Computer-Produced Movies

A computer-controlled display tube and camera can produce animated movies quickly and economically.

Kenneth C. Knowlton

An automatic, electronic microfilm recorder can plot points and draw lines many orders of magnitude faster than a human draftsman can. This machine and the electronic computer which controls it promise to facilitate the production of animated movies for a wide range of educational and research purposes—to the extent of making economically feasible some kinds of animated movies which heretofore have been prohibitively intricate, time-consuming, and expensive to draw and film.

The microfilm recorder, reduced to its essentials, consists of a display tube, similar to a television tube, but whose electron beam is controlled by signals, not from a broadcasting station, but from an electronic computer or a computer-written magnetic tape. Facing the display tube is a camera in which the advancement of the film is also under automatic control. The commands which this assemblage understands are the simple instructions to advance the film, to display a spot of a certain brightness at specified coordinates of, typically, a 1024-by-1024 raster on the tube face, or to draw a straight line segment from one such point to another. Some displays, in addition, can "type" characters from a large but fixed alphabet by means of a shaped electron beam which has passed through the appropriate stencil of its alphabet mask; in some other displays, characters are drawn, instead, by automatic plotting of appropriate patterns of spots or line segments.

In spite of the simplicity of its elementary operations, the machine can compose complicated pictures or series of pictures from a sufficiently large number of appropriately placed points and lines; it can draw and film these elements fast enough to make this not only a feasible but a desirable way to produce long series of such pictures. Current speeds for microfilm recorders are in the range of 10,000 to 100,000 points, lines, or characters per second. This is fast enough to produce in a matter of seconds a television-quality image consisting of a fine mosaic of closely spaced spots, or fast enough to turn out simple line drawings at a rate of several frames per second.

Still, for the movie producer to specify the desired pictures in terms of elementary points and lines is out of the question—this would usually be more difficult than drawing the pictures outright. The producer would like, instead, to describe the pictures in more sweeping and powerful terms, such as "type such-and-such a title, center each line, give the letters shadows, now shoot 150 frames." The job of the computer, equipped with an appropriate program, would then be to deduce, from a few statements in the powerful language, the very large number of corresponding instructions for the microfilm recorder, and thus actually to produce the pictures automatically.

Still another role of the computer may appear when the producer does not know in advance just what the desired sequence of pictures is—for example when he wants to describe to the computer, in yet more abstract terms, a hypothetical situation and the laws which govern it. Here the job of the computer is first to simulate this hypothetical system—that is, to follow its mathematical laws. A great deal of computation may be required to determine the successive states of the system before the computer can call upon its picture-drawing facilities to "photograph" the system.

I shall discuss in turn these two roles of the computer, drafting and simulation, citing examples of computer-produced movies and movie-making systems that my colleagues at Bell Telephone Laboratories and I have developed during the past 3 years. The three movies I mention were made by use of an IBM 7094 digital computer and a Stromberg-Carlson 4020 microfilm recorder.

The Computer as a Drafting Machine

My work in this area has concerned the development of a special programming language for animated movies and, necessarily, the development of the corresponding computer program that "understands" this language and carries out the designated operations (*1*). This language, called BEFLIX (for "Bell Flicks"), speaks of a picture as a large 252-by-184 array of spots, each of which is represented in computer storage by a number from 0 to 7, which indicates the intensity of light at that point. Pictures are built up and modified within the computer by appropriate manipulation of these numbers, and at the desired times these numbers are used to direct the microfilm recorder in displaying the entire array of 46,368 spots in order to expose one frame of film.

Figure 1 shows scenes from a movie which I have made by programming entirely in this language, a movie about the very process by which the film was made (*2*). The first of these scenes is a more or less traditional title scene, but it was produced with a minimum of human effort because the computer movie program contains patterns for the letters (in several sizes and fonts) and operations for automatically centering lines of text. The illusion of depth was achieved by drawing the title twice in black, with slight displacement between successive operations, and finally once in light gray. (It was not much harder to tell the computer to do it three times than to do it once, and the additional computation time involved was insignificant.)

Some of the picture-drawing capabilities of the computer are demonstrated by the second and third scenes in Fig. 1, which, incidentally, depict the physical equipment involved. These two pictures were produced by instructions of the BEFLIX language such as those for drawing straight lines (consisting of dots in the BEFLIX system), or drawing arcs and other

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curves, or "painting" an area with a solid shade of gray, or copying contents of one area onto another, or shifting the contents of an area up, down, right, or left a specified number of raster positions. There are also operations for automatically filling a region that has been outlined by a specific shade of gray, for enlarging a part of a picture or a whole one, and for gradually dissolving one picture into another which has been drawn on an auxiliary "drawing board" within the computer.

In all, the language contains about 25 kinds of instructions, each of which is punched on an IBM card with appropriate parameters specifying just where and how the operation is to be performed and how many movie frames are to be produced at intermediate stages of the operation. For example, the instruction for drawing a straight line requires the programmer to specify beginning and end points, width of line in raster units, shade of gray, and the speed at which the line is to be drawn, expressed as the number of raster units the line should advance between successive frames of the movie.

The BEFLIX language actually does not do much which cannot be done by normal methods. In many cases, however, drawings can be made with far less human effort than when drawn manually, especially drawings which exhibit symmetries or periodicities. In the second scene shown in Fig. 1, for example, the 33 lights on the computer console were produced by giving instructions for drawing only one of them, with the positions at which these instructions were to be performed. In fact, it was not even necessary to give an explicit list of positions to the computer, but only the rules for enumerating these positions.

Finally, a big payoff comes, for the movie programmer as for other programmers, with the accumulation of a library of subroutines pertaining to a specific area. The second movie on any topic is nearly half finished when the first is done, for the basic subroutines for drawing and manipulating the pictures involved—atoms or spacecraft or electronic circuit components—are already written and checked out. The movie programmer has at this point developed a higher and more powerful language designed for animating his particular subject matter.

The economics of computer animation is, of course, the fundamental question: it should now be a surprise to no one that a computer, given sufficiently detailed instructions, can create on a display tube any desired picture or series of pictures; the question is whether the man-given instructions can be sufficiently concise and whether the computer can determine and produce the display quickly enough to make this a desirable way to do animation. The answer is definitely yes, to judge from the movie of Fig. 1. This is a 17-minute film and thus about 25,000 frames long. However some of the frames are identical and so there are only 3000 unique pictures. Now these 3000 pictures were actually produced by approximately 2000 lines (or punched cards) of BEFLIX programming, which took me 2 months as the sole producer-programmer. The other major expense was 4 hours of 7094 computer time (2 hours for program checkout and 2 hours for "production" run).

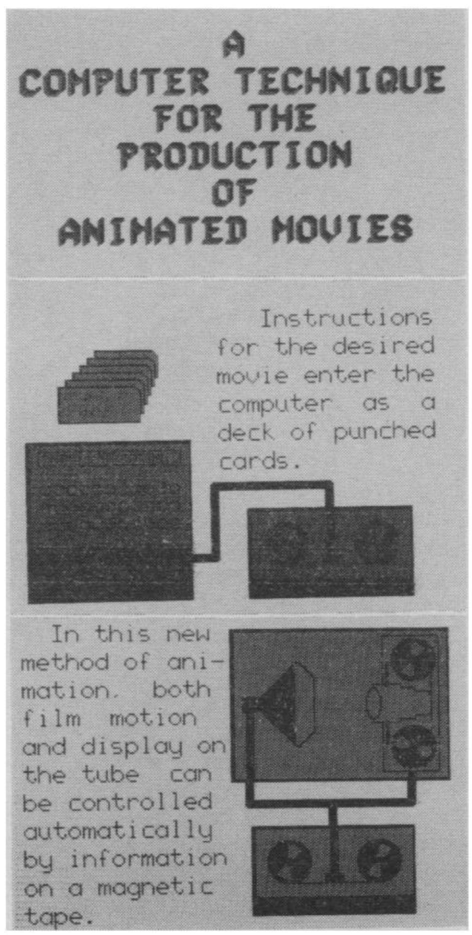

Fig. 1. Scenes from a movie about the BEFLIX movie language. The movie was produced entirely by the process which it describes. Scenes are composed of 252-by-184 arrays of variously shaded spots. (Top) Title scene. (Center) Scene depicting a computer and the tape on which it writes spot-by-spot description of pictures. (Bottom) Scene depicting the magnetic tape controlling a microfilm printer containing a display tube and a camera.

Other incidental costs bring the total cost up to $600 per minute of film, which already falls at the lower edge of the range for manual animation of this quality and complexity; costs of computer animation will undoubtedly go down with increases in size and speed of computers, with development of special-purpose peripheral equipment better suited to movie-making, and with further development of computer languages for the purpose. With efficiency improved only slightly from what we have now, it will also be feasible to improve the resolution of pictures and to do animation in color, both of which will require more computation but only a slight increase, if any, in programming effort.

The computer should, therefore, soon be able to do animation in many areas, particularly educational areas such as physics, chemistry, and mathematics, which have much to gain when their more or less traditional schematic diagrams can be brought to life by animation at costs which do not overwhelm the usually hard-pressed educational budget.

This is not to say that all or most animation presently done by hand will eventually be done by computer. In fact, it is difficult to imagine at this point how one could formalize for the computer the rules for drawing familiar cartoon characters. Instead, it is the more schematic and geometric forms for which the computer will be used to advantage.

The Computer as a Simulator

The movie-making potential of the computer is further extended by its ability to perform prodigious numerical calculations, such as may be involved in simulating hypothetical systems. It was one such simulation which led to a movie by E. E. Zajac, which was chronologically the first of the three films under discussion, and scenes of which appear in Fig. 2 (*3, 4*).

The basic problem on which Zajac was working was one of celestial mechanics: given a certain mechanism for orientation and stabilization of a communications satellite with respect to the earth, and given certain initial conditions of insertion of the satellite into orbit, what is the satellite's resultant motion? The hypothetical satellite under investigation had a long axis, and it is represented by a domino-shaped box in the scenes shown. Orientation of the satellite, with one end eventually pointing constantly toward the earth, is achieved by the gravity-gradient torque—that is, the torque resulting from the earth's gravity's pulling ever so slightly harder on the end of the satellite which is nearer to the earth. This results in general in an oscillatory motion; damping of this oscillation is accomplished by two gyros mounted within the satellite, with axes free to swing through a prescribed range, but with viscous damping (*5*).

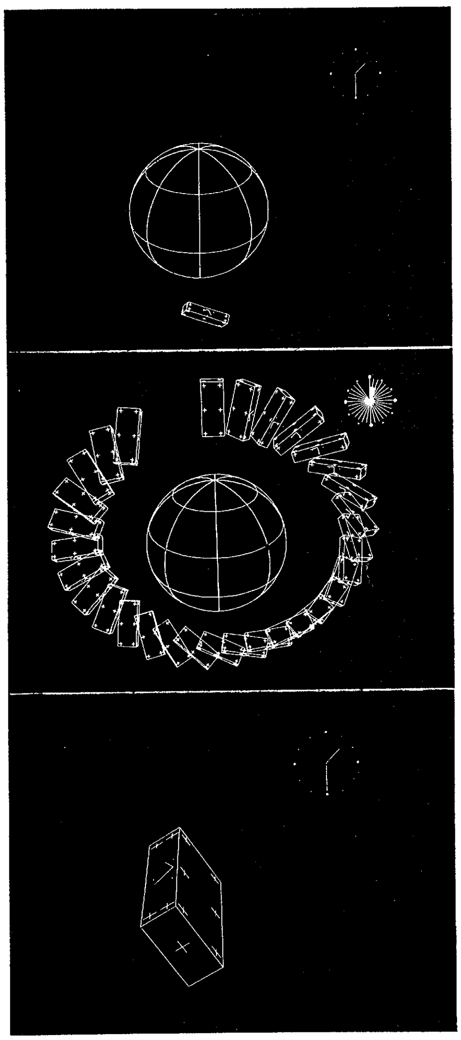

Fig. 2. (Top) Single frame from a computer movie by E. E. Zajac made during a satellite-orientation study. Satellite is depicted as rectangular box with "+" signs to identify sides. Clock, also computer drawn, counts orbits. Picture is composed of straight-line segments. (Center) A composite from several frames, showing the earth only once but with multiple exposures of satellite and clock. (Bottom) Another view of the motion illustrated in the preceding scene, but from a frame of reference that moves with the satellite (lines on side show instantaneous orientation of gyros). This illustrates that a minor change in the program can yield a very different but useful movie.

The satellite's motion is described by complicated differential equations for which we have no solution in closed form. In such a situation, the applied mathematician usually resorts to numerical integration by computer, as Zajac did, to determine by iterative procedure the position, velocity, orientation, and angular momentum of the satellite and its gyros for successive moments of time. But the resulting tabulation of these quantities, if such a listing had actually been produced, would have been difficult to interpret even for the specialist, and of no use to the layman. Instead, the results of the computation were automatically put out as a series of perspective drawings showing the computed positions of these objects as a function of time. The result is a movie which gives, to the specialist and layman alike, a much better feeling of the dynamics of the process than would the reams and reams of paper output.

One scene of Zajac's movie (Fig. 2, first scene) shows the earth in the center and the satellite below it. Different faces of the satellite are identified by different numbers of "+" signs, and the instantaneous positions of the gyro axes are indicated by the two additional line segments on the side of the box, the dots there representing stops which limit gyro motion. The clock in the upper right, also computer-drawn, counts orbits, with one "hour" of clock time equal to one orbit. The second scene is a composite drawing showing the earth just once (it rotates in the movie), but with superimposed images of the satellite and clock from every fifth frame of a section of the film.

The pictures in Zajac's movie were produced not by means of a large-scale movie-making system but rather by special-purpose subroutines written specifically for drawing an earth, satellite, and clock in the forms illustrated. The earth and satellite subroutines produced perspective drawings by mathematically projecting lines from significant points of these objects back to a viewing point; places where these lines pierced an imaginary "picture plane" gave positions of the corresponding points in the picture. The clock was always drawn, in effect, directly on the picture plane. Finally, the computer instructed the microfilm recorder in constructing pictures, here composed of several dozen line segments and a few dots, as contrasted with BEFLIX pictures containing tens of thousands of dots.

Here, then, is an example of a movie that probably would not have been made without the automatic microfilm recorder. It is true that a few dozen manually produced line drawings on clear plastic "cels" would have sufficed for the earth and individual clock hands—to be photographed, as is common in traditional animation, by stacking up several cels in appropriate relative positions to give many different composite pictures from a few drawings of individual objects or parts. Yet every frame of the movie would have required an individually drawn satellite, since the satellite and its gyros appear in so many different ways. The human draftsman would have had to follow the results of the computer simulation, plotting and drawing the box with inhuman accuracy and perseverence, for thousands of such drawings in order to match the quality and quantity of a few minutes' worth of output of the microfilm recorder.

A still further advantage in producing movies by computer is that the programmer in effect composes many scenes or movies at once, since a slight but meaningful change in the computer program can yield a very different but useful scene. By changing the rules of display, for example, Zajac was able to produce views of the satellite such as that of the third scene in Fig. 2, which shows the same motion as the previous scene, but where the viewer imagines himself to be following closely behind the satellite in an orbiting reference frame. He was also able to investigate a wide range of orientation and stabilization mechanisms and a range of initial conditions of insertion into orbit, simply by adjusting the appropriate parameters and rerunning the program to produce another movie.

In this way many movies can be made where just one would have been made by usual techniques. This should please many people. Consider, for example, the educator making a movie on molecular structure, who may, understandably, be sensitive about the way atoms are portrayed. He should be happier about computer animation for two reasons: first, he himself or someone working very closely with him will be the programmer, thus avoiding a multi-level heirarchy of command with its inescapable communication problems. Second, if the first attempt does not produce the desired esthetic or pedagogical effect, then it is not at all out of the question, as it might be with manual animation, to make the appropriate change in rules and try again: the marginal cost of redoing a scene or an entire movie can be an order of magnitude less for computer animation. This ability to actually view a large family of movies in search of the one or a few that best serve the purpose at hand is a marvelous and formerly unthinkable luxury for the movie maker.

Computer Movies in Education

Scenes from a movie made strictly for educational purposes appear in Fig. 3. This film, entitled "Force, Mass, and Motion" (*6*) and produced by F. W. Sinden, describes the motion of two bodies acting under Newton's law, $f = ma$, for a number of different central force laws and a range of initial velocities. For example, the first scene in Fig. 3 depicts two bodies with different masses (indicated by different sized circles) to which velocities (shown by the arrows) are about to be imparted and whose motion is to be governed by the inverse square (gravitational) law. The center of mass of the system is marked by a cross. The resultant motion of these bodies is the apparently complicated pair of paths traced out in the animated sequence, one frame of which is shown as the second scene in Fig. 3. The film then views the same motion from a frame of reference in which the center of mass is fixed, demonstrating that the motion is simpler than it first appeared, as exhibited by the ellipses being traced out in the third scene in Fig. 3. Pictures in this film, like those in Zajac's, consist of straight line segments, drawn by special purpose subroutines for animating this particular subject matter.

Sinden's film contains many other scenes demonstrating motion under other central forces: those which vary with the distance between the bodies as r^{-3}, r^{-1}, r^3, and r^∞. The last scene in Fig. 3, for example, shows two bodies tracing out their paths as determined by a force which varies as the cube of the separating distance. Arrows in the figure show instantaneous direction and magnitude of the force.

This 10-minute film as a whole is an elegant and esthetically beautiful lesson in physics: its total effect, I believe, cannot be matched by hours of hand-waving at a blackboard or with physically realizable demonstration equipment. (The world of the computer is in one sense the perfect physics laboratory, for the laws of physics can here be idealized or revised to degrees impossible to approximate with other teaching aids.) And it is another film that probably would not have been made without the computer, for to achieve the same accuracy and smoothness of animation would have been all but impossible by normal means, whereas animation by computer was easy because the mathematical laws governing the situation portrayed were simple.

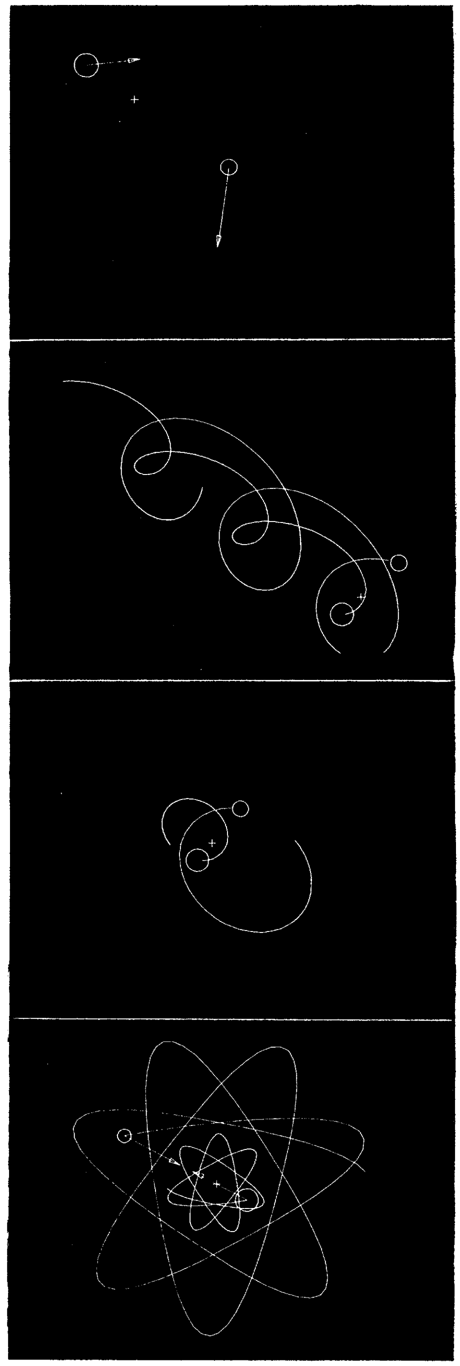

Fig. 3. Scenes from F. W. Sinden's computer-produced movie "Force, Mass, and Motion." (Top) Two bodies acting according to the inverse-square law, with arrows showing velocities to be imparted to them at time $t = 0$. (Top middle) Bodies tracing paths which result from initial conditions and inverse-square (gravitational) force; cross indicates center of mass of the system. (Bottom middle) Same motion as shown above, but viewed in a frame of reference moving with the center of mass; in this frame, paths are ellipses with common focus at center of mass. (Bottom) Two bodies acting under a force which varies as the cube of the separating distance; arrows show instantaneous direction and magnitude of the force on each.

Summary

Automatic microfilm recorders can draw pictures orders of magnitude faster than a human draftsman can. They are therefore ideally suited for the production of animated movies if they can be instructed by a digital computer which accepts abstract or high-level descriptions of pictures or situations and reduces them to elementary picture elements of points and lines. The movies and movie-making systems thus far developed do in fact demonstrate the feasibility of producing a wide variety of animated movies by these methods.

The computer performs one or sometimes two distinct jobs. In all cases it renders, in terms of points and lines, a series of pictures which have been described to it in a more powerful or abstract way. In addition, it is sometimes called upon to do a great deal of calculation in order to determine just what the picture or situation to be portrayed is as a function of time. The latter job is usually called simulation of a hypothetical model and it is done by integrating differential equations or by otherwise following the mathematical laws which govern the model. In both jobs the computer and electronic display hardware excel because of the speeds at which they work and hence because of the magnitude of the tasks they can undertake.

Thus many research, demonstration, and educational movies are only now becoming feasible to produce, because of the complexity of the subject matter being animated—such as three-dimensional vector fields, changing in

time, as encountered in fluid dynamics and electrodynamics. The new machinery and display techniques enhance our picture-drawing capabilities so dramatically that they provide a qualitative as well as quantitative extension of the jobs that can be done.

References and Notes

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Ernst Mach: Biographical Notes

Few of his contemporaries believed him, but few were his equal in physics, physiology, or philosophy.

H. W. Pittenger

Ernst Mach was 23 years old when, as he was to record later, he "began to pay attention to the labors of investigators to whom [he] had occasion to refer. . . . [He] recognized that the salient characteristics of their procedure lay in the choice of the simplest, most economical, most direct means to attain the end desired" (*1*).

This "economy of thought" and clarity in methodology became his stepping-stones across the then still unclear waters of optics, physics, physiology, psychology, and philosophy (*2*). Einstein acknowledged Mach's work as predecessor to his own. In *Science* in 1940 he wrote, "The strange part played by space (or the inertial system) within the mechanical foundation was also clearly recognized, and criticized with especial clarity by Ernst Mach" (*3*).

Mach, an Austrian, was born on 18 February 1838 in Moravia, which now is the south-central section of Czechoslovakia. His boyhood was spent on a farm where his father taught him history, elementary mathematics, geometry, and classical languages. We can imagine that on a farm in the early 19th century he observed the fundamental mechanics of the pulley and the lever. During his boyhood he spent 2 days a week at work with a cabinetworker. The training he received was to show in the straightforward simplicity of his later constructions for experiments.

Although Mach is best known for the work that gave the term "Mach number" to the world, his contributions to other fields were enormous. His lucid, beautiful writing loses none of its poetry in translation. In addition to influencing Einstein, Mach's philosophy of science was probably the inspiration for the quantum mechanics of Werner Heinsenberg (*4*).

In 1860 Mach earned his doctorate in physics at the University of Vienna, which had been the cultural center of Austria for more than 500 years. He remained there, teaching physics, until 1864, when he was appointed a professor at the University of Graz, situated about 225 kilometers southwest of Vienna. Mach taught mathematics and physics at Graz for 3 years, leaving to become professor of physics at the University of Prague. He remained at Prague 28 years before returning to his alma mater. The University of Vienna created for him a new chair, Theory of Inductive Sciences. Long after his death, Mach's influence was felt by his successors, and the chair became the center of the small international group of scientists, engineers, mathematicians, and philosophers who formed the Vienna Circle.

Mach was a prodigious writer on subjects that interested him; and those subjects he attacked with great thoroughness. His *Principles of Physical Optics* (*5*), in addition to being a scholarly critique, is a history of optics. Beginning with Aristotle, Plato, and Euclid, he examines the contributions of more than 200 others in a sprightly and most readable way. His impatience with Descartes, apparent in other of his works, is quite evident here. Speaking of the law of refraction, Mach says of Descartes (*5*, p. 33):

> It was easy for him as an applied geometrician to bring Snell's law [*6*] into a *new* form, and as a pupil of the Jesuits to "establish" this form. Descartes, however, had too little of the disposition or the ways of a scientist to discover the law by observation, and to examine it carefully from a theoretical point of view.

In 1883, Mach's *Die Mechanik in ihrer Entwickelung* (*1*) was published in Leipzig. Now available in English as *The Science of Mechanics* (*7*), this book is at once a dissection of Newtonian concepts and the seed for a new school of philosophy which proclaimed that a statement (and hence a theory) was not valid unless subject to experimental proof or disproof. To Mach "absolute time" and "absolute space" were meaningless, but the world in 1883 took little notice of his acute perception of the meaning of meaning.

Invading the private domain of Newton, he had the audacity to propose the theory that the inertia of a body was a function of that body's distance from all other bodies in the universe. The theory has outlived its detractors and persists today as "Mach's principle."

English translations are also available of Mach's *Popular Scientific Lectures* (*8*), *Space and Geometry* (*9*), and *The Analysis of Sensations* (*10*). The last, parts of which were published in English in volume 1 of the *Monist*, was misunderstood or derided as unscientific by most of his contemporaries. It was here that Mach distinguished between time sensations and the time of the physicist, which

> does not coincide with the system of time-*sensations*. When the physicist wishes to determine a period of time, he applies as his instruments of measurement, *iden-*

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