

# Reconstructing Galileo's Inclined Plane Experiments for Teaching Purposes

Falk RIESS, Peter HEERING, Dennis NAWRATH  
Physics Education/History and Philosophy of Science, University of Oldenburg

## Abstract

Galileo performed his free fall experiments with the inclined plane in 1603 and published them in his *Discourses on Two New Sciences* (1638). The setup consists of a “*piece of wooden moulding or scantling, about 12 cubits long, half a cubit wide, and three finger-breadths thick*” with a channel cut in it, and a bronze ball rolling down. The running time was measured (by a variety of means) dependent on the inclination of the plane, and so the law of the “retarded” free fall could be determined.

We rebuilt the apparatus and reconstructed the experiments Galileo might have made the results of which will be made available on the internet in the form of video recordings. Inquiry based learning environments could comprise the question of time measurement and the derivation of the respective formula.

## Introduction

One of the best known experiments with respect to the discussion of free fall is the inclined plane experiment that was published by Galileo Galilei in 1638. This experiment has been analysed by the Oldenburg group with the replication method. Currently, we are working on teaching material that will give access to our experiences with this set-up for teachers and students. Moreover, we are reconstructing a demonstration apparatus developed in the 18<sup>th</sup> century to teach free fall and the superposition principle.

## Historiographical background

"One of the most controversial issues in the history of science has been the question of how far Galileo's achievement in mechanics was dependent on the use of experiment" (Naylor 1976, 153). When this statement was published, the controversy was almost settled. Whilst in the beginning of the 20<sup>th</sup> century, most historians of science followed in particular Mach's notion of Galileo being the father of experimental practice, things changed when the philosopher Alexandre Koyré questioned whether Galileo had actually performed the experiments he described in his publications (Koyré 1966), (Koyré 1968). In 1961, Thomas Settle used a reconstruction in order to show that it is possible in principle to carry out the

experiments described by Galileo (Settle 1961)<sup>1</sup>. Moreover, he also used this set-up to develop an understanding of the experimental procedures as well as the skills necessary for the experiment.

The question of whether Galileo actually did experiments or not came almost to an end with Drake's finding of a manuscript page obviously containing experimental data (Drake 1973). However, the publication of this manuscript did not end the discussion of *how* Galileo could have performed his experiments.

Two years later, Drake published another paper on Galileo's inclined plane experiment. One of the questions still unsettled in the discussion of historians was related to the time measurement in Galileo's experiments. In his published accounts, Galileo referred either to his pulse or to a water clock. Both methods appeared to be too inaccurate to be useful in establishing a mathematical relation. In his paper, Drake proposed another method of timing that was available to Galileo and actually could be related to his private context. As he came from a family of musicians<sup>2</sup>, Galileo may have used rhythms in order to measure very short time intervals: Thus it may have been possible for Galileo to realise the time measurement by deciding "when a single set of external sounds agrees with a strong internal rhythm. Those who have studied music with a professional performer know how remarkably the last ability can be developed" (Drake 1975, 103)<sup>3</sup>.

Even though this paragraph is just a brief sketch of the historical discussions of Galileo's inclined plane experiments, it should get clear that questions with respect to aspects such as accuracy, measuring procedures, communication of experimental results, and what is to be taken as an inductive approach can be connected with this experiment. Apart from that, the scientific meaning of the experimental findings is still highly relevant: This is probably one of the reasons why several attempts to redo the experiment have been carried out<sup>4</sup>.

The attempts to reconstruct Galileo's experiments that have been discussed up to now have in common that the experiments were redone in order to develop a further understanding in historiographical or epistemological questions. Some of the papers published in connection with these questions formed part of the basis of Jürgen Teichmann's work who used a reconstructed inclined plane for didactical purposes. This set-up was used to demonstrate in teaching situations that the content of the manuscript page published by Drake could be interpreted as data (Teichmann 1979).

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<sup>1</sup> The attempt to actually redoing Galilean experiments in order to show that they can actually be carried out - contrary to Koyré's statements - was not limited to Settle, some ten years later James MacLachlan published further evidence that several of Galileo's experiments that were considered to be thought experiments could actually be performed. See (MacLachlan 1973) and (MacLachlan 1976).

<sup>2</sup> Actually, in the field of musical theory Galileo's father Vincenzo carried out "true scientific experiments in the sense in which we have defined that term: the manipulation of physical objects for the purpose of verifying a mathematical rule ..." (Drake 1970, 497). Thus, Galileo was not only familiar with music but also with this method of demonstrating mathematical relations.

<sup>3</sup> For this discussion, an earlier observation of Drake is relevant: "In the sixteenth century, music and mechanics were more obviously closely related sciences than they are today" (Drake 1970, 487). For a critical discussion of Drake's analysis that includes the redoing of experiments with the inclined plane see Naylor (1980).

<sup>4</sup> For a recent attempt to redo Galileo's inclined plane experiments see [http://galileo.rice.edu/lib/student\\_work/experiment95/index.html](http://galileo.rice.edu/lib/student_work/experiment95/index.html), 2005-09-06.

## Galileo's description of his experiments

*A piece of wooden moulding or scantling, about 12 cubits long, half a cubit wide, and three finger-breadths thick, was taken; on its edge was cut a channel a little more than one finger in breadth; having made this groove very straight, smooth, and polished, and having lined it with parchment, also as smooth and polished as possible, we rolled along it a hard, smooth, and very round bronze ball. Having placed this board in a sloping position, by raising one end some one or two cubits above the other, we rolled the ball, as I was just saying, along the channel, noting, in a manner presently to be described, the time required to make the descent. We repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse-beat. Having performed this operation and having assured ourselves of its reliability, we now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half of the former. Next we tried other distances, compared the time for the whole length with that for the half, or with that for two-thirds, or three-fourths, or indeed for any fraction; in such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true for all inclinations of the plane, i.e., of the channel, along which we rolled the ball. We also observed that the times of descent, for various inclinations of the plane, bore to one another precisely that ratio which, as we shall see later, the Author had predicted and demonstrated for them.*

*For the measurement of time, we employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water which we collected in a small glass during the time of each descent, whether for the whole length of the channel or for part of its length; the water thus collected was weighed, after each descent, on a very accurate balance; the differences and ratios of these weights gave us the differences and ratios of the times, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results (Galilei 1954, 178-179).*

## The Oldenburg version of the inclined plane

In order to develop an understanding of Galileo's practice as well as to develop potential teaching materials, we decided to analyse the inclined plane experiment with the replication method<sup>5</sup>.

According to the dimensions given by Galileo in his publication our replica consists of a wooden block of 666.5 cm x 28 cm x 9 cm. A channel shaped like a semicircle was cut into it, 3.5 cm wide and 1.5 cm deep (fig.1 and 2). One end of the inclined plane was lifted by the help of a cuboid, its measures were 110cm \* 55cm \* 28cm.

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<sup>5</sup> For a brief sketch of this method as it is used by the Oldenburg group see (Heering 2005). Detailed discussions (in German) are to be found in (Heering 1998), (Rieß 1998) and (Sichau 2002).



Fig. 1: Reconstructed inclined plane



Fig. 2: Details of the inclined plane and the semicircle shaped channel

The channel was lined with a parchment-like paper to smooth it, the transitions between the pages were smoothed by fine sandpaper. We use brass balls of 20, 25, and 30 mm diameter (fig.3); Galileo did not give the size of the balls he used.



Fig. 3: Brass balls used in the experiments placed in the reconstructed semicircle of the inclined plane

## Time measurement

As already mentioned, in the description of his experiment Galileo refers to a method of time measurement called the water clock. In our experiments we used a similar device (fig.3). The water clock consists of a 25 l plastic vessel which can be opened and closed at the lower end by the help of a stopcock. Provided that the filling height is sufficient there is a linear relationship between past time and the quantity of water which can be determined by weighing or with the help of a measuring cylinder. As it turns out while redoing the experiment, a central experimental difficulty is the coordination between the signal of the running ball and starting and stopping the clock.



Fig. 4: Water clock

In the experiments, opening and closing the stopcock of the water clock turned out to be by far too imprecise so that the procedure was modified: Instead of using the stopcock, the flow of water through the flexible tube behind the stopcock was suspended with the thumb of one hand. In the experiment, the ball was released with the other hand and at the same time, the water clock was started by removing the thumb. When the ball reached the end of the inclined plane, the sound was taken as the signal to suspend the flow of water with the thumb again. In

series of measurements, the ball was released in a manner that it had to roll  $\frac{1}{4}$ ,  $\frac{1}{2}$ ,  $\frac{3}{4}$ , and the entire length of the plane until it reached the end. These experiments led to the following results:

Water /ml quarter of the length	Water/ml half the length	Water/ml three quarters of the length	Water/ml entire length
24,5	33,5	41,5	45,5*
24,0	33,5	40,5	47,5
23,5	33,5	40,0	46,0
23,5	34,5	42,5	47,0
23,5	32,5	41,0	46,5
23,5	32,0	40,5	47,5
23,5	33,5	40,0	46,0
23,5	32,5	40,5	47,5
25,0*	33,5	41,5	47,5
24,0	34,0	41,0	46,0
$\sigma=23,72$	$\sigma=33,30$	$\sigma=40,9$	$\sigma=46,83$

Table 1: Results for a ball with a diameter of 30 mm and an angle of the inclined plane of  $5^{\circ}$ <sup>6</sup>

As can be seen from these data, the time deviation of the measurement between two individual runs can be up to 2.5 ml. This amount corresponds to 0.25 seconds and is longer than the value given by Galileo who had claimed to have gotten results with a deviation of no more than a tenth of a pulse (about one tenth of a second). Thus, it appeared to be questionable whether our set-up differs in some relevant detail from Galileo's, whether we have to develop necessary skills in order to achieve data with a deviation as little as indicated by Galileo, or whether Galileo's claim with respect to the accuracy of his measurements can be taken as justified.

In order to develop an understanding of the possible accuracy that can be obtained with the modification of the time measuring procedure suggested by Stillman Drake, we started to use adjustable strings (fig.5) to create a steady rhythm which can be compared with the musical rhythm of a lute player.

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<sup>6</sup> The data with an \* resulted from runs that were judged as being erroneous and thus were not included in calculating the mean. All data reproduced in this paper result from the independent experimentation of B. Graalman to whom we are indebted as we benefit in our discussion significantly from the results of her experimental skills. Her experiences are documented in Graalman (1999).



Fig. 5: Ball touching a string

Eight strings were initially adjusted at equal distances and then moved during several runs in positions that the tones of the strings were in rhythm with the music. However, this method turned out to be less accurate than we expected. Actually, we learned that it is easier to perform the experiment without any music but to have a steady rhythm in mind and to adjust the strings in a manner that the tones of the strings were in time with this rhythm. If several runs had shown no necessity to change the position of any of the strings, the distances of the strings were determined. These experiments were performed with different inclination angles of the plane. The following results are characteristic:

Distance of the string from starting point/cm	Multiple of 3.1 cm	Theoretical distance/cm	Deviation/cm	Deviation/%	Deviation of time/s
3,1	1,0				
12,3	4,0	12,4	-0,1	-0,8	0,00
27,8	9,0	27,9	-0,1	-0,4	0,00
49,9	16,1	49,6	+0,3	+0,6	+0,01
78,8	25,4	77,5	+1,3	+1,7	+0,02
110,0	35,5	111,6	-1,6	-1,4	-0,03
150,4	48,5	151,9	-1,5	-1,0	-0,02
197,6	63,7	198,4	-0,8	-0,4	+0,01

Table 2: Results at an angle of  $1.9^\circ$  and no external rhythm

From these results it gets clear that it is actually possible to use an inclined plane in order to demonstrate the law of free fall.

Having been able to get reproducible data with the inclined plane experiment that can serve as an illustration of the law of free fall, the next steps in our project will be to document the inclined plane experiment in a manner that this documentation can be placed online.

Moreover, we are attempting to reconstruct another device: a set-up that has been described by Willem Jacobus 's Gravesande (1688-1742) in his *Mathematical Elements of Physicks* and which was probably constructed by Jan van Musschenbroek (1687-1748). This apparatus which is nowadays kept in the [Boerhaave Museum Leiden](#)<sup>7</sup> (see Fig. 6) was designed to demonstrate the law of free fall as well as the principle of superposition. A ball is released at the top of the jump, rolls down and then flies through four brass rings which show that the ball's trajectory is parabolic.



Fig. 6: Teaching apparatus constructed by Jan van Musschenbroek, kept at the Museum Boerhaave

Experiments with both reconstructed apparatus are to be videotaped and will be placed online, thus enabling teachers as well as students to get an idea of those early attempts to demonstrate the laws of free fall. The materials developed in connection with this project will be published at <http://ppp.unipv.it/map/><sup>8</sup>.

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<sup>7</sup> We are indebted to Hans Hooijmaijers who made this set-up accessible to us so that we could get all the information necessary to reconstruct this apparatus. A brief description of the set-up can be found in de Clercq (1997).

<sup>8</sup> This is the webpage of the 'The MAP prOject', which is a European Commission project (Comenius 2.1, Grant Agreement number: 118873 - CP - 1 - 2004 - 1 - GR - COMENIUS - C21). We appreciate that our project benefits significantly from the financial support that we receive within this project.

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