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Galileo's Explorations In Science[1]

Explorations today apply the resources of science to obtain the most exact and useful information possible; we may call those "explorations *by* science." In this paper I shall describe some explorations long ago, through which science itself began to assume modern form. The explorer was Galileo, most of whose work consisted of what I call "explorations *in* science" contributing directly to astronomy and physics rather than to the application of science in other kinds of inquiry. Those in turn required him to make new explorations *of* science, when strong opposition to his discoveries and opinions made Galileo realize that the traditional view of science stood in the way of new explorations. During the seventeenth century the older abstract and philosophical approach to nature gained a new dimension of concreteness and utility, though only through a long struggle. Galileo's vision of new sciences was born in a society quite different from ours —a society in which admiration for the wisdom of the past was very great. He received the usual rewards and punishments that society metes out to such individuals, in his case so dramatically that the name of Galileo has come to stand as a symbol of discovery and of the battle for freedom of inquiry and expression.

Whether or not historically accurate, the story of Galileo and the Leaning Tower of Pisa offers me a good place to begin, since it comes near the start of Galileo's career and it mirrors the society in which the Scientific Revolution took place. As a young professor of mathematics at the University of Pisa, Galileo was teaching his students something that contradicted the physics of Aristotle that they had learned from their professors of philosophy. Galileo told them that heavy bodies dropped from a height would fall at the same speeds regardless of their weights, provided only that they were fairly heavy and were both of the same material. Aristotelian professors had told them that speeds in fall were proportional to weights; and if students then were like students now, they probably corrected Galileo. He replied by inviting them to bring along the philosophers and witness an actual test from the Leaning Tower. There they saw that a weight several times as heavy as another one of the same material did not reach the ground appreciably faster. Yet no professor appears to have changed his teaching. It was probably not a mere coincidence that Galileo's contract at Pisa was not renewed when it expired in 1592, and he moved to the University of Padua where he taught until 1610.

Late in life, writing notes in the margin of a book by an opponent, Galileo mentioned a reason for which he had doubted Aristotle's rule when he himself was still a beginning student at Pisa. He remembered that in a hailstorm he had seen hailstones the size of a walnut striking the ground together with others smaller than a pea. If Aristotle had been right, the larger stones should have got far ahead of the others in so long a fall. We cannot blame Galileo's students, since they may not have seen hailstorms, which are even rarer at Pisa than in Halifax. But we can blame the professors who misinformed them, whether or not they had observed hailstorms. University science had always in the past depended not on observation but on pure logic. Hence if there was a logical weakness in Aristotle's rule of fall, professors of philosophy should have spotted it. Because something Galileo wrote while still at Pisa exposed such a logical defect, there was something wrong not just with Aristotle's rule of fall, but with the whole approach to science. It was only by accident that Galileo had observed and remembered what he did. But it was not just by accident that he conducted an exploration *of* science as taught to him.

In a treatise on motion he wrote at Pisa, Galileo showed that Aristotle's rule could be refuted by logic alone. Two identical bricks would fall side by side; no doubt about that. If a piece of string was tied to them they still would. Shortening the string could not change that. Hence two bricks tied together end to end would fall at the same speed as either brick alone. Now throw away the string and glue the bricks together; no reason appears why this double brick of double weight should fall faster than two bricks tied together — or either one alone. In fall, one brick cannot weigh down on the other and push it faster. As Galileo remarked, that would be as impossible as it is to stab a man who is running away as fast as you are chasing him.

What Galileo's reasoning proved was not how heavy bodies actually fall, but that by using logic alone Aristotle had reached one conclusion and Galileo reached the opposite. To know what actually happens —that is, to have a *useful* science of physics — it is necessary at least once in a while to put matters to the test of actual observation. The Leaning Tower story extends far beyond a single fact of physics. It pictures a certain society and two views about the nature and purpose of science in competition for the minds of students, and does this in a way that throws light on Galileo's career and on the entire Scientific Revolution of the seventeenth century. The question whether this episode took place exactly as Galileo's first biographer described it is irrelevant to that picture. What is relevant is the question why pure logic, application of which the philosophers regarded as truly scientific exploration of nature, had in four centuries failed to lead professors to Galileo's paradox. Even a similar test that had been published in Holland in 1586 failed to affect the teaching of Aristotle's rule as university physics.

The Scientific Revolution began with such events and reached its climax half a century after Galileo's death in the work of Sir Isaac Newton, whose *Mathematical Principles of Natural Philosophy* was published in 1687 and established the basis of modern science. Twenty years earlier a group of Galileo's disciples published a book of scientific explorations in the name of a new scientific academy that adopted the motto *provando e riprovando* — testing, and testing again. This academy called itself the *Cimento,* meaning "ordeal' or even "torture," and the book was a collection of experimental investigations by which nature was put to the torture and forced to answer questions independently of philosophical opinion. The book was translated from Italian into English and Latin, was widely read throughout Europe, and had much to do with the founding and the policies of other early scientific academies.

I do not mean to imply that logic and philosophical debate dropped out of science; far from it. But a truly new dimension was added to natural philsophy, as physics was then called, when deliberately designed experiments became an integral part of exploration in science. As Galileo put his point vividly in the famous *Dialogue Concerning the Two Chief World Systems,* philosophers had discussed a world on paper, whereas he and his friends were talking about the sensible world around them. When Galileo explored that world, he discovered not only errors in Aristotelian natural philosophy, but also previously unsuspected laws governing nature. As Shakespeare, who was born the same year as Galileo, had Hamlet say: "There are more things in heaven and earth than are dreamt of in your philosophy."

It was no accident that thinkers as different as Shakespeare and Galileo, living far apart and writing for very different purposes, were both awake to the infinite variety of nature. In 1592, when Galileo moved to Padua and Shakespeare was revitalizing the English stage, a full century had gone by since Columbus had discovered the New World. It had been a century of exploration without rival in all past time. New plants, strange animals, even members of a race of men previously unknown in Europe had been brought back by navigators to show the truth of what must at first have seemed only tall tales invented by sailors. New things prepared the way for new ideas, though not quite sufficiently for the new sciences of Galileo, at least among those men who had always held authority in science. Had they been ready to listen; had professors of philosophy given support rather than oppositon to Galileo's discoveries and his view of science, theologians would not have intervened and Western culture might have been spared one of its greatest setbacks, of which some effects still linger today. I refer to the breaches that exist between religion, science, and philosophy itself.

"More things in heaven and earth" was what Shakespeare wrote in 1604. It was discovery of new things in the heavens that brought Galileo fame in 1610, only a year after his exploration of motions on the earth had yielded discoveries invaluable to Newton, who later credited Galileo for them. But Galileo did not publish those until near the end of his life, and since his explorations in the heavens were both more spectacular and more directly the source of oppositon from philosophers, I shall speak of them first and leave Galileo's explorations in physics to the last.

In March 1610 Galileo published at Venice a little book written in Latin, especially for the attention of astronomers and philosophers as he proclaimed on the title-page. He called it *Sidereus Nuncius,* or "The Starry Messenger," and in it he recounted discoveries made with the newly invented Dutch telescope which Galileo had improved to a power sufficient for astronomical use. For several months he enjoyed a virtual monopoly on telescopes that magnified twenty or more times, though instruments as strong as the ordinary fieldglass were not uncommon. Those had already made previously unseen stars visible, and Galileo's book included some in maps of familiar constellations. Because Aristotle had made it a basic principle of science that nothing new could ever appear in the heavens, even those observations stood as a challenge to the philosophers. Still worse was in store for them in Galileo's book, for it contained not just simple telescopic observations, but two new scientific conclusions against other principles of Aristotelian science.

The first of these concerned the moon. According to Aristotle, all heavenly bodes were perfectly spherical. Galileo declared that the moon's surface was rougher than that of the earth, covered with deep craters and high mountains. That did not follow from simple telescopic observation, as did the existence of stars too small to be seen with the naked eye, but was deduced from the detailed effects of changing illumination of the moon by the sun. Rims of lunar craters were first lighted on the side away from the sun; the sunlight then spread, as Galileo watched, in the pattern familiar to dwellers in terrestrial valleys. Sometimes isolated points of light appeared suddenly beyond the illuminated part of the moon, widening out and finally joining with that portion, just as earthly mountain peaks first catch the sunlight which then spreads downward. Now, to reason about heavenly bodies by analogy with the earth was objectionable to natural philosophers, who sharply distinguished celestial from terrestrial things. Galileo, on the contrary, regarded simple analogy as the best scientific approach — if not the only one possible. Noting the time required for complete illumination of one lunar mountain, he calculated its height as four miles, greater than any known to him on earth. So the moon, perfectly round in official science, was even rougher than the earth, not only relatively but absolutely.

An argument brought against Galileo's illustrates the character of official science that was defended against new observation and deduction. Two philosophers, one in Italy and one in Germany, maintained that the moon's surface was perfectly smooth and consisted of transparent crystal. What Galileo saw, they said, lay inside this perfectly transparent shell, not on the surface. Galileo was asked by a friendly cardinal to comment. He replied that he would accept this crystal surface if his adversaries, with equal courtesy, would allow him to make mountains of it even higher than the one he had measured. How could they be sure that enormous irregularities did not exist, when they themselves assumed the moon's crystalline surface to be transparent? Their assertion, he said, was based on selecting one of many possibilities and then declaring that one to be true.

The reasoning on which Aristotelians founded their conclusion was assumed perfection of the heavenly substance, and Galileo summed it up for them in his *Dialogue* thus:

> Being ingenerable, incorruptible, unalterable, invariant and eternal, celestial bodies must be absolutely perfect; and being perfect entails their having all kinds of perfection. Therefore their shape is perfect, which is to say that it is spherical; and absolutely so, not just approximately.[2]

Galileo's own spokesman in the *Dialogue* had this to say:

> These doctors of philosophy never concede the moon to be less polished than a mirror; they would like it to be more so, if that can be imagined. ... If they were to grant me any unevenness, however slight, I would grasp for some other, a little greater; and since perfection consists in infinitesimals, a hair spoils it as badly as does a mountain.[3]

The verbal and logical explorations that prevailed in science before Galileo departed from his visual and rationally deduced evidences, introduced with the telescope along with common terrestrial analogies. A second scientific exploration described in the *Starry Messenger* destroyed still another Aristotelian principle — that all heavenly bodies circle the earth as the unique center of celestial motions. Galileo's account shows how astronomical discovery is so embedded in the process of scientific exploration that it is hardly possible to set an exact moment for any discovery. Galileo wrote:

> On the seventh of January in this present year 1610, at the first hour after sunset when I was viewing the heavenly bodies with a telescope, Jupiter presented its body to me; and because I had prepared an excellent instrument I perceived — as I had not before, through weakness of my previous telescope — that beside the planet there were three starlets, very small indeed, but quite bright. Although I thought them to belong to the great host of fixed stars, they did arouse my curiosity somewhat by their appearing to lie exactly in a straight line parallel to the ecliptic [that is, along the zodiac or path of all the planets], and by their being more splendid than other stars their size.[4]

Since it is known that Galileo had seen three satellites of Jupiter, it is usually said that Jupiter's satellites were discovered on the night of 7 January 1610. In the same way we say that America was discovered on 12 October 1492, though on that day Columbus still believed that he had arrived at lands already known to earlier explorers like Marco Polo. Galileo thought at first that he was observing three fixed stars, similar to hundreds he had seen through his telescope on other nights, these three being distinguished only by their lying along a certain straight line, as fixed stars close together rarely do, and by their being rather bright for their size. So Galileo did not express amazement, or even decide to follow up the observation, as he did later when he recognized a true scientific discovery. His narrative continued:

> I paid no attention to the distances between the starlets and Jupiter, for as I said, I believed them at the outset to be fixed stars. Now, returning to the same investigation on January eighth, led by I know not what, I found a very different arrangement. The three starlets were now all to the west of Jupiter, closer together, and at equal distances apart.[5]

The element of luck that enters into nearly every scientific discovery is seen from Galileo's remark that he did not know what led him to look again at Jupiter. The element of observational skill that always enters into scientific discovery, and the faith in one's memory that nearly always does, are shown by his certainty as to the previous position even though at the time he had not especially attended to it. For next he wrote:

> At this point, though I still did not direct attention to the question how the starlets had gathered closer together, I did become concerned with the question how Jupiter could be eastward of all three stars when the night before it had been west of two of them. I wondered whether Jupiter was not moving eastward, contrary to the calculations of astronomers, and by that motion had got ahead of the starlets. Hence I awaited the next night with great interest. But my hope was disappointed, as the sky was then everywhere covered by clouds.[6]

Not only observational skill and memory, but also knowledge of planetary astronomy was needed at this step toward discovery. At that time Jupiter appeared from the earth to be moving westward among the fixed stars, as occasionally it does when the swifter-moving earth overtakes and passes it in their journeys around the sun. What Galileo saw did not seem to fit with that. The simplest solution might have been to suppose some error in the astronomical tables, since it would have been ridiculous to ascribe motion to what Galileo was assuming to be fixed stars. Another observation would confirm or contradict the tables, but of course that would require a clear sky. The next night was clear, and Galileo wrote:

> On the tenth of January ... there were only two starlets, the third, I supposed, being hidden behind Jupiter. As before, they were in a straight line with Jupiter and lay precisely along the zodiac. Noticing that, I knew that there was no way in which the change could be ascribed to Jupiter's motion alone. Yet I was certain that these were the same stars as before, no others in fact being visible for a long way along the line of the zodiac to either side of Jupiter. Thus my puzzlement was now transformed into amazement. Sure that the apparent changes of place belonged not to Jupiter but to the observed starlets, I resolved to pursue this investigation with greater care and attention.[7]

Galileo's amazement marked his realization that inescapable consequences of what he had seen could not be fitted with accepted science. Because he had considered every possibility as he went along, he was next forced to conclude that he was observing previously unknown *planets*, as all wandering stars were then called. That completed the destruction of Aristotle's principle forbidding new things in the heavens, already shaken by the existence of stars too small to be seen with the unaided eye. Moreover, it opened the way for rejection of still another ancient principle. On the night of 13 January Galileo first saw all four of the Jovian satellites which can be seen without powerful modern telescopes, no others having been found until 1890. On the fifteenth he concluded that their motions could be rationally explained only if they revolved around Jupiter as a center, contrary to the ancient notion that all celestial motions must have the earth as their center. Thus a series of discoveries occurred during the course of this exploration before any final scientific conlcusion was drawn. It is debatable which night should be called the date of discovery of Jupiter's principal satellites. On January seventh they were seen as fixed stars, and even the discovery on January tenth that the starlets must be moving did not reveal that they revolved around Jupiter.

Galileo's astronomical explorations were far from ended in 1610, but these first few had been enough to draw fire from many astronomers as well as all natural philosophers. Ground of opposition ranged from Aristotle's authority in science to charges that Galileo had deliberately perpetrated some hoax. Others argued that because curved glass distorts vision, Galileo himself had been fooled by mere optical illusions. He did not reply in print, though two or three of his friends did, while Galileo confined his own remarks to letters. He offered a reward to any philosopher who produced a telescope that could show optical illusions around one bright point and not around others. To the great German astronomer, Johann Kepler, who had supported him from the first, Galileo wrote that philosophers acted as if their wordy arguments were incantations that could conjure the new celestial objects out of the sky.

With Galileo the days of wordy magic came to an end for science. The whole verbal basis of accepted science was faulty; as Galileo later wrote, the great book of nature stood always open, but could not be read without one's knowing the language of mathematics. Astronomy had been written in that language ever since Ptolemy devised a system for calculating from past observations any planetary position, past or future. Physics, however, still remained qualitative. No one had yet provided mathematical means for calculating the positions of a heavy body falling to the earth, even straight, let alone after being thrown. That was exactly what Galileo had been doing when the telescope diverted his attention to astronomy, so I shall now turn back to his early explorations in physics.

At the time of the Leaning Tower episode not even Galileo, let alone Aristotle, had reasoned correctly about the fall of heavy bodies. Galileo had got closer to the truth, but he still had a long way to go. The real problem that had remained was to analyze accelerated motion, which in 1592 Galileo regarded as a mere temporary condition at the very beginning of fall, after which the body quickly attained a constant speed. Not until 1603 did he realize the need to take acceleration into account in his explorations of free fall. How he came to realize that need is made clear by examining his letters and working papers from 1602 to 1609.

By 1602 Galileo had noticed that as a pendulum dies down with smaller and smaller swings, it still takes the same time for each swing, somehow adjusting its own speeds to the distances it has to travel. Using a pendulum eight or ten feet long, he explored this more closely and noticed that the bob goes on accelerating even when its path is almost horizontal. It followed that a ball rolling down an inclined plane would go on accelerating no matter how long the plane was. That contradicted Galileo's older idea that a steady speed is soon reached in free fall, which should always be faster than descent along an incline. Galileo was willing enough to abandon his former idea, but a new puzzle now arose. Before he began to consider acceleration seriously he had already reasoned out a remarkable theorem, which was that the same time is consumed in straight motion of a heavy body from any point on the rim of a vertical circle to its lowest point, regardless of the length and slope of the connecting line. Actual tests showed his theorem to be true. Galileo now realized that the whole motions were accelerated, but that he had derived his theorem without taking acceleration into account. That puzzled him so much that it led to his exploration of mathematical physics, his most important contribution to modern science.

The fact was that Galileo's true theorem had been derived from false assumptions. People often overlook that true conclusions may follow logically from false premises, though no false conclusion can be logically reached from true premises. For example if we assume that polar bears are found in all very hot countries, and that Canada is a very hot country, it will follow that polar bears are found in Canada, as indeed they are. In arriving at his remarkable theorem, Galileo had assumed that acceleration could be ignored and that speed along an incline is steady at a rate depending only on the slope. When he later realized that acceleration cannot be ignored, he needed to find out exactly how the speeds increase during acceleration in natural descent.

That is a difficult thing to find out, for several reasons. Actual fall of heavy bodies is very swift and therefore hard to observe. Nor can speeds be measured directly, and in fact "speed" had never been mathematically defined. To measure speed indirectly, Galileo had to measure distances, which was easy, and also times, which were then hard to measure with accuracy. After some useless guesses at a rule of increasing speeds, Galileo settled down to scientific exploration of his problem. First, to slow the motion down, he could roll a ball down a gentle slope and assume that the rule for *increase* of speed would remain the same as for straight fall, though the *speeds* would be quite different. He chose a slope of only sixty parts in two thousand, which is an angle less than two degrees. Along a grooved plane at this angle Galileo allowed a bronze ball to roll from rest through a distance of two metres, which takes about four seconds of time. To divide that into eight equal times, he used musical beats of a half-second. Finally, he measured the distances from rest to where the ball was at the end of each time. Because the times were equal, the speed during each time was proportional to the distance measured. These distances, and likewise the speeds, were found to go up proportionately to the odd numbers 1, 3, 5, 7 ... and so on. Adding those numbers to get total distances from rest gave Galileo the square numbers 1, 4, 9, 16 ... and so on. In that way Galileo found the law of falling bodies, which states that distances from rest are as the squares of the elapsed times.

The law of fall was found early in 1604, though Galileo did not publish it until years later. When he did, he did not explain how he had discovered it, but described instead the apparatus he had used to verify it for different slopes and different distances. The process of discovery remained unknown until about five years ago, when I found among Galileo's working papers at Florence one on which he had written his original measurements together with notes and diagrams that made it possible to reconstruct his experiment. Previously there had been many debates among historians of science over the origin of the law of fall. Some believed Galileo to have found it by measurements, but others thought he had followed the ideas of medieval natural philosophers, while still others said he found the law by pure mathematics and never even tested it experimentally. That is still a very popular theory, despite the fact that for useful physics it is necessary at some point to connect every conclusion with the sensible world by careful measurements.

The trouble with official science up to Galileo's time was, as he said, that it dealt only with a world on paper. Galileo created a new science of motion linked to the actual world. Only incredible good luck could account for that if he merely substituted pure mathematics for Aristotle's traditional pure logic. Something more was necessary, and that something turns out to have been exact measurement. Measurements produce numbers that reveal mathematical laws. That is why physicists describe the apparatus and procedures of measurement that anyone can use in verifying the same results.

Now, when Galileo finally published his new science of motion, he described apparatus and procedures that others could duplicate, rather than those I described for the original discovery. In his *Two New Sciences* of 1638 Galileo included a way of comparing small times by collecting and weighing water flowing through a small hole in a large bucket while a ball rolls through some exact distance measured in advance. In 1961 a historian of science built the apparatus described by Galileo, followed his procedures, and found that twice the accuracy claimed by Galileo could actually be attained. Of course we can now make measurements more accurate than Galileo could, but his method of exploration in science, producing results that can be duplicated by others, has not basically changed since he first devised it. That method replaced the verbalisms of Aristotelian natural philosophy that, as we saw in the Leaning Tower episode, had allowed different people to reach diametrically opposite conclusions.

What I have said would be enough to establish Galileo as a pioneer explorer in, and of, science; but I am not yet through. What Galileo published in 1638, and guaranteed to be accurate within one-tenth of a second, fell far short of the precision he himself had attained in 1604. Modern analysis of his experiment shows that Galileo's accuracy in timing by half-second musical beats brought his original measurements of distances within a precision of one-sixtieth of a second. But of course he could not guarantee that kind of accuracy in tests by others, because individuals differ widely in their abilities to keep exact musical time. At beats of one-half second nearly anyone can detect a deviation of one-twentieth of a second, while trained musicians are sensitive to errors of one-hundredth of a second. Galileo's father and brother were professional musicians, while he himself was a talented amateur on the lute. The precision of his own original experiment is thus understandable, though it may sound incredible because we are used to using precision instruments and forget the capabilities of our own senses.

Some other things about Galileo's procedures are surprising. One that I have already mentioned is that, without a precedent to copy in science, when he published a procedure for verifying a mathematical law he took care to make it objective, so that anyone could follow it. He even specified the range of experimental error. Another is that Galileo avoided the use of measurements of single distances, times, or speeds. He used everything in the form of *ratios,* so that units of time or distance cancelled out, and anyone in England or France could test the law he discovered in Italy when there were no standard units of measurement. Likewise, by sticking to ratios, he did not have to specify such things as the size of hole in the bucket, because the *ratio* between volumes of water flowing through any hole while the ball rolls through distances in a given ratio will be the same no matter how much water flows, or how fast.

His law of fall enabled Galileo to solve many problems about motions of heavy bodies, starting in 1604. In 1608 he applied the rule of speeds in acceleration to test an old idea of his, that speed remains uniform in horizontal motion without friction. To do this he gave his ball various speeds in known ratios, having it drop from a level table to the floor, and measuring its distances of horizontal advance during fall. A by-product of this exploration was Galileo's discovery that projectiles travel in parabolic paths. Together with his law of fall that led on to Newton's laws of inertia and gravitation, which remained the foundations of modern physics until Einstein modified them. To me it seems that an ear for music and a talent for devising experiments did more than philosophy in laying a basis for modern physics as early as 1608.

In 1610 Galileo resigned his professorship at Padua and moved to Florence to become court mathematician to the Grand Duke of Tuscany. As he said in a letter applying for that position, he wanted to be free from teaching to pursue his researches and to publish. Because his telescopic discoveries had contradicted official university science, he may also have wished to avoid conflicts with the professors of philosophy. But there was no escape; at Florence, in 1611, Galileo became embroiled in a controversy with philosophers over the floating of solids placed in water. The book on hydrostatics he published in 1612 was written in Italian, as were all his later books — not in Latin for the benefit of philosophers and astronomers. Galileo saw little hope of reforming university science, as is clear from a letter he wrote to a friend at Padua:

> I wrote my last book in the common language because I want everyone to read it. What inspires me to do this is my seeing how students in the universities, sent indiscriminately to become doctors or philosophers, apply themselves in many cases to professions when unsuited for them, while others who would be apt are occupied with family cares and other pursuits remote from the literary. Now, I want them to see that just as Nature has given them, as well as philosophers, eyes to see her works, so she has also given them brains to understand them.[8]

It might seem unlikely that explorations in hydrostatics would interest the general public, but Galileo's results were so surprising, and so easy to check by carrying out simple experiments, that the book sold out quickly and a second, expanded edition was printed two months later. Four philosophers attacked it in print and then formed a league whose members opposed everything Galileo said from that time on. The reason was that Galileo questioned their whole conception of science, and especially the idea of finding causes, without which Aristotelian natural philosophy could not survive. Finding laws sufficed for Galileo's science.

In 1613 Galileo published a book on sunspots, at the end of which he came out for the first time in print in support of Copernican astronomy and predicting its ultimate victory. That gave his foes a way to strike at him as if religion rather than philosophy had been called in question. Late in 1613 a philosophy professor at Pisa told Galileo's employers, in his absence, that belief in motion of the earth was contrary to the Bible.

A Benedictine abbot happened to be present who had been a student of Galileo's at Padua and was now professor of mathematics at Pisa. Speaking as a theologian he defended Galileo, to whom he also reported what had happened. Galileo addressed to him a long letter on religion and science to make his own beliefs quite clear.

In 1614 Galileo reached the age of fifty. He enjoyed the friendship of cardinals and other Church dignitaries, to say nothing of the very Catholic ruling family at Florence. No churchman had attacked Galileo or his science. Philosophers of the hostile league considered getting some priest to attack his views, but were rebuked at the home of the archbishop of Florence. Yet near the end of 1614 a young priest did denounce the Galileists from the pulpit of a principal church. Another priest copied Galileo's letter on religion and science and sent it to the Roman Inquisition for investigation. Galileo's position was that no conflict could exist between God's word in the Bible and God's works in Nature. The words of scripture had often been found to be metaphorical and to require interpretation by theologians. Scientific understanding of natural phenomena, on the other hand, required only sensible experience and necessary demonstrations. Those could better serve as a basis for biblical interpretation than the other way round. In judging scientific findings, Galileo wrote, the last thing to be consulted were scriptural passages. The Inquisition turned this letter over to a qualified theologian, who reported that it contained good Catholic doctrine, though some of its expressions might offend pious ears. The matter was dropped by the Inquisition.

Galileo, however, feared that Copernican books would be prohibited unless responsible Church officials were fully informed about new discoveries and the new direction of science. He asked permission from the Grand Duke to visit Rome, where he could clear his own name and explain the new astronomy to theologians. The Tuscan ambassador at Rome cautioned the Grand Duke against letting Galileo to come there and argue about the moon, because the pope was unfavourable to intellectuals. Nevertheless the Grand Duke sent Galileo to Rome and even lodged him with the ambassador, implying state approval of Galileo's mission. At Rome Galileo wrote out his theory of the tides, which he linked to simultaneous rotation and revolution of the earth. It was a scientific but mistaken theory, based on the kind of motions we feel when seated in those amusement park devices that spin us around at the end of a long beam that is simultaneously revolving. Such motions of the earth would disturb the waters in large seas, and Galileo reasoned that they accounted for tides.

Despite Galileo's arguments the theologians empowered to qualify disputed propositions ruled that the Copernican motions were foolish and absurd in philosophy, and rash or even heretical in the Catholic faith. They did not consider metaphorical language in the Bible, but shifted their responsibility for interpreting scripture to the very philosophers who opposed Galileo. Copernican books were placed under regulation by an official edict early in 1616.

Galileo had lost his battle, but he had said all along that he would abide by any official Church ruling, and he was as good as his word. For several years he wrote no more about Copernicanism. Instead he took up an exploration *by* science of a practical problem, the determination of longitude on ships at sea. Galileo proposed that navigators use positions of Jupiter's satellites as a kind of celestial clock. He brought his tables of satellite motions to a high degree of reliability, but he failed to persuade admirals and sea-captains to accept his scientific solution of their practical problem.

In 1618 three comets appeared and Galileo entered into a long controversy with Jesuit astronomers over such phenomena. This led in 1623 to Galileo's main book containing explorations *of* science, called *The Assayer.* Science could advance, he believed, only by giving up vain pretensions and settling down to practicable goals:

> To put aside hints and speak plainly, and dealing with science as a method of demonstration and reasoning that is capable of human pursuit, I hold that the more this partakes of perfection, the smaller the number of propositions will it promise to teach, and even fewer will it conclusively prove. Consequently the more perfect it becomes, the less attractive it will be, and the fewer its followers. On the other hand magnificent book titles and grandiose promises attract the natural curiosity of mankind and hold men forever involved in fallacies and chimeras, without ever offering them one single sample of that sharpness of true proof by which the taste may be awakened to know how insipid is the ordinary fare.[9]

Just as this book was being printed, an old friend and admirer of Galileo's became pope, and the book was dedicated to him. In 1624 Galileo went to Rome to pay homage to the new pope, who was an intellectual and wanted the support of others. He was aware that the 1616 edict was making that difficult to secure, especially in Germany where Copernicanism was flourishing. Galileo undertook to write, as a Catholic scientist, a book that would show that the Church edict did not hamper scientific explorations, but only forbade unauthorized biblical interpretations and imprudent statements that motion of the earth had been proved. Foreign misunderstanding of the edict would be countered, the Church would benefit, and Italian primacy in science would continue. The pope liked the idea, and Galileo spent five years writing his book as a dialogue on the tides. But when its publication was licensed he was compelled to alter the title and with it the basic plan of organization. The consequences were disastrous; even the pope turned against Galileo, who was tried and condemned by the Inquisition. The book he wrote to rescue his church from consequences of an action he had warned it against has ever since been looked upon as an impudent defiance of that same church.

That is not the usual interpretation of the events; it is my interpretation after long study of Galileo's career. I regret that time does not allow me to tell the whole complex story; that would require a lecture all by itself. Instead I have shown you Galileo as an explorer at a time when science as a mode of exploration of the universe was first assuming its modern form. What stood in its way was not just religious conservatism, but the vanity of a whole intellectual tradition that claimed to explain all of nature in one grand plan. In conclusion I shall read some remarks by an eminent modern scientist that encourage me greatly as a historian. In his bicentennial address to the American Academy of Arts and Sciences, Professor Victor Weisskopf said, in part:

> Since the beginning of culture man has been curious about the world in which he lives; he has continually sought explanations for his own existence and for the existence of the world — how it was created, how it developed and brought forth life and humankind, and how one day it will end. Early ideas on that subject were developed in a mythological, religious or philosophical framework. All these ideas have a common characteristic: they are directed to the totality of the phenomena; they want to account for everything that is. They intend to present the absolute truth by attempting to give immediate answers to the fundamental questions of existence such as Why is the world the way we find it? What is life? What is the beginning and the end of the universe?
>
> Several hundred years ago human curiosity took a different turn: instead of reaching for the whole truth, people began to examine definable and clearly separable phenomena. They asked not ... How was the world created? but How do the planets move in the sky? In other words, general questions were shunned in favour of limited ones to which it seemed easier to get direct and unambiguous answers.
>
> Then the great miracle happened. The restraint was rewarded as the answers to limited questions became more and more general. The renunciation of immediate contact with absolute truth, the detour through the diversity of experience, allowed the methods of science to become more and more penetrating and the insights to become more and more fundamental. The study of moving bodies led to celestial mechanics and an understanding of the universality of the gravitational law. ... Thus something like a scientific world view arose in the twentieth century, a synthesis of scientific insights gained over the past five hundred years.
>
> The world view of natural science differs ... from the religious, mythological and philosophical ones. ... What it perceives as "the scientific truth" is steadily revealed in partial steps, sometimes big ones, sometimes small ones and sometimes even steps backward. Some present knowledge will turn out to be mistaken.[10]

It is this moderate world view that began with Galileo's explorations in science. As he wrote in his famous but illfated *Dialogue;*

> There is not a single effect in Nature, not even the least that exists, such that the most ingenious theorists can arrive at complete understanding of it. The vain presumption of understanding everything can have no other basis than never understanding anything. For anyone who had experienced just once the perfect understanding of one single thing, and who had truly tasted how knowledge is achieved, would recognize that of the infinity of other truths he understands nothing.[11]

NOTES

1. This is essentially the text of a lecture given in the 1981 Killam Lecture series at Dalhousie University.
2. Galileo, *Dialogue Concerning the Two Chief World Systems*, tr. S. Drake (Berkeley, 1953), p. 84
3. *Dialogue*, p. 80.
4. Galileo, *The Starry Messenger*, tr. S. Drake in *Discoveries and Opinions of Galileo* (New York, 1957), p. 51.
5. *Starry Messenger*, pp. 51-2.
6. *Starry Messenger*, p. 52
7. *Starry Messenger*, p. 52.
8. *Discoveries*, p. 84.
9. Galileo, *The Assayer* in *Discoveries*, pp. 239-40.
10. *Bulletin, The American Academy of Arts and Sciences*, vol. xxxv, no. 2 (November, 1981), pp. 4-5.
11. *Dialogue*, p. 101.