EVOLUTION OF SCIENTIFIC THOUGHT
LABORATORY III

Galileo's Inclined Plane Experiment

At Galileo's trial of 1632/33, the *Dialogue on the Two Chief World Systems* was "prohibited by public edict," and Galileo himself was sentenced to "formal imprisonment in this Holy Office at our pleasure."[1] The sentence was shortly commuted to house arrest at Galileo's villa at Arcetri, outside Florence. There, Galileo resumed work on a book on motion, eventually published in Holland in 1638—the *Discourse on Two New Sciences*. This book was also written in the form of a dialgue, with the same three characters: Salviati, Sagredo, and Simplicio, who discuss a treatise written by our "Academician" (or sometimes "Author")—that is, Galileo. Unlike the Dialogue, however, this new book was not about astronomy—the two new sciences were "the resistance of solid bodies to separation," and "local motion."

By "local motion," Galileo had in mind the analysis of inertia, falling bodies, and projectile motion for which we remember him. He had worked on these ideas for most of his life—for example, his understanding of the principle of inertia was surely among the factors that led him to support a Copernican cosmology. Moreover, his work on motion was the starting point for many other 17th century scientists, including Newton. So it is important to understand something of this side of Galileo's work.

It would be beyond the scope of the course to do a full treatment of how Galileo's ideas on motion developed—the question is complex, and a complete discussion gets fairly mathematical. We know he started out as a fairly conventional Aristotelian. His early lecture notes, for example, seem to have been borrowed from some of the Jesuit mathematicians at the Collegio Romano. But over the years, Galileo slowly moved away from that tradition, and as he did so, developed the ideas he expounded both in the *Dialogue* and the *Discourse*.

One of the problems Galileo analyzed is that of a freely falling object. His analysis is very close to the one we use today in beginning physics courses. We say that the acceleration is constant, and use that assumption to show that an object falling from rest moves a distance that is proportional to the square of the time it takes the object to fall:

$$\text{distance} \propto \text{time}^2$$

(The symbol $\propto$ means "proportional to." Another form in which you may have seen this result is

$$s = \frac{1}{2}gt^2$$

where s = distance, t = time, and g is the acceleration of gravity. (By acceleration, we mean the rate at which velocity is changing—that is, how fast an object is speeding up or slowing down.)

---

[1] Finocchiaro, page 310

This last equation would have made no sense to Galileo. How, he might ask, can a *distance* be proportional to a *time*. It can only make sense to talk about the ratio of two *like* quantities—two distances, for example, or two times. Thus, Galileo would have expressed his free fall law by saying that the ratio of the distances through which two objects fell is proportional to the ration of the squares of the times. In equation form—which Galileo did not use, but which is more familiar today—we would write

$$\frac{s_1}{s_2} = \frac{t_1^2}{t_2^2}$$

Galileo derived this result geometrically, from the assumption that the acceleration is constant (that is, the assumption that the velocity increases at a constant rate).

But is the assumption correct? Galileo describes an experiment in which he claimed to have tested the result. Here is the passage in the *Discourse*—first, the statement of the law:

> Proposition II.
>
> If a moveable descends from rest in uniformly accelerated motion, the spaces run through in any times whatever are to each other as the duplicate ratio of their times; that is, as the squares of those times.

Salviati, Sagredo, and Simplicio work out some of the consequences of this theorem, after which the conversation proceeds as follows:

> *Simplicio* Really I have taken more pleasure from this simple and clear reasoning of Sagredo's than from the (for me) more obscure demonstration of the Author [that is, Galileo], so that I am better able to see why the matter must proceed in this way, once the definition of uniformly accelerated motion has been postulated and accepted. But I am still doubtful whether this is the acceleration employed by nature in the motion of her falling heavy bodies. Hence, for my understanding and for that of other people like me, I think that it would be suitable at this place to adduce some experiment from those (of which you have said that there are many) that agree in various cases with the demonstrated conclusions.
>
> *Salviati* Like a true scientist, you make a very reasonable demand, for this is usual and necessary in those sciences which apply mathematical demonstrations to physical conclusions, as may be seen among writers on optics, astronomers, mechanics, musicians, and others who confirm their principles with sensory experiences that are the foundations of all the resulting structure. I do not want to have it appear as waste of time on our part, as if we had reasoned at excessive length about this first and chief foundation upon which rests an immense frame work of infinitely many conclusions—of which we have only a tiny part put down in this

book by the Author, who will have gone far to open the entrance and portal that has until now been closed to speculative minds. Therefore as to the experiments: the Author has not failed to make them, and in order to be assured that the acceleration of heavy bodies falling naturally does follow the ratio expounded above, I have often made the test in the following manner, and in his company.

In a wooden beam or rafter about twelve braccia long, half a braccio wide, and three inches thick, a channel was rabbeted in along the narrowest dimension, a little over an inch wide and made very straight; so that it would be clean and smooth, there was glued within it a piece of vellum, as much smoothed and cleaned as possible. On this beam there was made to descend a very hard bronze ball, well rounded and polished, the beam having been tilted by elevating one end of it above the horizontal plane from one to two braccia, at will. As I said, the ball was allowed to descend along the said groove, and we noted (in the manner that I shall presently tell you) the time that it consumed in running all the way, repeating the same process many times, in order to be quite sure as to the amount of time, in which we never found a difference of even the tenth part of a pulse beat.

This operation being precisely established, we made the same ball descend only one-quarter the length of this channel, and the time of its descent being measured, was found always to be precisely one-half the other. Next making the experiment for other lengths, examining now the time for the whole length [compared to] the time of one-half, or with that of two- thirds, or of three-quarters, and finally with any other division, by experiments repeated a full hundred times, the spaces were always found to be to one another as the squares of the times. And this result held for all inclinations of the plane; that is, of the channel in which the ball was made to descend, where we observed also that the times of descent for diverse inclinations maintained among themselves accurately that ratio that we shall find later assigned and demonstrated by our Author.

As to the measure of time, we had a large pail filled with water and fastened from above, which had a slender tube affixed to its bottom, through which a narrow thread of water ran; the water was received in a little beaker during the entire ti;me that the ball descended along the channel or parts of it. The little amounts of water collected in this way were weighed from time to time on a delicate balance, the differences and rations of the weights giving us the differences and ratios of the ti;mes, and with such precision that, as I have said, these operations repeated time and again never differed by any notable amount.

Simplicio It would have given me great satisfaction to have been present at these experiments, but being certain of your diligence in making them and your fidelity in relating them, I am content to assume them as most

> certain and true.
>
> *Salviati* Then we may resume our reading, and proceed.[2]

Did Galileo in fact conduct such an experiment? And if he did, was it accurate enough to justify the claims he made for it—that it was accurate enough to confirm the t^2 law? Martin Mersenne, a French friar and close friend of Descartes, who assisted in getting the *Discourse* published, nevertheless seems to have wondered if the experiment had been this good.

More recently, the Frence historian of science Alexandre Koyré has written

> A bronze ball rolling in a "smooth and polished" wooden groove! A vessel of water with a small hole through which it runs out and which one collects in a small glass in order to weigh it afterwards and thus measure the times of descent . . . : what an accumulation of sources of error and inexactitude! [3]

But another contemporary historian has tried to repeat the experiment, and has argued that Galileo could indeed have performed it much as described.[4]

Who is right here? And what role does experiment play in science. We will approach these questions by attempting to duplicate Galileo's experiment as closely as we can. I have tried to reconstruct Galileo's apparatus as closely as possible, water clocks and all! (Stillman Drake has suggested another possible way Galileo might have measured time: recalling that Galileo's father was a prominent musician, Drake has suggested that Galileo measured time by "beating time" as the ball rolled down the plane! Feel free to sing to your apparatus if the spirit moves you!!)

Begin the experiment by becoming familiar with the apparatus. Work out for yourself what sort of data you will need to take, and how you will take it. Make some practice runs. Be sure you practice with the water clock as well as with the inclined planes. It might also be interesting to do a few runs with a modern stopwatch, and see how the results compare. As always, keep a careful record of what you are doing in your laboratory notebook.

When you are satisfied with your plan for doing the experiment, talk it over with me, and then do the experiment. It might be of interest to compare your results with those of others in the class. In writing your conclusions, you may wish to address the following questions:

- Do your results appear to confirm the t^2 law? How well do you trust your data?

---

[2] *Discourse*, Third Day; Drake translation, pages 166ff.

[3] Alexandre Koyré, "An Experiment in Measurement," *Proceedings of the American Philosophical Society* **97** (1953), 222–237.

[4] Thomas B. Settle, "An Experiment in the History of Science," *Science* **133** (1961), 19–23.

- Could Galileo have used this experiment to confirm the t^2 law?
- Is it in your opinion possible that Galileo used this experiment to *discover* the t^2 law?

This list is of course not inclusive. What other points of interest did you come across in doing the experment?