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Experimental history: swinging pendulums and melting shellac

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Four hundred years ago Galileo Galilei aimed a telescope at the sky. He revolutionized astronomy. Equally revolutionary were his experiments in physics. Unlike his astronomical observations the experiments remain difficult to understand and replicate even today. Two centuries after Galileo, Augustin Coulomb demonstrated experimentally the law of electrostatic force. It has never been successfully replicated. Yet both Galileo and Coulomb were exquisite experimentalists. The fact is that revolutionary experiments in physics are never finished. They are open for investigation for generations to come.

The element of experimentation

> The workshop of the scholar in the history of science is the periods in which his authors lived. He should know those periods' ways of life and belief and education, both the common and the eccentric; their political histories; their variety in aspects; their social and economic structures, their architectures, literatures and arts. He should feel at home in the houses of those times, sit easily in their chairs, both figurative and wooden, and discern what was then mostly admired or rejected in painting and sculpture and decoration. He should have read not only the books that carried the intellectual products of his period but also those that were then the fare of young minds as they were taught, such books having been commonly of an earlier time. The student who does not command, as a minimum, the main episodes of Holy Scripture, classic mythology, and the corpus of Golden Latin is glaucomatose in the modes of thought of Western men educated before 1900 [1].

We should pay heed to Clifford Truesdell's admonition. One element, however, appears to be missing or not explicitly emphasised in Truesdell's admirably concise discourse on method. It is the element of experimentation. Books, the fine arts and literary accounts are not enough those who strive to feel at home in the old houses of science. Over the past few years, students of the sciences, especially historians of science, have learned that to understand better the house of modern science they must relive the very experiences that emerge *in vivo* in the laboratories of the sciences. For there is one thing that sets modern science (beginning *ca*. 1600 s) apart from everything that came before. It is not mathematics or economics or the burgeoning capitalist social context, it is the emergence of controlled experiment as the privileged means of scientific inquiry. Indeed, it was an approach that was really cross cultural (as far as seventeenth-century geopolitics goes), with experimentation remarkably recognizable in the England of the Civil War, in the Padua of the Republic of Venice, at the Court of the Medici in Florence, or in the Rome of the papal Princes, to name only a few experimental hotspots.

Here, I set myself the modest task of recounting the vicissitudes of my attempts at replicating experiments done long ago. I will focus on two examples spanning two centuries, which somewhat strikingly show some evidence of an underlying pattern. My story begins with Galileo Galilei (1564–1642) in Padua and ends in Paris with Charles Augustin de Coulomb (1736–1806).

A Galileo myth

In 1961, historian Thomas Settle debunked a Galileo myth [2]. Around the middle of the twentieth century, historians such as Alexandre Koyré doubted that Galileo really performed the famous experiments expounded in his books [3]. In Koyré's view, Galileo only imagined his experiments. Nothing was really ever built or tested, said Koyré. The inclined plane, the pendulum and many other examples thus became, in Koyré's mind, figments of Galileo's imagination. But Settle showed that Galileo's thought experiments were most likely figments of the historian's imagination. Settle set up an inclined plane roughly similar to Galileo's, let balls roll down it and measured the time they took to descend using a "water clock" as Galileo says he did. According to Settle, the measurements that Galileo hints at were plausible. The Koyré thought-experiment myth evaporated.

I recently embarked upon a similar enterprise. I became fascinated with the law of pendulum isochronism, which states that all simple pendulums will swing in the same time regardless of the amplitudes of the oscillations. Galileo steadfastly stuck to this claim throughout his life, arguing that experimentation had revealed this property of pendulums. Historian Ronald Naylor (who judiciously replicated some pendulum experiments) and others (who didn't) resumed the Koyré myth. Since the isochronism claim, as we nowadays know, is false – that is, pendulums do not swing in the same time regardless of the amplitudes of the oscillations – Galileo must have fallen victim of his

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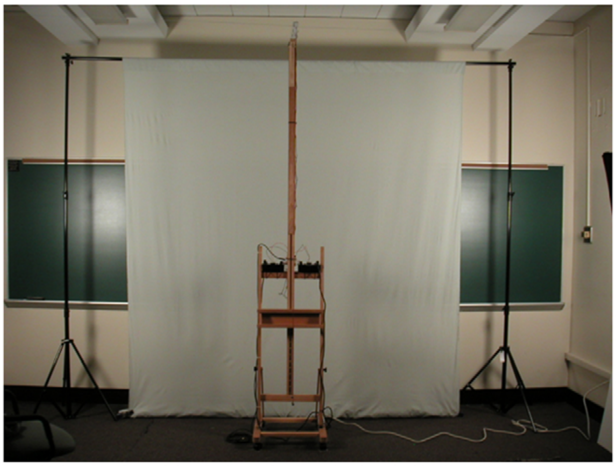

Figure 1. A modified easel served as wooden structure from which I hung two strings carrying two small lead bobs. The white screen behind the easel improved the quality of the videos shot to document the experiment.

imagination, argued Naylor and others. Either that or experimental ineptitude [4].

I decided to take Galileo at his word. In 2006, I set up a pendulum apparatus as close as possible to that outlined by Galileo himself (Figure 1). Unfortunately Galileo does not describe the apparatus accurately. In fact, he sketchily tells us about hemp strings and lead balls attached to them, without going into any details. So the apparatus must be reinvented, if you like.

Assuming that he had performed the experiments, my goal was to replicate his pendulum setup to see the world as Galileo might have seen it. He lived in a time when physics was not mathematized. Indeed, the very notion that physics can be mathematized is one of Galileo's lasting contributions to modern science. In his time, when he was a student at Pisa in the 1580s, physics was a loose bundle of ideas inherited from the Greeks, mostly from Aristotle, via the mediation of the Latin Middle Ages. Projectiles keep going after being released by their projectors because air keeps pushing them for a while, as the most in vogue theory of the time would have it (though there were variations). Theirs is a violent motion. Heavy things fall downwards because the centre of the earth is the natural place for them to achieve their natural state of rest. Theirs is a natural motion. Pendulums are constrained motions. Is the motion of a pendulum violent or natural? Why does it turn back after reaching a summit? Why do violent motions cease? Why does a stone thrown upwards eventually invert its motion and start falling downwards? Does its speed become zero at the point of inversion? Is there a rest at the point of inversion?

This is the *physics* in the context of which Galileo began his investigations of pendulums and the physics of motion. One has to learn how to reason within such a *physics* if one is to see the world of pendulums through the eyes of the young Galileo. Old books are indispensable to learn the old physics. But they are not sufficient to decide about the thought-experiment myth. One has to build the apparatus, humbly, and learn again how to see with the eyes of the young Galileo.

This is how I relearned how to measure the lengths of two equal pendulums, or rather how I decided that my two pendulums were of the same length: I cut two hemp strings [5] of the same length (about 92 inches, following Galileo); first of all, I cut one and then the second after making their ends coincide. I hung two pendulums made with the hemp strings knotted to two 1-ounce lead balls, adjusting the knots until I was satisfied by visual inspection that the two pendulums were of the same length [6]. The pendulums were removed from the perpendicular and let go at the same instant. After a short while and contrary to my expectations, they started losing synchronism. I thought that there might be something wrong with the apparatus or with the way I released the bobs. I repeated the test with the same results. I tried from the other side of the apparatus with the same results. Finally, I considered whether the lengths of the pendulums might in fact not be the same. By *length of the pendulum* I mean the resulting length of the string plus the radius of the ball to which the bob is attached, once the pendulum has been hung from the frame. The operation of mounting the pendulum affects its length. The reason for the asynchrony was that visual inspection had failed as a criterion of equality for the lengths of pendulums.

There is no way of making sure that the two lengths are the same other than letting the pendulums swing together for as long a time as possible, and observing that they will oscillate synchronously. (Pay attention that here synchronicity is not be confused with isochronism.) The two pendulums function together as a combined accumulator of the delays due to the inevitable difference in lengths of the pendulums. Therefore, in order to guarantee that pendulum experiments are significant, one has to work patiently until one is satisfied that for an *arbitrarily* defined interval of time the pendulums will swing synchronously. I finally settled on a *reasonable* time window of five minutes. Beyond that time limit I knew I would have to expect the results to become less and less reliable since asynchrony would start to develop. I spent my first morning attempting to solve this problem.

This was only the beginning of my pendulum adventure. I discuss the details and perplexities in a recent book [7]. In the course of my experiments, I also shot a large number of videos, which are freely available at http://www.exphps.org [8]. My conclusion is that under certain circumstances, Galilean pendulums can be made to appear isochronous, so it is perfectly plausible – even likely – that Galileo did conduct these experiments. This can be stated with some confidence since until now the basis for denying that Galileo really got his hands dirty was the historians' skepticism that the results he reports are plausible. But if we now know that pendulums are not truly isochronous, why do they appear to be so with Galileo's apparatus? The answer is, in part, because with small bobs (like those used by Galileo) and within a certain range of amplitudes, aerodynamic resistance dampens the bobs' large, initial swings so quickly that it makes them march isochronously for some time afterwards.

In sum, the question is to what extent an experiment has well-defined borderlines that demarcate its confines with theoretical speculation. My hunch is that there are no such borderlines. Experience shows things in their dynamic aspect. Theory is a continuation of experiment with cognitive means in order to see the conclusions to which things tend with the mind's eye. An experiment can be cognitively expanded, in other words.

We can understand the opinion at which Koyré and others had arrived. These historians had trouble realizing that experiment means more than can actually be seen under one set of circumstances. Galileo was no doubt a master of experiment but also a genius of the cognitive expansion of experiment.

Coulomb's law

The re-enactment of Galileo's pendulum experiments suggested a way to address question marks that hang over another famous experiment in the history of science.

> In June 1785, Charles Augustin Coulomb, a retired military engineer, announced his latest invention to the Paris Academy of Sciences: the torsion balance, an extremely sensitive instrument able to measure even minute forces to an unprecedented degree of accuracy. With it Coulomb claimed to have demonstrated that electrostatic repulsion indeed varies inversely as the square of the distance. That experiment, together with another presented in 1787, eventually led physicists to designate the fundamental equation of electrostatics as "Coulomb's law" [9].

However, ever since Coulomb's 18th century revelation, physicists have struggled to repeat his celebrated experiment, raising questions about whether he too might have been engaged in thought rather than actual experimentation.

Recently, historian Alberto Martínez argued that previous efforts to replicate Coulomb's experiment had failed because they had not paid sufficient attention to the detail of his experimental setup. By closely following the instructions left by Coulomb himself, Martínez demonstrated that the simple procedures of the experiment could indeed be replicated and the results that Coulomb published could be obtained within a reasonable range of variability [10]. The doubts that cast a shadow on Coulomb's experimental setup had been laid to rest. Or so it seemed.

In 2008, we (that is, myself, Elay Shech, and Eric Hatleback, two graduate students in my department at the University of Pittsburgh) decided to refine the apparatus built by Martínez since we were dissatisfied with a detail of his experiment. We were assisted by Jed Buchwald of the California Institute of Technology, who had also assisted Martínez. Buchwald generously made available to us glass pieces of a torsion balance identical to that previously used by Martínez (Figure 2).

We noticed that Martínez had not made the needle of the balance with genuine sealing wax as Coulomb had done. Martínez had used modern plastic instead. The difference seemed negligible to us at the time since what matters, we initially thought, should be the electric insulation quality of the material, and thus plastic might do as well as sealing wax (essentially a mixture of shellac, a tree resin such as Venetian turpentine and some colorant such as cinnabar). Nevertheless, we spent virtually the whole of 2008 learning how to produce a working shellac-based needle, such as that used by Coulomb.

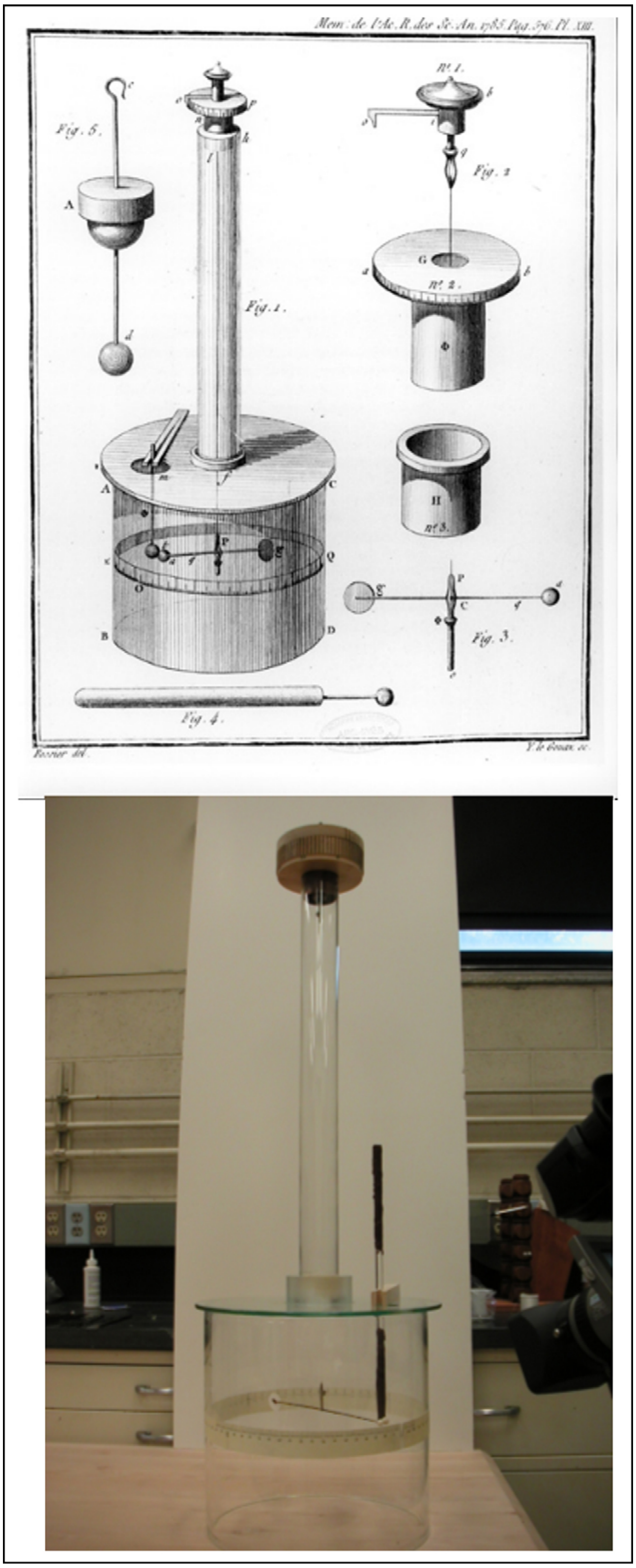

Figure 2. Above: The original engraving of Coulomb's torsion balance. Below: The Coulomb torsion balance in our laboratory. The shellac-based needle lies horizontally. For a description of the apparatus see Martínez's paper.

Try as we might we could not replicate the results. Whereas we succeeded in replicating Martínez's results with a plastic needle, we failed to arrive at Coulomb's law using a needle more like that used by Coulomb. In the process we realized how much one can learn from the material culture of a science if one is willing to get one's hands a little dirty. First, we had to source shellac and the other basic ingredients. Then, we had to figure out how to produce a thin needle.

Eventually, we came to the conclusion that the needle is the crux of the whole matter. It is the combination of the insulating properties of the needle and its weight that determines whether one can replicate the results that Coulomb claimed. The needle must weigh no more than about 1 g, possibly much less, and certainly the lighter the better. The rotational inertia of the needle sets the responsiveness of the apparatus when the operator turns the graduated micrometer at the top of the balance (Figure 2). The faster the response the quicker the needle will settle to an equilibrium position between the electrostatic repulsion of the two balls that have been charged and the tensional reaction of the silver wire. However, the charge placed on the two balls will leak out gradually, especially in humid conditions, and therefore the experiment has to be conducted quickly so one can assume that the charge leakage is negligible during the time needed to take the three measurements specified by Coulomb.

With this setup, based on a historically accurate needle made of genuine sealing wax, we were unable to reach the exponent of 2 that Coulomb arrived at for his electrostatic law. In 2008, the closest we got was an exponent of about 1.8. One variable that we discovered makes a difference is the shellac from which the wax is made (Figure 3). We have no idea what kind of shellac Coulomb might have used; there are many varieties since they come from different places and different insects. Thus, it is conceivable that the needle's insulating properties can yet be improved. In the meantime, one way to explore this issue further is by computer simulation, a modern take on cognitive expansion supplemented by digital technology.

Figure 3. Learning how to make thin needles out of melted wax and a silk thread. We used a modern electric cooker to heat the wax, but at the beginning we tended to burn the delicate shellac all too easily before we finally figured that a constant, adequate temperature is best. What would Coulomb have used to keep his wax melted while trying to pass the silk thread into it to craft a needle? How do you let the wax set so that the needle will come out straight and not wavy?.

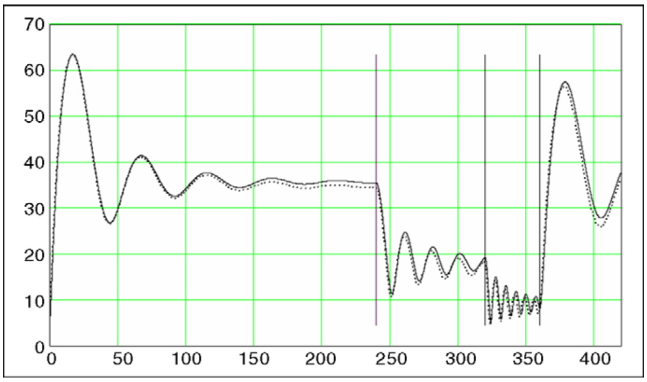

Figure 4. A graph generated by the computer model of the Coulomb apparatus. The vertical axis is angular position of the needle in degrees. The horizontal axis is time in seconds. Two curves are shown. The dotted line is the same model as the continuous line but takes into account the loss of charge. The details are irrelevant here but the reader should notice the oscillations in position of the needle before settling to equilibrium. They indicate that there is a problem of deciding when a reading on the scale of position can be made since the needle takes a lot of time before coming to rest. Hence the importance of the weight of the needle since it determines its rotational inertia and thus the waiting time before the observer can make a reliable reading.

I programmed a computer model of the Coulomb apparatus to find out what conditions are needed to arrive at the exponent of 2 claimed by Coulomb. The results are perplexing. The computer model reveals that alterations to the materials and set-up used in our reconstructed apparatus are unlikely to improve significantly upon the current exponent of 1.8 (Figure 4). This is because, as simulations show, the apparatus described by Coulomb seems already to be working close to an optimal condition.

Ultimately, though, a computer model is only that, a powerful but very imperfect representation of the real world. So the question of whether Coulomb actually did perform this experiment remains open. One possibility is that Coulomb performed the experiment but went on to expand it cognitively into an ideal type. Indeed, the account that Coulomb gives of his experiment has an aura of sanitation that is at odds with the fraught experience of constructing a thin needle from sealing wax and then setting up the apparatus without breaking it. Here and there in Coulomb's papers, one has the impression that the apparatus he describes, *or a better version of it* which is left for the reader to develop, will work in a certain way, and that the numbers that he gives are only an *indication* of the numbers that one can get in principle, not necessarily a faithful representation of the numbers that he actually got.

The value of experiment

In conclusion, I formed the impression that we should think of a great scientific experiment as never beginning and never ending. It has been tried many times and it should be retried again and again for it is inexhaustible. It can be cognitively expanded in the mind in multiple directions. This cognitive expansion is what consummate experimentalists such as Galileo and Coulomb seem to have done with pleasure, and this is why sometimes scholars have concluded that their experiments were only thought experiments. Furthermore, the idea that an experiment should be a conclusive test of preconceived theories, an *experimentum crucis*, is totally naïve. It is true that sometimes the protagonists of science themselves have misled us into thinking that this is the case, that there are indeed crucial experiments. But real experiments fail to be crucial, as I have learned. Rather, they offer us the opportunity for further cognitive expansions, even after centuries.

Revisiting a historical experiment is much more than replicating its purported *original* results; it is like an *in vivo* archaeology of knowledge; it is about learning a whole new culture and above all learning from it. There is no such thing as a scientific experiment in the sense of an event which has been accomplished once and for all. We continue to learn from swinging pendulums and melting shellac.

Finally, in the wake of other scholars who preceded me in getting their hands dirty, I will suggest that interesting points can be raised for historians of science by engaging with the science itself. Experimental history opens up new, genuinely historical avenues of enquiry.

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5 Hemp is a material that would have been easily available in Galileo's time. Linen also would have been available. Galileo says “spago” or “spaghetto”, i.e. thin string, which implies that the string's material would probably have been hemp or linen

6 The choice of the lead balls is somewhat problematic. Galileo does not specify the size of the lead balls he uses, but the words he chooses seem to indicate that he used very small balls, roughly the size of musket balls, or little more. Musket balls at that time would have been in the range of 1–2 ounces (28–56 g)

7 Palmieri, P. (2008) *Re-discovering the Techniques of Seventeenth-century Science. Re-enacting Galileo's Experiments.* The Edwin Mellen Press, (Lewiston)

8 The website http://www.exphps.org is devoted to Experimental History and Philosophy of Science, a research project that I have started at the University of Pittsburgh. Experimental History and Philosophy of Science aims at deepening our understanding of the role of experimentation in the natural sciences by replicating landmark experiments or inventing new ones

9 Martínez, A. (2006) Replication of Coulomb's Torsion Balance Experiment. *Archive for History of Exact Sciences* 60, pp. 517–563

10 See Martínez's paper, quoted above, for a résumé of the question updated to 2006. There is also a fascinating collection of essays in Blondel, C. and Dörries, M., eds (1994) *Restaging Coulomb. Usages Controverses et Réplications autour de la Balance de Torsion*, Leo S. Olschki, (Florence)