A New Look at Heron's "Steam Engine"

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Communicated by C. A. WILSON

I. *The Problem.*

HERON (*Pneumatica* 2.11) describes a device:

Λέβητος ὑποκαιομένου σφαιρίον κνώδακα κινεῖσθαι. Ἔστω λέβης ὑποκαιόμενος ἔχων ὕδωρ ὁ AB καὶ ἐπιπεφράχθω τὸ στόμιον τῷ ΓΔ πώματι: τούτῳ δὲ συντετρήσθω σωλὴν ἐπικαμπὴς ὁ EZH, οὗ τὸ ἄκρον εἰς κοῖλον σφαιρίον ἐνηρμόσθω τὸ ΘK: τῷ δὲ ἄκρῳ τῷ H κατὰ διάμετρον ἔστω κνώδαξ ὁ ΛM βεβηκὼς ἐπὶ τοῦ ΓΔ πώματος. ἡ δὲ σφαῖρα ἐχέτω δύο σωληνάρια ἐπικαμπῆ κατὰ διάμετρον συντετρημένα αὐτῇ καὶ ἐπικεκαμμένα ἐναλλάξ. αἱ δὲ καμπαὶ ἔστωσαν πρὸς ὀρθὰς ἐπινοούμεναι καὶ διὰ τῶν H, Λ εὐθειῶν. συμβήσεται οὖν θερμαινομένου τοῦ λέβητος τὴν ἀτμίδα διὰ τοῦ EZH εἰς τὴν σφαῖραν ἐμπίπτουσαν ἐκπίπτειν διὰ τῶν ἀνακεκαμμένων ‹σωληναρίων› εἰς τὸ πῶμα καὶ στρέφειν τὴν σφαῖραν, καθάπερ ἐπὶ τῶν χορευόντων ζῳδίων.

The translation is:

A cauldron heated from below, a sphere to move against points. Let there be a cauldron heated from below containing water (AB) and let it be closed at its opening by the lid (ΓΔ); through this lid let a bent tube (EZH) be pierced, the end of which let be fitted into the hollow sphere (ΘK). Diametrically opposite to the end H let there be a point (ΛM) ‹attached› firmly to the lid ΓΔ. And let the sphere have two little tubes, bent, pierced diametrically opposite in it and bent oppositely. Let the bends be orthogonally arranged and through the lines HΛ. Then it will follow that, the cauldron being warmed, the steam (atmis) falling into the sphere through EZH will fall out through the bent-back ‹little tubes› to the lid and will turn the sphere, just as in the case of the dancing figures [2.3].

HERON's "Steam Engine", more often admired than understood, is usually used as a point of departure in criticising ancient technological progress. I suggest that rather than retrojecting ideas due to the industrial revolution back 1700

years,[1] we ought to seek to understand HERON's device (which he himself never called a "steam engine") on its own terms. This is done by examining the technological antecedents of the device and its probable purpose. Then an investigation of the origins of the modern viewpoint and some speculation on "progress" are attempted.

I. Technological Antecedents

Humanists are familiar with source criticism of ideas, literature and art; less often do we see the analogue in the history of ancient technology.[2] The presumption is the same — inventions more often develop or evolve incrementally than spring full-grown from the brow of HEPHAISTOS. The evolution of HERON's device can be traced with fair certainty.[3]

In HIPPOKRATES *de Natura Pueri* 17.4 (Littré 7.498.17–24), of the late fifth century,[4] a demonstration is described, which is alleged to support the author's theory of ontogeny. A pipe (αὐλίσκος) is connected to a bladder (κύστις) containing a mixture of Earth, sand and lead filings (μολίβδου κνήσματα λεπτὰ). Water is poured in and the pipe blown through (Figure 1). The result (as the author correctly claims) will be that the contents will precipitate in layers differentiated by substance (lead, sand, earth).[5] While the author's ontogeny is scarcely

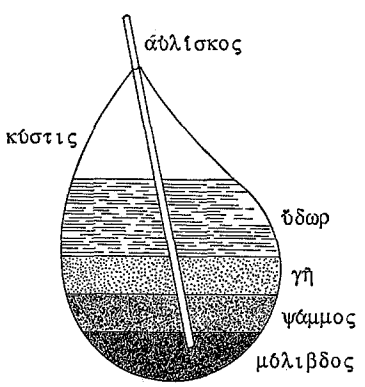

Fig. 1. Bladder in HIPPOKRATES (*NatPuer* 17.4)
(figure courtesy SUSAN GUINN CHIPMAN).

[1] For HERON's date (*fl.* 55–68 A.D.) see PAUL KEYSER, "Suetonius *Nero* 41.2 and the Date of Heron Mechanicus of Alexandria," *Classical Philology* **83** (1988) 218–220.

[2] E. W. MARSDEN, *Greek and Roman Catapults* **1** (Oxford 1969) has attempted to set out the history of catapults in this way, while A. G. DRACHMANN, *Ktesibios, Philon and Heron: A Study in Ancient Pneumatics* (Copenhagen 1948) = *Acta Historica Scientiarum Naturalium et Medicinalium* 4 similarly investigates the antecedents of some pneumatic devices.

[3] Though not traced by DRACHMANN (above, n. 2).

[4] See R. JOLY, *Hippocrate* **11** (Paris 1970) 23.

[5] HIPPOKRATES significantly does not say densitity — the concept does not seem to have been clear yet, *cp.* PAUL KEYSER, *Classical Journal* **81** (1986) 233, n. 19. Was the bladder transparent (διαφανής)? *Cp.* the modern "snowstorm toys" and HERON's transparent altar (2.3).

proved by the analogy, this type of "pressure vessel" is, I believe, the ancestor of a device described by STRATON.

STRATON fr. 64 WEHRLI (= pp. 112.13–113.22 GOTTSCHALK) contains a description of a spherical metal "bladder" to which a bronze "straw" is soldered with tin (Figure 2); it is possibly an invention of KTESIBIOS.[6] This is pressurized by blowing into it (*cp.* HIPPOKRATES) and the subsequent outrush of air correctly adduced as evidence for the compressibility (συστολή) of air. Similarly suction generates a partial vacuum (ἄθροισις κενοῦ), confirmed by the subsequent inrush.

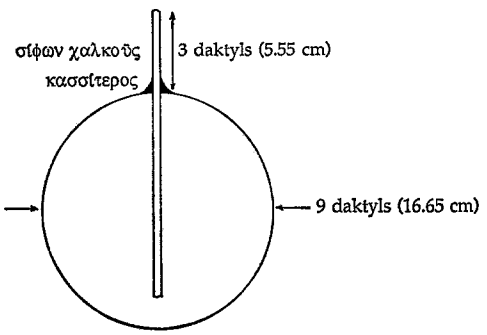

Fig. 2. STRATON fr. 64 W
(figure courtesy SUSAN GUINN CHIPMAN).

The earlier HIPPOKRATIC argument by analogy has been refined to a demonstration or test of a theory (that of STRATON). The development may be due to an observation that aspirating the straw collapsed the bladder or (more likely) that the bladder expanded and stiffened (like a wind-bellied sail) when blown into. This dates to the early third-century B.C.

PHILON *Pneum.* 7 describes what modern scholars call the thermoscope (*cp.* HERON *Pneum.* 2.8: καλουμένη λιβάς, = "Dripper"). In this device, probably of the late second century B.C. (Figure 3), water is drawn into or forced from a pressure vessel identical to that above, by the application of heat or cold.[7] The

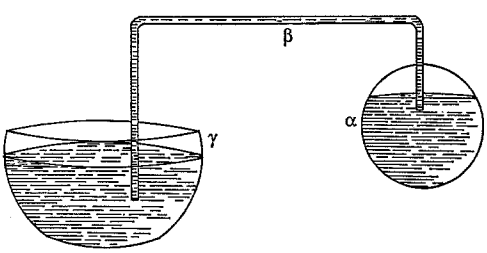

Fig. 3. PHILON's Thermoscope
(after CARRA DE VAUX; figure courtesy SUSAN GUINN CHIPMAN).

[6] The fragment is preserved in HERON, *Pneumatica* (SCHMIDT 16–18). A. G. DRACHMANN (above, n. 2) 89, 91–2 assigns the device to KTESIBIOS, which may well be; that VITRUVIUS 10.7.4 omits it from the list of KTESIBIOS' accomplishments is no evidence.

[7] See DRACHMANN (above, n. 2) 49 and 119–23 or M. R. COHEN & I. E. DRABKIN, *A Source Book in Ancient Science* (Harvard 1948) 255–6.

opposite end of the bent "straw" (siphon) is immersed in a reservoir of water, in an open vessel (Γ): I use the conventional labels for majescule letters throughout the text (the MS figures themselves have "miniscule letter-labels and script" throughout). One further level of abstraction has been reached, and it is notable that changes in temperature are used to generate the changes of pressure. HERON *Pneum.* 2.8 describes an improved version of this ancestor of the thermometer,[8] in which evaporative losses are eliminated. A modern version of this, in which the vessel Γ becomes a closed sphere above the pressure vessel A, is a toy called the "Handboiler" (Figure 7). The thermoscope was probably invented when someone put water into STRATON's device and left it in the sun — the resultant drips christened the device. Pouring water into STRATON's device would not have seemed unreasonable in light of the antecedent HIPPOKRATIC device, which designedly contained water.

The next stage of the development was probably reached at some time before HERON and after PHILON (*i.e.*, about the first century B.C.). Here an increase in air pressure via one tube causes the ejection of water via another. This device, called the "Squirt" (Fig. 4), is the ancestor of insecticide sprayers (and aerosol cans), and is described in HERON, *Pneum.* 1.10. It depends for its operation on a watertight ground joint (stop-cock = σμήρισμα). DRACHMANN convincingly argues that smerismata themselves are found in PHILON only in the Arabic interpolations and are otherwise attested only after PHILON.[9] On the other hand, two lines of evidence combine to suggest that the "Squirt" itself was known before HERON. The

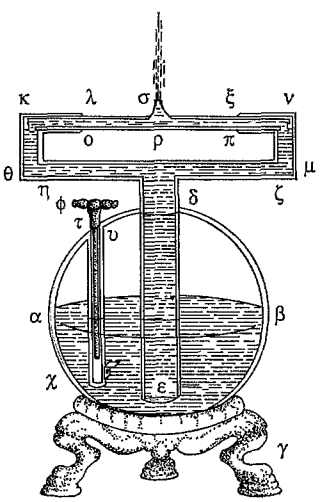

Fig. 4. HERON's Squirt (after SCHMIDT)
(figure courtesy SUSAN GUINN CHIPMAN).

[8] WILHELM SCHMIDT, "Zur Geschichte des Thermoskops," *Abhandlungen zur Geschichte der Mathematik* **8** (1898) 163–73; *cp.* also M. K. BARNETT, "The development of thermometry and the temperature concept," *Osiris* **12** (1956) 269–341 (see pp. 269–73 on the ancient thermoscope), who is mainly interested in the Renaissance developments.

[9] DRACHMANN (above, n. 2) 50.

placement of this device (at *Pneum.* 1.10) as one of the first few in HERON's book, with other elementary devices (1.1–9, 11), suggests that HERON thought it elementary. And work on pneumatics continued (*cp.* SALLUST *Historiae* fr. 2.70.3 M and VITRUVIUS 10 *passim*), so that some devices must have developed in the interval. Second, the air inlet in HERON's squirt lacks a valve — the piston would need to be removed on every stroke — which argues for a more primitive origin.[10] Taking DRACHMANN's arguments concerning smerismata together with the points adduced concerning the "Squirt" suggests that the "Squirt" was invented after PHILON and before HERON.

In any event the device represents a further development — pressure is communicated to the vessel by one tube and relieved by another. It squirts water "with great violence" from the orifice Σ, when the pressure is raised using the piston pump TY/ΦX. (The outlet valves, the smerismata, are at ΚΛΟ and ΝΞΠ — rotating inside sleeve joints, like the outside sleeves which adjust the suction on the hoses of vacuum cleaners.[11]) Again the ejectum is water, and the vessel is spherical (the best shape to withstand the pressure).

HERON remarks on the great violence of the liquid ejection (ἀναπιέζεται εἰς τὸ ὕψος αὐτόματον καὶ μετὰ βίας πολλῆς: *Pneum.* 1.10 [SCHMIDT 70.9–10]). While HERON was not familiar with NEWTON's third law ("to every action there is an equal and opposite reaction"),[12] it is a Law of Nature and must have operated. That is — if the liquid squirted forth μετὰ βίας πολλῆς, the spherical container experienced a recoil of equal violence.[13] I suggest that observing this recoil would not have been a great difficulty for a Mechanicus of HERON's caliber (*cp.* his own notation of the force of the jet from the force pump *Pneum.* 1.28, τῆς τοῦ ὑγροῦ βίας).[14] The observation would have been eased had there been even the slightest asymmetry in the construction of the outlet tube or if the device were ever discharged with the outlet smerisma not vertical, as then the whole apparatus could

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[10] DRACHMANN (above, n. 2) 101–2.

[11] It may not be completely clear from figure 4, but at K and N the tube ΛΞΠΡΟ (the rotatable tube) has one small opening each, on the side. When Σ points upward the openings are facing downward and allow the water in Θ and M to pass through the holes at K and N and so out. When Σ points down the holes are facing upward and are blocked by the walls of the outside tube. If the smerismata were well-made the water would not flow at all till Σ was nearly vertical — but any design would allow some water to flow with Σ near but not exactly vertical — it is in this position that the device could tip.

[12] Or was he? *Cp.* ARISTOTLE, *MotuAnim* 3.699b4–5: ὡς γὰρ τὸ ὠθοῦν ὠθεῖ, οὕτω τὸ ὠθούμενον ὠθεῖται, καὶ ὁμοίως κάτ' ἰσχύν. See also P. TASCH, "Conservation of Momentum in Antiquity: A Note on the Prehistory of the Principle of Jet-Propulsion," *Isis* **43** (1952) 251–2. MARTHA CRAVEN NUSSBAUM, *Aristotle's De Motu Animalium* (Princeton 1978) is silent on this point.

[13] *Cp.* AMMIANUS MARCELLINUS 23.4.5 on the recoil of the onager: *concussione violenta.*

[14] And *cp.* similarly on pumps C. LUCILIUS, Jr. *Aetna* 324–8 (for date and authorship see P. B. PAISLEY & D. R. OLDROYD, "Science in the Silver Age," *Centaurus* **23** [1979] 1–20) and SENECA *Quaestiones Naturales* 2.16, both contemporaries of HERON.

have knocked itself over by the force of the recoil (much as an inflated and unknotted toy balloon jets about).

Once this recoil had been observed, it would have been a relatively easy step (comparable to the three steps between the four apparatus above) to make objects move by the force of the expelled air. That heat could cause this expulsion PHILON had shown and HERON knew (see above on the thermoscope and HERON *Pneum.* 1.12, 2.21). In addition, VITRUVIUS 1.6.2 preserves the description of an Aeolus, a hollow bronze (sphere?) with a small hole, which when filled with water and heated produced a *uehemens flatus*. Causing motion by the expansion of gas and consequent expulsion of fluid is most simply done by using expelled liquid as a counterweight, as in HERON *Pneum.* 1.38 (opening temple doors). Next, the recoil effect of escaping air can be used to move or turn something (dancing figures as at 2.3). This is clearly earlier than 2.11, the "steam turbine", as 2.11 refers to 2.3. Having noted the force of his liquid-filled squirt and of the heated liquid-filled Aeolus,[15] HERON probably sought to increase the effect by the use of heated water. (A natural step in view of the fact that water was considered to be chilled and condensed air — *cp.* HERON *Pneum.* proem [SCHMIDT p. 10].[16]) Thus the "steam turbine" was born (Figure 5).

II. Heron's Purpose

What was HERON's purpose in building his "steam turbine"? He himself never tells us nor even gives it a name. It has not been pointed out, as far as I know, that HERON's device is inherently the wrong design to produce much in the way of useable power.[17] The rotating sleeve joint H must either have excess friction or excess leakage, in either case reducing the efficiency of the device. The sphere would have insufficient inertia to give a smooth output for varying load (*i.e.*, it is a poor flywheel), and it would spin too fast (over 1000 RPM) to allow simple reduction gearing to transmit the power. The spherical shape is to no purpose for generating power, a cylinder would have been easier to make, and it is difficult

[15] The connection has long been noted — HERON's device is often called an "aeolipyle." See ULRICH VON WILAMOWITZ-MOELLENDORFF, *Griechisches Lesebuch* II.2 (Berlin [1]1902, [5]1932; repr. Dublin/Zürich 1966) 163 (a reference I owe to W. M. CALDER III). See also R. HALLEUX, "Problèmes de l'Energie dans le monde ancien," *Etudes Classiques* **45** (1977) 49–61, who on p. 54 notes that "la turbine d'Héron ... est un perfectionnement [de l'éolipile]". Similar (and cited by HALLEUX) is W. L. HILDBURGH, "Aeolipiles as fire-blowers," *Archeologia* **94** (1951) 27–55.

[16] Following STRATON, fr. 88 WEHRLI = p. 110.10–13 GOTTSCHALK, who is of course following ARISTOTLE, *e.g. Phys.* 4.5 (213a2–3), *De Caelo* 3.7(305b14–24), *de Generatione et Corruptione* 2.3–4 (330a30–31b36) or *Meteor.* 3.4 (373b13–7). See J. E. BOLZAN, "Chemical combination according to Aristotle," *Ambix* **23** (1976) 134–44 and *cp.* PAUL KEYSER, "Horace *Odes* 1.13.3–8, 14–16: Humoural and Aetherial Love," *Philologus* **133** (1989) 75–81.

[17] *Cp.* J. G. LANDELS *Engineering in the Ancient World* (Berkeley/Los Angeles 1978) 29 who approaches this recognition ('the device is very inefficient') but does not consider alternate designs; similar is HALLEUX (above, n. 15) 54, who also (54–55) notes that the "vraie turbine à vapeur" is related to the water-wheel.

to attach to a sphere any sort of gearing (necessary for power transmission — *cp.* HERON's windmill, *Pneum.* 1.43). HERON was a mechanical genius — I find it most unlikely that he would have made so many unnecessary mistakes of design.

A much better design (and one which HERON could have invented) would have been the impulse steam turbine: a steam jet driving a device like a water-wheel (Figure 6). The vaned water-wheel (and rim with compartments) was certainly known to HERON, having been invented by the first-century B.C. (*cp.* VITRUVIUS 10.4.3, 10.5.1),[18] and HERON applied it to his invention of the windmill (*Pneum.* 1.43).[19] Further — since he knew of water-driven wheels and had invented the air-driven wheel, and since steam is water in the process of becoming air (HERON *Pneum.* proem., cited above) — there is no doubt in my mind that such a device "could have been" invented by HERON, had he seen any need to do any-

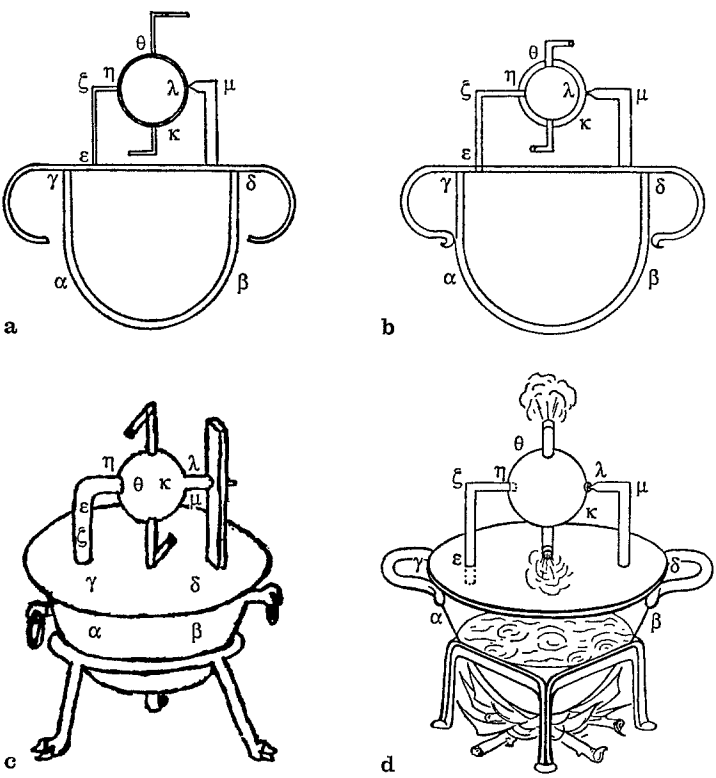

Fig. 5. HERON's Steam Engine (*a* from MS Brit. Mus. Harl. 5899, *b* from Taurinensis, *c* from Brit. Mus. Burn. 81, *d* from SCHMIDT).

[18] For a discussion see LANDELS (above, n. 17) 63–70 and J. P. OLESON, *Greek and Roman Mechanical Water-lifting Devices: The History of a Technology* = *Phoenix* Suppl. **16** (Toronto 1984) 325–50.

[19] For a discussion, see A. G. DRACHMANN, "Heron's Windmill," *Centaurus* 7 (1961) 145–151 and A. G. DRACHMANN, *The Mechanical Technology of Greek and Roman Antiquity* = *Acta Historica Scientiarum Naturalium et Medicinalium* **17** (Copenhagen 1963) 206.

thing so industrial.[20] I suggest that *Pneum.* 2.11 was never intended as a device to generate motive power.

DRACHMANN has suggested that all but 1.1–11 of the *Pneum.* is unfinished and represents notes in various stages.[21] It is clear from the proem and the earlier chapters (note particularly that on siphons) that HERON intends to demonstrate certain theories with at least some of his devices. In *Pneum.* 1.10, concerning the

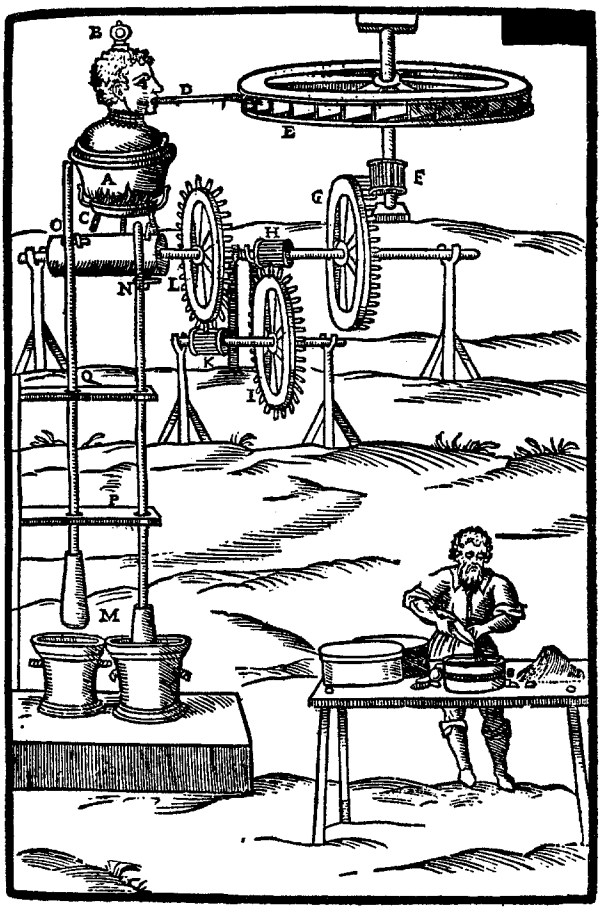

Fig. 6. BRANCA's Steam Turbine (from his *Le machine*, 1629).

[20] Amusingly, the first post-Renaissance steam engine was just this device: see GIOVANNI BRANCA, *Le Machine* (Rome 1629; repr. Readex Microprint, *Landmarks of Science*, 1967) pt. 1, fig. XXV. For discussion, see ELIJAH GALLOWAY, *History and Progress of the Steam Engine* (London 1829; repr. Readex Microprint, *Landmarks of Science*, 1975) 7–8 (with redrawn figure); DIONYSIUS LARDNER & JAMES RENWICK, *The Steam Engine Familiarly Explained and Illustrated*[5] (Philadelphia 1848) 45; J. C. POGGENDORFF, *Geschichte der Physik* (Leipzig 1879) 531; H. DIELS, *Antike Technik* (Leipzig [1]1914, [2]1920) 61–3 with original figure; and H. W. DICKINSON, *A Short History of The Steam Engine* (Cambridge 1939) 192–3, with original figure. The last two (DIELS and DICKINSON) doubt the practically of a steam-driven open-air water wheel.

[21] DRACHMANN (above, n. 2) 79–80.

"Squirt" already alluded to, he suggests that this purpose is to demonstrate that air may force water to rise, "contrary to nature". I would compare the very similar effect in *Pneum.* 2.6, the ball levitated by steam: again against nature, though HERON had not completed the chapter and does not say so. Instead of water above air, here we have even earth above air.[22] HERON also demonstrates the static suspension of a sphere in *Pneum.* 2.7, which probably reflects Stoic cosmology.[23] The remark ("contrary to nature") in *Pneum.* 1.10 reveals that (in line with the Peripatetics THEOPHRASTOS,[24] STRATON,[25] ARCHIMEDES[26] and

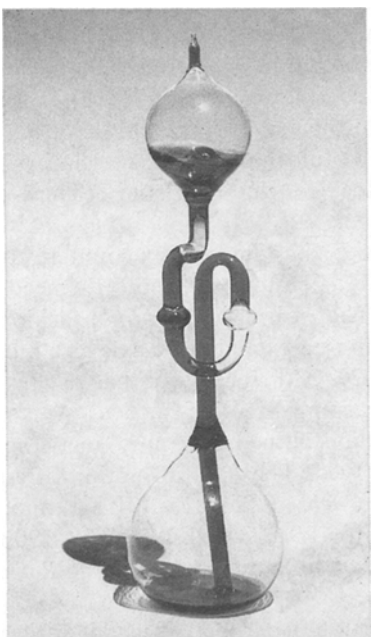

Fig. 7. "Handboiler" toy (ca. 15 cm tall) derived from HERON's Thermoscope (photograph courtesy K. M. KRONENWETTER).

[22] Solids are earthy — ARISTOTLE, *Meteor.* 4.7 (384a3–b23) and 4.10 (378b10–9a24); *cp.* I. DÜRING, *Aristotle's Chemical Treatise: Meteorologica, Book IV = Göteborgs Högskolas Arsskrift* 50 (Göteborg, 1944) 45–7 and 55–6. Much later, PAPPOS points in the same direction, *Synt.* 8.2: μεγάλα γὰρ οὗτοι [μηχανικοὶ] βάρη διὰ μηχάνων πάρὰ φύσιν εἰς ὕψοι ἀνάγονειν ἐλάττονι δυνάμει κινοῦντει.

[23] R. S. BRUMBAUGH, *Ancient Greek Gadgets and Machines* (New York 1966) 107, and R. S. BRUMBAUGH & PAUL H. SHERRICK, "Pneuma and the Earth in Space: A Reconstructed Stoic Demonstration Apparatus (*Heron*, Pneumatica 46)," *Studium Generale* **17** (1964) 263–66.

[24] In the *De Lapidibus* and the *De Igne* THEOPHRASTOS seems to be gathering data that do not fit the "standard model" (note his remark in *De Igne* 1). See G. E. R. LLOYD, *Magic, Reason, and Experience* (Cambridge 1979) 210–1, n. 421 on Theophrastos *De Lapidibus* 48ff.

[25] See H. B. GOTTSCHALK, *Straton of Lampsacus: Some Texts = Proceedings of the Leeds Philosophical and Literary Society* **11.6** (1965) 95–182.

[26] *Cp.* CH. MUGLER, "Archimède répliquant à Aristote," *Revue des Etudes Grecques*

XENARCHOS[27]) here at least HERON intended some criticism of ARISTOTLE's system. There is also VITRUVIUS' statement (1.6.2): *licet aspicere et de latentibus caeli rationibus artificiosis rerum inuentionibus diuinitatis exprimere ueritatem.*

We may combine this observation with a passage in ARISTOTLE *De Motu Animalium* 2 to suggest the true purpose of HERON's device. ARISTOTLE (698b12–21) is arguing that any animal, to move, must be supported (ἀπερειδόμενόν) on something unmoved (ἀκίνητον) and resisting (ἀντερείδοι and *cp.* ὑποδώσει). He then (698b21–9a10) supports this conclusion with the evidence (μαρτύριον) that a person inside a boat, if he does not push on something outside, can never move the boat, "not even if he were Boreas". He argues that no amount of breath blown from inside the boat will move it, since the blower is not supporting himself on something unmoved and external (669a5–6). Since ARISTOTLE (*MA* 3) connects this conclusion with the circular heavenly motions (698b9–12 and 699a11–700a6),[28] presumably he would have granted a similar impossibility in the case of circular motion. He does conclude that the heavens cannot be moved by any internal agent (699b10–11).

I suggest that what HERON has devised is a counterexample — a machine which demonstrates the possibility of motion without the need for an external supporting (ἀπερείδον) medium. That it is supported in a fashion on its axis need cause no difficulty. ARISTOTLE himself excludes the axis as a motive power in the case of the heavens (*MA* 3 [699a20–22]]. It is clear that in HERON's device the κνώδακα designedly provide no resisting function such as ARISTOTLE's theory would require.[29] Perhaps a renaming is in order: autokinetic sphere.

Another purpose is served. The natural motion of air (the hot ejectum here) is upwards (ARISTOTLE *De Caelo* 1.2 [269a15–19]) and only the first body ("aither") has a natural circular motion (*De Caelo* 1.3 [269b18–270b31]). Yet here air causes a circular motion, contrary to nature (*cp.* HERON *Pneum.* 1.10 and 2.6, noted above).[30]

For those who seek modern parallels, perhaps rather to be compared is the rocket, of the principle of which this is the earliest demonstration. In any case, it is a clever, crucial experiment and successful.[31]

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64 (1961) 58–81. MUGLER discusses ARCHIMEDES' use of a small force (amplified by a machine) to drag a ship up onto land (PLUTARCH, *Marcellus* 14) in light of ARISTOTLE's statement (*Physics* 7.5 [250a89–b7] that a minimum force is necessary to move any large thing.

[27] *Cp.* STRABO, 14.5.4 and see P. MORAUX, "Xenarchos (5)," *Real-Encyclopädie der classischen Altertumswissenschaft* **9**A (1967) 1422.42–35.45. His fragments are in SIMPLICIUS *in De Caelo*; see also S. SAMBURSKY, *Physical World of Late Antiquity* (London 1962; repr. Princeton 1987) 124–30 for comment.

[28] For discussion, see MARTHA CRAVEN NUSSBAUM, *Aristotle's De Motu Animalium* (Princeton 1978) 121–42.

[29] This gives point to the observation of LANDELS (above, n. 17) that the rotating joint (smerisma) must either rub or leak: no doubt HERON's leaked, and thereby proved to an observer that the axis provided no friction.

[30] Note that XENARCHOS had, over half a century before, argued against the existence of any "aither": *Against the Fifth Element.* See above, n. 27.

[31] Relevant may be PAPPOS, *Synt.* 8.2, who mentions that those who construct

III. Scholarship on Heron's Pneumatica 2.11

It is clear from the foregoing that the imputation of a steam engine to HERON is an unwarranted retrojection of post-Renaissance ideas.[32] A brief examination of the scholarly comment (both from classicists and historians of science and technology) on the passage is instructive; no pretense of completeness is made.

LEONARDO DA VINCI suggested the use of steam jets (from a VITRUVIAN Aeolipyle = Aeolus) to turn a spit (automated rotisserie), a suggestion later repeated by J. WILKINS (1648),[34] though neither seems to have connected HERON's device with the idea.[35] ROBERT BURTON (1621) in *The Anatomy of Melancholy* 2.2.4 refers to HERON: "What so intricate and pleasing withal, as to peruse and practise Hero Alexandrinus' works, *de spiritalibus, de machinis bellicis, de machina se movente, Jordani Nemorarii de ponderibus, ...*"[36] The first is surely *Pneumatica*, the second *Belopoiica*, and the third probably *Automatica*: thus, though he may seem to refer to *Pneum.* 2.11 with understanding, the third entry is only a title. W. SCHMIDT surveys the acquaintance held by the 17th century, of HERON and notes that GIAMBATTISTA DELLA PORTA's (ca. 1600) steam engine was probably influenced by HERON's device.[37] The trend was already setting.

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models of the heavens make use of the uniform circular motion of water (ὁμάλὴ καὶ ἐγκυκλίος κινήσις ὕδάτος). Such models are first attested in I BC: LUCR. 5.513–5; CICERO, *de Republica* 1.14 (21), assigned to ARCHIMEDES, *cp.* E. DIJKSTERHUIS, *Archimedes* (New York 1957, repr. Princeton 1987), 23–5; CICERO, *Natura Deorum* 2.88 of POSEIDONIOS, see A. S. PEASE; *M. Tulli Ciceronis De Natura Deorum* 2 (Cambridge 1958) *ad loc.* (pp. 766–9) and K. REINHARDT, "Poseidonios," *Real-Encyclopädie der classischen Altertumswissenschaft* **22** (1953) 567.32–42 on his Ouranologium; and DEREK J. DESOLLA PRICE, *Gears from the Greeks* (New York 1975). Elsewhere I hope to treat somewhat of these; meanwhile see ALOIS SCHLACHTER, *Der Globus*, ed. F. GISINGER = *Stoicheia* **8** (Leipzig/Berlin 1927) 48–54.

[32] For an amusing parallel case, *cp.* K. R. POPPER, "Back to the Presocratics," *Proc Aristotelian Soc* **59** (1958/9) 1–24, who (p. 3) suggests that THALES' Earth floating on water "strangely anticipates the modern [*i.e.*, WEGENER's now standard] theory of continental drift"; refuted by G. S. KIRK, "Popper on Science and the Presocratics," *Mind* **69** (1960) 318–339 at 328; KIRK is followed by D. R. DICKS, *Early Greek Astronomy to Aristotle* (Ithaca 1970) 226, n. 52. KIRK and DICKS are right to reject such anachronistic retrojections.

[33] An interesting absence is B. FARRINGTON, *Greek Science: Its Meaning for Us* pt. 2 (London 1949; repr. 1953, 1980) who does not even mention HERON's "steam engine": curious in a book devoted to the thesis that ancient science was paralysed by its abstraction from concrete application into organized logic, an abstraction allegedly mediated by the "universal cleavage of society into freeman and slave", pp. 302–303.

[34] See LYNN WHITE, Jr., *Medieval Technology and Social Change* (Oxford 1962) 92; he cites J. WILKINS, *Mathematical Magick* (London 1648) 149.

[35] *Cp.* W. SCHMIDT, "Leonardo da Vinci und Heron von Alexandreia," *Bibliotheca Mathematica* 3.3 (1902) 180–7, who believes that LEONARDO was often influenced by HERON's devices; *cp.* BOAS (below n. 52) 40–41.

[36] In the A. R. SHILLETO edition (London 1893; repr. New York 1973) v. 2, p. 110; in the edition of FLOYD BELL & PAUL JORDAN SMITH (New York 1927, 38, 41) p. 461; in the edition of HOLBROOK JACKSON (London 1932; repr. 1972) v. 2, p. 95.

[37] W. SCHMIDT, "Heron von Alexandreia im 17. Jahrhundert," *Abhandlungen zur Geschichte der Mathematik* **8** (1898) 195–214; see pp. 210–2.

By the 19th century, well after the diffusion of various types of the modern steam engine, it was apparently universally assumed that HERON had built something that could be called a steam engine (though there are differences of opinion concerning its merit). These I survey in chronological order, with a concluding summary.

MEIKLEHAM [STUART] (1824) places HERON at the end of his parade of Anecdotes and claims that "[t]his simple and effective apparatus, though described but as a philosophical toy ... confer[s] on Hero the honour of having invented and constructed the FIRST STEAM ENGINE".[38] ELIJAH GALLOWAY (1829) claims that the expansive force of steam was first used by HERON, "merely in an ineffectual toy."[39] LARDNER & RENWICK (1848) note that HERON's "method of using steam" could "be transmitted by ordinary mechanical contrivance to any machinery which its power might be adequate to move."[40] BENNETT WOODCROFT translated the Pneumatics and entitled HERON's device "Steam Engine", without comment.[41]

The *communis opinio* up to the end of the First World War seems to follow the lead of MEIKLEHAM. J. C. POGGENDORFF (1879) sees HERON's device as a demonstration of "Dampf als bewegende Kraft" and the ancestor of the steam-engine (Dampfmaschine).[42] CURT MERCKEL (1899) describes the contents of HERON's *Pneumatica* thus:

> ... eine grosse Anzahl hydraulischer und pneumatischer Apparate ... die in der Mehrzahl zwar auf Spielereien hinaus laufen, unter welchen sich aber auch einige, wie die Feuerspritze (d. h. die Ktesibische Pumpe) und die Aeolipile befinden, die auf Beachtung Anspruch erheben können. In der Aeolipile erblickt mann im Allgemeinen den ersten Vorläufer der Dampfmaschine.[43]

MOYER (1908) in a thorough and scientific survey of steam engines describes HERON's device as the "first steam turbine", "which was used to open the doors of temples" (MOYER has confused HERON *Pneum.* 2.11 with 1.38, in which expanding air causes water to fill a container which then functions as a counterweight and

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[38] ROBERT MEIKLEHAM (under the pseudonym R. STUART), *Historical and Descriptive Anecdotes of steam-engines, and of their inventors and improvers* (London [2]1824) 3, which I was able to consult courtesy of the Special Collections Dept. of the University of Virginia Library. *Cp.* also p. 6: "Branca is considered by his countrymen to be the inventor of the Steam Engine; ... [t]o this he certainly has no claim; neither can his engine be compared with Hero's for its ingenuity nor to De Caus's for its efficiency".

[39] GALLOWAY (above, n. 20) 6.

[40] LARDNER & RENWICK (above, n. 24) 41–2.

[41] BENNET WOODCROFT, *The Pneumatics of Hero of Alexandria* (London 1851; ed. M. B. HALL and repr. London/New York 1971).

[42] POGGENDORFF (above, n. 20) 16, 526–7; he surveys the history of the invention of the steam engine on pp. 525–558.

[43] CURT MERCKEL, *Die Ingenieurtechnik im Alterthum* (Berlin 1899) 38.

opens the doors).[44] EWING (1911) states "the [modern] steam turbine in its characteristic feature finds crude prototypes in apparatus [such as Hero's] primitive steam reaction turbine."[45] HERMANN DIELS (1914, 1920) brought his wide knowledge of ancient technology to bear on the device, and considered HERON's "Dampfkugel" to be the "Keim der modernen Dampfmaschine."[46] NEUBURGER (1919), whose work was done before and during the war though published after, indicates that HERON's device "may be called the first turbine that was made."[47]

Two strands exist in the thread of twentieth-century interpretation, According to the earlier one, the device is nought but a toy, which was later used by Renaissance and modern engineers as a starting point from which to develop the steam engine (*cp.* GALLOWAY). More recently (perhaps following DRACHMANN [1948]) various historians have sought to explain the device as a failed or aborted steam engine and have sought to explain the shortfall.

Foremost in the first group we find the influential classical scholar WILAMOWITZ, who called the device a *Spielzeug*.[48] USHER (1929, 1959) simply states that "it is generally held that the actual development of the steam turbine was based on experimental work with the principles embodied in Hero of Alexandria's reaction sphere."[49] DICKINSON (1939) states that "[o]ne of the toys described by Hero is the reaction wheel" and believes noone ever thought "that [the devices] might serve some useful purpose."[50] MARIE BOAS HALL (1949, 1971), after a long study of HERON's *Pneum.*, concludes that the "devices are mainly ... toys ... as in the device usually called a 'steam engine', really a reaction turbine, whose description makes it plain that it was one of a series of such."[51] Similar is her earlier study on the influence of HERON's *Pneumatica,* wherein she remarks that HERON's device "was the basis of the earliest attempts at steam-engine design" (true in itself, but not convincing as an exegesis of HERON's device).[52] SAMBURSKY (1956) delves no further into the matter than to note that "Hero's ... instruments for demonstrating the motive power of steam ... were in fact toys, rather than means of harnessing the forces of nature ... Steam power was never exploited on

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[44] JAMES AMBROSE MOYER, *The Steam Turbine*: *A practical and theoretical treatise for engineers and designers* (New York 1908) 4.

[45] J. A. EWING, "Steam Engine," *Encyclopedia Brittanica*[11] **25** (1911) 818.

[46] DIELS, (above, n. 20) c. 3 (pp. 57–63).

[47] ALBERT NEUBURGER, *Die Technik des Altertums* (Leipzig [1]1919, [2]1921, [3]1922); tr. HENRY L. BROSE (London/New York 1930; repr. 1969) 231.

[48] WILAMOWITZ (above, n. 15) 163.

[49] A. P. USHER, *A History of Mechanical Inventions* (Cambridge [1]1929, [2]1959) 392; he is slightly more precise and accurate than others in his description of the device.

[50] DICKINSON (above, n. 20) 185–92, including two MS drawings and a discussion of 18th and 19th century models. He mentions HERON in connection with the steam engine only once in *History of Technology* **4**, ed. C. SINGER (Oxford 1958) 168.

[51] MARIE BOAS HALL, *The Pneumatics of Hero of Alexandria* (London/New York 1971) XII.

[52] MARIE BOAS, "Hero's *Pneumatica*: A Study of its Transmission and Influence," *Isis* **40** (1949) 39–49, see p. 45.

a technical scale."[53] DECAMP (1960), the science-fiction writer and historian of technology, in his wide-ranging and widely-read survey (the only one of the authorities here cited to have appeared in a mass-market paperback edition), claims that HERON's "steam engine" was "most pregnant with future possibilities", but that "Hero never claimed that it was more than a toy" (misleading: there is no claim of any kind in HERON's text).[54] LLOYD (1973) denies "that all the elements of a steam engine are already present, potentially, in this toy," but offers no deeper explanation of its existence.[55]

The second group is headed by DRACHMANN (1948, 1963), who, having described HERON's device, concluded that "the construction of the steam engine had to wait until it was possible to make iron pipes and put them together with screws [he means threaded joints]."[56] CROMBIE (1959) confuses BRANCA's steam engine and HERON's: "the turbine device described by Hero of Alexandria, a jet of steam directed onto a wheel with blades."[57] LYNN WHITE, Jr. (1962), calls HERON's device a "toy steam reaction turbine" and remarks that "it is strange that [the ingenious technicians [of the Hellenistic Age] did not make greater progress in developing sources of power."[58] BRUMBAUGH (1966) describes the device as "the first record we have of the steam engine," and remarks "[n]ever have the potentialities of a new discovery gone less appreciated."[59] LINDSAY's (1974) book-length essay is motivated by a search for sources of mechanical power in antiquity and he can only describe the device as a "steam-engine", but admits that "the ancients ... felt no impulse to use the power except in ... toys."[60] CASSON (1977) describes HERON's device as "the earliest example on record of a steam engine" and proceeds to speculate (futilely I believe) as to why no "ancient technician ever took the crucial step of elevating [it] into machinery that could carry out a useful job."[61] HALLEUX (1967) discusses HERON's machine, but only concludes that technical and epistemological difficulties precluded a practical result.[62] LANDELS (1978), like DIELS before him, constructed a model of the "steam engine" and concluded that "this form of steam engine" could "almost certainly not"

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[53] S. SAMBURSKY *Physical World of the Greeks*, tr. M. DAGUT (London 1956; repr. Princeton 1987) 230. I do not cite the original (modern Hebrew) version.

[54] L. SPRAGUE DE CAMP, *The Ancient Engineers* (New York 1960), often reprinted, 261–3. He does acknowledge that "it is useless to expect people to attack problems that they don't know exist" (262).

[55] G. E. R. LLOYD, *Greek Science After Aristotle* (London 1973) 103–4, 106.

[56] DRACHMANN (above, n. 19) (1963) 206; *cp.* also DRACHMANN (above, n. 2) 128: "[*Pneum.*] 2.11 is the well-known first attempt to make a steam turbine."

[57] A. C. CROMBIE, *Mediaeval and Early Modern Science* **2** (New York 1959) 250.

[58] WHITE (above, n. 34) 80.

[59] BRUMBAUGH (above, n. 23) 108, see also 4, 10, and 107. Contrast his understanding of *Pneum.* 2.7, the cosmological model— above, n. 23 (with SHERRICK, 1964).

[60] JACK LINDSAY, *Blast Power and Ballistics: Concepts of Force and Energy in the Ancient World* (New York 1974) 335–7.

[61] L. CASSON, "Energy and Technology in the Ancient World," *Mysteries of the Past*, ed. J. THORNDIKE (New York 1977) 140–154, see pp. 140–1; repr. in LIONEL CASSON, *Ancient Trade and Society* (Detroit 1984) 130–52, see p. 131.

[62] HALLEUX (above, n. 15) 54–6.

have been "a practical power source".[63] GRANT & KITZINGER (1988) follow LANDELS (1978).[64]

That the device was a toy or demonstration steam engine seems to have been the dominant view in the nineteenth century, and up to the Great War.[65] Thereafter two opposing camps seem to have grown up: either the device is merely a toy (WILAMOWITZ, USHER and later historians of science), *or* it is a failed steam engine in the sense that the ancients "could have" made a "working" version "if only ..." (DRACHMANN and later commentators).

IV. Speculation and Conclusion

Given that (in light of this work) none of the three points of view just listed is satisfactory, what may we say? Usually the device is seen as a failure, either technological or epistemological, but I have argued that HERON's device or machine is neither toy nor failure because not an engine. Rather it is a successful crucial experiment criticising ARISTOTLE's theory of motion. While this is only one of HERON's many devices, it has acquired a crucial significance in discussions of ancient progress. It is often stated that the lack of development of HERON's steam engine into a practical and widely used machine shows some defect of ancient science or technology. That an oft-cited proof-text is shown to be irrelevant does not disprove a thesis, but its removal may be cause for a reappraisal. (Even in the new view advocated here, the question of progress seems to have force: "if Heron's device demonstrates motion without resistance, why was so little progress made in over a thousand years in developing theories of motion?")

EDELSTEIN[66] surveys the classical and Hellenistic periods (down to 30 B.C.) at length and concludes that some notion of progress (as a social and scientific phenomenon) was always extant. DODDS briefly counters and wishes to restrict the prevalence of this idea to the fifth century B.C., or to scientists, and notes a broad correlation between actual scientific progress and the expectation thereof.[67] SENECA, a contemporary of HERON, writes "ueniet tempus quo ista quae nunc latent in lucem dies extrahat et longioris aeui dilegentia" (*Quaestiones Naturales* 7.25.4), and "ueniet tempus quo posteri nostri tam aperta nos nescisse mirantur" (*Quaestiones Naturales* 7.25.5). Thus the fundamental epistemological question

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[63] LANDELS (above, n. 17) 28–31. LANDEL's model achieved speeds of ca. 1500 RPM, a bit less than half the speed of the modern (60-Hz) electric motor at 3600 RPM, and he notes that it "may well have been the most rapidly rotating object in the world of his time" (p. 29). For earlier models, see DIELS (above, n. 20), DE CAMP (above, n. 54) 262, and DICKINSON (above, n. 20). DICKINSON records JAMES WATT's conclusion that the model device of WOLFGANG VON KAMPELEN in 1784 was impractical.

[64] M. GRANT & R. KITZINGER, *Civilization of the Ancient Mediterranean: Greek and Roman* **1** (New York 1988) 350.

[65] GALLOWAY (above, n. 20) provides an odd exception.

[66] L. EDELSTEIN, *The Idea of Progress in Classical Antiquity* (Baltimore 1967).

[67] E. R. DODDS, "The Ancient Concept of Progress," *The Ancient Concept of Progress and Other Essays* (Oxford 1973) 1–25.

is answered in general terms: HERON probably "could" have conceived the notion of making a "better" steam engine, had he made one at all. He certainly does seem to have conceived that ARISTOTLE's theory of motion was defective and therefore potentially modifiable or replaceable with a better theory.

Given that it was possible for the ancients (or some of them at any rate) conceive of progress in general, the question is often posed — "Why did they not make more progress in science?" And HERON's "steam engine" is alleged as a case in point (in fact, as we have seen, one of the *best* cases). There are roughly three explanations suggested for the alleged failure of scientific and technological progress: the class-structure (Marxistic) explanation, the technological explanation and the explanation I refer to as the epistemological.[68]

The class-structure explanation argues that a) the literate upperclasses were occupied with philosophy and physical theory, but despised the lower-class artisans and workers who made machines and so theory was never incarnate in experiment, and b) the ready availability of dependent labor (slaves) obviated the necessity for an industrial revolution. I shall not here attempt a detailed refutation of this theory (which has been more and more modified and qualified of late), though I note that neither premise is certain. As to the first — the attitude is deduced from the impoverished scraps of *belles-lettres* that have survived JULIUS CAESAR, Jihad and the Fourth Crusade; but are the stage-plays of SOPHOCLES (say) any better as a source of the sociology of ancient science than are the novels of HAWTHORNE or HEMINGWAY for modern science? At any rate the Ionians and SOCRATES often used homely analogies for scientific ideas: I cite only the famous clepsydra passage of EMPEDOCLES, fr. 100 DK[6] (*cp.* ANAXAGORAS in [ARISTOTLE] *Problemata* 16.8 [914b9–5a24] and HERON *Pneum.* 1.7), and "Socrates" at ARISTOPHANES *Nubes* 95–7. Moreover, KTESIBIOS and STRATON may have collaborated (*cp.* above on STRATON's device), and DIONYSIUS I got over his distaste for *techne* in 399 B.C. to sponsor the invention of the catapult (DIODORUS SICULUS 14.42). As to the second premise — the ready availability of serfs in the Middle Ages did not prevent technological innovation.[69] A serf behind a better plow turns more turf for his liege, just as a Southern black slave gins more cotton for his master using ELI WHITNEY's machine, and just as Roman slaves in Spanish mines pump more water treading water wheels. Machines make slaves more efficient: slavery does not preclude industry.

The technological argument may be paraphrased "the ancients could not advance much beyond the point they did reach due to the lack of certain devices not yet invented or of power sources not yet exploited."[70] The simple statement inherently begs the question — why then were the devices necessary not invented or the power sources not exploited? Various attempts are made to avoid this circle,

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[68] For two recent, but by no means definitive, surveys see HALLEUX (above, n. 15) and OLESON (above, n. 18) 397–408.

[69] *Cp.* WHITE (above, n. 34) and idem, *Medieval Religion and Technology: Collected Essays* (Berkeley/Los Angeles 1978).

[70] *Cp.* especially for power sources HALLEUX (above, n. 15) and for devices J. J. HALL, "Was Rapid Scientific and Technical Progress Possible in Antiquity?," *Apeiron* **17** (1983) 1–13.

which I shall not refute in detail. I merely note that none of GILBERT's work on the magnet, none of HARVEY's work on circulation, none of COPERNICUS' ideas (already in ARISTARCHOS anyway) and none of GALILEO's observations[71] required new technology or power. Technological advances may well have needed just as much time as they did take. Many things are easy once you know how (for example, the telescope, the microcope, the circulation of the blood, even buttons or zippers), but take a long time to discover. A classical philologist might well ask: "Why did Aristarchos of Byzantion, one of the greatest of the ancient philologists, not discover Porson's Law or Bentley's Digamma?" Students of the Magna Carta or the American Constitution might well ask, "Why did Polybios or Cicero, with their interest in constitutional theory, not think of the balance of powers?" Students of Classical Art History might well ask: "Why was the Archaic Art unable to depict old age?"

The epistemological argument is roughly that the Greeks did not "advance" because they did not care to, being interested in other matters.[72] Ancient technology was dominated by artistry and skill in search of quality not quantity, and the aim of ancient science was knowledge not power. Yet GALILEO's pendula seem very classical and his experiment of dropping weights certainly is (*cp.* PHILOPONOS' earlier attempt[73]), and neither seeks power, only knowledge. (And even modern scientists often forego fame, family, and fortune for science.) Nor is quality of craftsmanship inconsistent with new ideas (in physical theory or anywhere else). I suggest that this argument is the theoretical counterpart of the technological argument above: some ideas simply take a long time to develop.

It is deceptively easy to suppose that some factor must have blocked progress. But I would like to combine the second and third points above — ancient science and technology went only as far as they did because both take a long time to build up to the rapid pace seen in modern times (*cp.* the exponential growth law as seen in compound interest or population growth). Ideas and devices evolve (as I have shown for HERON's autokinetic sphere) and do so slowly.

HERON's machine is neither toy nor failed power source. It is an experiment (and the Greeks did do such[74]), an experiment which shows the falsity of

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[71] Not even the telescope: lenses existed in antiquity — *cp.* G. SINES & Y. A. SAKELLARAKIS, "Lenses in Antiquity," *American Journal of Archaeology* **91** (1987) 191–6 — and a Galilean telescope required only two such lenses.

[72] See specially M. I. FINLEY, "Technical Innovation and Economic Progress in the Ancient World," *Economic History Review* (2) **18** (1965) 29–45 and J. P. VERNANT, "Some remarks on the forms and limitations of Technical Thought among the Greeks," *Myth and Thought among the Greeks* (London 1983), a translation of *Mythe et Pensée chez les Grecs* (Paris 1965), 279–301.

[73] R. SORABJI, ed., *Philoponus and the Rejection of Aristotelian Science* (Ithaca 1987) 14.

[74] *Cp.* J. BURNET, "Experiment and Observation in Greek Science," *Essays and Addresses* (Edinburgh 1930; repr. Freeport, New York 1968) 253–64; HANS DILLER, "ΟΨΙΣ ΑΔΗΛΩΝ ΤΑ ΦΑΙΝΟΜΕΝΑ," *Hermes* **67** (1932) 14–42; W. A. HEIDEL, *The Heroic Age of Greek Science* (Baltimore 1933; repr. New York 1971) 162–92; OTTO BLÜH, "Did the Greeks perform experiments?," *American Journal of Physics* **17** (1949) 384–8; L. BOURGEY *Observation et expérience chez Aristote* (Paris 1955) 113–22 (translated as

ARISTOTLE's belief that motion requires friction or resistance. As such it is no anomaly but finds its natural place in the history of ideas and of the reception of ARISTOTLE.[75]

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[75] The germ of the idea of this paper came to me during a seminar by R. RENEHAN, on ARISTOTLE's language, given for the Classics Department at the University of Colorado in April 1988. The earliest form of this paper was given as a George A. Miller, Ancient Technologies and Archaeological Materials, and Archaeological Institute of America triply-sponsored seminar at the University of Illinois, Champaign-Urbana, in February 1989. I have benefitted from stylistic advice from W. M. CALDER III (Illinois) and CURTIS WILSON (St. John's, Annapolis). I am grateful to all of the above.