just marine life. Many medical advances, for example, have been underpinned by research on marine organisms, such as studies of the animal immune system in sea anemones and sea star larvae, the fertilization of sea urchin eggs, squid nerve cells, and barnacles.

Marine life also represents a vast source of human wealth. It provides food, medicines, and raw materials, offers recreation to millions, and supports tourism all over the world. Marine organisms can also cause problems. For example, some organisms harm humans directly by causing disease or attacking people. Others harm us indirectly by injuring or killing other marine organisms that we value for food or other purposes. Marine organisms can erode piers, sea walls, and other structures in the ocean, foul ship bottoms, and clog pipes.

At a much more fundamental level, marine life helps determine the very nature of our planet. Marine organisms produce around half of the oxygen we breathe and help regulate the earth's climate. Our shorelines are shaped and protected by marine life, at least in part, and some marine organisms even help create new land. In economic terms, it has been estimated that the ocean's living systems are worth more than $20 *trillion* a year.

To make full and wise use of the sea, to solve problems marine organisms create, and to predict the effects of human activities on the ocean, we must learn all we can about marine life. In addition, marine organisms provide valuable clues to the earth's past, the history of life, and even our own bodies. This is the challenge, the adventure, of marine biology.

THE SCIENCE OF MARINE BIOLOGY

Marine biology is really the more general science of biology applied to the sea rather than a separate science. Nearly all the disciplines of biology are represented in marine biology. There are marine biologists who study the basic chemistry of living things, for example. Others are interested in whole organisms: how they behave, where they live and why, and so on. Other marine biologists adopt a global perspective and look at the way entire oceans function as systems. Marine biology is thus both part of a broader science and itself made up of many different disciplines, approaches, and viewpoints.

Marine biology is closely related to oceanography, the scientific study of the oceans. Like marine biology, oceanography has many branches. Geological oceanographers, or marine geologists, study the sea floor. Chemical oceanographers study ocean chemistry, and physical oceanographers study waves, tides, currents, and other physical aspects of the sea. Marine biology is most closely related to biological oceanography, so closely, in fact, that the two are difficult to separate. Sometimes they are distinguished on the basis that marine biologists tend to study organisms living relatively close to shore, whereas biological oceanographers focus on life in the open ocean, far from land. Another common distinction is that marine biologists tend to study marine life from the perspective of the organisms (for example, studying what an organism eats), while biological oceanographers tend to take the perspective of the ocean (for example, studying how food energy cycles through the system). In practice there are so many exceptions to these distinctions that many marine scientists consider marine biology and biological oceanography to be the same.

A marine biologist's interests may also overlap broadly with those of biologists who study terrestrial organisms. Many of the basic ways in which living things make use of energy, for example, are similar whether an organism lives on land or in the sea. Nevertheless, marine biology does have a flavor all its own, partly because of its history.

The History of Marine Biology

People have been living by the sea since the dawn of humanity, and seafood is thought to have been crucial to early human survival and migration. The earliest known stone blades, from 165,000 years ago, were discovered in a seaside cave in South Africa, along with piles of shells from Stone Age clambakes and the earliest traces of ochre pigment, thought to be used for symbolic body painting and decoration. Ancient bone or shell harpoons and fishhooks have also been found, as well as the earliest known jewelry in the form of shell beads from as long as 110,000 years ago. As they used its resources, people steadily gained a store of practical knowledge about the sea.

FIGURE 1.1 Micronesians like these Satawal Islanders from Yap Atoll in the Federated States of Micronesia have navigated the Pacific for millennia in canoes much like this one.

Knowledge of the ocean and its organisms expanded as people gained skills in seamanship and navigation. Ancient Pacific Islanders had detailed knowledge of marine life, which their descendants still retain (Fig. 1.1). They were consummate mariners, using clues such as wind, wave, and current patterns to navigate over vast distances. The Phoenicians were the first accomplished Western navigators. By 2000 B.C. they were sailing around the Mediterranean Sea, Red Sea, eastern Atlantic Ocean, Black Sea, and Indian Ocean.

The ancient Greeks had considerable knowledge of nearshore organisms in the Mediterranean region (Fig. 1.2). The Greek philosopher Aristotle is considered by many to be the first marine biologist. He described many forms of marine life and recognized, among other things, that gills are the breathing apparatus of fish.

During the centuries known as the Dark Ages, scientific inquiry, including the study of marine life, came to a grinding halt in most of Europe. Much of the knowledge of the ancient Greeks was lost or distorted. Not all exploration of the ocean stopped, however. During the ninth and tenth centuries the

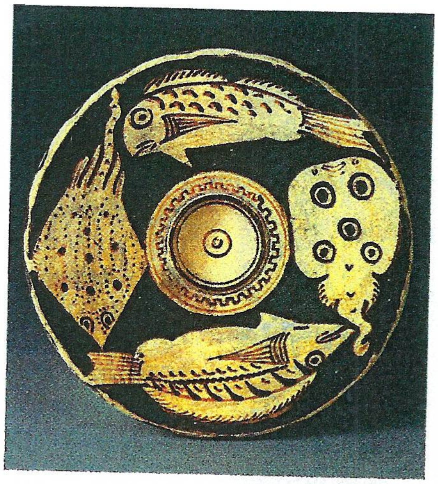


FIGURE 1.2 This Greek plate from around 330 B.C. reflects a considerable knowledge of marine life. The fish at the right is an electric ray (*Torpedo*), which the ancient Greeks used to deliver the first electrical stimulation therapy.

Vikings continued to explore the northern Atlantic. In A.D. 995 a Viking party led by Leif Eriksson discovered Vinland, what we now call North America. Arab traders were also active during the Middle Ages, voyaging to eastern Africa, southeast Asia, and India. In the Far East and the Pacific, people also continued to explore and learn about the sea.

During the Renaissance, spurred in part by the rediscovery of ancient knowledge preserved by the Arabs, Europeans again began to investigate the world around them, and several undertook voyages of exploration. Christopher Columbus rediscovered the "New World" in 1492—word of the Vikings' find had never reached the rest of Europe. In 1519 Ferdinand Magellan embarked on the first expedition to sail around the globe. Many other epic voyages contributed to our knowledge of the oceans. Fairly accurate maps, especially of places outside Europe, began to appear for the first time.

Before long, explorers became curious about what lived in the ocean they sailed. An English sea captain, James Cook, was one of the first to make scientific observations along the way and to include a full-time naturalist among his crew. In a series of three great voyages, beginning in 1768, he explored all the oceans. He was the first European to see the Antarctic ice fields and to land in Hawaii, New Zealand, Tahiti, and a host of other Pacific islands. Cook was the first to use a chronometer, an accurate timepiece that enabled him to determine his longitude precisely, and therefore prepare reliable charts. From the Arctic to the Antarctic, from Alaska to Australia, Cook extended and reshaped the European conception of the world. He brought back specimens of plants and animals and tales of strange new lands. Though Cook was generally respectful and appreciative of indigenous cultures, he was killed in 1779 in a fight with native Hawaiians at Kealakekua Bay, Hawai'i.

By the nineteenth century, it had become common for vessels to take a naturalist along to study the organisms encountered. Perhaps the most famous of these shipboard naturalists was Charles Darwin, another Englishman. Beginning in 1831, Darwin sailed around the world on HMS *Beagle* for five years, horribly seasick most of the time. The *Beagle*'s primary mission was to map coastlines, but Darwin made detailed observations of all aspects of the natural world. This set off a train of thought that led him, years later, to propose the theory of evolution by natural selection (see "Natural Selection and Adaptation," p. 79). Though best known for the theory of evolution, Darwin made many other contributions to marine biology. He explained, for example, the formatio of the distinctive rings of coral reef called atolls (see "How Atoll Form," p. 320). He used nets to capture the tiny, drifting organisms known as plankton, which marine biologists continue to d today (Fig. 1.3). Darwin's many interests also included barnacles Specialists still refer to his treatise on them.

In the United States the most important early exploratory voyage was probably the United States Exploring Expedition o 1838–1842, often called the "Wilkes Expedition" after its leader, Lt. Charles Wilkes of the U.S. Navy. The expedition included only 11 naturalists and artists, derisively called "clam diggers" by the rest of the crew, and some historians conclude that it was more about projecting American influence than scientific discovery. Wilkes was by all accounts a vain and cruel man who promoted himself to Captain as soon as he left port, and upon his return was court-martialed for flogging his crew to excess. Only two of the expedition's six ships made it home. Nevertheless, the Wilkes Expedition's achievements were impressive. The expedition charted 2,400 km (1,500 mi) of the coast of Antarctica, confirming it as a continent, as well as the coast of the Pacific Northwest of North America. It explored some 280 islands in the South Pacific, collecting information about peoples and cultures as well as flora and fauna. The 10,000 biological specimens included some 2,000 previously unknown species (Fig. 1.4). The expedition, the first international survey sponsored by the U.S. government, also laid a foundation for government funding of scientific research.

The *Challenger* Expedition By the middle of the nineteenth century, a few lucky scientists were able to undertake voyages specifically to study the oceans, instead of having to tag along on ships doing other jobs. One was Edward Forbes, who in the 1840s and 1850s carried out extensive trawling of the sea floor, mostly around his native Britain but also in the Aegean Sea and other places. Forbes died prematurely in 1854, at the age of 39, but was the most influential marine biologist of his day. He discovered many previously unknown organisms and recognized that sea-floor life varies at different depths (see "Biodiversity in the Deep Sea," p. 378). Perhaps his most important contribution, however, was to inspire new interest in the life of the sea floor.

Forbes's contemporaries and successors, especially from Britain, Germany, Scandinavia, and France, carried on his studies of sea-floor life. Their ships were poorly equipped and the voyages short, but their studies produced many interesting results. They were so successful, in fact, that British scientists managed to convince their government to fund the first major oceanographic

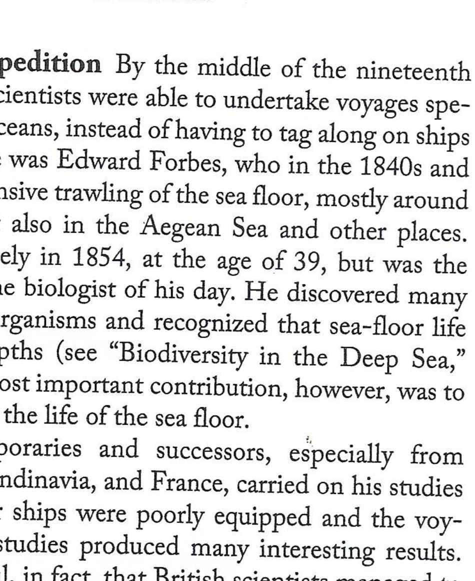


FIGURE 1.3 These marine scientists are hauling in a net known as a "bongo net" used to capture minute marine plankton. One is signaling instructions to the winch operator.

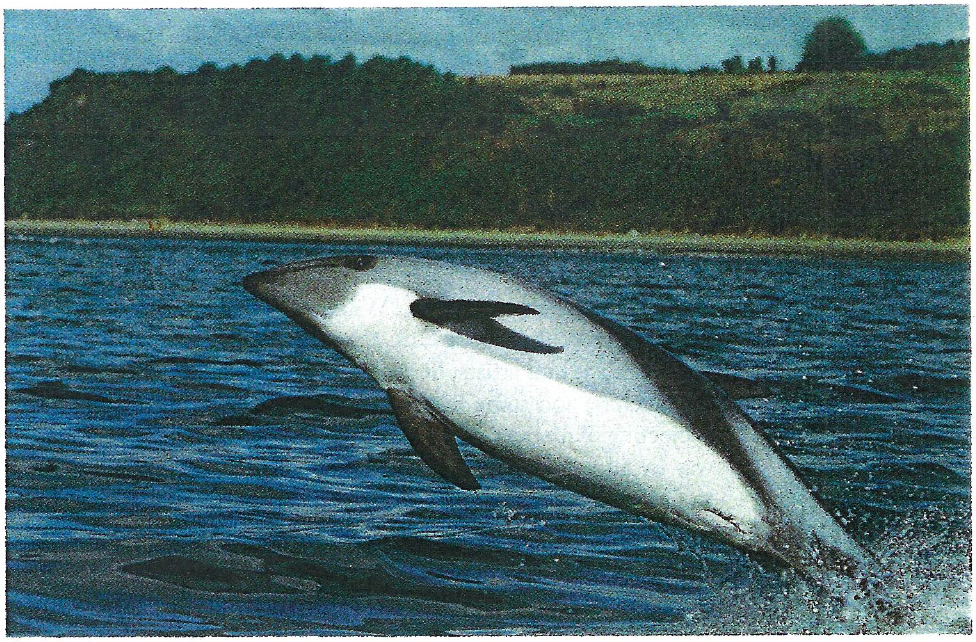


FIGURE 1.4 Peale's dolphin (*Lagenorhynchus australis*), named after the Wilkes Expedition naturalist who first described it, is one of 2,000 marine and terrestrial species discovered by the expedition.

expedition, under the scientific leadership of Charles Wyville Thompson. The British navy supplied a light warship to be fitted out for the purpose. The ship was named HMS *Challenger.*

Challenger underwent extensive renovations in preparation for the voyage. Laboratories and quarters for the scientific crew were added, and gear for collecting samples in deep water was installed. Though primitive by modern standards, the scientific equipment on board was the best of its day. Finally, in December 1872, *Challenger* set off.

Over the next three and a half years, *Challenger* and her crew sailed around the world, gathering information and collecting water, sediment, and biological samples (Fig. 1.5). The sheer volume of data gathered was enormous—it took 19 years to publish the results, which fill 50 thick volumes. *Challenger* brought back more information about the ocean than had been recorded in all previous human history.

It was not just the duration of the voyage or the amount of information collected that set the *Challenger* expedition apart from earlier efforts. The expedition set new standards for ocean research. *Challenger's* scientists collected data in a more systematic way than previous expeditions, and kept meticulous records. For the first time, scientists began to get a coherent picture of what the ocean was like. They also learned about the enormous variety of marine life, for *Challenger* brought back thousands of previously unknown species. Thus, the *Challenger* expedition laid the foundations of modern marine science.

Other expeditions continued the work begun by *Challenger,* and major oceanographic cruises continue to this day. In many ways, though, the voyage of the *Challenger* remains one of the most important in the history of oceanography.

The Growth of Marine Labs Even before the *Challenger* set off, biologists were excited about the organisms brought back by ocean expeditions. Unfortunately, the vessels had quarters for only a few scientists. Most biologists only got to see the

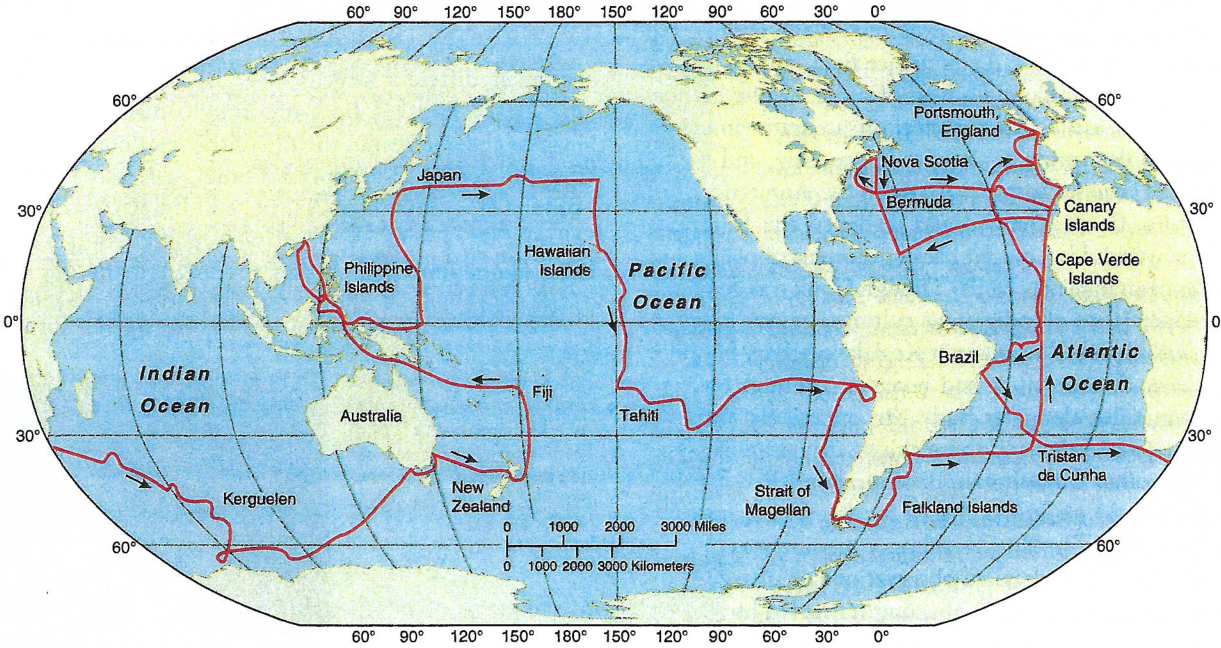


FIGURE 1.5 The route of the *Challenger* expedition, which from 1872 to 1876 conducted the first systematic survey of the world ocean.

dead, preserved specimens that the ships brought back to port. Such specimens revealed much about marine life around the world, but biologists wanted to know how the organisms actually lived: how they functioned and what they did. Living specimens were essential for this, but ships usually stayed in one place for only a short time, making long-term observations and experiments impossible.

As an alternative to ships, biologists began to work at the seashore. Among the first were two Frenchmen, Henri Milne Edwards and Victor Andouin, who around 1826 began making regular visits to the shore to study marine life. Other biologists soon followed suit. These excursions offered the opportunity to study live organisms, but there were no permanent facilities and only a limited amount of equipment could be taken along. Eventually, biologists set up permanent laboratories where they could keep organisms alive and work over long periods. The first such laboratory was the Stazione Zoologica, founded in Naples, Italy, in 1872—the same year the *Challenger* embarked. The laboratory of the Marine Biological Society of the United Kingdom was founded at Plymouth, England, in 1879.

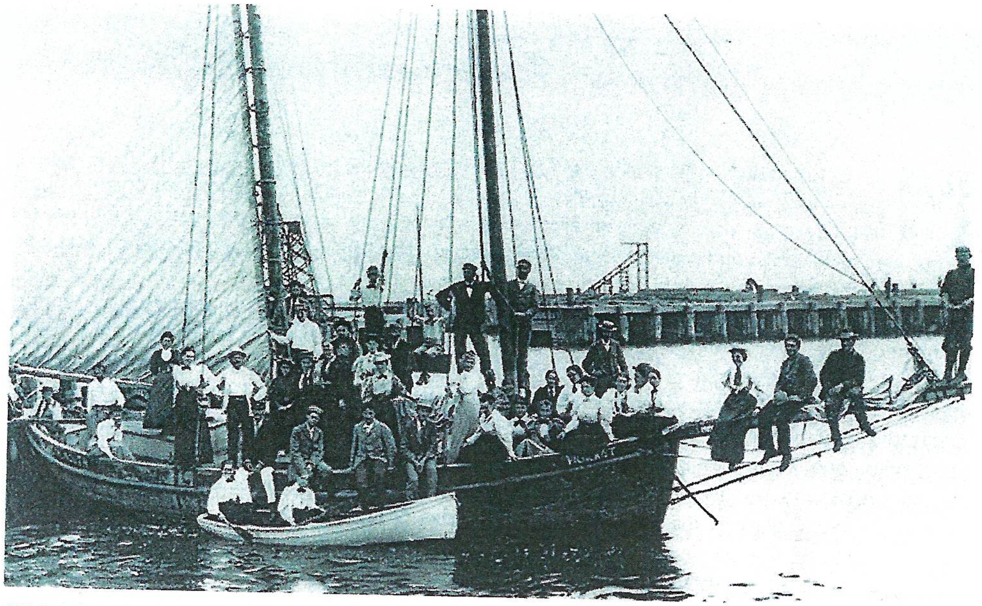


FIGURE 1.6 Scientists and crew at the Marine Biological Laboratory at Woods Hole, Massachusetts, *circa* 1888.

The first major American marine laboratory was the Marine Biological Laboratory at Woods Hole, Massachusetts. It is hard to pinpoint the exact date when this laboratory was established. The first marine laboratory at Woods Hole was started by the United States Fish Commission in 1871, but it did not flourish. Several other short-lived laboratories subsequently appeared in the area. Harvard biologist Louis Agassiz, who also studied many of the specimens collected by the Wilkes Expedition, established a laboratory on nearby Cape Ann in 1873. In 1888 this laboratory moved to Woods Hole and officially opened its doors as the Marine Biological Laboratory (Fig. 1.6). It is still one of the world's most prestigious marine labs.

After these early beginnings, other marine laboratories were established. Among the earliest in the United States were the Hopkins Marine Station in Pacific Grove, California, Scripps Institution of Oceanography in La Jolla, California, and the Friday Harbor Marine Laboratory in Friday Harbor, Washington. In the ensuing years, more laboratories appeared all over the world, and new ones are being established even today.

The onset of World War II had a major effect on the development of marine biology. A new technology, **sonar,** or *so*und *na*vigation *r*anging, was developed in response to the growing importance of submarine warfare. Sonar is based on the detection of underwater echoes—a way of listening to the sea (Fig. 1.7). The ocean, long thought of as a silent realm, was suddenly found to be full of sound, much of it made by animals. During wartime, learning about these animals was no longer the casual pursuit of a few interested marine biologists but a matter of national security. As a result of this urgency, several marine laboratories, such as Scripps and the Woods Hole Oceanographic Institution (established in 1929), underwent rapid growth. When the war ended, these labs not only remained vital research centers, but continued to grow.

The years immediately after World War II saw the refinement of the first practical **scuba,** or *s*elf-*c*ontained *u*nderwater *b*reathing *a*pparatus. The basic technology was developed in occupied

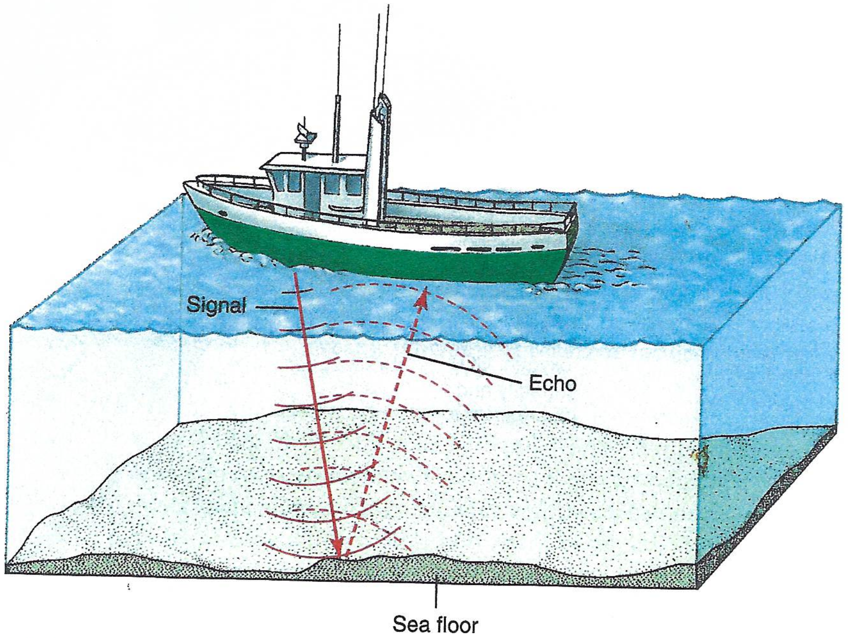


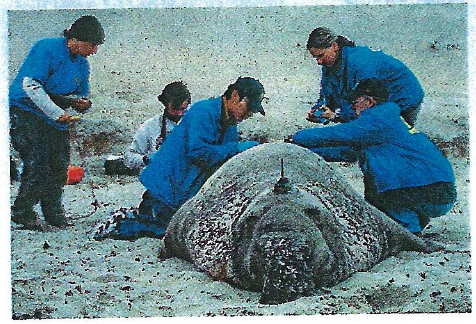
FIGURE 1.7 A ship uses sonar by "pinging," or emitting a loud pulse of sound, and timing how long it takes the echo to return from the sea floor. The water depth can be determined from the return time. This, the most common form of sonar, is called "active sonar" because the sounds used are actively generated by the equipment.

Observing the Ocean

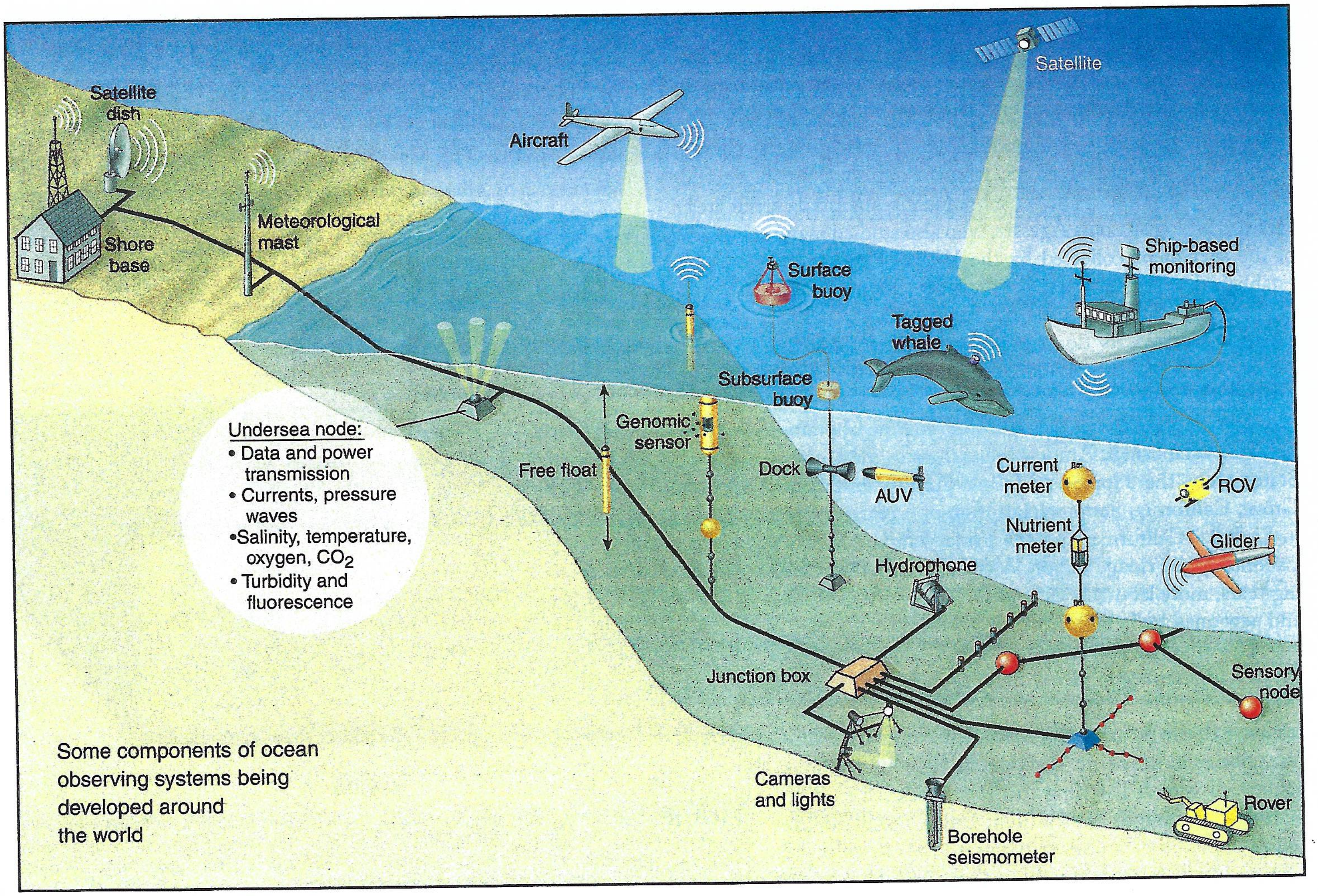
Most of the ocean is incredibly remote, and difficult and expensive to get to. The ocean is also a vast, interconnected network, and conditions at one place are affected by events far away. To cap things off, events such as storms and earthquakes—not to mention the interactions and movements of marine organisms—occur suddenly, making them hard to capture unless you happen to be in just the right place at the right time. Ships, submarines, and scuba diving, and studies in the laboratory and on the shore, will always have an important place in marine science, but they can't provide the continuous coverage of broad areas of the ocean, throughout its depths, that is needed to really understand the ocean. Satellites can observe vast areas of the ocean (see "Marine Biology Today," p. 7), but only at the surface.

A range of new technologies is allowing scientists—and the general public—to observe the oceans in ways that would have seemed like science fiction not long ago. In the Argo system, for example, 3,000 or more automated floats, looking a bit like torpedoes turned on end, are scattered throughout the ocean. Each float continuously bobs between the surface and a depth of 2,000 m (6,600 ft), over about 10 days, continuously measuring water temperature and salinity and transmitting the data via satellite when at the surface. Argo floats are providing huge amounts of new information, especially from areas, such as the winter seas around Antarctica, that are difficult to study from ships. A few Argo floats have now been equipped with sensors to measure oxygen, and additional sensors are being developed, as well as floats that can go even deeper. Oceanographers have also launched robotic gliders that cruise across entire oceans for years at a time, like Argo floats, collecting data and surfacing to relay the data by satellite.

Oceanographers are also wiring the sea floor, providing power and communications for an amazing array of instruments that measure currents and water chemistry, detect the slightest sea-floor tremors, and track biological activity. The first such system in the United States was the Long-term Ecosystem Observatory (LEO), installed off the New Jersey coast in 1996. LEO, now known as the Coastal Ocean Observation Laboratory (COOL), has grown to include underwater gliders, shore-based radar,



Marine biologists fit a southern elephant seal (*Mirounga Leoninia*) with electronic instruments.



Some components of ocean observing systems being developed around the world ship measurements, and moored instruments, and is being integrated with similar systems into a single network covering the United States from Maine to Florida. In the Pacific, the first cables for the Victoria Experimental Network Under the Sea (VENUS) were laid in 2006 off the coast of British Columbia, Canada, and for the Monterey Accelerated Research System (MARS) off the coast of California in 2007. VENUS and MARS are both now fully operational. Venus and MARS form part of a larger network, the North East Pacific Time-integrated Undersea Networked Experiments (NEPTUNE) Observatory, which extends from British Columbia to Oregon. NEPTUNE is itself part of an even larger program, the Ocean Observatories Initiative. Similar networks are being developed in Europe, Japan, the Gulf of Mexico, and the Arctic Ocean. Exciting new devices are on the way, such as genomic sensors that will not only measure the abundance of plankton but also identify their DNA, and docking stations where free-ranging autonomous underwater vehicles (AUVs) can charge batteries and download information. There are even proposals for self-powered AUVs that use plankton for fuel.

Like all cutting-edge endeavors, developing these observing networks has its challenges. High-tech electronics can be fickle even in the laboratory, much less the depths of the sea. A NEPTUNE scientist says, "We're learning a lot, which is another way of saying that things are breaking." But most of NEPTUNE's instruments are transmitting photos, audio, and video—in vast amounts—that are freely available online, and the system will only get more reliable.

The networks have also brought unexpected benefits, in part because they are used by scientists from widely varying disciplines. For example, marine geologists use the NEPTUNE network to monitor for earthquakes, but the endangered fin whale (*Balaenoptera physalus*) sings at a sound frequency that interferes with the earthquake measurements. The geologists developed software tools to identify and filter out fin whale songs that marine biologists are now using to track the whales. In another example, forensic scientists have used VENUS's underwater video to monitor the decomposition of pig carcasses in the ocean to help them determine the time of death of human bodies recovered from the sea.

Not all ocean observing systems are inanimate—marine animals are being recruited to help. Seals, sea lions, sharks, and other large marine animals move underwater faster than humans can ever hope to follow, and are unlikely to behave naturally when humans are present. To get a firsthand look at what these animals do beneath the surface, scientists developed "crittercam," a compact underwater video camera that is attached to the animals themselves. Crittercam has been deployed on sea turtles, sharks, whales, seals, sea lions, and penguins. It provided the first underwater views of feeding humpback whales using curtains of bubbles to herd herring, socia diving behavior in Adélie (*Pygoscelis adeliae*) an chinstrap (*P. antarctica*) penguins, and the movements of endangered sea turtles in Mexic A crittercam attached to a sperm whal (*Physeter catodon*) provided new views of life i the deep sea.

Scientists use animals to study th ocean as well as the animals themselves. A "Autonomous Underwater Sampler" is anothe name for an animal, such as an elephant seal with a transmitter glued to its back. Originall the transmitters, which measure temperature depth, and salinity, were used to record th diving behavior of the animals, but oceanographers realized that the sensors also provide valuable data on ocean circulation, and th animals can go to places that scientists can' access any other way.

Ocean observing systems aren't just fo science. They bring concrete benefits to society In 2006, for example, COOL helped forecast th track of Tropical Storm Ernesto for emergenc response authorities and the public. Observin networks are providing early warning of tsunamis, potentially saving hundreds of thousands o lives (see "Waves That Kill," p. 58). The system will help forecast earthquakes and storms, track the effects of climate change, monitor fish populations, and make shipping more efficient. Ocean observatories will save lives and money, and help humanity make wiser use of the oceans—and indeed the entire ocean planet.

France by the engineer Émile Gagnan to allow automobiles to run on compressed natural gas. After the war, Gagnan and fellow Frenchman Jacques Cousteau modified the apparatus, using it to breathe compressed air under water. Cousteau went on to devote his life to scuba diving and the oceans.

Using scuba, marine biologists could, for the first time, descend below the surface to observe marine organisms in their natural environment (Fig. 1.8). They could now work comfortably in the ocean, collecting specimens and performing experiments, though they were still limited to relatively shallow water, generally less than 50 m (165 ft).

Marine Biology Today

Oceanographic ships and shore-based laboratories are as important to marine biology now as ever. Today many universities and other institutions operate research vessels (Fig. 1.9). Modern ships are equipped with the latest equipment for navigation, sampling, and studying the creatures that are collected. Many, like *Challenger*, were originally built for other uses, but growing numbers of vessels are purpose-built for scientific research at sea.

In addition to ships as we normally think of them, some remarkable craft are used to study the marine world. High-tech submarines can descend to the deepest parts of the ocean, revealing a world that was once inaccessible (Fig. 1.10). Various odd-looking vessels ply the oceans, providing specialized facilities for marine scientists (Fig. 1.11).

Marine laboratories, too, have come a long way since the early days. Today labs dot coastlines around the world and are used by an international community of scientists. Some are equipped with the most up-to-date facilities available. Others are simple field stations, providing a base for scientists to work in remote areas. There are even undersea habitats where scientists can live for weeks at a time, literally immersed in their work (Fig. 1.12). Marine laboratories are important centers not only of research, but also of education. Many offer hands-on undergraduate courses in which students can study marine biology firsthand, and most provide facilities where graduate students begin their careers in marine science.

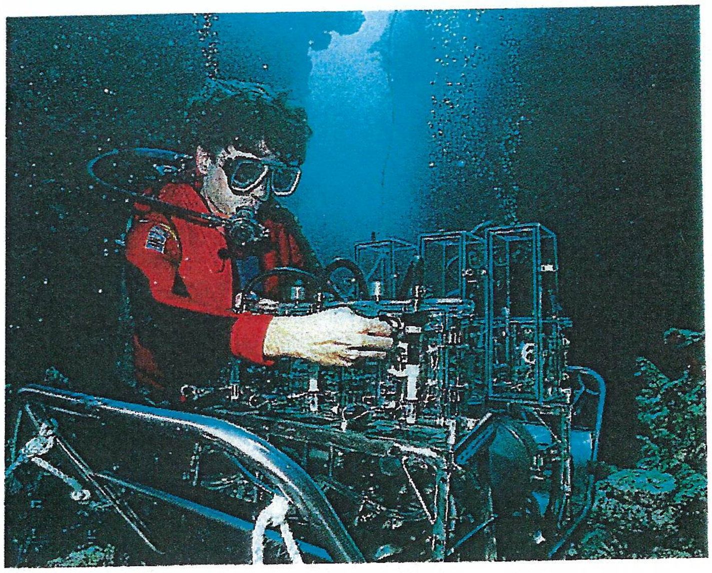


FIGURE 1.8 Scuba is an important tool in the work of many marine biologists. This scientist is using an apparatus called a respirometer to measure the production and consumption of oxygen by organisms on a coral reef.

FIGURE 1.10 *Alvin*, a deep-sea submarine operated by the Woods Hole Oceanographic Institution, is one of the most famous vessels in the history of marine science.

New technology offers exciting opportunities for studying the oceans. It goes almost without saying that computers and electronics have had profound impact. Satellites peer down at the ocean and, because they are so far away, can view huge areas of the ocean all at once to capture the big picture (Fig. 1.13). Much of our knowledge of large-scale features like ocean currents has been provided by this **remote sensing** technology. Satellites only see the surface of the ocean, however, and a lot of the action is a long way down. Submarines are one way to penetrate the depths, but scientists are making increasing use of underwater robots, including remotely operated vehicles (ROVs), which are controlled from the surface, and autonomous underwater vehicles (AUVs; see Fig. 16.23), which operate independently of direct human control. Marine scientists are also developing an array of instruments that sit on the bottom, float in place, drift with the currents, or are even attached to animals (see "Observing the Ocean," p. 6). Space technology has a role to play here as well; many oceanographic instruments relay their data through satellites.

Marine biologists today use every available tool in their study of the sea, even some decidedly low-tech ones (Fig. 1.14). Information about the ocean pours in at an ever-increasing pace. Much is yet to be learned, however, and the oceans remain a realm of great mystery and excitement.

FIGURE 1.9 The R/V *Thomas G. Thompson*, operated by the University of Washington, was the first of a new generation of research vessels. These vessels offer increased work space and can travel to research sites more quickly and stay there longer than earlier research ships.

THE SCIENTIFIC METHOD

Marine biology is an adventure, to be sure, but it is also a science. Scientists, including marine biologists, share a certain way of looking at the world. Students of marine biology need to be familiar with this approach and how it affects our understanding of the natural world, including the ocean.

We live in an age of science. Advertisers constantly boast of "scientific" improvements to their products. Newspapers regularly report new breakthroughs, and many television stations have special science reporters. Governments and private companies spend billions of dollars every year on scientific research and education. Why has science come to occupy a position of such prestige in our society? The answer, quite simply, is that it works! Science is among the most successful of human endeavors. Modern society could not exist without the knowledge and technology produced by science. Everyone's lives have been enriched by scientific advances in medicine, agriculture, communication, transportation, art, and countless other fields.

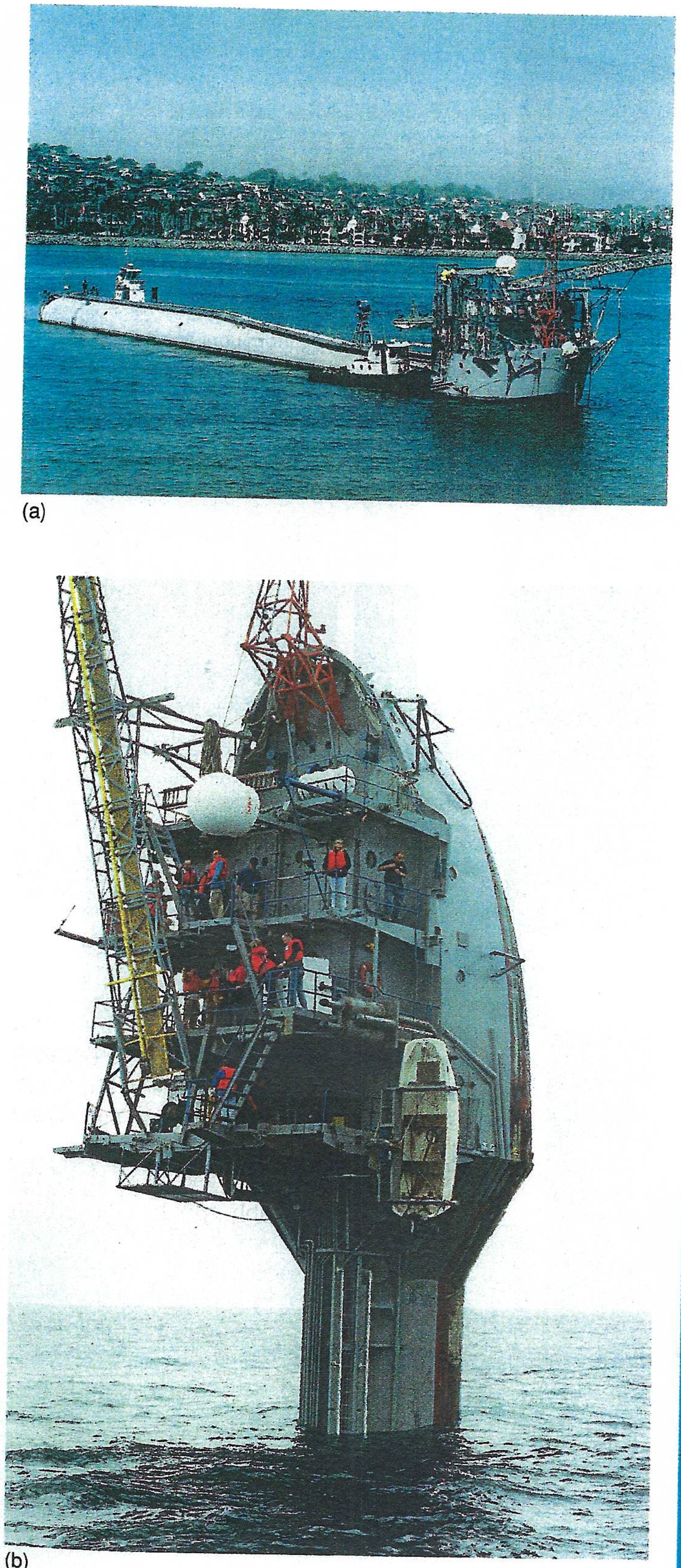


FIGURE 1.11 R/V *FLIP,* short for *f*loating *i*nstrument *p*latform, operated by Scripps Institution of Oceanography, provides a stable platform for research at sea. (*a*) Most of the hull consists of a hollow tube that floats while the vessel is towed into position. When the hull is flooded and sinks, *FLIP* swings into a vertical position (*b*) in which it is largely unaffected by the rise and fall of waves.

Much of the practical success of science results from the way it is done. Scientists do not see the world as a place where things just happen, for no reason. They assert instead that the universe can be explained by physical laws. Scientists don't go about discovering these laws haphazardly; they proceed according to time-tested procedures. The set of procedures that scientists use to learn about the world is called the **scientific method.**

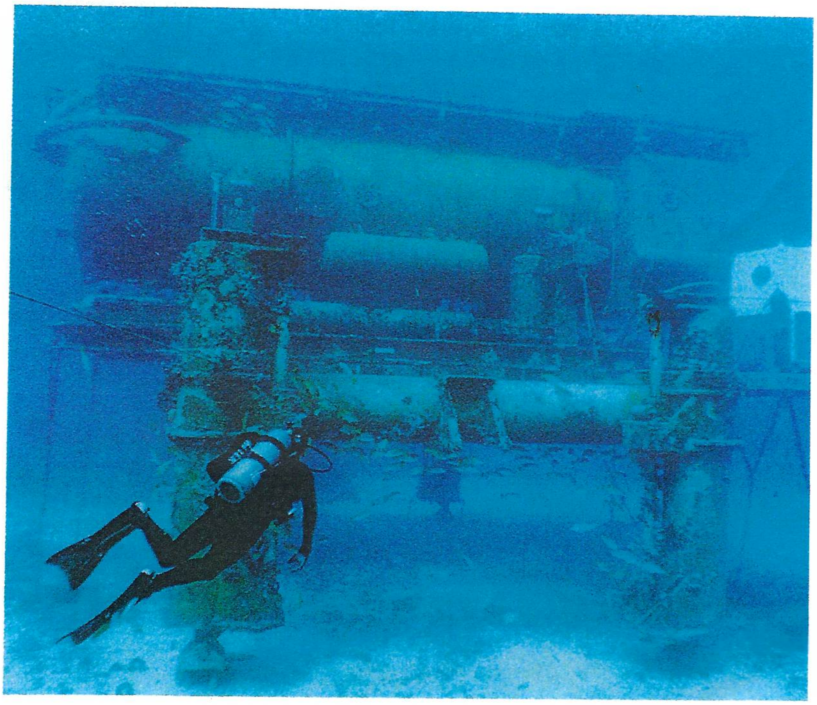
Scientists sometimes disagree over the fine points of the scientific method. As a result, they may apply the method in slightly different ways. In spite of these minor differences, most scientists do agree on the basic principles of the scientific method, which should be seen as a flexible framework guiding the study of nature and not a rigid set of rules.

Observation: The Currency of Science

The goal of science is to discover facts about the natural world and principles that explain these facts. At the heart of the scientific method is the conviction that we can learn about the world only through our senses or with tools that extend our senses. Microscopes, for example, extend our vision to help us see what is otherwise too small to see. Thus, scientific knowledge is fundamentally derived from the observation of nature. Scientific conclusions are based on observations, and not on preexisting ideas of how the world is or should be.

One of the advantages of relying on observations is that they can be verified by others. A person's thoughts, feelings, and beliefs are internal. No one really knows what goes on in the mind of another. On the other hand, the world studied by scientists is external to any single person. Different people can look at the same object. Sensory perception may be imperfect, and scientists, like anyone else, are not always impartial, but the

FIGURE 1.12 A diver swims outside *Aquarius,* the world's only underwater marine science laboratory. *Aquarius* is located in the Florida Keys Marine Sanctuary at a depth of about 20 m (60 ft). The living quarters are in the large cylinder at the upper left, which, fortunately for the crew, is larger than it appears here because it is further away than the diver.



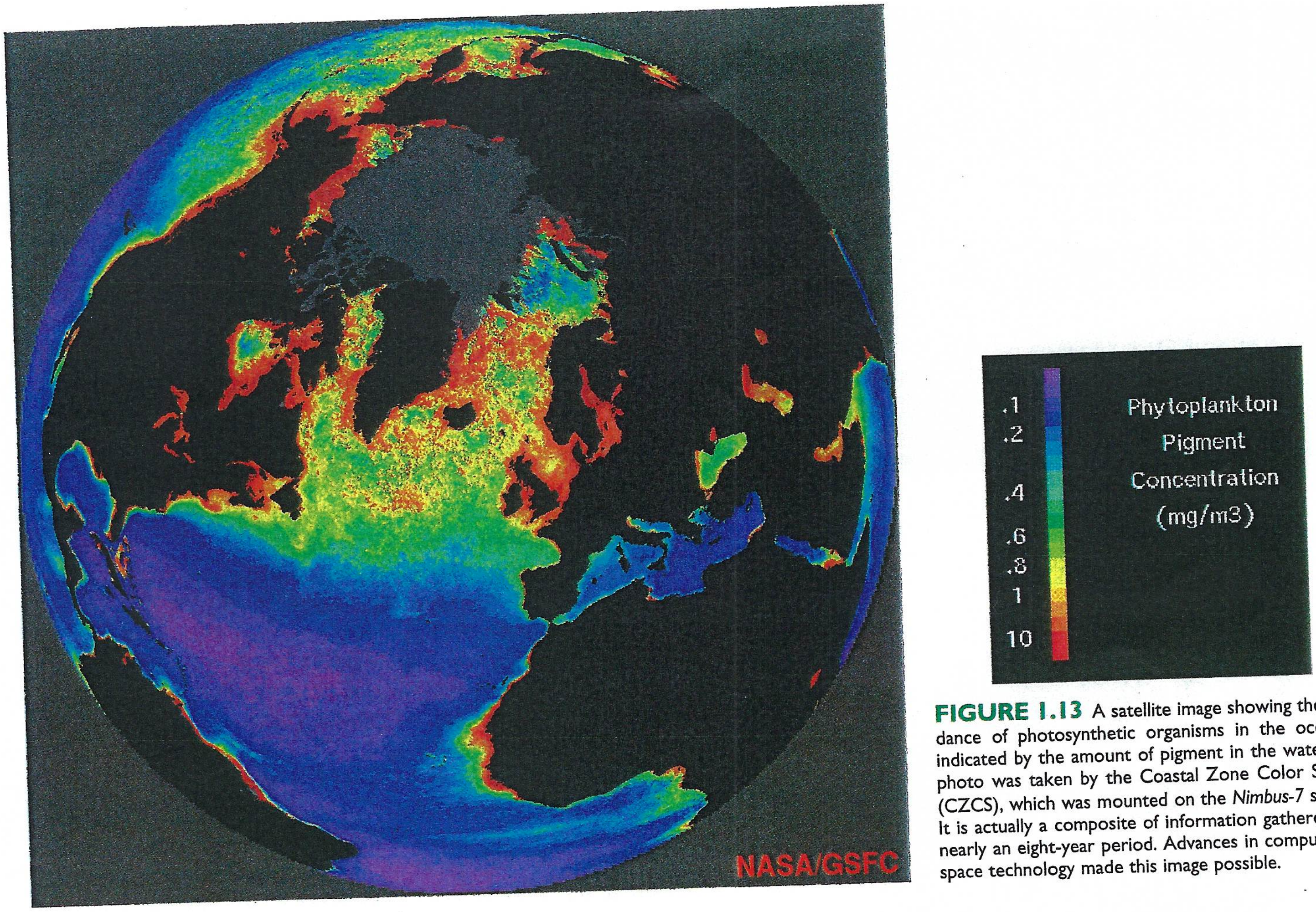


FIGURE 1.13 A satellite image showing the abundance of photosynthetic organisms in the ocean, as indicated by the amount of pigment in the water. This photo was taken by the Coastal Zone Color Scanner (CZCS), which was mounted on the *Nimbus-7* satellite. It is actually a composite of information gathered over nearly an eight-year period. Advances in computer and space technology made this image possible.

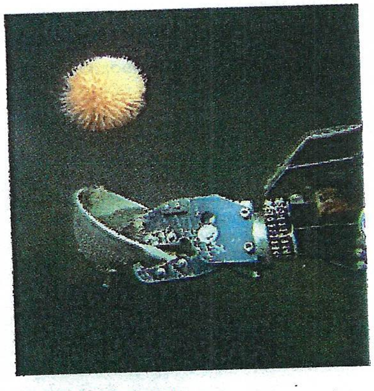


FIGURE 1.14 High-tech meets low-tech: The robotic arm of the ROV *Ventana* captures a pom-pom anemone (*Liponema brevicornis*) in an ordinary kitchen colander. © MBARI 1998

object is there for all to see. Thus, there is a way to check and validate any one person's observations.

Observation is critical to all phases of the scientific method. To begin with, it allows us to describe the natural world. The only way to learn what organisms live in a particular part of the ocean, how many of them there are, how fast and how large they grow, when and how they reproduce, what they eat, how they behave, and so on, is to observe that part of the ocean and the organisms living there. Exploration and description are vitally important parts of marine biology, constantly revealing new information. Previously unknown species, for example, are discovered almost every week (see "The Census of Marine Life," p. 216). New technologies, such as underwater cameras that reveal the behavior of whales (see "Observing the Ocean," p. 6) or genetic techniques that have uncovered vast numbers of previously unknown marine microbes (see "Tiny Cells, Big Surprises," p. 92), regularly improve our ability to observe the sea and make new discoveries. Each finding leads to new observations. The discovery of completely unknown and unexpected ecosystems at deep-sea hot springs, for example, led biologists to look for—and find—similar ecosystems in other parts of the ocean (see "Hot Springs, Cold Seeps, and Dead Bodies," p. 379).

As they observe more and more about the world, scientists inevitably seek to explain their observations—*why is that species of seaweed found only in a certain depth range?*—and to make predictions—*will the fishing be good next year?* The desire to explain and predict in turn guides yet more observation.

Two Ways of Thinking

To describe, explain, and make predictions about the natural world, scientists use two basic forms of thinking. In **induction,** one uses observations to arrive at general principles. Reasoning from general principles to specific conclusions is called **deduction.** Scientists once argued about which way of thinking is acceptable, but now generally agree that both induction and deduction are indispensable.

Induction When using induction, a scientist starts with a series of individual observations. Ideally, he or she has no goal or preconceptions about the outcome and is completely objective. The scientist then uses these observations to reach a general conclusion. For example, suppose a marine biologist examined a sailfish (Fig. 1.15), a shark (Fig. 1.16), and a tuna (Fig. 1.17) and found that they all had gills. Because sailfishes, sharks, and tunas are all fishes, he might draw the general conclusion *All fishes have gills.* This is an example of induction.

In the process of induction, general conclusions are made on the basis of specific observations.

The scientist must be careful in using induction. The step from isolated observations to general conclusion critically depends on the number and quality of the observations and on recognizing their limitations. If the biologist stopped after examining the sailfish, which happens to have a bill, he might use induction to make the false conclusion *All fishes have bills.* Even after examining all three fishes, he might have concluded *All marine animals have gills* instead of just *All fishes have gills.* This is where deduction comes into play.

FIGURE 1.15 The Atlantic sailfish (*Istiophorus albicans*). The long projection on the snout is called the bill.

FIGURE 1.16 A tiger shark (*Galeocerdo cuvier*). The five vertical gill slits can be seen just in front of the pectoral fins.

Deduction In deduction, scientists start with a general statement about nature and predict what the specific consequences would be if that statement is true. The general statement might be based on hunch or intuition, but it is usually based on observations. Suppose our marine biologist used induction to make the general statement *All marine animals have gills.* He might then reason that if all marine animals have gills and whales are marine animals, then whales must have gills. The biologist has used a general statement about all marine animals to make a statement about a particular kind of marine animal.

In the process of deduction, specific predictions are made by applying general principles.

Testing Ideas

Scientists are never content to simply make statements about the world and let it go at that. Instead, they are obsessed with testing the statements to see if they are, in fact, true. Both induction and deduction lead the scientist to make statements that *might* be true. A statement that might be true is called a **hypothesis.** A crucial feature of the scientific method is that all hypotheses are tested, usually again and again. This insistence on testing is one of the great strengths of the scientific method. Incorrect hypotheses are usually quickly weeded out and discarded.

Constructing the Hypothesis Scientific hypotheses must be stated in a way that allows them to be critically tested. What this means is that it must be possible, at least potentially, to *disprove* the hypothesis if it is false. Sometimes this is simple. For example, the hypothesis that whales have gills is easy to test. All the biologist has to do is examine a whale to see if it has gills. By doing so, he would find that whales have lungs, not gills (Fig. 1.18). He would have proven the hypothesis *Whales have gills* false. He would also disprove the more general hypothesis *All marine animals have gills.* The steps our marine biologist used to construct and test these hypotheses are illustrated in Figure 1.19. This line of reasoning is not entirely imaginary. Aristotle used similar logic in the fourth century B.C., observing not only that whales breathe with lungs and not gills, but that unlike most fishes they give birth to live young instead of laying eggs. Unfortunately, Aristotle's recognition that whales and other marine mammals are not fishes was lost to Western science for more than two millennia.

The term "fish" is used for a single individual or for more than one individual of the same species.
The term "fishes" is used to refer to more than one species of fish.

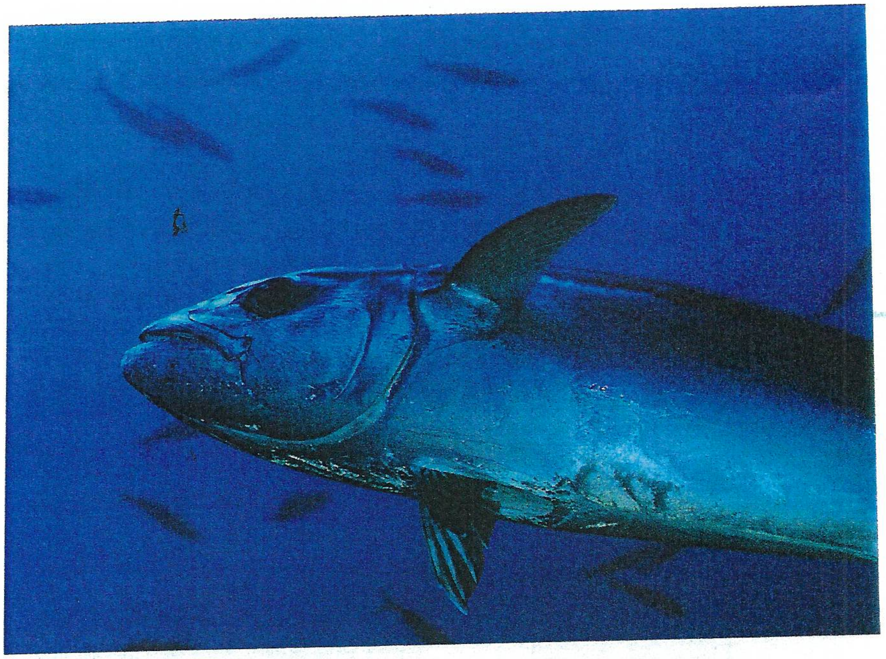


FIGURE 1.17 A dogtooth tuna (*Gymnosarda unicolor*) from Kiritimati (Christmas Island), in the Republic of Kiribati in the South Pacific.

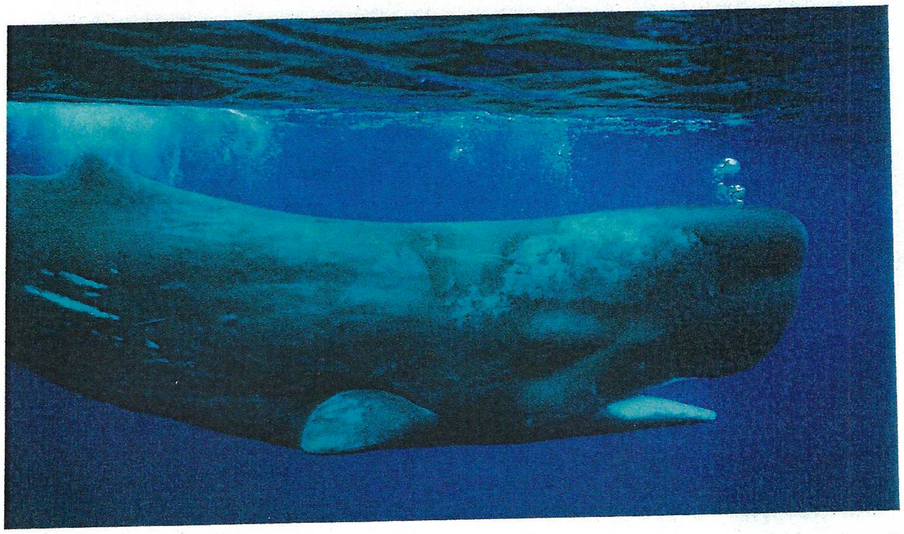


FIGURE 1.18 A sperm whale (*Physeter catodon*) exhales bubbles of air from its lungs through the blowhole on top of its head.

Hypotheses are often much more complicated than whether or not an animal has gills. Marine organisms are affected by weather and current patterns, the abundance of food and predators, natural cycles of reproduction and death, human activities, and a host of other factors. Marine scientists increasingly express their understanding of how such factors interact by constructing models, in the form of mathematical and computer models that predict what will happen in a given set of circumstances. Although complex, such models are really just hypotheses that can be tested by comparing the predictions with what is actually observed.

People sometimes make the mistake of proposing hypotheses that cannot be fairly tested. Someone who believes in mermaids might say, *There are mermaids in the ocean*. The problem with this hypothesis is that it could never be *proved* to be false. An army of marine biologists could spend their entire careers looking for a mermaid without finding one, but the true believer could always say, *The mermaids are there, you just didn't find them.* No matter how hard they looked, the biologists could never prove that there are no mermaids. Therefore, the statement *There are mermaids in the ocean* is not a valid scientific hypothesis because it is not **testable.**

A scientific hypothesis is a statement about the world that might be true and is testable. A testable hypothesis is one that at least potentially can be proved false.

The Nature of Scientific Proof It must be possible to disprove a hypothesis, at least in principle, before the hypothesis is a scientific one. But how can a hypothesis be proved true? This question has always troubled scientists, and the answer may trouble you too. In general, no scientific hypothesis can be absolutely proved true. For example, consider the hypothesis that all fishes have gills. It is easy to see that this hypothesis can be proved false by finding a fish without gills. But even though every fish so far examined has gills, this does not prove that *all* fishes have gills. Somewhere out there may lurk a fish without them. Just as it cannot be proved that there are no mermaids, it can never be proved that all fish have gills.

In science, then, there are no absolute truths. Knowing this, scientists could throw up their hands and look for another line of work. Fortunately, most scientists have learned to accept and deal with the lack of absolute certainty that is inherent in science by making the best of the available evidence. All scientific hypotheses are examined and tested, poked and prodded, to see if they agree with actual observations of the world. When a hypothesis withstands all these tests, it is conditionally accepted as "true" in the sense that it is consistent with the available evidence. Scientists speak of *accepting* hypotheses, not *proving* them. They accept the hypothesis that all fish have gills because every attempt to reject it has failed. At least for now, the hypothesis fits the observations. The good scientist, however, never quite forgets that any hypothesis, even a personal favorite, could suddenly be thrown out the window by new information. No hypothesis is exempt from testing, or immune to being discarded if it conflicts with the evidence. The bottom line in science is observation of the world, *not* preconceived human ideas or beliefs.

No hypothesis can be scientifically *proved* to be true. Instead, hypotheses are *accepted* for as long as they are supported by the available evidence.

Testing the Hypothesis Because hypotheses generally can't be proved to be true, scientists, somewhat surprisingly, spend their time trying to disprove, not prove, hypotheses. More confidence can be placed in a hypothesis that has stood up to hard testing than in an untested one. Thus, the role of the scientist is to be a skeptic.

Often scientists are trying to decide among two or more **alternative hypotheses.** After looking at the sailfish, shark, and tuna, our imaginary marine biologist advanced two possible hypotheses: that all fish have gills and that all marine animals have gills. Both hypotheses were consistent with his observations to that point. After examining a whale, he rejected the second hypothesis and, in doing so, strengthened the first one. He arrived at the best hypothesis by a process of elimination.

Real marine biologists rarely have it as easy as our imaginary one, who was able to construct and then test his hypotheses about gills with just a few simple observations. Hypothesis testing usually requires carefully planned, painstaking observations. Occasionally a new observation or set of observations leads to the complete rejection of an accepted hypothesis, which has been termed a "scientific revolution." Such discoveries make headlines, but most of the time the scientific process is a gradual one in which hypotheses are continually refined and modified, and new alternatives proposed, as more information becomes available.

Hypotheses can often be tested by making the right kind of observations of the natural world, at the right time and place. Improved observing systems (see "Observing the Ocean," p. 6) and continuing ocean exploration (see "The Census of Marine Life," p. 216) are constantly revealing more of the ocean's secrets.

Sometimes, however, the conditions needed to test a hypothesis do not occur naturally and scientists must manipulate nature, that is, perform an **experiment,** to make the necessary observations.

In experiments, scientists create artificial situations to test hypotheses because they cannot make the necessary observations under natural conditions.

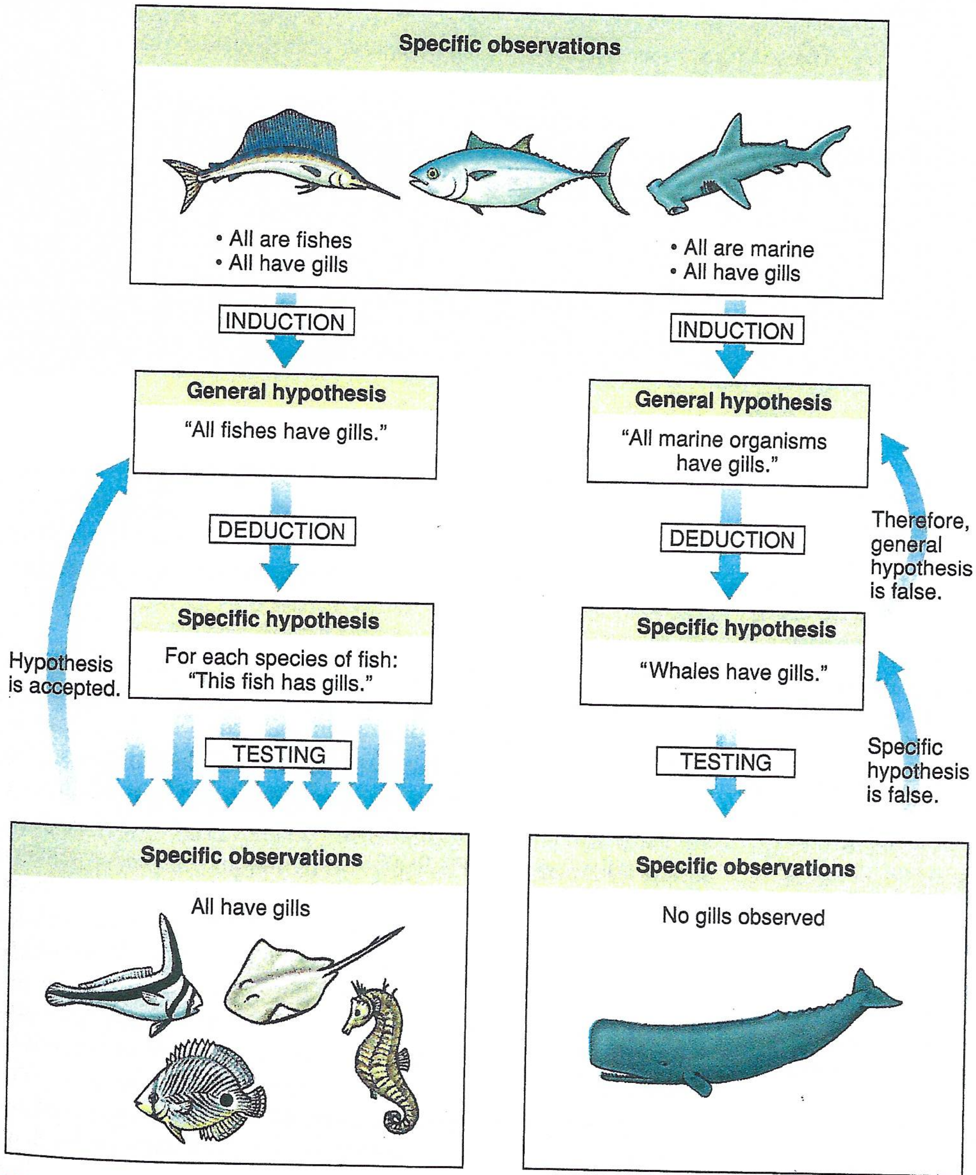


FIGURE 1.19 An example of the use of the scientific method. Two hypotheses were derived from the same observations. When tested by further observations, one hypothesis (left) is accepted and one (right) is rejected.

Suppose another marine biologist decides she wants to find out how water temperature affects the growth of mussels. She might be able to find two places, one warm and one cold, and measure how fast mussels grow at each place. The temperature at any given place changes all the time, however, and she would probably have difficulty finding two locations where one is always warmer than the other. Even if she does, the difference in temperature would not stay the same and there would probably be many other differences between the two places. The mussels might be different, for example. They might be eating different foods or different amounts of food. There might be pollution or an outbreak of disease at one of the sites. In any natural situation, there would be countless factors other than temperature that could explain differences in mussel growth. Factors that might affect observations are called **variables.**

Faced with all these variables, the biologist decides to perform an experiment. She collects mussels from one place and divides them at random into two groups. Now she knows that the mussels in the two groups are pretty much the same. She places the two groups into tanks where she can control the water temperature and grows one group in warm water, the other in cold. She feeds all the mussels the same amounts of the same food at the same time, protects the mussels from pollution and disease, supplies both holding tanks with seawater from the same source, and keeps all the other living conditions exactly the same for both groups. Because all these variables are the same for both groups, the biologist knows that they

EYE ON SCIENCE

Carbonate Experiments on the Reef

Experiments performed out in the ocean are as important to marine biology as those done in the lab. One of many examples is a research program being conducted on remote Pacific island coral reefs. Human activities are increasing the amount of carbon dioxide (CO_2) in the ocean. This may stimulate the growth of organisms such as corals and seaweeds, which use CO_2, to grow. The increased CO_2, however, makes the ocean slightly more acidic (see "Ocean Acidification: The Other CO_2 Problem," p. 236), which interferes with the formation of calcium carbonate skeletons and shells in organisms that have them. This includes reef corals and many coral reef algae, known as calcareous algae (see "The Organisms That Build Reefs," p. 307). Increasing CO_2 levels are likely to affect coral reefs, and in particular may encourage "fleshy," noncalcareous algae to take over from corals and calcareous algae.

Marine biologists have a lot of information from laboratory experiments about how some reef corals and algae respond to changes in CO_2 and acidity. There are, however, hundreds of different corals and algae on reefs, many of which are difficult to grow in the laboratory. Conditions on reefs are highly variable from place to place and over time, partly because of the metabolisms of the organisms themselves, which affect the water chemistry and each other as they grow. Furthermore, the reef itself is made of calcium carbonate and affects the chemistry. This complexity can't be replicated in the lab, so biologists need to do experiments in the field to determine the effects of increasing CO_2 on natural reefs.

In one series of experiments, the biologists place "benthic tents," clear plastic pyramids, over different combinations of corals and algae growing on a reef. The tents let natural light through, but retain the volume of water around the organisms. The scientists install electronic sensors inside the tents, and also pump out water samples, to measure how the different organisms, together and in combination, affect acidity, oxygen levels, and calcium carbonate chemistry as they grow.

The scientists are also studying how changes in acidity affect the growth of unconfined corals and algae, by using "minireefs." The minireefs are just cinderblocks on which small pieces of coral and algae are attached. The biologists place the minireefs in different parts of the reef where the acidity regime is known to vary naturally, and install a sensor to measure the acidity. They measure the organisms' growth rates, and compare them to the acidity regime experienced. Early results indicate that calcareous algae grow best if the acidity levels are fairly constant, and are inhibited by wide fluctuations in acidity.

Even in the field, though, the laboratory has its uses. Light is one of the main factors controlling the growth of corals and algae, and on a natural reef the light level constantly changes with the time of day and cloud cover. To measure how light affects the organisms in their field experiments, the biologists take specimens into a shipboard laboratory, where they measure their growth under precisely controlled light levels. This approach is typical of marine biology, in which lab and field experiments complement each other to answer complex questions about life in the sea.

For more information, explore the links provided in the Marine Biology Online Learning Center.

cannot be responsible for any differences observed in mussel growth. The only difference between the two groups is temperature.

To prevent a variable from affecting the experiment, the scientist has two options. One is to artificially keep the variable from changing—for example, by giving all the mussels exactly the same food. The other is to make sure that any changes that do occur are identical for both groups. By supplying both tanks with seawater from the same source, for example, our biologist ensures that any changes in the quality of the water affect both groups of mussels equally. Variables that are prevented from affecting an experiment are said to be **controlled,** and the experiment is called a **controlled experiment** (Fig. 1.20). Since the biologist has controlled the effects of other variables while growing the mussels at different temperatures, she can be more confident that any observed difference in growth rate between the two groups is due to temperature.

Similarly, the biologist could study how food supply affects mussel growth by keeping the mussels at the same temperature but giving them different amounts of food. Experiments thus allow the effects of different variables to be separated. The way that variables interact can also be studied. The mussels could be maintained in different *combinations* of temperature and food supply, for example, to see whether the temperature at which they grow fastest depends on how much food they get. Experiments aren't just for the laboratory—many important experiments are done out in the real world (see "Carbonate Experiments on the Reef," above, and "Transplantation, Removal, and Caging Experiments," p. 256).

The Scientific Theory Many people think of a theory as a rather shaky proposition, and most of us have heard people ridicule some idea or other because it was "only a theory." The public usually reserves such scorn for controversial or unpopular theories. The theory of gravity, for instance, is rarely criticized for being "only a theory" even though physicists have no accepted explanation of why gravity exists. People often say "theory" in everyday conversation to mean speculation or just one of several possible explanations for something, but scientists don't use the term **scientific theory** to refer to a controversial or provisional hypothesis. A hypothesis, or set of hypotheses, is not considered a scientific theory until alternatives have been ruled out and the hypothesis has passed every possible test. A scientific theory is supported by overwhelming evidence and represents a comprehensive explanation of our observations of how the world works. It is an established scientific principle that guides the search for new knowledge by leading to new, testable hypotheses.

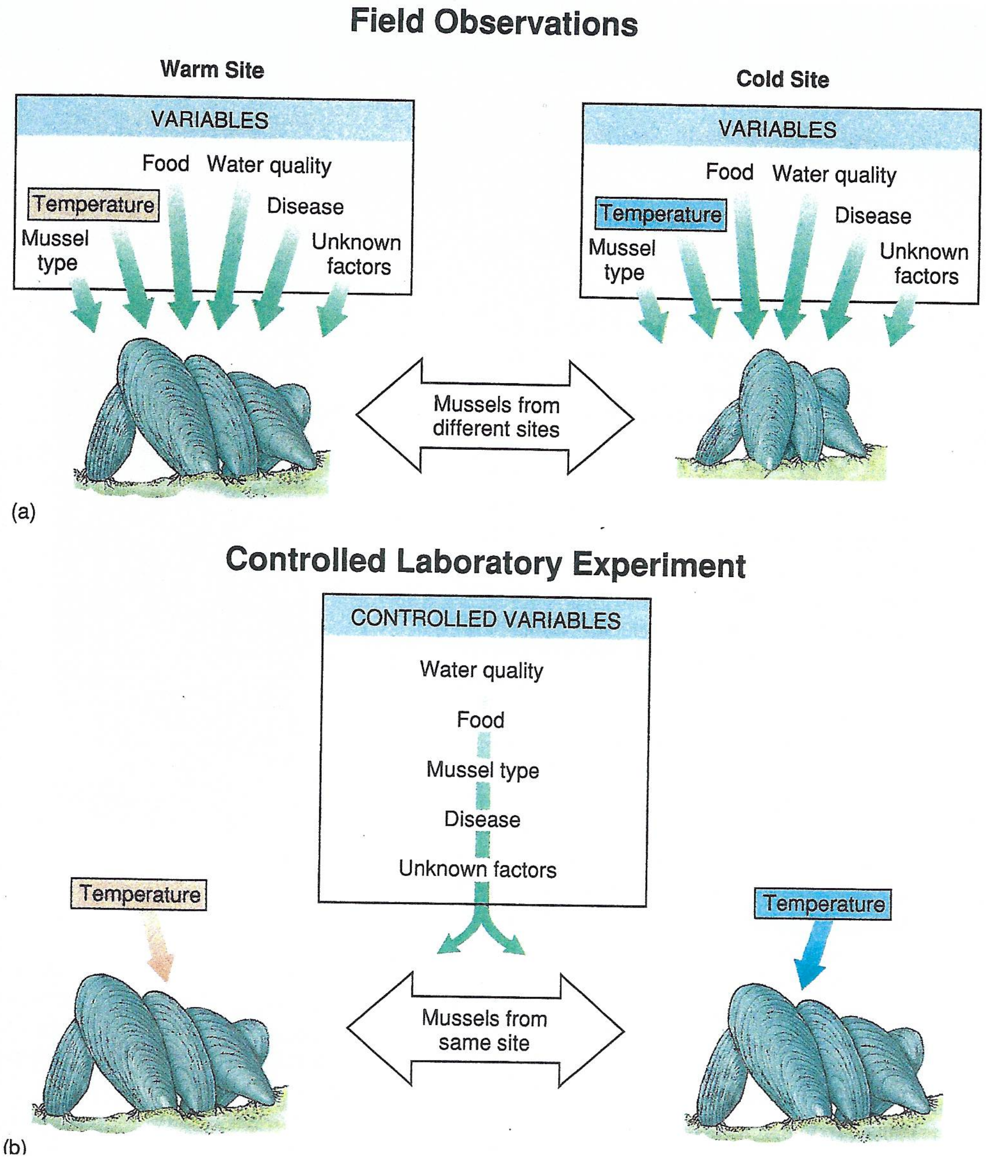


FIGURE 1.20 (*a*) Many different variables might produce differences between groups of mussels at different locations. (*b*) Controlling the variables in an experiment allows the effects of a single factor—in this case, temperature—to be tested. This example describes a laboratory experiment, but experiments are often performed in the field.

It must be remembered, however, that a theory is still a hypothesis, albeit a well-tested one. As with other hypotheses, theories cannot be absolutely proved and are accepted as true only as long as they are supported by evidence. Good scientists accept theories for the time being because the best available evidence supports them. They also recognize that any theory could be overturned by new evidence.

A scientific theory is a hypothesis that has been so extensively tested that it is generally regarded as true. Like any hypothesis, however, it is subject to rejection if enough evidence accumulates against it.

Limitations of the Scientific Method

No human enterprise, including science, is perfect. Just as it is important to understand how and why the scientific method works, it is important to understand the limitations of the scientific method. For one thing, remember that scientists are people too; they are prone to the same human shortcomings as anyone else. Scientists may be attached to favorite theories even when confronted with contradictory evidence—being wrong can be hard to accept. Like anyone else, they may let personal biases affect their thinking. No one can be completely objective all the time. Fortunately, factual errors are usually corrected because hypotheses are tested not just by one person but by many. The practical success of science is evidence that the self-checking nature of the scientific method does work most of the time.

Science also has some built-in limitations. Ironically, these limitations arise from the same features that give the scientific method its power: the insistence on direct observation and testable hypotheses. This means that science cannot make judgments about values, ethics, or morality. Science can reveal how the world is, but not how it should be. Science cannot decide what is beautiful. Science can't even tell humanity how to use the knowledge and technology it produces. These things all depend on values, feelings, and beliefs, which are beyond the scope of science.

John Steinbeck and Ed Ricketts

People mostly know the American writer John Steinbeck as the author of such beloved works as *The Grapes of Wrath, Of Mice and Men,* and *East of Eden.* Less well known are Steinbeck's contributions to marine biology, which resulted largely from his close friendship with a man named Ed Ricketts.

Steinbeck and Ricketts first met in 1930—by Steinbeck's account, in a dentist's office in Pacific Grove, California. Steinbeck had a long-standing interest in marine biology and had wanted to meet Ricketts for some time. Ricketts owned the Pacific Biological Laboratory, located near the Hopkins Marine Station and the present site of the Monterey Bay Aquarium. Ricketts collected specimens of marine life along the Pacific coast and sold them to universities and museums. He was immensely popular in the area and knew more about marine biology than anyone around.

The two men became close friends almost immediately. Before long Steinbeck, then struggling as a writer, was spending a lot of time hanging around his friend's laboratory, going on collecting trips, and assisting in day-to-day operations. Steinbeck got so involved in this work that he could even get excited about a microscope:

> *My dream for some time in the future is a research scope with an oil immersion lens, but that costs about 600 dollars and I'm not getting it right now.... Oh boy! Oh boy! Sometime I'll have one.*[1]

John Steinbeck would eventually credit Ricketts with shaping his views of humanity and the world, and characters in at least six of Steinbeck's novels were based on Ricketts. The most famous is Doc, the main character of *Cannery Row,* who runs the "Western Biological Laboratory":

> *It sells the lovely animals of the sea, the sponges, tunicates, anemones, the stars and buttlestars [sic], the sunstars, the bivalves, barnacles, the worms and shells, the fabulous and multiform little brothers, the living moving flowers of the sea, nudibranchs and tectibranchs, the spiked and nobbed and needly urchins, the crabs and demi-crabs, the little dragons, the snapping shrimps, the ghost shrimps so transparent that they hardly throw a shadow.... You can order anything living from Western Biological and sooner or later you will get it.*[2]

The friendship was beneficial to marine biology as well as to literature. Their expedition to Mexico produced *The Sea of Cortez,* a scientific report that is also part literature and part travelogue. The book lists the more than 600 species collected by the pair, including some 60 that were new to science. The trip was not all work, however: The authors report taking "2,160 individuals of two species of beer."

Ed Ricketts's most enduring contribution to marine biology was the 1939 publication *Between Pacific Tides.* Written with Jack Calvin, a friend of Ricketts and Steinbeck, *Between Pacific Tides* is a comprehensive guide to the seashore life of the Pacific coast of North America. Revised and updated, it is still used by amateurs and professionals alike.

Though Ricketts was an able biologist and was largely responsible for the content of *Between Pacific Tides,* he had difficulty getting his observations and ideas down on paper. Steinbeck almost certainly helped him write the book and get it published. When Ricketts felt that the publisher, Stanford University Press, was dragging its feet, Steinbeck fired off this sarcastic letter:

> *Gentlemen:*
>
> *May we withdraw certain selected parts of* Between Pacific Tides *which with the passing years badly need revision. Science advances but Stanford Press does not.*
>
> *There is the problem also of the impending New Ice Age.*

Ed Ricketts.

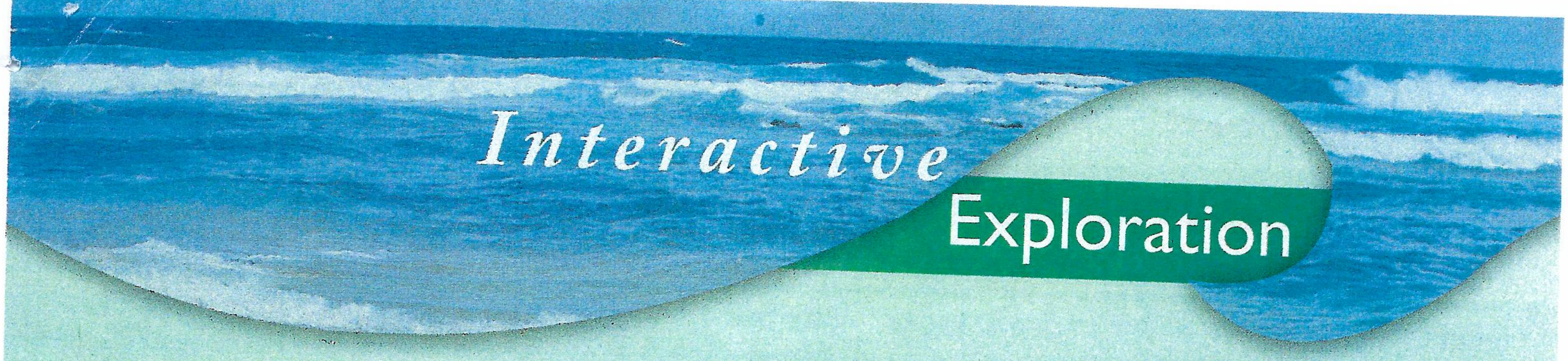
> *Sometime in the near future we should like to place our order for one (1) copy of the forthcoming (1948, no doubt) publication,* The Internal Combustion Engine, Will it Work?[3]
>
> *Sincerely,*
> *John Steinbeck*
> *Ed Ricketts*
>
> *P.S. Good Luck with* A Brief Anatomy of the Turtle.

Ed Ricketts was killed in a train accident in 1948. Steinbeck, saddened at the death of his friend, wrote, "There died the greatest man I have ever known and the best teacher."

---

[1] "2/17/48 to Gwyndolyn Steinbeck" by John Steinbeck and Ed Ricketts, copyright 1952 by John Steinbeck, © 1969 by The Estate of John Steinbeck, © 1975 by Elaine A. Steinbeck and Robert Wallsten, "12/15/1939 letter to Elizabeth Otis" by John Steinbeck, from *Steinbeck: A Life in Letters* by Elaine A. Steinbeck and Robert Wallsten, editors, copyright 1952 by John Steinbeck, © 1969 by The Estate of John Steinbeck, © 1975 by Elaine A. Steinbeck and Robert Wallsten. Used by permission of Viking Penguin, a division of Penguin Group (USA) Inc.

[2] "Chapter 5," from *Cannery Row* by John Steinbeck, copyright 1945 by John Steinbeck. Renewed © 1973 by Elaine Steinbeck, John Steinbeck IV and Thom Steinbeck. Used by permission of Viking Penguin, a division of Penguin Group (USA) Inc.



Interactive Exploration

The *Marine Biology* Online Learning Center is a great place to check your understanding of chapter material. Visit **www.mhhe.com/castrohuber9e** for access to interactive chapter summaries, chapter quizzing, and more! Further enhance your knowledge with videoclips and weblinks to chapter-related material.

Critical Thinking

1. Most of the major advances in marine biology have come in the last 200 years. What do you think are the reasons for this?
2. Recall that the statement "There are mermaids in the ocean" is not a valid scientific hypothesis. Can the same be said of the statement "There are *no* mermaids in the ocean?" Why?
3. Imagine you are a marine biologist and you notice that a certain type of crab tends to be larger in a local bay than in the waters outside the bay. What hypotheses might account for this difference? How would you go about testing these hypotheses?
4. Many species of whale have been hunted to the brink of extinction. Many people think that we do not have the right to kill whales and that all whaling should cease. On the other hand, in many cultures whales have been hunted for centuries and still have great cultural importance. People from such cultures argue that limited whaling should be allowed to continue. What is the role that science can play in deciding who is right? What questions cannot be answered by science?

For Further Reading

Some of the recommended reading may be available online. Look for live links on the *Marine Biology* Online Learning Center.

General Interest

Barnes, C. R., M. M. Best, and A. Zelinski, 2009. The NEPTUNE Canada regional cabled ocean observatory. *Sea Technology*, vol. 49, no. 7, July, pp. 10–14. An overview of one of the new deep-ocean observing systems.

Curry, A., 2008. Raiders or traders? *Smithsonian*, vol. 39, no. 4, July, pp. 24–30. During the early Middle Ages, Norsemen raided and traded their way across thousands of miles of sea to the east and south of their homeland. Setting sail aboard a replica Viking ship gives researchers an insight into the lives of these intrepid seafarers.

Earth monitoring. *Nature*, vol. 450, no. 7171, 6 December 2007, pp. 778–790. A special collection of articles about monitoring the earth's natural systems.

Eident, K., 2012. A long voyage to get a new ship. *Oceanus*, vol. 49, no. 2, Spring, pp. 18–21. A lot of planning goes into building a new research ship.

Griggs, J., 2008. Robot gliders take the deep sea's pulse. *New Scientist*, vol. 200, no. 2684, pp. 28–29. Autonomous underwater gliders are set to roam the seas for years at a time, relaying oceanographic data to scientists by satellite.

Marean, C. W., 2010. When the sea saved humanity. *Scientific American*, vol. 303, no. 2, August, pp. 54–61. When a "mini ice age" nearly drove early humans extinct, marine resources on the south coast of Africa pulled them through.

Pietsch, T. W., 2011. Plumier's passion. *Natural History*, vol. 119, no. 7, July–August, pp. 30–16. A seventeenth-century French monk conducted meticulous studies of fish, including anatomical diagrams.

Pringle, H., 2007. Follow that kelp. *New Scientist*, vol. 195, no. 2616, 11 August, pp. 40–43. America's first inhabitants may have traveled from Siberia in small boats following the belt of kelp forests along North Pacific coasts.

Quammen, D., 2004. Was Darwin wrong? *National Geographic*, vol. 206, no. 5, November, pp. 2–35. Yes, evolution is a theory—that means it is the best available explanation for a vast body of evidence.

Schrope, M., 2009. The lab at the bottom of the sea. *Nature*, vol. 457, no. 7226, 8 January, pp. 141–143. A first-hand account of a stay in the underwater laboratory, *Aquarius*.

Smith, R., 2008. Beyond the blue horizon. *National Geographic*, vol. 213, no. 3, March, pp. 106–123. Recent archaeological finds help piece together the puzzle of how ancient Polynesian sailors navigated their way across the Pacific.

Stix, G., 2009. Darwin's living legacy. *Scientific American*, vol. 300, no. 1, January, pp. 38–43. After 150 years of scrutiny, Darwin's theory of evolution by natural selection still underpins the science of biology.

Sulloway, F. J., 2006. The evolution of Charles Darwin. *Smithsonian*, vol. 36, no. 9, December, pp. 58–69. Darwin rigorously followed the scientific method, even when his conclusions challenged his deeply held religous beliefs.

Tindall, B., 2004. Tidal attraction. *Sierra*, vol. 89, no. 3, May/June, pp. 48–55, 64. A look at the same tide pools studied by Ed Ricketts and John Steinbeck—but many aren't what they once were.

Wheelwright, J., 2003. Sea searchers. *Smithsonian*, vol. 33, no. 10, January, pp. 56–62. Scientists launch an unprecedented effort to track the movements of marine animals using the latest electronics and satellite technology.