Sun, Moon and Earth, and the distances between them. These measurements were milestones in the history of astronomy, representing as they do the first tentative steps on the road to understanding the entire universe. As such, these measurements deserve to be described in a little detail.

Before any celestial distances or sizes could be calculated, the ancient Greeks first had to establish that the Earth is a sphere. This view gained acceptance in ancient Greece as philosophers became familiar with the notion that ships gradually disappear over the horizon until only the tip of the mast could be seen. This made sense only if the surface of the sea curves and falls away. If the sea has a curved surface, then presumably so too does the Earth, which means it is probably a sphere. This view was reinforced by observing lunar eclipses, when the Earth casts a disc-shaped shadow upon the Moon, exactly the shape you would expect from a spherical object. Of equal significance was the fact that everyone could see that the Moon itself was round, suggesting that the sphere was the natural state of being, adding even more ammunition to the round Earth hypothesis. Everything began to make sense, including the writings of the Greek historian and traveller Herodotus, who told of people in the far north who slept for half the year. If the Earth was spherical, then different parts of the globe would be illuminated in different ways according to their latitude, which naturally gave rise to a polar winter and nights that lasted for six months.

But a spherical Earth raised a question that still bothers children today – what stops people in the southern hemisphere from falling off? The Greek solution to this puzzle was based on the belief that the universe had a centre and that everything was attracted to this centre. The centre of the Earth supposedly coincided with the hypothetical universal centre, so the Earth itself was static and everything on its surface was pulled towards the centre. Hence, the Greeks would be held on the ground by this force, as would everybody else on the globe, even if they lived down under.

The feat of measuring the size of the Earth was first accomplished by Eratosthenes, born in about 276 BC in Cyrene, in modern-day Libya. Even when he was a little boy it was clear that Eratosthenes had a brilliant mind, one that he could turn to any discipline, from poetry to geography. He was even nicknamed Pentathlos, meaning an athlete who participates in the five events of the pentathlon, hinting at the breadth of his talents. Eratosthenes spent many years as the chief librarian at Alexandria, arguably the most prestigious academic post in the ancient world. Cosmopolitan Alexandria had taken over from Athens as the intellectual hub of the Mediterranean, and the city's library was the most respected institution of learning in the world. Forget any notion of strait-laced librarians stamping books and whispering to each other, because this was a vibrant and exciting place, full of inspiring scholars and dazzling students.

While at the library, Eratosthenes learned of a well with remarkable properties, situated near the town of Syene in southern Egypt, near modern-day Aswan. At noon on 21 June each year, the day of the summer solstice, the Sun shone directly into the well and illuminated it all the way to the bottom. Eratosthenes realised that on that particular day the Sun must be directly overhead, something that never happened in Alexandria, which was several hundred kilometres north of Syene. Today we know that Syene lies close to the Tropic of Cancer, the most northerly latitude from which the Sun can appear overhead.

Aware that the Earth's curvature was the reason why the Sun could not be overhead at both Syene and Alexandria simultaneously, Eratosthenes wondered if he could exploit this to measure the circumference of the Earth. He would not necessarily have thought about the problem in the same way we would, as his interpretation

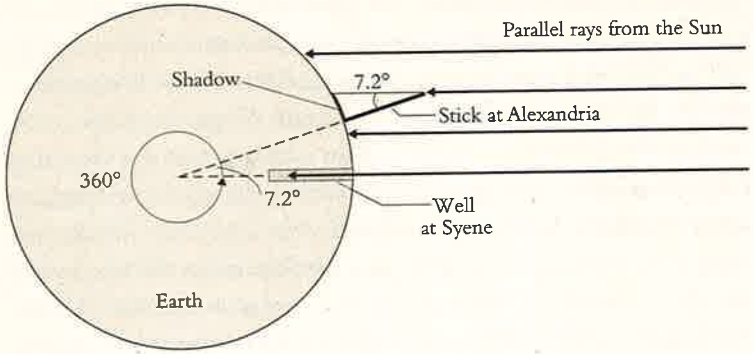

Figure 1 Eratosthenes used the shadow cast by a stick at Alexandria to calculate the circumference of the Earth. He conducted the experiment at the summer solstice, when the Earth was at its maximum tilt and when towns lying along the Tropic of Cancer were closest to the Sun. This meant that the Sun was directly overhead at noon at those towns. For reasons of clarity, the distances in this and other diagrams are not drawn to scale. Similarly, angles may be exaggerated.

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of geometry and his notation would have been different, but here is a modern explanation of his approach. Figure 1 shows how parallel rays of light from the Sun hit the Earth at noon on 21 June. At exactly the same moment that sunlight was plunging straight down the well at Syene, Eratosthenes stuck a stick vertically in the ground at Alexandria and measured the angle between the Sun's rays and the stick. Crucially, this angle is equivalent to the angle between two radial lines drawn from Alexandria and Syene to the centre of the Earth. He measured the angle to be 7.2°.

Next, imagine somebody at Syene who decides to walk in a straight line towards Alexandria, and who carries on walking until they circumnavigate the globe and return to Syene. This person would go right round the Earth, traversing a complete circle and covering 360°. So, if the angle between Syene and Alexandria is only 7.2°, then the distance between Syene and Alexandria represents

${}^{7.2}/_{360}$, or ${}^{1}/_{50}$ of the Earth's circumference. The rest of the calculation is straightforward. Eratosthenes measured the distance between the two towns, which turned out to be 5,000 stades. If this represents ${}^{1}/_{50}$ of the total circumference of the Earth, then the total circumference must be 250,000 stades.

But you might well be wondering, how far is 250,000 stades? One stade was a standard distance over which races were held. The Olympic stade was 185 metres, so the estimate for the circumference of the Earth would be 46,250 km, which is only 15% bigger than the actual value of 40,100 km. In fact, Eratosthenes may have been even more accurate. The Egyptian stade differed from the Olympic stade and was equal to just 157 metres, which gives a circumference of 39,250 km, accurate to 2%.

Whether he was accurate to 2% or 15% is irrelevant. The important point is that Eratosthenes had worked out how to reckon the size of the Earth scientifically. Any inaccuracy was merely the result of poor angular measurement, an error in the Syene–Alexandria distance, the timing of noon on the solstice, and the fact that Alexandria was not quite due north of Syene. Before Eratosthenes, nobody knew if the circumference was 4,000 km or 4,000,000,000 km, so nailing it down to roughly 40,000 km was a huge achievement. It proved that all that was required to measure the planet was a man with a stick and a brain. In other words, couple an intellect with some experimental apparatus and almost anything seems achievable.

It was now possible for Eratosthenes to deduce the size of the Moon and the Sun, and their distances from the Earth. Much of the groundwork had already been laid by earlier natural philosophers, but their calculations were incomplete until the size of the Earth had been established, and now Eratosthenes had the missing value. For example, by comparing the size of the Earth's shadow cast upon the Moon during a lunar eclipse, as shown in Figure 2, it was possible to deduce that the Moon's diameter was about one-quarter

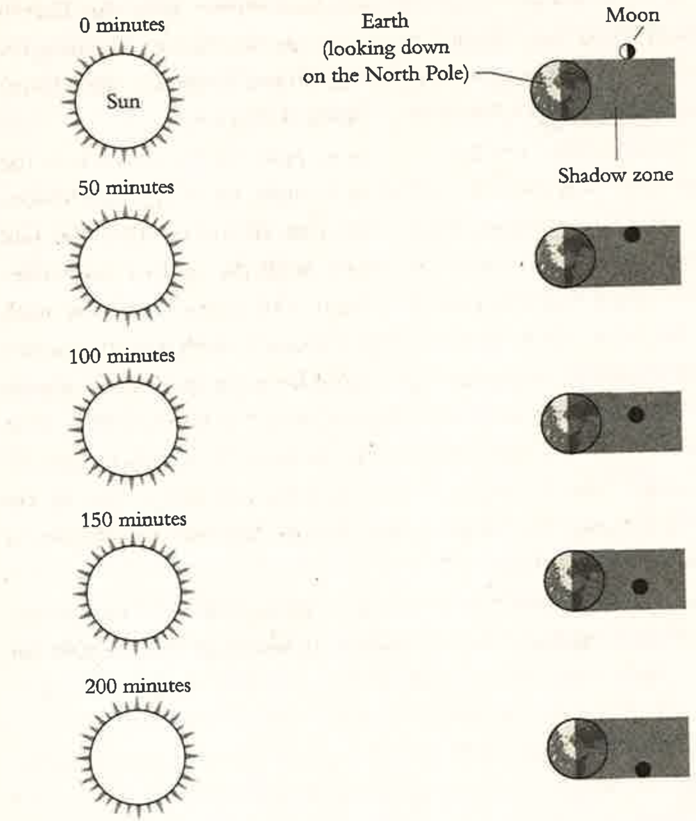

Figure 2 The relative sizes of the Earth and the Moon can be estimated by observing the Moon's passage through the Earth's shadow during a lunar eclipse. The Earth and Moon are very far from the Sun compared with the distance from the Earth to the Moon, so the size of the Earth's shadow is much the same as the size of the Earth itself.

The diagram shows the Moon passing through the Earth's shadow. In this particular eclipse – when the Moon passes roughly through the centre of the Earth's shadow – it takes 50 minutes for the Moon to go from touching the shadow to being fully covered, so 50 minutes is an indication of the Moon's own diameter. The time required for the front of the Moon to cross the entire Earth's shadow is 200 minutes, which is an indication of the Earth's diameter. The Earth's diameter is therefore roughly four times the Moon's diameter.

of the Earth's. Once Eratosthenes had shown that the Earth's circumference was 40,000 km, then its diameter was roughly (40,000 ÷ π) km, which is roughly 12,700 km. Therefore the Moon's diameter was (¼ × 12,700) km, or nearly 3,200 km.

It was then easy for Eratosthenes to estimate the distance to the Moon. One way would have been to stare up at the full Moon, close one eye and stretch out your arm. If you try this you will notice that you can cover the Moon with the end of your forefinger. Figure 3 shows that your fingernail forms a triangle with your eye. The Moon forms a similar triangle, with a vastly greater size but identical proportions. The ratio between the length of your arm and the height of your fingernail, which is about 100:1, must be the same as the ratio between the distance to the Moon and the Moon's own diameter. This means that the distance to the Moon must be roughly 100 times greater than its diameter, which gives a distance of 320,000 km.

Next, thanks to a hypothesis by Anaxagoras of Clazomenae and a clever argument by Aristarchus of Samos, it was possible for

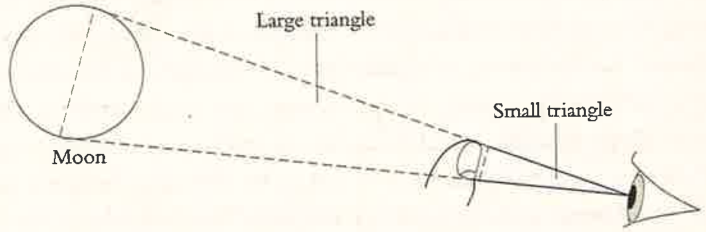

Figure 3 Having estimated the size of the Moon, it is relatively easy to work out the distance to the Moon. First, you will notice that you can just block out the Moon with a fingertip at arm's length. Therefore, it becomes clear that the ratio of a fingernail's height to an arm's length is roughly the same as the ratio of the Moon's diameter to its distance from the Earth. An arm's length is roughly a hundred times longer than a fingernail, so the distance to the Moon is roughly a hundred times its diameter.

Eratosthenes to calculate the size of the Sun and how far away it was. Anaxagoras was a radical thinker in the fifth century BC who deemed the purpose of life to be 'the investigation of the Sun, the Moon and the heavens'. He believed that the Sun was a white-hot stone and not a divinity, and similarly he believed that the stars were also hot stones, but too far away to warm the Earth. In contrast, the Moon was supposed to be a cold stone that did not emit light, and Anaxagoras argued that moonshine was nothing more than reflected sunlight. Despite the increasingly tolerant intellectual climate in Athens, where Anaxagoras lived, it was still controversial to claim that the Sun and Moon were rocks and not gods, so much so that jealous rivals accused Anaxagoras of heresy and organised a campaign that resulted in his exile to Lampsacus, in Asia Minor. The Athenians had a penchant for adorning their city with idols, which is why in 1638 Bishop John Wilkins pointed out the irony of a man who turned gods into stones being persecuted by people who turned stones into gods.

In the third century BC, Aristarchus built on Anaxagoras' idea. If moonshine was reflected sunshine, he argued, then the half Moon must occur when the Sun, Moon and Earth formed a right-angled triangle, as shown in Figure 4. Aristarchus measured the angle between the lines connecting the Earth to the Sun and Moon, and then used trigonometry to work out the ratio between the Earth–Moon and Earth–Sun distances. He measured the angle to be 87°, which meant that the Sun was roughly 20 times farther away than the Moon, and our previous calculation has already given us the distance to the Moon. In fact, the correct angle is 89.85°, and the Sun is 400 times further away than the Moon, so Aristarchus had clearly struggled to measure this angle accurately. Once again, accuracy is not the point: the Greeks had come up with a valid method, which was the key breakthrough, and better measuring tools would take future scientists closer to the true answer.

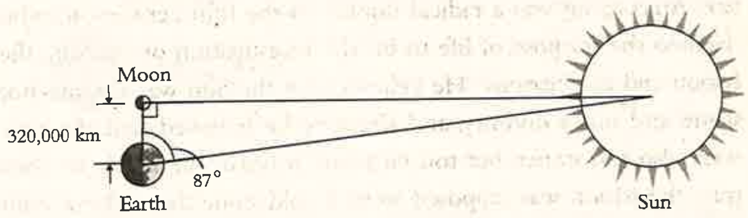

Figure 4 Aristarchus argued that it was possible to estimate the distance to the Sun using the fact that the Earth, Moon and Sun form a right-angled triangle when the Moon is at its half phase. At half Moon he measured the angle shown in the diagram. Simple trigonometry and the known Earth–Moon distance can then be used to determine the Earth–Sun distance.

Finally, deducing the size of the Sun is obvious, because it is a well-established fact that the Moon fits almost perfectly over the Sun during a solar eclipse. Therefore, the ratio of the Sun's diameter to the Sun's distance from the Earth must be the same as the ratio of the Moon's diameter to the Moon's distance from the Earth, as shown in Figure 5. We already know the Moon's diameter and its distance from the Earth, and we also know the Sun's distance from the Earth, so the Sun's diameter is easy to calculate. This method is identical to the one illustrated in Figure 3, whereby the distance to and height of our fingernail was used to measure the distance to the Moon, except that now the Moon has taken the place of our fingernail as an object of known size and distance.

The amazing achievements of Eratosthenes, Aristarchus and Anaxagoras illustrate the advances in scientific thinking that were taking place in ancient Greece, because their measurements of the universe relied on logic, mathematics, observation and measurement. But do the Greeks really deserve all the credit for laying the foundations of science? After all, what about the Babylonians, who were great practical astronomers, making thousands of detailed

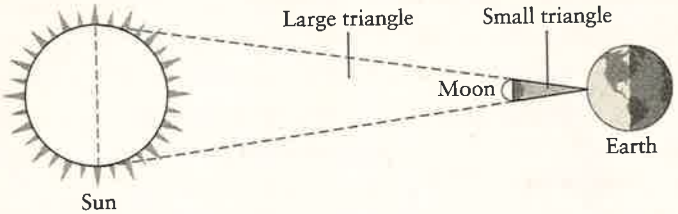

Figure 5 It is possible to estimate the size of the Sun, once we know its distance. One approach is to use a total solar eclipse and our knowledge of the Moon's distance and diameter. A total solar eclipse is visible only from a small patch on the Earth's surface at any given time, because the Sun and the Moon appear almost the same size when viewed from the Earth. This diagram (not to scale) shows how an eclipse observer on the Earth is at the apex of two similar triangles. The first triangle stretches to the Moon, and the second triangle to the Sun. Knowing the distances to the Moon and to the Sun and knowing the diameter of the Moon is enough to deduce the diameter of the Sun.

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observations? It is generally agreed by philosophers and historians of science that the Babylonians were not true scientists, because they were still content with a universe guided by gods and explained with myths. In any case, collecting hundreds of measurements and listing endless stellar and planetary positions was trivial compared with genuine science, which has the glorious ambition of trying to explain such observations by understanding the underlying nature of the universe. As the French mathematician and philosopher of science Henri Poincaré rightly declared: 'Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.'

If the Babylonians were not the first proto-scientists, then what about the Egyptians? The Great Pyramid of Cheops predates the Parthenon by two thousand years, and the Egyptians were certainly far in advance of the Greeks in terms of their development of weighing scales, cosmetics, inks, wooden locks, candles and many other inventions. These, however, are examples of technology, not science.

Technology is a practical activity, as demonstrated by the Egyptian examples already given, which helped to facilitate death rituals, trading, beautification, writing, protection and illumination. In short, technology is all about making life (and death) more comfortable, while science is simply an effort to understand the world. Scientists are driven by curiosity, rather than comfort or utility.

Although scientists and technologists have very different goals, science and technology are frequently confused as being one and the same, probably because scientific discoveries often lead to technological breakthroughs. For example, scientists spent decades making discoveries about electricity, which technologists then used to invent light bulbs and many other devices. In ancient times, however, technology grew without the benefit of science, so the Egyptians could be successful technologists without having any grasp of science. When they brewed beer, they were interested in the technological methods and the results, but not why or how one material was being transformed into another. They had no inkling of the underlying chemical or biochemical mechanisms at work.

So, the Egyptians were technologists, not scientists, whereas Eratosthenes and his colleagues were scientists, not technologists. The intentions of the Greek scientists were identical to those described two thousand years later by Henri Poincaré:

> The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. If nature were not beautiful, it would not be worth knowing, and if nature were not worth knowing, life would not be worth living. Of course I do not here speak of that beauty that strikes the senses, the beauty of qualities and appearances; not that I undervalue such beauty, far from it, but it has nothing to do with science; I mean that profounder beauty which comes from the harmonious order of the parts, and which a pure intelligence can grasp.