Section VIII: The Development of Modern Science

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5. Newton

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5. Newton

Abstract
Isaac Newton (1642-1727) was born and educated in England. He attended Trinity College, Cambridge, and there found the inspiration for his prodigious work that was to synthesize and extend the labors of Copernicus, Galileo, Kepler, and others beyond the wildest dreams of any of them. Newton was the intellectual giant who set the direction of the physical sciences on the paths they were to follow undeviatingly into the twentieth century. [excerpt]

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Contemporary Civilization, Isaac Newton, Royal Society of London, Physics

Disciplines
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Comments
This is a part of Section VIII: The Development of Modern Science. The Contemporary Civilization page lists all additional sections of Ideas and Institutions of Western Man, as well as the Table of Contents for both volumes.

More About Contemporary Civilization:
From 1947 through 1969, all first-year Gettysburg College students took a two-semester course called Contemporary Civilization. The course was developed at President Henry W.A. Hanson's request with the goal of "introducing the student to the backgrounds of contemporary social problems through the major concepts, ideals, hopes and motivations of western culture since the Middle Ages."

Gettysburg College professors from the history, philosophy, and religion departments developed a textbook for the course. The first edition, published in 1955, was called An Introduction to Contemporary Civilization and Its Problems. A second edition, retitled Ideas and Institutions of Western Man, was published in 1958 and 1960. It is this second edition that we include here. The copy we digitized is from the Gary T. Hawbaker ’66 Collection and the marginalia are his.

Authors

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5. Newton

Isaac Newton (1642-1727) was born and educated in England. He attended Trinity College, Cambridge, and there found the inspiration for his prodigious work that was to synthesize and extend the labors of Copernicus, Galileo, Kepler, and others beyond the wildest dreams of any of them. Newton was the intellectual giant who set the direction of the physical sciences on the paths they were to follow undeviatingly into the twentieth century.

We must note that Newton encountered none of the opposition that was the lot of Copernicus, Galileo, or Kepler, and which resulted in their works being placed on the Index. In fact, Newton was afforded all the honor and esteem during his lifetime that came to the others only after death. For this we have to thank the more receptive state of mind that flourished in seventeenth and eighteenth century England. The spirit of scientific inquiry was evident in a group of men who met weekly in London beginning about 1645 and who finally grew into the Royal Society of London, chartered in 1662. The Royal Society was the forerunner of similar organizations that were to come into existence near, and often in opposition to, the principal centers of learning throughout Europe and America. The members considered themselves "divers worthy persons, inquisitive into natural philosophy and other parts of human learning and particularly of what hath been called the New Philosophy or Experimental Philosophy." The society began publishing the Philosophical Transactions in 1665 for the dissemination of information contained in papers by the members, reports on new observations, and notices of newly published scientific books. This began a tradition of publishing new works by scientists that has served as an indispensable part of the scientific world to this day. One of the early leaders of the society was Robert Hooke (1635-1703), an outstanding experimentalist. He wrote of the purposes of the society:

The business and design of the Royal Society is --

To improve the knowledge of naturreal things, and all useful Arts, Manufactures, Mechanick practices, Engynes and Inventions by Experiments -- (not meddling with Divinity, Metaphysics, Moralls, Politicks, Grammar, Rhetorick, or Logick).

To attempt the recovering of such allowable arts and inventions as are lost.

To examine all systems, theories, principles, hypotheses, elements, histories, and experiments of things naturall, mathematicall, and mechanickall, invented, recorded or practiced, by any considerable author ancient or modern. In order to the compiling of a complete system of solid philosophy for explicating all phenomena produced by nature or art, and recording a rational account of the causes of things.
In the mean time this Society will not own any hypothesis, system, or doctrine of the principles of natural philosophy, proposed or mentioned by any philosopher ancient or modern, not the explication of any phenomena whose recourse must be had to original causes (as not being explicable by heat, cold, weight, figure, and the like, as effects produced thereby): nor dogmatically define, nor fix axioms of scientificall things, but will question and canvass all opinions, adopting nor adhering to none, till by mature debate and clear arguments, chiefly such as are deduced from legitimate experiments, the truth of such experiments be demonstrated invincibly.

And till there be a sufficient collection made of experiments, histories, and observations, there are no debates to be held at the weekly meetings of the Society, concerning any hypothesis or principal of philosophy, nor any discourses made for explicating any phenomena, except by speciall appointment of the Society or allowance of the president. But the time of the assembly is to be employed in proposing and making experiments, discoursing of the truth, manner, grounds and use thereof, reading and discoursing upon letters, reports and other pages concerning philosophicall and mechanical matters, viewing and discoursing of curiosities of nature and art, and doing such other things as the Council or the President shall appoint. *

In the environment that nurtured free and critical inquiry and that gave access to the work that had gone before, Newton was able to exert his full energies on the scientific problems at hand without getting tangled in external controversy. He retired to Woolsthorpe, his birthplace, during the plague (1665-1666). In these years, his twenty-fourth and twenty-fifth, he began work on his method of fluxions (which was to become the calculus), discovered the binomial theorem, performed experiments on the nature of color, and gave some time to the problem of universal gravitation. On the last subject he began to wonder if the force that held the planets in their paths might not be related to the force that draws projectiles back to the earth's surface. He wrote down his line of reasoning later in his System of the World:

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Newton combined Kepler's third law of planetary motion with the equation for centripetal force to derive the result that the gravitational force directed from the various planets toward the sun must vary proportionally with \(1/r^2\), where \(r\) is the distance measured from the sun. He reasoned that if the forces which hold the moon in its orbit around the earth and which bring projectiles back to the earth are in fact the same, then the ratio of the acceleration of gravity at the earth's surface to the centripetal acceleration of the moon must equal the ratio of \(1/r_e^2\) (\(r_e = \text{earth's radius}\)) to \(1/r_m^2\) (\(r_m = \text{radius of moon's orbit}\)). Of this work he wrote:

And the same year [1666] I began to think of gravity extending to the Orb of the Moon, and having found out how to estimate the force with which [a] globe revolving within a sphere presses the surface of the sphere from Kepler's Rule of the periodical times of the Planets being in a sesquisecular [3/2th power] proportion of their distances from the centres of their Orbs I deduced that the forces which keep the Planets in their Orbs must [be] reciprocally as the squares of their distances from the centres about which they revolve; and thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the Earth, and found them [to] answer pretty nearly. **

Because of his own reticence and distaste for debate, most of Newton's work lay unpublished for about twenty years, until in 1684 Edmund Halley (1656-1742), a famous physicist and

astronomer, probably best known for his work on the comet which now bears his name, urged him to gather his labors in a single work and present them to the Royal Society. Newton spent about eighteen months on this chore (doing some chemistry experiments at the same time), and the Royal Society decided to publish the work as a book. In a fashion not unusual for scientific societies, it soon found that it had insufficient funds to do the job. Halley, although having some financial difficulties of his own, undertook the financing. The book was published in 1687 and was titled Philosophiae Naturalis Principia Mathematica (The Mathematical Principles of Natural Philosophy), often referred to simply as the Principia. It is unlikely that any single scientific work has ever matched the Principia in scope, rigor of proof, imagination, and in its effect on scientific and non-scientific thought, either contemporary or subsequent. It is no exaggeration to say that the principles enunciated in the Principia formed the unchanging basis for physics, astronomy, and engineering for over two hundred years, until Einstein forged his theory of relativity.

The book begins with a set of definitions: mass, quantity of motion (now called momentum), and force. To define velocity and acceleration, some comments on space and time are needed. Newton furnished them.

Hitherto I have laid down the definitions of such words as are less known, and explained the sense in which I would have them to be understood in the following discourse. I do not define time, space, place, and motion, as being well known to all. Only I must observe, that the common people conceive those quantities under no other motions but from the relation they bear to sensible objects. And thence arise certain prejudices, for the removing of which it will be convenient to distinguish them into absolute and relative, true and apparent, mathematical and common.

I. Absolute, true, and mathematical time, of itself, and from its own nature, flows equally without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequal) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year.

II. Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space; such is the dimension of a subterraneous, an aerial, or celestial space, determined by its position in respect of the earth. Absolute and relative space are the same in figure and magnitude; but they do not remain always numerically the same. For if the earth, for instance, moves, a space of our air, which relatively and

Absolute time - one single clock controlling all other clocks

Absolute space - all is always the same.
in respect of the earth remains always the same, will at one time be one part of the absolute space into which the air passes; at another time it will be another part of the same, and so, absolutely understood, it will be continually changed.

III. Place is a part of space which a body takes up, and is according to the space, either absolute or relative. I say, a part of space; not the situation, nor the external surface of the body. For the places of equal solids are always equal; but their surfaces, by reason of their dissimilar figures, are often unequal. Positions properly have no quantity, nor are they so much the places themselves, as the properties of places. The motion of the whole is the same with the sum of the motions of the parts; that is, the translation of the whole, out of its place, is the same thing with the sum of the translations of the parts out of their places; and therefore the place of the whole is the same as the sum of the places of the parts, and for that reason, it is internal, and in the whole body.

IV. Absolute motion is the translation of a body from one absolute place into another; and relative motion, the translation from one relative place into another. Thus in a ship under sail, the relative place of a body is that part of the ship which the body possesses; or that part of the cavity which the body fills, and which therefore moves together with the ship; and relative rest is the continuance of the body in the same part of the ship, or of its cavity. But real, absolute rest, is the continuance of the body in the same part of that immovable space, in which the ship itself, its cavity, and all that it contains, is moved. Wherefore, if the earth is really at rest, the body, which relatively rests in the ship, will really and absolutely move with the same velocity which the ship has on the earth. But if the earth also moves, the true and absolute motion of the body will arise, partly from the true motion of the earth, in immovable space, partly from the relative motion of the ship on the earth; and if the body moves also relatively in the ship, its true motion will arise, partly from the true motion of the earth, in immovable space, and partly from the relative motions as well of the ship on the earth, as of the body in the ship; and from these relative motions will arise the relative motion of the body on the earth. As if that part of the earth, where the ship is, was truly moved towards the east, with a velocity of 10010 parts; while the ship itself, with a fresh gale, and full sails, is carried towards the west, with a velocity expressed by 10 of those parts; but a sailor walks in the ship towards the east, with 1 part of the said velocity; then the sailor will be moved truly in immovable space towards the east, with a velocity of 10001 parts, and relatively on the earth towards the west, with a velocity of 9 of those parts.

Absolute time, in astronomy, is distinguished from everything else - can be explained by mechanical models.
relative, by the equation or correction of the apparent
time. For the natural days are truly unequal, though
they are commonly considered as equal, and used for a
measure of time; astronomers correct this inequality that
they may measure the celestial motions by a more accurate
time. It may be, that there is no such thing as an equable
motion, whereby time may be accurately measured. All mo-
tions may be accelerated and retarded, but the flowing of
absolute time is not liable to any change. The duration
or perseverance of the existence of things remains the
same, whether the motions are swift or slow, or none at
all; and therefore this duration ought to be distinguished
from what are only sensible measures thereof; and from
which we deduce it, by means of the astronomical equation.
The necessity of this equation, for determining the times
of a phenomenon, is evinced as well from the experiments
of the pendulum clock, as by eclipses of the satellites
of Jupiter.

As the order of the parts of time is immutable, so also
is the order of the parts of space. Suppose those parts
to be moved out of their places, and they will be moved
(if the expression may be allowed) out of themselves. For
times and spaces are, as it were, the places as well of
themselves as of all other things. All things are placed
in time as to order of succession; and in space as to
order of situation. It is from their essence or nature
that they are places; and that the primary places of things
should be movable, is absurd. These are therefore the
absolute places; and translations out of those places, are
the only absolute motions.

But because the parts of space cannot be seen, or
distinguished from one another by our senses, therefore
in their stead we use sensible measures of them. For
from the positions and distances of things from any body
considered as immovable, we define all places; and then with
respect to such places, we estimate all motions, consider-
ing bodies as transferred from some of those places into
others. And so, instead of absolute places and motions,
we use relative ones; and that without any inconvenience
in common affairs; but in philosophical disquisitions, we
ought to abstract from our senses, and consider things
themselves, distinct from what are only sensible measures
of them. For it may be that there is no body really at
rest, to which the places and motions of others may be
referred.

But we may distinguish rest and motion, absolute and
relative, one from the other by their properties, causes,
and effects. It is a property of rest, that bodies really
at rest do rest in respect to one another. And therefore
as it is possible, that in the remote regions of the fixed
stars, or perhaps far beyond them, there may be some body
absolutely at rest; but impossible to know, from the
position of bodies to one another in our regions, whether
any of these do keep the same position to that remote
body, it follows that absolute rest cannot be determined
from the position of bodies in our regions. *

Newton then set down his famous three axioms, or laws of motion:

**LAW I**

Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

Projectiles continue in their motions, so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are continually drawn aside from rectilinear motions, does not cease its rotation, otherwise than as it is retarded by the air. The greater bodies of the planets and comets, meeting with less resistance in freer spaces, preserve their motions both progressive and circular for a much longer time.

**LAW II**

The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that force be impressed altogether and at once, or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added to or subtracted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both.

**LAW III**

To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may so say) will be equally drawn back towards the stone; for the distended rope, by the same endeavor to relax or unbend itself, will draw the horse as much towards the stone as it does the stone towards the horse, and will obstruct the progress of the one as much as it advances that of the other. If a body impinge upon another, and by its force change the motion of the other, that body also (because of

* Isaac Newton, *Mathematical Principles of Natural Philosophy*, in *ibid.*, pp. 6-9. This and the succeeding excerpts from the *Principia* are used with permission.
the equality of the mutual pressure) will undergo an equal change, in its own motion, towards the contrary part. The changes made by these actions are equal, not in the velocities but in the motions of bodies; that is to say, if the bodies are not hindered by any other impediments. For, because the motions are equally changed, the changes of the velocities made towards contrary parts are inversely proportional to the bodies. This law takes place also in attractions,... *

The first law is a more precise statement of Galileo's law of inertia. The second law is the source of the equation \( F = ma \) (force equals mass times acceleration) that plays an important role in the study of mechanics. It was nearly stated by Galileo. Newton was the first to give a clear statement of the third law.

The Principia showed the way to solve a tremendous variety of perplexing problems, but for our purposes here some of the astronomical results are the most important. Using the law of universal gravitation (that any two bodies exert attractive forces on each other proportional to the product of their masses and inversely proportional to the square of the distance between them) and the laws of motion, Newton was able to show that the laws which regulate the motions of the moon about the earth, the earth and other planets about the sun, a stone thrown from the earth's surface, the oceans' tides, and many more are all the same. The Newtonian laws of motion superseded Kepler's laws, because the latter were deducible from the former. Newton showed in a striking way that the physics of the heavens is the same as the physics of the earth. He even accounted for some of the irregularities in the motions of the moon and planets. The thoroughness with which he solved a tremendous number of problems is difficult to describe. Only a reading of the Principia itself can show the magnitude of Newton's intellect.

To the question whether the earth rotates about the sun or the sun about the earth, Newton had an answer. Both rotate about their joint center of gravity which because of the sun's great mass is within the surface of the sun. In fact, the entire solar system rotates about the center of gravity of the sun and all the planets, the center of gravity itself remaining motionless. The center of gravity of two masses \( M_1 \) and \( M_2 \) is shown in the following figure. The center of gravity, \( C \), is at the point where \( M_1 r_1 = M_2 r_2 \).

![Diagram of center of gravity](image)

If we were to stand on the sun, the earth would appear to move about us on an elliptical orbit. If we stand on the earth, the sun appears to move about us on an elliptical orbit. Actually both the sun and the earth are moving about the center of gravity, but the sun's motion is much less since the center of gravity is very close to the center of the sun.

The spirit of Newton's approach to nature is exhibited clearly in the Rules for Reasoning in Philosophy which he included in the Principia:

**RULE I**
We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

To this purpose the philosophers say that Nature does nothing in vain, and more is in vain when less will serve; for Nature is pleased with simplicity, and affects not the pomp of superfluous causes.

**RULE II**
Therefore to the same natural effects we must, as far as possible, assign the same causes.

As to respiration in a man and in a beast; the descent of stones in Europe and in America; the light of our culinary fire and of the sun; the reflection of light in the earth, and in the planets.

**RULE III**
The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.

For since the qualities of bodies are only known to us by experiments, we are to hold for universal all such as universally agree with experiments; and such as are not liable to diminution can never be quite taken away. We are certainly not to relinquish the evidence of experiments for the sake of dreams and vain fictions of our own devising; nor are we to recede from the analogy of Nature, which is wont to be simple, and always consonant to itself. We no other way know the extension of bodies than by our senses, nor do these reach it in all bodies; but because we perceive extension in all that are sensible, therefore we ascribe it universally to all others also. That abundance of bodies are hard, we learn by experience; and because the hardness of the whole arises from the hardness of the parts, we therefore justly infer the hardness of the undivided particles not only of the bodies we feel but of all others. That all bodies are impenetrable, we gather not from reason, but from sensation. The bodies which we handle we find impenetrable, and hence conclude impenetrability to be an universal property of all bodies whatsoever. That all bodies are movable, and endowed with
certain powers (which we call the inertia) of persevering in their motion, or in their rest, we only infer from the like properties observed in the bodies which we have seen. The extension, hardness, impenetrability, mobility, and inertia of the whole, result from the extension, hardness, impenetrability, mobility, and inertia of the parts; and hence we conclude the least particles of all bodies to be also all extended, and hard and impenetrable, and movable, and endowed with their proper inertia. And this is the foundation of all philosophy. Moreover, that the divided but contiguous particles of bodies may be separated from one another, is matter of observation; and, in the particles that remain undivided, our minds are able to distinguish yet lesser parts, as is mathematically demonstrated. But whether the parts so distinguished, and not yet divided, may, by the powers of Nature, be actually divided and separated from one another, we cannot certainly determine. Yet, had we the proof of but one experiment that any undivided particle, in breaking a hard and solid body, suffered a division, we might by virtue of this rule conclude that the undivided as well as the divided particles may be divided and actually separated to infinity.

Lastly, if it universally appears, by experiments and astronomical observations, that all bodies about the earth gravitate towards the earth, and that in proportion to the quantity of matter which they severally contain; that the moon likewise, according to the quantity of its matter, gravitates towards the earth; that, on the other hand, our sea gravitates towards the moon; and all the planets one towards another; and the comets in like manner towards the sun; we must, in consequence of this rule, universally allow that all bodies whatsoever are endowed with a principle of mutual gravitation. For the argument from the appearances concludes with more force for the universal gravitation of all bodies than for their impenetrability; of which, among those in the celestial regions, we have no experiments, nor any manner of observation. Not that I affirm gravity to be essential to bodies; by their vis insita I mean nothing but their inertia. This is immutable. Their gravity is diminished as they recede from the earth.

RULE IV

In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.

This rule we must follow, that the argument of induction may not be evaded by hypotheses. *

We have traveled a long way from Plato's original question. Ptolemy tried to answer Plato, keeping within the imposed conditions, but even he had to take liberties with the conditions, principally the one requiring the earth to be at the center of the universe. Copernicus thought that by casting out this one condition entirely, he could best answer the question in the spirit in which Plato asked it. But the condition that the earth be central in the universe had by then become more important, for nonscientific reasons, than Plato's question or its answer. Man was content, and possibly even pleased, with his central position in the order of things. He did not like the idea that he was clinging to a mere bit of dust, like any other bit, whirling through space with unheard of speeds. Galileo and Kepler not only discarded the condition, they cast aside the entire question and began groping for a new question. They upset hard-won and long-standing concepts that had given a unity to such diverse areas of knowledge as religion, philosophy, and science. We cannot be surprised that the defenders of these concepts were vigorous in their opposition to the intruders. Man seems to prefer the comfort of the familiar and to be embittered by anything that disturbs the security he finds in that comfort. The new science, by its independence of any religious belief, became an uncomfortable burden for the man who wanted to hold on to his faith.

Newton cast off all conditions on the answer to the problems of physics and astronomy except the conditions of consistency, wide application, and agreement with observation. With only these conditions imposed upon the answer, Plato's question no longer makes sense and is discarded.

In light of the success that Newton experienced in the realm of the physical sciences, it is not surprising that men in such diverse fields as economics, philosophy, politics, and sociology should try to construct mechanical models and to deal with them as Newton had done. These attempts constitute a part of the eighteenth century Enlightenment, to be discussed in Chapter X.

So that we with our hindsight do not become too smug in our criticism of the opponents of the new sciences, we need only recall that even Newton's physics was eventually found to be vague and to conceal undefined and undefinable terms. And there were those who defended Newton and attacked the newer physics of the twentieth century with arguments that made them sound disturbingly like those who vilified Galileo. Some find it difficult to understand that science is never likely to reach the end of its path -- to have all the right answers.