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René Descartes and the Birth of Neuroscience

Vaucanson's Duck

In 1738 the 29-year-old French watchmaker Jacques de Vaucanson exhibited in the garden of the Tuileries what may be one of the most celebrated robots of all time, a life-size mechanical duck that stood on an elaborate wooden base (figure 1.1). Largely covered with feathers, Vaucanson's automaton was almost indistinguishable from a real duck. When activated, the robotic duck raised its head, looked about, flapped its wings, and even ate from a bowl of grain. The food the duck ate was processed internally, pressed into pellets, and excreted. A feat that must have elicited cries of delight from the children in Vaucanson's audience. The duck performed all of these behaviors so precisely that audiences often refused to believe it was an artificial construct.

The production of this behavior, which would have been unremarkable in a real duck, was accomplished by a clockwork of springs, cams, and levers hidden in the robot. The duck was a machine in which the geometric interaction of carefully shaped pieces of metal, wood, and rubber produced a nearly perfect simulacrum of a predetermined fragment of normal duck behavior.

Vaucanson's duck raised for eighteenth-century audiences ancient questions that still haunt modern neuroscience: Are the mechanical interactions that occur inside each of us sufficient to generate the complex patterns of behavior that we actually produce? What is it that defines us as human beings, the complexity of the behavior that we produce or the specific patterns of interacting matter that appear to generate our behavior? Is there some property that lies beyond our current understand-

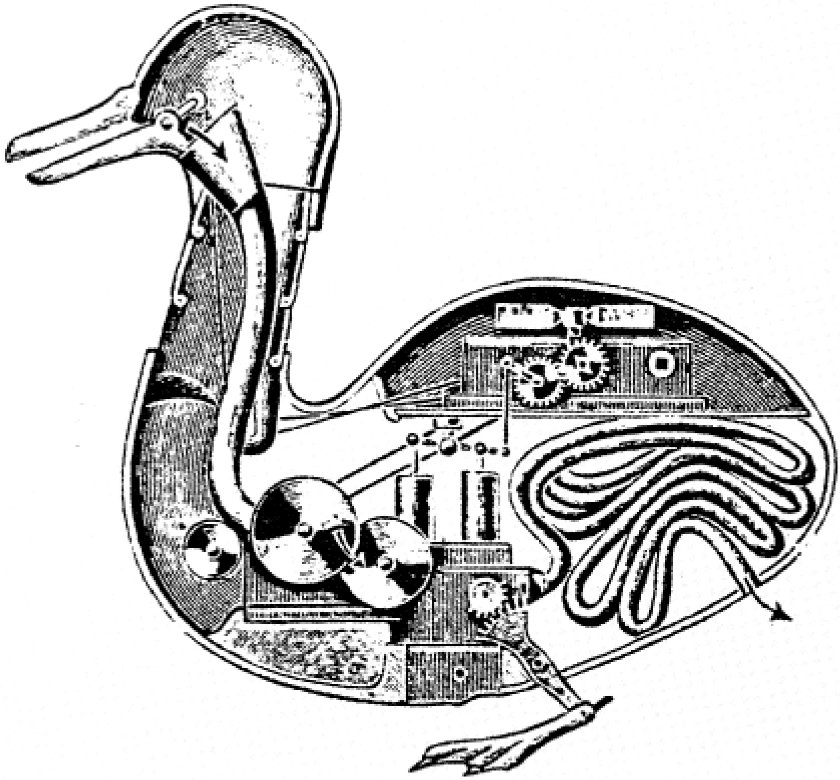

Figure 1.1
Vaucanson's duck (Eco and Zorzoli, *The Picture History of Inventions*. Macmillan, 1963).

ing of both behavior and causal material interactions which is critically responsible for the interaction of behavior, brain and mind?

Vaucanson's duck asks us to decide whether we can hope to understand human or animal brains by understanding the clockwork interplay of matter from which they are constructed. It asks us to decide whether any mechanical device could ever be used to understand how a real organism, like a duck, might actually work. Are physical principles enough, or does the essence of *duckishness* include some property that no machine or model, however complex, can ever capture?

Answering this question has been a central goal of neuroscience, psychology, philosophy, and even mathematics over the course of the last several centuries. Over the course of the period since about 1900, each of these disciplines has made enormous progress toward an answer. Today, one could even argue that there is surprising unanimity among mainstream scholars about how this question *should* be answered. But despite this unanimity, there is no certainty that the common answers to these questions are anything like correct.

Like many contemporary books in neuroscience, this volume is an attempt to develop, at a physiological level, answers to the question of how behavior, brain, and mind are related. To accomplish that goal, the book proceeds in two stages. First, it examines what we, as a scientific culture, believe today. How we came to our current synthetic view from a series of physiological and mathematical insights that have developed since the seventeenth century. The second half of the book provides an alternative to this current synthesis. It presents a viewpoint that has been gaining adherents since the 1990s among economists, psychologists, and neurobiologists who have begun to combine forces in order to explore a radically different model of how behavior, brain, and mind are related. This book is, in some sense, a manifesto for this alternative viewpoint, which is coming to be known as neuroeconomics. But before turning to that new synthesis, we begin by examining how our modern physiological views of behavior, brain, and mind evolved.

René Descartes

It is almost an axiom in scholarly circles that neuroscience, as we conceive of it today, began in the seventeenth century with the work of the French mathematician, philosopher, and physiologist René Descartes (figure 1.2). Descartes was born in 1596 in the town of La Haye, France, now known as Descartes. His family was of the minor nobility, and he was trained in the Jesuit educational system that dominated seventeenth-century ecclesiastic France, taking both a bachelor's and a law degree.

Descartes is probably best known today, three and a half centuries after his death in 1650, for his studies of metaphysics. His efforts to answer the question What is it that we can truly know about the universe? He answered that question with the famous Latinate assertion *Cogito ergo sum*, I think, therefore I am. For Descartes, this assertion seemed axiomatically true, and throughout his metaphysics he argued that any idea as clear and distinct as the *cogito* must also be true.

Figure 1.2
René Descartes (Hulton Archive, BE023664).

In addition to his study of metaphysics, Descartes was a mathematician at a time when proofs were still made geometrically. Arrangements of triangles were used to express theorems about ratios and square roots. Spirals were used to demonstrate the rates at which classes of numerical quantities increased. Descartes produced a number of geometric proofs of this kind. He was a creditable mathematician, inventing analytic algebra and producing a textbook on mathematics, among other accomplishments.

But it was as a physiologist that Descartes's work was most lastingly influential and unique. As we will see, his work as both a metaphysician and as a mathematician had led him to believe that almost any phenomenon in the physical world could be fully described in the simple geometric terms that described interacting physical processes. This led him to suggest mechanical explanations for even the most complex physiological events. It was in developing this line of thought that he was most revolutionary, because no one before Descartes had ever seriously proposed that phenomena as complex as behavior could be viewed as the product of purely physical interactions in physiological systems.

In the 1630s Descartes made this proposal explicit by describing a model of how physical interactions in the material world could give rise to humanlike behaviors. A linkage between behavior and a mechanical system of the type that Vaucanson would use to construct his duck a century later:

> I assume their body [the body of an imaginary creature similar in all ways to humans] to be but a statue, an earthen machine formed intentionally by God to be as much as possible like us. Thus not only does He give it externally the shapes and color of all the parts of our bodies; He also places inside it all the pieces required to make it walk, eat, breathe. (Descartes, 1664)

How could such a mechanical device ever hope to produce complex behavior if it could rely only on the geometric interactions of clockwork internal components?

> We see clocks, artificial fountains, mills, and similar machines which, though made entirely by man, lack not the power to move of themselves, in various ways. And I think that you will agree that the present machine could have even more sorts of movements than I have imagined and more ingenuity than I have assigned, for our supposition is that it was created by God.

Similarly you may have observed in the grottoes and fountains in the gardens of our kings that the force that makes water leap from its source [hydraulic pressure] is able of itself to move diverse machines and even to make them play instruments or pronounce certain words according to the various arrangements of the tubes through which the water is conducted. (Descartes, 1664)

Given then, that mechanical processes can in fact produce some kinds of behavior, what kinds of mechanical interactions would a model human employ?

And truly one can well compare the nerves of the machine that I am describing to the tubes of the mechanisms of these fountains, its muscles and tendons to divers other engines and springs which serve to move these machines, its animal spirits to the water which drives them, of which the heart is the source and the brain's cavity the water main. Moreover, breathing and other such actions which are ordinary and natural to it, and which depend on the flow of the spirits, are like the movements of a clock or mill which the ordinary flow of water can render continuous. External organs which merely by their presence act on the organs of sense and by this means force them to move in several different ways, depending on how the parts of the brain are arranged, are like strangers who, entering some of the grottoes of these fountains, unwittingly cause the movements that then occur, since they cannot enter without stepping on certain tiles so arranged that, for example, if they approach a Diana bathing they will cause her to hide in the reeds; and if they pass farther to pursue her they will cause a Neptune to advance and menace them with his trident; or if they go in another direction they will make a marine monster come out and spew water into their faces, or other such things according to the whims of the engineers who make them. (Descartes, 1664)

The material world was, Descartes argued, a spectacularly complex clockwork that could be studied, explained, and described by lawful physical principles. The material world could explain, at least in part, even the relationship between behavior and brain.

In the 1630s, when Descartes wrote those words, he was essentially alone in arguing that even aspects of human behavior could be the subject of physical study, but he was not alone in arguing for a scientific and material explanation of the universe. This was the end of a period during which a close-knit group of European scholars were working together to lay the foundation for our modern scientific view of the world. In particular, four Europeans working during this period were developing similar arguments about how we could study and understand the world around us. In England the philosopher and politician Francis Bacon was arguing for a concerted European effort to construct a logical and materialistic explanation for physical phenomena with an experimental method. The English physician William Harvey (who had briefly been Bacon's doctor) was applying this experimental approach to the study of a very specific physiological problem, the puzzle of why the blood is in constant motion. In Italy, the physicist Galileo Galilei was attempting to devise a systematic approach to physical phenomena observed in the heavens and on earth. Finally, in France and Holland, Descartes was attempting to bring all of these threads together in an effort to devise a new approach to the study of behavior, brain, and mind. All four of these men were struggling to give birth to what we think of today as science.

For them this struggle was taking place against the backdrop of medieval Scholasticism, an intellectual system that had dominated European thought for 500 years. In order to understand how much these four men, and Descartes in particular, accomplished for modern neuroscience, it is essential to understand the Scholastic tradition within which they were educated and which they worked so hard to change. The Scholastic tradition in physiology and medicine was a well developed and well codified body of knowledge. It represented the accumulated wisdom of the Greek and Roman cultures as translated and analyzed by generations of scholars. This tradition included clearly presented views on the relationship between behavior, brain, and mind. As educated men, Bacon, Harvey, Galileo, and Descartes would all have been intimately familiar with the writings of the great ancient authors, a familiarity that most scientists lack today. So in order to better understand what Descartes accomplished, we must first turn to the ancient physiologists whose studies defined the biomedical world Descartes inherited.

Understanding the Ancients

For a physician or physiologist working in Europe anytime between 1200 and 1600 there were a number of biomedical texts available: texts on the structure of the body and the brain, texts on the functions of organs, and texts on the treatment of disease. Almost all of these books were attributed to a single individual, the Roman physician Galen.

By the year 1000 Galen was, quite simply, the most influential biologist in the history of man, a position he retained until well into the eighteenth or nineteenth century. For a millennium, no European or Arab scholar could claim even a passing knowledge of physiology without having read Galen's books in detail.

Born in A.D. 129 or 130 in the town of Pergamum, Galen was educated in what was even then considered an ancient and classical medical tradition. A tradition rooted in the much earlier works of Hippocrates and, to a lesser extent, Plato. Galen completed his basic medical training at the age of 19. He had studied the works of the ancient authors and gained some valuable practical experience of medicine in Pergamum, but at that point he moved to Alexandria to pursue further study. In modern terms, he moved to Alexandria to pursue a fellowship in something like internal medicine.

In Galen's time, the second century, Alexandria was the seat of medical and academic scholarship. The famous library and eminent medical school there were without peer anywhere in the world. It contained manuscript copies of essentially every extant book, and one can only imagine the experience of a promising 19-year-old physician from the provinces who suddenly found himself among the entire accumulated medical knowledge of civilization. While in Alexandria, Galen had the opportunity to read medical books that had been written throughout the Roman Empire. He would have read ancient works, too, like the writings of Hippocrates and his colleagues; of famous challengers to the Hippocratic tradition; and of the modern supporters of both views. Galen probably read thousands of biomedical texts, texts that have almost all been lost in the intervening two millennia.

After 5 years at Alexandria, poring over the library's contents and studying with famous and influential physicians, Galen did what any conscientious young doctor would have done: He returned home to Pergamum. There he took up residence and received his first appointment, official surgeon to the Pergamum gladiators, a job that certainly must have provided steady work.

Galen's reputation as a learned physician grew in Pergamum, and at about the same time that Marcus Aurelius was crowned emperor

(A.D. 161), Galen decided to move to Rome, the administrative seat of the world. According to Galen's own reports, while living in Rome he lectured, demonstrated anatomical dissections, and proved himself a much more brilliant and thoughtful physiologist than any living member of the Roman medical establishment. Generally, he seems to have made an academic nuisance of himself. We know that much of this self-aggrandizement must be true; he obviously was well known and respected, because after only a few years in the city, he was appointed physician to the emperor. We also know that he made powerful enemies among the medical elite of Rome. Only 6 years after arriving, he was forced to flee Rome—as he tells the story—under cover of darkness, in order to evade his enemies. In 168 he was back in Pergamum.

But Galen was not to remain in Pergamum for long. A year later Marcus Aurelius recalled him to Rome by imperial order. And in the years that followed, he served as a physician and adviser to Aurelius and to Aurelius's son, Emperor Commodus.

Throughout all of these years, Galen wrote voluminously on subjects ranging from autobiography to practical philosophy, but he focused his efforts on analyzing and codifying the complete body of medical knowledge available to a physician of the emperor. His medical books served, and were meant to serve, as a complete distillation of the physiological knowledge of the world, a final common source for medicine. Of course achieving this level of coverage was not something that could be completed in a single volume. Galen wrote between 130 and 500 books during his life. (The exact number is hotly debated, but was probably much closer to 130 than to 500.) Unfortunately, only about 80 of Galen's books survive today.

Modern readers, perhaps surprisingly, find Galen quite readable. His writing reveals a physician who was arrogant, passionately judgmental, fantastically well read, and obviously brilliant. He rarely hesitates to provide us, his successors by almost 2000 years, with a clear insight into his character and his motivations. In his book *On the Passions*, for example, he admits (somewhat obliquely) to being both too passionate and too judgmental in his nature. In the second century he strikes a modern tone when he blames his mother for these qualities:

> Now, personally, I cannot say how I got my nature. It was, however, my great good fortune to have as my father a most good-tempered, just, efficient, and benevolent man. My mother, on the other hand, was so irascible that she would sometimes bite her serving-maids, and she was constantly shouting at my father and quarreling with him, worse than Xantippe with Socrates. (Galen, A)

For physicians and physiologists educated during the Scholastic period that followed, the two most important of Galen's books were probably *On the Usefulness of Parts* (Galen, B) and *On the Natural Faculties* (Galen, C). These are works with which Descartes was intimately familiar. In them Galen lays out a complete medical system, a theory of physiology. It was this system that became the de facto standard for medical belief and practice throughout the Middle Ages and into the Renaissance. Any physician educated in Europe or in the Arab world would have read every word of these two books in medical school, and perhaps dozens of other works by Galen. Being a doctor without knowing exactly what Galen had written about every organ and every disease would have been as unthinkable before 1800 as being a doctor without going to medical school would be today. In this way the medical world of Rome in the second century was projected forward as the unchallenged archive of all physiological knowledge.

The medical world of Galen was, therefore, the medical world of Europe throughout the Middle Ages and during the early Renaissance. And in that world, the fundamental tension that Vaucanson's duck would represent fifteen centuries later had already been the subject of debate for centuries. The Greek philosophers Epicurus and Democritus (whom even Galen would have considered Ancients) had argued that the world was composed entirely of matter and that causal interactions among this matter must, in principle, account for all physical events. Democritus's theory that all matter was composed of tiny, indivisible elements that he called *atoms* pertained as clearly to the human bodies of Galen's gladiators as it did to the stadiums in which they fought. Motion in matter is caused, Democritus and his colleagues proposed, when atoms collide with each other. These tiny mechanical interactions combine to yield all the material events that we observe in the world around us.

Democritus and his intellectual forebears had realized this raised an essential dilemma. If all the events that take place in the universe are the product of tiny particles colliding with each other according to simple physical laws, then the behavior each of us produces must also be the product of these tiny, lawful material collisions. Our own actions must therefore be *predetermined* by simple physical laws. What we will do in the future must be as determinate as the movement of a stone down a steep hill. And thus our own sense that human behavior is unpredictable, even volitional, must be no more than an illusion.

Plato's response to this line of argument, which was at least as well known to Galen as to any of us, was to argue that the world was much more than it seemed, that the true nature of the world existed on a metaphysical plane that our physical senses could not penetrate. We humans are all, Plato argued both to Galen and to us in the metaphor of the cave presented in his book *The Republic*, unable to perceive reality as it truly exists. Instead, the reality we see can be likened to the shadows cast on a wall by *true reality*. What seems to us to be the material world is simply a dim reflection of the true causal world. It is in that inaccessible true causal world that the real relationship between behavior and mind is forged.

Plato's views on this issue were not unchallenged in the ancient world. For Galen the most significant of these challenges came from his own hero, the fourth century B.C. physician and contemporary of Plato, Hippocrates. In Galen's time the writings of Hippocrates were almost 600 years old and had become the foundation of the corpus of Roman medicine. The views of Hippocrates were often challenged during Galen's life, but always taken very seriously. For Galen, the ideas of Hippocrates were almost without exception the final word in medical truth.

Unlike Plato, Hippocrates was a physician, and as a physician he recognized that, at least for some diseases, cause and effect can be deduced, and theoretical frameworks can be developed which explain physical phenomena in terms of simple materialistic causes. Seeking to reconcile the materialistic worldview of a physician with the notion that human behavior was unpredictable, and thus must reflect something more than simple material interactions, Hippocrates suggested a brilliant compromise. Humans were, he proposed, a combination of material and nonmaterial processes. The body itself was, he acknowledged, a physical object governed by the interaction of material components, but all of the body was in turn governed by a nonmaterial process, the soul.

For Galen, as the great interpreter and codifier of Hippocrates, bodies were complex physical machines. The actions of those machines reflected both material interactions and causal forces associated with the nonmaterial human soul. Physical diseases could reflect injury to either of these two processes: the material process of the body or the nonphysical process of the soul. Accordingly, Galen devoted his writing not only to a study of organ physiology but also to the study of human morality, because both of these domains could play critical roles in disease.

How could Galen explain the ability of these two disparate processes, the material body and the nonmaterial soul, to interact and produce behavior? The answer was that sensations gathered by the material body were passed to the nonmaterial soul for analysis. The soul then produced organized behavioral responses by activating the nerves and muscles of the body. For Galen the question of how these two processes interacted reduced to a question of *where*. Where was it that the soul interacted with the body to receive sensation and produce movement? Was the answer to this central question, as Aristotle had argued, that the heart served as the critical link between the material and nonmaterial properties of humans? Or was it, as Hippocrates had argued, the brain and spinal cord that linked behavior and mind?

In seeking an answer to that question, Galen describes what could be loosely called an experiment in his book, *On the Doctrines of Hippocrates and Plato* (Galen, D). You know when you go to a really important festival, Galen asks us, and they have plans to sacrifice a bull by cutting out its heart? You must have noticed that if the priests are really good, they get that heart out and onto the altar so fast that the heart still beats as it sits on the stone. Have you ever noticed what the bull is doing when this happens? You probably noticed that the bull, even when deprived of his heart, is still moving, even running around. Now how could that be the case if the source of all behavior, if the ability of the soul to elicit movement in the physical body, was resident in the heart? Once the link between mind and body had been broken by the removal of the heart, the body should have become immobile.

Now consider, he goes on, the kind of sacrifice in which the priests cut the spinal cord in the neck with a sword. You must have noticed that as the spinal cord is cut, the bull immediately drops to the ground, deprived of all power to move. The only explanation for this, Galen concludes, is that body and mind are linked thorough the organs of the brain and spinal cord. For Galen this largely resolved the question of how behavior and mind are related. They are related thorough the organ of the brain.

Galen goes on in this book, and in others, like his dissection guide *On Anatomical Procedures* (Galen, E), to further develop this theme. The soul must take physical residence in the brain, from whence it can receive sensations that are gathered by the sense organs and use that information to exert its will, via the spinal cord, on the muscles of the body. The soul does this by means of the pneuma. (The Greek word *pneuma* is strictly translated today as "breath," but even as recently as Descartes's time the function of respiration was unknown. For Galen, breath had more to do with a nonmaterial force or spirit that could play a causal role linking mind and body than it did with aerobic metabolism.) For Galen, then, the mind was a nonphysical process resident in the brain that, through the vehicle of the pneuma, actuated behavior. Mind and body are related because the mind receives sensory information from the body and in turn actuates the body's musculature.

Galen's work was monumental. And it would be fairly accurate to say that in the year 200 his books represented the accumulated anatomical and medical knowledge of human history. But with the rise of medieval Scholasticism his works became more than a compilation of existing knowledge. They became the unquestionable authority on all things medical.

The Scholastic period was marked by a turn away from direct observation and toward a study of *The Ancients*. The dominant view of this period was that the Greeks, and to a lesser extent the Romans, had gained an essentially complete knowledge of the universe. The goal of any scholar, therefore, was to attempt to recover that knowledge by a study of these ancient authors. This was as true for knowledge about mathematics or philosophy as it was for knowledge about medicine. Galen became the spokesman for The Ancients on all medical matters, and his writings became the definition of biomedical truth.

This shift toward the study of ancient sources, and the absolute belief in the infallibility of those sources, affected all areas of endeavor, but it had an enormous impact on medicine and physiology. During this period, Galen's work became *The Standard* for understanding physiology and thinking about how the mind and body were related. It was his notion that sensory data were passed to the nonmaterial mind, which then activated the material body that formed the core of neuroscience before Descartes.

The Renaissance

Almost a millennium after Galen, in the early twelfth century, the first hint of the upcoming Renaissance began to show itself in medical and physiological circles. At that time there were four major medical schools in Europe: Salerno and Bologna in Italy, and Paris and Montpellier in France. Manuscripts from those schools indicate that by the twelfth century a new practice entered medical education, the dissection of pigs. This was terribly important because it meant that the study of Galen's anatomical writings was being supplemented by the examination of actual bodies, albeit the bodies of pigs. To the best of our knowledge the first medical school dissection guide was produced around this time, the *Demonstratio Anatomica*, probably written in Salerno.

What is important to consider in thinking about these dissections is that it had been a millennium since the last formal dissections or experiments had been performed, during the Roman period. In the intervening centuries texts, not bodies, had been the source of all anatomical knowledge among medical professionals. But it is equally important to remember that these dissections in the twelfth century were not meant to challenge or test the authority of the Galenic texts; they were meant to serve as teaching tools. Challenging Galen's texts would have been unthinkable in the twelfth century. Were you, a medical student, to discover a discrepancy between the body of your pig and Galen's text, you would never have thought of this as a challenge to Galen's accuracy. Much more likely was the possibility that this reflected an error on your part, or at worst an error in the copying or translation of Galen.

By 1300, these dissections of pigs began to be supplemented by an even more audacious undertaking, the dissection of human cadavers. This probably began at the medical school in Bologna, but by the middle of the century had spread to all four of the great European medical schools. Ultimately, this kind of direct observation could only demonstrate the limitations and errors of Galen's texts, even though a direct challenge to Galen's authority was still hundreds of years off. But when that challenge came, it came suddenly and revolutionized Western medicine in a decade after a millennium of stability.

The critical step in challenging Galen's authority was the work of a Belgian-born physician, Andreas Vesalius (figure 1.3). Vesalius, like any academic physician of his period, had received a proper education in the classics and had an excellent knowledge of both Latin and Greek. Like all medical students, he was obliged to read Galen in incredible detail by his mentors, who included Jacobus Sylvius (for whom the cerebral aqueduct is named). In 1536, an outbreak of war caused Vesalius to return from Paris to his native Louvain, and there he procured his first corpse, which he apparently stole from an execution block along a roadside. Throughout the next year Vesalius conducted one or more anatomies (human dissections), demonstrating to medical observers in Louvain a level of manual skill in dissection that was widely acknowledged to be extraordinary. Over the course of the next 10 years or so, Vesalius continued to teach and dissect, and his teachings began to take on a clearly challenging tone with regard to the established doctrine of Galen's corpus. This series of challenges reached a head in 1543 when Vesalius published his great anatomical monograph, *De Humani Corporis Fabrica*, a book often referred to as the beginning of modern anatomical science.

In the *Fabrica*, Vesalius set out to offer an alternative to the medieval method of study and proposed directly that experimental anatomy was the only appropriate method for understanding the body. In the dedication of the *Fabrica* he wrote:

> I am aware that by reason of my age—I am at present 28 years old—my efforts will have little authority, and that, because of my frequent indication of the falsity of Galen's teachings, they [the books of the *Fabrica*] will find little shelter from the attacks of those who were not present at my anatomical dissections or have not themselves studied the subject sedulously; various schemes in defence of

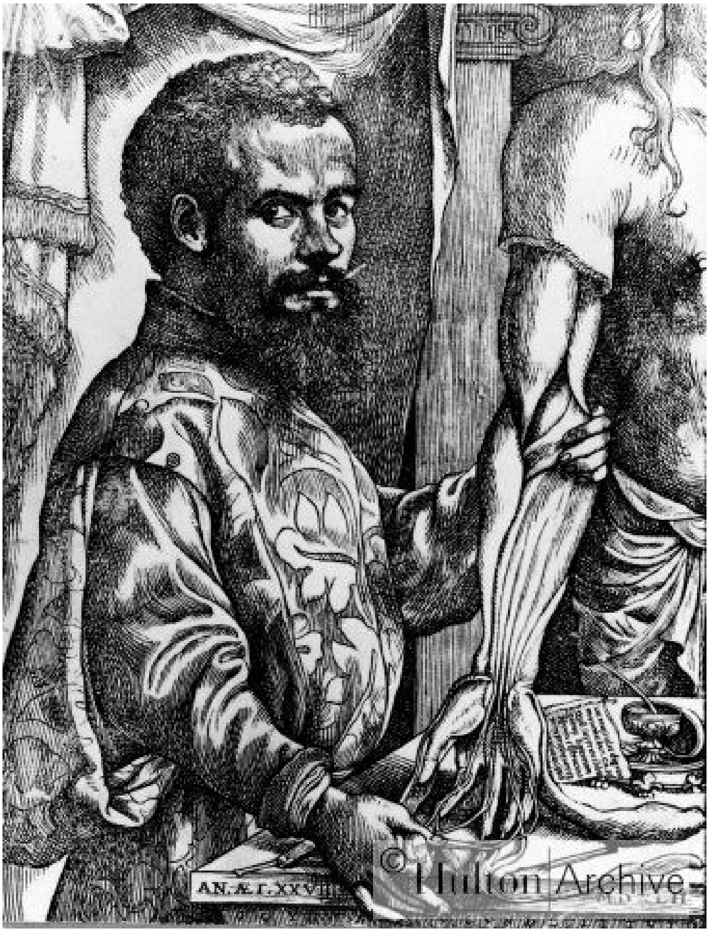

Figure 1.3
Andreas Vesalius (Octavio Digital Publishing's *De Humani Corporis Fabrica*).

Galen will be boldly invented unless these books appear with the auspicious commendation and great patronage of some divine power [Charles V, to whom the *Fabrica* was dedicated].

The preface continues in a similar manner:

that the detestable manner by which usually some conduct the dissection of the human body and others present the account of its parts, like latter day jackdaws aloft in their high chair, with egregious arrogance croaking things that they have never investigated but merely committed to memory from the books of others, or reading what has already been described. The former are so ignorant of languages that they are unable to explain their dissections to the spectators and muddle what ought to be displayed according to the instructions of the physician who, since he has never applied his hand to the dissection of the body, haughtily governs the ship from a manual. Thus everything is wrongly taught in the schools, and days are wasted in ridiculous questions that in such confusion less is presented to the spectators than a butcher in his stall could teach a physician. (Vesalius, 1543; O'Malley, 1964)

Vesalius's work is often cited as *the* defining moment that began modern biology. It was an effort that brought together the spirit of inquiry which characterized the Renaissance with a willingness to challenge authority, an approach that would come to define modern biomedical science. (In fact, the woodcuts for the *Fabrica* were most likely made in the Venetian painter Titian's workshop.)

The work of Vesalius and the other great sixteenth-century anatomists thus provided Descartes and his colleagues with two critical advances over their medieval forebears. First, the growing body of accurate anatomical knowledge that these physicians provided served as a starting point for a more modern and observationally based physiology. It became possible to use very precise anatomical data about the central nervous system to formulate theories about how behavior could be generated by living animals. Second, and perhaps more important, Vesalius made it possible to challenge the ideas of Galen and the ancient wisdom that he represented.

Francis Bacon

In Europe, the challenge to the scientific wisdom of the ancients was conducted simultaneously on several fronts. Perhaps the most theoretical and direct challenge was brought by the English nobleman and philosopher Francis Bacon. In many ways Bacon's challenge must have been an essential starting point for Descartes.

Bacon was, without a doubt, one of the great intellects of the seventeenth century. Over the course of a checkered career he served as a member of Parliament, Solicitor General, Attorney General, Lord Keeper, and Lord Chancellor, but all of this political accomplishment reflected an incredibly cynical nature. He was, by his own admission, a servile flatterer who probably was as comfortable taking bribes as offering them. In fact, after being created first Baron Verulam and later Viscount St. Albans, Bacon was convicted of bribery and sentenced to imprisonment in the Tower of London. He was released from the Tower after a brief imprisonment but was officially excluded from the verge of the court. This was an English sentence that prevented Bacon from placing himself within 12 miles of the official current residence of the sovereign, who was at that time James I. At a scholarly level this must have been an incredible problem for Bacon. James was almost always resident in London, and this would have prevented Bacon from entering any of the great libraries of that city.

Bacon's fame, at least among natural scientists working in the nineteenth and twentieth centuries, stems from his philosophical writings in general and from his most celebrated philosophical work, the *Novum Organum* (New Organ, 1620). The *Novum Organum*, as Bacon saw it, was a book designed to serve as a replacement for Aristotle's treatise on how knowledge could be acquired, a book known as the *Organum* in Latin. (Bacon, to be sure, never underestimated himself.)

Partly as a result of his conviction for bribery, and partly because he was not great at finishing huge undertakings, Bacon never really completed the *Novum Organum*, although he did finish and publish a significant portion of it. In fact, the *Novum Organum* was supposed to be only the first book of his larger work *The Great Instauration*, a six-volume series. Bacon had very high hopes for the *Instauration*, beginning it with the lines "Francis of Verulam [his latin nom de plume at the time] reasoning thus with himself came to this conclusion that the knowledge of his thoughts would be of advantage to present and future generations."

While the *Organum*, like Bacon, was in many ways deeply flawed, it was also very influential and really was one of the first books to expand on the idea that *experimental* science would be important for developing a deeper understanding of the natural world. This is an idea he presented clearly in the preface to *The Great Instauration*. It should be widely admitted, he argued,

That the sciences are in an unhappy state, and have made no great progress; and that a path must be opened to man's understanding entirely different from that known to men before us, and other means of assistance provided, so that the mind can exercise its rightful authority over the nature of things.

It should be said frankly that the wisdom which we imbibed principally from the Greeks seems merely the boyhood of knowledge, with the characteristics of boys, that it is good at chattering, but immature and unable to generate. For it is fruitful of controversies and barren of works.... In the same way also, the sciences as we know them have charming and fair seeming general features, but when it comes to details, down to the parts of generation as it were, where they should yield fruit and works, then arguments and barking disputations arise, and in these they terminate, and are all the issue they can yield.

Furthermore, if these sciences were not altogether defunct, what has been the case throughout the many ages now past could, it seems, hardly have come about, that they have stuck more or less motionless in their tracks and have made no advances worthy of mankind, often to the point where not only what was once asserted remains an assertion still, but where also a question once raised remains a question still, not answered by discussion but fixed and fed thereby.... In the mechanical arts, on the other hand, we see the opposite happening, for they grow and become more perfect by the day, as if partaking of some breath of life; and in the hands of their first authors they often appear crude and somewhat clumsy and shapeless, yet in the course of time they take on new powers and usefulness, to such a degree that men's eager pursuit of them ceases and turns to other things before these arts shall have reached the summit of their perfection. By contrast, philosophy and the intellectual sciences stand like statues, worshipped and celebrated, but not moved forward. In fact they sometimes flourish most under their first authors, only to decline thereafter. For when men ... have once surrendered their minds and have given their allegiance to the opinion of some man, they bring no enlargement to the sciences themselves, but merely act as servile functionaries and attendants to glorify certain authors....

Now what the sciences need is a form of induction that will analyze experience and take it apart, and through due exclusions and rejections necessarily come to a conclusion. And if that common art of logic and reasoning by induction involved so much labor and exercised such great intellects, how much more work is involved in this other method, which is drawn not only from the inner recesses of the mind, but also from the very bowels of Nature?...

To remedy these things, I have sought most carefully everywhere to find helps for the sense, and supply substitutes where it forsakes us, and correctives where it is at variance [with the truth]. *And I try to bring this about not so much with instruments as by experiments. For the subtlety of experiments is far greater than that of the sense itself, even though assisted by the most delicate of instruments* [my italics]. (I am speaking of those experiments that are skillfully and expertly thought out and framed for the purpose of the inquiry.) I do not therefore attach much importance to the immediate and natural perception of the sense; but I arrange it so that the sense judges only the experiment, the experiment the point in Nature. And for this reason I think that, as regards the sense (from which all knowledge of Nature must be sought, unless we wish to act like madmen), we stand before it as a priest of a religion and skillful interpreter of its oracles; and while others only profess to support and cultivate the sense, I do so in actual fact. These then are the preparations that I make for kindling and bringing to bear the light of Nature. (Bacon, 1620)

Bacon was an experimentalist arguing that ancient Scholastic beliefs should be discarded in favor of new ideas derived from experimental data. Historians often joke that this novel devotion to experiment ultimately cost Bacon his life. In March 1626, at the age of 65, Bacon was driving in his carriage north of London across a field of snow when he began to wonder whether snow would delay the putrefaction of flesh. Seized with a desire to examine this idea experimentally, Bacon purchased a chicken and stuffed it with snow. The story goes that while doing this, Bacon caught bronchitis (from the dead chicken, one wonders?) and died a month later.

William Harvey

The two people who went farthest in describing the new science that Bacon advocated were the famous Italian astronomer/physicist Galileo Galilei and the English physician William Harvey. In most essays on the experimental method, scholars proceed from this point to describe Galileo's science and his philosophy. Without a doubt, Galileo stands as the central figure in the general development of the scientific method because he gave birth to modern physics when he invented the scientific method used in physics today. In addition, Galileo was a prolific writer, and although his work can be hard for a modern scholar to read (fairly boring, actually), he did deal openly with major philosophical questions about the role of experiment and direct observation in the acquisition of knowledge. Finally, the fact that the Church charged Galileo with heresy for defending the intellectual results of his experiments after a long and very public trial, certainly does not hurt his modern reputation. (Although I am sure Galileo did not see any advantage in having to publicly recant his heretical beliefs and spend the end of his life under house arrest.)

From the point of view of physiology, however, Galileo's work was less significant than the work of William Harvey. At the same time that Galileo was advancing physics through observation and experiment, William Harvey was demonstrating that even the bodies of men could be studied and understood as material phenomena, using the new experimental approach that Bacon was championing.

One of the major physiological questions facing medical scientists in the middle of the seventeenth century was to understand the purpose and function of the heart and blood. In Harvey's day it was widely known that arteries pulsed, as did the heart, and that veins did not. Why did the heart and arteries pulse, and why was the pulse so absolutely critical for life? What function, if any, did the veins serve? Capillaries had not yet been discovered, so there appeared to be no connection between the arterial system and the venous system, although both were clearly connected with the heart. Finally, what role did the lungs play in relation to the heart? Great vessels connected the heart and lungs, but to what end? And how was all of this related to the breath, Galen's pneuma, which was also essential for life?

Before Harvey, efforts to answer these questions with anatomical study had proven largely fruitless. One could, for example, observe changes in the size of the heart during each beat, but what did that mean? Many of Harvey's colleagues had suggested that the expansion of the heart (what we would call the filling phase) was driven by an expansion of the blood itself when exposed to some factor that was present inside the heart. Descartes, who was writing at this time and who would later challenge Harvey directly on this point, argued that the heart played a central role in heating the blood. He argued that this heated blood then traveled through the arteries to heat the body. It was, however, William Harvey who realized that in order to solve this mystery, one would have to follow the advice of Francis Bacon and develop a set of experiments to test a series of hypotheses.

The passages that follow are taken from Harvey's masterwork, *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus* (An Anatomical Disquisition on the Motion of the Heart and Blood in Animals, 1628). In this book, which is actually quite short, Harvey describes a series of experiments, which he calls "demonstrations," by which he tests the hypothesis that the left side of the heart pumps blood into the arteries. That the blood flows through a theoretical construct we now call a capillary (which would be discovered decades later by Malpighi) to the veins. That the blood then flows slowly through the veins, which have valves to prevent backflow, to the right side of the heart. That the right side of the heart pumps blood to the lungs where it goes through a second set of capillaries (and is presumably exposed to some factor in the breath or air) and then enters the left side of the heart to repeat the process. The extract below details the experiment by which Harvey attempts to prove that the blood flows in only one direction through the veins. Of course this is critical to his overall argument and, just as important, it flies in the face of most accepted knowledge about the venous system (figure 1.4).

But that this truth may be made the more apparent, let an arm be tied up above the elbow as if for phlebotomy (A, A, fig. 1). At intervals in the course of the veins, especially in labouring people and those whose veins are large, certain knots or elevations (B, C, D, E, F) will be perceived, and this is not only at the places where the branch is received (E, F), but also where none enters (C, D): these knots or risings are all formed by valves, which thus show themselves externally. And now if you press the blood from the space above one of the valves, from H to O, (fig. 2) and keep the point of a finger upon the vein inferiorly, you will see no influx of blood from above; the portion of the vein between the point of the finger and the valve O will be obliterated; yet will the vessel continue sufficiently distended above that valve (O, G). The blood being thus pressed out, and the vein being emptied, if you now apply a finger of the other hand upon the distended part of the vein above the valve O, (fig 3.) and press downwards, you will find that you cannot force the blood through or beyond the valve; but the greater effort you use, you will only see the portion of the vein that is between the finger and the valve become more distended, that portion of the vein which is below the valve remaining all the while empty (H, O fig. 3).

It would therefore appear that the function of the valves in the veins is the same as that of the three sigmoid valves [in the heart] which we find at the commencement of the aorta and pulmonary artery, viz., to prevent all reflux of blood that is passing over them.

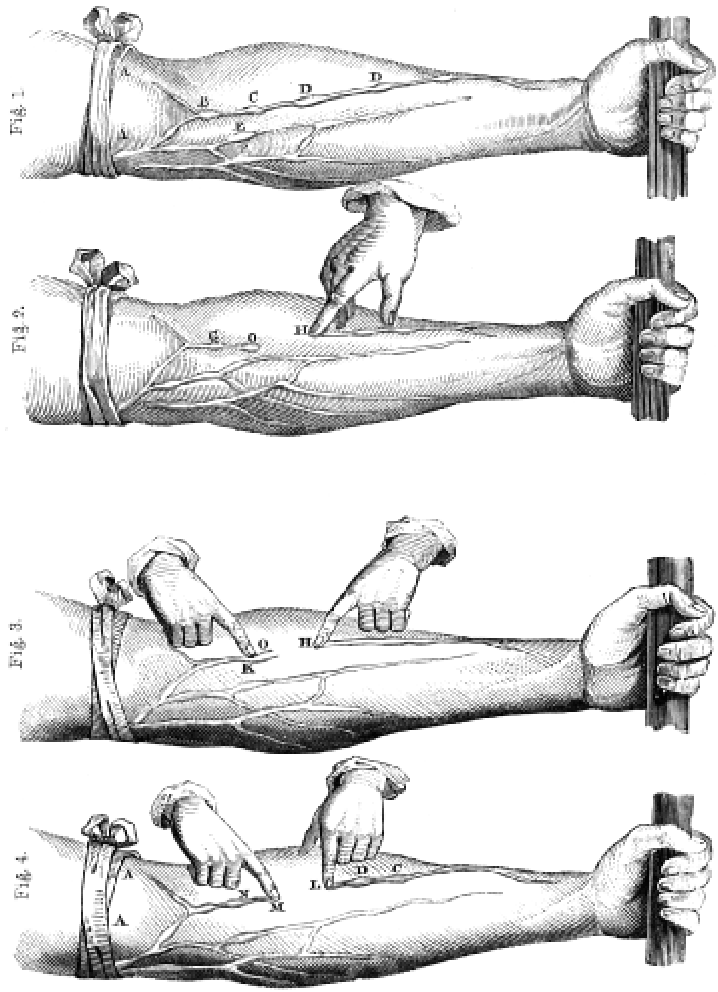

Figure 1.4
William Harvey's figures 1–4 (Octavio Digital Publishing's *Exercitatio Anatomica de Motu Cordis*). Note: Image above is from a later edition than the one reproduced in the Octavio edition. The image in the Octavio edition is much nicer.

That the blood in the veins therefore proceeds from the inferior or more remote to superior parts, and towards the heart, moving in these vessels and in this and not in the contrary direction, appears most obvious.

But this other circumstance has to be noted: The arm being bound, and the veins made turgid, and the valves prominent, as before, apply the thumb or finger over a vein in the situation of one of the valves in such a way as to compress it, and prevent any blood from passing upwards from the hand; then, with a finger of the other hand, streak the blood in the vein upwards till it has passed the next valve above, (N, fig. 4) the vessel now remains empty; but the finger at L being removed for an instant, the vein is immediately filled from below; apply the finger again, and having in the same manner streaked the blood upwards, again remove the finger below, and again the vessel becomes distended as before; and this repeat, say a thousand times, in a short space of time. And now compute the quantity of blood which you have thus pressed up beyond the valve, and then multiplying the assumed quantity by one thousand, you will find that so much blood has passed through a certain portion of the vessel; and I do now believe that you will find yourself convinced of the circulation of the blood and its rapid motion. (Harvey, 1628)

Most of the *De Motu* is devoted to a series of similar experiments that, together, are intended to prove Harvey's hypothesis that the heart circulates the blood through the vascular system. As a set of sequential experiments the book is overwhelmingly convincing; it is hard to imagine doubting the conclusions it presents. (Although Descartes seems to have been very pig-headed about this.) But as a philosophical work, many modern students find the book a bit disappointing. At each experiment, Harvey draws his conclusions but he never seems to draw attention to the fact that he is inventing a new way to do science. He never organizes the experiments clearly enough around the hypotheses they test, nor does he draw attention to the process of hypothesis testing around which the book is organized. He never draws any attention to the fact that he is changing more than cardiac physiology: that he is changing all of biology.

This may in part reflect Harvey's essentially conservative nature; he was, after all, a quintessential establishment figure. In London, Harvey served as physician to James I (the same king from whose court Bacon was excluded) and was a close friend to King Charles I after James's death. The execution of Charles at the end of the English Civil War came as a huge personal blow to the aging Harvey, and the radical government around Cromwell always distrusted Harvey because of his association with the monarchy.

Despite these setbacks, and Harvey's conservative nature, his work had an enormous impact on physiology and Harvey was quickly venerated as the leading biologist of his century. Busts of Harvey were placed in the Royal College of Physicians and elsewhere with inscriptions alluding to his divine nature and certain immortality. In short, Harvey came to define biological experimental science as we know it today.

There is, however, no escaping the fact that while Harvey was doing science, he was not writing like a modern physiological scientist. This may in some measure have precluded his approach to our problem of how mechanistic approaches to bodily functions could be reconciled with our perception that human behavior is fundamentally unpredictable.

Descartes's Synthesis

How can we reconcile Vaucanson's duck with our own sense of free will and the inescapable observation that so much of human behavior seems chaotic and unpredictable? The behavior of Vaucanson's duck is fully determined by its construction. Cams and levers interact; the mechanical laws of cause and effect dictate not just how the duck will behave in the next second, but how all of its behavior will be structured. If humans are just very complicated versions of Vaucanson's duck, as Democritus and his colleagues suggested, then all of our actions are predetermined, human unpredictability and free will are illusions, and in a moral sense no person can be held causally responsible for his or her actions. But what is the alternative? That nonmaterial events, events which lie outside the province of descriptive or experimental science, account for human behavior. That the tools of science that Galileo, Bacon, and Harvey were developing could *not* be applied to studies of how the mechanical hardware inside of humans and animals *makes* us behave. How, in short, can we hope to develop a truly scientific approach to behavior, brain, and mind, which seems to require a mechanistic approach, when free will and moral responsibility seem to require a nonscientific approach? Even Harvey had shied away from this problem.

Descartes, really quite brilliantly, thought of a solution to this dilemma by proposing a two-tiered system that would become the standard solution to the puzzle of behavior, brain, and mind for at least three centuries:

"These men will be composed, as we are, of a soul and a body; and I must first describe for you the body; then, also separately, the soul; and finally I must show you how these two natures would have to be joined and united to constitute men." With those words Descartes began his masterwork on the problem of how the neurobiological basis of behavior could be made the subject of scientific study, *L'Homme* (The Treatise on Man).

Descartes proposed that all observable human behavior could be divided into two categories, the simple and the complex. Simple behaviors were those in which a given sensation always, deterministically, produced the same behavioral response. Touching a man's foot with fire always causes him to withdraw the foot. This tight mechanistic linkage between sensation and action, Descartes argued, showed two things. First, that the behavior was entirely, or almost entirely, unaffected by free will. Second, that it had exactly the mechanistic properties which the emerging scientific method could engage. Complex behaviors, in contrast, were those in which the linkage between sensation and action was unpredictable and subject to the vagaries of volition. These behaviors, Descartes proposed, more nearly followed the Galenic model. They were produced when sensory data were transmitted from the nervous system to the nonmaterial soul, the soul made a decision about what course of action to undertake, and this volitional command was then passed to the machinery of the body for execution.

Descartes laid out this basic framework in a number of works, but he developed it most completely in *L'Homme* which was completed in 1637. *L'Homme* was written during the 1630s as the second section of a much larger work called *The World*. *The World* was to have been composed of two or three major portions: *The Treatise on Light*, *The Treatise on Man*, and perhaps his work *On the Soul*. Current evidence indicates that *Light* and *Man* were both completed in 1637; *Soul* may have been drafted at the same time and destroyed by Descartes. In any case, no copy of *On the Soul* exists today.

The 1630s were, however, not a very good decade for the emerging scientific method. In 1630 Galileo had published his masterwork, *Dialogo Sopra i Due Massimi Sistemi del Mondo, Tolemaico e Copernicano*, A Dialogue Concerning the Two Chief World Systems, Ptolemaic and

Copernican (Galilei, 1630). In that book Galileo had presented his voluminous evidence that the Earth, and the other planets, revolved around the sun. Six years earlier Galileo had traveled to Rome to discuss his Copernican views with Pope Urban VIII, who had been a friend and patron when he was still Cardinal Barberini. This was important because the Copernican system was controversial for two reasons. First, the Copernican system was a direct contradiction of the Scholastic Aristotelian tradition, a tradition in which the Earth lay immobile at the center of the universe and the bodies in the heavenly sphere circled around it. This was the wisdom of the Ancients. Second, the wisdom of the Ancients on this point was supported by Holy Scripture. The Bible distinctly describes the sun as *traveling across the heavens* from dawn to dusk in a number of places. In defense of both Aristotelian Scholasticism and Holy Scripture, the Vatican had ruled that the sun must circle the Earth.

In fairness, Urban found himself in a tough spot when he confronted his old friend Galileo, who was insisting that the Earth must circle the sun. The Counter-Reformation was in full swing as the cardinals and the pope tried desperately to defend themselves and the Church against the rapidly growing Protestant disciplines of northern Europe. Johannes Kepler, a German Protestant, had produced an elegant geometric system for describing the motions of the heavenly bodies that contradicted both the wisdom of The Ancients and Holy Scripture. Finally here was Urban's arrogant old friend Galileo presenting very compelling empirical evidence supporting Kepler's geometric presentation of the Copernican system as an accurate description of the true universe. After six audiences Urban and Galileo worked out an essential compromise. Galileo would have to accept that the Earth was the center of the universe; he could, however, as a purely hypothetical exercise, continue to work out his mathematical and empirical analyses of the Keplerian system. But it was to be understood that this was an intellectual endeavor only, not an effort to prove that Copernicus was right.

The product of this discussion, the *Dialogo*, presents the transcript of a fictional discussion, involving three friends, about the two world systems. Although the book does contain a preface stating that the work is purely hypothetical, nobody who has read the book can be in any doubt about what Galileo is attempting to prove. Galileo quite effectively demolishes the Ptolemaic system. Then, after demolishing this system, which he had promised Pope Urban VIII he would defend, the *Dialogo* gives the last word to the character charged with defending the Ptolomaic system, a character who has been unceremoniously named Simplicio. After having been humiliated and ridiculed throughout the book, Simplicio is permitted to say, as the book closes, "Well, it may look Copernican in every respect, but God can do whatever he wants and it ain't really Copernican at all." Suffice it to say that Urban was less than delighted with this, and Galileo, though in poor health, was immediately ordered to Rome to face the Inquisition. In a plea bargain, Galileo confessed to having overstated his case and to having inadvertently produced the appearance of heresy. The book was of course banned, and Galileo was placed under house arrest for the remainder of his life.

When news of this scientific debacle reached Descartes, a subject of His Most Catholic Majesty King Louis XIII (although Descartes was then resident in Holland), he made the only rational decision that he could, and decided to suppress *The World* rather than risk the Inquisition. As a result *L'Homme* was not published in complete form until 1664, 14 years after Descartes's death. Descartes probably made the right decision. In 1667 the Church placed all of Descartes's works on the Index of Forbidden Books.

Even though *L'Homme* did not reach the press until the 1660s, the effect of this book and of a closely related book, *Les Passions de l'Ame* (The Passions of the Soul, 1649) was enormous. In these books Descartes argued that the essentially dual nature of human behavior permitted a wide range of physiological investigations into the relationship between behavior, brain, and mind. Like Epicurus, Descartes argued that the brain was an organ which existed within the material world. Many classes of behaviors were the deterministic product of this organ acting alone. The scientific method could always be used to explain these simple deterministic behaviors. But like Galen, Descartes argued that human behavior was also the product of the nonmaterial soul. That it was the complex, unpredictable, nondeterministic behaviors which were the product of this nonphysical organ. In studying these behaviors one had to be content, as Galen had been, with identifying the brain locus at which the soul exerted its effects on the brain and the body. Descartes even carried this Galenic notion inside the brain, arguing that the site of this interface was the pineal gland.

Descartes's dualism was thus *the* critical conceptual advance that permitted physiological studies of behavior to begin. Based upon the Cartesian dualist formula, simple deterministic behaviors would become the province of purely physiological study: Whenever a stimulus always produced a fixed behavioral response in a man or animal, then the deterministic material approach of science could be used to understand how the clockwork of the brain generated that behavior. But the dualist approach also recognized that unpredictable and nondeterministic behaviors did exist, and that the clockwork scientific explanations available to seventeenth-century scientists could not hope to mechanistically explain those behaviors. Complex and unpredictable behaviors would remain the province of philosophers, inaccessible to physiological study because these behaviors were the product of processes that resided outside the physical world within which physiologists could construct experiments.

Vaucanson's mechanical duck challenged his eighteenth-century audiences to decide whether a real duck was more than an assemblage of mechanical components that produced ducklike behavior. For the philosophers in Vaucanson's audience, who lived in a post–Cartesian world, the answer to that question was both yes and no. For many simple behaviors, the mechanical duck and a real duck were very much the same at a philosophical level. Both were causal deterministic machines that yielded predictable behavior. But for these post–Cartesians some portion of a real duck was also much more. The apparent ability of the real duck to behave unpredictably was evidence that a nonmaterial process, which lay outside the province of science, was also, at least occasionally, at work.