Dividing the World

Physics is at its core a science of measurement, which requires clearly dividing the world into an observer, an observed system, and a method of interacting with the system. The ability to successfully characterize a system in this way went hand-in-hand with our understanding of the world around us. What properties can an observer exploit to reliably quantify any aspect of a system of interest? The specifics of what this entails rests on the full range of details of our physical theory of nature. From the beginning, a central system of interest of course was our fundamental platform for observation, the Earth itself. An early example is the Greek mathematician Eratosthenes' (276-195 BCE) measurement of the circumference of the Earth [304, p.

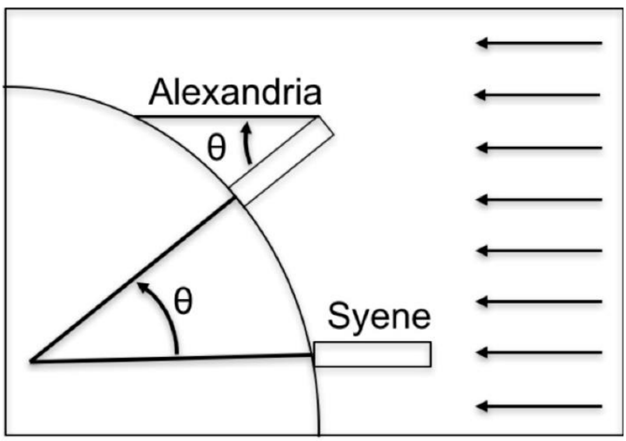

Figure 5.2: Eratosthenes' Measurement of Earth's Circumference.

75] based on his observation of the sun's angle of elevation. His physical theory consisted of the assertion that the sun's rays are parallel since the sun is located at a great distance and the knowledge that the rays fall vertically at noon on the summer solstice at Syene, a city located a known distance southeast of Alexandria, Figure 5.2. At the same date and time, Eratosthenes could observe in Alexandria that sunlight fell at an angle of approximately 1/50 of a circle (≈7.2 degrees) from the vertical, allowing him to find the Earth's circumference using straightforward geometry. This method can remarkably give results to within 1% accuracy, showing the power of even the simplest underlying theory of light-matter interaction if applied with insight and imagination to the act of measurement.

This is the key to the methodology of physics, as we understand it today: an astute combination of empirical measurement and conceptual argument is necessary to deduce the state of the world around us. As discussed in detail in Chapter 6, neither an empirical tabulation of facts nor conceptual argument alone is sufficient to carry out the deductive construction of a consistent picture of the physical universe. Both the empirical and the conceptual are necessary and how to combine and balance these human activities has been argued for centuries as the modern view of science gradually emerged. One of the earliest recorded conceptual arguments for the form of the universe was the Greek philosopher and mathematician Archytas' (428-327 BCE) thought experiment to deduce the infinity of space. Archytas argued that if he extends his staff, the end of the staff will designate a point beyond which the staff can again be extended. This process can then be repeated without limit, implying the infinity of space [305, p. 125], Figure 5.3 [306]. However, the argument was not accepted by Plato (429-347 BCE) or Aristotle (348-322 BCE). Nonetheless, Archytas' argument had great influence and was adapted by the Epicureans and the Stoics. Variations of it are found in versions by John Locke (1632-1704) and Isaac Newton (1642-1727). The application of empirical measurement to this fundamental question would have to wait until the 20th century when both observational methods and theory were sufficient to address cosmology. Modern physics would eventually answer that space could be finite without having an edge, as presupposed by Archytas' argument. However, this was a precedent in the role of thought experiments for the deduction of physics.

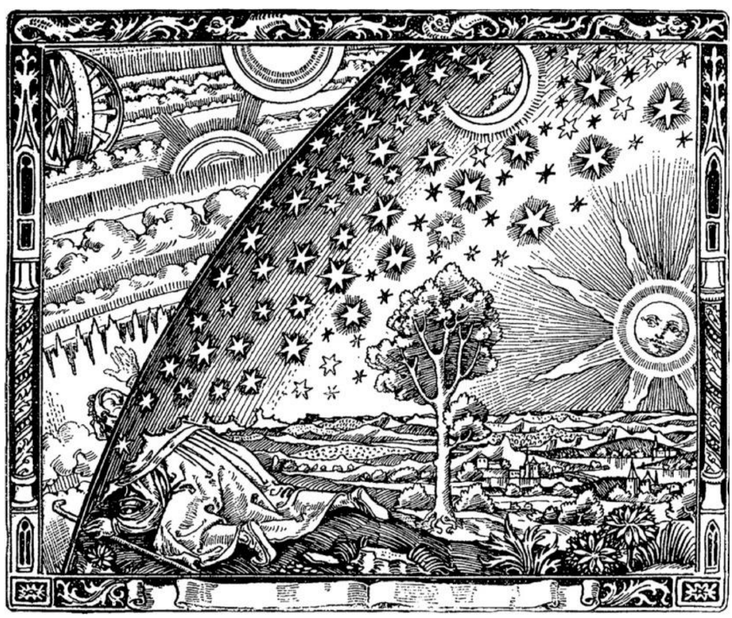

Figure 5.3: Archtyas extends his staff and peers under the edge of the firmament discovering the hidden workings of the universe and its cosmic machinery. The end of the staff will designate a point beyond which the staff can again be extended. This process can then be repeated without limit, implying the infinity of space.

Meanwhile, the development of measurement would gradually be extended to all parts of science. Measurement was of interest for both understanding our world and for the utilitarian purpose of exploiting the observed properties of the world. As civilizations have developed since antiquity, it had been essential to establish increasingly accurate and standardized weights and measures for the range of physical quantities needed for architecture, exploration, agriculture, manufacturing, commerce and other aspects of societies. The earliest attempts used arbitrary standards centered on practical measures and were not based on fundamental understanding. This gradually became more sophisticated, as requirements were more exacting and advances in the sciences led to the elements resembling modern metrology utilizing rational systems of units. It was found that the relation of measurement to the underlying physical properties of the world can be subtle and necessarily requires fundamental research in the physical sciences. The discoveries in thermodynamics, electromagnetism, atomic physics and other fundamental areas could be applied to standards of measurement. Measurement can generally be defined as the correlation of numbers with entities [307], usually in terms of ratios of quantities using standards. The result is an extraction of information or a reduction of uncertainty about a quantity using the methods of statistics and sampling. Each particular type of quantity (e.g., length, time, mass, temperature, etc.) has its associated specialized methods developed for the accurate determination of the measurement. This concept of quantity, although foreshadowed by the ancient Greeks, can be traced back to Newton who had defined in the *Principia Mathematica* [308]:

> *Quantity of matter is a measure of matter that arises from its density and bulk conjunctly.*

Quantity of matter is today referred to as mass and played a crucial role in his theory of gravity. Newton concluded in Volume 3 of the *Principia*:

> *Gravity acts on all bodies universally and is proportional to the quantity of matter in each.*

Newton estimated the constant of proportionality, called G, but more than 100 years elapsed before Henry Cavendish (1731-1810) measured it in the laboratory using his innovative method of the torsion balance, in which two small test masses are suspended from a fine wire and gently twisted [309, p. 136]. Gravity is so much weaker compared to other forces and cannot be shielded from outside gravitational influences that measurements of "Big G," as it is often called in metrology circles today, have still not improved much beyond Cavendish's result. The torsion balance was another inspired method of coupling to the world to carry out an act of measurement. Cavendish claimed he was "weighing the world" since the mass of the earth can be obtained once G is known. Attempts by our civilizations to weigh or "measure the world" in all its variety eventually extended from the deepest parts of the cosmos to the most basic constituents of matter making up our world and including that of the investigators themselves.

The observations of our universe now span some 15 billion years in time and roughly 34 orders of magnitude in size ($10^{-12} - 10^{22}$ cm). The investigations that we are privy to necessarily are those which take place from an unexceptional planet orbiting an ordinary star located at the edge of a typical galaxy. The biology of these same investigators traces back to protein molecules containing the same hydrogen produced in the embryonic processes of the universe. The terrestrial world of the investigators may be modest compared to the grand structures observed in the universe at large but it contains the one known instance of consciousness with its capacity to be self-aware: we are aware that we are measuring the world. This becomes significant when considering the peculiar problem of measuring our own thinking activity, as the division of the world into an observer and observed system can then become ambiguous. This issue of identifying where the border between the observer and the observed lies will be seen to play a key role in our story of measurement. This is especially evident in the contrast between classical and quantum physics.