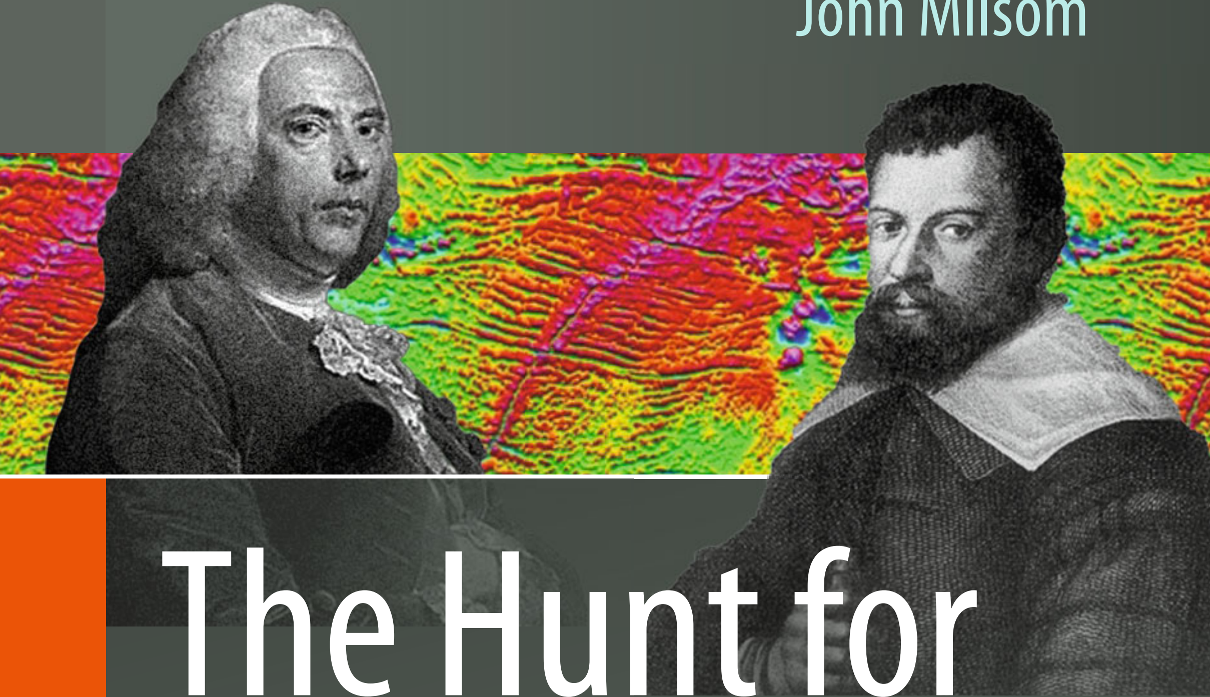
John Milsom



The Hunt for Earth Gravity

A History of Gravity Measurement from Galileo to the 21st Century

Springer

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Top: Rose de Freycinet arrives in Timor. Painting by Jacques Arago. Bottom: Marooned in the Arctic. The caption reads "The Arctic Dandies during their residence on Melville Island, 1819–1820. Drawn by Captain Sabine and partly coloured by him in 1822, completed by Edward Noble his godson in 1906". Most of the 'dandies' seem rather under-dressed for temperatures that remained below −15°C from November until March. © 2015 Christies Images Limited

John Milsom

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A History of Gravity Measurement from Galileo to the 21st Century

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… we come now to the other questions, relating to pendulums, a subject which may appear to many exceedingly arid
Galileo Galilei: Two New Sciences

Preface

There are proper physicists and there are exploration geophysicists. To proper physicists, their brothers and sisters in exploration are people of uncouth lifestyles and suspect intelligence who abuse the most fundamental and mysterious force in the universe (gravity—the one that they themselves still do not understand) by treating it as a mere tool for looking at rocks. Few such people have ever worried about the possible non-equivalence of inertial and gravitational mass (although Loránd Eötvös did, in 1890, and revolutionised gravity surveying by designing a practical torsion balance), and even fewer bother about the role of gravity in Special or General Relativity, or the possible use of quantum gravity to reconcile classical physics and quantum theory. The question of whether or not the Higgs boson exists and, if it does, whether it really does give mass to everything else, does not keep them awake at night. Instead, they take their instruments out into the 'field', which may be a real field, or a desert, or a forest, or an ocean, or a city street and, having mapped the changes in gravity to the best of their ability, they try to understand what they are being told about the rocks beneath their feet. It seems somehow appropriate that the universal constant of gravitation, which holds everything together, is known as 'Big G', while the local gravity field with which explorationists content themselves is merely 'little g'.[1]

[1] Referred to from here onwards simply as 'g'.

As the list of things that do not worry explorationists might suggest, the break with other physicists came only in the twentieth century, and with Einstein. Before him, theirs were shared histories, involving some astounding insights and some improbable characters. The people who investigated ‘g’ in the fifteenth, sixteenth, seventeenth, eighteenth and nineteenth centuries had interests far wider than mere gravity measurement, but this book is concerned only with their efforts to do this (and, in some cases, with the effects those efforts had on them).

Mixed in with these stories are some of my own memories. It may be presumptuous to talk about these in a book that figures giants such as Galileo, or to compare the trivial discomforts of modern fieldwork with the truly horrific challenges faced by the Frenchmen who, in 1730, went to South America to discover the shape of the Earth, but my hope is that this sometimes very personal approach can give people who know little about the Earth’s gravity field some insight into the reasons why so many people have devoted so much of their time to its study during the past 500 years.

If this book has any readers, they may be people who know something about physics but little geology, or people who know geology but not physics or people with only a layman’s knowledge of either. The pattern used tries to cope with this. The numbered chapters are the history and are generally in rough chronological order, although there are overlaps. Any dated sections within them are anecdotal and subject to the defects of my own memory (I was never a diarist), with positions determined by topics and not by chronology. Chapter 2 is entirely anecdotal and is out of sequence, because its aim is to give readers an early feeling for where the book is heading. A final section of ‘Codas’ (Chap. 14) is included for those who not only feel comfortable with graphs and equations, but would like to read about them.

Presteigne, UK John Milsom

Acknowledgements

One of the more stressful aspects of writing a non-fiction book is the need to obtain permission to reproduce copyright material, and particularly illustrations. In my case, the load has been lightened by the generous responses and encouragement that I have received from many of the people and organisations contacted. In some cases, the end result was that I was provided with far better copies of the pictures than I had been able to find elsewhere. So, my very special thanks to Helena Ingham of Christies for the high-resolution image of the Arctic Dandies that forms half the frontispiece, to Valerie Shrimplin of Gresham College for the similarly excellent image of the original college, to the British Geological Survey for their pictures of the torsion balance in use in the 1930s, to John Noonan of Oil Search for photographs of an early LaCoste gravity metre in use in Papua in the late 1930s, to Michel van Camp for the pictures of his superconducting gravity meter and his son in use as a test mass and to Christopher Jekeli for his pictures of the Bell accelerometer and of a camper van containing an entire airborne gravity metre being driven on to a C-135. Ute Schiedermeier of the Siemens Historical Institute in Berlin confirmed my identification of William Siemens in the picture of him and his brothers, as well as giving permission for its use.

It is now hard to imagine attempting a project of this sort without the facilities provided by the Internet. Original sources which had in the past to be sought in the dusty recesses of scattered libraries are now available online. The decision by the Royal Society to digitise the whole of their Philosophical Transactions archive and to make it freely available has been especially important. And, as far as reproduction of extracts from recent material is concerned, I have been especially fortunate in the very relaxed attitude adopted by the Society of Exploration Geophysicists.

I also had helpers on the ground. Paola Marshall and the Braschi-Levi family from Bologna took photographs for me in Italy, Richard Dingley photographed the Oude Kerke in Delft, and my daughter Anna took the photograph of the Islington canal tunnel. My daughter Kate produced the drawings of Galileo's gears and the Chimborazo experiment. Where no other source is given, photographs, drawings and images are those that I have produced myself. All images of the gravity field were prepared using the Geosoft suite of programmes, and in marine areas are based on grids placed online by David Sandwell at http://topex.ucsd.edu/cgi-bin/get_data.cgi. Line drawings were prepared in CorelDraw.

Many people gave me encouragement along the way. Jason Ali, Gary Barnes, Mark Davies, Matthew Engel, Richard Howarth, Ed Lake, Ian Nash, Barry Oliver, Mike Rego and John Smallwood all read excerpts at various stages in the writing process and provided helpful and incisive criticisms. Ted Metcalfe helped me with Galileo and Magne Njåstad with the geography of Trondheim. And very special thanks are due to my two daughters, Anna and Kate, and especially to Marijana Dworski, bookseller extraordinary, who stuck with the project through thick and thin, and who also provided some of the books that I have used.

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Introduction

From sea level near the North Pole to sea level at the equator, 'g', the Earth's gravity, decreases by about half of one per cent. Travel to Ecuador, take a trip inland, and climb to the top of Chimborazo, which is as far from the Earth's centre as it is possible to get with feet still firmly planted on the ground, and the overall decrease amounts to about two-thirds of one per cent. These are small differences, but modern gravity metres can measure 'g' to one part in a billion. In the future, they may become easier and quicker to use, and cheaper, but there would be little point in making them more accurate. They are already sensitive to changes of less than half a centimetre in their height above sea level.

The Seconds Pendulum

Galileo discovered many things about gravity, but it was left to a Dutchman, Christiaan Huygens, to do the maths and write down the equations that govern the motions of 'simple' pendulums, in which point masses are supported by weightless threads, and of the 'compound' pendulums that exist in the real world. One of his aims in doing so was to find the length of a pendulum that would beat seconds exactly, and what he also showed was that its length would be directly proportional to 'g'. From his time onwards until the beginning of the twentieth century, values of 'g' were routinely quoted in terms of this length.

The idea is simple, but there is room for confusion. The time taken by a pendulum to swing from one extreme to another and back again is known as its period and, for good mathematical reasons, this is considered by physicists to be its fundamental property. Early clock makers, however, were concerned with what was easily observable, and a pendulum is most easily observed when it is vertical. This happens twice in every period, and what has come to be universally acknowledged as the seconds pendulum has a half period, not a full period, of one second. Its length is very close to one metre, which is pure coincidence since the metre was originally defined as one forty-millionth part of the polar circumference of the Earth.

Units in Renaissance (and Later) Science

Anyone interested in the history of science has to learn to navigate a maze of units. In the history of gravity, lengths were measured not only in *braccia*, *toises*, *lignes* and the English, Rhenish, Roman and Royal (French) feet, but also in Galileo's own private *punti*, which nobody else used. The factors that convert one to another are usually known only to parts per thousand, but parts per million can be very significant in modern gravity measurements. Moreover, the accepted factors may not always be the right ones, in any particular case. Either Riccioli's measurement of the height of the Asinelli Tower in Bologna was wrong, by a considerable margin (which would call into question all his other work) or the Roman foot that he used was slightly different from the foot used in Rome.[2]

To add further to the confusion, translators have not always left well alone. The Tuscan *braccio* that was familiar to Galileo has on occasion been translated as cubit, and cubit as fathom. Any attempt to use the accepted conversion factors on these translated units must end in disaster.

Even where translation was not involved, uncertainties persisted well into the nineteenth century. Henry Kater, the originator of the reversible pendulum, found it necessary to specify the length of his '*pendulum vibrating in seconds in London*' according to 'Sir G. Shuckburgh's standard' (in which it was 39.13860 inches), General Roy's scale (39.13717 inches) and Bird's Parliamentary Standard (39.13842 inches). The differences amounted to several parts in a hundred thousand, in a science that even then was hoping for parts per million. Eventually, and presumably in despair, Kater gave up trying to measure 'g' and made a career out of defining standards of mass and length for the British government.

[2] See discussion in Chap. 14, Coda 2.

Time

Where time is concerned, things are easier. The difficulties faced by early scientists in measuring it were daunting, but the basic standard was in little doubt. A second is one-sixtieth of a minute, and a minute is one-sixtieth of an hour and an hour is one twenty-fourth of a day. It is true that, because the Earth orbits the sun but not the stars, there is a difference between the sidereal day, which is measured by the stars, and the solar day measured by the sun but this was well understood in the seventeenth century. Riccioli, who made the first respectable estimates of 'g', using pendulums as well as falling weights, had only to specify which sort of day he was using for everyone who was interested to understand.

There is one exception. The French Revolution introduced to the world the decimal second, which was equal to one-hundredth of a decimal minute which was equal to one-hundredth of a decimal hour which was equal to one-tenth of a solar day, and which was therefore equal to 1.1574 ordinary seconds. Even in revolutionary France, it was never popular and was quickly abandoned but as late as 1821, and seven years after the restoration of the French monarchy, it was still being used by French scientists when reporting the results of pendulum observations in France, Spain and the British Isles (e.g. Biot and Arago 1821).

Units for Gravity

The problems with units of length (and mass) all but vanished when the standardised version of the metric system, the Systeme International (SI), was adopted in 1960, but the gravity world was poorly served by the SI committees. All geophysicists should now be using units based on metres and seconds, and 'g', as an acceleration, should be measured in metres per second per second, often written as metres/sec^2 and officially as m s^{-2}. However, no special name was given to this unit, leaving the people who worked with 'g' on a daily basis to flounder about expressing its changes in terms of a 'practical' unit equal to a millionth of a metre per second per second, officially written as μm s^{-2} and requiring recourse to the special character set on their word processors every time a value had to be written down. Some chose to use this unit but call it, ambiguously, the 'gravity unit' or 'g.u.', but many others preferred to stick to the previous standard with a memorable name, the Gal, equal to 1 cm/sec^2. The practical unit for geological purposes is one-thousandth of a Gal, officially written mGal but voiced as milligal (which is the way it is written in this book).

On the Earth's surface, 'g' is reasonably close to 10 m s^{-2}, or a million milligals, making it easy to think of the gravity effects of geology in terms of parts per million or ppm. Changes of a few tenths of a milligal can be important when looking for caves and cavities (Fig. 1), changes of a milligal or a few milligals when looking for mineable orebodies and of a few tens of milligals when defining the limits of sedimentary basins. Because there are ten $\mu m\ s^{-2}$ to a milligal, the significance of features on a gravity map for which the units have not been specified may be in doubt by a factor of ten, and this can be a real cause of misinterpretation.

In recent years, the technology has advanced to such an extent that it is not just 'g' but its gradient that is being measured. For this, there is a practical unit, free of the prefixes that characterise the Systeme Internationale. It is the Eötvös unit, and it represents a change of just one milligal over a distance of 10 kilometres, or of one $\mu m\ s^{-2}$ over a kilometre.

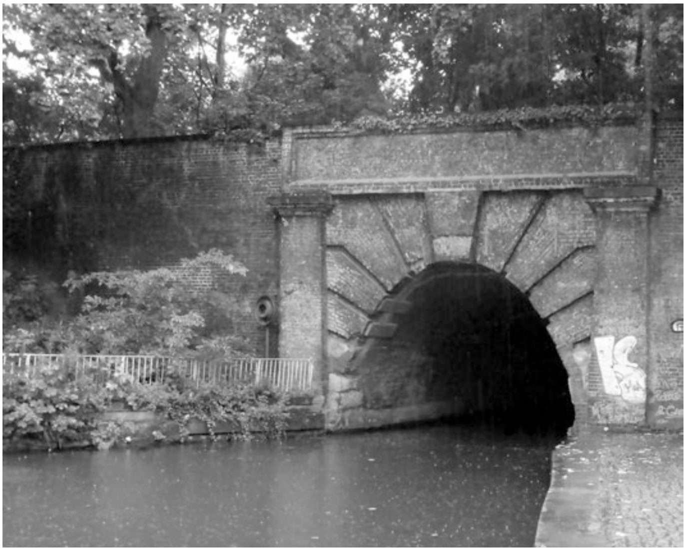

Fig. 1 The Islington canal tunnel, North London. Its effect on 'g', amounting to a few hundredths of a milligal, is just measurable by modern gravity metres on the road above it (*Photograph* Anna Milsom)

A Note for Obsessives

The phrase 'acceleration due to gravity' is a common one, and it therefore seems right and proper that 'g' should be measured in units of acceleration. The justification for doing so goes back to Newton, whose first law states that the acceleration of a body in free space is proportional to the force acting on it divided by its mass, and whose Law of Gravitation then implies that all masses in free space will receive an acceleration proportional to the gravity field. It is, however, arguable that this focuses attention on effects rather than causes, that the proper units should be of force divided by mass, and that the Gal should be defined as one dyne per gram and the SI unit as one Newton per kilogram. The numerical values would be unchanged.

All units, if used often enough, acquire a life of their own. When a boy racer gets his first car and dreams of whipping it up to (in Britain or America) a hundred miles an hour, he is not thinking of a hundred miles of road and the hour it would take him to drive down it. He is thinking 'fast'. Similarly, for the people who use it all the time, the milligal is not something to be thought of in terms of centimetres or seconds, and still less of 'seconds squared'. Much more simply, a hundred milligals means big, while a hundredth of a milligal is barely measurable.

Reference

Biot J-B, Arago F (1821) Recueil d'observations géodésiques, astronomiques et physiques executées en espagne, en france, en angleterre et en écosse. Courcier, Paris

1
The Beginning

There can be little doubt about one thing.

It all began with Galileo (Fig. 1.1).

He was, after all, the first person to show that the distances travelled by objects propelled only by gravity are proportional to the squares of the travel times. He was also the first to say that a weight on a string (a simple pendulum) always takes the same time to complete a swing, regardless of how far it swings and how heavy the weight, and to establish a relationship between this time and the length of the string. He thus pioneered both of the methods that have since been used to measure 'g'. Up until the middle of the 20th Century the most accurate way of doing this was to time a pendulum. More recently, it has been the rates of fall of objects in vacuum chambers that have been measured.

The Biographers

Most of the hundreds, or thousands, of books written about Galileo concentrate on his trial and the events that led up to it. Straightforward descriptions of the known facts compete with elaborate conspiracy theories that have him confessing to a lesser offence to avoid being consigned to the fire for a greater one. Dealing with this torrent of information is like wading into a river in full flood. There is a great deal of rubbish coming down. There are large gaps in the contemporary accounts, and much unsupported speculation in what has been written since. Thankfully, I am only trying to follow

J. Milsom, *The Hunt for Earth Gravity*,
https://doi.org/10.1007/978-3-319-74959-4_1

Fig. 1.1 Galileo at forty, when he was making his experiments with Swing, Roll and Fall. 19th Century engraving by Giuseppe Calendi, based on a painting by Santi di Tito

the history of ideas about the Earth's gravity field, and the task of tracing Galileo's part in that story has been manageable. Of the recent authors, I have only really engaged with three: Alexandre Koyré, Stillman Drake and Arthur Koestler. These were writers with very different views. Koyré admired Galileo as a master of the thought experiment but scorned his lab techniques, while Drake saw him as the first great experimental scientist.

Drake was an interesting character in his own right. His lifelong obsession with Galileo took him from financial consultancy in California to the professorial chair at the University of Toronto that he occupied until his death. He was a prolific writer, the author or co-author of more than a hundred books and papers about Galileo, but he was no scientist. His greatest contribution was to learn 16th Century Italian and then spend long hours puzzling his way through the mass of surviving documents, including some two hundred sheets of chaotically semi-legible folio notes, that Galileo left behind and which, in three hundred and fifty years, no-one else had had the stamina to unravel.[1] These were not proper lab books or formal records of results but jottings for immediate use, made on any piece of paper or parchment that happened to be handy. They were not dated, and were not kept in any sort of order. The entries on any one sheet might have been made on widely separated dates, and on at least one occasion a scrap of paper from one sheet was pasted on to another.[2] Drake provided a path through this wilderness but in many cases his interpretations were mere guesses and some of his translations and explanations are incomprehensible. He was also highly partisan, always showing Galileo's actions in the best possible light and treating his science as beyond reproach. His final haul of real experimental results was pitifully small, but enough to counter the very negative views of Alexander Koyré, which at that time were generally accepted.

Koestler provided another perspective. He was clearly unable to decide whether he disliked the Catholic Church more or less than he disliked Galileo, and he gave neither an easy ride. Of Galileo he said that much of his fame rested on discoveries that he never made and on actions that he never performed, and he listed some of them. They included the inventions of the telescope, the microscope, the thermometer and the pendulum clock, and the discoveries of sun spots, the law of inertia and the parallelograms of forces and motions. It is, however, hardly Galileo's fault if he has sometimes received credit that he never claimed, and Koestler did have to admit that the man who even he described as an 'outstanding genius' had earned his place amongst the shapers of human destiny by founding the science of dynamics. When he quoted Newton's famous statement to the effect that 'If I have been able to see farther, it was because I stood on the shoulders of giants', he identified these giants as Kepler, Galileo and Descartes (Koestler 1959; p. 358).

It is, perhaps, being over-pedantic to point out that it was to kinematics, not dynamics, that Galileo made his most important contributions, and that when Newton made his statement he was talking about optics.

---

[1]Images of the folios can now be accessed, together with notes and text transcriptions, through the website of the National Library in Florence, http://www.imss.fi.it/ms72/index.htm or the Max Planck Institute for the Study of the History of Science; http://www.mpiwg-berlin.mpg.de/Galileo—Prototype/index.htm.

[2]Drake (1990), referred to in the text as *Pioneer Scientist*. Drake's standing at the National Library in Florence must have been very high indeed, since he persuaded the director to have the pasted strip removed so that he could read what was written underneath.

The Legends

Koestler also identified as mere myths events that cannot be proven to have either happened or not happened. He was, for example, adamant that when, in 1633, Galileo was forced by the papal court to deny that the Earth moved around the Sun, he did not add, under his breath, "*Eppur si muove*"—'and yet it does move'. But how would anyone (including Koestler) know? Whether or not you think it believable largely depends on your opinion of Galileo.

Koestler also said that Galileo never threw down weights from the Leaning Tower of Pisa (Fig. 1.2 centre), and there he has to be granted at least technical accuracy. If Galileo did take weights of different sizes up the tower, he would surely not have thrown them down. That would have made it very difficult to prove that they fell at the same speed. The whole point of such towers is that they are great places from which to drop things.

The tale of the tower is, of course, one of the legends by which Galileo is chiefly remembered, and there are always people who want to spoil good stories by claiming that they are mere inventions. Their duller and more mundane versions often seem depressingly plausible, but the evidence for this story being a fiction is actually weaker than the evidence for it being a fact. Did he really climb the tower and drop from it (perhaps) a cannon ball and a musket ball? No, say the sceptics, because if he had he would have recorded it in his notebooks. It is, they say, a tale that was first told by Viviani, and not circulated until long after Galileo's death.[3]

Is this convincing? Geologists are taught at the very start of their training that absence of evidence is not evidence of absence. It is fair to at least ask where Galileo would have written about such an event. In his letters to his favourite daughter in a convent? Unlikely, since she was not even born until eight years after he had ceased to live in Pisa, and in any case those letters were all destroyed by her abbess after her death (Sobel 1999). We have only her letters to him. A similar fate may have befallen much of his other correspondence, as former colleagues scrambled to distance themselves from a convicted heretic.

In his scientific notebooks? There are no notebooks, just loose sheets of scribblings. Moreover, what we do know about Galileo suggests that he would not have considered this a proper experiment, to be written down. For one thing, if he did do it, he would not have been the first. Simon Stevin had dropped a musket ball and a cannon ball from the conveniently tilted tower of the Oude Kerk in Delft (Fig. 1.2 left) in 1586 (Dijksterhuis

[3]For a relatively recent brief review of the arguments, see Segré (1989).

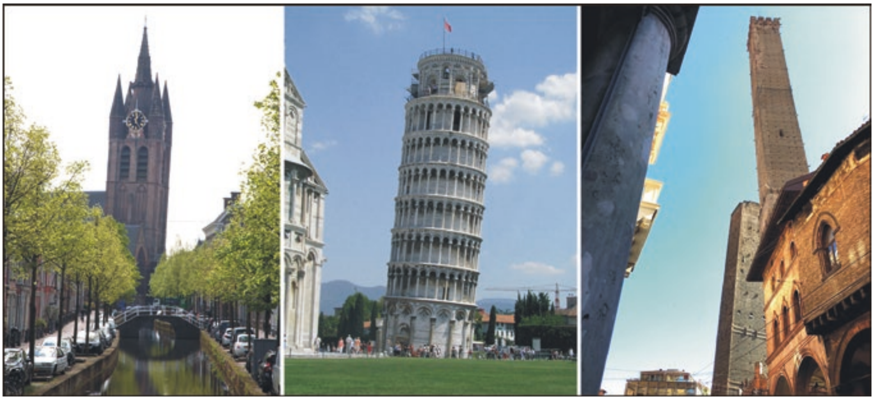

Fig. 1.2 The Three Towers. From left to right: The Oude Kerk in Delft, from which Simon Stevin dropped weights several years before Galileo may have done the same thing in Pisa (*Photo* Richard Dingley). The Leaning Tower of Pisa (*Photo* Warwick Mihaly). The Asinelli Tower in Bologna, used by Riccioli to make the first respectable estimates of 'g' (*Photo* The Braschi-Levi family)

1943), three years before Galileo was appointed to the chair of mathematics in Pisa, and there had been others. If Galileo knew of any of them, he would not have thought his own demonstration worth recording.

It is also not true that there is nothing in Galileo's writings to suggest that it happened. For most of his life he was locked in combat not with the church, but with Aristotle, who had died some two thousand years before. In his last book, *Two New Sciences* (Galilei 1638), he wrote.

> Aristotle says that "an iron ball of one hundred pounds falling from a height of a hundred cubits reaches the ground before a one pound ball has fallen a single cubit". I say they arrive at the same time. You find, on making the experiment, that the larger outstrips the smaller by two finger-breadths; … now you would not hide behind these two fingers the ninety-nine cubits of Aristotle, nor would you mention my small error and at the same time pass over his very large one.[4]

This does read as if it was not Galileo but someone else who made the demonstration, but *Two New Sciences* was written as a dialogue and the 'you' was Simplicio, an imagined Aristotleian disputant who had to be con-

[4]The quotations are from the translation from the Italian and Latin by Henry Crew and Alfonso de Salvio, entitled *Dialogues concerning Two New Sciences* and referred to in the text as *Two New Sciences*. The page numbers of the original Italian edition were inserted by the translators in their text, and these are given, separated by a right slash, after the page numbers of the translation.

founded. This was Galileo's favourite way of writing, and gives some insight into his thinking. A modern scientist is able to subject his theories to critical appraisal, first by his colleagues and then by his wider peer group. That route was not available to Galileo, whose critics would merely have repeated the words 'Aristotle said …'. He had to provide his own peer review. If there was no real person making the statement, then it is likely that he made the test himself. 'Two finger-breadths' sounds like observation, not theory.

Moreover, Viviani was not just any biographer. He was Galileo's last student, and his companion during the last four years of his life under house arrest. He was present when the old man died, and was the only one of his many biographers who had actually known him. As Galileo's sight failed, it was to Viviani that he dictated his final work. During the long years of confinement, their conversations must have wandered over many events that had not seemed worth writing about when they actually happened.

An even more convincing argument for the truth of the story comes from what we know of Galileo's character. If he did make such a demonstration, it would probably have been between 1589 and 1591, when he was teaching mathematics at Pisa University. His own writings, and the descriptions left by his contemporaries, all reveal a man who loved a good argument (as long as he won) and arguments about Aristotle must have been almost daily events during this time. How could he not, on at least one occasion, have decided to prove his opponents wrong with a simple demonstration? Viviani's description (Viviani 1654) suggests that he might have done it a number of times, because

> he showed that the speeds of bodies of different weights, moving in the same medium, were not in proportion to their weight, as described by Aristotle, but that they move at the same speed, this he demonstrated with repeated experiments made from the height of the bell tower of Pisa with the help of other teachers, philosophers and all the students.[5]

Viviani did not, as is known from comparisons with other contemporary accounts, get everything right, but his identifiable errors were mainly, and predictably, about dates. Mistakes of that sort would be expected in the ramblings of an old man reminiscing about events long ago. 'All the students' could not, of course, be strictly true, but who would expect it to be? It was certainly not intended to mean 'all the students in Italy', let alone in Europe,

[5]Excerpt translated by Ted Metcalfe.

so why should it be taken to mean, as some have argued, 'all the students in Pisa'? It is much more likely that it referred to all the students in a particular class, or taking a particular course. It is surely quite improbable that Viviani would have made all this up, without Galileo himself having said anything about it. It may not have happened in exactly the way described, but not all the things that people in their seventies remember are exactly true. That doesn't mean they are mere inventions.

Yet another story concerning Galileo that is now often dismissed as myth is that, as a bored teenager forced to sit through interminable services in Pisa cathedral, he used his own pulse to time the swing of a lamp hanging from the ceiling. Once again Viviani is the only source we have for this story but it has, in its unembellished form, a ring of truth. Dava Sobel (Sobel and Andrews 1998) talked of this as 'an early mystical experience', but Galileo was the least mystical of men, and the most straightforward version is likely to be the most accurate. When trapped with nothing to do, and nothing interesting happening, the mind wanders. It is entirely believable that a youthful Galileo would pass otherwise unproductive time in this way, and in *Two New Sciences* (p. 47/141) he showed that he thought such observations commonplace. And, after all, unless something of the sort had happened, why would he have begun experimenting with pendulums? It is much more difficult to accept Koyré's claim that Galileo made his great discovery by comparing the times of swing of pendulums of the same length, but first and foremost '*by hard mathematical thinking*' (Koyré 1953).

Koyré's conclusion is all the more remarkable because Galileo lacked the mathematical tools to treat the motion of pendulums, and the discussions of their motion in *Two New Sciences* are based around experiments and observations. The textbooks that Koyré scorned for repeating Viviani's story of the pulse and the chandelier at least had some basis in a near-contemporary text, however unreliable. Koyré had none, and his picture of Galileo sitting down at his desk and deciding what it was that he was going to think about mathematically that day is almost laughable. It may possibly be how he himself worked, but few, if any, scientists work like that. Science advances because someone becomes curious about something. There has to be a trigger, and it is just as likely to be a lamp swinging from a ceiling as anything else.

There is one other possibility, which would reflect less well on Galileo. Leonardo da Vinci had sketched a design for a clock using a pendulum many years earlier, and an Arthur Koestler might suggest that Galileo had known about this and that, in telling Viviani the story of the lamp, he was trying to establish his claim to originality, if not priority. But Leonardo's sketch does not necessarily mean that he had noticed the constancy of the times of swing. In all clocks, the energy needed to keep them going is supplied through devices known as escapements, and a typical escapement for a pendulum clock will only work if the swing is always almost the same. Leonardo might have based his idea for a clock (which was never built) on nothing more than that the same swing always takes the same time.

There is one more argument against the truth of the story, which to Koyré seemed conclusive. What is now pointed out as 'Galileo's lamp' was not there when he was a teenager. The cathedral guides have an answer to that, and one of which Galileo himself would have been proud. *Do you think that, before that, they worshipped in the dark?*

Galileo and Aristotle

In the satirical pamphlet Dialogue Concerning the New Star, Matteo, one of two argumentative peasants, is recorded as asking *What has philosophy to do with measuring anything?* The pamphlet was published in 1605 (the 'new star' being the object now sometimes known as 'Kepler's Supernova') and is generally accepted as the work of Galileo. It is easy to imagine him saying this, grumpily, in response to some particularly inane remark, and then stomping off, leaving no time for a reply. It is especially easy to sympathise because geologists also have been obstructed, on at least three important occasions, by 'philosophers' (i.e. theoreticians) who told the field observers, with absolutely certainty, that what they observed could not be true.[6] The 'philosophy' that Galileo, through Matteo, was talking about was the idea, grounded in the somewhat suspect writings of Claudius Ptolemy in the Second Century AD,[7] that the Earth was fixed in space and that the sun orbited around it.

Galileo had not only the followers of Ptolemy to cope with but, still more immovably, the followers of Aristotle. Why they had such a stranglehold on philosophy at the start of the 17th Century is something of a mystery. It is sometimes supposed that it was because they had the backing of the church, but there was no theological reason why this should have been so. Aristotle

[6]The first of the three was the conflict with the theoreticians of the Church who assigned the Earth an age of only 6000 years. Having (mainly) won that battle, geologists then had to contend with Lord Kelvin, who claimed that the Earth could not be more than 50 million years old—still nowhere near enough. Thirdly, they were faced with physicists who told them that the continents could not possibly have moved relative to each other, despite all the field evidence that indicated that they had.

[7]A modern view can be found in Newton (1977).

may have been an early monotheist but, having lived several centuries before the birth of Christ, he was by definition a pagan and therefore not, in the sight of the Church, a person deserving of any special respect. And while the ideas of an Earth that is fixed and a sun that rotates around it are firmly grounded in good solid common sense and observation, there was much in Aristotle that offended against both. Galileo spent much of his time pointing this out, and in doing so upset most of his fellow academics.

A good example of his approach can be found in *Two New Sciences*, which he had published following a trial that would have cured any sensible person of being controversial. He, however, evidently still enjoyed confronting paper opponents whose arguments he could destroy and who could not call on the services of the inquisition to back them up. Only a few pages into the book we find him renewing his old war with Aristotle over the motions of falling bodies. Rather than relying on experiments that he was by that time too ill to make, he based his attack on contradictions in his opponents' thinking. At its heart was a very basic question—what does it take for a collection of bits to be regarded as a single body? He himself did not have to answer that question, because, whether one body or multiple bodies, according to him it made no difference to their rate of fall. But the followers of Aristotle did have to give an answer, because they thought that a cannon ball and a musket ball would fall at very different speeds, and therefore had to be able to say at what speed they would fall if they were linked by a light but rigid rod.

Aristotle valued theory over observation. It seemed obvious to him that heavy objects <u>should</u> fall faster than light objects, and that their speeds of fall <u>should</u> be proportional to their weights, and so he wrote that it was so, despite what must have been almost daily experiences to the contrary. It is now almost impossible for us to even enter the mind of such a person, but it was for his unthinking followers that Galileo reserved his contempt. For the man himself he showed respect. He said that

> … we come now to the other questions, relating to pendulums, a subject which may appear to many exceedingly arid, especially to philosophers who are continually occupied with the more profound questions of nature. Nevertheless, the problem is one which I do not scorn. I am encouraged by the example of Aristotle whom I admire especially because he did not fail to discuss every subject which he thought in any degree worthy of consideration. (Two New Sciences 94–95/138)

Aristotle looked at the universe and speculated about its ultimate origin, and that was not a path that Galileo chose to follow. Rather, he contented himself with discovering the laws by which it operated. Why those laws existed was of less interest. That he was, throughout his life, an ardent Catholic must have helped shape this attitude, since to such a person the ultimate cause would always have been God. Scientists, to him, were in the business of discovering how God had arranged things, not why.

A Route Map

In tracing the history of Galileo's investigations of gravity, I have relied mainly on what he himself said in *Two New Sciences* and what Drake, in his various publications, said about the folio notes. The task would have been much easier had it been possible to follow him in supposing that Galileo discovered the square-law relationship between the distance travelled by an object in free fall and the time of fall by first studying pendulums, then relating pendulums to fall and only then relating fall to descents down inclined planes.

If this is true, it is rather odd that vertical fall was treated in *Two New Sciences* only as a special case of the Law of Roll that governs descents down inclined planes. Nor is the sequence the one that Drake himself followed in the first chapter of *Pioneer Scientist*. In this complex and in places almost incomprehensible account, Galileo is described as reaching his final enlightenment in a series of stages from which logical method and progression are entirely absent. It might be argued that to expect these things of a Renaissance scholar is unrealistic, but there is very little in Galileo's own writings or in what his contemporaries said about him that fails to strike a chord with the modern mind. To appreciate this, it is necessary only to compare the ease of translating his works (mainly in Italian, an innovation in its own right) into English with the near-impossibility of translating the Latin of his contemporary, Johannes Kepler.

It is not difficult to take the information assembled by Drake and construct a far more believable progression. It would be that:

1. Galileo notices (perhaps in Pisa cathedral—why not?) that things on strings swing more slowly when the strings are longer, and is sufficiently intrigued to investigate further.
2. He very quickly finds that the angle of swing does not affect the time of swing, as long as the angle is not too large. He wrongly, but under-