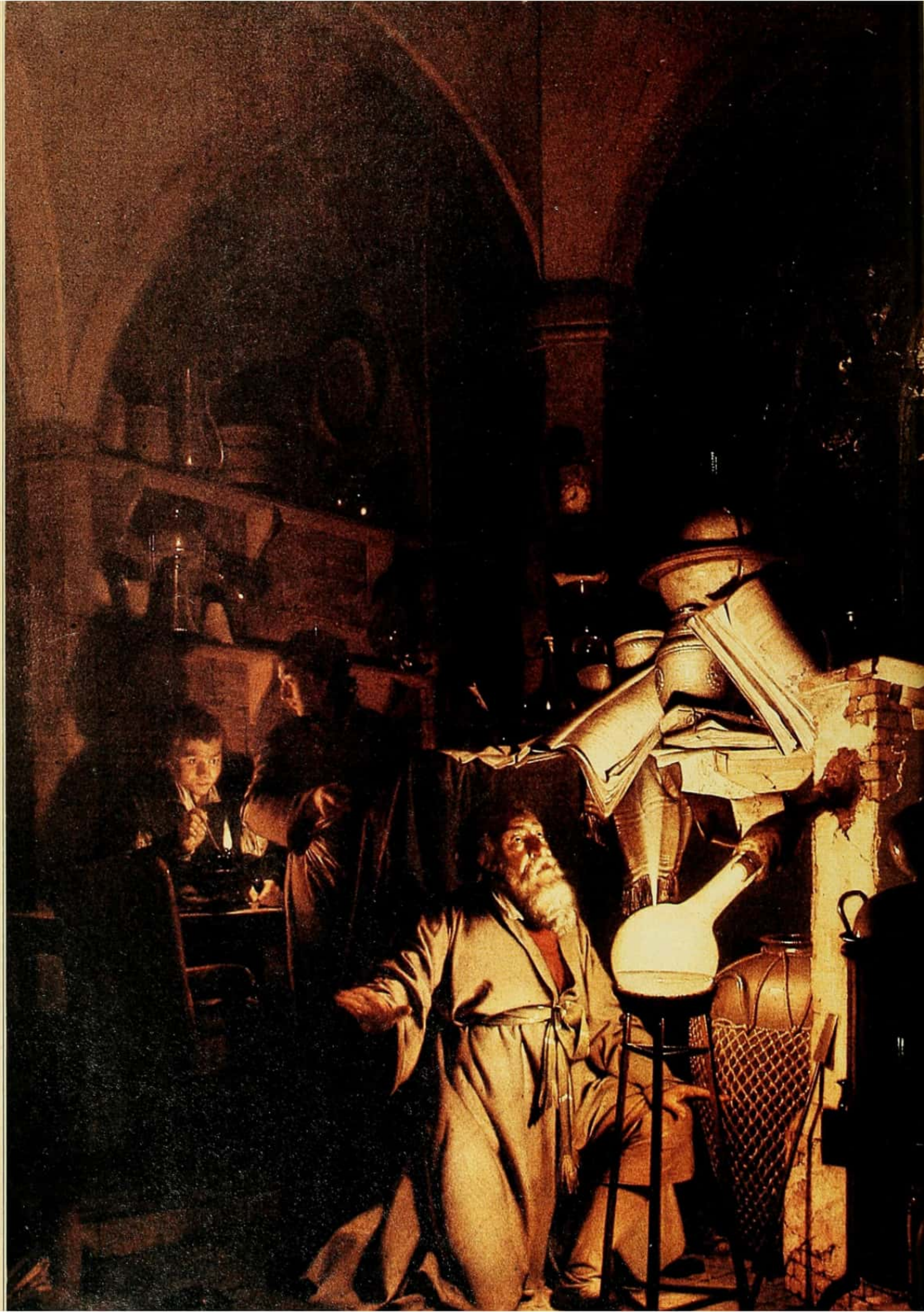


e Alchemist, *by Joseph Wright of rby, ca. 1768.*
y Museum and Art Gallery, Derby, England

# )f Sealing Wax and String

*ıe late, eminent science historian argued that unsung geniuses "with aıns in their fingertips" often have brought about major scientific breakthroughs*

/ Derek J. deSolla Price

In the 1920s, practically every piece of earch physics equipment in British lab- ıtories was stuck all over with red Bank England sealing wax because this was : best cement available for holding a :uum. A little later, when apparatus d to be dismantled and scientists had to able to break and regain vacuums ickly, the cement of choice became sticine. During the golden age of ex- rimental physics early in this century all ›gress seemed to depend on a band of in- ıious craftsmen, with brains in their fin- tips, who exploited a great many little- ɔwn properties of materials and other :ks of the trade. These tricks not only ıde all the difference in what could or ıld not be done in a laboratory; to a ge extent, they determined what was covered.

The phenomenon is not confined to ysics, to any particular country, or even the present century. At one point in the d-nineteenth century, knowledge of w synthetic dyestuffs dominated biolog- l research because they could be used stain substances and thereby reveal new uctures under the microscope. For a ıg time, this gimmick, rather than the tics of the microscope, directed scien- c exploration. Similarly, elegant tricks :h polarized light were applied to all ts of fields before American physicist bert Michelson used polarized light to cover that the speed of light is constant.

One has only to read such masters as ılileo, Newton, Maxwell, and Einstein, d inventors such as Edison, to realize ıt each set great store by, and derived :at benefit from, miscellaneous craft in- mation that was usable in scientific ex- riments. The great masters of this prov- :e were not by any means always great cognitive contributors. Many were anonymous and unsung lab assistants, such as Lord Rutherford's man, George Crowe, or J.J. Thomson's aides, Ebeneezer Everett and W.G. Pye. These three assistants went on to found the Cambridge Instrument Company, one of the first high-technology electronic companies of Britain. Thomson and Rutherford were genius experimenters who happened to be rather clumsy, and their assistants were crucial to progress. In fact, much of the apparatus used in the Cavendish Laboratory at Cambridge, where both men worked, was held together by sealing wax and string, not out of poverty, but because the experimenters had a dozen pairs of clever hands feverishly tearing down and rebuilding the apparatus as the experiments were pushed in new directions.

The flavor and tradition of this experimentation are markedly different from, and perhaps even in conflict with, the standard view of the role of experiment in science. This view is found in those banal texts that preach on "the scientific method," and it is implicit in the writings of the majority of my colleagues, who approach science as theoreticians and have little feeling for bench science. Interestingly enough, a new breed of historian, laboring in what is called the "anthropology of science," has been looking at the behavior of scientists in laboratories. The findings are surprisingly different from what one would expect.

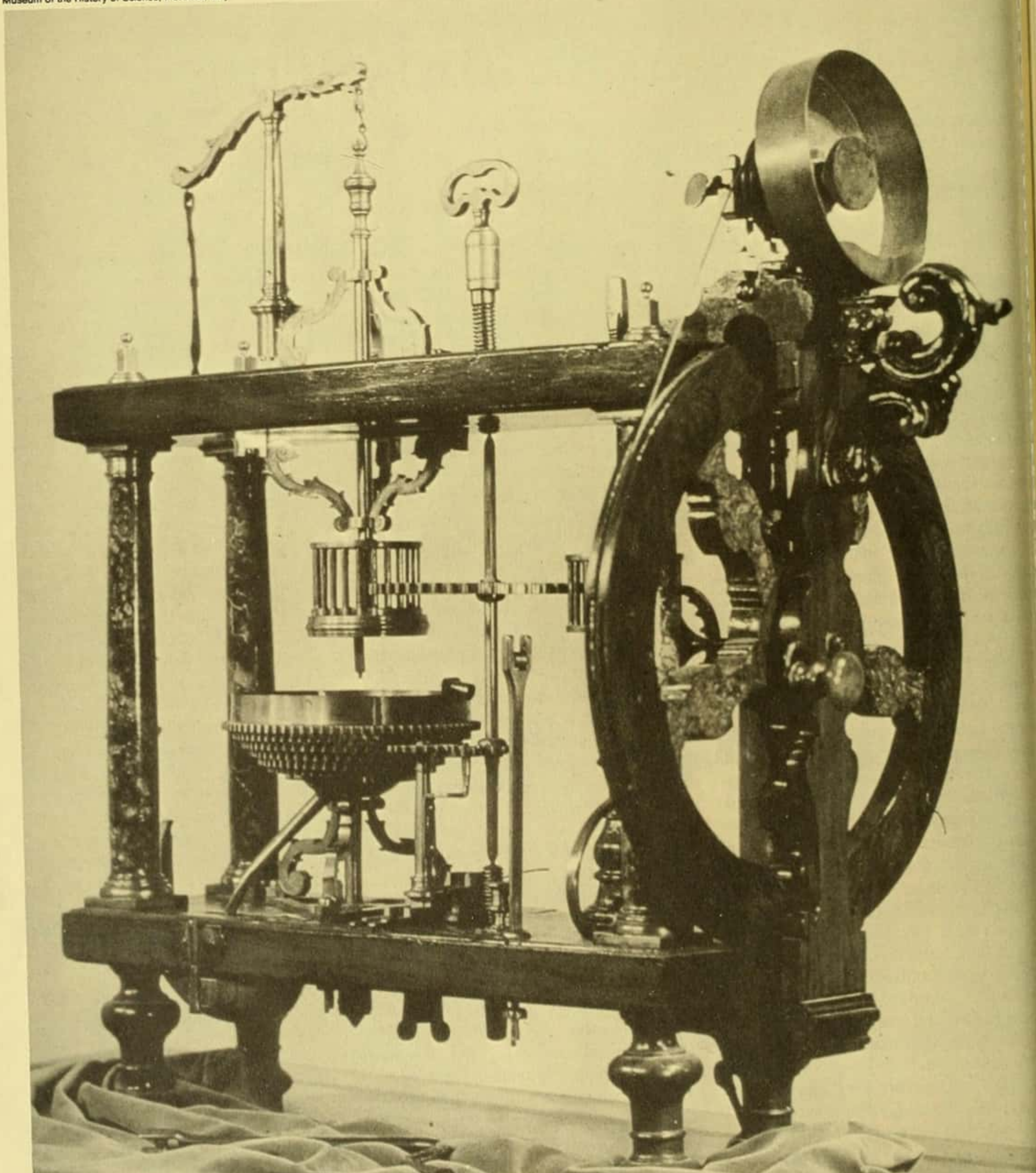
The standard view, which I ask you now to reject as being rare in history and not at all the essence of scientific enterprise, is that the scientist creates hypotheses and sends them out to be tested by making a trial of the prescribed "experiment." Herbert Butterfield and Thomas Kuhn have described the inspired thought that leads to great and revolutionary changes in science as "shifts in paradigm." According to this view, the thought is what's important; laboratory instruments are simply passive tools made to do jobs to order. They exist only to confirm or invalidate what the thinker has hypothesized.

What actually goes on in laboratories is of a different nature. Since the seventeenth century, and perhaps even earlier, experiment has more often meant "experience" in the use of various techniques. The idea is to find out what will happen when you try certain techniques, and the hope is that in the finding out, you will discover facts of nature that fall outside the range of what was known before. The procedure is far from being cut and dried and the theoreticians and experimenters are far from being in the master/servant relationship in which they are usually cast. In many societies there is a clear social class difference, and the lab worker is considered a "mere engineer" doing the bidding of more creative intellects who make the cognitive advances. On the contrary, skilled experimenters are masters of a very peculiar and crucially important technology. Their work is at the core of high technology and represents a tradition that is autonomous and did not arise from the cognitive core of science, but from other technologies devised for quite different purposes. Much more often than is commonly believed, the experimenter's craft is the force that moves science forward.

Another remarkably widespread wrong idea that has afflicted generations of science policy students is that science can in some mysterious way be applied to make technology. People quite commonly seem to believe that there is a great chain of be-

*The invention of the lens polishing lathe in the early seventeenth century made it possible to grind thick concave lenses. "Jeweler's rouge" used in the lathes aided the grinding and polishing work. This eighteenth-century lathe is attributed to Frati.*

Museum of the History of Science, Florence, Italy



g that runs from basic science to applied ience and then to development of new chnology in an orderly fashion. In fact, : have almost no examples of an increase understanding being applied to make :w advances in technical competence, ıt we have many examples of advances technology being puzzled out by theore- :ians and resulting in the advancement knowledge. It is not just a clever histori- .l aphorism, but a general truth, that hermodynamics owes much more to the eam engine than the steam engine ever ved to thermodynamics." Again and ;ain, we have known and controlled ther well the know-how of new tech- ques and technologies without under- anding the know-why. We often (but not ways) eventually understood why the chnique worked and this then led to odifications and improvements, giving e impression that science and technol- ;y advance hand in hand. But the arrow causality has largely been from the chnology to the science.

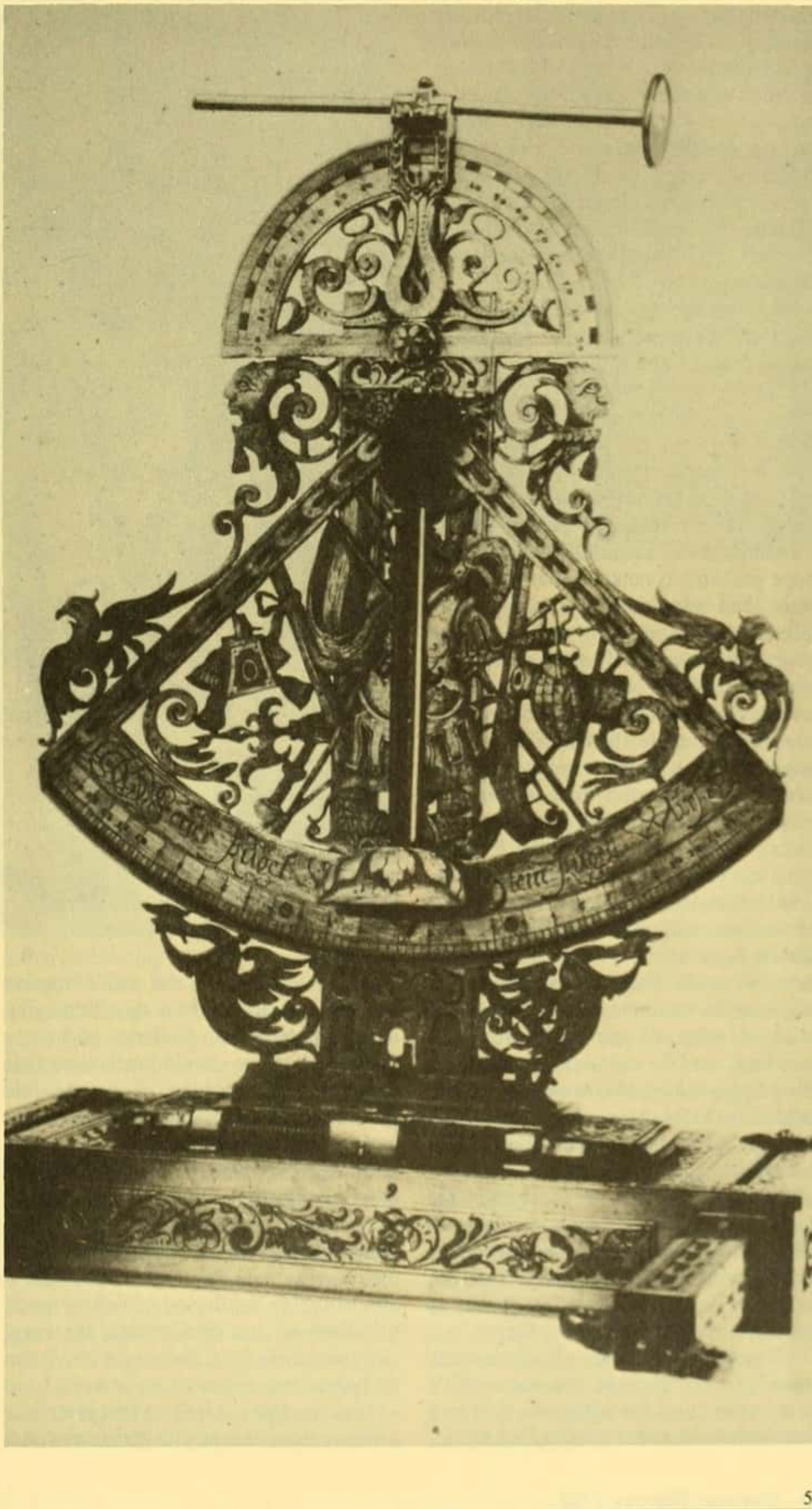
The simple truth is that one uses a tech- que, rather than an idea, to do some- ing to something else. Maxwell's elec- omagnetic theory, to give an overworked :ample, was not simply applied to invent diotelegraphy and then the technologies radio and TV broadcasting. His theory as a tremendous unifying concept that :plained the nature of light and sug- :sted one could produce similar wave ra- ation electrically. The trick was not to nderstand in detail why it might be done ıt to find ways to generate and detect ıch waves.

Thus, the early history of radio was not much a matter of physics, as the control experimental techniques such as spark ıps or of devices such as coherers and de- ctors. Quite often the devices worked, ıt no one knew why until later.

If experiment were only the application theory and the handmaiden of its mak- 's, then invention would be a set of foot- ıtes appended to the history of science. imilarly, if all science were produced just be applied to the world of industry, a lot the history of science would be foot- ıtes appended to a history of technology. either of these, of course, is anywhere

*Right through the Middle Ages, many instruments were not so much useful as symbolic. A device such as this gunsight, made by the German inventor Christopher Trechsler der Elder Mechanicus in 1622, demonstrated that the gunner who owned it "was an educated man."*

Mathematisch-Physikalische Salon, Dresden, G.D.R.



*The thick concave lenses produced on the glass lathe could be used to create charming visual illusions. These "perspective glasses" became the rage of Europe, as depicted by Johannes Strandanus in this lithograph, dated about 1600. A few years later, Galileo used the thick concave lens, along with a thin convex lens, to discover that the moon has mountains.*

Bibliothèque Royale Albert I, Brussels, Belgium

near the truth. The truth can only be found in some combination, the dialectical interaction of science and technology. In order to write a concurrent history of the two areas that is more than a chronology, we must be concerned with the historical causality of it all. Why do events happen when they do and the way they do? One key lies in the understanding of the craft techniques that have dominated science since the seventeenth century.

Many science historians hold, for example, that instruments began as tools of measurement, initially used for astronomy and then in the related crafts of time keeping, navigation, surveying, and gunnery. This is far from the truth. Ptolemy described elaborate instruments for astronomy but used his naked eye for observations. Anybody who used instruments for astronomy before the invention of the telescope probably concluded that they were worse than using nothing at all. Reasonably sized instruments in antiquity were only able to measure the position of heavenly bodies within one degree but the naked eye could make estimates four or five times more precise than that. In astronomy, one can use less than perfect observations, separated by long intervals, of heavenly bodies in critical positions to obtain extremely accurate results. Ptolemy was a master in the use of such methods.

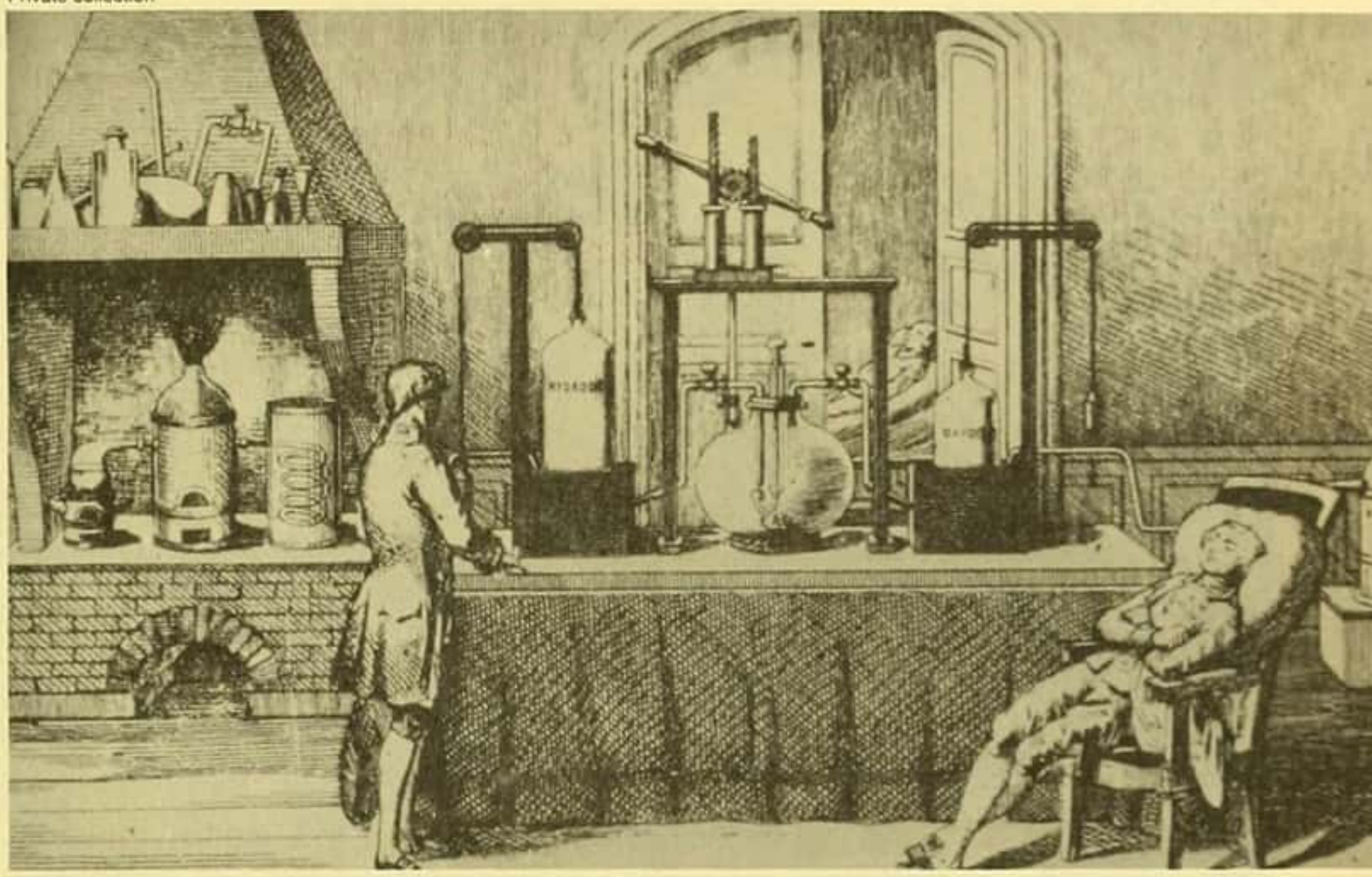
In fact, many of the best-crafted instruments from antiquity right through the Middle Ages were not instruments of observation at all. They were symbols. The astrolabe, for example, was a plane simulation of spherical astronomy. It might have been used for calculation, and it was often suggested but almost never used as a divided circle for observation. I suppose it was popularized to show the virtues of useless but beautiful mathematics. Actually, it was probably made and acquired for much the same reason we have globes in an elegant and learned library, as an embodiment of theory. Astrolabes were not even used for practical pedagogy but to symbolize the possession of a theory.

Many other varieties of instruments served a similar purpose. Ancient sundials were not so much for telling the time in a clockless world as for symbolizing the inexorable circles of the sun's motion through the year and the day. Surveying devices popularized geometry and trigonometry, but one should not believe that estimating the height of inaccessible towers on the other side of the river was ever a need of society. Good navigators never trusted their instruments, nor, indeed, should they have. An eyeball estimate of the height and direction of the polestar was all one needed, and for this no instruments were required. A compass is almost useless until one knows how much to adjust for the declinations, the magnetic variances from the north (which can be twenty-five degrees east or west).

In short, I do not believe that there was serious measurement with instruments before the sixteenth century, but there did emerge a high craft of making models and simulations such as astrolabes, armillary spheres, globes, and sundials. In the sixteenth century, gunnery instruments came into vogue, but one only has to look at them to know that they were symbols, devices to let one know the master gunner was an educated man, rather than working devices used in the heat of battle.

Of course, instruments did not remain only symbolic. Two crucial episodes, Galileo's use of the telescope in 1609 and Galvani and Volta's discovery of current electricity just before 1800, brought on revolutions in scientific thinking. But these two well-known stories are archetypical cases in point. In both, the technology

*Making water from scratch: A 1790 engraving portrays an experiment to produce water out of its elements, hydrogen and oxygen. Within a decade a scientific revolution was to begin that would lead to high technology.*
Private collection



ne before the science, and for that rea- s, the interaction between them is worth r alling in detail.

Galileo made his first telescopic ob- s vations and published them in a little b ok, *The Heavenly Messenger*, in 1610. I made his reputation, achieved the so- c led Copernican revolution, and popu- l ized what was known for the next cen- t y as "the new philosophy." Ironically, t whole chain of events occurred be- c use of an improvement in the technol- o y of eyeglasses. The making of eye- g sses for reading was a craft trade that g w to accommodate all the manuscript c pyists of the thirteenth century, the age of the great cathedrals and monastic insti- t ions. The trade moved to the cities and flourished mightily when the printing of books began. In the late sixteenth century the glass lathe was introduced, making it possible to grind several lenses at once and also to produce—as objects of curiosity—powerful, thick concave lenses.

Thin concave lenses had been used for more than a century, but thick concave lenses were now sold to people caught up with painting or visual illusions of perspective, who used them as "perspective glasses." Once the new lens became available, it suddenly became possible to see a rather interesting effect by combining two lenses. We now know that there are many different things that can be done with a pair of lenses. Both the Keplerian telescope and the microscope use combinations of convex lenses, but they demand that everything be in nearly perfect focus before you can see any more than a blur. The Galilean type of telescope began with the idea that as soon as you hold a powerful concave lens to the eye and a simple weak convex lens at arms length, the clock in the church tower jumps out at you. Many artisans from around the world enjoyed that illusion in the early 1600s, but it was two lens grinders from Middleburg in the Low Countries who first decided to market the telescope as a military invention, a device for spying on enemy armies. In fact, the telescope's narrow field of vision made it an unlikely spying device—but the two lens grinders thought they could sell it anyway. When the telescope was used militarily centuries later, it was used, not for spying, but for signaling.

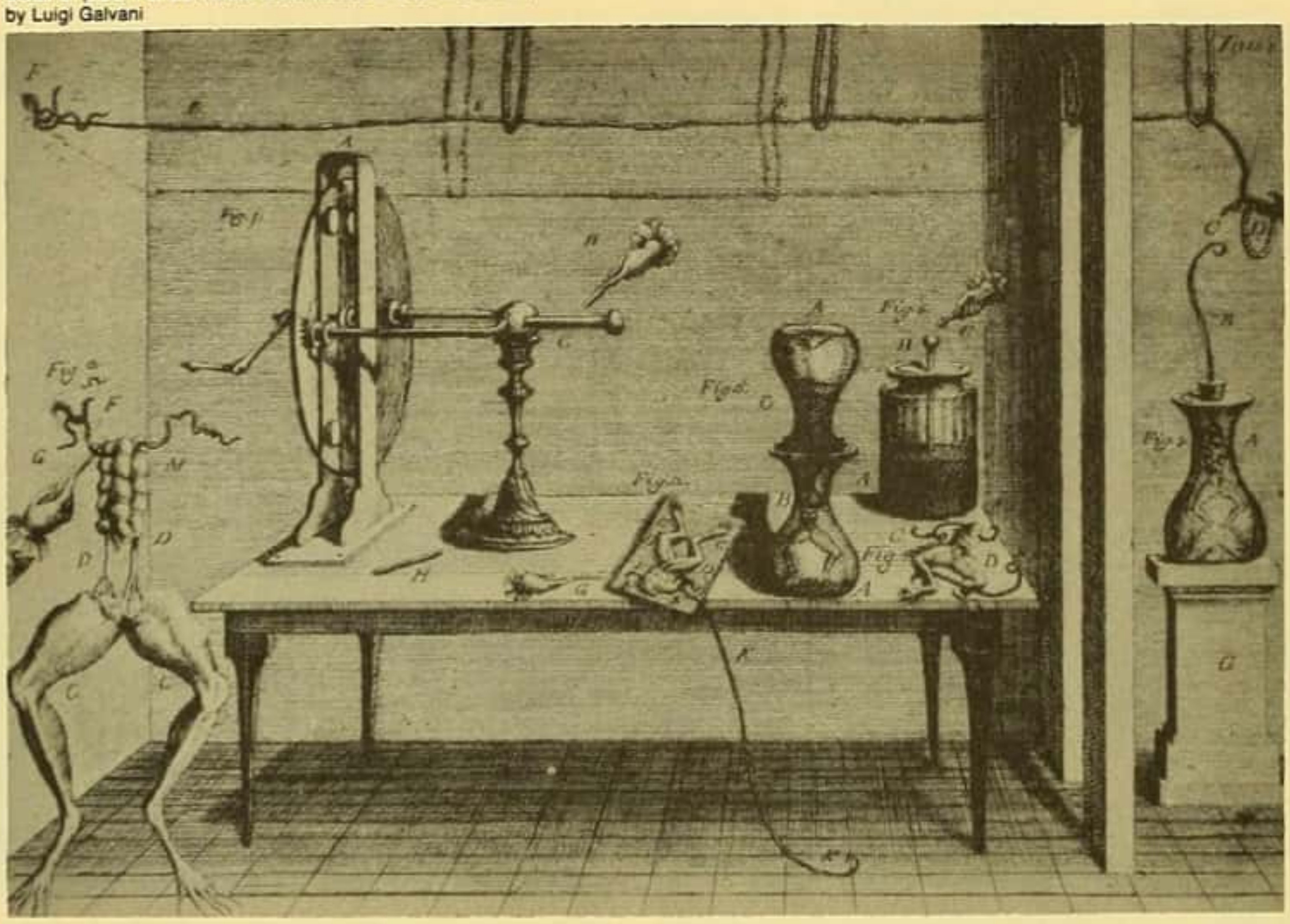
Galileo was consulted by Venetian authorities about the new lens because he was an uncommonly aggressive would-be consultant, part of the first generation of university professors who got their fees from students and patrons rather than from the establishment. It seems that he duplicated the invention and used it with little difficulty despite its tiny field of view. Galileo turned the telescope on the moon. Then a few days later, he looked at the moon again.

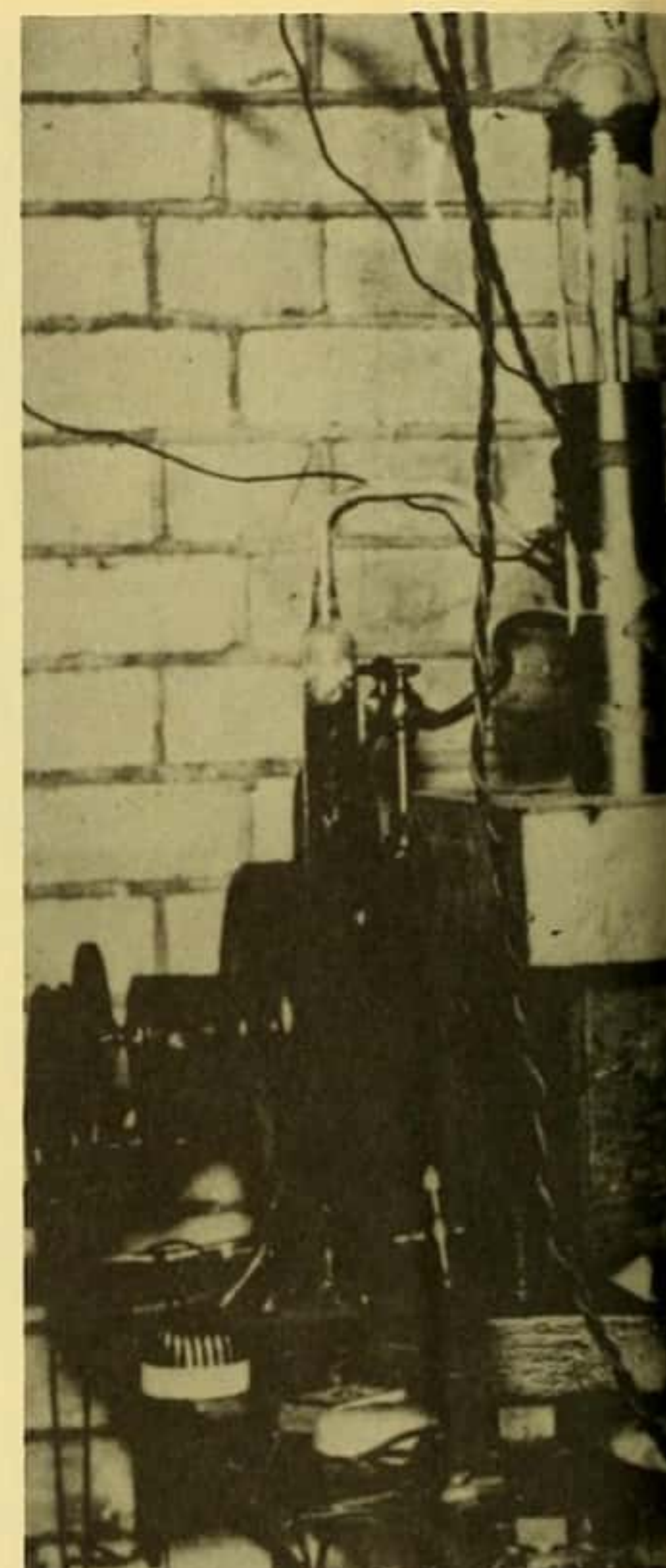
His revelation—the decisive and traumatic event—probably came with that second look. For Galileo saw that the shadows of the mountains on the moon had shifted and he easily estimated from the shadows that the mountains of the moon were about the same height as the mountains of the earth. Suddenly, it was a fact that the moon had mountains and seas. It was, moreover, a fact of nature that nobody had ever known before.

The enormity of the discovery must have been apparent immediately and it changed not just the career of Galileo and

*Luigi Galvani used an electrostatic generator to shock dead frogs, making their leg muscles contract. The experiment, which was illustrated in his 1791 book, did not "draw him near the secret of life" but it did draw him near the secret of current electricity.*

Detail of plate 1 of *De Viribus Electricitatis In Motu Musculari*, by Luigi Galvani





theories of astronomy but also the nature of scientific scholarship. For the first time, a person had made a discovery totally unavailable to other people and by a process that did not involve deep and clever thought. Galileo had discovered what was effectively a method of artificial revelation that simultaneously promised to add a great deal to the domain of science. The method itself created furious opposition from embattled church conservatives who were in the throes of the Reformation.

No matter what you thought of the method, it was difficult to dispute the new facts revealed through the telescope. They were facts that could fill anyone with awe—that Jupiter has satellites, that Venus has phases and is not self-luminous but lit by the sun, that there are enormous numbers of dim stars. The whole picture of the universe was changed and it became a Copernican picture, not a Ptolemaic one. Without the telescope, no worthy theorist ever would have made the switch to a model of the universe whose planetary kinematics seemed so much more complex and less accurate than the accepted model.

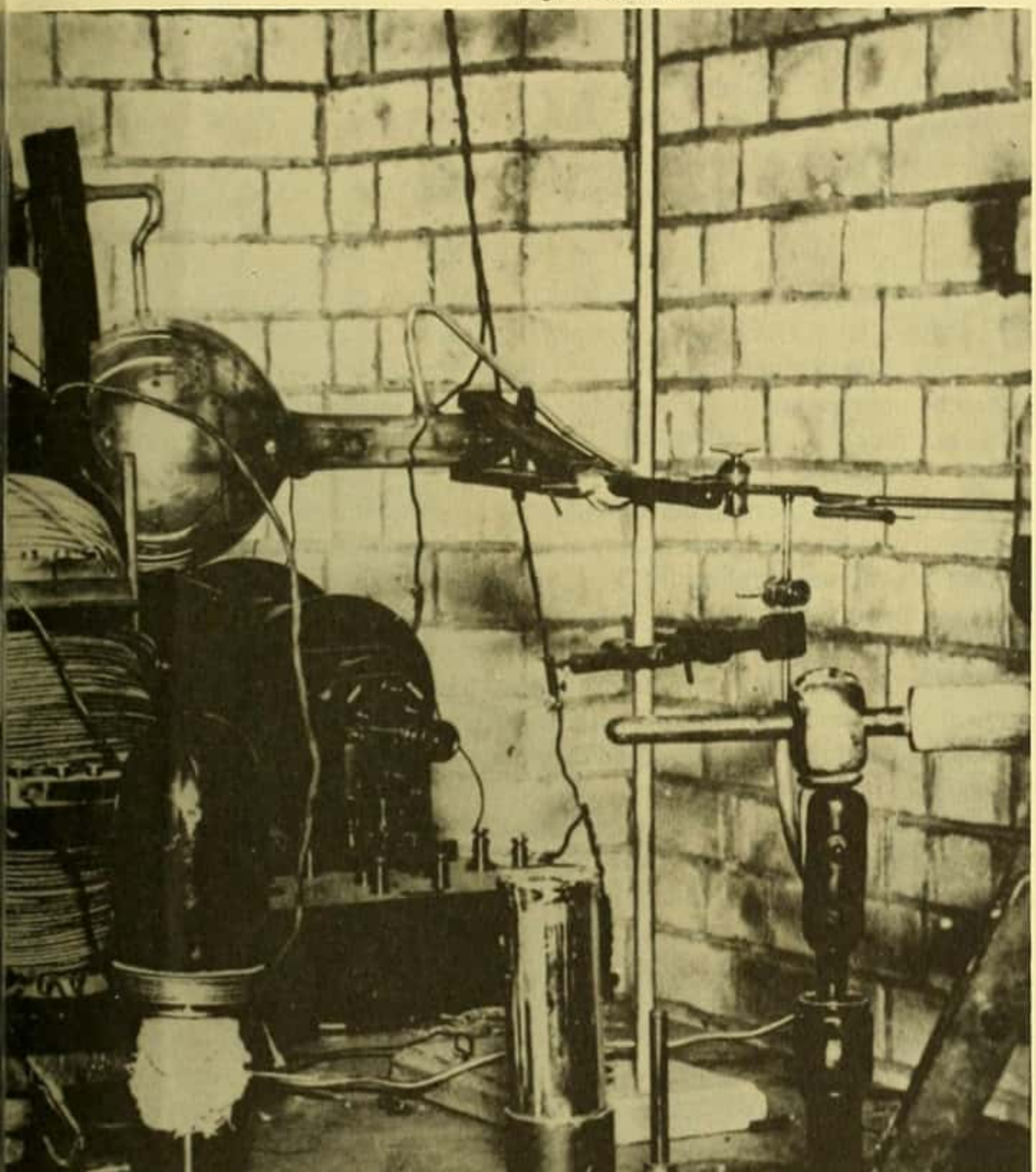
The telescope became a craze, and not just because of the particular discoveries. It represented a chance to "tune in and turn on" to the new philosophy of using instruments to find out things beyond the reach of the natural senses and not deducible by mere brain power. Every available technology was mobilized to develop more instruments with which more unsuspected facts of nature could be discovered. Once you had the telescope it was natural to study optics and find out why the device worked. From that work, other types of telescopes emerged and so did the microscope. Suddenly everyone was trying to dream up new ways to modify lab instruments and imbue them with the magic of the telescope. Work on the pumps for firefighting and mining led to the discovery of the vacuum pump and to the discovery of air itself as a gas. Thermoscopes and thermometers created a new world in which one thought more clearly about heat, knowing that neither pepper nor passion was really hot.

In short, the scientific revolution, as we call it, was largely the improvement and invention and use of a series of instruments of revelation that expanded the reach of science in innumerable directions, and almost fortuitously. Of course, there was more to it than that. There were theoreticians like Newton, whose mathematical analysis of dynamical astronomy and mechanics created the first great unification in modern science. There was the creation of the scientific academies which gave amateurs a chance to do re search and publish in journals. Their step by-step progress advanced knowledg much faster than it would have if they ha remained an unaided and unconnecte group of people off writing books by them selves. But predominantly it was the in struments, not any special logic of Franci Bacon, that gave rise to the new philoso phy, and those instruments came out o technologies that owed nothing to physics owed nothing to a desire to test theory.

The scientific revolution was pretty wel spent by the end of the seventeenth cen tury and things were rather quiet until th end of the eighteenth century, when an other revolutionary advance in technolog rocked science again. This time the ad

*At the Cavendish Laboratory at Cambridge, clever tinkerers used sealing wax and string to hold the vacuums in apparatus such as this mass spectrometer of about 1890. At many points in science history, craft information known to experimenters, rather than deep thought, determined what was discovered.*

Original source unknown



nce was to trigger the creation of noth- ; less than what we commonly call high hnology. As usual, it began with a emingly innocuous laboratory observa- n—not of the moon but of a frog.

Anatomist Luigi Galvani of Bologna d been using an electrostatic generator give dead frogs a shock, making their uscles contract. This was a very hot area research at the time, because the idea ld that the electric fluid passing into a g's nerves was stimulating its vital flu- , which in turn were causing the lifelike itch. Galvani and others felt that the ex- riment was drawing them near the se- t of life. But then Galvani noticed nething strange: the frog's muscles itched if you simply touched metal to em with the electric generator disconnected. They even twitched when hanging from a brass hook on an iron railing.

In Pavia, Alessandro Volta read Galvani's accounts of these experiments, began performing similar experiments, and decided that perhaps there was something about metal itself that could produce electric fluid. Volta started working with metal disks and soon found that electric fluid could be produced by putting a pair of disks around anything moist and acidic. A pile of such disk pairs produced a plentiful supply of electric fluid. This fluid, or current, was immediately recognized as a powerful chemical agent capable of causing the first new chemical effects since fire and water. Electric current could decompose water into gases and move the coating of one metal onto another. In a remarkably short time, many new chemical elements were discovered through electrolysis. Once people learned about such active elements as sodium and potassium a lot of new chemistry was up for grabs.

Within less than a generation, chemistry changed from being a deskful of alchemical supplies to being laboratories run by scientists like Davy and Faraday and Liebig. Out of these laboratories—where good chemists could analyze and synthesize at will—came fertilizers that could turn barren land fertile again, artificial dyestuffs that rejuvenated the textile revolution, antiseptics and anesthetics that created a new technology of surgery. Even while this was happening, lab scientists continued to study the nature of electricity. They soon realized it was more than a chemical juice and discovered its almost mystical relationship with magnetism. The subsequent realization that electricity is a form of energy was eventually to lead to the age of Edison.

Such an abbreviated history can only hint at the forces unleashed by the discovery of the electric battery. Moreover, the chemical revolution that followed was not just a series of cognitive advances; it transformed the lives of all people. Most of this happened not because of some new theories of Lavoisier or because of his careful measurements. It happened as a result of a lab experiment to find the secret of life in the back legs of a frog.

A wonderful irony of this period is that scientists began using the new electrical and magnetic apparatus to conduct all sorts of experiments. Somehow a few people got mixed up about how it had all happened, for it was precisely during this period that pioneers like William Whewell were writing histories of science that canonized these experimental procedures into the scientific method. It is true, however, that during this period, science had become the methodical testing of a rich store of hypotheses in electricity and chemistry. Simultaneously, there were new inventions and the public began to identify science with technology.

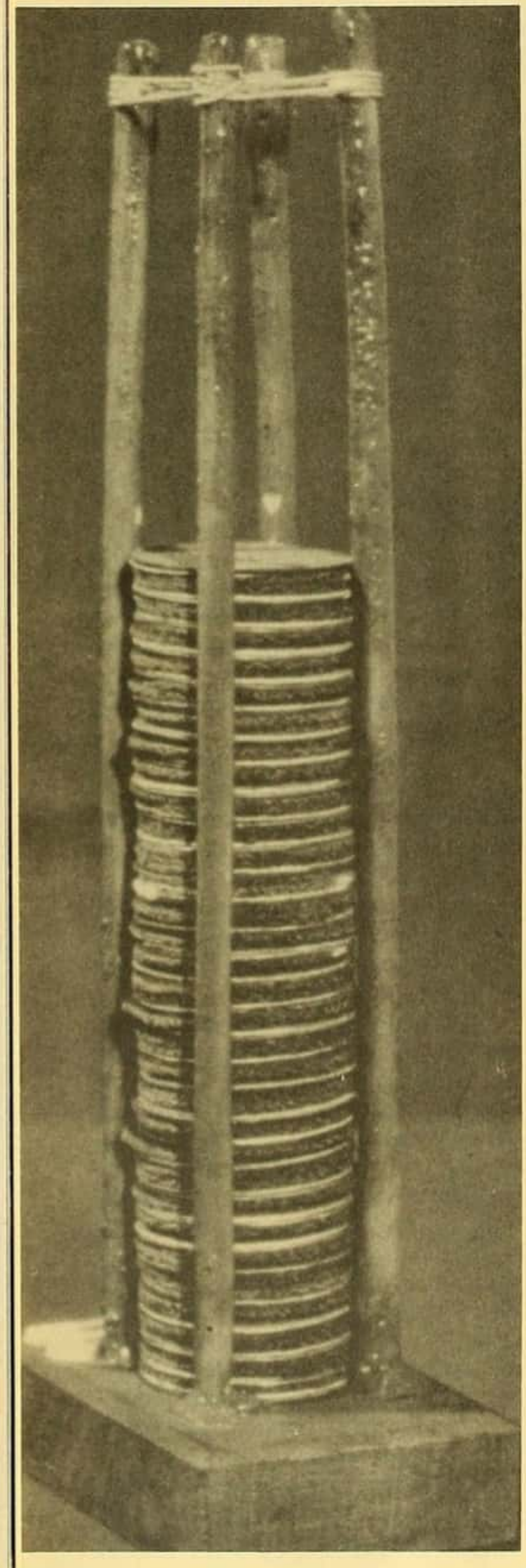
In the 1830s, universities started installing chemical laboratories, partly to fill what was now considered an educational

*Alessandro Volta of Pavia (1745–182*

Artist and original source unkno

*Volta's piles of disk pairs were the first wet battery. Volta started toying with disks after he read of Galvani's frog experiments and decided that metal might be the source of "electric fluid."*

Museo Nazionale della Scienza e della Technica Leonardo da Vinci, Milan, Italy



necessity and partly to train the new working class of the industrial revolution. Then in the 1870s the first physics labs were started up. Students were taught the art of precise measurement on such complex instruments as the Kew magnetometer. Of course, measurement is the heart of empirical procedure. But in about 1896, X-rays were discovered accidentally and so was radioactivity. Once again, the physical sciences broke out from their established boundaries and the laboratories began searching for new effects that would reveal the universe in different terms.

During the next several decades all scientists strived for was the discovery of unknown techniques, preferably ones that were aesthetically pretty, as well as interesting and revealing. The prime area of interest was creating a better vacuum and as a result scientists began working with sealing wax and string, which they used to tear down and build up apparatus a dozen times a day. Again, the new techniques were often discovered and used before they were understood. Mountaineering buff C.T.R. Wilson was trying to make artificial clouds, in the laboratory where Lord Rutherford happened to be doing his radioactivity experiments, when he accidentally discovered the cloud chamber, which enables you to see the tracks of atomic particles. Rutherford, who employed George Crowe as a lab assistant, discovered induced radioactivity while doing a dull series of measurements designed to test out his ideas about the transparencies of several gases to alpha particles.

It would be easy to extend this list of technological devices applied to science right up to the present. The Edison effect, Cerenkov radiation, the creep of liquid helium were all phenomena that revealed something we did not know before. Such experimentation is really a sort of fishing expedition, an adventure, because you never quite know what you will catch or what will happen. It cannot really be planned with an eye on any particular objective, though it is common to cite some goal as a necessary condition for getting funding. If a technique can be exploited in a new way, we have to push it—even though we may not know where it will take us. It also seems clear that we can nev know if the technical trick that causes much excitement in the laboratory m also be marketable by some bright entr preneur. I remember Patrick Haggert founder of Texas Instruments, telling m of his amazement that a gimmick h dreamed up to exploit the first mass pr duction of transistors ran away with th market. Nobody thought that the transi tor radio was more than a quick Christma fad. Nobody realized it would sell all ov the world and open up whole parts of th globe to modern communications.

The same sort of scenario evolved out work on the high-gradient furnace in th 1930s. The furnace had been develope very carefully and cunningly to make art ficial gems, and it was discovered that th furnace was particularly effective at mal ing rubies. Right about the time th method was perfected, rubies for minut bearings became an important strateg material in World War II.

Whether we are talking about a hug apparatus, such as a radiotelescope, or neat lab trick, such as Lowry's method protein analysis, instruments and tec niques are of crucial importance to sc ence as well as technology. But we ce tainly don't treat them that way. I science, whenever money is short, we pr fer to spend it on people rather than har ware. In social standing the technical ex perts and lab people are regarded a servants. The actual instrument industr is insignificant compared with other in dustries, such as automobiles or steel. Bu such an industry could be the point of or gin for giant inventions that set off whol new industries.

For four hundred years we have bee transforming the world by applying tech nology to science and thereby winnin new techniques as well as new understand ing. Every year in America we spend a lit tle less on hardware and on the relativel undirected experimental play with it. It i time to recognize what a powerful exoge nous force the experimental craft has bee and to incorporate the unmistakable les sons of history into our current policies fo science and our understanding of the his tory itself. □