

Chapter 2

Heaviness, Lightness, Sinking and Floating

Weight, for Aristotle, is inextricably bound with matter and motion in a way that goes to the very core of his concepts of nature (*physis*), the student of nature (physicist), and the accompanying body of knowledge, namely, physics. Motion in this context refers to anything that changes in time. This means all forms of change, excepting sudden transitions. The transition from absence to presence of contact, for example, falls outside of what Aristotle calls motion and outside of study and analysis as physical process. Things either do or do not make contact, and cannot be in half or quarter contact. Once established, contact may weaken or intensify in time, and these are proper motions. But if contact weakens gradually to the point of breaking, then the first instant of no contact belongs to the next phase of timed change, which is now in the category of drawing apart, and no longer in the category of weakening contact. So only continuous change comes under the domain of physical process, where continuous means infinitely divisible in time. With this qualification, the study of physical process in Aristotle's sense, namely of timed transitions, encompasses all the natural sciences, and not just the specialized subject that nowadays goes by the name of physics.

All material objects are capable of change, according to Aristotle, and whatever changes through time must have a material substrate.¹ While a great variety of

¹The question of what is the essential material substrate is not relevant to our discussion, but the following may be noted: Pure substances like gold or silver may be taken for the material substrate of statues, but the differences between gold and silver show that each of them is already a combination of material substrate and form. To avoid endless regression, Aristotle posits the existence of a formless fundamental substrate that can carry any and all forms relating to matter. *Hulé*—the term associated with the fundamental substrate is not exclusive to it. Aristotle would use *hulé* as the golden substrate of a statue in one context, and as the fundamental substrate, that carries the form of a material element, like earth, in another. In the latter sense, even the five elements are not fundamental, but *hulé* can never actively exist in pure formless state. Pure *hulé*, then, has no independent existence any more than pure form. The following restriction, however, must still always hold: all the *hulé* in the eternal and never created cosmos is, and always has been, locked into the celestial and terrestrial elements. The ether is non-transmutable, and while the terrestrial elements are mutually transmutable, none can appear out of nothing, and none can disappear into nothing. Therefore, the finite size of the cosmos necessarily implies a limited supply of *hulé*, and the idea that *hulé* is potentially of unlimited quantity cannot be defended against the eternity and strict finiteness of the Aristotelian universe.

transitions is available to material objects, they all share the ability to partake in one fundamental type of motion, namely, spatial displacement, or locomotion. Since nothing is more fundamental than motion that involves displacement accompanied by no other change, the fundamental elements of motion must belong to the category of pure locomotion. To the extent that *material* elements exist, they must exhibit motions that serve as first principles of motion in the sense that "...first principles must not be derived from one another nor from anything else, while everything has to be derived from them." (*Physics* I.v.188^a27-28). It must be stressed that Aristotle does not suggest that all natural motions, such as color change, heating and cooling, or hardening and softening, are reducible to locomotion. He sees locomotion as fundamental in the sense that anything capable of some form of change must also be capable of locomotion.² In that sense locomotion is fundamental to all motion. Therefore, the first principles of locomotion, to which all locomotion is reducible, are indicative of the fundamental elements of matter, which must be present in all that changes. Since locomotion takes place along paths:

All physical bodies and magnitudes are in themselves, we say, mobile in respect of place; for we maintain that nature is a principle of movement in them. And all movement in respect of place, which we call locomotion, is either straight, in a circle, or a combination of these; for these two alone are simple. The reason is that these magnitudes alone are simple, the straight line and the circular. Movement about the center, then, is in a circle, movement upwards and downwards is rectilinear. By 'movement upwards' I mean movement away from the centre, by 'movement downwards' that towards the centre. So that all simple locomotion must be away from the centre, towards the centre, or about the centre. (*On the Heavens*, I.ii.268^b14-24, Leggatt 1995).

Note that Aristotle refers to the line and the circle as magnitudes, not merely as qualitative forms. A given line is inalienable from its length, just as a circle cannot be imagined without a size for its radius. To Aristotle, the study of physics already at its most elementary level must involve magnitudes. Merely qualitative considerations can never fully capture the subject matter of physics.

Since some bodies are simple and others compounds of these (I mean by 'simple' all those that have a principle of movement according to nature, such as fire, earth, their forms, and

²"A thing is said to be prior when its existence is a prerequisite for the other things to exist, but not vice versa, [...] So Change of place must be primary, because neither increase nor decrease nor alteration, nor again coming to be or ceasing to be, are necessary prerequisites for movement, but the continuous movement which the first agent of change imparts is a necessary prerequisite for the existence of these other kinds of change." (*Physics*, VIII.vii. 260^b17–18 [...] 26–28, Waterfield). The reference to a prime agent of movement is explicit here, and the intention must be to the prime movers studied in the *Metaphysics*. These agents induce the uniform rotations of the celestial ether spheres, which force continuous locomotion in the terrestrial region, as described in *Meteorology* I. ii.339^a20–32. But, "...there is no necessity at all for the thing that changes place to be either increased or altered, nor, certainly, to come into being or be destroyed; but none of these is possible if there is not the continuous process which the first mover sets in motion." (*Physics*, VIII. vii.260^b28-29, Sachs) All of this shows that locomotion is a necessary (though not in itself sufficient) condition for all other types of change.

their congeners), movements must also be simple or some kind of combination, and simple bodies must have simple movements, compound bodies combined movements (moving according to that component which predominates).

Thus, if there is such a thing as simple movement, and movement in a circle is simple, and the movement of a simple body is simple and simple movement belongs to a simple body (for even if simple movement belongs to a compound body, it will belong according to that component which predominates), there must be a simple body that is such as to move in a circle according to its own nature. (*On the Heavens*, I.ii.268^b26-269^a6, Leggatt 1995).

Guided by these observations, Aristotle identifies three types of simple motions, and hence three types of elemental matter: straight upward motion exhibits the nature of the elementally light; straight downward motion exhibits the nature of the elementally heavy; circular motion about the center exhibits the nature of the elementally weightless. By upward and downward in this context, Aristotle always means respectively away from or toward the one and only center of the universe, so the entire discussion presupposes a spherical geometry for the entire material universe.

Since some of the things that have been said are being assumed, while others have been proved, it is clear that all body does not possess lightness or weight. What we mean by 'the heavy' and 'the light' must be assumed at the moment sufficiently for our present need, but more accurately later, when we shall examine their essence. Thus, let that which is such as to move towards the centre be 'heavy', that such as to move from the centre 'light', that which sinks below all downward-moving bodies 'heaviest', and that which rises above all upward-moving bodies 'lightest'. Then everything that moves down or up has to possess lightness, weight, or both (this last, however, not in relation to the same thing; for bodies are heavy and light in relation to one another, as is air in relation to water, and water to earth). But the body that moves in a circle cannot possess weight or lightness; for it cannot move towards or from the centre either naturally or counter-naturally. (*On the Heavens*, I.iii.269^b18-31, Leggatt 1995).

A word on nomenclature is required here. Translations of Aristotle often use the words "weight" and "heaviness" interchangeably for the Greek "*baros*." This could result in confusing relative and absolute weightlessness. That a proper mixture of cork and steel neither sinks nor rises in water merely makes it weightless in a relative sense; in air the mixture's heaviness will immediately become apparent, in mercury it will immediately become light. So "weight" throughout this essay designates either the potential or active presence of heaviness, lightness, and all composite measures of them. Weightlessness designates the very absence of such presence, namely, the inability of the weightless to partake, naturally or by force, in up and down motion. Hence:

But the body that moves in a circle cannot possess weight or lightness; for it cannot move towards or from the centre either naturally or counter-naturally. For rectilinear locomotion does not belong to it naturally, since the locomotion of each single body is single, and so it will be the same as one of the bodies that move in this manner. Were it to move counter-naturally, then if movement downwards is counter-natural, movement upwards will be natural, but if movement upwards is counter-natural, that downwards will be natural; for we laid down that, with contraries, when one movement is counter-natural for a thing, the other, contrary movement is natural. Since the whole and the part (for instance, the entire earth and a small clod) move naturally to the same place, a first upshot is that this body

possesses neither lightness nor weigh at all since otherwise it could move either towards or from the centre according to its own nature; next, that it cannot be moved spatially by being drawn upwards or downwards, for it cannot possibly be moved with another movement either naturally or counter-naturally, neither it nor any of its parts—the same argument for the whole as for the part.” (*On the Heavens*, Liii,269^b29-270^a12, Leggatt 1995)

Weightlessness in the above sense is the fundamental nature of Aristotle’s ether that dominates the celestial region (from the sphere of the moon outward).

Weight is the fundamental nature of all terrestrial matter, below the sphere of the moon. Circles have no points that serve as unique starting and ending points; all straight line segments do. In contradistinction from the weightless ether that has no contrary in keeping with the character of a circle,³ the realm of weight is defined between two extremes—the absolutely heavy and the absolutely light. Being absolute, they derive directly from the absolute size of the universe, which must, therefore, be finite to prevent infinite absolute heaviness and lightness.⁴ Between them, all continuous transitions take place (and it should be understood that for Aristotle, the actively light is always potentially heavy, and vice versa, since both belong to the same family of straight motions). Earth is the absolutely heavy element. Fire is the absolutely light element. Aristotle considers that in order to ensure a continuous spectrum from the absolutely heavy (earth) to the absolutely light (fire) two and only two more elements are required, water and air. These reflect relative heaviness and lightness in the sense that regardless of size, a bubble of air always rises in water, and a drop of water always sinks in air, while fire always rises in air, and earth always sinks in water. Natural up and down motion, then, characterizes the terrestrial elements, and they are mutually transmutable by virtue of belonging to the same spectrum between absolute heaviness and lightness. The celestial element is characterized by circular motion. It cannot transmute into any of the terrestrial elements and vice versa. While terrestrial matter can be forced to move in concentric circles about the earth, celestial matter cannot be forced to move up or down. Terrestrial physics is therefore based on laws of motion that are distinct from the laws of motion that underlie astronomy, or celestial physics. Both belong to the realm of physics to the extent that they study matter in motion, and not to mathematics, which studies forms and magnitudes in abstraction from matter and without recourse to time.⁵

³This does not mean that Aristotle rejects the possibility of contrary motions in the ethereal realm. Indeed, he states explicitly (*Physics* VIII.viii.262^a9-12) that any circular motion has a contrary that will counteract and arrest it. This, however, is a contrariety that lacks a critical feature of linear motion, in which contrary motions go to contrary places, while in circular motion, all rotations and their contraries go from the same starting point to the same ending point.

⁴Since heaviness is actively expressed by the speed of a heavy object’s natural motion, Aristotle argues that an infinite universe implies infinitely fast natural motions, which is absurd. More on this in Appendix A.

⁵I find this the only way to make consistent sense of Aristotle’s reference to astronomy and optics as the more physical of the mathematical subjects: “...one must see how the mathematician differs from one who studies nature (for natural bodies too have surfaces and solids and lengths and points, about which the mathematician inquires), and whether astronomy is different from or part

A naturally falling stone, then, is not driven down by its heaviness. It does so by nature. Heaviness is not a force that pushes or pulls a stone downward, and in this sense it features as the formal cause of natural fall rather than its efficient cause. The efficient cause is primarily whatever transmuted a bulk of light matter into heavy matter, say, a bubble of elemental air into a clod of elemental earth. Once the transmutation is complete, the clod of earth will fall down by virtue of being earth, and not because some efficient cause called “heaviness” is forcibly driving it down. A secondary efficient cause of natural fall is that which removes a block that prevents the natural downward motion of a heavy object. In this secondary sense, heaviness is an efficient cause of natural fall to the extent that it overcomes any external blockage to the motion,⁶ including in particular the ever-present impedance offered by the medium. Considering all of this, a heavy mobile’s weight cannot present a load against itself since the heaviness is not a force that acts against the mobile in the first place. Any relationship between speed and weight (heaviness or lightness) in either natural motion or its direct contrary must enter the scheme in a way that is distinctly different from the way it enters forced motion as discussed in Levels 1, 2, and 3.

The picture changes with respect to the medium. Heaviness, according to Aristotle, is that with which a naturally moving mobile cleaves its way through a medium. The inescapable conclusion is that a mobile’s heaviness acts as an external force against anything outside the mobile that stands in its way down. The medium, however, differs from other obstacles in its ability to absorb moving force from external original movers. Whether or not the moving force that a heavy object builds into the medium applies back to the original heavy mover remains to be seen (see further development ahead). Even under the assumption that the medium directly effects or contributes to natural downward motion it remains objectionable to suppose that the heaviness, which cannot reasonably act against itself as a load, does present a load against the medium’s contribution to the motion that reflects the very nature of heaviness.

(Footnote 5 continued)

of the study of nature. For if it belongs to the one who studies nature to know what the sun and moon are, but none of the properties that belong to them in themselves, this would be absurd, both in other ways and because those concerned with nature obviously speak about the shape of the moon and sun and especially whether the earth and the cosmos are of spherical shape or not. The mathematician does busy himself about the things mentioned, but not insofar as each is a limit of a natural body, nor does he examine their properties insofar as they belong to them because they pertain to natural bodies.” (*Physics*, II.2.193^b22-34, Sachs 1995). Astronomers and students of optics do not study the properties of circles and lines per se as the mathematicians do; rather, they are reasoning about planetary motions and rays of light *in terms* of circles and lines. Mathematicians, by contrast, may point to figures in the sand, but it is not sand figures that they reason about, but abstract geometrical ones independent of all material constraints. Once given, the curvature of a nose may be studied as an abstract mathematical figure, but its constraint as belonging to a nose is physically imposed and cannot be derived in the abstract (See *Physics*, I. iii.186^b21-22, and II.ii.194^a6).

⁶*Physics*, VIII.iv.255^b14-256^a3.

It appears, then, that the dynamics of terrestrial vertical motion differs from the dynamics of terrestrial horizontal motion in the way that weight (heaviness or lightness) figures into them. In vertical motion, whether reflecting natural weight only or a combination of weight and any additional vertically acting agency, weight is a source of motion, and figures as an additive component to vertically acting external agencies. As the next quote shows, Aristotle indicates this additive aspect of natural vertical motion. However, he says very little about terrestrial horizontal motion, and some minimal guidance with regard to horizontal motion must be interpolated to obtain a measure of theoretical completeness. Specifically, in horizontal motion, which is never natural and always forced, let the heaviness (or lightness) of a body figure in as a load, which is inversely proportional to speed. However, an individual who cannot lift a loaded wagon could still push it horizontally. Therefore, while load in horizontal motion bears direct proportionality to weight (heaviness or lightness), it differs from the property “weight” as inextricably associated with vertical motion. Vertical in this context means radially up or down, and horizontal means in a circle around the center of the earth. Both vertical and horizontal motion require contributions from the medium that provides the effective force and resistance to motion, and we have already seen that according to Aristotle, motion without a medium (namely, in a void) invariably leads to paradoxes. The following statement by Aristotle focuses on the role of the medium (air, in this case) as effective mover and how it combines with natural motion:

All movement is either natural or enforced, and force accelerates natural motion (e.g. that of a stone downwards), and is the sole cause of unnatural. *In either case the air is employed as a kind of instrument of the action,*⁷ since it is the nature of this element to be both light and heavy. In so far as it is light, it produces the upward movement, as the result of being pushed and receiving the impulse from the original force, and in so far as it is heavy the downward. *In either case the original force transmits the motion by, so to speak, impressing it on the air.* That is the reason why an object set in motion by compulsion continues in motion though the mover does not follow it up. Were it not for a body of the nature of air, there could be no such thing as enforced motion. *By the same action it assists the motion of anything moving naturally.* (*On the Heavens*, III.ii.301^b20-30, Guthrie, 1939, my italics).

The scope of the above quotation goes clearly beyond the specific case of natural fall from rest, and we cannot escape the task of trying to find how natural and forced motions combine. Particularly instructive at this stage are two arguments by Aristotle, showing how the discussion of natural motion ties quantitatively with the principles of level 1 (that is, *Physics* VII.v):

That some bodies must owe their impulse (ρόπήν) to weight or lightness can be shown as follows. (i) We agree that they move of necessity. But if that which moves has no natural impulse it cannot move either towards or away from the centre. Suppose a body A to be weightless, and another body B to have weight, and let the weightless body move a distance CD and the body B move in an equal time CE. (The heavy body will move farther.) Now if the heavy body be divided in the proportion in which CE stands to CD (and it can quite well

⁷ πρὸς ἀμφοτέρω δὲ ὥσπερ ὀργάνῳ χρῆται τῷ ἀέρι

bear such a relationship to one of its parts), then if the whole traverses the whole distance CE, the part must traverse CD in an equal time. Thus that which has weight will traverse the same distance as that which has none, and this is impossible. The same argument applies to lightness (*On the Heavens*, III.ii.301^a24-301^b1, Guthrie 1939).

The second argument considers the possibility that the motion of a weightless body is forced, and hence obeys the principles of motion under force. If so—Aristotle puts down as claim to be proved—then at any finite time the weightless body will be moved to infinity: “Moreover, if there is to be a moving body which is neither light nor heavy, its motion must be enforced, and it must perform this enforced motion to infinity” (Guthrie). The proof goes as follows:

That which moves it is a force (δύναμις τις), and the smaller, lighter body will be moved farther *by the same force*. Now supposed A, the weightless body, is moved the distance CE, and B, the heavy body, the distance CD in an equal time. If the heavy body be divided in the proportion in which CE stands to CD, the part cut off from it will as a result be moved CE in an equal time, since the whole was moved CD. For *as the greater body is to the less, so will be the speed of the lesser body to that of the greater*. Thus a weightless body and a heavy body will be moved an equal distance in the same time, and this is impossible. Seeing, therefore that the weightless body will be move a greater distance than any other given body, it must travel to infinity. The necessity for every body to have a definite weight or lightness is now clear. (*On the Heavens*, III.ii.301^b5-18, Guthrie, 1939, my italics).

The first thing to note about these two arguments is that neither constitutes a demonstration of inherent paradox in the concept of weightlessness falling naturally or by force. What they do show is the incompatibility of weightlessness falling naturally or moved by force with (1) the proportion relating heaviness to natural speed of fall; (2) with the proportion relating heaviness to forced speed; and (3) with the finite size of the universe. The two proportions and the finiteness of the universe are here taken for granted. The reader is assumed to know and accept them, and then it is quickly shown that under these fundamental restrictions, certain things are disallowed.

The first argument in particular betrays Aristotle’s fascination with mathematical physics: “We agree that they move of necessity. But if that which moves has no natural impulse it cannot move either towards or away from the centre.” This is so by basic postulates that are already assumed for this discussion, and nothing further needs to be added by way of proof. The redundancy of the mathematical proof that Aristotle supplies underscores the importance that he attached to elaborating the argument in mathematical terms.

The two arguments, which follow one another in quick succession, are the closest Aristotle comes to teaching how to combine the principles of forced and natural motion. The demonstrations follow his usual habit of representing the relevant magnitudes by the lengths of line segments (not supplied by diagram with the text in this case, but they are clearly intended and easy to draw). The importance of these examples to our discussion warrants a closer look. Consider first the generalized principle italicized in the second case: When two objects of different weights (say heaviness, to keep things unambiguous) are moved by the same force, then their weights and speeds are inversely proportional, that is $W_1:W_2::V_2:V_1$. Note that while the example compares distances covered in equal times, the general principle

(italicized) is formulated in terms of speeds. This justifies our use of speed in levels (1) and (2). The argument is clearly intended generally, and so we may as well take the proportion to hold under all conditions, for variable as well as uniform speeds.

Keeping this in mind, consider the first case. Here we have a weightless body *A* falling naturally at speed V_A , and a heavy body *B* falling naturally at speed V_B . We represent the heaviness of *B* and the speeds V_A , V_B , by the respective parallel line segments FH, EJ, EI (Fig. 2.1):

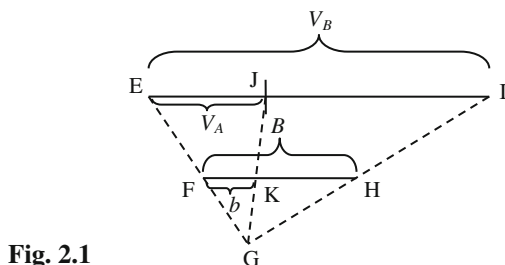


Fig. 2.1

Extend the lines through EF and IH until they meet at G. Draw JG, cutting FH at K. Then clearly, where $EI = V_B$, $EJ = V_A$, $FH = B$, and $FK = b$:

$$\frac{V_B}{B} = \frac{EG}{FG} = \frac{V_A}{b} \Rightarrow b : B :: V_A : V_B$$

This demonstrates Aristotle's contention that a part b of *B* can always be marked such that its ratio to *B* is as the ratio of the weightless body's assumed finite speed V_A is to *B*'s speed, V_B . The motivation to construct this proportion in the first place is the postulate that in natural fall, the weights relate directly as the speeds, and then follows the inevitable conclusion that no finite speed, however small, can be assigned to the weightless body, which cannot, therefore, fall at all.

Turning to the second example, draw $OE = V_B$ and $OF = V_A$. Extend FO to H and let OH be the weight of *B* (Fig. 2.2). Draw from H a line parallel to EF, and mark by G its intersection with the extension of EO. Let the length of OG be b , and clearly, by the constructed similarity of triangles OEF and OGH:

$$V_A : V_B :: B : b.$$

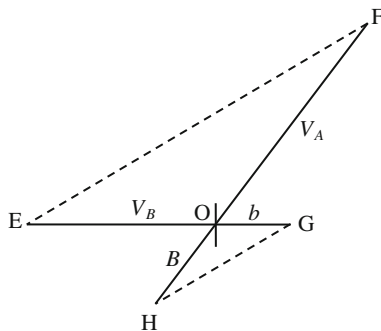


Fig. 2.2

Once again, a simple construction vindicates Aristotle's claim that given speed V_A forced upon a weightless body A , and speed V_B generated in a heavy body B by the same force, a body of heaviness b may always be found such that the two finite weights are inversely as the two given speeds. To the extent that such is the proportion of heavy weights to speeds under the effect of the same force, it turns out that the speed of the weightless body must be increased indefinitely, or else there will always be a heavy object moved at the same speed by the given force. But an infinite speed means a universe of infinite extension, contradicting the finite size of the universe, which is here taken to be beyond dispute.

Note that the weights and the speeds need not be drawn using the same units of length. Speed lines may be measured in millimeters, weight lines in inches, and the equality of ratios will remain unaffected as long as each quality has its standard of length. That is to say, once the lengths OE and OF have been drawn proportionate to the given values of V_B and V_A respectively, OH representing B may be drawn to any arbitrary length, and the procedure ensures that its ratio to OG representing b will remain invariable.

The difference between forced and natural motion should be quite clear. In natural fall, heavy weights and speeds relate *directly*: $W_1:W_2::V_{n1}:V_{n2}$. The speeds of the same W_1 and W_2 moved by some given force are *inversely* as the weights: $W_2:W_1::V_{f1}:V_{f2}$. (V_n and V_f stand respectively for natural speed and forced speed).

Proper combination of the principles of forced motion and the principles of natural motion must specify how force, mobile, and motion relate along the line of natural motion and along a line transverse to the line of natural motion. With respect to vertical motion, two versions can be constructed for the interaction between a body's heaviness and the medium as effective mover. While different in their mode of explaining the vertical motion associated with heaviness (or lightness) combined with some external moving agency, the resulting motion is identical in both cases.⁸ In version (a), the natural heaviness impregnates the medium with effective moving force that causes active movement. Here, natural heaviness competes with any external upward force in the medium, and to the external mover this competition manifests itself either as resistance of a heavy object to forced upward motion (or as resistance to downward motion in excess of the motion due to its inherent heaviness). In version (b), heaviness does not impregnate the medium with an effective force that moves the body downward, and its active nature manifests itself directly as downward motion. In other words, downward motion is not the result of some dynamical interaction between heaviness and the medium as effective mover; rather, downward motion is fundamentally the active expression of heaviness. From this stems the resistance of a heavy object to an external lifting agency as it impregnates the medium with effective upward moving force (or to an external agency that attempts to impregnate the medium with effective force to

⁸See Appendix D for a mathematical demonstration that the two version lead to identical descriptions of motion.

speed the heavy body beyond its natural downward speed). The following points further clarify the main features of the two versions:

1.

- a. Heaviness unopposed by the upward directed action of some external agency operates on the medium in a downward direction as an external agency, stressing to cleave it while infusing it with effective moving power, in accordance with level 3 above. Heaviness, then, competes *in the medium* as a downward agency against any opposed external agency. The net intensity of the source that builds effective moving force into the medium is proportional to the difference between the internal heaviness and the overall intensity of any external opposing agency. Therefore, only an external agency greater than the heaviness of a mobile will have an excess over it that can infuse upward effective force into the medium, moving the mobile upwards against its weight. The excess over natural heaviness, then, acts as the power of an original mover building a net upward moving force in the medium. Constant upward speed will obtain once the rate of force decay in the medium matches the infusion of effective force into the medium. Once contact between the external agency and the mobile is broken, the built-up force in the medium will gradually decay with no counteracting infusion, sustaining a decelerating upward motion until it dissipates altogether. But the process will not cease here, because the heaviness constantly strives to build downward effective force into the medium. Therefore, downward motion will take over with accelerating rate while downward driving force builds up in the medium under the effect of heaviness. Terminal speed is reached when the dissipation of force in the medium matches the rate of force infusion into it by the downward force of heaviness. An external agency acting downward, then, builds into the medium downward effective force beyond what the mobile's natural heaviness does. Once disconnected from the mobile, the downward motion will decelerate back to the speed associated with the effective force that the heaviness builds into the medium by itself. At all stages, however, whether the motion is purely natural or a combination of natural and unnatural components, the effective force in the medium is operating, and in this sense all motion, natural or not, has a forced aspect.
- b. Heaviness is a principle of motion internal to the body. To external bodies, including the medium, it appears as an external moving agency. To the heavy body itself, the medium manifest itself by its resistance to being cleaved, and by the additional resistance reflected against a heavy body as it impregnates the medium with effective force to move external objects *other than* itself. In this case, the effective force that an external upward source infuses into the medium acts directly against the inherent principle of motion that the natural heaviness of the mobile represents. Once again, even when supporting a motionless object, an external force must exert itself to keep

inflow of upward effective force into the medium so as to exactly counteract the natural heaviness of the object. In this rendition, a heavy body moves up only once the surrounding medium contains an effective force greater than the body's heaviness. Upward motion will first accelerate as the excess over weight in the medium builds up, and continue at constant speed once decay matches input at this higher level of effective force. Upon removal of the external source, the upward effective force in the medium will decay, as always. When its continuously dropping level exactly balances the natural heaviness of the mobile, the mobile will pass through an instant of rest, but downward motion will follow at accelerating rate as the effective force drops further and further below the natural heaviness. Terminal speed settles in once all the effective force is exhausted, with the magnitude of the speed directly proportional to the heaviness, and inversely to the resistance of the medium to being cleaved. Note again that in this version heaviness does not infuse the medium with effective force to move itself. Therefore, under this understanding of the dynamics, natural motion is unforced—the medium is cleaved by the heaviness and the resulting speed reflects only the heaviness mitigated by the resistance of the medium to being cleaved and the additional difficulty of loading it with effective force to move other objects. The motion of a heavy body either hurled or released from rest will be exactly the same in both versions. But physically, while in version (a) the medium builds up downward force to account for the acceleration, here it is the difference between the decaying upward force in the medium and heaviness that accounts for the downward acceleration. Under this interpretation, when Aristotle speaks of force aiding natural motion, he should be understood as referring to downward external agencies building extra effective downward force into the medium to directly aid the natural heaviness. This alternative is worth keeping in mind because it corresponds exactly to Hipparchus's account of prolonged motion, with the possibility of transferring the medium's active role into the body, and leaving the medium only with a purely resistive effect.⁹

2. So far, it seems plainly clear that the transition from upward to downward motion is perfectly smooth, passing through rest at a single instant of time, so that the body never rests for any duration, no matter how small. However, this aspect will require an important modification following the discussion concerning the threshold of motion in the next section.
3. In a direction transverse to the line of natural motion, load is proportional to the heaviness of the body moved, so that speed is directly proportional to the external mover's strength, and inversely proportional to the load. This does not

⁹For a more detailed comparison of Aristotle's active medium to the idea of in-body impetus, and whether Hipparchus really originated the idea, see ahead, "Hipparchus on the Theory of Prolonged Motion."

imply that a body's load against horizontal motion is quantitatively equal to the body's heaviness. The physical distinction between the behavior of a heavy weight in vertical motion and its related load in horizontal motion must not be forgotten: even an extraordinarily powerful human cannot lift up vertically a packed cart weighing half a ton, but it takes no more than average human strength to push it along a horizontal floor. However, since all relations without exception take the form of proportions, the ratio of two heavy loads is invariably the same as the ratio of their respective weights, and it becomes a matter of indifference to use weight ratios only.

When a hurled object moves in a direction other than radially up or down, the radial and horizontal aspects of its motion must be analyzed separately according to the principles outlined above, and then combined into a full account of the result. There is no room for plausible doubt with regard to Aristotle's ability to combine directed magnitudes. In Eudoxan homocentrics, which Aristotle describes in *Metaphysics* XII.viii, velocities are directionally superimposed as a matter of course. In *Physics* VIII.viii.262^a13 Aristotle indicates that motion up is not the opposite of motion sideways, and they cannot cancel each other. *Meteorology* I. ii.339^a20-32 describes how the circular motion of the ether confers a forced circular (horizontal) component on the natural vertical motion of the terrestrial elements, providing the source of the variable motions observed in the terrestrial region. The *Mechanical Problems*, presumably written by Aristotle's students, clearly teaches the parallelogram method of combining directed magnitudes, and also argues very cogently that when a constant horizontal speed is combined with a variable vertical speed, the result is motion along a plane curve. Given all of this, it is implausible to assume that Aristotle was incapable of combining all manners of vertical and horizontal motions.

Figure 2.3 is a qualitative graphical representation of the stages of upward flight. At t_0 , an upward moving agent that has been holding an object at rest against its heaviness suddenly increases power beyond the object's weight. At t_1 , it breaks contact with the object, which behaves as a thrown object from this point on. The force curve shows the resulting development of effective moving force in the medium for version (a), and the same curve shows the difference between the body's heaviness and the changing effective force in the medium for version (b). The associated speed and position curves illustrate the resulting motion. When marked above the time-axis, the magnitudes of the effective force and the speed represent upward tendencies; when marked below the time-axis, they represent downward tendencies. Position above the time-axis represents position above the throwing platform from which motion began; position below the time-axis represents position below the throwing platform.

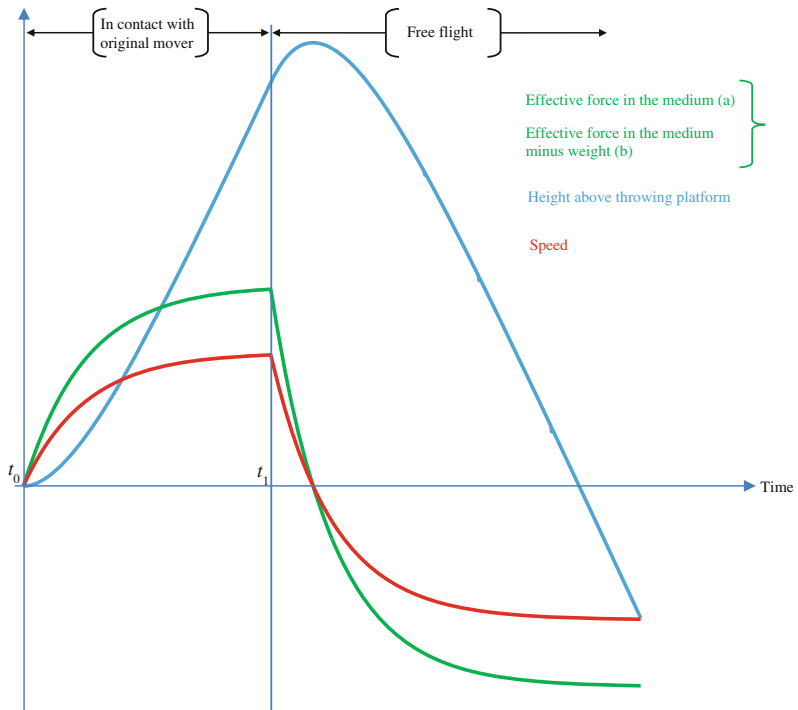


Fig. 2.3

Summary: The Main Features of Aristotle's Theory of Terrestrial Locomotion

We now have the basic framework of Aristotle's theory of matter in motion. The main features, in brief outline, are as follows ("motion" throughout this summary refers exclusively to spatial displacement):

1. All natural motions are unforced. All unnatural motions are forced.
2. For all terrestrial mobiles, natural motion is either radially toward the center of the universe (heavy mobiles) or radially away from the center of the universe (light mobiles).
3. Accordingly, all terrestrial mobiles are classified along a common scale of weight, from the absolutely heavy earth, to the absolutely light fire.
4. Weightlessness is the inability to partake in either the heavy or the light. Such is the nature of the celestial ether, which cannot, accordingly, change its distance from the center of the universe, and can only move on spherical surfaces around

it. The theory of celestial motion therefore follows different principles than the theory of terrestrial motion. The rest of this outline is restricted to the theory of terrestrial motion.

5. The speed of forced motion transverse to the direction of natural motion is directly proportional to the strength of the effective moving force, and inversely proportional to the medium's resistance and the magnitude of the mobile's load.
6. The speed of forced motion along the line of the mobile's natural motion is directly proportional to the difference between the effective force and the mobile's weight, and inversely proportional to the medium's resistance.
7. Aristotle makes a clear distinction between original movers and the effective force that they generate to move mobiles actively. The effective force always resides in the surrounding medium. Original movers, therefore, always move mobiles indirectly by impressing effective force into the medium. The medium is always the direct instrument of active motion.
8. The force that an original mover impressed on the medium does not disappear immediately when the original mover ceases its activity. Rather it decays slowly. This assumption enables Aristotle to explain why hurled mobiles continue to move for a while after they broke contact with their original movers.
9. All of the above features obtain support from explicit indications by Aristotle. Aristotle does not provide an explicit discussion of the onset of motion to complement his discussion of the decay of motion. In continuation of his line of thought with regard to the gradually decelerating motion of projectiles after breaking off from their original movers, it is postulated here that it also takes time for original movers to build impressed force into the medium. This complements Aristotle's account by matching the gradual deceleration of forced motion with a complementary gradual acceleration under the influence of an original mover.

Certain refinements are still necessary, beginning with the most important qualification of the theory so far—the threshold of motion.

Bodies and Media

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