Sennacherib, Archimedes, and the Water Screw

The Context of Invention in the Ancient World

STEPHANIE DALLEY and JOHN PETER OLESON

This article will present the cases for and against Archimedes as the original inventor of the most striking and famous device attributed to him, the water screw. It takes the form of a case study that focuses as much on the context and motives for the invention as on the possible inventor himself. In brief, an Archimedean water screw consists of a cylinder containing several continuous helical walls that, when the entire cylinder is rotated on its longitudinal axis, scoop up water at the open lower end and dump it out the upper end. Both Aage Drachmann and John Oleson have summarized the literary and archaeological evidence from the classical world suggesting that Archimedes (287–212 B.C.) was the first person to design and construct a mechanical water-raising screw, and they accept him as the inventor.[1] Stephanie Dalley, on the other hand, reinterpreting a passage of cuneiform Akkadian and a statement by Strabo, has proposed that the water screw was

Dr. Dalley is Shillito Research Fellow in Assyriology at the Oriental Institute and Somerville College, University of Oxford. She has published primary editions of cuneiform texts from excavations in Iraq and Syria and from museums in Britain, as well as specialized studies and more general books. She has translated all the Assyrian texts used in this article. Dr. Oleson is professor of Greek and Roman Studies at the University of Victoria, British Columbia. His areas of fieldwork and research include ancient hydraulic technology, Roman harbors and their construction, and the Roman Near East. He has published widely in all these areas. Except where otherwise noted, he has translated all the Greek and Latin texts cited in the article. The authors are grateful to a number of scholars for their assistance with this article, including Richard Dight, Peter Kingsley, David Oates, Simon Raikes, and the *Technology and Culture* referees.

0040-165X/03/4401-0001$8.00

1. Aage G. Drachmann, "The Screw of Archimedes," *Actes du VIIIe Congrès International d'Histoire des Sciences, Florence-Milan* (Florence, 1958), 3:940–43; John Peter Oleson, *Greek and Roman Mechanical Water-Lifting Devices: The History of a Technology* (Toronto, 1984), 291–94, and "Water-Lifting," in *Handbook of Ancient Water Technology*, ed. Örjan Wikander (Leiden, 2000), 217–302, esp. 242–47 on the water screw.

already known during the reign of the Assyrian king Sennacherib (704–681 B.C.) and that the design was put to use in spectacular fashion to water his palace garden at Nineveh.[2]

The precise identification of the inventor of a device or procedure is problematic, since nearly every technological advance is the result of long accumulation of human experience. As any modern patent lawyer can attest, it is difficult to document the originality of even a complicated or specialized technique or device. This problem is compounded for ancient technological innovations because firsthand documentary records are rare, and historical texts, where they exist, can be unclear, mistaken, or tendentious.[3] The frequent lists of "inventors" in Pliny's *Natural History* (especially 7.191–215) are an example of the doubtful attribution in the mid-first century of particular devices and techniques to individuals. Ancient authors occasionally preserve a story of invention that sounds convincing and fits into the known contemporary cultural and technological context—for example, Vitruvius's charming depiction (*On Architecture* 9.8.2–4) of the youthful inventions of the Alexandrian Ctesibius (third century B.C.), who provided helpful gadgets for his father's barber shop.[4]

Memorable and entertaining as such stories are, there is no method by which modern scholars can distinguish genuine biographical detail from an etiological fiction containing plausible details added to increase the immediacy. Fortunately, identification of a specific individual inventor is far less important or interesting than an understanding of the historical and cultural context that spawned the invention and fostered its reception. The precocious Ctesibius sounds like the young Thomas Edison, enlivening his modest surroundings with innovative gadgets, setting the stage for his later accomplishments through induction, invention from the bottom up. Occasionally we hear of the motives and procedures of a royal patron in the classical world, of top-down innovation. The historian Diodorus Siculus (Diodorus of Sicily), for example, writing in the mid-first century B.C., describes a sort of think tank set up by the ambitious King Dionysius I of Syracuse

2. Stephanie Dalley, "Ancient Mesopotamian Gardens and the Identification of the Hanging Gardens of Babylon Resolved," *Garden History* 21 (1993): 8–10; "Nineveh, Babylon and the Hanging Gardens: Cuneiform and Classical Sources Reconciled," *Iraq* 56 (1994): 51–54; "More about the Hanging Gardens," in *Of Pots and Plans: Papers on the Archaeology and History of Mesopotamia and Syria Presented to David Oates in Honour of his 75th Birthday*, ed. Lamia Al-Gailani Werr et al. (Cambridge, 2002). The main focus of Dalley's research is her proposal that the famous Hanging Gardens of Babylon, praised by Greek and Latin authors, were actually the gardens of Sennacherib's palace at Nineveh.

3. *P. Edfou* 8, a third-century B.C. papyrus document from Egypt, may be an exception; see Oleson, *Mechanical Water-Lifting*, 146–47, and "Water-Lifting," 289.

4. See the discussions of this passage in Oleson, *Mechanical Water-Lifting*, 109–10, and "Water-Lifting," 290. Many of the passages in Greek and Latin authors on inventors are gathered in John Humphrey, John Oleson, and Andrew Sherwood, *Greek and Roman Technology: A Sourcebook* (London, 1998), 588–97.

(430–367 B.C.) to solve a particular problem of military technology (*History* 14.41.3–4, 42.1). The high wages, performance bonuses, and focused work groups would not be out of place in a modern computer company:

> Dionysius, therefore, immediately assembled technicians, commanding them to come from the cities he ruled, and luring them from Italy and Greece—and even from Carthaginian territory—with high wages. For he intended to manufacture weapons in great numbers and projectiles of every sort. . . . After assembling a great number of technicians, he divided them into work-groups according to each one's own talents. . . .
>
> In fact, the catapult was invented [εὑρέθη] in Syracuse on this occasion, since the most able technicians were gathered together from all over into one place. The high wages stimulated their enthusiasm, along with the numerous prizes offered to those judged the best.

A similar situation later on in Alexandria is reported by Philo of Byzantium (fl. ca. 200 B.C.), who in his book on catapults (*Belopoeika* 50), reports that Alexandrian craftsmen derived systematic rules for catapult construction "because they were heavily subsidized by kings who loved prestige and fostered technology."[5] By the third century, at least, the prestige of the patron seems to have become as important as the practical benefit of these innovations.

The public inscriptions of the Near Eastern, Greek, and Roman cultures naturally celebrate the accomplishments of the great persons who set them up, and all ancient historians relied heavily on the biographical approach. In such a climate, the innovations of an anonymous technician were routinely attributed to his patron, and credit for an invention was more readily assigned to a famous personality—divine, human, or eponymous—than to a research group, a slave, or no one at all. In particular, the name of a known inventor or scientist could easily attract the credit for anonymous inventions appropriate to his métier. Stories about the young Ctesibius, of course, were repeated, or even created, because of his later accomplishments. It has also been suggested that some of the inventions attributed in antiquity to Archimedes, the most famous ancient technician and polymath, may have been developed by other individuals, possibly long before he lived. The genius of Archimedes, like that of Leonardo da Vinci, became the stuff of legend even during his lifetime.[6]

During April 1999 the authors served as joint technical advisors and participants in the production of a British Broadcasting Corporation (BBC) television film titled "The Hanging Gardens of Babylon," which examined the theory that the water screw was known in Assyria in the seventh century B.C.

5. Translation, Michael J. T. Lewis, "The Hellenistic Period," in Wikander, 634.

6. Eduard J. Dijksterhuis, *Archimedes* (Copenhagen, 1956), 14–32; Dennis L. Simms, "Archimedes the Engineer," *History of Technology* 17 (1995): 46, 65–67.

JANUARY
2003
VOL. 44

In the course of the film Oleson supervised the construction of two full-scale wooden water screws and shadufs (counterbalanced sweeps with buckets, used for raising water) to experiment with techniques of irrigation, and Dalley advised on the casting of a small bronze water screw. The wooden water screws were built largely according to the detailed instructions given by Vitruvius (*On Architecture* 10.6.1–4), while the bronze water-screw design was based on a description in an Assyrian text called *The Palace without a Rival*. Neither of us having succeeded in convincing the other about the chronology of the water screw during the filming, we subsequently decided to collaborate on this article, presenting the evidence in a more scholarly fashion and with a focus on the cultural context of invention and innovation in both periods.

In the course of our discussions, we became acutely aware of the extent of the gulf between scholars who study the classical cultures and those who study the cultures of the ancient Near East, especially Mesopotamia. Historians of "ancient" technology have traditionally given preferential treatment to the accomplishments of the Bronze Age Egyptian and the Greek and Roman cultures, while ancient Mesopotamian achievements tend to be relegated to the specialist publications of Sumerian scholars or Assyriologists, such as the recent synthesis by Ariel Bagg.[7] Given the deep roots of Greco-Roman culture in the Near East, this lack of exchange is a serious impediment to research.

One cause for this gap in communication arises from the separation of the study of Indo-European languages from that of the Semitic languages. In addition, judgments about racial and linguistic superiority or polemical views of "orientalism" were for a long period innate in various branches of learning in western scholarship. The *Black Athena* controversy has recently made these issues very clear, at least in North America.[8] Another factor is the esoteric difficulty of cuneiform, progress in the understanding of which, though rapid in recent years, has yet to make its way into general works such as encyclopedias and general overviews. There are far greater gaps in the information than is the case for the Greek and Roman cultures. A seemingly obvious question to a classicist, "Why is there no evidence of the water screw for several centuries?" is astounding to an Assyriologist,

7. Ariel Bagg, *Assyrische Wasserbauten* (Mainz, 2000); see the detailed review by Stephanie Dalley forthcoming in *Archiv für Orientforschung* 48. Bagg (201–3, 206–7, 277–79) objects to Dalley's proposal that Sennacherib made use of the water screw largely on the basis that no other early evidence for the device exists.

8. In essence, many African-Americans accept Martin Bernal's proposal that the Egyptians were blacks, that the culture and accomplishments of the Greeks were based on black Egyptian accomplishments, and that this cultural heritage has been repressed as a result of Eurocentrism and racial prejudice. Martin Bernal, *Black Athena: The Afroasiatic Roots of Classical Civilization*, 2 vols. (London, 1987). For a critique of Bernal's argument, see Mary R. Lefkowitz and Guy MacLean Rogers, eds., *Black Athena Revisited* (Chapel Hill, N.C., 1996).

who has to take into account, on a regular basis, long distances between oases of information. Greek culture follows an unbroken thread of tradition through the Renaissance, whereas the civilization of Mesopotamia has had to be reconstructed after complete loss. Its attractions are less obvious: even in modern times, with an increase in multicultural perspectives and easy travel, the decayed mud-brick palaces of Assyria cannot compete with the stone monuments of the classical world, and this is a severe disadvantage nowadays when visual media are dominant. Finally, the phenomenon of the named, national culture-hero has affected our appreciation of ancient Mesopotamian culture. In ancient Mesopotamia, creative efforts, whether in literature or technology, were either anonymous or attributed to the royal patron. Among Greeks and Romans, inventions or principles could be attributed, rightly or wrongly, to famous men such as Archimedes and Pythagoras, and appealing human-interest stories recorded or constructed.[9] But despite the anonymity of their engineers, the Mesopotamian cultures made major advances in hydraulic technology.

Assyrian Kings and Technology

Sennacherib ruled a vast area that stretched from Tarsus, in what is now southern Turkey, to the eastern border of Egypt, and from Armenia to Bahrain (fig. 1). It was the duty of a successful Assyrian king not only to enrich the nation through conquest but also to display power through fine buildings, the patronage of great art, and engineering works to manage the supply of water to his great cities. Provided that the technology was available, he had the manpower and the raw materials to achieve whatever he wanted, regardless of time, expense, or detriment to the health of his workmen.[10]

Numerous long inscriptions survive that suggest Sennacherib had a direct personal interest in engineering, beyond what his position required, and the material remains of spectacular canals, tunnels and an aqueduct prove the veracity of the texts.[11] He channeled water from several mountain streams east of Nineveh across varied terrain, making eighteen different channels, beginning at Bavian, 50 kilometers away to the northeast. The

9. Note, for example, Pliny's account of the inventors of navigation, *Natural History* 7.206–9. The phenomenon in general is discussed in detail by Adolph Kleingünther, Πρῶτος εὑρετής (Leipzig, 1933), and John F. Healey, *Pliny the Elder on Science and Technology* (Oxford, 1999), 347–52.

10. See, for example, Albert K. Grayson, "Assyria: Sennacherib and Esarhaddon (704–669 B.C.)," *Cambridge Ancient History*, rev. ed., vol. 3, pt. 2 (Cambridge 1991), 103–119.

11. Thorkild Jacobsen and Seton Lloyd, *Sennacherib's Aqueduct at Jerwan* (Chicago, 1935); Fuad Safar and Faraj Basmachi, "Sennacherib's Project for Supplying Erbil with Water" (in Arabic), parts 1 and 2, *Sumer* 2 (1946): 50–52; 3 (1947): 23–25. Dalley is grateful to Lamia Al-Gailani Werr for translating the Arabic text.

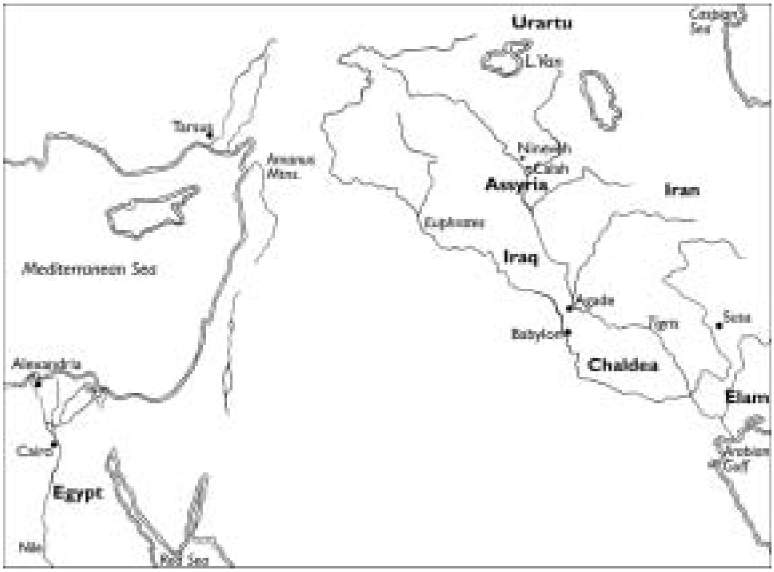

FIG. 1 Map of Mesopotamia and the Levant. (Drawing by Stephanie Dalley.)

flow crossed a wide valley on an aqueduct more than 280 meters long and 22 meters wide, built up on freestanding stone arches, and entered Nineveh at just the right height to irrigate the lower portions of the garden built outside Sennacherib's palace. Some of the water was diverted to irrigate orchards and fields to the north of Nineveh.[12] To accommodate surges in the water flow, Sennacherib constructed an artificial marshland, an excellent solution that municipal engineers have recently reinvented; such marshes absorb and delay flow, filter the water, and attract wildlife. He was particularly pleased to have designed an automatic sluice that "opens by itself, without using a spade or a shovel, and allows the waters of prosperity to flow. Its gate is not opened by any action of men's hands."[13] At Arbela, Sennacherib built an underground tunnel to bring high-quality water into the city, constructing it like a *qanat* (an underground aqueduct with shafts to the surface at intervals), and recorded his deed on an inscription (badly eroded) at the entrance.[14] Works such as these show how completely the Assyrians had mastered the principles of hydraulic engineering.

12. Julian E. Reade, "Studies in Assyrian Geography: Sennacherib and the Waters of Nineveh," *Revue d'Assyriologie* 72 (1978): 47–72, 157–80, and *Reallexicon der Assyriologie*, s.v. "Nineveh," 406.

13. *Chicago Assyrian Dictionary* (Glückstadt, Ger., 1980), s.v. "narpasu." The numerous volumes of this dictionary that have appeared over fifty years are organized by letters of the alphabet.

14. Safar and Basmachi; see also Jørgen Laessøe, "Reflexions on Modern and Ancient

Water Screws in Sennacherib's Palace Gardens at Nineveh?

In an Akkadian inscription written on a clay prism, Sennacherib describes at great length his main achievements in improving Nineveh with a palace, a palace garden, and various measures for water control. His southwest palace, known as "the Palace without a Rival," and the gardens that were raised up beside it are described together and termed "a Wonder for All Peoples." The text touches on both of the topics important to a discussion of the water screw before Archimedes: bronze casting and water control.[15]

One passage mentions large bronzes of various shapes for a variety of purposes, cast using a new method, and the installation of some of them for the purpose of raising water:

> Whereas in former times the kings my forefathers had created copper statues imitating real forms, to put on display inside temples, and in their method of work they had exhausted all the craftsmen for lack of skill and failure to understand principles [?]; they needed so much oil, wax and tallow [or lanolin] for the work that they caused a shortage in their own lands—I, Sennacherib, . . . knowledgeable in all kinds of work, took much advice and deep thought over making that work: great pillars of copper, colossal striding lions, such as no previous king had ever constructed before me, with the technical skill that [the god] Ninshiku brought to perfection in me, and . . . I invented a technique for copper and did it skillfully. I created clay molds as if by divine intelligence for great cylinders and *alamittu* palms, tree of riches; twelve fierce lion-colossi together with twelve mighty bull-colossi which were perfect castings; twenty-two cow-colossi invested with joyous allure, plentifully endowed with sexual attraction; and I poured copper into them over and over again; I made the castings of them as perfectly as if they had only weighed half a shekel each. . . .
>
> In order to draw water up all day long I had ropes, bronze wires and bronze chains made, and instead of shadufs [*makâte*] I set up the great cylinders [*gišmahhu*] and *alamittu* palms over cisterns. I made those royal lodges look just right. I raised the height of the surroundings of the palace to be a Wonder for all Peoples. I gave it the name: "Incomparable Palace." A park imitating the Amanus mountains I laid out next to it, with all kinds of aromatic plants, orchard fruit trees. . .[16]

Oriental Waterworks," *Journal of Cuneiform Studies* 7 (1953): 29. The question of the *qanat* at this date is discussed in more detail by Dalley, "Water Management in Assyria from the Ninth to Seventh Centuries B.C.," *ARAM* 13/14 (2002): 443–60.

15. D. D. Luckenbill, *The Annals of Sennacherib* (Chicago, 1924), 94–127.

16. Translation by Dalley. For *makâte*, see *Chicago Assyrian Dictionary* (Glückstadt, Ger., 1977), s.v. "makutu." The sequence of sentences is particularly disjointed here, and results from the way in which royal inscriptions reused and recombined passages from other, more extensive inscriptions.

JANUARY
2003
VOL. 44

Some of the bronze castings were architectural items in the form of animals, probably used as column bases. It has been calculated that they weighed up to 43 tons, an enormous mass made possible by new casting methods.[17] The items used to raise water are described as a "great tree trunk" (*gišmahhu*), which is the word used for a cylinder (for example, in mathematical problem texts), and as an *alamittu* palm tree. In fact, it is the molds that are described as being these two, separate items, not the casting itself, which Dalley interprets as a bronze water screw. The weight of such a bronze screw cannot be calculated with any accuracy, since length, diameter and thickness of metal are all unknown, but if we assume dimensions similar to those of wooden Roman water screws or the BBC reproductions (3 meters long, with a diameter of 0.45 meters), they would have weighed 2 or 3 tons.[18]

Dalley has proposed the hypothesis that the term *alamittu* was used metaphorically to indicate the spiraling helix of such a water screw.[19] The spiral form itself had been familiar to engineers in both northern and southern Mesopotamia since the Middle Bronze Age, and was used in mud-brick columns constructed of trapezoidal bricks laid in a decorative spiral pattern (fig. 2), some of them still visible in Sennacherib's day.[20] In addition, some stone and terra-cotta sculptures show palms with a spiral-patterned trunk.[21] The difficulty of finding an appropriate technical term in the languages of preindustrial cultures is well illustrated by the Assyrian usage of *gišmahhu*, "great tree-trunk," for a hollow cylinder, and by the Greek use of κοχλίας, "snail," for a spiral or helix. Nevertheless, the recognition that a helical form hidden inside a cylinder could be used to raise water is a significant conceptual leap.

17. Stephanie Dalley, "Neo-Assyrian Textual Evidence for Bronze-Working Centres," in *Bronze-Working Centres of Western Asia, c. 1000–539 B.C.*, ed. J. Curtis (London, 1988), 97–110.

18. Personal communication with Dalley by Andrew Lacey of Bronze Age Castings in London, who carried out the casting of a small bronze screw for the BBC program.

19. Dalley, "Ancient Mesopotamian Gardens" and "Nineveh, Babylon and the Hanging Gardens" (both n. 2 above). For a duplicate text, see Alexander Heidel, "The Octagonal Sennacherib Prism in the Iraq Museum," *Sumer* 9 (1953): 117–88.

20. See David Oates, "Innovations in Mud-Brick: Decorative and Structural Techniques in Ancient Mesopotamia," *World Archaeology* 21 (1990): 388–406, and Eleanor Robson, *Mesopotamian Mathematics* (Oxford, 1999), 142–45. The ziggurat built by Sargon II at Khorsabad was reconstructed as a spiral staircase rising up a circular tower, and it is often shown thus in books on the history of architecture. However, a recent study has indicated that the tower consisted of superimposed rectangles, on which a spiral staircase could not have been fitted; see Jean-Claude Margueron, "Étude architecturale," in *Khorsabad* (Paris, 1995), 190–93.

21. For example, at Larsa, Ur, Tell al Rimah, Tell Haddad, Tell Basmusian. The identification of the *alamittu* palm as *Chamaerops humilis* in the *Chicago Assyrian Dictionary* (Glückstadt, 1963), s.v. "alamittu," can now be seen to be incorrect; Dalley, "More about the Hanging Gardens" (n. 2 above).

FIG. 2 Spiral column façade at Tell al Rimah, northern Iraq, Middle Bronze Age. (David Oates, "The Excavations at Tell Al Rimah, 1966," *Iraq* 29 (1967), pl. XXXII.b.)

Sennacherib's new water-lifting device for his palace garden was cast in bronze, and thus combined his metallurgical and hydraulic interests. His father, Sargon II, was also personally interested in the techniques of mining, smelting, and alloying.[22] To show such a detailed interest in technical matters, to be enthusiastic about innovative technology, is unusual in the writings of Mesopotamian kings. At the time when Sennacherib recorded his achievements, the craft of the bronzeworker was steadily being displaced by the new craft of the ironworker. The process of change was a slow one, partly for reasons of social status. The bronzeworker had a high standing in society and was attached to the palaces and temples from which his patronage came. The ironworker, on the other hand, came as a tinker, a refugee, a displaced foreigner, and his material, iron ore, was common. Worked iron could not be reused as easily as bronze and decayed more readily, which made it unsuitable for storing as treasure or using as currency.[23] In these circumstances, bronze production grew specialized, drawing upon its royal

22. Andreas Fuchs, *Die Inschriften Sargons II aus Khorsabad*, rev. ed. (Göttingen, 1994), 128–30; see also Dalley, "Neo-Assyrian Textual Evidence."

23. On the issues surrounding early ironworking, see John E. Curtis et al., "Neo-Assyrian Ironworking Technology," *Proceedings of the American Philosophical Society* 123

patronage to create works of art and interesting devices. Sennacherib, like his father, was an ideal patron because he took a personal interest in the processes involved and described them in his royal inscriptions.

Hollow casting is attested in Mesopotamia as early as the dynasty of Agade (circa 2334–2279 B.C.) by the bronze head of Sargon found at Nineveh.[24] The outer layer of an object was hollow cast by a typical lost-wax technique, but using a copper alloy containing only 1 percent tin along with some lead, iron, silver, nickel, bismuth, and cobalt. The object was then filled with a different copper alloy, composed of 11 percent tin and significantly less of the other added metals, the core thus having a much lower melting point and so not melting the outer layer.[25] Concentric casting with different alloys was practiced in Elam on the border of Babylonia in the fourteenth century B.C., as attested by the statue of Napirasu, which even in its present truncated state is 1.29 meters tall and weighs 1,750 kilograms.[26] The solid bulls and lions cast by Sennacherib were presumably made by a similar method, except that Sennacherib claims to have dispensed with the wax and tallow used in the first stage of the casting in order to produce even larger objects than were previously possible.

Two hollow bronze cylinders from Susa that date to the twelfth century indicate clearly the technological heritage Sennacherib could draw upon in casting his cylindrical water-lifting devices.[27] The one on display in the Louvre is 4.36 meters long, 0.18 meters in diameter, its irregular walls around 1.5 centimeters thick—more or less the same length as the water screws proposed for Nineveh, but smaller in diameter. The estimated weight is 125–30 kilograms.[28] Although the casting of a helix inside a cylinder is a more complex task, it is clear Sennacherib had at his disposal the metallurgical skills needed to produce large bronze water screws.

As part of the BBC program, and in an attempt to reconstruct Assyrian casting procedures, Andrew Lacey cast a small-scale water screw, using 60 kilograms of bronze. The furnace was constructed simply and in the open

---

(1979): 369–90; Radomir Pleiner and J. K. Bjorkman, "The Assyrian Iron Age: The History of Iron in Assyrian Civilizations," *Proceedings of the American Philosophical Society* 118 (1974): 283–313; Theodore A. Wertime and James D. Muhly, *The Coming of the Age of Iron* (New Haven, Conn., 1980).

24. Herbert Maryon and Harold J. Plenderleith, "Fine Metalwork," in *A History of Technology*, ed. Charles Singer et al. (Oxford, 1954), 1:623–27. On the history of bronze hollow casting and the use of piece molds in the Near East and later in Greece, see Denys E. L. Haynes, *The Technique of Greek Bronze Statuary* (Mainz, 1992). Many of the bronze casting techniques used by the Greeks were developed in the Near East.

25. Andrew Lacey estimates that the difference was about 100 degrees Centigrade.

26. Prudence Harper, Joan Aruz, and Françoise Talon, *The Royal City of Susa* (New York, 1992), 132–35.

27. In the Louvre, dated by the Elamite inscription they carry; Friedrich W. König, *Die elamischen Königsinschriften* (Graz, Aus., 1965), 17 n. 45.

28. Dalley thanks Peter Northover for this calculation.

air, and the casting accomplished largely with tools and materials appropriate to an early Iron Age culture. Lacey fashioned a wood-and-rope model for the helix, coated with clay and suspended inside a separate cylinder of baked clay that encased the whole. The molds for the helix and the cylinder were separate, and the casting they produced was a unitary bronze screw with a hollow center, the helix and the surrounding cylinder cast as a single piece. A separate bronze rod was then inserted as the axle. No wax was used, since Sennacherib implies that wax was not needed for his new method of casting, or at least not in such huge quantities as previously. The shape is ideal for casting, since there are no awkward angles where air might be trapped and the metal flows smoothly through the mold. There do not appear to be any technical obstacles to the casting of a large water screw as a single unit, other than the difficulties inherent in any large casting project.

Dalley has argued that two passages in classical literature also imply the existence of water screws in Sennacherib's garden at Nineveh: Strabo *Geography* 16.1.5 and the later Philo of Byzantium, better known as Philo the Paradoxographer, *On the Seven Wonders of the World* 1.4.[29] Both passages describe the method of raising water for the Hanging Gardens of Babylon. Dalley has made a good case that these gardens never existed in Babylon

29. That is, the Byzantine writer of paradoxes (i.e., marvels), not the Hellenistic engineer. Philo of Byzantium, the engineering author of circa 200 B.C., keeps popping up in the discussion of the water screw, usually because of a confusion with an author better referred to as Philo Byzantinus or Philo the Paradoxographer, a paradoxographer and rhetorician of the fourth century A.D. The later Philo wrote a handbook on the seven wonders of the ancient world and describes the use of water screws at the Hanging Gardens of Babylon. Wilhelm Kroll, "Philon (49)," *Realencyclopädie*, vol. 20, bk. 1 (1960), 54–55; Kai Brodersen, *Reiseführer zu den Sieben Weltwundern, Philon von Byzanz und andere antike Texte* (Frankfurt, 1992), 15. Peter A. Clayton and Martin Price, eds., *The Seven Wonders of the Ancient World* (London, 1988), 170, are aware of the late date of the Philo who wrote on the seven wonders, but one of the contributors to their book, Irving L. Finkel, "The Hanging Gardens of Babylon" (38–58), unaccountably refers to him in the text as "Philo of Byzantium who probably flourished around 250 B.C." (45). This inconsistency, combined with the popularity of Clayton and Price's book, has misled many later authors, including Dalley; see "Nineveh, Babylon and the Hanging Gardens" (n. 2 above), 53.

But it is nonetheless useful to consider why Philo of Byzantium (the Hellenistic technical writer, fl. ca. 200 B.C.) does not mention the water screw anywhere in the fragments of his work that have survived in Greek, or in Latin and Arabic translations. Of the possible nine books of his compendium, only two are wholly extant, and a few other fragments deal only with war machines. The two books that remain would not necessarily have included the screw, since the *Parasceuastica* (preserved in Greek) deals with catapults and his *Pneumatica* (preserved in Arabic) deals with siphons and related devices. So it is possible that Philo the engineer, and his teacher Ctesibius of Alexandria (*floruit* 270 B.C.), knew of the screw in Egypt before the time of Archimedes, and we have been unlucky in the chance survival of texts that happen not to mention screws. This silence of the sources, of course, allows one to argue exactly the opposite as well. Hellenistic technical writing, like Assyrian landscape relief, survives only erratically.

proper, but that later authors knew Nineveh under the name Babylon and were describing Sennacherib's garden in Nineveh.[30] If she is correct, Strabo's description of Babylon in the later first century B.C. may be derived from some earlier source, even though his description of the Near East seems to be based in part on personal travel. Quintus Curtius Rufus also records that the gardens (like the other world wonders) were still flourishing in his own day (first century A.D.?).[31] The apparent transfer of the Hanging Gardens from Nineveh, later known as "Old Babylon," on the Tigris, to Babylon on the Euphrates was permanent. Many travelers confused the two rivers because of numerous branching streams and canals connecting them.

Strabo wrote (*Geography* 16.1.5): "The topmost story is approached by a stairway that has water screws [κοχλίας] installed alongside, by means of which those assigned to the task used to raise water up continuously into the gardens from the Euphrates." The arrangement makes technological sense. A series of water screw installations was constructed from the river to the top of the garden structure, parallel to stairs providing access presumably both to the individuals rotating the water screws and to other service personnel, as well as to those seeking pleasure. Strabo says the screws were set alongside steps that led to the top of the terraced garden, possibly a stepped corridor protected from the sun by a mud-brick barrel vault or leafy arbors. There is a similar passage in a description of the same "Gardens of Babylon" by his contemporary Diodorus Siculus (*History* 2.10.6): "There was one [gallery] with shafts from the highest level and water-lifting machines [ὄργανα] by means of which a quantity of water was drawn up from the river, although no one outside could see the activity."

There is no way to determine what sort of water-lifting device Diodorus thought was in use here, although the mention of "shafts" [διατομάς] might imply a vertical lift by means of ropes, rather than a hidden, sloping corridor for water screws. In this case, the animal-operated bucket and pulley (the *čerd*) may be considered an option, and it was known in Mesopotamia by at least the fourth century B.C.[32] Neither Strabo nor Diodorus,

30. See Dalley, "Nineveh, Babylon and the Hanging Gardens," also "Why Did Herodotus not Mention the Hanging Gardens?" forthcoming in *Herodotus and His World: Essays in Memory of George Forrest*, ed. Peter Derow and Robert Parker (Oxford).

31. Strabo traveled widely (cf. *Geography* 2.5.11), particularly in the Near East and Egypt (2.5.12), but the precise extent of his journeys is unclear. Curtius Rufus *History of Alexander* 5.1.32–35.

32. Ctesias of Cnidus, *Persica*, in Felix Jacoby, *Die Fragmente der griechischen Historiker*, vol. 3, pt. C (Leiden, 1958), 484–85, no. 688, frag. 34a-b. See Oleson, *Mechanical Water-Lifting* (n. 1 above), 39–41. The reconstruction by Stevenson of an irrigation system for the gardens based on wheels with compartmented rims, turned by treading, is essentially feasible, but not supported by any archaeological or literary evidence: D. W. W. Stevenson, "A Proposal for the Irrigation of the Hanging Gardens of Babylon," *Iraq* 54 (1992): 35–55.

however, refer to animals, and the long walkway needed for a *čerd* is likely to have been visible to onlookers.

The account of the "Hanging Gardens of Babylon" in the handbook to the Seven Wonders of the World written by Philo the Paradoxographer in the fourth century A.D. is derived from unknown sources, and rendered in typically florid Byzantine Greek. Philo describes the associated irrigation system as follows (1.4): "Streams of water issuing from springs higher up flow partly downward in a direct course, partly are forced upwards through bends and spirals to gush out higher up, being pushed through the twists of these devices by mechanical forces. So, brought together in frequent and commodious sources at a high level, these waters irrigate the whole garden. . . ."[33] The mention of bends, spirals, and twists make it clear that the water-lifting device intended could only be a water screw. The supply system is mixed, however, since the author also mentions the provision of some of the water by gravity flow, presumably to the lower portion of the gardens.

There is no other evidence in Assyrian inscriptions for knowledge of the water screw, and no illustrations of water screws in surviving Assyrian relief sculptures. The absence of representations, however, is hardly surprising, given the low survival rate for these reliefs. The one relief sculpture that may illustrate the garden itself is a badly damaged panel only 35 percent complete (fig. 3). It was set up at Nineveh during the reign of Ashurbanipal, Sennacherib's grandson, who was unfortunately the last king to use such bas-reliefs.[34] Ever since its discovery, attempts have been made to compare details of the garden relief with the descriptions of the Hanging Gardens by Strabo and Diodorus Siculus: an aqueduct brings water into the garden halfway up the slope, and artificial terraces thick with plants are built up on stone vaults. One of the drawings made of a now missing fragment has recently been recognized as providing further details of the gardens: at the top of a steep slope is a pillared walkway supporting trees growing on the thick roof. This detail is found in the depiction of the gardens by Philo the Paradoxographer, who describes stout columns with beams set on top supporting soil and trees.[35] No water-lifting devices, however, are visible in the surviving portion of the relief.

Of the known ancient water-lifting devices, the water screw best fits the words of Sennacherib's inscription as interpreted by Dalley, but neither the

33. Translation based in part on that of David Oates in Finkel, 46; see also Brodersen, 24–25. Although late and a rhetorician, the reputation of Philo the Paradoxographer for conveying accurate information about the ancient "wonders" has been upheld by Denys E. L. Haynes, "Philo of Byzantium and the Colossus of Rhodes," *Journal of Hellenic Studies* 77 (1957): 311–12.

34. British Museum no. 124939. See Dalley, "Nineveh, Babylon and the Hanging Gardens," 51–52; Pauline Albenda, "Landscape Bas-Reliefs in the Bit Hilani of Ashurbanipal," *Bulletin of the American Schools of Oriental Research* 224 (1976): 49–72, fig. 4.

35. Reade, "Studies in Assyrian Geography" (n. 12 above). Dalley deals with some of these issues at length in "More about the Hanging Gardens" (n. 2 above).

JANUARY
2003
VOL. 44

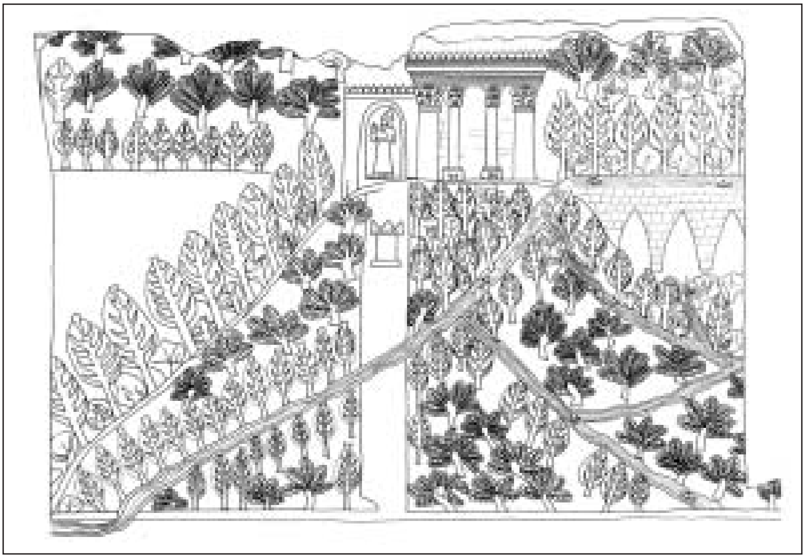

FIG. 3 The British Museum Nineveh garden relief. (Drawing by Stephanie Dalley.)

inscription nor the visual evidence prove the existence of the water screw in the seventh century B.C. Only the passage in Strabo is early enough and clear enough to carry some authority, and yet there is no guarantee that the water screws he mentions appeared in his source or that the source itself predates Archimedes. The water screws might even have been retrofitted at the gardens after their invention by Archimedes, to replace some other, less efficient method of irrigation.[36]

None of these passages mentions the method of turning the devices. In her 1992 article, Dalley suggested that the screws she reconstructs were turned with a crank mounted on the upper end of the axle.[37] This approach, however, is almost certainly wrong, since it seems that the principle of the true crank was not discovered until the second century B.C., when it appears in rudimentary form on rotary querns, and it was apparently not put to use in ancient machinery.[38] The inertia of such heavy bronze water

36. Oleson, *Mechanical Water-Lifting*, 293

37. Dalley, "Nineveh, Babylon and the Hanging Gardens" (n. 2 above), 53.

38. Aage G. Drachmann, "The Crank in Graeco-Roman Antiquity," in *Changing Perspectives in the History of Science*, ed. Teich Mikulás (London, 1973), 33–51, marshals the evidence that the crank did not exist in antiquity, with the possible exception of one application by Archimedes to turn a pulley system. Simms (n. 6 above), 100 n. 5, rejects even this limited use, probably correctly. Michael J. T. Lewis, *Millstone and Hammer* (Hull, 1997), 15, presents a typically iconoclastic, but halfhearted, argument that the

screws and the friction of their bearings would have made it impossible to drive them by means of humans treading the top of the barrel, as shown in Roman illustrations of wooden screws. Any method that requires cogs may be discounted, since the cog also seems to have been unknown before the Hellenistic period.[39] The mention of ropes, wires, and chains in connection with the water-lifting device of Sennacherib's inscription suggests to Dalley that the screws she restored at Nineveh were driven by a system of chains wound around the barrels and hauled from below.

The hinge sockets that took the weight of the enormous doors at some Near Eastern palaces provide a possible parallel for the bearings. These doors were strapped to a vertical, cylindrical beam, which was set into a copper-lined stone socket and rotated to open the door leaf.[40] Lard and other oils were supplied to doorkeepers, some presumably for lubrication.[41] The wooden double doors with bands of bronze found at Balawat near Nineveh weighed at least 1,120 kilograms.[42] They date to about two hundred years earlier than Sennacherib and were provided with sockets made of a very hard, dense, black stone.[43] The bearings for the screws might have been similar, the shaft bedded in journal or thrust bearings lined with copper or bronze and kept well oiled. The splashing water lifted by the screws would also have served to lubricate the bearings.

Lack of evidence prohibits precise calculation of how much water had to be raised from one terrace to another in the gardens at Nineveh. The height of the terraces above the aqueduct is not known, nor do we know how many trees or which species were grown there. Diodorus Siculus describes the size of the garden as "like a Greek theater, 4 *plethra* on each side" (roughly 120 meters).[44] The BBC water screws lifted approximately 150 liters per minute (9,000 liters per hour) for short periods of time over a height of about 1.5 meters.[45] This discharge is equivalent to 162 cubic

---

small rotary hand quern might have been known as early as the seventh century B.C. The evidence he cites is secondhand and extremely doubtful.

39. Oleson, *Mechanical Water-Lifting* (n. 1 above), 370–80; cf. Donald R. Hill and M. T. Wright, "Byzantine and Arabic Mathematical Gearing," *Annals of Science* 42 (1985): 87–138, and Derek J. de Solla Price, "Gears from the Greeks: The Antikythera Mechanism, a Calendar Computer from ca. 80 B.C.," *Transactions of the American Philosophical Society*, n.s., 64 (1974): 7.

40. Described by Andrea Büsing-Kolbe, "Frühe griechische Türen," *Jahrbuch des Deutsches-Archäologisches Institut* 93 (1978): 66–174.

41. Armas Salonen, *Die Türen des alten Mesopotamien* (Helsinki, 1961), 120–21.

42. Dalley is grateful to Chris Addison for his help with calculations. They are based on the weight of dried conifer timbers, and do not include the quite substantial weight of the bronze bands, doorknobs, and locks. A total weight of 2 tons is realistic.

43. Peter R. S. Moorey, *Ancient Mesopotamian Materials and Industries* (Winona Lake, Ind., 1999), 337.

44. Diodorus Siculus *History* 2.10.2.

45. This figure is strikingly close to White's estimate of the discharge of the Vitruvian

meters of water in an eighteen-hour day. Such a high rate of discharge suggests that just one or two series of water screws would have been sufficient to irrigate the gardens, perhaps working only a few hours each day. In addition, not all the water would have had to be lifted to the highest terrace. Two series of screws might have been used to lift water as high as the midpoint of the total lift, with irrigation water being drawn off from the sumps on each terrace, while only one series continued on to the higher terraces. It is also possible that the aqueduct illustrated in the British Museum's Nineveh relief and alluded to by Philo the Paradoxographer brought water in high enough that only the top few terraces had to be irrigated by lifted water. Given the absence of specific details about the gardens, however, it is impossible to provide detailed statistics of need or potential discharge.

It should be emphasized that if the object cast by Sennacherib was a water screw, it could not have represented the first use of that mechanism for raising water. There must have been working examples in wood that inspired or were copied for the bronze casting, since nobody would cast such a device full-scale in bronze unless he already knew it would work. Just as the sophistication of the Antikythera cog mechanism (by far the earliest material evidence for gearing) was part of a long period of technical evolution largely hidden from us, so the manufacture of Sennacherib's screw in expensive and intractable bronze was presumably the result of considerable previous experience and practical use.[46] Since wood rarely survives in Mesopotamia, we are unlikely ever to find wooden water screws there.

In summary, the details of the Palace without a Rival inscription as reinterpreted by Dalley remain the principal pre-Hellenistic evidence for the existence of the water screw. This interpretation is supported by Strabo's description of the Hanging Gardens of Babylon only if one attributes the gardens to Sennacherib at Nineveh rather than to another king in Babylon and accepts the antiquity of Strabo's sources. The same provisos affect interpretation of the passage in Philo the Paradoxographer.

If the screw was invented or adopted by the Assyrians in the seventh century B.C., they would likely have introduced it into Egypt when they took control of the Nile Valley in the mid-seventh century, where Archimedes might have seen it at work four centuries later. A passage in Deuteronomy (11:10), probably dating to the seventh century B.C., mentions that in Egypt, unlike Palestine, men watered their gardens "with their feet." The phrase may refer to the shovel work necessary for impounding and

---

water screw: 2,000 gallons/hour (9,092 liters/hour) by a one-man water screw over a head of 4 feet (1.22 meters). See Kenneth D. White, *Greek and Roman Technology* (London, 1984), 194. See also Landels's estimates of 9,600 to 14,100 liters/hour, in John G. Landels, *Engineering in the Ancient World* (London, 1978), 63.

46. M. Arnoldi and Karlheinz Schaldach, "A Roman Cylinder Dial: Witness to a Forgotten Tradition," *Journal of the History of Astronomy* 28 (1997): 107–17.

channeling irrigation water in the Nile Valley, or it may simply be a metaphor for hard labor. But if the phrase is to be interpreted literally, the only appropriate irrigation devices would be the water screw or the wheel with compartmented rim, and for the latter there is no evidence earlier than the third century B.C.[47] One might expect Egyptian paintings to show screws in action in the Nile Delta during the Persian or early Ptolemaic periods if they existed then, but by that time the vogue for landscape art, so popular in the Late Bronze Age period of the New Kingdom, had passed.[48] One can only hope that more evidence will come to light in the future.

Did Archimedes Invent the Water Screw?

Is the case for Archimedes as the inventor—or even the reinventor—of the water screw any stronger than that for Sennacherib? Without doubt Archimedes wrote a mathematical treatise on spirals, for which the main application known at that time was the water-lifting screw. The question is, was he responsible also for the mechanical invention?[49] And even if we cannot verify that he invented (or reinvented) the device, what was the context that spawned the innovation? The design of the everyday Greek and Roman water screw, in contrast to the heavy bronze device of Sennacherib, with its problematic drive chains, has a powerful simplicity. A double or triple helix was built of wood strips (or occasionally bronze sheeting) around a heavy wooden pole. A cylinder was built around the helices using long, narrow boards fastened to their periphery and waterproofed with pitch, and tread-

47. Although few scholars would allow a date as late as the third century B.C. for this text, a late date cannot be ruled out, so the evidence it provides is not conclusive. Oleson, *Mechanical Water-Lifting* (n. 1 above), 98–99, dates it to the seventh century B.C. and suggests that the text might in fact refer to the shaduf or the compartmented wheel.

48. Jaromír Málek, *Egyptian Art* (London, 1999), 368.

49. For discussions of the Greco-Roman water screw, see Oleson, *Mechanical Water-Lifting*, 291–301, and "Water-Lifting" (n. 1 above), 242–51. Archimedes' treatise on spirals is discussed by Wilbur R. Knorr, "Archimedes and the Spirals: The Heuristic Background," *History of Mathematics* 5 (1978): 43–75. The design of the hypothetical wooden water screws that might have preceded Sennacherib's palace design, of course, is completely unknown. The related principle of threaded bolt and nut was known by the third century B.C., but practical application seems to have come only in the first century B.C. Because of the difficulty of cutting accurate threads, small metal bolts were rare even in the Roman period, seen most often in jewelry and luxury metal objects. The threaded bolt and nut were most commonly manufactured on a very large scale in wood, for use in grape, olive, or clothes presses. The metal carpenter's screw for wood was unknown in antiquity. See Franz Kiechle, "Zur Verwendung der Schraube in der Antike," *Technikgeschichte* 34 (1967): 14–22; Aage G. Drachmann, "Heron's Screwcutter," *Journal of Hellenic Studies* 56 (1936): 72–77; Rudolf Kellermann and Wilhelm Treue, *Die Kulturgeschichte der Schraube*, 2nd ed. (Munich, 1962); Barbara Deppert-Lippitz et al., *Die Schraube zwischen Macht und Pracht: Das Gewinde in der Antike* (Sigmaringen, Ger., 1995).

JANUARY
2003
VOL. 44

FIG. 4 Pompeii, House of Menander, fresco of Egyptian water screw in operation. (Photo by John Peter Oleson.)

ing cleats were fastened around the outside of the barrel, toward the center (figs. 4 and 5). Screws of this type, which might be 2 meters to 3 meters long, turned on simple metal pivots at each end of the axle. All surviving representations of the water screw in action show a single individual standing on the treads to work the screw, which is set at a low angle, and the literary texts describe only treading. The treader balanced and partly supported himself on a pole stuck in the earth nearby or on a horizontal beam supported by a thatched sun shelter, and moved the treads with his feet. There is a fresco representation of an agricultural water screw in the House of Menander at Pompeii (fig. 4), and Philo Judaeus provides a clear description of such a water screw action in the first century A.D. (*De confusione linguarum* 38):

> Compare the screw, the water-lifting device. There are some treads around the middle on which the husbandman steps whenever he wants to irrigate his fields, but naturally he keeps slipping off. To keep from continually falling, he grasps something sturdy nearby with his hands and clings to it, suspending his whole body from it. In this way he uses his hands as feet and his feet as hands, for he supports himself

FIG. 5 The BBC water screw, complete and mounted. (Photo by John Peter Oleson.)

with his hands, which are generally used for working, and he works with his feet, which customarily serve as supports.

For a high angle of installation, such as might be needed for draining deep mines or lifting water up a steep slope, a different method of rotation may have been used, but no descriptions or representations of a screw at such an angle exist to show how this might have been done.

All the surviving archaeological evidence for the water screw dates to the first century A.D. or later, and the few possible papyrological references belong to the first and second centuries A.D. Greek literary sources, however, begin in the second half of the third century B.C. Vitruvius (*On Architecture* 10.6.1–4) provides the best ancient description of the water screw, and complete instructions on how to construct it. After adapting the design to reduce the number of helices to two, the procedures outlined by Vitruvius were followed without difficulty during design and construction of two full-size water screws for the BBC television production (fig. 5).

Diodorus of Sicily associates the water screw with Archimedes in a passage concerned with irrigation in the Nile Delta (*History* 1.34.2): "[T]he Nile . . . in its annual inundation always deposits new mud, and the inhabitants easily irrigate the whole region by means of a certain device which Archimedes the Syracusan invented [ἐπενόησε], called the screw [κοχλίας] on account of its design."[50] Here we meet a crux of interpretation which is

50. Felix Jacoby, *Die Fragmente der griechischen Historiker*, vol. 2, pt. A (Leiden,

applicable also to other passages discussed below. Common meanings of the verb ἐπινοεῖν include *to think about*, *to think of*, *contrive*, *purpose*, *observe*, *invent*. It can be seen that one might substitute "observed" or "found" for "invented" without disturbing the narrative or the syntax significantly.

A second passage in Diodorus (*History* 5.37.3–4), probably quoted from the first-century B.C. author Posidonius, contains two cruxes.[51] Not only can the verb εὑρίσκω be ambiguous, allowing the meanings *to find*, *find out*, *discover*, *invent*, *get*, *gain*, and *earn*, but τεχνίτης, "craftsman," might be either a direct reference to Archimedes or a generic term for the inventive human being. The passage describes the working of mines in Spain:

> At a depth they sometimes break in on rivers flowing beneath the surface whose strength they overcome by diverting their welling tributaries off to the side in channels. Since they are driven by the well-founded anticipation of gain, they carry out their enterprises to the end, and—most incredible of all—they draw off the streams of water with the so-called Egyptian screw [Αἰγυπτιακοὶ κοχλίαι], which Archimedes the Syracusan invented [εὗρεν] when he visited Egypt. By means of these devices, set up in an unbroken series up to the mouth of the mine, they dry up the mining area and provide a suitable environment for carrying out their work. Since this device is quite ingenious, a prodigious amount of water is discharged with only a small amount of labor, and the whole torrent is easily discharged from the depths into the light of day. One might reasonably marvel at the inventiveness of the craftsman [Archimedes?] not only in this, but also in many other even greater inventions celebrated throughout the whole world, each of which we shall discuss carefully in turn when we come to the age of Archimedes.

The translation of εὗρεν as "invented" in this passage finds support in the use by Diodorus of the same verb to record the invention of siege engines by Dionysius of Syracuse's think tank, in a passage quoted above. It is also possible to find support in the famous story of Archimedes' discovery of the principle of specific gravity while floating in a basin at a public bath in Syracuse (Plutarch *Moralia* 1094C): He leaped out of the tub in his excitement, crying εὗρηκα (also from εὑρίσκω), "I've found it!" (the solution to the problem confronting him, that is), and ran home naked through the streets.[52] But should account be taken of the essential difference

1961), 213, no. 86, frag. 19, attributes this passage to an unknown work by Agatharchides of Cnidus, who wrote in the third quarter of the second century B.C.

51. Ibid., 309, no. 87, frag. 117. The passage probably originated in an unknown work by Posidonius of Apamaea written in the first half of the first century B.C.

52. Oleson, *Mechanical Water-Lifting*, 92–93.

between discovering a preexisting law and inventing a new mechanical device? Archimedes cannot be said literally to have invented the principle of displacement. Thus the verb in Plutarch may mean *to come across*, *discover*, rather than *to devise first*, *to originate* (in the sense known to patent law), and some scholars interpret it in this way.[53] According to this interpretation, preexistence of the water screw would also explain why Posidonius (in Diodorus Siculus) calls them "Egyptian screws" here and in a similar fragment quoted in Strabo *Geography* 3.2.9.

On the other hand, one also can interpret εὗρεν in the passage from Posidonius to indicate that—as with the discovery of specific gravity—Archimedes observed the principles of spirals and helices in nature and applied his analysis of natural phenomena to the solution of a human engineering problem. This seems to have been Vitruvius's understanding, since in his version of the story Archimedes "cried out in a loud voice that he had found what he was seeking" (*On Architecture* 9, preface 9–10, "*significabat clara voce invenisse, quod quaereret*"). Vitruvius lists Archimedes among the superior innovators who based their practical inventions on mathematics and natural laws (*On Architecture* 1.1.17): "Archimedes and Scopinas of Syracuse. They have left to posterity many treatises on machinery and timekeeping devices in which mathematics and natural law are used to make discoveries and explain them." Unfortunately, the verb is too common and the contexts in which it is used are too fluid to allow the modern reader precise semantic distinctions.

Finally, mention must be made of Plutarch's description (*Marcellus* 14.4–9) of how mechanics was a subject entirely distinct from geometry, and how King Hiero of Syracuse had trouble persuading Archimedes "to turn his art somewhat from abstract notions to material things." This comment is unique and probably represents rhetorical posturing, but it is interesting to note that Plutarch reports Hiero's motivation to have been "prestige," like that of the contemporary Ptolemies, who subsidized applied research in Alexandria.[54] In this context he calls Archimedes δημιουργός (14.9), a term for "craftsman" with more mythical overtones than that used by Posidonius.

Another passage which can be interpreted to show that Archimedes invented the water screw is quoted by Athenaeus (*Philosophers at Dinner* 5.207–208) from Moschion's *Treatise on the Great Ship of Hiero of Syracuse*,

53. For example, Dijksterhuis (n. 6 above), 21–22; Brian Cotterell and Johan Kamminga, *Mechanics of Pre-Industrial Technology* (Cambridge, 1990), 94; and doubts expressed by Morris R. Cohen and Israel E. Drabkin, *A Sourcebook in Greek Science* (Cambridge, Mass., 1948), 350–51. Contrary arguments are collected in Oleson, *Mechanical Water-Lifting* (n. 1 above), 291–94. Danielle Bonneau, *Le Régime administratif de l'eau du Nil dans l'Égypt grecque, romaine, et Byzantine* (Leiden, 1993), 97–98, accepts Archimedes as the inventor.

54. See Lewis, "The Hellenistic Period" (n. 5 above), 635.

JANUARY
2003
VOL. 44

written sometime soon after 241 B.C.[55] "And the bilge, although of a remarkable depth, was pumped out by a single man operating a water screw [διὰ κοχλίου], which Archimedes invented [ἐξευρόντος]." The verb used here, ἐξευρίσκειν, has a range of meaning: *invent*, *discover*, *find out*.[56] Although the water screw is not well adapted to bilge pumping and was soon replaced for this purpose by chain pumps and force pumps, Moschion may have had information either that Archimedes invented the water screw and then put it to use in this highly experimental ship, or that Archimedes found the screw in Egypt and introduced it to the people of Syracuse, inventing a new use for it.[57] According to the long, detailed text quoted in Athenaeus, Archimedes was the technical overseer (γεωμέτρης ἐπόπτης) of the whole project (*Philosophers at Dinner* 5.206d).[58]

Oleson believes that the fragments of Moschion, Agatharchides, and Posidonius (as quoted in Athenaeus and Diodorus Siculus) can be interpreted to indicate either that Archimedes invented the water screw or that during or soon after his lifetime and in the course of the second century B.C. individuals familiar with his life and work believed that he had invented a new device called the water screw. In either case, the chronology suggests that the device was invented around the time of Archimedes, in the particularly fertile climate of practical innovation associated with the Museion, the Museum at Alexandria.[59] Dalley interprets the evidence to show that he was associated with the screw only because of his treatise on spirals, his observation of preexisting screws in use in Egypt, and his adaptation of the device for Hiero's ships.[60] Dijksterhuis is another scholar who believes that Archimedes found the water screw already in use when he visited Egypt, arguing that "neither Strabo, nor Philo of Byzantium [*sic*], nor Vitruvius, who all three mention or describe [the water screw], associate it with the name of Archimedes."[61] These objections are groundless, since it is clear

55. Felix Jacoby, *Die Fragmente der griechischen Historiker*, vol. 3, pt. B (Leiden, 1964), 677, no. 575, frag 5.3.

56. Compare, in particular, Aeschylus *Prometheus Bound* 460, 469 (to invent mathematics, writing, and inventions); Herodotus *History* 1.8 (to invent rules); Plato *Republic* 566b (to devise a petition).

57. Landels (n. 45 above), 66, is probably correct that a single water screw could not have provided enough lift to pump out Hiero's large (and thus deep-hulled) ship. For a full discussion of the ship, see Jean M. Turfa and Alwin G. Steinmayer, "The Syracusia as a Giant Cargo Vessel," *International Journal of Nautical Archaeology* 28 (1999): 105–25. On bilge pumps, see Oleson, "Water-Lifting" (n. 1 above), 263–67, 298–99.

58. See Peter Kingsley, "Artillery and Prophecy: Sicily in the Reign of Dionysius I," *Prometheus* 21 (1995): 15–23.

59. On the special character of the technological climate in Hellenistic Alexandria, see Lewis, "The Hellenistic Period."

60. In the twelfth century, Eustathius (*ad Iliadem* M 293) also attributes the invention of the water screw to Archimedes, but—despite his deep classical learning—his testimony is too late to carry any particular weight.

61. Dijksterhuis (n. 6 above), 21–22.

from the context that by "Philo of Byzantium" Dijksterhuis intended Philo Judaeus of Alexandria, whose description of a screw in action (quoted above) in fact does not mention Archimedes.[62]

The absence of Archimedes' name from some of the texts that mention the water screw is certainly not conclusive. For comparison, Ctesibius's works have been lost, but descriptions of gadgets and hydraulic devices specifically attributed to him have been preserved in the works of Philo of Byzantium, Vitruvius, and Hero of Alexandria. Ctesibius's name is associated in particular with the piston-operated force pump, called *Ctesibica machina* by Vitruvius (*On Architecture* 10.7.1). In the mid-first century A.D., however, Hero describes the same force pump in detail but calls it only a σίφων, omitting any reference to the inventor. A parallel could be drawn with instances where Archimedes' water screw is termed only "Egyptian screw" or simply "screw." In the passages of his *Geography* which mention the water screw, Strabo is concerned with the design of the Hanging Gardens of Babylon (16.1.5), the location of the Roman fort at Old Cairo (17.1.3), and the means of watering the many islands in the Nile river (17.1.52). There is no reason to mention Archimedes in any of these contexts.

Whether the screw was introduced into the Nile Delta by Archimedes on behalf of Ptolemy II or arrived four centuries earlier under Assyrian occupation, the device was ideally suited to that environment. The water screw is particularly effective for low lifts, such as irrigation along the low-lying banks of the Nile Delta. In addition, the device is essentially self-purging and can lift water that is thick with silt and vegetable matter. There are no small intake holes or compartments to clog, the water simply flows unrestricted over smooth-walled surfaces.[63] A passage in Strabo (*Geography* 17.1.52) describes this situation: "There are a great many islands scattered along the course of the Nile. Some are completely covered during the flood, others only in part, and the particularly high spots are irrigated with water screws [κοχλίαις]."

The water screw remained a typical image of the Egyptian landscape in literature and art through the Roman period.[64] Numerous terra-cotta reliefs and one fresco representing water-screw installations at work have survived from the Roman imperial period, along with one model.[65] None

62. See n. 29 above.

63. Herbert Addison carried out experiments with a reconstructed water screw showing, among other results, that the capacity of the water screw is greatest at lower lifts and falls off very rapidly as the angle of inclination approaches the complement of the angle of the vanes; "Experiments on an Archimedean Screw," *Institution of Civil Engineers* 75 (1929): 3–15. There is a more sophisticated mathematical model in Chris Rorres, "The Turn of the Screw: Optimal Design of an Archimedes Screw," *Journal of Hydraulic Engineering* 126, no. 1 (2000): 72–80.

64. For example, the fresco of an Egyptian water-screw installation at Pompeii; see Oleson, *Mechanical Water-Lifting*, 241–42, and "Water-Lifting," 247–49 (both n. 1 above).

65. Oleson, *Mechanical Water-Lifting*, 207–9, 227, 241–42.

of this evidence coincides with the period of Archimedes and his immediate successors, showing the incompleteness of the pictorial record.[66] There are, of course, no representations of water screws that predate Archimedes. One possible explanation for the absence of any evidence of the existence of the water screw between the examples Dalley reconstructs for Sennacherib's garden and those embedded in the literary sources for Archimedes' career is that the device fell out of use, was forgotten, and was reinvented by Archimedes or a near contemporary. Although the water screw has in fact never fallen out of use since Archimedes, it has allegedly been reinvented several times. The sixteenth-century Italian polymath Girolamo Cardano says he had heard of a blacksmith in Milan who thought he was the first to invent this device and went insane from joy. The nineteenth-century engineer Thomas Ewbank reports that he, too, as a boy heard of a shoemaker who had suffered the same delusion.[67] If these stories are true, it may be significant that both these individuals were workmen who—in addition to never having been exposed to a water screw in operation—presumably did not have access to the classical authors or the numerous books on applied technology already available in the sixteenth century.[68] Whether true or not, the stories arose in environments not dissimilar to that of Hellenistic Alexandria.

Conclusions

What can we conclude from all this? The chronology of the first discovery of the water screw is still clouded in uncertainty. Sennacherib was interested in the problems of water supply, and he constructed some sort of clever or spectacular device to assist the irrigation of his gardens at Nineveh. The Palace without a Rival inscription applies metaphorical terminology that an Assyriologist with a knowledge of the water screw can argue refers to that device. We know that the water screw existed by at least the mid-third century B.C., since literary sources describe it in explicit terms. It seems likely that Archimedes invented (or reinvented) the device in Egypt at the request of one of the Ptolemies to solve irrigation problems in the Nile Delta, but this conclusion is not certain. The design of the water screw can be interpreted as either an offshoot of Archimedes' research into the mathematics of

66. Örjan Wikander, *Exploitation of Water-Power or Technological Stagnation?* (Lund, 1984), discusses the lack of chronological overlap between archaeological and literary evidence for the existence of mechanical devices in classical antiquity.

67. Girolamo Cardano, *De subtilitate* (Basel, 1554), quoted in E. M. P. Evans, "Ancient Mining," *Antiquity* 17 (1943): 52. The craftsman is described as a *faber ferrarius*. Thomas Ewbank, *A Descriptive and Historical Account of Hydraulic and Other Machines for Raising Water* (London, 1842), 139.

68. For example, Agostino Ramelli, *Le diverse e artificiose machine del capitano Agostino Ramelli* (Paris, 1588), which contains several devices utilizing the water screw.

spirals or the very inspiration for that research.[69] If the water screw did, in fact, exist in Mesopotamia early in the seventh century B.C., what is particularly interesting is the observation that it seems either to have fallen out of use completely or to have been so completely divorced from the realities of urban society in Mesopotamia and Egypt that Archimedes could be awarded credit for its invention or rediscovery almost five hundred years later.

If the water screw had such a negligible impact on the cultures of the eastern Mediterranean before the time of Archimedes, the actual date of its original invention is of little importance. But the similarity of the conditions in seventh-century Nineveh and third-century Alexandria that might have led to its discovery is striking. Both cultures depended completely on exogenous river systems to supply water for irrigating their rich, alluvial soils, and on technologies and regulations that facilitated irrigation agriculture. Both were ruled by royal houses interested as much in broadcasting the prestige and imagery of technological success, the tangible evidence of human triumph over the forces of nature, as in the practical results. Sennacherib conquered the river, forcing it to serve humankind, and commemorated the results in public reliefs and inscriptions. He also constructed his show garden for his queen, to heal her homesick memories for the verdant mountain slopes of her native land, and he irrigated the artificial mountainside conspicuously with conduits and some water-lifting device, commemorating it in the same manner as what seem to us his more practical accomplishments. The pharaohs boasted of their control of the Nile in a similar manner. Their technological heirs, the Ptolemies, made astute practical use of the water screws, catapults, and giant ships designed by their court scientists, but they delighted as well in the banquet table gadgetry designed by Ctesibius and in automated parade floats that paraded such cleverness to the public.[70]

One significant difference, however, sets the Ptolemaic response apart. In the premodern period, specific, individual, nonmythical inventors are only rarely given credit for their efforts and insight, but at Alexandria and (to a lesser extent) Syracuse in the mid-third century there was a brief historical moment in which individual genius was recorded. If one of Sennacherib's engineers found the water screw in use along an irrigation canal, or dreamed up the device on the basis of an understanding of natural and man-made spiraling forms, the credit belonged to his absolute ruler. Archimedes, in contrast, was given personal credit for the water screw, which grew out of his personal intellectual interests, and for many other devices constructed for his patrons there and in Syracuse. Before him in Alexandria,

69. Knorr (n. 49 above).

70. See, for example, Athenaeus *Philosophers at Dinner* 5.198e–f, and, in Athens, a mechanical snail that left a trail of slime: Polybius *History* 12.13.11. There is a popular discussion of this phenomenon in Robert S. Brumbaugh, *Ancient Greek Gadgets and Machines* (New York, 1966).

Ctesibius and Philo of Byzantium benefited from the same sort of celebrity. In contrast, the members of the think tank that worked for Dionysius of Syracuse 150 years previously remain anonymous, as do nearly all the innovative engineers and architects who transformed the Mediterranean world during the Roman empire.[71] The question of why individual technicians remained associated with their innovations in mid-third century B.C. Alexandria and Syracuse cannot be answered here, but the presence of the Museion, a well-funded, more or less independent research institute in Alexandria, undoubtedly played an important part, along with the well-documented rivalry of King Hiero II of Syracuse with Ptolemy II, Ptolemy III, and Ptolemy IV.[72] The very fact of the potential recognition of individual effort and accomplishment may also have been a trigger for innovation. But this florescence was brief, and the attitudes and structures typical of the ancient world had to fall away before an individual such as Leonardo da Vinci could once again derive personal fame from his inventions.

71. Innovation, in fact, could be perilous, as an "urban myth" circulated in Rome in the first century A.D. emphasizes. An anonymous craftsman supposedly invented "flexible" or "unbreakable" glass, and he showed a specimen to the emperor Tiberius (14–37 A.D.) in the hope of a great reward. After determining that no one else knew the secret, Tiberius had him killed in the fear that the invention would ruin the bullion-based economy. The story is preserved in a number of first-century texts: Petronius *Satyricon* 50–51; Pliny *Natural History* 36.195; Dio Cassius *History* 57.21.6.

72. On the Museion and its scientists, see Eduard Müller-Graupa, "Museion," *Realencyclopädie* vol. 16, no. 1 (1933), 797–821; Lewis, "The Hellenistic Period" (n. 5 above), 632–35; Michael J. T. Lewis, "Theoretical Hydraulics, Automata, and Water Clocks," in Wikander, *Handbook of Ancient Water Technology* (n. 1 above), 343–69.