Opinion Page

Beware the Greeks: Sources for the History of Gravity in Science Teaching

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Galileo did not discover gravity, and neither did Newton, however for a variety of reasons their contributions were formalised as the discoverers of gravity and all that came before naive, archaic or backward. Their stories became the legends which all scholars had to learn, and the precise historical events forgotten and hidden. Galileo in 1591 (Hilliam, 2005), who had been working on the trajectory of cannonballs for some time allegedly dropped two cannonballs from the bell-tower of Pisa cathedral in the presence of the professors and demonstrated that Aristotle was incorrect (Viviani, 2008).

Newton had his *annus mirabilis* in 1666 where it was alleged that have observed an apple falling from a tree, and in which he hit upon the law of universal gravitation (Anon., 1998-2019). However, their main contribution to science was to help to unify a variety of other disparate issues, especially the movement of heavenly and earthly bodies, within a new systematic physics.

Prior to Galileo and Newton, there were, of course, both notions of gravity and inertia, but they functioned somewhat differently. Ancient and medieval authors certainly had a notion of gravity which was integrally related to their understanding of the earth as spherical, it simply wasn't a Newtonian understanding of gravity.

Unlike the post Newtonian understanding of gravity as a force independent of the falling body, ancient and medieval authors conceived of gravity as a product of the weight of a falling or rising object – which is how we got the term from the Latin *gravitas*, meaning 'weight'. Their notion was that all things in the universe had a "proper place" which they sought to reach. Now, since earth is the heaviest element, it naturally tries to amass itself at the bottom, ie. centre, of the universe in a uniform manner. Whereas, on the contrary, fire, being lighter than air, always tries rise above the air. This is why, if we accidentally dislocate an object from its natural position, it will be drawn to its natural position. Hence, things composed of mostly earth and water tend towards the centre of the earth whereas things made mostly of air and fire tend away from the centre of the earth. The problem of centres is an important point for Ancient commentators.

Plato and Aristotle

When Plato introduces the topic of gravity, motion and sphericity in his *Timaeus*, this is how he contextualises it:

> The nature of the light and the heavy will be best understood when examined in connexion with our notions of above and below; for it is quite a mistake to suppose that the universe is parted into two regions, separate from and opposite to each other, the one a lower to which all things tend which have any bulk, and an upper to which things only ascend against their will. For as the universe is in the form of a sphere, all the extremities, being equidistant from the centre, are equally extremities, and the centre, which is equidistant from them, is equally to be regarded as the opposite of them all. [...] the tendency of each towards its kindred element makes the body which is moved heavy, and the place towards which the motion tends below, but things which have an opposite tendency we call by an opposite name (Plato, 360 BC).

As we are well aware, one of the key ancient texts is Aristotle's *On the Heavens* (Aristotle, 350 BC) in which issues of weight and relative position are key concern. He uses this idea of gravity to explain both the sphericity and immobility of the earth. He argues that, if all things have a natural movement, and, under pain of incoherence, can't have two opposite natural movements, it follows that the earth must be immobile, since the earth is simply the accumulation of all the mass in the universe which tends towards the centre, it would require a greater force than that totality of mass to move it, which is absurd:

> For a single thing has a single movement, and a simple thing a simple: contrary movements cannot belong to the same thing, and movement away from the centre is the contrary of movement to it. If then no portion of earth can move away from the centre, obviously still less can the earth as a whole so move. For it is the nature of the whole to move to the point to which the part naturally moves. Since, then, it would require a force greater than itself to move it, it must needs stay at the centre (Aristotle, 350 BC).

This also demonstrates that the earth must be spherical since the sphere is the only shape in which the extremities are all equidistant to the centre. Likewise, were the earth unequally distributed, it would then shift so that its centre of gravity matched the centre of the universe:

> The earth, it might be argued, is at the centre and spherical in shape: if, then, a weight many times that of the earth were added to one hemisphere, the centre of the earth and of the whole will no longer be coincident. So that either the earth will not stay still at the centre, or if it does, it will be at rest without having its centre at the place to which it is still its nature to move. Such is the difficulty. A short consideration will give us an easy answer, if we first give precision to our postulate that any body endowed with weight, of whatever size, moves towards the centre. Clearly it will not stop when its edge touches the centre.

> The greater quantity must prevail until the body's centre occupies the centre. For that is the goal of its impulse. Now it makes no difference whether we apply this to a clod or common fragment of earth or to the earth as a whole. The fact indicated does not depend upon degrees of size but applies universally to everything that has the centripetal impulse. Therefore earth in motion, whether in a mass or in fragments, necessarily continues to move until it occupies the centre equally every way, the less being forced to equalize itself by the greater owing to the forward drive of the impulse (Aristotle, 350 BC).

Titus Lucretius Carus: ca. 99 - 55 BC

But this idea of a centre to the universe is central to classical criticism of the sphericality of the earth. Lucretius' poetic-form argument against the spherical earth centres on the counter-intuition of the idea of there being a cosmic centre:

> And in these problems, shrink, my Memmius, far / From yielding faith to that notorious talk: / That all things inward to the centre press; / And thus the nature of the world stands firm / With never blows from outward, nor can be / Nowhere dis-parted since all height and depth / Have always inward to the centre pressed / If thou art ready to believe that aught / Itself can rest upon itself; or that / The ponderous bodies which be under earth / Do all press upwards and do come to rest / Upon the earth, in some way upside down, / Like to those images of things we see / At present through the waters. They contend, / With like procedure, that all breathing things / Head downward roam about, and yet cannot / Tumble from earth to realms of sky below, / No more than these our bodies wing away / Spontaneously to vaults of sky above; / That, when those creatures look upon the sun, / We view the constellations of the night; / And that with us the seasons of the sky / They thus alternately divide, and thus / Do pass the night coequal to our days, / But a vain error has given these dreams to fools,

> / Which they've embraced with reasoning perverse / For centre none can be where world is still / Boundless, nor yet, if now a centre were, / Could aught take there a fixed position more / Than for some other cause 'tmight be dislodged. / For all of room and space we call the void / Must both through centre and non-centre yield / Alike to weights where'er their motions tend. / Nor is there any place, where, when they've come, / Bodies can be at standstill in the void, / Deprived of force of weight; nor yet may void / Furnish support to any,- nay, it must, / True to its bent of nature, still give way. / Thus in such manner not at all can things / Be held in union, as if overcome / By craving for a centre (Lucretius, ca 55 BC) Book 1: 1052 – 1082

The Lucretian notion did not survive antiquity. Rather, both the sphericality of the earth and the notion of natural movement towards proper place were adopted into the middle ages more or less universally. But this is only really the beginning of the story, and in particular, Aristotle's discussion of the matter received no end of discussion.

John Philiponos the Grammarian - ca. 490 – 570

Galileo is credited with refuting Aristotle's theory of falling bodies. Aristotle thought that heavier bodies fall faster, in proportion to their weight (Aristotle, 350 BC). But, as Galileo knew, skepticism about this theory had been expressed by Ioannes Philoponos - Ἰωάννης ὁ Φιλόπονος - also known as John of Alexandria a teacher, Christian theologian, and philosopher in Alexandria.

Philoponus became one of the earliest thinkers to reject Aristotle's dynamics and propose the theory of impetus - ἐνέργεια τις ἀσώματος κινητική (p. 642) - i.e., an object moves and continues to move because of an energy imparted in it by the mover and ceases the movement when that energy is exhausted. This insightful theory was the first step towards the concept of inertia in modern physics, although Philoponus' theory was largely ignored at the time because he was too radical in his rejection of Aristotle.

> But this [view of Aristotle] is completely erroneous, and our view may be completely corroborated by actual observation more effectively than by any sort of verbal argument. For if you let fall from the same height two weights, one many times heavier than the other you will see that the ratio of the times required for the motion does not depend [solely] on the weights, but that the difference in time is very small... (Philiponi, 1888) v17, p. 683)

John Philoponus' refutation of the Aristotelian claim that the elapsed time for a falling body is inversely proportional to its weight. Philoponos denied that the speed of motion was proportional to the weight of the bodies.

> This is a complete error, as we can see through observation better than through any abstract proof If you drop two bodies of vastly different weight.from the same height, you will see that the difference in the time that it takes for them to foll is not at all proportional to their difference in weight; it is, in fact, a small difference (Philiponi, 1888) v17, p. 683)

Philoponos rarely receives credit for this breakthrough, made over one thousand years before Galileo.

John Buridan: ca. 1300 – 1358 AD

Consider now two issues discussed by one of the most prominent late medieval Master of Arts, John Buridan. First, concerning the movement of the earth, Buridan approaches this problem through the question of whether the earth is actually the centre of the universe. As part of his discussion he nicely recapitulates his understanding of the Aristotelean mechanics of the problem - when these they say 'world' these authors normally mean what we would call the the 'universe':

> For we suppose that the place designated absolutely as "upward", insofar as one looks at this lower world, is the concave surface of the orb of the moon. This is so because something absolutely light, ie. fire, is moved towards it. For since fire appears to ascend in the air, it follows that fire naturally seeks a place above the air, and this place above the air is at the concave [surface] of the orb of the moon; because no other element appears to be so swiftly moved upwards as fire. Now the place downward ought to be the maximum distance from the place upward, since they are contrary places. Now that which is the maximum distance from the heaven is the middle of the universe. Therefore the middle of the universe is absolutely downward. But that which is absolutely heavy – and earth is of this sort – ought to be situated absolutely downward. Therefore, the earth naturally ought to be in the middle of the universe or be the middle of the universe. (Grant, 1974, p. 502).

Secondly, Buridan also discusses the problem of falling bodies and acceleration. He begins by addressing and rejecting three other views on why this happens:

1. that a falling object heats the air around it, rarifying the air and reducing overall friction;
2. that objects are attracted to their proper position to a greater degree the closer they are, hence as an object falls its velocity increases with the increased attraction; and
3. that as an object falls there is less air to get in the way so it falls faster.

He then sets out his own idea, that objects have a certain impetus (an early notion of inertia). Thus as they fall they are not only moved by their gravity, but also by their impetus and while the former is constant, the latter accumulates:

> It is my supposition that the natural gravity of a stone remains always the same and similar before the movement, after the movement, and

> during the movement. ... I suppose also that the resistance which arises from the medium remains the same or is similar ... Third, I suppose that if a moving body is the same, the total mover is the same, and the resistance also is the same or similar, the will remain equally swift, since the proportion of mover to moving body and to the resistance will remain [the same]. Then I add that in the movement downwards of the heavy body the movement does not remain equally fast but continually becomes swifter. From these [suppositions] it is concluded that another moving force concurs in the movement beyond the natural gravity ... And you have an experiment [to support this supposition]: If you cause a large and very heavy smith's mill [ie. a wheel] to rotate and you then cease to move it, it will still move a while longer by this impetus it has acquired. Nay, you cannot immediately bring it to rest, but on account of the resistance from the gravity of the mill, the impetus would be continually diminished until the mill would cease to move. And if the mill would last forever without some diminution or alteration of it, and there were no resistance corrupting the impetus, perhaps the mill would be moved perpetually by that impetus. (Grant, 1974, p. 282)

Nicholas Oresme: ca. 1351 – 1382 AD

As we have seen, the Aristotelean account of centres demands a geocentric cosmology. However, as we saw with Buridan, this was eroding in the late middle ages, with the suggestion that actually the earth was indeed subject to rectilinear motion, albeit very slightly. Likewise both Buridan and Nicholas Oresme argued that, while they did not think that the earth rotates on its axis, there is no good reason on offer to think that it doesn't, besides this conflict with the general Aristotelean system. Oresme ends his discussion of the matter noting, perhaps in faint prelude to the problems Galileo would face 250 years later, that:

> [A]fter considering all that has been said, one could then believe that

> the earth moves and not the heavens, for the opposite is not clearly evident. Nevertheless, at first sight, this seems as much against natural reason as, or more against natural reason than, all or many articles of our faith. (Grant, 1974, p. 510)

Although his concern for matters of faith may be driven in this case by the fact that Oresme has written this work in French, not Latin. But I digress, with Nicholas Copernicus (1473-1543) and the relocation of the centre of the universe at the sun, the Aristotelean account of gravity must give way:

> For the apparent irregular movement of the planets and their variable distances from the Earth – which cannot be understood as occurring in circles homocentric with the Earth – make it clear that the Earth is not the centre of their circular movements. Therefore, since there are many centres, it is not foolhardy to doubt whether the centre of gravity of the Earth rather than some other is the centre of the world. I myself think that gravity or heaviness is nothing except a certain natural appetency implanted in the parts by the divine providence of the universal Artisan, in order that they should unite with one another in their oneness and wholeness and come together in the form of a globe. It is believable that this affect is present in the sun, moon, and the other bright planets and that through its efficacy they remain in the spherical figure in which they are visible, though they nevertheless accomplish their circular movements in many different ways. Therefore if the Earth too possesses movements different from the one arounds its centre, then they will necessarily be movements which similarly appear on the outside in the many bodies; and we find the yearly revolution among these movements. (Grant, 1974, pp. 515-516)

Marcus Tullius Cicero: 106 – 43 BC

This lack of real explanation makes sense, as with the breakdown of Aristotelean final causation in physics, which explained the need for things to return to their proper place, gravity became a very mysterious force. Even with Newton, it isn't really explained, it is only described. But it is enough that his laws adequately account for the observable motions of bodies. To finish, and come full circle, we resort to Cicero to state the cause of gravity:

> For all its [ie. the universe's] parts in every direction gravitate with a uniform pressure towards the centre. Moreover busy conjoined maintain their union most permanently when they have some bond encompassing them to bind them together; and this function is fulfilled by that rational and intelligent substance which pervades the whole world as the efficient cause of all things and which draws and collects the outermost particles towards the centre. Hence if the world is round and therefore all its parts are held together by and with each other in universal equilibrium, the same must be the case with the earth, so that all its parts must converge towards the centre (which in a sphere is the lowest point) without anything to break the continuity and so threaten its vast complex of gravitational forces and masses with dissolution. And on the same principle the sea, although above the earth, nevertheless seeks the earth's centre and so is massed into a sphere uniform on all sides, and never floods its bounds and overflows (Cicero, 1933) 2.45. 115-6)

Very generally this is all appears to be an implication of Lucretius's broader atomic theory, according to which the universe is constituted by an infinity of infinitesimal entities called atoms, whose seemingly random activity underlies all the higher order features of the universe. One of the constituent features of this view is that space is both infinite and homogeneous, in opposition to much of the ancient tradition, as is seen in Plato, Aristotle, and in this Stoic position expressed by Cicero.

According to Aristotle, the cosmic centre - at the centre of the earth - is a different sort of space than, say, the upper atmosphere, which is a different sort of space from the heavenly spheres - outer space. Each of these spaces is characterised by different fundamental elements: earth/water for the centre; air/fire for the atmosphere; special-fire/aether for outer space; and different sorts of motion: downward for the centre; upward for the atmosphere; circular for outer space.

Conclusion to the sources

Lucretius, on the other hand, there is only really one sort of matter, atoms, whose natural state is linear motion of some sort, and only one sort of space, similar to the Cartesian expanse that we are familiar with. As such, he doesn't think that atoms discriminate between different bits of space: "all place and space …must yield a passage through middle or not-middle equally to weights [ie. atoms], wherever their movements tend". Instead everywhere they tend 'downwards' or move erratically as a result of their constant interactions. The implication of this is that there can't be a privileged centre in relation to which where some elements properly rest, since all atoms are constantly in motion regardless of location: "Nor is there any place in which bodies …can lose the force of weight and stand still in the void". Newton didn't "discover gravity." He "discovered" or "constructed" the inverse square law of gravitational force, and used this as a way to unite a lot of physical ideas that had previously been separate.

Teaching Gravity

A typical demonstration I give whenever I lecture on this is as follows. Imagine I am in front of you, and I drop something. Usually it is a ball, pen or other item at hand, because you work with what you have. I ask: "What do you see?" The phenomenological answer is: "the object moved from my hand to the ground / table." This is essentially a "non-theoretical observation" or a naive observation, it is merely a description of the phenomena. I then ask why did it do this? Here's where different theories come into play.

If you asked Aristotle what happened, he might say that the object is mostly made out of earth - one of the four elements, and so it moves in the direction that is natural for earth, which is to say, on the ground. If the object was made out of air it would have floated away. You can tell that an object is made out of earth because it will also fall through water, whereas things made out of water will not. So in short: the object traveled "down" because "down" is the direction that is naturally associated with things made of earth. There is more to it, but this gets at the gist of Aristotle's notions of gravity. He also thought the speed of falling was connected to the mass of the object, for example.

Now many other authors worked on the question of falling bodies between Galileo did not address key questions – he sought only a numerical way of estimating what would happen in this case, *not* an underlying *cause* or philosophical or metaphysical explanation. As he wrote in 1605: "What has philosophy got to do with measuring anything?" Galileo's approach in much of his non-Copernican work was as a self-styled mathematician, not as someone searching for deep causes. In the work he is most famous for – relating to his Copernicanism, he of course *was* making philosophical/metaphysical arguments. In most of his other work, he was exclusively *kinematical*, e.g., explaining *how* things happen but deliberately NOT *why* they happen.

Newton's specific contribution was to say: all objects with mass exert an attractive force, called gravity. This force is directional proportional to the mass of the object, and falls off at an inverse square rate. This same force accounts not only for the pen moving towards the center of the Earth's mass, but also is used to explain the orbits of comets, planets, and even the association of the tides with the rotation of the Moon around the Earth. This, in other words, is a vastly *larger* claim that just saying, "things will fall when dropped." It's wrapping a lot of different ideas into a new idea, and posits a specific *force* as the cause of them.

It is of note that in his time, the fact that Newton could not explain how this force worked, or what it was "made of," was controversial. The physics of Descartes had essentially worked to expel "occult" notions from scientific work, and Newton – an occultist – was claiming a mysterious force was acting on everything. Newton's law of gravity was invoked even in his lifetime, and certainly in the 18th century, as the "model" of what scientific theories ought to be: simple, broadly applicable, a piece of information that seemed to unify a wide variety of phenomena into one common understanding. This is why Newton was so impressive then and now. It's not that people didn't think that falling bodies would fall before Newton: it's that they didn't really understand what was going on when they saw such things, or that it was the same force responsible for so many other things.

Some teachers like to point out to the students that when they say that gravity is pulling the object down, they are *completely wrong*, which often shocks them. The modern answer is that Einstein actually came up with a totally *different* explanation for what is happening when we see that object fall: it is traveling along the shortest path through space-time, which is warped by the presence of mass. This explanation is really no more familiar or alien sounding that Aristotle's answer, or even Newton's, if you are not accustomed to it.

Because we teach gravity as a "force" idea in most educational contexts – you have to get pretty far along in science before they start really talking about General Relativity, even in basic terms – most students find Newtonian concepts so "natural" that they find it very hard to imagine they were ever "constructed" or "discovered." All of this is to say: it is not that Newton said, "there is a thing called *gravity*, and no one has used a name like this before." Plenty had people had used the concept of gravitas to denote "heaviness", and a corresponding quality of levitas to denote "floatiness," but their use of the term is not at all the same as Newton's. Newton's concept of gravity would have been as alien to Aristotle as Einstein's is to most people today – and certainly Einstein's would have been alien to Newton. Newton's concept of gravity is *not an observation of a phenomena* but *an explanation for how it works* – a theory – as well as a unifying principle that explained a wide variety of phenomena.

Crease (2003) notes that falling-body experiments continue to be very popular, and they were, for example, voted into the top 10 "most beautiful experiments".

He believes that the answer is related to the fact that, as everyday experience suggests, heavier bodies do fall faster than light ones. Whereas Aristotle had codified this observation into an entire framework that was oriented by the everyday observations he was seeking to explain, involving an agent that exerted a force against resistance. Although this framework fails to incorporate acceleration, it is still the one that we mainly live in and that mainly works for us. However, some mention or full explanation of Galileo's Pisa experiment also features as the architypal falling-body experiment and it finds its way into textbooks Figure 1., and websites for school science Figure 2, or even tourist websites, Figure 3, and finally in revision books, Figure 4.

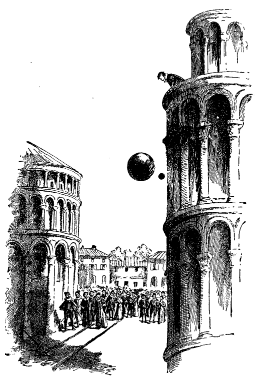

Figure 1. A rather impossible depiction of Galileo's Pisa experiment

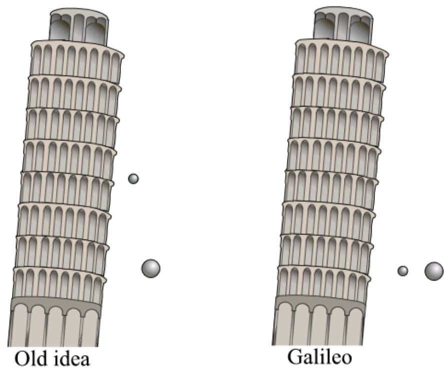

Figure 2. Galileo's Pisa experiment in wikibooks

Modern educators have fabricated Galileo's Pisa experiment and some teachers have tried to replicate the fabrications in their teaching laboratories. However, it does remain an important 'thought experiment' which follows the opinion of Settle (1983, 1992)[1] on the experiment as a historical event. Segre (1989) points out that nowhere in all his writings did Galileo himself describe the event and that it does appear to be a 'construct' of Viviani.

1. Reprinted in *The Galileo Project*

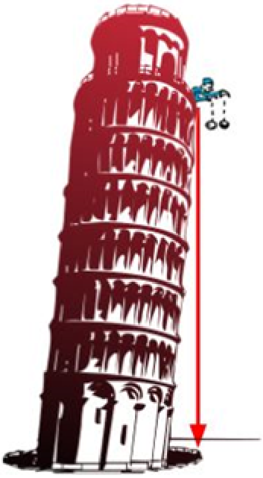

Figure 3. Galileo's Pisa experiment from leaningtowerpisa.com

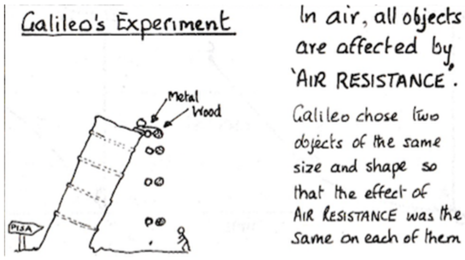

Figure 4. Galileo's Pisa experiment in an O Level Physics book

The Irish government-funded Discover Primary Science & Mathematics / ESERO teachers' activity on Gravity claims the following:

Until Galileo's time (around 1600 AD) people thought that heavier things fell faster than light things. Galileo was an Italian scientist who experimented (up to then they mainly just thought!) and found that things with different weight fell at approximately the same speed.

This segment is grossly incorrect as it assumes lack of experimentation prior to Galileo, which the Ancient and Byzantine Greeks were well known for, and that Aristotle was unquestioned, either in his own time or since. It seems to mirror the position of de Grijs (2017) that Aristotle was held to be some kind of demigogue, which Galileo would replace, and be more acceptable as a scientist:

> The turn of the 17th Century saw a step change in scientific thinking, from blindly following the Aristotelian worldview to the first critical attempts at pursuing the modern scientific method, from the Middle Ages to the Enlightenment.

Unfortunately, this perspective is a 'western' European perspective which tends to ignore the wider reality in history and assumes the milieu in 16th /17th century Florence / Papal States to be the universal condition everywhere at all times. It is somewhat surprising that such a view prevails and is encouraged even today. We also have to be careful that 'blindly following the Aristotelian worldview' can be code for singling-out any particular religious group turning Galileo into a *cause célèbre* for something that Galileo himself would not have contemplated. It is also possible as Bolotin (1997) has argued that Aristotle never intended his writings to be taken as finally polished theories of how the world works, rather they were rhetorically coated. There is a great need to reevaluate what we teach in science - regardless of the level and it is our duty to teach the correct version. The Ancient and Byzantine Greeks were experimentalists and thinkers both. So long as history is disembodied from science, and science content not taught, teachers are doomed to blindly follow ignorance. We may indeed fear the Greeks, but they do bear gifts.

Acknowledgement

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