What happens when balls of different diameter are let roll down the whole length of the inclined plane?

Eric Hatleback
University of Pittsburgh

Introduction

Recently, a subculture of experimental recreation has emerged in the history of science field. The present paper is aimed at evaluating this subculture from a methodological standpoint. Specifically, it appears as though, just as experimental recreation has become established as a legitimate off-shoot of history of science proper, so, too, several separate off-shoots have begun to emerge from experimental recreation according to the purpose for which the recreation is undertaken. Three particular types of experimental recreation can be identified, with each of the three serving a different role in the process of historical investigation.

Part 1 of this project introduces the three types of recreation through a survey of experimental recreation that is chiefly focused on the Galileo literature. Part 2 furthers the findings of Part 1 by providing a case study of the newly-developed third branch of experimental recreation, the philosophical recreation. The focus is Galileo’s inclined plane, and the findings provide reason to question Galileo’s justification for using the inclined plane experiment in the development of his theory of moving bodies.

Part 1: The Branches of Experimental History of Science

A survey of the literature involving historical recreations reveals that three distinct branches of experimental history of science have come to the fore, one of which will be the focus of Part 2 of this work. Typically, the methodology involved in any particular recreation is revealed by the thesis presented by the author undertaking the recreation.[1] This being the case, the simplest means of establishing the goal of the present paper is to investigate the goals of the authors involved in experimental recreation. Broadly speaking, three general types of thesis are to be found: (1) to establish (or refute) the occurrence of the original historical experiment; (2) to establish (or refute) the veracity of the data, results, or other specifics reported from the (accepted) occurrence of the original historical experiment; and (3) to inspect the original use of the historical experiment by the historical figure for the purposes of investigating the role played by the experiment for the experimenter in theory development or the acquisition of scientific knowledge.

Type (1) will be referred to as *historical legitimacy* recreations, type (2) will be referred to as *historical accuracy* recreations, and type (3) will be referred to as *philosophical* recreations. The bulk of the extant literature involves historical legitimacy and historical accuracy recreations, whereas philosophical recreations are nascent but vital to the growth of the experimental recreation movement; Part 2 of the paper will present one such case of the novel type. This part of the paper will display the fundamental differences among the three types by examining examples of each type.

1.1 Historical Legitimacy Recreations

Thomas Settle is widely credited with initiating the experimental recreation niche. His work, spurred by the accusations of Alexander Koyré against Galileo's use experiment, involved the aim of demonstrating that it is plausible that Galileo actually

[1] Note that the success or failure of either the recreation or the author's analysis is irrelevant for the purposes of this investigation; what matters is *the intent of the author* in performing the recreation, and this (nearly always) is revealed by the thesis that the author chooses to defend in his or her work.

performed his famous inclined plane experiment.[2] Here is his thesis in that work: "I hope to show that this experiment [Galileo's inclined plane], once conceived and brought to full maturity, is simple, straightforward, and easy to execute."[3] While there is no doubt that Settle fleetingly discusses the importance of this experiment to Galileo's intellectual development (which might supply reason in the present project to label Settle's recreation as philosophical), there is likewise no doubt that his *chief* aim in performing the recreation is to demonstrate the legitimacy of Galileo's claim to have performed the experiment in Renaissance Italy.[4]

Following Settle, there have been others. James MacLachlan recreates Galileo's wine-and-water globe experiment to show "that this phenomenon occurs exactly as Galileo described."[5] Stillman Drake discusses a recreation of the pendulum experiments intended to demonstrate that Galileo's described result (that even after many passes, two equal oscillating pendulums of different amplitude will not disagree by more than a single pass) is not fictitious.[6] MacLachlan also investigates the historical legitimacy of the pendulum experiments en route to claiming that "[Galileo's] report of observations of two lead balls on equal long strings is shown by reconstruction to have been a real experiment. His report of similar observations with balls of cork and lead is shown to be an imaginary experiment."[7] (MacLachlan's work is a good reminder that historical legitimacy recreations need not all conclude in the affirmative.) And my own recreation

---

[2] For Koyré's sweeping accusations against Galileo's use of experiment, see Koyré (1943, 1953, 1960, and 1978). Settle's work on the inclined plane, to be discussed presently, appears in Settle (1961).
[3] Settle (1961), 20.
[4] The issue of separating the types of recreation will be further addressed below.
[5] MacLachlan (1998), 90. The recreation itself is the focus of MacLachlan (1973). See that article, along with Beltrán (1998) and MacLachlan (1998) for the full published conversation concerning the wine-and-water globe experiment.
[6] Drake (1975).
[7] MacLachlan (1976).

of Galileo's two-bucket experiment is largely—though like Settle's work on the inclined plane, not *exclusively*—concerned with demonstrating that Galileo actually undertook the experiment in question.[8]

It is clear, then, that the distinguishing feature of historical legitimacy recreations is their binary set of results. Recreations of this type yield only two possible conclusions: the experiment *was* performed by the historical figure in the historical setting, or the experiment *was not* performed by the historical figure in the historical setting.

1.2 Historical Accuracy Recreations

Consider the following objective from outside the Galileo field, put forth by Alberto Martínez in his recreation of Coulomb's torsion balance experiment:

> Since, it seems, no successful attempts to reproduce Coulomb's results have ever been reported, the early establishment of the fundamental law of electrostatic repulsion has become an exemplary case in the history of science: one in which it would seem that a leading scientist interwove experimental facts with idealizations using rhetorical devices proper to his idiosyncratic community…The present paper analyzes Coulomb's original work on the law of repulsion in light of a new series of replications of his experiment. We will argue, contrary to recent claims, that Coulomb's report of 1785 constitutes an accurate description of the material components, procedures, and results of his experimental researches.[9]

As the beginning of the passage indicates, Martínez unquestionably accepts that Coulomb performed the experiment in its original historical setting. At issue are some of the particulars *about* the original experiment, including the results (data) obtained by

---

[8] Hatleback (unpublished).
[9] Martínez (2006), 517.

Coulomb. Because historical legitimacy recreations seek only to verify (or falsify) the occurrence of the original experiment, and some recreations (such as Martínez's) take that point as assumed, the latter type of recreation must be fundamentally different from the former. These historical accuracy recreations seek to establish (or refute) the veracity of the data, results, or other specifics reported from the (accepted) occurrence of the original historical experiment.

In returning to the Galileo literature, other examples of historical accuracy recreations are on offer. Some recreations of this type, such as some of Drake's work with the inclined plane experiment, involve mathematical models coupled with rudimentary physical recreations intended to investigate the veracity of historical data sets.[10] MacLachlan likewise combines physical recreation with theoretical investigation for the pendulum experiments, claiming in one instance that "[Galileo's] claim that the period of a pendulum is independent of amplitude is shown to be based more on mathematical deduction than on experimental observation."[11]

Historical accuracy recreations, then, differ from historical legitimacy recreations first and foremost with respect to their initial assumption that the historical figure did in fact perform the original experiment. This, the sole avenue of exploration for historical legitimacy recreations, is assumed in the affirmative from the outset in historical accuracy recreations. Furthermore, historical accuracy recreations oftentimes involve the theory of the historical figure, something that is (for the most part) unnecessary for historical legitimacy recreations. As suggested by the examples provided, the theory is

[10] Drake (1973). Concerning the inclined plane experiments, see also Hahn (2002). Though Hahn does not involve physical recreation, his work provides a good example of the theoretical component often involved in historical accuracy recreations, as will be discussed momentarily.
[11] MacLachlan (1976), 173.

useful in the historical accuracy context for investigating whether a data set originated from experiment or from theoretical deduction, and it can also be useful in combination with the physical reconstruction when attempting to decipher the settings of particular parameters of the experiment.

1.3 Philosophical Recreations

Because Part 2 will focus exclusively on one example of a philosophical recreation, the comments here on the type will be brief. Like historical accuracy recreations, the underlying assumption of a philosophical recreation is that it was originally undertaken by the historical figure. As in the case of historical accuracy recreations, this makes philosophical recreations fundamentally different from historical legitimacy recreations. However, unlike historical accuracy recreations, the philosophical variety are concerned not with *what* results or data were obtained by the historical figure, but rather with *how* the historical figure used those results.

Paolo Palmieri provides one such example. [Paolo—here's where I want to put a few lines concerning your book, but I never got the chance to see it. It will go here as an example for philosophical recreations, provided there are sections that fit here nicely!]

Thus, in a sense, there exists a chain of order in the experimental recreation discipline. Historical legitimacy recreations investigate whether the original experiment took place. Historical accuracy recreations assume this to be true, but further investigate whether the historical figure accurately conveyed the data, results, or other experimental information. Philosophical recreations assume the accuracy of the details and results of the original experiment, but further investigate the concept of the experiment and how the historical figure used the experiment for theoretical purposes.

1.4 A Note of Clarification

It may appear that instances of technical overlap among the three classifications of experimental history of science can arise. For example, my two-bucket recreation aims to demonstrate that Galileo actually performed the experiment (and thus it is of the historical legitimacy type), but the results—the "data" in this case—consist of nothing more than observations of physical phenomena, so in that sense, the recreation could be interpreted as an attempt to corroborate Galileo's "data" and the "data" of the reconstruction (and thus it could be construed as being of the historical accuracy type). But such instances can be dispelled by noting that historical accuracy recreations involve an implicit assumption that the experiment in question *was actually historically performed*, whereas historical legitimacy recreations are defined (in part) by their lack of such an underlying assumption. For the two-bucket case, there can be no doubt that the two-bucket investigation makes no assumption that the experiment was performed by Galileo, and so it sought to investigate historical legitimacy.

To be sure, a single recreation can impart upon the experimenter more than one bit of information. For example, genuine doubt about the historical legitimacy of an experiment can prompt a recreation which, upon completion, verifies that the experiment was performed in its historical setting, but which also exposes the inaccuracy of the data claimed to be obtained in the original historical setting. But these must nevertheless be viewed at two *different* sides of the same coin. The author's intent must include historical legitimacy (in this example) first and foremost, for historical accuracy can only come into play under the assumption of historical legitimacy, and likewise for distinguishing historical accuracy recreations from philosophical recreations.

The following sections provide a case study involving a philosophical recreation of Galileo's inclined plane experiment.

Part 2: A Philosophical Recreation of Galileo's Inclined Plane Experiment

In building upon the work of Settle, the following passage from his paper served as the launching point for yet again recreating Galileo's inclined plane experiment: "We note further that Galileo, though presenting his results as valid for all slopes, only claimed to have successfully tested relatively shallow ones. Whether this was the result of experimental insight alone or of poor results obtained at steeper inclinations we do not know."[12] This, coupled with Galileo's description of the plane being inclined "by elevating one end of it above the horizontal plane from one to two braccia," provided the initial sketch of the investigation.[13]

The report provided here will focus on one particular component of Galileo's use of the inclined plane. Settle identifies the two primary theoretical ratios that Galileo seeks to establish with the inclined plane as

(1) $$\frac{S_1}{S_2} = \frac{T_1^2}{T_2^2} \text{ and}$$

(2) $$\frac{T_1}{T_2} = \frac{L_1}{L_2} \times \left(\frac{H_2}{H_1}\right)^{\frac{1}{2}},$$

[12] Settle (1961), 22.
[13] Galileo (1638), 169.

where *S* is distance traveled, *T* is time, *L* is plane length, and *H* is vertical plane height (the vertical measure from the point of the ball's release to its stopping point.).[14] As Settle notes, these are deduced in Proposition II Theorem II and Proposition V Theorem V (respectively) in Galileo's text.[15]

The inclined plane experiment, in its complete form, presents the continuum of cases that lie between the fully horizontal case (in which zero roll would take place) and the fully vertical case (in which free fall supersedes the presence of the plane). Just beyond horizontal, the ball is very much under the influence of friction, and just before vertical, the ball skids and slides down the plane rather than rolling smoothly. In both extreme cases, the extraneous factors cause misalignment between the theoretical and experimental values.

Given the imperfection of the experimental setup, it seems reasonable to question whether Galileo witnessed any of the degeneration due to the nature of the experiment en route to claiming that the results 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.[16]

Exploration of this claim is particularly salient given the lack of specificity that Galileo provides concerning the inclinations he actually tested: the two passages just provided find him claiming that the differences in plane elevation were "diverse," yet also merely a difference of "one to two braccia."

---

[14] Settle (1961), 21.
[15] Galileo (1638), 166-167 (for formula (1)) and 177-178 (for formula (2)).
[16] Galileo (1638), 170.

Did Galileo witness “poor results,” as Settle speculates? In this case, “poor” experimental results (from Galileo’s perspective) would consist of results that fail to conform to (1) or (2). Here, the chief concern will be (2). The recreation is aimed at discovering whether Galileo would have witnessed “poor” results even at the relatively shallow inclinations that he specifically references. Such results, if it is likely that Galileo witnessed them, would serve as justification for more extensive inquiry into Galileo’s use of the experiment in establishing his theory.

2.1 The Apparatus

I wish to avoid painstakingly recounting each aspect of the process of the reconstruction, chiefly because I followed approximately the same course described by Settle in his reconstruction, though also because many of the details are immaterial to the results obtained.[17] Instead, I note some of the differences: the plane is secured from above on the inclined end by a rope-and-anchor system that allows it to be raised and lowered to virtually any height, it has a (removable) ½” semicircular groove, the timing apparatus is a large (20-liter) water dispenser with an on/off valve coupled with an electronic laboratory scale, and the plane is approximately 22 feet long.[18]

Given that Settle already performed the recreation for the purposes of historical legitimacy, I had no qualms about utilizing the electronic scale, which Galileo did not

[17] I do not mean to downplay the difficulty involved in creating a suitable apparatus, because it certainly was no easy (or brief) undertaking. Rather, I am hoping to avoid excessive redundancy with respect to Settle’s description of the creation of the apparatus.

[18] These contrast with Settle’s fixed-height plane, ¼ “ rectangular groove, flower-pot-and-stem timing apparatus with volume readings rather than weights, and 18 foot plane length.

have at his disposal, because the operation of the apparatus still involved the traditional manual release and capture of water utilized by both Galileo and Settle.[19]

The crucial distinction between the present reconstruction and Settle's version is the array of balls available for selection. Since Galileo does not specify the size of the ball in the original experiment, it is not known whether the ball traveled down the plane "on the rails" (that is, touching the plane in two places) or fully within the groove (touching the plane in just one place, namely the bottom of the groove). Settle performed his recreation using a billiard ball and a steel ball bearing, the diameters of which both exceeded the ¼" groove in Settle's plane, meaning that both versions of his recreation yielded data only of the "rails" type of experiment. My reconstruction involved brass balls of various sizes, including three sizes that fit within the ½" groove and two sizes that were larger and rode "on the rails."

2.2 The Data

The "one to two braccia" range specified by Galileo stretches approximately from $22.7''$ of elevation to $45.4''$ of elevation over the length of a full 12-braccia plane, or approximately 4.78° to 9.59°.[20] Settle's inclination (for the trial for which he reports data) is slightly less than the low end of this spectrum, at approximately 3.73°. Since Settle demonstrated that no degeneration of the experiment occurs at this height, I

[19] In a sense, the electronic scale brought this recreation closer to the procedure that Galileo followed, since Galileo weighed the collected water to measure the elapsed time. Settle modified this procedure by measuring the volume of the water collected in a graduated cylinder.

[20] Since Settle's reconstruction is the launching point for this reconstruction, I utilized his estimation for the length of one braccio.

adjusted my plane to a value very close—3.75°—to obtain my base-rate data.[21] Then, using a pair of higher-elevation runs, I was able to witness degeneration in the experimental results (when compared to the theoretical values from equation (2)) as follows.

Recall (2): $\frac{T_1}{T_2} = \frac{L_1}{L_2} \times \left(\frac{H_2}{H_1}\right)^{\frac{1}{2}}$. Since all three of my trials were performed over the entire length of the plane, the $\frac{L_1}{L_2}$ component reduces to 1, leaving the theoretical ratio of the times proportional to the square root of the inverse ratio of the heights. Thus, using $H_1 = 16.5''\,(3.75^\circ)$, $H_2 = 42''\,(9.59^\circ)$, and $H_3 = 49.5''\,(11.33^\circ)$, the theoretical ratios for the times come out to be

(3) $$\frac{T_1}{T_2} = 1.595\text{, and}$$

(4) $$\frac{T_1}{T_3} = 1.732\,.$$ [22]

After performing 20 runs at each height for each of the five different sizes of ball, the averages for each trial and the relevant ratios of the times were computed. They are displayed on Table 1:

	1"	$\frac{3}{4}$"	$\frac{7}{16}$"	$\frac{3}{8}$"	$\frac{5}{16}$"
T_1	140.175 g	149.640 g	148.765 g	151.000 g	149.645 g
T_2	93.555 g	99.995 g	92.920 g	93.465 g	92.285 g
T_3	89.380 g	94.900 g	89.705 g	88.410 g	88.920 g

[21] To see the full set of trials and the times for all of the particular runs incorporated in this particular project, please see the Appendix.
[22] Note that equation (2) does not incorporate any components that deal with the mass of the ball or whether the ball rides on the rails or fully within the groove.

$\frac{T_1}{T_2}$	1.498	1.496	1.601	1.616	1.621
$\frac{T_1}{T_3}$	1.568	1.577	1.658	1.708	1.683

Table 1 The average experimental values obtained in 20-run trials at the respective heights for each of the five different sizes of ball are given in the first three rows. The final two rows give the experimental ratio of the times as indicated.

Given (3) and (4) above, it is an easy procedure to calculate the distance between the theoretical values the experimental values. The differences are provided on Table 2.

	1"	$\frac{3}{4}$"	$\frac{7}{16}$"	$\frac{3}{8}$"	$\frac{5}{16}$"
$\frac{T_1}{T_2}*$ (*Theoretical)	1.595	1.595	1.595	1.595	1.595
$\frac{T_1}{T_2}$ (Experimental)	1.498	1.496	1.601	1.616	1.621
$\frac{T_1}{T_3}*$ (*Theoretical)	1.732	1.732	1.732	1.732	1.732
$\frac{T_1}{T_3}$ (Experimental)	1.568	1.577	1.658	1.708	1.683
$\left\lvert \frac{T_1}{T_2}* - \frac{T_1}{T_2} \right\rvert$	.097	.099	.006	.021	.026
$\left\lvert \frac{T_1}{T_3}* - \frac{T_1}{T_3} \right\rvert$	.164	.155	.074	.024	.049
Degeneration	.067	.056	.068	.003	.023

Table 2 The theoretical (calculated from equation (2)) and experimental ratios of the times are given in the first four rows for each of the five ball sizes. The fifth and sixth rows show the distance between the theoretical and experimental values. The final row shows the experimental degeneration, calculated according to how much more error is present at H_3 than is present at H_2**.**

The final three columns are the most important for the present investigation. With the exception of a single ball size (the $\frac{3}{8}''$ size), the experiment exhibits substantial degeneration when raising the plane from 9.59° to 11.33°, a mere 1.74° higher.[23]

To instantiate what this degeneration means, consider the case of the $1''$ ball.[24] It shows degeneration of .067 when the plane is raised from 9.59° to 11.33°. This may not appear to be much, but in order to correct the degeneration—that is, in order to maintain the .097 error present between $\frac{T_1}{T_2}$ and $\frac{T_1}{T_2}*$ for $\frac{T_1}{T_3}$—the average from T_3 would need to be reduced from 89.380g to 85.734g, a difference of 3.646g. As indicated by the data in the Appendix, for this ball and this height, not a single run (of 20) even came close to 85.734g: the lowest outlier was 88.3g. It is important to highlight that this adjustment would not bring $\frac{T_1}{T_3}$ into alignment with $\frac{T_1}{T_3}*$; rather, this substantial adjustment only would have maintained the error (.097) exhibited between $\frac{T_1}{T_2}$ and $\frac{T_1}{T_2}*$.

Thus, even the shallow slopes that Galileo mentions in the range of one to two braccia of elevation display a calculable degeneration from theoretical values as the plane is raised to (and *slightly* beyond) the upper portion of the range.

The array of ball sizes is very important to this argument, for it alleviates the potential concern that the degeneration might occur only in one of the two possible types of experiment ("on the rails" or in the groove). Since the degeneration was consistent

[23] Note that even in the case of the "exception," the error actually swung from .021 *above* the theoretical value to .024 *below* the theoretical value, for a total swing of .045 that gets nullified by the absolute value function.

[24] The following procedure can be followed for each of the other cases; the first case is merely given here for explanatory purposes.

across the two experiment types, it can be viewed as a phenomenon of the plane and not the groove (or balls).[25]

In sum, upon returning to Settle's query concerning whether Galileo's testing and reports of strictly shallow angles is "the result of experimental insight alone or of poor results obtained at steeper inclinations," it appears that there is a strong case for the latter disjunct: he stuck the shallow angles in his published work on the experiment because of poor data obtained at steep inclinations. This is the likely scenario because already at the shallow angles that Galileo *does* reference, there is noticeable degeneration from the expected values given in (2). Furthermore, there is no reason to suspect that Galileo would have failed to notice the degeneration, especially given the diligence he claims to have put into the experiment.

2.3 Implications and Conclusion

How did Galileo come to terms with these experimental inconsistencies? That is, how did Galileo justify to himself that he could use the results he obtained from the inclined plane in support of his theory when he knew that the plane only gave him theory-friendly data within a relatively narrow window of the available parameters?

It is of crucial importance to note that while the answers to these questions lie outside the scope of the present project, these are questions that could not legitimately be asked about Galileo's philosophical justifications before recreating the historical experiment. Importantly, this is not to say that such questions have not been asked; the questions

[25] Note that although the level degeneration was fairly consistent across the trials, the balls that rode on the rails definitely exhibited a wider absolute divergence from the theoretical values. (To see this clearly, compare the theoretical and experimental values across the spectrum of heights on Table 2.) This, to me, seems like a fairly strong premise that could be used to argue that Galileo's original experiment involved rolling balls that fit *within* the groove.

posed in the previous paragraph certainly are not of a type that has never been previously posed by historians of science. However, the driving premise behind such enquiries—the evidence that Galileo *must have* grappled with those issues—is left merely as assumption until one performs the experimental recreation to generate empirical support in favor of that premise. The case study provided here is a very good demonstration of a recreation that effectively justifies one's asking of certain philosophical questions about historical figures. As explained in the first part of the paper, that is the distinction that sets the philosophical recreation apart from each of the other two types of experimental recreation.

What is the importance of all of this? Perhaps the most noteworthy result is that philosophical recreations can be clearly classified as the subject matter of history and philosophy of science, by contrast with historical legitimacy and historical accuracy recreations, which are strictly within the domain of history of science. While this result does not in any way impact the work of particular authors or particular projects, it is nevertheless important because it signifies an evolution in the growing discipline of experimental recreation.

What began merely as a means of settling a historical dispute has progressed to the point of introducing modern philosophy of science backwards into the history of science. This move is not at all novel, but now it has novel justification. In effect, history and philosophy of science now has a new tool at its disposal.

Much, of course, is left to be investigated. Within the context of Galileo's work, the questions concerning Galileo's use of the inclined plane in the development of his theory of motion are intriguing avenues of research. This is particularly true given the findings of Part 2, namely that Galileo probably witnessed the degeneration of the experimental setup that he devised.

Also, since the studies presented here focused primarily on the Galileo literature, it would be both interesting and worthwhile to survey other paths of historical experimentation. Perhaps most importantly, it remains to be seen what the analysis of past experiments via recreation can teach us about modern experimentation and especially about the progression of philosophy of science from the historical context to the present.

Appendix: Table of Data

Slope	$\frac{16.5''}{252''} \approx 3.75^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	1"	
Times (g)	142.2	140.8
	139.1	140.0
	142.2	142.0
	139.3	141.7
	139.2	139.6
	140.0	139.1
	141.3	139.9
	137.3	139.5
	140.2	138.5
	140.7	140.9
Mean	140.175	

Slope	$\frac{16.5''}{252''} \approx 3.75^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{3}{4}''$	
Times (g)	149.3	151.1
	150.0	151.1
	148.7	150.3
	149.5	147.7
	148.9	149.9
	147.1	151.5
	148.0	151.2
	148.7	149.7
	151.7	148.5
	150.8	149.1
Mean	149.640	

Slope	$\frac{16.5''}{252''} \approx 3.75^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{7}{16}''$	
Times (g)	159.5	149.2
	154.5	144.6
	150.4	148.0
	152.4	149.9
	148.2	147.3
	148.8	146.7
	150.9	145.0
	148.4	143.1
	146.6	147.1
	151.7	143.0
Mean	148.765	

Slope	$\frac{16.5''}{252''} \approx 3.75^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{3}{8}''$	
Times (g)	154.4	147.8
	152.0	152.5
	153.6	151.0
	148.9	149.8
	152.0	151.7
	153.8	147.9
	154.6	151.0
	148.2	150.1
	150.0	151.2
	150.2	149.3
Mean	151.000	

Slope	$\frac{16.5''}{252''} \approx 3.75^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{5}{16}''$	
Times (g)	149.8	151.8
	150.4	149.0
	147.6	151.5
	149.3	149.2
	149.8	151.1
	149.3	148.0
	151.1	148.7
	149.4	149.1
	146.3	149.5
	152.0	150.0
Mean	149.645	

Slope	$\frac{42''}{252''} \approx 9.59^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	1"	
Times (g)	90.3	92.9
	91.5	94.5
	92.7	94.0
	91.7	93.7
	95.4	94.3
	92.9	93.6
	94.8	97.6
	92.7	93.6
	94.8	93.5
	94.6	92.0
Mean	93.555	

Slope	$\frac{42''}{252''} \approx 9.59^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{3}{4}''$	
Times (g)	99.7	100.0
	101.3	99.1
	99.4	102.4
	99.2	99.8
	98.7	99.5
	99.3	100.9
	100.5	102.1
	98.6	99.0
	100.0	100.4
	98.2	101.8
Mean	99.995	

Slope	$\frac{42''}{252''} \approx 9.59^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{7}{16}''$	
Times (g)	91.8	92.2
	92.8	90.7
	89.0	92.6
	93.0	93.4
	93.3	93.9
	95.7	93.6
	91.8	93.8
	93.1	93.2
	92.4	95.5
	93.3	93.3
Mean	92.920	

Slope	$\frac{42''}{252''} \approx 9.59^{\circ}$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{3}{8}''$	
Times (g)	92.7	92.3
	92.3	93.4
	95.5	93.1
	96.8	92.9
	94.5	93.7
	93.0	96.3
	94.0	92.9
	94.7	91.5
	92.9	92.6
	92.8	91.4
Mean	93.465	

Slope	$\frac{42''}{252''} \approx 9.59^{\circ}$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{5}{16}''$	
Times (g)	89.9	91.6
	90.7	88.3
	90.7	93.4
	91.1	90.7
	93.7	93.8
	93.7	92.9
	94.0	93.5
	93.1	93.6
	92.6	92.9
	93.3	92.2
Mean	92.285	

Slope	$\frac{49.5''}{252''} \approx 11.33^{\circ}$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	1"	
Times (g)	89.7	89.2
	89.5	85.7
	89.9	89.8
	89.4	90.0
	88.3	88.1
	89.0	89.6
	89.7	91.2
	88.9	90.4
	89.2	89.2
	90.9	89.9
Mean	89.380	

Slope	$\frac{49.5''}{252''} \approx 11.33^{\circ}$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{3}{4}''$	
Times (g)	93.2	94.9
	93.6	93.8
	93.6	94.8
	94.0	93.5
	96.0	94.2
	93.1	96.3
	100.5	96.2
	97.6	94.9
	94.2	92.7
	96.6	94.3
Mean	94.900	

Slope	$\frac{49.5''}{252''} \approx 11.33^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{7}{16}''$	
Times (g)	89.8	88.3
	92.1	88.7
	86.3	86.8
	88.9	89.5
	91.8	90.1
	90.4	92.2
	90.5	87.8
	90.3	91.9
	90.4	87.8
	91.1	89.4
Mean	89.705	

Slope	$\frac{49.5''}{252''} \approx 11.33^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{3}{8}''$	
Times (g)	88.1	89.0
	86.5	88.4
	86.2	88.9
	87.3	88.4
	89.9	87.7
	90.0	88.6
	88.3	89.0
	89.1	87.6
	90.3	88.0
	89.0	87.9
Mean	88.410	

Slope	$\frac{49.5''}{252''} \approx 11.33^\circ$	
Groove	$\frac{1}{2}''$	
Ball Type	Brass	
Ball Size	$\frac{5}{16}''$	
Times (g)	89.4	88.7
	86.8	90.9
	89.2	88.4
	90.0	86.3
	87.7	88.3
	89.7	91.9
	88.6	87.6
	88.8	87.9
	91.7	88.2
	90.0	88.3
Mean	88.920	

References

Beltrán, A. (1998). Wine, water, and epistemological sobriety. *Isis*, *89*, 82-89.

Drake, S. (1973). Galileo's experimental confirmation of horizontal inertia: Unpublished manuscripts. *Isis*, *64*, 291-305.

Drake, S. (1975). New light on a Galilean claim about pendulums. *Isis*, *66*, 92-95.

Galilei, Galileo. (1989). *Two New Sciences* (S. Drake, Trans.). Toronto: Wall & Emerson, Inc. First published 1638.

Hahn, A. (2002). The pendulum swings again: A mathematical reassessment of Galileo's experiments with inclined planes. *Archive for History of Advanced Sciences*, *56*, 339-361.

Hatleback, E. (Unpublished). Galileo's two-bucket experiment.

Koyré, A. (1943). Galileo and Plato. *Journal of the History of Ideas*, *4*, 400-428.

Koyré, A. (1953). An experiment in measurement. *Proceedings of the American Philosophical Society*, *97*, 222-237.

Koyré, A. (1960). Galileo's treatise "De Motu Gravium": The use and abuse of imaginary experiment. *Revue d' Histoire des Sciences*, *13*, 197-245.

Koyré, A. (1978). *Galileo Studies* (J. Mepham, Trans.). Hassocks, Sussex: The Harvester Press Limited. (First published 1939).

MacLachlan, J. (1973). A test of an "imaginary" experiment of Galileo's. *Isis*, *64*, 374-379.

MacLachlan, J. (1976). Galileo's experiments with pendulums: Real and imaginary. *Annals of Science*, *33*, 173-185.

MacLachlan, J. (1998). Experimenting in the history of science. *Isis*, *89*, 90-92.

Martínez, A. (2006). Replication of Coulomb's torsion balance experiment. *Archive for History of Exact Sciences*, *60*, 517-563.

Settle, T. (1961). An experiment in the history of science. *Science (New Series)*, *133*, 19-23.