From the things that have been ascertained and investigated thus far, I believe it has been sufficiently well established that there is present in animals an electricity which we... are wont to designate with the general term “animal.”... it is seen most clearly... in the muscles and nerves.

—Luigi Galvani, 1791

Nerve Spirits and Juices

The seventeenth century was a time of great accomplishments in the brain sciences. Thanks in part to Thomas Willis and his associates in England, the advances included a much-improved neuroanatomy, a host of new terms to describe parts of the brain, and fresh attempts to associate brain structures with behavioral functions. Additional changes included better clinical descriptions of neurological diseases and a greater willingness to intervene surgically. Nevertheless, as was true during the Renaissance, scientific advancements did not proceed equally along all fronts. In particular, investigators living in the opening decades of the eighteenth century still could not boast about knowing how the nerves work.

Three different theories of nerve function were debated as the seventeenth century drew to a close. First, many scientists still adhered to the notion of spirits running through the hollow nerves to contract the muscles or convey impressions to the brain. This was an ancient idea, but René Descartes, among others, embraced it.

A second theory held that the nerves secrete droplets of fluid onto the muscles to activate them. Thomas Willis, for example, thought that when nerve fluids mixed with blood and fermented, they could cause minute “explosions,” which would result in muscular contractions.

The third theory was the idea that the nerves transmit information by vibration. This idea found its champion in Sir Isaac Newton, who attributed color perception to different waves of light causing corresponding vibration patterns in the nerves from the eye to the brain.

Each of these notions of nerve action—ethereal spirits, fluids, and vibrations—had serious problems. Not only was each hard to test, but each seemed to be at odds with laboratory findings. For instance, in 1677 Francis Glisson, a physics professor
at Cambridge University, took a glass tube closed at one end, put his arm in it, and
then filled it with water. He hypothesized that more water should be displaced by
the inflow of spirits into his arm when he flexed his muscles. Yet he found no more
displacement when he did this.

At about the same time, an Italian scientist by the name of Giovanni Borelli de-
cided to test the theory of spirits in a slightly different way. In 1680 he immersed the
limb of an animal in a tub of water and cut some of its muscles. To his surprise, no
bubbling ferment came out. Based on what he failed to see, he too questioned
whether a case could be made for nerve spirits inflating the muscles.

Experiments in which nerve bundles were tied off also left many scientists
scratching their heads. In theory, the buildup of spirits or juices should cause the
nerves to swell just behind the knot. Not only were the experimental results inco-
sistent with this expectation, but when the nerves were then cut, drops of fluid failed
to materialize. Findings of this sort forced Albrecht von Haller, the leading
physiologist of the mid-eighteenth century, to assert that if the nerves secrete some
sort of a vital juice, it cannot be anything like water. Moreover, he doubted whether
any fluid encountered in everyday life could move fast enough to account for nerve
actions.

As for vibrations, the third idea, this notion seemed wrong to most scientists from
the start. The immediate problem was that the nerves appeared soft and pulpy. They
were not pulled tight like the strings of a bow, which vibrate when struck. In addi-
tion, they did not spring back when cut. For these reasons, the idea of nerve vibra-
tions was criticized by Herman Boerhaave. In a lecture given in 1743, the esteemed
Leiden physician referred to vibration theory as just another “repugnant” idea.

Could the use of newly constructed microscopes shed some light on the prob-
lem? Anton Van Leeuwenhoek, the pioneering microscopist who published some of
his findings in 1674, was distressed when he failed to observe an opening in the optic
nerve of a cow. After all, Galen had written that such an opening could be seen by
simply holding the severed optic nerve up to the sun. Other fledgling microscopists
searched high and low for hollow openings in the nerves, a prerequisite for theories
involving nerve spirits or juices. To their dismay, such openings could not be found
at all or demonstrated in a manner that inspired confidence.

Steno, the Dane who was critical of Descartes and Willis for their fanciful theo-
ries of brain function, did not mince words when it came to expressing his own
doubts about existing theories of nerve action, especially those involving mysterious
animal spirits. In 1667, after having conducted some experiments of his own, he
complained:

We are still more uncertain about what relates to the Animal Spirits. Are they
Blood, or a particular Substance separated from the Chyle by the Glands of the
Mesentery? Or are they derived from a Lymphatic Serum? ... Our common
Dissections cannot clear up any of these difficulties.

Physiologists in the opening decades of the eighteenth century consequently had
many good reasons to be skeptical of existing theories, whether based on animal
spirits, fluids, or vibrations. Obviously, there was a need for a more plausible mecha-
nism of nerve action—a theory based on an agent that could work rapidly, be manip-
ulated, and perhaps even be measured. In short, there was a demand for a fresh start.
The Spark

During this period of rising frustration with existing nerve theories, some scientists began to wonder whether the nervous system may work by electricity, a term coined by the British physicist William Gilbert around 1600. But was there a single figure dominating the study of electricity at this time? Because so many people were involved with electricity, and because knowledge about electricity led to developments in so many different scientific fields, some broad-minded historians say no. When discussions narrow to just the history of neurophysiology, however, one name stands above the rest. As put by historian Mary Brazier: "In the history of the electrical activity of the nervous system the outstanding figure is, without rival, that of Galvani."7

Luigi Galvani (Fig. 8.1) worked in the last quarter of the eighteenth century. But, as Brazier herself admits, given the Zeitgeist, or spirit of the time, Galvani’s experiments and theories were not as revolutionary as they were evolutionary. Galvani studied electricity with animals because this was one of the most exciting things an aspiring scientist could do, and he was the recipient of a wealth of experimental findings and new ideas. The favorable climate that existed when he worked can best be appreciated by looking at some of the phenomena that attracted him to the field.

The Instruments

Let us begin by looking at the use of electricity in the healing arts. As we have already seen, fish with electric organs were known to the ancients (see Chapter 4).8 Scribonius Largus and Gislen used shocks from the electric ray to treat headache, gout, paralysis and various other disorders in ancient Rome. They sometimes had patients stand barefoot on a live ray or more than one fish to increase the effect. The therapeutic use of these fish continued in the Middle East after this time and was known to the Europeans.

Nevertheless, finding electric fish for therapy or experimentation was not always
easy. Special machines for creating electricity on demand were needed. These appeared as "friction machines," but not until the eighteenth century. They were made of globes of sulfur, porcelain, or glass that were rubbed by hand.\(^9\) Once electrically charged, an individual could produce a spark by touching an object or even another person. Inventors soon found a way of generating "electrical fire" simply by touching revolving glass globes, cylinders, or plates.

Once electrically charged by a friction machine, a man could set a glass of brandy ablaze by throwing a spark from his tongue. Johann Winkler, a professor at Leipzig, often demonstrated this unexpected phenomenon at social gatherings to the delight of his guests.\(^9\) For the nobility who were looking for new ways to amuse themselves, spectacles of this sort were the talk of the town.

Johann Krüger was of a more serious frame of mind when he learned about the new frictional machines. He envisioned a role for them in mainstream medicine. In 1744 he wrote:

But what is the usefulness of electricity, for all things must have a usefulness, that is certain. We have seen it cannot be looked for either in theology or in jurisprudence, and therefore nothing is left but medicine. The best effect would be found in paralyzed limbs to restore sensation and reestablish the power of motion.\(^11\)

With the advent of the Leyden jar in 1745, storing and releasing electrical charges on demand became much easier. This device, named for the Dutch city south of Amsterdam in which it was invented (now spelled Leiden), allowed electricity to be stored until needed. The often-cited man of the hour was Petrus van Musschenbroek, a very talented instrument maker and a pupil of Herman Boerhaave (A similar device for conserving and releasing electricity was constructed at about the same time in the north of Germany.\(^12\))

The typical Leyden jar has a narrow neck with a rubber stopper. A metal foil coating over the glass (except at the top) serves as an outer conductor, whereas a liquid (or, later, metal) inside the jar serves as an inner conductor. After a frictional machine is connected to the jar, the separation of the inner and outer conductors by the glass allows the charge to be conserved. The charge can be released when wires from both conductors touch a person or an animal. As the early researchers quickly found out, the discharge could throw a grown man off his feet and even kill a small animal.

In the hands of Abbé Jean Antoine Nollet, the man who coined the term "Leyden jar," the device made for some truly spectacular demonstrations.\(^13\) He made a nine-hundred-foot line of Carthusian monks jump en masse when they held hands and completed a circuit to a fully charged Leyden jar. The instrument, however, was destined to be used for more than just entertainment. Nollet himself stressed that it should be utilized therapeutically. He reported some success with one in a military hospital in Paris, and even wrote a book about how to apply electricity to paralyzed body parts.

Although some cautious physicians felt that electricity was overrated as a cure-all, Leyden jars and electrical machines now made their way into Europe's more progressive hospitals and clinics. Between 1750 and 1780 more than twenty-five articles on curing paralyses with electricity appeared in just one French periodical, the *Journal de Médecine*. But many scientists still did not view electricity as the mysterious
fluid of the nerves. Instead, they held tight to the idea that electricity worked its wonders by increasing the flow of sluggish juices in the nerve canals.

A Most Unusual Trio

Electrotherapy became so popular in Europe and North America that many individuals who were not formally trained as physicians began to practice it. Some hoped to make their fortunes by administering shocks to sick and injured patients. Other medical “outsiders” were drawn to it by a wish to help humanity or by a desire to become famous.

Three people who are much better known in other domains illustrate just how alluring electrotherapy had become. The first is John Wesley, the English religious reformer and founder of the Methodist Church. Wesley did not formally attend medical school or pass any kind of certifying examination, but this did not dampen his enthusiasm when it came to applying the new technology.14

In his Primitive Remedies, which first appeared in 1747, Wesley listed 288 medical conditions that he thought could be prevented or healed by electricity.15 He was convinced that no remedy from nature was as good as an electrical machine for disorders of the nervous system. He suggested fifty to a hundred weak shocks for most medical conditions. For paralyses, he recommended electrifying the malfunctioning limb once per day for three months. Wesley had been using his “electrical fire” therapeutically for many years before he published The Desideratum or, Electricity Made Plain and Simple by a Lover of Mankind and Common Sense.16 This pamphlet appeared in 1759 and was so popular that it quickly went through several editions.

A second nonphysician who had something to say about medical electricity was Benjamin Franklin. He worked on his electrical science in Philadelphia from 1747 to 1755. His experiments with kites and lightning rods are well known. In 1751 he published a series of letters he had written to friends in London as Experiments and Observations on Electricity, Made at Philadelphia in America.17 But in 1759, when the medical use of electricity was already widespread, he penned a letter to John Pringle of the Royal Society of London expressing his doubts about electricity as an effective treatment for paralyses:

I never knew any advantage from electricity in palsies that was permanent. And how far the apparent temporary advantage might arise from the exercise in the patients’ journey, and coming daily to my house, or from the spirits given by the hope of success, enabling them to exert more strength in moving their limbs, I will not pretend to say.18

The last member of this most unusual trio was Jean-Paul Marat, who treated patients in England and France.19 Marat aspired to be a respected healer and reported successes with electricity for a variety of ailments, including paralyses and pain. He even recommended it for children who were failing to develop properly. But like Franklin, Marat saw limits to electrotherapy. He mentioned that it cannot cure epilepsy and cannot cause malignant tumors to undergo remission. Marat published his most important works on electricity in 1782 and 1784.20 The latter was awarded first prize in a French competition.
Today Marat is much better remembered for his politics during the French Revolution and for his fanaticism during the Reign of Terror. A self-proclaimed “friend of the people,” Marat was instrumental in sending many innocent men and women to the guillotine. Charlotte Corday, a member of the opposing Girondist revolutionary party, finally took a knife hidden under her dress and killed him while he was writing on a desk that covered his medicinal bath. Marat’s dramatic death in 1793 was immortalized by his friend Jacques-Louis David, the leading French painter of the Neoclassical period (Fig. 8.2).

In contrast to Marat’s fanaticism, Franklin’s diplomacy during and after the American Revolution are remembered more positively. Even the Europeans viewed Franklin as a talented statesman, journalist, and scientist in the culture-starved American colonies. As for John Wesley, he is best remembered today as the founder of the Methodist Church. By purchasing electrical machines for the practice of medicine and by turning to God, he strove to save the largest number of bodies and souls in what he claimed would be the most economical way.

The Nature of Animal Electricity

Those individuals who first thought that electricity might be the “fluid” of the nervous system listened carefully to what the electrotherapists were saying. Even after eliminating the outright frauds from the picture, the claims for electrotherapy were impressive and supportive of the idea that electricity might be the key to understanding nerve action. After all, what other force was known to have such an effect on the vital processes of the body? Was anything else more effective in eliciting muscular contractions? And was there any other agent that could travel as fast as electricity?

Stephen Gray, Stephen Hales, and Alexander Monro (Primus), three early
eighteenth-century scientists in Great Britain, were among the first to write that electricity could be the mysterious fluid of the nerves. Others followed with stronger statements. Still, it was a long jump from the observation that people could be electrically charged to the claim that electricity underlies normal nerve action.

One of the biggest problems was the idea that it may not be possible to confine electricity to just the nervous system. What would prevent electricity from leaking out of the nerves onto surrounding tissue? This was a legitimate concern, and it was an issue that kept many researchers a respectable arm’s length away from the idea that electricity must be the mysterious agent of nerve action.

Back to Electric Fish

Some of the mysteries surrounding electricity were cleared up during the 1770s, when a few scientists decided to take a fresh look at the specialized fish that had so amazed the ancients. Unlike their predecessors, this new generation of explorers had better instruments for studying these fish. They also had well-thought-out questions they wanted answered. At the top of most “wish lists” was the most crucial questions of all: How could researchers be sure that the shocks released by electric fish are really electrical in nature?

The task of understanding how these specialized fish may function began in earnest in the second half of the seventeenth century. An Italian scientist by the name of Francesco Redi described the painful shocks of the electric ray (also called the torpedo fish) in 1666, and his student, Stefano Lorenzini, examined the electric organ itself just a few years later. In 1678, Lorenzini wrote:

The Cramp-Fish hath not this stupefying Quality in all the Parts of his whole Body, but only in one particular Part, and this determin’d or particular Part is those two hooked Muscles . . . which unless they are immediately touched with the bare Flesh, produce no Effect at all; and besides, in touching those Parts, it is necessary that the Fibres of those said Muscles be contracted, to produce the Effect on the naked Part of those who touch them.

John Walsh arrived on the scene about a hundred years later and conducted a series of landmark studies on torpedo fish caught off the French coast. In 1774, he presented some of his findings at a meeting of a scientific academy in France. He also penned several letters to Benjamin Franklin that were published a year later. A report by Walsh on the larger English ray followed in 1774.

Walsh described how an electric ray could discharge fifty or more shocks in a minute and a half. He also showed how its electricity could be transmitted through wires. He noted that it was important to have the wires connected to the upper and lower surfaces of a healthy ray to experience the full effect, which he found indistinguishable from the shock produced with a Leyden jar.

Walsh hypothesized that the shock from the fish is due to the buildup and release of compressed electrical fluid. The electrical organs draw their charge from the nerves, like a Leyden jar, store it for eventual release. To Walsh, the only real difference between the fish and a Leyden jar was that the ray could decide whether or not to release its own shocks. This, he said, is evidenced by the fact that it closes its eyes when it begins to release electricity.
Having satisfied himself that these fish can generate electrical shocks, Walsh enlisted the aid of Dr. John Hunter, an English surgeon skilled in anatomy, to study the fine structure of the ray's electrical organs. Hunter found that these specialized organs make up about half of the ray's body and have a hefty nerve supply. They are composed of a large number of perpendicular columns, each made of many hexagonal discs separated from each other by a thin layer of fluid (Fig. 8.5). A small ray may possess about five hundred columns; a large one almost twelve hundred.

Knowing that the shocks originate only from this highly specialized organ was of considerable importance to Walsh. It meant that the charge somehow does not dissipate into surrounding tissues. The fact that the fish do not electrocute themselves meant that there must be some sort of insulation around the electric organs and the nerves associated with these specialized structures.

The Royal Society awarded the Copley Medal to Walsh for his outstanding work, but conservatives in the scientific establishment still expressed their doubts about the specialized fish. What these fish discharge may act like electricity and feel like electricity, they admitted, but is it really electricity?

The trouble was that the shocks from these creatures were not accompanied by flashes of light or popping sounds. Without a flash and a crackle, or at least something akin to lightning and thunder, many scientists remained unconvinced that these fish were really producing electricity. The fact that a charged ray or eel would fail to deflect pith balls hanging on strings or thin gold leaf (as do other electrically charged objects) made the doubting Thomases even more suspicious.

Ever hopeful of quieting his critics, John Walsh continued his experiments. His idea was to form a circuit from the fish to some onlookers using wire and tinfoil, and then to make a thin cut in the foil. At first, the electric spark did not jump the gap, in contrast to what Walsh had found when he used a fully charged Leyden jar. Still, he persevered and, by making a thinner cut in the tinfoil and working in a dark room, he showed that a discharge from an electric eel can produce a spark capable of jumping a small gap.

Unfortunately, Walsh died before he was able to publish the results of his crucial experiment. But in 1795, the year in which Walsh passed away, his most important experiment was described by Tiberius Cavallo, who witnessed the demonstration:
The strongest shocks of the _gymnopus_ will pass a very short interruption of continuity in the circuit. ... When the interruption is formed by the incision made by a penknife on a slip of tin-foil that is pasted on glass, and that slip is put into the circuit, the shock in passing through that interruption, will shew a small but vivid spark, plainly visible in a dark room.\(^{26}\)

There were fewer doubters about fish electricity once this experiment became known. Yet it was one thing to say that electricity from a specialized fish can produce an electrical shock, and quite another to conclude that frogs, barnyard animals, and even humans can also generate electricity. The ability to generalize from some unusual fish to other life forms was one of the issues foremost on people's minds when Luigi Galvani stepped out of obscurity.

**Galvani and His *Commentary***

Aloisio Luigi Galvani was born in 1737.\(^{27}\) He was a mild-tempered man, a good husband, and a kind doctor, who shied from publicity. He was also an honest, modest person, quite content to spend almost his whole life in one location, the northern Italian city of Bologna. Inclined at first to study theology, Galvani found anatomy, physiology, and medicine more to his liking. Before turning to the study of electricity, he worked on skeletal development, on the comparative anatomy of the ear, and in the field of obstetrics.

Galvani probably spent some time studying with Leopoldo Caldani, a Bolognese scientist who looked upon electricity as the strongest possible stimulus for animal tissue. He obtained degrees in medicine and philosophy and eventually took Caldani's place as professor of anatomy at the University of Bologna. Much of his own research, however, took place at his home. There Galvani kept many electrical devices, including machines for producing electricity by friction, primitive condensers, and Leyden jars. His primary subject was the frog, but he went on to experiment on sheep and even people. Among his assistants was his talented wife, Lucia Galeazzi, the daughter of his anatomy teacher.

From his notebooks, we know that Galvani began to experiment with the _fluido elettrico_ (electrical fluid) in the 1770s. Although he wrote four memoirs on his electrophysiological research during the 1780s, for unknown reasons he decided not to publish his findings at the time.\(^{28}\) The treatise that made Galvani famous was published in 1791. It was entitled _De viribus electricitatis in motu musculari commentarius_ (Commentary on the Effects of Electricity on Muscular Motion).\(^{29}\)

In his _Commentary_, Galvani traced his experiments in chronological order, explaining the logic behind each study and elaborating on the results. Here one can find the young scientist expressing surprise when an unexpected finding emerged and showing enthusiasm for new evidence to suggest that "animal electric fluid" does, in fact exist. Throughout the work Galvani strives for synthesis, never losing sight of the whole while assembling the parts.

Galvani tried to establish four points when he packaged his many experiments together. The first is that a frog muscle can be made to twitch when touched by a metal scalpel held by a person near an electrical machine shooting sparks. This strange event first occurred in a room where his assistants were amusing themselves with
one of his devices (Fig. 8.4). The apparatus threw a spark at precisely the same time that a scalpel in his hand touched a nerve leading to a frog’s leg muscle. It caused a quick contraction of the leg muscles that caught everyone off guard.

Galvani repeated the contraction-at-a-distance experiment and found that touching the nerve with a scalpel in the absence of a spark did nothing. These experiments showed that electricity could be conveyed through the human body (hardly a new finding) and that the exposed nerve of the frog could be activated with electricity to produce a seemingly natural muscle contraction (again, not particularly new). Galvani, however, went a step further. He emphasized that the muscle contraction occurred without the usual circuit involving direct contact with wires and machines. Without the closing of a circuit, he argued, the spark must have triggered natural electricity in the nerves themselves!

Galvani, impressed with his serendipitous finding, set forth to vary his basic experiment even more. The result was his second contention—a long wire can take the place of a person in the experiment. Moreover, it did not matter if living frogs were substituted for isolated nerves and muscles, or if sheep and chickens were substituted for frogs. The experiments failed only if his assistant cut the long wire or if the researchers tried to use nonconductors, such as silk or glass.

In Part II of his Commentary, Galvani described experiments with atmospheric electricity, some dating back to 1780. Studies with lightning rods attached to frog limbs led to his third major point—the muscles can be made to twitch even without man-made generators. Functionally, there is no difference between Nature’s own lightning and shocks from electrical machines; both are capable of stimulating frog legs. Energized by Benjamin Franklin’s famous kite experiments, Galvani seemed oblivious to the fact that lightning had killed a number of other foolhardy experimenters who set forth to study or capture it.
Galvani’s last finding was that two dissimilar metals making contact with a nerve attached to a muscle can make the muscle contract. He observed this when he used brass hooks to hang fresh frog legs and live frogs from the iron railings outside his house. His intent was to study how changes in atmospheric conditions could affect his preparations. He noticed that the frog legs moved not only when there were thunderstorms but also when the sky was cloudless. The contractions occurred more reliably when he deliberately pressed the brass hooks holding his specimens against the iron railings. Comparable experiments conducted inside his house had precisely the same effect, showing that it did not have to do with atmospheric electricity. Galvani then tried different metals and found that some combinations worked better than others, whereas using just a single metal had no effect at all.

Not all of the experiments described by Galvani were successful. In contrast to his work on the peripheral nerves and musculature, he was unable to get muscles to contract by stimulating the brain itself. In this he was not alone. But by 1803 Giovanni Aldini, his devoted nephew and a tireless coworker, had completed a number of successful experiments on the exposed brains of oxen. Aldini showed that he could produce movements of the eyelids, lips, and eyes. On an even more surrealistic note, he also collected fresh human heads at the base of the guillotine and found that he could evoke grimaces, jaw movements, and eye openings by passing current through the brain (Fig. 8.5).36

Galvani probably began his work with few preconceived notions, but he clearly developed a thesis as he progressed. In Part IV of his Commentary, he proposed that animal electricity is secreted by the brain and distributed through the inner core of the nerves to the muscles. The nerves, he explained, must have a fatty or oily covering, which prevents leakage of the electricity to surrounding tissues. His “proof” of this insulation came when he “distilled” a few nerves and obtained some droplets of oil. He further hypothesized that the nerves lose their insulation where they come in contact with the muscles. The muscles, in turn, receive and store the electricity like Leyden jars. Only when there is a proper trigger will there be a discharge.

FIGURE 8.5
A plate from Aldini showing experiments with electricity being performed on humans after decapitation.
Impact

Galvani’s landmark treatise of 1791 had a major impact on other scientists, even though some of his experiments and the very idea of animal electricity were not completely original. In retrospect, it was really Galvani’s planning, execution, and interpretation of a large number of experiments, rather than any one preparation, that commanded the attention of the scientific community. No one before him had brought such an array of experimental material into the arena. No one’s research was able to serve as such a stimulus for other physiologists and physicians to conduct their own studies. And no one had made a stronger case for the concept of intrinsic animal electricity in birds, tortoises, sheep, and even humans than did Luigi Galvani in 1791.

The theoretical jump to mammals now seemed complete. It began with the ancients discovering electric fish. It turned to frictional machines for producing electricity in the seventeenth century, was extended to atmospheric electricity by Franklin, and then was led back to electric fish by Walsh. Now, because of Galvani, many scientists saw animals without specialized electrical organs for shocking their prey operating by a subtle electrical force—one that could travel with incredible speed from the brain through insulated nerves.

Theories based on animal spirits, nerve fluids, or the idea of nerve vibrations were now discarded. Electricity, proclaimed by Galvani to be the true agent of nervous action, was by far a more plausible force. With electricity flowing through the nerves, scientists finally had an animating power that was natural, and one they could see, manipulate, and try to measure.

Johann Friedrich Blumenbach, a leading physiologist and anthropologist who worked in Göttingen, Germany, quickly recognized the importance of Galvani’s experiments and ideas. He contrasted them to the highly speculative ideas of nerve action proposed by Descartes and Willis in the previous century. In 1795 Blumenbach wrote the following about Galvani:

By the combined labours of experimental physiologists in different parts of the world, this branch of science was at length matured for giving birth to another discovery, which will probably be found of equal importance, in explaining the phenomena, and in removing the diseases of the animal system, with that which consigned to immortality the name of the illustrious Harvey. The discovery to which I wish at present to direct the attention of the reader is that of, what is usually called “animal electricity,” or, the existence and operation of a fluid extremely similar to electricity in the living animal system. For the fortunate Galvani, professor of anatomy at Bologna, was referred the honour of lighting by accident on this beautiful and divine discovery—a discovery which entitles its author to be ranked with the great promoters [of] science and the essential benefactors of man.32

Emil du Bois-Reymond, the leading neurophysiologist in the mid-nineteenth century, wrote that Galvani created a scientific storm, equaled only by the political upheavals occurring in Europe at the end of the eighteenth century.33 Tongue in cheek, he went on to express dread for the future of European frogs. With thousands
of zealous scientists out to catch, dismember, and electrify them, these once common and truly lovely creatures, he feared, would soon be headed for extinction.

As for practicing physicians, they increasingly believed that electricity was indeed the long-sought magic pill (The new theriae) that could cure just about any ailment. Galvani himself strongly advocated electrotherapy and, with his concept of animal electricity, found a way to explain seizures and other disorders of the nervous system.

Unfortunately, Galvani enjoyed little of the fame that followed the publication of his Commentary. He never recovered emotionally from his wife's death in 1791, the year in which the Commentary appeared. In addition, after Napoleon created the Cisalpine Republic in Italy, Galvani refused to take an oath of allegiance to the new state. As a result, he lost his appointments and affiliations in 1798. To make matters worse, another Italian, a man considered much more knowledgeable about physics and electricity than Galvani, was now assailing him and what he had to say.

The Fight with Volta

Alessandro Volta (Fig. 8.6) was born in the beautiful northern Italian town of Como in 1745. Attracted to the electrical sciences even before his eighteenth birthday, he was a skilful and imaginative physicist who paid attention to even the smallest details. Holding a chair at the University of Pavia, he was the acknowledged authority on electrical matters during the closing decades of the eighteenth century.

Volta replicated many of Galvani’s experiments and at first concluded that Galvani was a hero worthy of praise for his scientific acumen and conclusions. In 1792 he called his experiments “great” and “brilliant.” Soon afterward, however, he began to wonder whether Galvani was correct in his interpretations. The more Volta thought about it, the more he became convinced that elettricita metallica (electricity from two different metals) could explain practically all of Galvani’s findings.

By 1793 Volta’s short period of admiration for his compatriot had come to an end. He now voiced the opinion that Galvani’s experiments did not prove that elet-
tricità animale (intrinsic animal electricity) really existed. Electricity from the torpedo and other specialized fish was one thing. But electricity generated by frogs and mammals? This was unproved and probably nonsense. As far as he was concerned, Galvani and Aldini were only able to show that electricity can be a very powerful stimulus for nerves and muscles. They did not prove that muscles contract under natural conditions because of electricity intrinsic to the body.

Volta was correct in pointing out that many of Galvani’s preparations were flawed. Galvani, who hated controversy, understood what Volta was saying about experimental artifacts and did not deny that some of his findings could have resulted from his use of different metals. He therefore set forth to demonstrate the existence of animal electricity without using different metals. With Aldini to help, he designed several experiments to demonstrate that muscle contractions could be triggered with just one metal or, even better, no metals at all.35

In one such experiment, they dipped the end of a nerve and its detached leg muscle in mercury. They found that the nerve was still able to stimulate the isolated muscle, even though only a single metal was involved. In this case, the mercury could be no more than a conductor of electricity from one tissue to another.

Another important experiment was published as a supplement to a treatise that appeared in 1794. The name of the author was not given, but authorities are convinced that both the treatise and its supplement were written by Galvani, probably with the help of Aldini.36 The experimenter exposed a frog muscle and then cut the spinal cord. When the cut end of the spinal cord touched the muscle, there was a reliable twitch. No machines, scalpels, wire, mercury pools, or brass hooks were even involved.

In 1797 Galvani followed up on this experiment by showing that the nerve from the leg of one frog can stimulate a nerve in another frog’s leg and make a muscle contract. Here, he argued, was the best evidence yet for the thesis that animal electricity exists in more than specialized fish.

After Galvani died in 1798, Aldini, now a professor of physics at the University of Bologna, continued the fight to defend his uncle’s theory of animal electricity against Volta’s continued onslaughts.37 Given the evidence now favoring animal electricity, Volta should have thrown in the towel and not returned to the ring to fight another round. Unfortunately, his sharply worded criticisms, based on such things as imperceptible differences in the mercury pool or humidity factors, continued almost unabated. In all, Volta wrote twenty memoirs and many letters between 1793 and 1800, always insisting that frogs, sheep, and humans were not generators of electricity. For reasons of his own, he remained absolutely fixated on the idea that metals or extrinsic factors could account for what others were calling intrinsic animal electricity.

Well after the once-healthy scientific debate had degenerated into a heated brawl, Alexander von Humboldt, the dean of German science, entered the fray as an unbiased, independent judge. The originator of the term galvanism repeated many of Galvani’s experiments in Berlin, including the one in which he let a nerve drop on a muscle. He also designed several new studies. Humboldt’s conclusion, published in 1797, was that both animal electricity and bimetallic electricity are real phenomena.38 With his pronouncement, and with Volta now showing more willingness to compromise, the fight seemed over.
After inventing the "pile" (wet-cell battery), however, Volta returned to argue effectively against Galvani's assertion that electricity originates in the brain, travels through the nerves, and is stored in muscles.39 Without question, Volta's understanding of the production of electricity by dissimilar conductors (such as those in the specialized organs of electric fish) making contact was significant. But most important, and in terms of the bigger picture, after the Galvani-Volta debates had ended the life sciences would no longer be driven by the animal-spirits paradigm of the past.

From Therapy to Gothic Horror

Electrotherapy now advanced even more rapidly, stimulated by new experiments performed throughout Europe, claims of successful clinical trials, and new instruments. The logic was simple: Nerves are electrically excitable, and nervous energy is electrical. From these two premises, nervous diseases can be explained and treated as electrical breakdowns.

Predictably, many clinicians made exaggerated claims for the therapeutic benefits of electricity. Given what some scientists who worked with laboratory animals were telling them, this is somewhat understandable. At times, even the so-called scientific literature resembled a veritable fantasy land.

Perhaps the most bizarre example of this exuberance in the post-Galvani era can be found in the work of a German physician-scientist by the name of Karl August Weinhold.40 He was among the many experimenters who maintained that the brain was like a battery with attached wires. But unlike most of his learned contemporaries, he was driven to prove this hypothesis.

In 1817, Weinhold described his work on kittens. In one experiment, he removed the cerebrum and cerebellum of a kitten and claimed that he was able to revive the dead animal by filling the cranial cavity with different metals (bimetallic electricity):

I removed with a small spoon, through an opening at the back of the head, the cerebrum and cerebellum, as well as, by means of a screw probe, the spinal cord. After this, the animal lost all life, all sensory functions, voluntary muscle movement, and eventually its pulse. Afterward, I filled both cavities with the aforementioned amalgam [zinc and silver]. For almost 20 minutes, the animal got into such a life-tension that it raised its head, opened its eyes, stared for a time, tried to get into a crawling position, sank down again several times, nevertheless finally got up with obvious effort, hopped around, and then sank down exhausted. The heartbeat and the pulse, as well as the circulation, were quite active during these observations. . . . Also, body temperature was fully restored.41

Weinhold's exaggerated description of this unfortunate kitten, and several related experiments with metals replacing brain, could easily have come from an imaginative novelist. In fact, his narrative is in many ways like the famous gothic horror story written by nineteen-year-old Mary Shelley at almost the same time. Mary, Percy Shelley, Lord Byron, and Dr. John Polidori each agreed to make up a ghost story while spending some time near Geneva, Switzerland. Their nightly conversations covered terror, theories of the origin of life, and galvanism.

The Prometheus legends especially intrigued the members of this group. Indeed,
Byron had written his celebrated poem "Prometheus" in 1816. In the original Greek myth by Aeschylus, Prometheus gave mankind fire from the sun, for which he was severely punished by Zeus. In a second version, which was more popular in Rome, Prometheus re-created people by giving life to a clay figure. The two ideas were fused in the second or third century A.D. The result was a story about how Prometheus stole fire from the sun and then used it to give life to inanimate human forms.

Mary Shelley, who enjoyed the Prometheus myths, was also familiar with some of the medical developments involving galvanism. She and Percy read and discussed medical science books, and she had attended lectures by leading scientists. She also had extensive conversations with Dr. Polidori, who had recently obtained his medical degree from Edinburgh. Percy Shelley himself had studied chemistry before being expelled from Oxford. He once tried to cure his sister's skin disorder with electricity and, to his dismay, managed to electrocute the family cat in the process.

Mary Shelley published her novel in 1818. Because electricity replaced the sun as the life-giving source in Frankenstein, she gave it the subtitle The Modern Prometheus. Throughout the first edition, and even more in the second edition, dated 1831, there were allusions to electrical machines, lightning, and the remarkable powers of galvanism (Fig. 8.7).

In the preface to a revised version of Frankenstein, she told how the group's earlier conversations about galvanism helped her construct the story:

Many and long were the conversations between Lord Byron and [Percy] Shelley, to which I was a devout but nearly silent listener. During one of these, var-
ious philosophical doctrines were discussed, and among others the nature of the principle of life, and whether there was any probability of its ever being discovered and communicated. They talked of the experiments of Dr. [Erasimus] Darwin... Perhaps a corpse would be re-animated; galvanism had given a token of such things.44

Chapter 5 of her novel opens with the following chilling paragraph:

It was on a dreary night of November, that I beheld the accomplishment of my toils. With an anxiety that almost amounted to agony, I collected the instruments of life around me, that I might infuse the spark of being into the lifeless thing that lay at my feet. It was already one in the morning; the rain pattered dismally against the panes, and my candle was nearly burnt out, when, by the glimmer of the half-extinguished light, I saw the dull yellow eye of the creature open; it breathed hard, and a convulsive motion agitated its limbs.45

The difference between Mary Shelley and Karl August Weinhold is that Mary Shelley knew she was writing fiction about the powers of electricity. Weinhold, in contrast, was so caught up in the electrical frenzy that he actually believed he could replace the nervous system of a dead animal with dissimilar metals to do more than just elicit some movements; he was convinced he could restore life. In retrospect, it is clear that both writers were swept up in the spirit of the times and the excitement that followed in the wake of Galvani’s Commentary.

Back to Science

Animal electricity effectively gave birth to the modern discipline of neurophysiology and also had a profound influence on electrotherapy. Yet in a very real way, the ideas championed by Galvani, Aldini, and even Volta preceded the measuring instruments needed to verify them. This is why the scientific community was so excited during the 1840s and 1850s, when Emil du Bois-Reymond began to build recording instruments (galvanometers) sensitive enough to detect electrical changes in nerves, and when his close friend Hermann Helmholtz indirectly, but correctly, estimated the speed of nerve conduction.

But this is jumping ahead of other developments. Even before the first quarter of the nineteenth century was over, another idea emerged that proved just as stimulating to the scientific and medical community as electricity. Some scientists began to assert that different mental “faculties”—such as language, mathematics, and even love of offspring—are controlled by distinctly different parts of the gray mantle of the brain, the cerebral cortex.

To appreciate how different functions of mind were assigned to specific cortical territories, we must now travel to Vienna to meet Franz Joseph Gall. En route we shall come upon Emanuel Swedenborg, a brilliant man who just might have been the first scientist to write in detail about cortical localization of function, but who is not often remembered for any of his thoughts about the brain.