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The Newtonian Achievement

The Newtonian Revolution

I. Bernard Cohen

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Editor's Introduction

The figure of Isaac Newton towers over early modern science. Recent scholarship has drawn our attention to the extraordinary range of his intellectual pursuits. For example, Newton spent more time in theological investigations than on mathematics and physics. Important research has also shown that activities which historians long dismissed as embarrassing aberrations, such as Newton's alchemy, were integral to his physics; his view of matter was strongly influenced by his alchemical thought.

But the fact remains that it is not his theology or alchemy that secured Newton's legacy, but rather his contribution to mathematics and physics. In this piece taken from a larger work on the concept of revolution in science, I. Bernard Cohen – one of the most important Newton scholars of the twentieth century and, like Hooykaas, a member of the first generation of academic historians of science – describes Newton as the apex of the Scientific Revolution and enumerates his contributions. Cohen rejects the often-repeated view that Newton synthesized the work of his predecessors. In fact Newton cleared away layers of error, not just of the ancients, but of earlier seventeenth-century figures such as Kepler, Galileo, and Descartes. His work was much more than a mere synthesis.

Just as importantly, Cohen attempts to identify what it was about Newton's method that allowed him to achieve so much; this he terms Newton's style. Many scholars have noted that the title of Newton's most important work, *Mathematical Principles of Natural Philosophy*, was unusual for the times. We saw in Westman that there was a fundamental distinction between mathematics and natural philosophy, yet here was Newton doing natural philosophy through

mathematics. Cohen describes here how Newton approached natural philosophy through mathematics in an entirely novel way.

Cohen argues that Newton's style is responsible for the magnitude of his accomplishments. It may seem paradoxical to us that Newton's greatest achievement, his theory of universal gravity, was greeted with profound skepticism by many of his contemporaries. For them natural philosophy identified causes. Mechanical philosophers such as the followers of Descartes insisted that true natural philosophy must provide a mechanical account of natural phenomena. They claimed that Newton's "force" of gravity was no different from the magicians' sympathies. Newton, however, refused to be drawn on what gravity actually was: "Hypotheses non fingo" (I do not fashion hypotheses), he famously stated. What enabled Newton to avoid getting bogged down in questions of what gravity was? Cohen suggests it was his approach to natural philosophy that began with mathematics, not with a preconceived natural philosophy. Newton began with a mathematical construct, a system of moving points devoid of matter. He then added mass to the points whose only attributes were that they attracted each other and determined that the points must move in elliptical orbit. He then compared his system to the real world and saw that his system accurately accounted for the real world. This alternation between mathematical construct and comparison with the real world was the essence of Newton's style. Rather than beginning with an attempt to explain what gravity is, Newton concluded simply that it must exist as this assumption predicted the real motions of the planets so accurately.

The Newtonian Revolution

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The Newtonian revolution differs from those other revolutions (actual or alleged) in science and in mathematics which we have been considering in that Newton was said in his own lifetime to have created a revolution. He was recognized by his contemporaries for the revolution of the calculus and for a revolution in the science of mechanics created by his *Philosophiae Naturalis Principia Mathematica*. From a historical vantage point, Newton was an extraordinary figure because he made so many fundamental contributions to different fields: pure and applied mathematics; optics and the theory of light and colors; design of scientific instruments; codification of dynamics and formulation of the basic concepts of this subject; invention of the primary concept of physical science (mass); invention of the concept and law of universal gravity and its elaboration into a new system of the universe gravity; invention of the gravitational theory of tides; and formulation of the new methodology of science. He also worked on heat, the chemistry and theory of matter, alchemy, chronology, interpretation of Scripture, and other topics. The range of his intellectual career never ceases to astonish.

The Newtonian revolution in mathematics had two aspects: the invention of the calculus (an honor he shares with Leibniz) and the application of mathematics to physics and astronomy. It was the latter which produced the Newtonian revolution in science (as opposed to a revolution in mathematics). Of course, Newton had great predecessors in the art of developing natural philosophy by mathematical principles: Stevin, Galileo, Kepler, Wallis, Hooke, Huygens. In this sense the Newtonian revolution in science was the culmination of a multiauthored effort, going back to the beginning of the Scientific Revolution, rather than the creation by Newton of something wholly new. Yet the simplest comparison of Newton's *Principia* with Kepler's *Astronomia Nova*, Galileo's *Two New Sciences*, Wallis's *Mechanics*, Hooke's writings on motion, or the treatment of accelerated motions in Huygens's treatise on the pendulum clock shows a difference of several orders of magnitude in depth, scope, and technique. It is because of the size of this quantum jump that Newton's *Principia* is the "epoch" (as Clairaut said in 1747) of a "revolution in physical science."

It is sometimes alleged that Newton created a synthesis, presumably putting together disparate ideas or principles of such scientists as Kepler, Galileo, or Hooke. But Newton's revolutionary science was hardly a melding or assembling of such ideas or principles, since in actual fact Newton's *Principia* declared their falsity. Surely a 'true' science cannot result from a mere amal-

gamation of false ideas and principles. Among such notions whose falsity is exhibited by Newton in the *Principia* are the following:

Kepler: the three planetary laws are "true" descriptions of the motion of the planets; a solar force exerted on those bodies diminishes directly as the distance and acts only in or near the plane of the ecliptic; the sun must be a huge magnet; because of its "natural inertia," a moving body will come to rest whenever the motive force ceases to act.

Descartes: the planets are carried around by a sea of aether moving in huge vortices; atoms do not (cannot) exist, and there is no vacuum or void space.

Galileo: the acceleration of bodies falling toward the earth is constant at all distances, even as far out as the moon; the moon cannot possibly have any influence on (or be the cause of) the tides in the sea.

Hooke: the centripetal inverse-square force acting on a body (with a component of inertial motion) produces orbital motion with a speed inversely proportional to the distance from the center of force: this speed law is consistent with Kepler's area law.

We may further observe that Newton also denied the existence of 'centrifugal' forces, which were basic to the development of Huygens's physics of motion. In their place Newton introduced a concept of 'centripetal' force, a name he chose because it was similar – though opposite in sense or direction – to Huygens's 'vis centrifuga'.

Comparison and contrast of Newton's *Principles of Philosophy* (the name he often used to refer to his book) and Descartes's *Principles of Philosophy* show the nature of the Newtonian revolution. For the critical reader one of the extraordinary aspects of Descartes's *Principles* is that it is devoid of mathematics, being largely devoted to philosophy and to philosophical principles of physics or natural philosophy. Only two of the four Parts deal with physics proper and the development of the cosmic system of vortices. Here Descartes does set forth the quantitative rules for impact which we have seen to be wrong in each example. Descartes included these rules as a subset of his third law of nature. But when Wallis published the true rules in the *Philosophical Transactions of the Royal Society*,[1] they bore the more restricted and more correct title of "Laws of Motion." Newton began his *Principles of Philosophy* with a set of "definitions" followed by "axioms or laws of motion," of which the first two correspond roughly to Descartes's first two laws of nature. Newton seems to have transformed the Cartesian "regulae quaedam sive leges naturae" into his own "axiomata sive leges motus." Newton's three laws of motion, the axioms to which he reduced the system of rational mechanics, were: (1) the principle

1 They were found independently also by Wren and Huygens (see Dugas 1955, ch. 5).

of inertia, that a body will persevere in its state of rest or of uniform motion straight forward unless acted on by an external force; (2) the relation of a force to its dynamical effect, that an impulsive (or continuous) external force produces a change (change in a unit time for a continuous force) in the momentum of a body in the direction of action of the force; (3) the equality of action and reaction.

Newton also transformed Descartes's title of *Principia Philosphiae* into *Philosophiae naturalis Principia mathematica*, thus boasting that in mathematicizing the principles he had constructed a natural philosophy rather than a general philosophy. Newton's *Principia* is not only mathematical in the development of the principles and in the proofs and applications of the propositions; it also sets forth a significant new mode of using mathematics in natural philosophy.

Newton's *Principia* is a remarkable book on many levels. It contains original results in pure mathematics (theory of limits and geometry of conic sections), it develops the primary concepts of dynamics (mass, momentum, force), it codifies the principles of dynamics (three laws of motion), and it shows the dynamical significance of Kepler's three laws of planetary motion and of Galileo's experimental conclusion that bodies with unequal weights will fall freely (at the same place on earth) with identical accelerations and speeds. It develops the laws of curved motions, the analysis of pendulums, and the nature of motions constrained to surfaces, and it shows how to deal with the motion of particles in continually varying force fields. Newton also indicates the way to analyze wave motions, and he explores the manner in which bodies move in various resisting mediums. The crown of all appears in the final book 3, in which he discloses the Newtonian system of the universe – regulated by gravity, by the action of a general force, of which one particular manifestation is the familiar terrestrial weight. Here Newton treats at length of the orbits of planets and their satellites, the motions and paths of comets, and the production of tides in the sea.

As an example of the new level of thought in the *Principia*, consider the motion of the moon with its apparent irregularities. For a millennium and a half, astronomers had dealt with the moon's motion by constructing geometric schemes without reference to cause. Now, Newton showed that the chief source of the 'lunar inequalities' was the phenomenon of perturbation, chiefly the result of the gravitational action of the sun as well as of the earth on the moon. With the publication of the *Principia* in 1687, it became possible to deal with this problem by starting from first principles or causes and then studying the effects. As a reviewer of the second edition of the *Prinicipia* observed, this was entirely a new way to deal with the problem.[2]

2 Newton, in fact, was not able to carry out this program fully, although he claimed to have done so. He was really successful only in accounting for what is called the variation and the nodal motion (see Cohen 1980, 76–77; Waff 1975; Chandler 1975). The review appeared in the Berlin *Acta Eruditorum*.

Perhaps the greatest triumph of all was the explanation that tides are caused by the gravitational pull of the sun and moon on the seas. "The ebb and flow of the sea," Newton declared (in bk. 3, prop. 24). "arise from the actions of the sun and moon." The magnitude of his achievement is shown by his prediction of the oblate shape of the earth on the basis of his analysis of precession and the nonsymmetrical pull of the moon on the earth's supposed equatorial bulge.

Some analysts would see the greatness of the *Principia* expressed in the commitment to an inertial physics; for Newton inertia is a property of mass. Newton is the first writer to make a clear distinction between mass and weight and to recognize, furthermore, that a body's mass has two separate and distinct aspects. Mass is a measure of the body's resistance to being accelerated or undergoing a change in its state of motion or of rest; this is its inertia. (Newton sometimes used the term 'force of inertia' or 'vis inertiae' – but this type of force differs from forces that are 'active' and that can produce accelerations.) But a body's mass is also a measure of the body's response to a given gravitational field. But why should there be a relation between a body's (inertial) resistance to acceleration and its (gravitational) response to a gravitational field? In classical physics there is no reason. Newton had the insight to recognize that this relation must rest on the foundation of experiment, and so he proceeded to prove by experiment this constancy between inertia and gravity. It is only in Einstein's relativity theory that there is a logical necessity for this equivalence of 'inertial' mass and 'gravitational' mass. Einstein greatly admired Newton for having had so deep an insight into this problem and for having recognized that the only Newtonian grounds for this equivalence were experimental.

The nature of the mathematics in Newton's *Principia* is often misunderstood. A superficial turning of the pages gives the impression that the mathematics used by Newton is geometry, particularly Greek geometry. The style seems to be that of Euclid or Apollonius. But a closer examination shows that Newton is developing the subject by the calculus, by stating relations geometrically in ratios and proportions and at once considering the 'limit' as a fundamental quantity vanishes (or is nascent). Hence, although Newton does not develop an algorithm of the calculus (or 'fluxions') which he then applies systematically, he does make extensive use of limiting procedures which are clearly equivalent to using the calculus or which can readily be translated into the symbolism of either the Newtonian or the Leibnizian algorithm. Recognizing this aspect of the *Principia*, the Marquis de l'Hôpital observed (as Newton proudly noted) that the mathematics of the book is almost entirely the calculus. This would be further evident to any careful reader from the development of the theory of limits in section 1 of book 1 and from the explicit theory of fluxions (the Newtonian version of the differential calculus) in section 2 of book 2. Additionally, the *Principia* was notable for other original uses of mathematics such as the extensive use of infinite series.

Newton's Style

The essence of Newton's revolutionary science, as I see it, is to be found in what I have called the 'Newtonian style'. This can be seen most easily in Newton's treatment of Kepler's laws in the *Principia*.[3] Newton begins with a purely mathematical construct or imagined system – not merely a case of nature simplified but a wholly invented system of the sort that does not exist in the real world at all. Here by 'real' world is meant only the external world as revealed by experiment and observation. In this system or construct, a single mass-point moves about a center of force. Newton shows by mathematics (bk. 1, prop. 1) that if in this construct or system a force is constantly directed from the orbiting mass point or particle to the immobile center of force, then Kepler's law of areas (his second law) will hold. He next proves the converse (prop. 3), that if the law of areas holds there must be such a centripetal or centrally directed force. Hence the existence of a centripetal force is proved to be both a necessary and sufficient condition for Kepler's law of areas. Then Newton shows that if the orbit is an ellipse, the central force must vary inversely as the square of the distance. Finally he proves that if under such a condition of force there are several orbiting mass points, which do not interact with each other – or (what comes to the same thing) if the motion of any given mass point is compared with what its motion would be at a somewhat different distance from the center – then Kepler's third or harmonic law will hold. Incidentally, we may observe that Newton has shown here for the first time the dynamical significance of each of Kepler's laws. Newton's procedure thus far constitutes a purely mathematical phase one.

In phase two, Newton compares his mental construct with the real world. At once, of course, he discovers that in the real world (for instance, in our solar system), orbiting bodies do not move about 'mathematical' centers of force but about other real bodies. The moon moves around the earth; the earth and the other planets move around the sun. Accordingly, in order to bring his mental construct or imagined system more into harmony with the real world, Newton modifies the system so that there are now two mass points. One is at the center and attracts the one which is moving in orbit, constantly drawing it away from its otherwise rectilinear inertial path. But according to the principle that to every action there must be an equal and opposite reaction (Newton's third law of motion), it follows that if the central body attracts the orbiting body, then the orbiting body must also attract the central body. Hence

3 This presentation of Newton's development of the law of universal gravity is an abridgment of the fuller presentation given in my *Newtonian Revolution* (1980), §§5.4–5.6. Here there may be found also an exposition of the stages of transformation of the concept of inertia leading to Newton's first law of motion.

the mental construct becomes enlarged to a system of two interacting bodies. Newton proceeds to show that under these circumstances the orbiting body does not any longer move in a simple ellipse around the central body at a focus; rather, he finds that both will move in ellipses around their common center of gravity.

This two-body system constitutes a modified phase one in which Newton once again develops mathematically the properties of his (now revised) mental construct. He next compares the modified system with the external world, a modified phase two. Of course, he finds that this system also does not conform to the real world around us. For instance, in our solar system there is not just a single planet moving around the sun but several. Accordingly, to make his mental construct conform more closely to the system of the external world, Newton moves onto yet another phase one. He introduces two or more mass points orbiting about the central mass point, not just one. It follows, again as a result of the application of Newton's third law, that each of these orbiting mass points both is attracted by the central body and attracts it. In other words, a consequence is that each orbiting mass point is both a body that can be attracted and a center of attractive force. Each of these orbiting bodies will act upon and be acted upon by every other orbiting body. The system contains bodies which act by perturbations on one another, and these perturbations produce a slight departure from Kepler's laws. Newton then proceeds to find the quantitative measure of the deviation from Kepler's laws in our solar system.

In this kind of contrapuntal alternation between mathematical constructs and comparisons with the real world, between a phase one and a phase two, Newton advances from a one-body system not only to a many-body system but also to a system of orbiting bodies which have satellites, such as the moons of the earth, Saturn, and Jupiter. Thus far he has been considering mass points rather than physical bodies, because he has not yet introduced considerations of size and shape, but eventually he shifts the level of discussion from mass points to physical bodies with significant dimensions and figures.

The progression I have described is not merely a twentieth-century after-the-fact analysis of the way Newton presents his subject in the *Principia*. It also corresponds to the documented stages of development of Newton's ideas.[4] In the autumn of 1684 Newton wrote a tract (*De Motu*) in which he presented the results of his study of Kepler's laws and other aspects of the subject. There he shows that a central force is a necessary and sufficient con-

4 I assume here, in the absence of any contradictory evidence, that in the successive versions of his preliminary tract *De Motu* and in the *Principia*, Newton was presenting his ideas and results more or less in the logical-chronological order in which he had developed them. See Cohen 1980, 248ff., 258ff.

dition for the law of areas, and that an elliptical orbit implies that the force varies as the inverse square of the distance, much as in the later *Principia*. But he has not as yet recognized that his proofs apply only to a mental construct of a one-body system and so he proudly writes: "Scholium: Therefore the major planets revolve in ellipses having a focus in the center of the sun and by radii drawn [from the planets] to the sun describe areas proportional to the times, entirely as Kepler supposed." Before long Newton realized that the planets cannot in fact move in simple Keplerian elliptical orbits. He saw that his results apply only to an artificial one-body system in which the earth is reduced to a mass point and the sun to an immobile center of force.

In December 1684 Newton completed a revised draft of *De Motu* that describes planetary motion in the context of an interactive many-body system. Unlike the earlier draft, the revised one concludes that "the planets neither move exactly in ellipses nor revolve twice in the same orbit." This conclusion led Newton to the following result:

> There are as many orbits to each planet as it has revolutions, as in the motion of the Moon, and each orbit depends on the combined motions of all the planets, not to mention the actions of all these on one another . . . To consider simultaneously the causes of so many motions and to define the motions themselves by exact laws allowing of convenient calculation exceeds, unless I am mistaken, the power of the entire human intellect.

Newton had come to perceive that the planets act gravitationally on one another. The passage cited above expresses this perception in unambiguous language: "eorum omnium actiones in se invicem" (the actions of all of them on one another). A consequence of this mutual gravitational attraction is that all three of Kepler's laws are not strictly true in the world of physics but are true only for a mathematical construct in which masses that do not interact with one another orbit either a mathematical center of force or a stationary attracting body. The distinction Newton draws between the realm of mathematics, in which Kepler's laws are truly laws, and the realm of physics, in which they are only "hypotheses" (or approximations), is one of the revolutionary features of Newtonian celestial dynamics.

In an early draft of what was to become book 3 of the *Principia*, Newton showed how considerations of the third law of motion led to the concept of a mutual force between the sun and each planet, between a planet and its satellites, and between any two planets. The same considerations lead to the revolutionary new idea that any and all bodies in the universe must "attract one another." He proudly presented this conclusion with the explanatory comment that in any pair of terrestrial bodies the magnitude of the attractive force is so small that it is unobservable. "It is possible" he wrote, "to observe these forces only in the huge bodies of the planets." Of all the planets, Jupiter and Saturn are the most massive, and so he sought orbital perturbations in their motions. With the help of John Flamsteed, Newton found that the orbital motion of Saturn is indeed perturbed when the two planets are closest together.

In book 3 of the *Principia*, which is concerned with the system of the world but is somewhat more mathematical than the earlier version, Newton treats the topic of gravitation in essentially the same way. First, in what is called the moon test, he extends the weight force, or terrestrial gravity, to the moon and demonstrates that the force varies inversely with the square of the distance. Then he identifies the same terrestrial force with the force of the sun on the planets and the force of a planet on its satellites. All these forces he now calls gravity. With the aid of the third law of motion he transforms the concept of a solar force on the planets into the concept of a mutual force between the sun and the planets. Similarly, he transforms the concept of a planetary force on the satellites into the concept of a mutual force between planets and their satellites and between satellites. The final transformation is the notion that all bodies interact gravitationally.

My analysis of the stages of Newton's thinking should not be taken as diminishing the extraordinary force of his creative genius; rather, it should make that genius plausible. The analysis shows Newton's fecund way of thinking about physics, in which mathematics is applied to the external world as it is revealed by experiment and critical observation. Because he did not assume that the construct is an exact representation the of physical universe, he was free to explore the properties and effects of a mathematical attractive force even though he found the concept of a grasping force "acting at a distance" to be abhorrent and not admissible in the realm of good physics. Next he compared the consequences of his mathematical construct with the observed principles and laws of the external world such as Kepler's law of areas and law of elliptical orbits. Where the mathematical construct fell short Newton modified it. This way of thinking, which I call the Newtonian style, is captured by the title of Newton's great work: *Mathematical Principles of Natural Philosophy*.

The law of universal gravitation explains why the planets follow Kepler's laws approximately and why they depart from the laws in the way they do. It was the law of universal gravitation which demonstrated why (in the absence of friction) all bodies fall at the same rate at any given place on the earth and why the rate varies with elevation and latitude. The law of gravitation also explains the regular and irregular motions of the moon, provides a physical basis for understanding and predicting tidal phenomena, and shows how the earth's rate of precession, which had long been observed but not explained, is the effect of the moon's pulling on the earth's equatorial bulge. Since the mathematical force of attraction works well in explaining and predicting the observed phenomena of the world, Newton decided that the force must "truly exist" even though the received philosophy to which he adhered did not and could not allow such a force to be part of a system of nature. And so he called for an inquiry into how the effects of universal gravity might arise.

Although Newton at times thought universal gravity might be caused by the impulses of a stream of aether particles bombarding an object or by variations in an all-pervading aether, he did not advance either of these notions in the *Principia* because, as he ultimately said, he would "not feign hypotheses" as physical explanations. The Newtonian style had led him to a mathematical concept of universal force, and that style led him to apply his mathematical result to the physical world even though it was not the kind of force in which he could believe.

Some of Newton's contemporaries were so troubled by the idea of an attractive force acting at a distance that they could not begin to explore its properties, and they found it difficult to accept the Newtonian physics. They could not go along with Newton when he said he had not been able to explain how gravity works but that "it is enough that gravity really exists and suffices to explain the phenomena of the heavens and the tides." Those who accepted the Newtonian style fleshed out the law of universal gravity, showed how it explains many other physical phenomena, and demanded that an explanation be sought of how such a force could be transmitted over vast distances through apparently empty space. The Newtonian style enabled Newton to study universal gravity without premature inhibitions that would have blocked his great discovery. The eighteenth-century biologist Georges Louis Leclerc de Buffon once wrote that a man's style cannot be distinguished from the man himself. In the case of Newton his greatest discovery cannot be separated from his style.

Acceptance of a Newtonian Revolution

There are numerous testimonials to the Newtonian revolution in science. The eighteenth-century historian of science Jean-Sylvain Bailly wrote that "Newton overturned or changed all ideas": his "philosophy brought about a revolution." Bailly was not content merely to state generalities concerning the Newtonian revolution in science. As he saw it, the key that in Newton's hands unlocked the celestial mysteries was mathematics: geometry. As Bailly put it: "What is supposed to make things move is what really makes things move; the demonstration was complete. Newton alone, with his mathematics [géométrie], divined the secret of nature."

With rare insight, Bailly saw that "the advantage of mathematical solutions is that they are general." The argument that if the planets move according to Kepler's laws, they must be "impelled by a force residing in the sun" depends only on mathematical or geometrical considerations and general principles of motion. No special physical properties of the sun appear in Newton's argument, which differs from Kepler's in that the latter had invoked such special qualities of the sun as its magnetic force and the orientation of its poles. Accordingly, the identical mathematical argument shows that the satellites of Jupiter and Saturn, subject to the same laws of Kepler, must be equally "impelled by forces residing in these two planets." In other words, Jupiter and Saturn are to their satellite systems what the sun is to the planetary system, the only difference being one of extent and power. And the same is true of the earth and our moon (Bailly 1785, vol. 2, bk. 12, sec. 9, pp. 486f.).

Bailly himself was willing to accept the concept and principle of a universal gravitating force, since so many phenomena were explained by its use: so many of the observed data and experiential laws could be derived by mathematics from the properties of universal gravity (sec. 4, pp. 555f.). He was aware, however, that at first many scientists (notably in France) made a distinction between the Newtonian system as mathematical and as a true natural philosophy. Thus with respect to Maupertuis, who (according to Bailly) "appears to us to have been . . . the first of our mathematicians to have used the principle of attraction," Bailly (vol. 3 ("discours premier"): 7) had to point out that "at first he considered it only in relation to its calculable effects; he accepted gravitation as a mathematician, but not as a physicist." That is, Maupertuis went along with the Newtonian mathematical system or construct (our phases one and two) but would not grant that in the system of the world (phase three) Newton was necessarily dealing with quality.

In fact, in a paper "On the Laws of Attraction" (1732), Maupertuis had been very explicit on this point. "I do not at all consider," he wrote, "whether Attraction accords with or is contrary to sound Philosophy." Rather, "Here I deal with attraction only as a mathematician [géomètre]." Maupertuis was concerned with attraction only as "a quality, whatever it may be, of which the phenomena are calculable, considering it to be uniformly distributed through all the parts of matter, acting in proportion to the mass." Maupertuis, in other words, accepts the Newtonian style and is willing, as "géomètre," to follow out the mathematical consequences of a law of gravitational attraction. Since the results accord with the phenomena observed in nature, Maupertuis then asks himself as natural philosopher whether there is such a force as a physical entity, or whether there may be some other reason why bodies act as if there were such a force. If such a force does exist, it must have a cause; and we may observe that his thought is still so embedded in the mechanical philosophy that he restricts himself to two material causes of this gravitational action: some emanation from within the attracting body or some kind of matter outside the body.

A similar acceptance of the Newtonian style is found in the writings of Clairaut. Clairaut explained that "M. Newton . . . says expressly that he is using the term *attraction* only while waiting for its cause to be discovered; and in fact it is easy to judge by the treatise on the Mathematical Principles of Natural Philosophy that its only goal is to establish attraction as a fact" (Clairaut 1749, 330).

By the end of the eighteenth century, the concept of a universal gravity had become generally accepted. In the preface of his great *Mécanique céleste* (published 1799–1825), Laplace – the second Newton of this subject – began (1829, p. xxiii):

> Towards the end of the seventeenth century, Newton published his discovery of universal gravitation. Mathematicians have, since that epoch, succeeded in reducing to this great law of nature all the known phenomena of the system of the world, and have thus given to the theories of the heavenly bodies, and to astronomical tables, an unexpected degree of precision. My object is to present a connected view of these theories, which are now scattered in a great number of works. The whole of the results of gravitation, upon the equilibrium and motions of the fluid and solid bodies, which compose the solar system, and the similar systems, existing in the immensity of space, constitute the object of *Celestial Mechanics*, or the application of the principles of mechanics to the motions and figures of the heavenly bodies. Astronomy, considered in the most general manner, is a great problem of mechanics, in which the elements of the motions are the arbitrary constant quantities. The solution of this problem depends, at the same time, upon the accuracy of the observations, and upon the perfection of the analysis.

Although Laplace was endowed with a philosophical turn of mind, as evidenced by his *Philosophical Essay on Probabilities* of 1814, he did not feel any need – a century after the *Principia* – to discuss whether or not it is reasonable for a force of attraction to extend itself through space. The second 'book' of the *Mécanique céleste*, "On the Law of Universal Gravitation and the Motions of the Centres of Gravity of the Heavenly Bodies," begins with a chapter "On the Law of Universal Gravitation, deduced from observation." We are "induced," he writes (1829, *1*: 249), "to consider the centre of the sun as the focus of an attractive force, which extends infinitely in every direction, decreasing in the ratio of the square of the distance." Wholly unabashed by the use of the Newtonian word 'attraction', and no longer repelled by the philosophical overtones of this word when considered at large and outside of the Newtonian context, Laplace concludes simply and straightforwardly that

"the sun, and the planets which have satellites, are endowed with an attractive force, extending infinitely, decreasing inversely as the square of the distance, and including all bodies in the sphere of their activity" (p. 255). Furthermore, "analogy leads me to infer that a similar force exists generally in all the planets and comets." He has no problem with conduding "that the gravity observed upon the earth is only a particular case of a general law extending throughout the universe" and that this "attractive force" does "not appertain exclusively to its aggregated mass" but is "common to each component particle" (p. 258). He hails the Newtonian "universal gravitation" as a "great principle of nature," that "all the particles of matter attract each other in the direct ratio of their masses, and the inverse ratio of the square of their distances" (p. 259).

The success of the theory and applications of universal gravitation, or of what – since Einstein – is called 'classical' mechanics (or Newtonian mechanics), caused this subject to become the model or ideal for all the sciences. For example, much of the mid and late nineteenth-century argument about the Darwinian revolution centered on method, often focused on the question of whether or not Darwin had adhered to or abandoned the method of Newton. Scientists in as diverse fields as palaeontology and biochemistry envisioned a day when their science would have its Newton and reach the perfection of Newton's *Principia*. Why, Georges Cuvier asked in 1812, "should not natural history also one day have its Newton?" And around 1930 Otto Warburg lamented that the Newton of chemistry (for which the need had been expressed by J. H. van't Hoff and Wilhelm Ostwald in 1887) "has not yet arrived" (see Cohen 1980, 294).

The Newtonian revolution had also a tremendous ideological component, equaled perhaps by only one other scientific revolution, the Darwinian. Isaiah Berlin (1980, 144) has summed up Newton's influence:

> The impact of Newton's ideas was immense; whether they were correctly understood or not, the entire programme of the Enlightenment, especially in France, was consciously founded on Newton's principles and methods, and derived its confidence and its vast influence from his spectacular achievements. And this, in due course, transformed – indeed, largely created – some of the central concepts and directions of modern culture in the west, moral, political, technological, historical, social – no sphere of thought or life escaped the consequences of this cultural mutation.

Newton, and his contemporary John Locke, symbolized great new ideas, comprising that "outstanding revolution in beliefs and habits of thought" (Randall 1940, 253) that marks the modern era beginning with the Enlightenment. In contemplating this effect, we today, at three centuries' remove, sometimes find it difficult to understand how unprecedented was Newton's actual achievement in producing a mathematical theory of nature. Only adjectives like 'extraordinary' or 'phenomenal' or 'amazing' can convey the awe that scientists and nonscientists felt when Halley's Newtonian prediction that a comet would appear in 1758 (long after both Halley and Newton were dead) was verified. Men and women everywhere saw a promise that all of human knowledge and the regulation of human affairs would yield to a similar rational system of deduction and mathematical inference coupled with experiment and critical observation. The eighteenth century became "preeminently the age of faith in science" (Randall 1940, 276); Newton was the symbol of successful science, the ideal for all thought – in philosophy, psychology, government, and the science of society.

The belief in a Newtonian type of "rule of nature" according to universal laws was well expressed by the eighteenth-century physiocrats. All "social facts are linked together," according to the physiocrats, "in necessary bonds eternal, by immutable, ineluctable, and inevitable laws" (Gide and Rist 1947, 2). These would be obeyed by individuals and governments "if they were once made known to them." The physiocrats not only believed that human societies are "regulated by *natural laws*," but held that there are "the same laws that govern the physical world, animal societies, and even the internal life of every organism" (p. 8). Enlightenment men and women discarded traditional concepts of human relations and the order of human society, hoping for their Newton, who – they were sure – was "just around the corner." This "Newton of social science," according to Grane Brinton (1950, 382) would produce the new "system of social science [that] men had only to follow to ensure the *real* Golden Age, the *real* Eden – the one that lies ahead, not behind." In 1748 Montesquieu published *The Spirit of the Laws*, in which he compared a well-working monarchy with "the system of the universe," in which there is "a power of gravitation" that "attracts" all bodies to "the center." As in the model of the *Principia*, Montesquieu "laid down . . . first principles" and found that the particular cases follow naturally from them.

On almost every conceivable level of thought and action in which rational principles could be applied, the Newtonian revolution had a significant impact. Even today, when Newtonian concepts of time, space, and mass, and even the Newtonian principles of gravitation, have suffered Einsteinian replacements, there are huge areas of science and of common experience in which Newtonian science still reigns supreme. These encompass all of the experience of daily life and the machines we ordinarily use (except 'nuclear' devices). The most spectacular event of our times – the exploration of space – is not an illustration of Einsteinian relativity but only a straightforward application of classical gravitational physics – the science achieved by Newton in his *Principia* and developed by two centuries of Newtonians into the great

science of rational mechanics and its central core of celestial mechanics. The Newtonian revolution was not only the apex of the Scientific Revolution, it remains one of the most profound revolutions in the history of human thought.[5]

5 The literature on Newton and the Newtonian revolution is vast, encompasing the findings of a large Newton research industry. A good entry into this area is by way of R. S. Westfall's monumental biography, *Never at Rest* (1980). On the developments in astronomy and mathematical physics that led to Newtonian science and on Newton's work in these areas, see the two books by René Dugas, *History of Mechanics* (1905 [1955]), *Mechanics in the Seventeenth Century* (1958 [1954]), and Westfall's *Force in Newton's Physics: The Science of Dynamics in the Seventeenth Century* (1971). Some of the ideas in this chapter have been presented by me in greater detail in my *The Newtonian Revolution* (1980), and in two articles: "The *Principia*, universal gravitation, and the 'Newtonian style,'" in Zev Bechler, ed., *Contemporary Newtonian Research* (1982), and "Newton's Discovery of Gravity" in the March 1981 issue of *Scientific American*, 1244: 166–179.

Major documents on the development of Newton's ideas on dynamics and celestial mechanics are available, with valuable commentaries, in *Unpublished Scientific Papers of Isaac Newton* (1962), ed. A. Rupert Hall and Marie Boas Hall; John W. Herivel's *The Background to Newton's Principia* (1965); and vol. 6 of the great edition of *The Mathematical Papers of Isaac Newton* (1974), ed. D. T. Whiteside. On the history of the *Principia*, see my *Introduction to Newton's 'Principia'* (1971). Anne Miller Whitman and I have completed a new English translation of the *Principia*, scheduled for publication in the near future.

Newton's *Opticks* is available in a convenient paperback edition; a full edition, with commentary and variant readings, prepared by Henry Guerlac, is to be published in 1985. The *Lectiones Opticae* is currently being published with a translation and commentary by Alan Shapiro. *Isaac Newton's Papers and Letters on Natural Philosophy and Related Documents* (1978 [1958]), ed. I. B. Cohen and Robert E. Schofield, contains facsimile reprints (with commentaries) of Newton's articles and related letters.

On the influence of Newton in the Enlightenment and after, the best introduction is still *The Making of the Modern Mind* (1940) by John Herman Randall, Jr. Another good general source is Herbert Butterfield's *The Origins of Modern Science* (1957 [1949]). See also Henry Guerlac's *Newton on the Continent* (1981), Margaret C. Jacob's *The Newtonians and the English Revolution* (1976), and Alexandre Koyré's *Newtonian Studies* (1965). Especially useful for the Enlightenment are Grane Brinton's *Ideas and Men: The Story of Western Thought* (1950) and Peter Gay's two volumes on *The Enlightenment* (New York, 1966–1969).