COURSE GUIDEBOOK

History of Science: Antiquity to 1700

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History of Science: Antiquity to 1700, Part I
Professor Lawrence M. Principe

COURSE GUIDEBOOK

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History of Science: Antiquity to 1700

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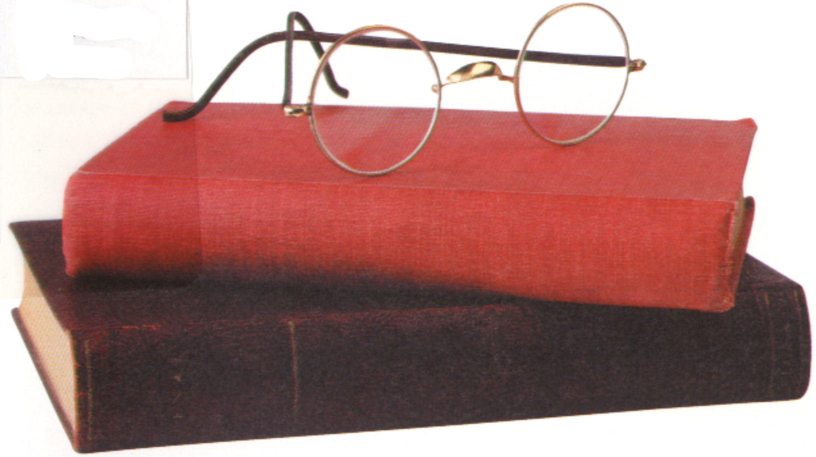
Part I



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History of Science: Antiquity to 1700
Part I

History of Science: Antiquity to 1700

Scope:

This course presents a survey of the history of science in the Western world from the second millennium B.C. to the early eighteenth century. The goal is to understand what science is; how, why, and by whom it has developed; and how our modern conception of science differs from earlier ideas.

The first twelve lectures deal with the ancient world. We begin with the observations of Babylonian astrologers and move to the varied conceptions of the natural world and methods for studying it worked out by the Greeks. Plato and Aristotle are key figures; their methods, worldviews, and challenges have influenced subsequent developments down even to our own day. We next consider the achievements of the later Hellenistic thinkers: Aristotle's successors, Ptolemy's astronomy, Archimedes' engineering and mathematics, among others. We then turn to the Roman versions of Greek learning, as well as to impressive examples of Roman technology. The collapse of the classical age and the attempts to preserve some of its legacy conclude this section.

The next twelve lectures treat the generally less-known science of the Middle Ages, from roughly 500–1400 A.D. After studying the response of the new religion of Christianity to Greek learning, we move to the rise of Islam and survey the Arabic world's embrace of Greek learning and culture and the significant contributions of the Muslim world in a range of scientific fields. Returning to the Latin West, we examine the discovery of Arabic and classical learning by European Christians and Latin developments in astronomy/astrology, physics, alchemy, the origin of the world, and many other areas. Several lectures deal with the rise and culture of cathedral schools, universities, Scholasticism, and intellectually minded religious orders. The fascinating and productive interplay of scientific and theological inquiry is key to this period.

The last twelve lectures cover the Renaissance and Scientific Revolution, from roughly 1450–1700. We begin with the novelties of the post-medieval period, which include a new interest in natural magic, a serious topic bearing some striking resemblances to modern science. Several lectures follow the construction of a new cosmology—Copernicus' heliocentrism, Tycho's observations, Kepler's laws, and Galileo's new physics. The expansion of European horizons with the discovery of the New World led to changes in natural history, as well as to the ways man viewed nature. The new views include those who envisioned a dead mechanical universe functioning like a clockwork, as well as those who saw a world infused with life and vital activity. One lecture looks at the enigmatic Isaac Newton, who created a powerful synthesis of seventeenth-century ideas, but who also spent more time pursuing alchemy, theology, and prophecy. The rise of scientific societies, the growth of technology, the development of chemistry, and calendrical reform provide further topics of study.

Several themes run through the course. Chief among these is the need to understand scientific study and discovery in historical context. Theological, philosophical, social, political, and economic factors deeply impact the development and shape of science. Of particular interest are the variety of ways in which human beings have tried over time to approach and describe the natural world, to evaluate their place in it, and to make use of it. Science is thus revealed as a dynamic, evolving entity, tightly connected to the needs and commitments of those who pursue it. The real context of even familiar scientific developments will frequently come as a surprise and can suggest alternative ways for present-day thinking and science to develop.

Lecture One

Beginning the Journey

Scope: This introductory lecture asks fundamental questions about the nature of science and its development, its importance to human civilization, and the reasons for studying its history. This lecture also introduces some themes that will recur throughout the course and provides an overview of the course in terms of the epochs and subjects to be covered.

Outline

I. The introductory lecture has three main components.

- **A.** The first part of the lecture examines why the history of science is worth studying and what science is.
- **B.** The second part looks at what the history of science contains and how it ought to be studied.
- **C.** The third part offers an outline of the content and organization of the course.

II. At present, science and technology are among the most powerful influences on human culture; therefore, understanding what science is and how it developed is crucial.

- **A.** What is science? What are its unique characteristics?
  1. While we all have some definition of science, our definitions are often based on the *current* form of science.
  2. As such, our definitions may be overly restrictive or even misleading if applied to earlier periods.
- **B.** The concepts of "science" and the "scientist" as generally understood today are modern conceptions dating from the nineteenth century.
  1. The word "science" derives from the Latin *scientia*, which simply means "knowledge." "Natural philosophy" was the usual term for the study of the natural world, which we today would generally call "science." Natural philosophy has a broader scope than modern science.
  2. Natural philosophy was done, naturally enough, by natural philosophers. The term "scientist" is a neologism, coined jocularly by William Whewell in 1834.
  3. Science as a profession—that is, as the exclusive domain of professionals who are trained and paid for this activity—is likewise largely a nineteenth-century development.

4. Consequently, we cannot understand the history of science if we take a narrow (that is, modern) view of its content, goals, and practitioners.
5. Such a narrow view is sometimes called "Whiggism" (an interest only in historical developments that lead directly to current scientific beliefs) and the implementation of modern definitions and evaluations on the past.

C. We can broadly define *science* (at least for the purposes of this course) as "the study of the natural world," while bearing in mind that that study's intentions, goals, practitioners, and methods have changed drastically over time.

III. Science is dependent on both the external reality of the natural world (the interpreted) and human culture (the interpreter). Thus, it is neither predetermined nor arbitrary.

A. Two perspectives on the history of science define the ends of the spectrum between predetermined and arbitrary development of science.

B. On the predetermined side lies "triumphalism," which views the *progress* of science as the gradual and progressive dawning of scientific truths on humanity.
1. This view has been favored by those arguing for the importance and uniqueness of science, but it tends towards arrogance and is incomplete.
2. Such a view fails to recognize the human character of scientific inquiry.

C. On the arbitrary side lies "social constructivism," which, in its strong form, sees even fundamental natural laws (such as the law of universal gravitation) as artifacts of human society. This view is favored by those arguing against the importance and uniqueness of science, but it fails to recognize the existence of a natural world independent of human perception or the real interest on the part of those who study nature in accurately describing it.

D. The reality lies in the middle, and the most interesting issues in the history of science look at the changing interactions between human beings (in their proper historical context) and the natural world.
1. The course of scientific development (and technology even more so) is responsive to the intellectual, political, economic, social, and artistic values and needs of a society and must be seen in such contexts.
2. The style and justification of scientific inquiry are also culturally based, being dependent particularly upon the philosophical and theological commitments of its practitioners.
3. Thus, it is absolutely crucial to maintain the various human contexts of scientific developments.

IV. We cannot possibly cover all the necessary material in this course; therefore, certain criteria of selection have been implemented.

A. The course will focus on natural philosophy ("science") and, to a lesser extent, technology in the Western world (defined as the immediate heirs of Greek thought, that is, Europe and the Middle East).

B. The history of mathematics and the history of medicine will be included only to the extent that they have an impact on the study of the natural world.

C. The history of education will be important at several points.

V. The course is divided into three sections on roughly chronological grounds.

A. The first section deals with the ancient world, from the ancient cultures of the Babylonians and Egyptians to the fall of the Western Roman Empire, roughly 2000 B.C. to 500 A.D.
1. Ancient philosophy—the ways of conceptualizing the natural world and man's place in it—is the crucial context for the development of the study of nature.
2. Engagement with the ancient sources described here forms the basis for the natural philosophy and technology throughout most of the subsequent two sections.
3. The intellectual foundations of modern science lie ultimately in classical Greek thought.

B. The second section deals with the medieval period (roughly 500 to 1400/1450 A.D.), both in the Christian and the Islamic worlds.
1. The interactions of the two great monotheistic religions with both the classical tradition and the natural world and with each other is central to this time period.
2. The relationship between science and religion is complex. The notion that there is an inherent "conflict" between science and religion is, however, a politically motivated construction of the nineteenth century. The following lectures should serve to efface that misconception.

C. The third section deals with the Renaissance and the "Scientific Revolution," roughly 1450 to 1700/1750.
1. The "Scientific Revolution" is a concept enunciated by twentieth-century historians of science. It holds that the modern scientific worldview was largely formed in the period between the publication of Copernicus' heliocentric theory (1543) and the death of Isaac Newton (1727).
2. In this section, we will examine the development of new worldviews (and the "dismissal" of Aristotle) and how they responded not only to new observations of the world, but also to new needs and aspirations of early modern society.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, chapter 1, pp. 1-13.

Supplementary Reading:

Sydney Ross, "Scientist: The Story of a Word," in *Nineteenth-Century Attitudes: Men of Science*.

Questions to Consider:

1. Think about how the practice of science resembles the practice of history. What are the similarities and differences? Are there intellectual methods distinctive to research in one or the other?
2. Consider your own thoughts about the relationship between science and religion. What are the bases of your thoughts on the issue? Where did you acquire these thoughts?

Lecture Two

Babylonians, Egyptians, and Greeks

Scope: This lecture explores the origins of man's study of the natural world. The Babylonians, with their complex mathematics and astronomical observation, and the Egyptians are considered first. We then proceed to the earliest Greek thinkers and consider their first "scientific" theories about the natural world and how these were distinct from earlier ways of envisioning and conceptualizing the world.

Outline

I. Where and when do we begin the study of the history of science?
   - A. Most historians of Western science begin with ancient Egypt and ancient Mesopotamia.
   - B. The ancient Egyptian and Mesopotamian cultures exerted influence on the ancient Greeks, who in turn laid the foundations for Western thought and the history of science.
   - C. Both cultures were literate and left historical records.

II. The Mesopotamian civilizations, in particular the Babylonian, developed and flourished in the first and second millennia B.C., largely in the area that is now Iraq. For historians of science, this culture's most noteworthy achievements were in mathematics and astronomy.
   - A. Our knowledge of Babylonian mathematics and astronomy results from that culture's almost obsessive record-keeping and the durable material, clay, on which they "wrote."
   - B. Babylonian mathematical notation was complex. It used both aggregation and place-notation and was both decimal and sexagesimal.
     1. Numerals 1–59 were written by *aggregation*, like the later Roman numerals.
     2. Starting with 60, the Babylonians used *place-notation*, as we do today. But while our system is based on powers of 10 (decimal), theirs was based on powers of 60 (sexagesimal).
     3. Place-notation was useful for expressing large numbers and fractions, which is difficult or impossible in aggregation.
     4. Babylonian mathematical texts also used "word problems" where unknown quantities need to be calculated from known data.
     5. The Babylonians may have chosen a base of 60 because its many factors make division easy and, possibly, because fractions and multiples of 60 occur in calendrical phenomena.
     6. The Babylonian sexagesimal system was used for astronomy for centuries and is still preserved today in angle measurements, for

example, 60 seconds in a minute, 60 minutes in a degree, and so on.

C. Babylonian astronomy compiled extensive records of heavenly bodies and their motions.
   1. Observations of the moon were especially critical because of their lunar-based calendar; solar observations were required for the regular adjustment of the lunar calendar to the solar year.
   2. By 600 B.C. and probably earlier, the Babylonians had compiled complex tables that allowed the prediction of celestial events, such as lunar phases and solar and lunar eclipses.
   3. Significantly, these predictive tables were compiled seemingly without any physical model of the universe to explain them.
   4. Observations were made by priests, and the needs they served were practical: maintenance of the calendar and astrological predictions of auspicious and inauspicious times.

III. The Egyptians created a flourishing civilization centered on the Lower Nile. Their mathematics and astronomy, however, were not as developed as the Babylonians.

A. Egyptian mathematics used an aggregation notation that was decimal.

B. Temples were oriented on certain terrestrial or celestial axes, which required observational skills and record-keeping over time.

C. Few mathematical texts survive, and those that do are quite rudimentary compared with Babylonian examples.

D. Egyptian astronomy produced a solar calendar of 360 days, with 12 months of 30 days each. The remaining 5 days were festival days and remained uncounted.

E. Egyptian metalworking, glassmaking, and other "chemical" manufacture developed to a high degree but as a craft tradition without apparent speculative or theoretical elements.

F. Although Egyptian civilization was marked by long-term stability (in general) and impressive feats of engineering and organization, study of the natural world was actually quite limited and closely tied to practical applications.

IV. The earliest Greek thinker (we know of) who inquired into the workings of the natural world is Thales (fl. 600–580 B.C.), a native of Miletus, a Greek colony on the coast of Asia Minor (currently Turkey).

A. No original writings by Thales survive, but four of his ideas have been transmitted to posterity by Aristotle.

B. One of Thales' key claims was that "everything is made of water."
   1. Aristotle claimed that Thales chose water because water is key to life and growth. On the other hand, it might also have been on account of the various forms water can take (ice, liquid, and

vapor). Moreover, Egyptian and Babylonian creation myths often begin with water.
   2. The signal importance of Thales' statement is that it is the first known attempt to identify a single material substratum out of which everything is made. (What is the world made of?) This project is ongoing today, albeit in modified form, in nuclear physics.
   3. A further importance is that Thales' statement marks a key distinction between the underlying, unseen reality of things and their external appearance. This distinction would prove key to Greek natural philosophy and is crucial to modern science.

C. Thales' fame in antiquity was based partly on his prediction of a solar eclipse that occurred in 585 B.C. during a battle between the Medes and the Lydians. To accomplish this, he probably used Babylonian tables, but he could not have actually predicted the exact day or place where the eclipse would be seen.

D. Other remarkable feats were attributed to Thales, and he developed a reputation in antiquity of mythic proportions. Some features of this character are still found today in popular contemporary conceptions and anecdotes about scientists and, whether or not they are true, in Thales' case, they tell us something about Greek culture and the place of the natural philosopher.

E. Although it is clear that Thales learned from earlier Babylonian and Egyptian works (some accounts say that Thales traveled to Babylon), he (and his Greek culture) are distinct from them in significant ways.
   1. Thales was an individual with distinctive ideas; these specific ideas were followed or opposed by subsequent thinkers.
   2. We know Thales by name, but we have no similar names to attach to Egyptian and Babylonian ideas.
   3. Thales' work was not exclusively practical; his thought dealt also with theoretical notions without practical application.
   4. Thales stands at the beginning of a tradition in Greek thought that involved the systematization and explication of observations and the search for causes and principles in nature. These are hallmarks of Western scientific and philosophical traditions of which we (at present) find little evidence in Egypt and Babylonia.

F. Much of the Greek legacy depends on a simple belief which remains at the core of modern scientific inquiry: The world is a regular place. It is not incomprehensible; it is intelligible.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, chapter 1.

G. E. R. Lloyd, *Early Greek Science: Thales to Aristotle*, chapter 1.

Supplementary Reading:

John North, *The History of Astronomy and Cosmology*, chapter 1, "Ancient Egypt" and chapter 2, "The Babylonians."

Otto Neugebauer, *The Exact Sciences in Antiquity*, chapters 2–5.

Philip Wheelwright, *The Presocratics*, chapter 2, "Thales."

G. S. Kirk, J. E. Raven, and M. Schofield, *The Presocratic Philosophers*, chapter 2.

Questions to Consider:

1. The Babylonians' apparent lack of interest in knowing *how* the universe worked—in spite of their ability to make use of observed astronomical cycles for prediction—can strike us as odd. Can you think of examples from modern culture where people make use of things regularly yet do not inquire about why they work? What are the conditions for such a situation? What are the results?
2. Some scholars suggest that Thales' (or more broadly, the ancient Greeks') initiation of scientific study of nature resulted, at least in part, from the nature of the Greek colonies. They point to the unstable, uncertain nature of these fledgling colonies and their contact (through trade) with various outside cultures and people and contrast this situation with the stable, uniform, established, and introspective societies of Babylonia and Egypt. What do you think of this theory? How might these Greek conditions favor the initiation of scientific inquiry?

Lecture Three

The Presocratics

Scope: Several Greek philosophers before the time of Socrates (d. 399 B.C.) grappled with an array of significant issues that laid the foundations of Western natural philosophical thought and method: What is the world made of? How do things change? Where did things come from? Do our senses show us reality? In this lecture, we study their varied explanations for the physical changes around us, their ideas on the origin (and end) of the world, and the new concept of atoms. We will also consider how the influence of Presocratic ideas has resounded in Western thought ever since.

Outline

I. Thales of Miletus (fl. 585 B.C.) was the first of a series of Greek thinkers who dealt, in part, with natural philosophical issues. They are grouped under the title of "Presocratics," that is, those living before Socrates (d. 399 B.C.).

   A. Although much of their work can be characterized as "philosophy," many of their questions and activities relate directly to natural philosophy. Several were involved in practical "scientific" affairs.

   B. Several Presocratic questions and formulations are fundamental to the Western scientific tradition.

      1. What is the world made of?
      2. How is the universe constructed? (Cosmology)
      3. Where did the world come from? (Cosmogony)
      4. How do changes in the world occur?
      5. How do we gain true knowledge of the natural world? Is the world orderly and knowable? Are the senses accurate guides? (Epistemology)

   C. No original texts survive from any Presocratic philosopher; we have only fragments transmitted by other ancient authors.

II. The "Milesian school"—Thales and his followers—is the earliest group of Presocratics.

   A. Anaximander (fl. 570 B.C.) was an associate of Thales and a few years younger than he.

      1. Anaximander is reputed to have introduced the *gnōmōn* to the Greeks. The *gnōmōn* was a stick placed in the ground, perfectly perpendicular, and used to measure the angle of the sun or moon above the horizon as well as for surveying and time reckoning.

2. Anaximander gave a physical and mathematical description of the earth and the universe and attempted to provide physical causes for astronomical phenomena.

B. A still younger colleague, Anaximenes (fl. 550 B.C.), chose air as the basis of all things. Condensation and rarefaction of air gave rise to different substances.

III. Two other Presocratics, Heraclitus of Ephesus (fl. 500 B.C.) and Parmenides of Elea (fl. 475 B.C.), gave largely opposing views of change in the physical world and the value of sense perception for studying it.

A. Central to Heraclitus' thought is the idea that "everything flows," that is, everything is changing constantly; you cannot step into the same river twice.

1. Fire is central to Heraclitus; it is the source and end of everything and emblematic of constant change.

2. Beneath the constant change, however, is a unity ("all things are one") found in the *logos*—the reason, principle, or proportion of things.

B. Heraclitus also valued the senses for giving knowledge of the natural world, but the senses must be rightly interpreted.

C. Parmenides of Elea in southern Italy (fl. 450 B.C.) dismissed change as mere illusion; nothing changes. This means that sense perception, as used in the observations central to most ideas of natural philosophy, is useless and vain.

1. Parmenides divided everything into two categories: that which is and that which is not.

2. He was looking for a constant principle in the world, just like his predecessors.

3. Parmenides' willingness to give up the testimony of the senses—his skepticism about sense perception—turns out to be important to much of modern science. For example, the senses do not indicate the speedy motion of the earth or the preponderance of void (indicated by atomic theory) in seemingly solid objects.

IV. All the foregoing Presocratics can be grouped as *monists*; that is, they held that although physical substances seem to be diverse, they actually all originate from a single source. An opposing school of *pluralists* held that there is more than original substance.

A. Empedocles of Agrigentum in Sicily (fl. 450 B.C.) is credited with the notion of the four elements—fire, air, earth, and water—which he considered as the "four roots" of things.

1. Empedocles also commented on the origin and ultimate destruction of the world and attributed this (and all intermediate changes) to opposing principles he called Love and Strife.

2. Empedocles is, in a sense, a compromise between Heraclitean change and Parmenidean constancy. But Empedocles also asserts the value of the senses, contrary to Parmenides.

3. Some Christians (much later) found Empedocles to be compelling. His portrait is painted in the frame surrounding Signorelli's fresco depicting the end of the world in the cathedral at Orvieto.

B. Empedocles cited the importance of randomness in the formation of the world, but Anaxagoras (c. 500 B.C.–c. 425 B.C.) denied this notion. For him, the world comes about by the action of *nous*, or mind.

V. The union of all these foregoing ideas appeared in the notion of atomism, promoted by Leucippus (fl. 430 B.C.) and Democritus of Abdera (fl. 420 B.C.).

A. Atoms are envisioned as indivisible (lit. "uncuttable") particles dispersed through void space.

B. Things are created and destroyed by the coming together and moving apart of atoms, but the atoms themselves are eternal. (Thus, both Heraclitean change and Parmenidean non-change are preserved.)

C. Atomism, though "familiar" to modern science, had little popularity and influence for several reasons.

1. It was rejected forcibly by Aristotle for logical and operational reasons.

2. The moral and expressly atheistic context of atomism, especially as it was developed later by Epicurus (b. 341 B.C.), made atomism distasteful to many in subsequent centuries, particularly to Christians.

3. Democritean and Epicurean atomism were, however, revived about 2,000 years later, in the seventeenth century.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, chapter 2, pp. 31-35.

G. E. R. Lloyd, *Early Greek Science: Thales to Aristotle*, chapters 2 and 4.

Supplementary Reading:

Philip Wheelwright, *The Presocratics*, chapters 2–6.

G. S. Kirk, J. E. Raven, and M. Schofield, *The Presocratic Philosophers*, chapters 3, 4, 6, 8, 9, 10, and 15.

Questions to Consider:

1. Think about the characteristic questions of the Presocratics noted in this lecture (see above, section I.B). What is the current scientific thinking on these issues? How many of these questions have been answered

conclusively? How many are no longer of interest to modern scientists (and why not)?

2. How much do you trust your senses in regard to providing true information about the world around you? How much do modern scientists (compare various fields) trust their senses? How can you verify the senses? How would you function differently in the world if you were to deny the senses to the degree that Parmenides did?

Lecture Four

Plato and the Pythagoreans

Scope: Plato, a student of the executed Athenian philosopher Socrates (d. 399 B.C.), has proven to be one of the most influential thinkers in history. This lecture recounts Plato's response to both the Presocratics and his contemporaries. Key to understanding Plato and his scientific impact is his view of reality and how this affects the value he places on observation (sense perception), the nature of true knowledge about the world, and how that knowledge is to be acquired. The influence of the secretive Pythagoreans is important both directly on Plato and through him, to the relationship between mathematics and the study of the natural world.

Outline

I. Plato, a follower of the executed Socrates (d. 399 B.C.), has had enormous impact on both philosophy and natural philosophy. He also marks a movement of intellectual activities from the more outlying Greek colonies to Athens.

- **A.** Plato's works, written in dialogue format, touch on many issues, including politics, ethics, and the living of a good life.
- **B.** His writings had significant impact on the history of science, owing in particular to:
  1. His theory of being (ontology).
  2. His theory of knowledge (epistemology).
  3. His emphasis on a mathematical basis for nature.
  4. The natural philosophy in his dialogue *Timaeus*.

II. The theory of Forms provides the basis of Plato's epistemology, ontology, and his impact on the history of science.

- **A.** According to Plato, the Forms are the eternal, unchanging exemplars of things. Objects in the world of sense are mere approximations of the Forms.
  1. There is, therefore, an ontological hierarchy in the world. At the lowest level are our imaginings of specific things, then the specific things themselves, then mathematical abstractions of things, then finally the Forms, of which the inferior versions are imperfect manifestations.
  2. This view is summed up in Plato's Parable of the Cave (*Republic*, Book VII), which claims that men who experience the world by sense alone are like prisoners in a cave who see only the flickering shadows of things upon the cave wall and believe that that is "all there is."

B. The Forms come with epistemological consequences, as well as ontological ones.
   1. True knowledge is knowledge of the Forms.
   2. We escape the delusion of sense perception (the cave) through the exercise of reason.
   3. Unlike Parmenides, Plato did not dismiss sense perception as mere illusion. Observation is a wholesome activity—when enlightened by reason—and is the starting point to regain knowledge of the Forms.

C. In terms of the history of science, Plato's insistence on the ontological and epistemological superiority of Forms urges the Platonist to move from particular observable objects to universals, that is, to frame universalized conceptions from individual objects. This is, in effect, a hallmark of "scientific" inquiry—the discovery of regularities and generalized principles from a collection of individual objects or observations.

III. The mathematical content (and other aspects) of parts of Plato's work derives from his association with Pythagoreans.

A. The school was founded by Pythagoras (b. c. 580 B.C.), but it is difficult to separate fact from fiction in regard to Pythagoras' life and teachings.
   1. Pythagoras, a contemporary of the Milesian school, was born in Samos.
   2. He supposedly traveled in Egypt, where he learned astronomy and mathematics.
   3. Pythagoras fled from the tyrant Polycrates to found a school in the Greek colony of Kroton in Sicily.

B. The Pythagorean school was based on communal living, rituals, and secrecy.

C. Pythagoras is famous today for "his" theorem about right triangles, but this must be placed in the proper context of the goals of his school.
   1. The Pythagoreans' great secret was that of incommensurables, that is, irrational numbers.
   2. The Pythagoreans were impressed by the existence of mathematical ratios in music and developed the notion of the "music of the spheres."
   3. The emphasis on mathematics arose from the Pythagorean notion that the world *was* number—the principles of mathematics are the principles of nature.

D. The Pythagorean school was primarily religious—a way of life, not some mathematical "think-tank."
   1. Among their beliefs, the Pythagoreans maintained the immortality of the soul and its transmigration and showed an interest in number mysticism.

   2. Their prime objective was to discover and to live the "good life"—namely, one in harmony with the cosmos—which would bring advancement to the soul.
   3. Mathematics was, thus, key to understanding harmony in the cosmos, in life, and in music.

E. The point for the history of science is nonetheless substantial—to what extent is the natural world expressible in mathematical terms?
   1. In physics today, actions, such as free-fall motion, are expressed in mathematical formulae, and mathematical manipulations allow for prediction of natural events.
   2. The revival of Pythagorean ideas and ideals in the sixteenth century was one of the factors leading to the increasing mathematization of the world, a key factor in the development of modern scientific views.

IV. Plato was deeply impressed by the Pythagoreans, possibly partly owing to the communal society they had created.

A. Platonic dialogues show numerous resonances with Pythagorean ideas—immortality of the soul, reincarnation, an interest in mathematics and harmony.

B. The resonances with Pythagoreanism and their natural philosophical consequences, as well as the theory of Forms, become clear in Plato's *Timaeus*, his most influential work in terms of the history of science.

Essential Reading:

Plato, *Republic*, Book VII.

David C. Lindberg, *The Beginnings of Western Science*, pp. 35–45.

G. E. R. Lloyd, *Early Greek Science: Thales to Aristotle*, chapters 3 and 6.

Supplementary Reading:

Philip Wheelwright, *The Presocratics*, chapter 7.

G. S. Kirk, J. E. Raven, and M. Schofield, *The Presocratic Philosophers*, chapters 7 and 11.

Questions to Consider:

1. Plato and the Pythagoreans were convinced of a close link between mathematics and the natural world. Does mathematics really provide a good description of the world? Is it equally useful in all branches of modern science? Why or why not?
2. Assuming the validity of Plato's doctrine of Forms, do you think everything (every individual object? every species of object?) in the natural world would have to be based on a Form? If so, what would be the consequences?

Lecture Five

Plato's Cosmos

Scope: This lecture begins with a study of Plato's *Timaeus*, in which the Athenian philosopher describes the cosmos and its creation, its fundamental building blocks, human anatomy, and other scientific topics. Plato's interests are not only natural philosophical but also ethical and social. Partly on account of the *Timaeus*, the pagan Plato found great acceptance subsequently among Christians, Muslims, and Jews and was, thus, enormously influential in a wide range of areas.

Outline

I. The *Timaeus* is important because it proved to be one of the most influential of Plato's dialogues, even if, nowadays, it would rarely be listed among the most important save by historians of science.

- **A.** It was the only work of Plato known to the Latin Middle Ages.
- **B.** It contains the majority of Plato's explicitly natural philosophical statements.
- **C.** It contains the story of Atlantis, which has fired the imagination for centuries.

II. The main discourse of the *Timaeus* provides a "likely account" of the origin and structure of the world and its contents.

- **A.** The world is created by the demiurge, a craftsman god. Unlike the Christian creator, the demiurge is neither omnipotent nor the only eternal being—the Forms and matter are coeval with him—nor is he a personal god.
  1. The demiurge creates the world from the existent unformed matter and uses the Forms as patterns, the way a builder uses a blueprint.
  2. But matter is inherently incapable of taking the Forms fully; it thwarts the best efforts of the demiurge. Thus, although the demiurge makes the best possible physical world, it remains imperfect relative to the eternal Forms.
- **B.** The universe is spherical; it rotates and is "alive."
  1. The universe is put together full of harmonies and mathematical intervals; the debt to Pythagoreanism is clear.
  2. Heavenly spheres guide the motions of the sun, moon, planets, and stars. Their motions are regular, mathematically harmonious, and kept within proper bounds.
- **C.** The *Timaeus* presents a matter theory based on a "geometrical atomism."
  1. The demiurge first fashions matter into regular triangles and combines these into the five regular polyhedra—tetrahedron, cube, octahedron, dodecahedron, and icosahedron—now known as the "Platonic solids."
  2. These polyhedra give rise to the four Empedoclean elements; the cube is earth; the tetrahedron, fire; the octahedron, air; and the icosahedron, water. These elements then go to form more complex mixed bodies.
  3. The elements can interconvert by falling apart into the original triangles, which then recombine into different polyhedra. (This interconversion is in contrast to Empedocles.)
  4. This theory, like much of the *Timaeus*, deals with human anatomy and physiology.
  5. Plato then deploys this theory to explain the natures of a wide variety of substances.
- **D.** A substantial portion of the *Timaeus* deals with human anatomy and physiology.
  1. The human body is prepared by lower deities created by the demiurge, but the human soul is created by the demiurge himself.
  2. The parts of the human body are designed to fit their functions.

III. Plato's *Timaeus* must be contextualized; Plato's interest here in cosmological, biological, and other natural philosophical topics needs to be explained.

- **A.** The *Timaeus* is linked with the *Republic*; the opening discourse refers to the topics of the *Republic* and summarizes the characteristics of the perfect state.
- **B.** The cosmology and other natural philosophical claims made in the *Timaeus* can thus be seen as part of Plato's notions regarding the proper ordering of the individual and of society.
  1. The repeated message of the *Timaeus* is that the world is created and governed by mind (*psychē*) not by chance or mere "nature" (*physis*).
  2. One implication is that if the world itself is intelligently ordered, the individual ought to be as well, and so too, the political state (rather than being left to chance).
  3. As each part of the human body is designed to fulfill a specific function, so too, each member of society should be designed to fulfill a specific function.
- **C.** The story of Atlantis fits into this scheme. The ancient Athenians were powerful enough to defeat the great power of Atlantis because they were orderly; that is, their society was like that of Plato's *Republic*.
- **D.** Natural philosophy plays an important role in learning to live rightly as an individual.

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1. Knowledge transforms the knower. A person's choice of objects of contemplation transforms his soul into their likeness. Contemplation of the cosmic harmonies and perfection makes our souls harmonious and perfect.
2. At the end of the dialogue, Plato makes (possibly tongue-in-cheek) remarks about the origin of animals from unfit (that is, unphilosophical) humans. Their unfitness comes from the neglect or improper use of their minds.

E. Even if the *Timaeus* is not primarily a natural philosophical work, its ideas were very influential. This happens frequently in the history of science—"scientific" ideas often develop and receive influence from sources well removed from what we would today rigidly define as "scientific."

IV. The *Timaeus* found welcome readers among Christians (and Muslims) because of resonances with revealed theology.

A. The world is created, not eternal.

B. The world is created by a single god, not a pantheon; that god is good, eternal, and pleased with his creation.

C. The world is created by intelligent design, not by chance.

D. The study of nature shows its design, teaches about the creator, and directs the wise man toward right living.

V. Several conclusions should be drawn about Plato's impact on scientific thought.

A. Plato's comments on the value of observation are mixed.
1. Observation of natural objects focuses (by necessity) on imperfect physical objects—dim reflections of the eternal Forms, knowledge of which constitutes *real* knowledge.
2. The fate of men turned into birds exemplifies the need for the natural philosopher to do more than simply observe nature; he must seek out both *causes* and *meanings* by the use of reason. These goals prove crucial in the history of science.
3. But observation of the world is a starting point for the rational ascent to the perfect, eternal Forms. *Timaeus* considers vision to be man's greatest physical ability.
4. Observation of the natural world, and the discovery of abstract laws governing it, reveals evidence of order and design in the world. The study of nature, thus, has a morally (or religiously) didactic purpose.

B. The existence of perfect Forms, inaccessible to our direct observation, implies that the key truths are *separate* from material objects, which feeds into the notion that principles must be abstracted from sense data.

This is widely perceived in the modern world as a key scientific principle.

C. The theory of Forms and a belief in the inherently mathematical nature of the world provide a background to new conceptualizations and formulations of nature, that is, ones in which the underlying truths of nature can be idealized in theoretical mathematical "laws." This is clear in the challenge reportedly given by Plato to astronomers.

Essential Reading:

Plato, *Timaeus*.

Supplementary Reading:

Plato, *Critias*.
R.M. Hare, *Plato*.

Questions to Consider:

1. How would a greater appreciation and acceptance of Plato's view of how knowledge transforms the knower change the practice and goals of modern science? How would it change your daily life?
2. How can we determine whether the world is a result of (Empedoclean) randomness or (Platonic) design?

Lecture Six

Aristotle's View of the Natural World

Scope: Like his teacher Plato, Aristotle had tremendous impact on the development of natural philosophy, its methodology, and its aims. This lecture introduces Aristotle, his writings, and his ideas as a response to his predecessors, the Presocratics and Plato. We focus here on Aristotle's views on the value of observation, the nature of change, the composition of matter, and what constitutes real knowledge of a thing. The characterization of Aristotle as first and foremost a "biologist" helps to make better sense of his worldview, and this is contrasted with the modern worldview based instead on physics.

Outline

I. Aristotle (384–322 B.C.), a student of Plato, produced a comprehensive corpus that includes the most expressly natural philosophical ("scientific") works seen hitherto. Aristotle's thought had major influence for 2,000 years, and many of his formulations continue to form the bases of our own thought.

- **A.** Aristotle's works include the study of ethics, politics, logic, and metaphysics, but those of special importance to the history of science deal with (in modern terms) physics, matter theory, cosmology, and biology.
    - **1.** Aristotle wrote more than 150 books, but only about 30 now survive, which still amounts to a substantial corpus.
    - **2.** Aristotle's writings as we have them are terse and are probably lecture notes rather than polished treatises.
- **B.** Aristotle's system was particularly attractive for many generations because it was seen as a comprehensive world-system that subsequent natural philosophers could work with.
- **C.** Aristotle says that the Presocratics studied nature but without a good method; Socrates and Plato had a good method but neglected the study of nature.

II. Aristotle makes frequent reference to Plato and the Presocratics and responds to them.

- **A.** Aristotle often disagreed with his teacher Plato on fundamental issues.
    - **1.** Aristotle rejected the Forms and Plato's ontology.
    - **2.** Aristotle was far more interested in the material world—the study of nature—than was Plato.
- **B.** Aristotle provides his own solutions to two chief questions of the Presocratics: "What are things made of?" and "What is the nature of change?"

    - **1.** Aristotle takes a monist position—the material substratum of everything is the same stuff.
    - **2.** This stuff is not a known substance (such as Thales' water) but a universal quality-less matter (*hylē*) sometimes called "prime matter."
    - **3.** Individual objects arise when matter is "imprinted" with a form (*morphē*). The form is the sum total of its qualities.
    - **4.** Matter takes the form the way a lump of wax takes the impression of a seal.
    - **5.** Matter and form never exist independently of each other.
    - **6.** Aristotle's matter and form theory is known as *hylomorphism.*
- **C.** Change is the replacement of one form by another; the prime matter remains unchanged. By preserving both constancy and change, Aristotle effects a "compromise" between Heraclitus and Parmenides.
    - **1.** Aristotle's world is more like Heraclitus' than Parmenides'. For Aristotle, the world is *dynamic.* "The only thing constant is change."
    - **2.** Change occurs along a continuum between pairs of contrary qualities.
    - **3.** The primary qualities are the pairs hot-cold and wet-dry. Prime matter plus a pair of these primary qualities gives the Empedoclean four elements.
    - **4.** Change always involves a movement from potentiality to actuality.
    - **5.** One thing cannot be turned into just any other thing, only into those things that it already is in potential. Grass can become milk in a cow's stomach, but a rock cannot.

III. True knowledge (*epistēmē*) is "causal knowledge," knowledge of *why* a thing is as it is. This is distinct from artifice (*technē*), which is knowledge of *how to do* something.

- **A.** There are four "causes" of things: the efficient (what makes it), the formal (what its form is), the material (what it is made of), and the final (what its reason for being is).
- **B.** The causes provide an exhaustive list of how an object relates to other objects; the causes situate an object in context, in correspondence with other objects.
- **C.** The final cause is the most difficult for moderns to accept, but it is the key to Aristotle's natural philosophy.
    - **1.** It preserves (and develops) the purposefulness of Plato's system and embodies Aristotle's view of "nature."
    - **2.** "Whatever Nature makes, she makes to serve some purpose."
- **D.** A fundamental divide separates natural and artificial things.

1. Natural things have an "internal principle of motion (or change)" that propels them toward their final causes. An acorn becomes an oak tree because, as we still say, that is "in its nature."
2. In some cases, external circumstances prevent a natural object from reaching its natural end. Art (*technē*) can sometimes help complete this end.
3. Artificial things lack the internal principle of change. Motion or change comes to them only from outside agents. Unlike an acorn, a planted bed rots, but *as wood* not *as bed*. Artificial things do not move toward their final ends without guidance from an external agent.
4. A division between artificial and natural objects persists today in popular imagination.

E. Final causes (teleology) are formally rejected by modern science, because they do not fit into modern worldviews that see a world without purpose or direction.

1. But final causes do seem to persist in the sciences, particularly in popularizations and in biology.
2. This last is a clue to understanding Aristotle rightly, because his worldview is best seen as stemming from his extensive experience in biology.

IV. Seeing Aristotle first and foremost as a biologist may help us better understand his thoughts and the reasons behind them.

A. Aristotle spent many years doing dissections and describing animals and plants; this was probably his main activity during his non-Athens years of 347–335 B.C.

1. He was a keen observer.
2. Even though he sometimes recorded mere hearsay, he also recorded several things that were not widely believed until nineteenth-century and twentieth-century biology showed them to be true.

B. For Aristotle, living things show the working of the natural world better than non-living.

1. Causation and directed purposefulness are clear in nutrition, growth, and anatomy. Purpose is very clear in dissections, of which Aristotle performed many, even though that book is lost.
2. The centrality of biological studies to Aristotle's thought helps make sense of the importance he accords to the final cause.
3. Aristotle's system stands in contrast to modern worldviews that base themselves on the behavior of non-living matter and forces (physics). For Aristotle, life helped explain the non-living world; for moderns, life has to be explained in terms of non-life.
4. Moderns have made a conscious choice to posit non-life physics as fundamental. This is not a self-evident choice. Aristotle made a different choice.
5. Armed with this realization, Aristotle's dynamics and cosmology will now make more sense.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, chapter 3.

Supplementary Reading:

Jonathan Barnes, *Aristotle: A Very Short Introduction.*

G. E. R. Lloyd, *Early Greek Science: Thales to Aristotle*, chapter 8.

Questions to Consider:

1. Aristotle clearly values *epistēmē* much more highly than *technē*. What are the relative values modern science (and culture) places on *technē* and *epistēmē*? How does this change the goals and practice of science?
2. Why does modern science consider physics-based viewpoints fundamental? Might the current biological revolution (re)assert the primacy of biological worldviews? Can we conceive of a biologically based physics?

Lecture Seven

Aristotelian Cosmology and Physics

Scope: Much of Aristotle's subsequent impact was on the basis of his cosmology, physics, and dynamics. This lecture looks at Aristotle's activity in these areas, bearing in mind his key interest in biology as a means of explaining his intentions. We first explore the structure of Aristotle's cosmos, then show how this relates to his physics of motion. We will conclude by demonstrating the utility of Aristotle's system by using it to explain everyday observations.

Outline

I. Aristotle's cosmology, dynamics, and physics all cohere and are best understood together and with reference to his biological preoccupations.

II. Aristotle took much of his cosmic order from contemporaneous astronomy. The earth is at the center, immobile (as common sense affirms); the celestial bodies move around it.

- **A.** The celestial bodies are carried by the motions of specific spheres arranged concentrically about the earth.
  1. The lowest sphere is that of the moon.
  2. The highest sphere is that of the fixed stars.
- **B.** Aristotle devised a complicated system with more than fifty spheres to account for all the motions of the sun, moon, and planets.

III. Aristotle's universe is divided into two distinct realms with distinctly different physics. The dividing line is the sphere of the moon.

- **A.** Below the sphere of the moon (the sublunary realm) is the realm of change.
  1. Here, things are composed of the four elements; things come to be and pass away.
  2. The four elements have "natural places." Earth, being heavy, has its natural place at the center of the universe; fire, being light, has its natural place just below the sphere of the moon.
  3. The elements have "natural motions" toward those natural places. They naturally move toward them in straight lines; thus, a stone, when dropped, moves toward the center of the earth by virtue of its nature. Similarly, the flame of a candle points upward.
  4. Given this notion, the earth must obviously be spherical (as the Greeks already knew) so that its surface is everywhere equidistant from the center. Moreover, earth's shadow cast on the moon during eclipses shows its shape.

- **B.** Above the sphere of the moon (the superlunary world), there is no change.
  1. Here, things are composed of a "fifth element" (quintessence, or *aether*); nothing comes to be or passes away. This is clear from Babylonian and Egyptian records, which never recorded any change in the celestial bodies or their movements.
  2. While the four elements have natural rectilinear motion toward their natural places, the fifth element has natural circular motion; hence, the heavens never "run down."

IV. Aristotle's dynamics flow from this cosmology, and his notions of motion are connected to biological exemplars.

- **A.** Aristotle has a broader definition of motion than we do. He posits three kinds: local motion (change of place, our idea of motion), motion of quality (change of form), and motion of quantity (change of magnitude). For example, an apple maturing from red to green is a natural motion of quality.
  1. This seems strange to us because our (physics-based) science is predominantly quantitative. Aristotle's (biologically-based) natural philosophy is primarily qualitative.
  2. This, again, is a *choice* of how to base a scientific world-system; neither is self-evident or right-wrong.
- **B.** Motions are of two kinds: "natural" (according to nature) and "violent" (contrary to nature).
- **C.** Natural local motion (a falling rock) is about finding a natural place by the influence of the "internal principle of motion or change."
  1. The mover is internal to the naturally moving object. It actualizes the potential; it moves the object toward the final cause of its motion, that is, being in its natural place.
  2. The growth of an acorn into a tree is, thus, analogous to the falling of a heavy body.
  3. The falling object does not stop until it either reaches its end (natural place) or is stopped (artificially) by the interference of an external agent.
- **D.** Violent motion (a rock thrown upward) is artificial and opposes natural motion.
  1. The mover is external to the artificially moving object (compare artificial objects, which have no internal principle of motion/change).
  2. Because the object moves contrary to nature, the violent (or artificial) motion soon perishes, the natural motion takes over, and the rock falls to earth (its natural place).
  3. But the rock keeps rising even after it leaves the hand (external agent) pushing it. Thus, there must be another external motive

agent; Aristotle postulates (not too successfully) that the motion is given by the medium through which it is moving.

V. The best way of really understanding Aristotle is to spend time thinking like an Aristotelian: identifying the four causes of specific objects, explaining observations in accord with Aristotelian views. When this is done, Aristotle's incredible utility for studying and explaining the world becomes clear, and his longevity as an authority is made easier to understand.

Essential Reading:

Aristotle, *Parts of Animals*, Book I, chapters i and v; Book II, chapter i.

Aristotle, *Physics*, Book II, chapters i-iii, viii-ix.

Supplementary Reading:

Terence Irwin and Gail Fine, *Aristotle: Selections*.

Questions to Consider:

1. For the next couple of days, choose various objects that you see and try to identify their four causes. Does the identification of the Aristotelian causes give you further insight into the objects and their places in the natural (or artificial) order of things?
2. Aristotle's world is suffused with the idea of "nature" as an explanatory principle. Think about the word "nature." What are the different meanings we assign to it? How do we continue to use "nature" as an explanatory principle? Reflect on the utility of this usage in both science and daily life.

Lecture Eight

Aristotle's Legacy and Hellenistic Natural Philosophy

Scope: Like Plato, Aristotle founded a school (the Lyceum) in Athens that perpetuated his work and ideas. This lecture also surveys the wider world of Hellenistic science that developed in the expanded Greek world created by Aristotle's student Alexander the Great. Special emphasis is paid to Alexandria, with its great Library and the Museum, and to the work and legends of Archimedes.

Outline

I. In 335 B.C., Aristotle returned to Athens after a twelve-year absence and founded a school called the Lyceum, similar to Plato's Academy. The Lyceum carried on some of Aristotle's natural philosophical projects.

A. Aristotle's immediate successor was Theophrastus (b. c. 371 B.C.); he headed the Lyceum from 322 to 286 B.C.

1. Theophrastus wrote authoritative texts on plants and minerals.
2. He disagreed with Aristotle on several issues, including the elemental status of fire and the universality of final causes.
3. He bought land and buildings for the Lyceum that ensured its stability and continuance.

B. The third leader of the Lyceum (286–268 B.C.) was Strato of Lampsacus.

1. None of Strato's works survives, but he was called "the physicist" in regard to his primary interest in natural philosophy, and he disagreed with Aristotle on many issues.
2. Strato conducted experiments to demonstrate his ideas.
3. He argued that falling bodies accelerate and used a stream of falling water and the dropping of weights into soft earth to show this.
4. He argued for the existence of the vacuum (contrary to Aristotle), using the compression and dilation of air as proof; he may well have been an atomist.

C. It is significant that the two immediate successors to Aristotle freely disagreed with him. This freedom to criticize is crucial to the development of Greek thought (and Western thought in general).

D. The Lyceum continued to function for more than two and a half centuries, until it closed around the middle of the first century B.C.

II. Around the time of Aristotle's death, the Greek world changed drastically. His one-time student Alexander the Great (356–323 B.C.) created a vast empire, initiating the Hellenistic age.

   A. The Hellenistic period is sometimes seen as a period of "decline" for Greek natural philosophy, but this is a matter of perspective.

   B. Hellenistic natural philosophers were busy elaborating and following out the programs initiated by Plato, Aristotle, Pythagoras, and others.

III. The city of Alexandria in Egypt, founded by Alexander in 332 B.C., became a major center of Hellenistic thought and culture.

   A. The Library and Museum of Alexandria (founded c. 300 B.C.) were chief centers of scholarship and were supported by (sporadic) royal and other patronage.

   B. Many scholars worked in Alexandria throughout (and after) the Hellenistic period.

      1. Euclid, known for his axiomatic and deductive system of geometry, was connected with the city in the third century B.C.

      2. Eratosthenes of Cyrene (c. 276–195 B.C.) was head of the Library. Among his accomplishments was an experiment to measure the size of the earth.

IV. Elsewhere in the Hellenistic world, further developments occurred in several areas of natural philosophy.

   A. In astronomy, Hipparchus (second century B.C.) compiled an extensive star catalogue, measured the distance of the moon from earth, and determined the length of the lunar cycle to within one second of the currently accepted value.

   B. Archimedes (c. 287–212 B.C.) studied in Alexandria but lived most of his life in his native Syracuse and produced advanced works on mathematics and mechanics.

      1. Archimedes' work shows a further step in the mathematization of natural phenomena.

      2. Tales of Archimedes' cleverness reached heroic proportions in antiquity, particularly in regard to his technological "wonders."

      3. One of these was a spherical contrivance that represented the motions of the sun, moon, and planets. It was seen and described by the Roman orator Cicero.

      4. Archimedes is most famous for the principle named after him ("Eureka!") and for supposedly setting the besieging Roman fleet on fire with mirrors.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, chapter 4.

Supplementary Reading:

G. E. R. Lloyd, *Early Greek Science: Thales to Aristotle*, chapter 9, and *Greek Science after Aristotle*, chapters 1–3.

Questions to Consider:

1. This lecture introduced the important idea of centers for learning—Aristotle's Lyceum and the Library and Museum of Alexandria. Why are such centers or institutions important? How do they benefit scholarly or scientific work? What is the nature and role of such institutions today?

2. The historical Archimedes (like many classical figures) is surrounded by myths. Myths may not be literally true, but they do tell us some important things, for example, about the myth-makers. What do the Archimedean myths say about Hellenistic and Roman expectations of natural philosophers and technologists?

Lecture Nine

Greek Astronomy from Eudoxus to Ptolemy

Scope: This lecture examines the development of systems of astronomy from Eudoxus and other followers of Plato to the one proposed by Claudius Ptolemy in Alexandria during the second century A.D. We examine how and why these systems were devised and how they were used. The differences in goals and claims between classical and modern astronomy are highlighted.

Outline

I. Observational astronomy was practiced by the Babylonians, Egyptians, and other ancient peoples, but without (as far as we know) an explanatory framework (physical astronomy). The thrust of Greek astronomy was to explain observations.

- **A.** The Presocratics gave physical descriptions of the universe, but despite some important conceptual steps, these descriptions were quite rudimentary and not well correlated with observations.
- **B.** In a crucial development, Plato is supposed to have challenged his students to devise a system for explaining the apparently irregular motions of the planets using a combination of uniform circular motions.

II. Observed celestial motions are quite complex; there are three distinct motions to be explained.

- **A.** The diurnal motion: Each day, the celestial bodies rise and set once, moving across the sky from east to west.
- **B.** The annual motion: Constellations visible in the summer are not seen in the winter. This is because each night, a given star rises slightly earlier than the night before. Thus, the stars, besides their diurnal motion, seem to revolve around the earth from east to west once in a year.
- **C.** The proper motion of the planets: The seven planets (the moon, Mercury, Venus, the sun, Mars, Jupiter, and Saturn) have their own motions of three kinds.
  1. Planetary proper motion is restricted to the zodiac, and the planets appear to move, at a variable speed, from west to east from night to night (that is, rising later each day) against the backdrop of fixed stars.
  2. With the exception of the sun and the moon, the planets occasionally stop (a station), move backward through the zodiac (retrogradation), stop again, then resume their usual motion.

  3. The planets—especially the moon—move in a wavy path, oscillating slightly north and south within the band of the zodiac during their east-west motions.

III. Plato's challenge was first taken up by his student Eudoxus of Cnidus (fl. 375 B.C.).

- **A.** Eudoxus' works are themselves lost, but they are transmitted to us by Aristotle, who adopted Eudoxus' general ideas.
- **B.** Eudoxus' universe is composed of 27 nested concentric spheres rotating at various, but uniform, speeds, with axes inclined to one another.
  1. The earth is immobile at the center.
  2. The highest sphere carries the fixed stars daily from east to west.
  3. The sun and moon are moved by a combination of the motions of three connected spheres; the highest rotates east to west and contributes the diurnal motion, the next rotates west to east and contributes the proper motion through the zodiac, and the lowest contributes the north-south motions in the zodiac. The *sum* of these three motions approximates the apparent motions of the planets.
  4. The other planets are moved by four spheres; the lower two account for retrograde and the slight north-south motions. Again, the *cumulative sum* of these *four motions* approximates the apparent motions of the planets.
- **C.** Eudoxus had success in expressing the complex observed motion as a sum of uniform circular motions, but his system failed to account for two well-known observations: The planets change in brightness (implying that their distances change), and the seasons are of different lengths (meaning that the sun's velocity was not constant).
- **D.** Subsequent natural philosophers, particularly Callippus of Cyzicus (fl. 330 B.C.) and Aristotle (both also Academy students), altered Eudoxus' system by adding further spheres.
  1. Aristotle was concerned about the communication of motion from one set of spheres to the next.
  2. He added numerous spheres to counteract this motion.
- **E.** Eudoxus' achievement was in attempting to "save the phenomena" by reducing apparent complex and irregular motions to a combination of underlying mathematical simplicity and regularity, a goal in harmony with Platonic commitments to an orderly world designed on mathematical principles.

IV. Two major innovations were suggested by other Greeks, although these were not widely accepted.

- **A.** Heraclides of Pontus (another student of Plato's Academy) suggested replacing the diurnal motion of the heavens with the diurnal rotation of the earth on its axis.

B. Aristarchus of Samos (third century B.C.) hypothesized a heliocentric system, in which the annual motion of the heavens was replaced by the annual motion of the earth around the central sun.

C. Both of these systems were in conflict with prevailing physics and common sense, and there was no evidence in their favor.

V. The culmination of Greek astronomy comes finally with Claudius Ptolemy (second century A.D.). Ptolemy's system formed the basis of astronomical thought and calculation for the next 1,500 years.

A. Ptolemy used the notions of the epicycle and eccentric to create a system different from the Eudoxian concentric spheres model.

1. Both innovations are probably the work of the mathematician Apollonius of Perga (fl. 220–190 B.C.) and were developed further by Hipparchus of Samos.
2. An eccentric is a planetary orbit whose center does not coincide with the center of the earth.
3. An epicycle is a "secondary orbit" on which the planets move, which is centered on a primary orbit (the deferent) around the earth.

B. The combination of epicycles and eccentrics explains all the observed phenomena: variable speed, retrograde motion, changes in planetary brightness (distance), and the inequality of the seasons.

C. The result was a system that was both explanatory and predictive.

VI. The reasons behind Greek astronomical speculation were diverse.

A. For Plato and his followers, physical astronomy was part of their program of revealing the design inherent in the universe and its mathematical basis.

B. For Aristotle, physical astronomy was part of his comprehensive system and interleaved with his physics.

C. For many Greeks, Ptolemy in particular, physical astronomy gave a better ability to calculate past and future celestial positions, necessary for astrology. Ancient astrology was a serious matter involving complex calculations.

VII. The level to which the physical models of the Greeks were taken to be "true descriptions" of the cosmos rather than models designed to "save the phenomena" probably varied among various theorists, but the question itself marks an essential difference between pre-modern and modern astronomy.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, chapter 5.

Supplementary Reading:

G. E. R. Lloyd, *Greek Science after Aristotle*, chapters 5 and 8.

John North, *The History of Astronomy and Cosmology*, chapter 4, "The Greek and Roman World."

Questions to Consider:

1. The Platonic interest in simple circular motions is based in part on Greek ideas of the harmonious and the aesthetic. Can you think of notions or guiding principles in modern science that are based on aesthetics?
2. Astrological prognostications have been made since the time of the Babylonians. What is the allure and promise of astrology that explains its longevity?

Lecture Ten

The Roman Contributions

Scope: The Romans produced a staggering civilization that was very different from that of the Greeks. In this lecture, we explore the differences between them in terms of scientific work. Specifically, the Romans' most notable achievements lay in technological advancements rather than the more speculative sciences of the Greek world. Here, we will explore not only the intellectual status of technology, but also how the pursuit of science responds to the needs and temper of a society, rather than developing according to some simple notion of "progress." We will examine several case studies of Roman engineering and technology.

Outline

I. The Romans, who had conquered most of the Greek world by the end of the first century B.C., showed little interest in the topics that Greek natural philosophers had pursued.

A. Science does not develop "automatically"; it is shaped in many ways by the prevailing culture.

1. The Romans' practically minded culture gravitated toward practical applications (technology), rather than speculative natural philosophy (science).
2. We have to disengage interest in scientific topics from other measures of a society's "success."

B. Technology is far more evident in Roman culture than original natural philosophy is.

II. The status of technology has long been problematic.

A. The practicality of "applied science" argues for its importance but also mediates against its study.

1. The deployment of scientific principles for practical affairs runs counter to much of both Platonic and Aristotelian ideals; *technē* is lower than *epistēmē*.
2. Some of this bifurcated evaluation of technology developed in the ancient world remains strong today.

B. Technology in the ancient world had two major aspects: the production of things useful to human life and of "wonders." This is similar to its position in the modern world.

1. In the Hellenistic world, Hero of Alexandria's works are filled with automata and "miraculous" devices, using air pressure or falling weights as driving forces.

2. Some topics that we would consider technological were primarily craft-knowledge in antiquity. They were practiced by workers guided solely by experience, with little or no theoretical content.
3. Knowledge of historical technology often comes more from artifacts than from texts.

III. The Roman Empire saw larger cities, required a high degree of administration, and undertook massive building programs. The success of these developments often depended on skillful technology.

A. One example is the Roman desire to provide an abundant supply of fresh, clean water to the cities.

1. Using tunnels, sluices, and aqueducts, Roman engineers were able to supply abundant water to cities across the empire.
2. The water line supplying the city of Nemausus (modern Nîmes) runs for 35 miles; about 20 miles runs underground (3 miles through solid rock) and about 4 miles, on elevated aqueducts (including the 1,100-foot-long, 180-feet-high Pont du Gard).
3. In cities, lead plumbing brought water directly into the houses of the rich.
4. The city of Rome used about 150 to 200 million gallons of water a day.

B. Roman city dwellings often developed new technology (such as central heating), but the attempt to build higher and higher buildings challenged the limits of the available materials.

1. One particular Roman invention in this regard was concrete.
2. The advance of technology is often checked by the physical limits of available materials.

C. The expanse of the Roman Empire—in which trade, communication, and the movement of the military were vital—required an extensive network of paved roads. By the third century A.D., there were over 4,000 miles of Roman roads.

D. The Romans also developed technologies of mass production, for example, in the manufacture of glass and other household items.

E. Curiously, comparatively little interest was shown in labor-saving devices or power sources; this is probably a result of the great abundance of slaves (as war booty).

Essential Reading:

Frances and Joseph Gies, *Cathedral, Forge, and Waterwheel*, chapter 2.

Supplementary Reading:

J. G. Landels, *Engineering in the Ancient World*, chapters 2 and 9.

G. E. R. Lloyd, *Greek Science after Aristotle*, chapter 7.

Questions to Consider:

1. Roman science and technology were quite different than their Greek counterparts, owing, in part, to the differences between Roman and Greek culture. How do the priorities set by our own culture mold and direct our science and technology? Think of examples of how our modern society's values would lead us to attribute little value to ideas and pursuits prized by the Greeks (and vice versa).
2. Does the modern scene for science and technology more resemble that of Greece or Rome? How and why?

Lecture Eleven

Roman Versions of Greek Science and Education

Scope: A more formalized system of education was one development of the Roman world, and the school system set up by the empire set the standards for the next 1,500 years. A related development was the "popularization" of Greek science for Roman readers, such as Lucretius' verse recapitulation of Epicurean atomism, *On the Nature of Things*. The initiation of the "encyclopedia" tradition is also part of the Roman contribution, such as Pliny the Elder's massive *Natural History*.

Outline

I. An example of a Roman contribution to the history of science is the Julian calendar—necessary for civil, religious, and financial purposes and used throughout Europe for nearly 1,600 years.

A. The development of this calendar again showcases the Roman interest in practical applications of natural knowledge.

B. The calendar was commissioned by Julius Caesar in the middle of the first century B.C., and the task of devising it was given to Sosigenes the Alexandrian.

1. Sosigenes began with the Egyptian 12-month solar calendar.
2. He determined the length of the solar year as 365.25 days and, thus, suggested a four-year cycle: three years of 365 days, followed by a fourth with an extra day in February.
3. To implement the Julian calendar, the immense error of the earlier Roman calendar of 10 months with uncounted winter days had to be corrected; the year (we call) 44 B.C., then, had to be 445 days long to bring the vernal equinox back to 25 March.
4. The regulation of the new calendar was the duty of Roman priests; indeed, time-keeping and calendrical maintenance was generally the province of priests—in Babylon, Egypt, Rome, and later in Latin Europe.
5. Sosigenes' year was eleven minutes too long, which meant that, over time, errors accumulated. The Julian calendar was corrected and reformed to its present state (the Gregorian calendar) by Pope Gregory XIII in the sixteenth century.

II. Although the Romans did not produce notable developments of Greek natural philosophy, they did produce popularized versions of it for Roman readers.

A. The Roman leisured classes had an interest in Greek learning and culture; this fashionability expanded the audience for Greek natural philosophy, but this audience operated at a rather low level.

1. As Horace wrote (*Epistles* II, I:156) "*Graecia capta ferum victorem capit et artis intulit agresti Latio*"—"Captive Greece captured the rude victor and introduced the arts to rustic Latium."
2. The Roman baths were an important locus for reading and learning.

B. Lucretius' *De rerum natura* (*On the Nature of Things*) was a popularization in verse of Epicurean atomism and philosophy.

C. While Eudoxus, Hipparchus, and others were generally little known in Rome, the *Phaenomena*, a work in verse by the Greek popularizer Aratus de Soli (third century B.C.), was the most popular work on astronomy and weather prognostication among the Romans, being generally read in Latin translations.

D. A comparable example from outside of natural philosophy would be Vergil's *Georgics*, and popular verse work on agriculture and country life.

III. The popularizing trend also produced a new genre of writing, the encyclopedia.

A. Encyclopedic works were intended to give an overview of the state of knowledge in a field and were well adapted to amateur readers.

B. For the history of science, the most important such work is the *Historia naturalis* (*Natural History*) by Pliny the Elder.

1. Pliny (23–79 A.D.) was an upper-class Roman official with an interest in natural philosophy and history. Of his eight known works, only the *Historia naturalis* survives. Pliny was killed in the eruption of Vesuvius that buried Pompeii on 24 August 79.
2. The *Historia naturalis* was completed in 77 A.D., is composed of thirty-seven books, and deals with astronomy, geography, zoology, botany, medicine, mineralogy, and various technical subjects in a plain and often entertaining style.
3. Pliny's text includes borrowings from acknowledged sources (Aristotle, Theophrastus, Eudoxus, and others), many of which are now lost in the original, as well as hearsay, folklore, and his own observations.
4. Pliny often moralizes while recounting natural philosophical information.
5. The *Historia naturalis* became a major source of natural knowledge throughout the Middle Ages.

IV. At the time of the Roman Empire, many Greek schools were available, as were Greek tutors, but the Romans developed a new kind of schooling with a "standardized" curriculum.

A. Such schools were frequented predominantly by the children of the urban middle class.

B. The basis of the Roman was borrowed, again, from late Hellenistic educational systems. Educated Romans, from the first century B.C., were expected to be bilingual.

C. The seven liberal arts—topics suitable for Roman aristocrats—were at the core of this curriculum.

1. Verbal arts—rhetoric, grammar, and dialectic—constituted the first course of study, later called the *trivium*.
2. Mathematical arts (as defined by Pythagoras)—arithmetic, geometry, astronomy, and music—constituted the second, later called the *quadrivium*.

D. The real innovation of the Romans came in the form of "professional" schools—first law, then in the fourth century, medicine.

E. The late imperial Roman educational system formed a major basis for schools for the next 1,000 years, and some traces of the Roman organization of education survive today.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, pp. 133–149.

Supplementary Reading:

William Stahl, *Roman Science*.

Questions to Consider:

1. What does the desire for popularized versions of Greek science among the Romans say about their society? Can your answer also explain the relative lack of interest among the Romans for the more technical aspects of Hellenistic natural philosophy?
2. What sorts of studies common in modern education are missing from the trivium and quadrivium? Can you identify how the emphases were different in classical education versus the more modern?

Lecture Twelve

The End of the Classical World

Scope: After a long period of decline, the city of Rome fell to barbarians in 476 A.D. This lecture visits that time and immediately thereafter to see what of classical scientific and philosophical thought was saved from the wreck of classical civilization—how, why, and by whom. The rise of Christianity is key here, and this lecture also deals with why the Middle Ages inherited only what it did from the classical world. This topic brings up a consideration of the cultural factors on which the continuance of science and technology depends.

Outline

I. The decline of the Roman Empire disconnected the Latin West from Greek natural philosophy—that is, from the established sources and centers of scholarship.

A. From the second to the fifth centuries A.D., the knowledge of Greek language and culture dwindled in Roman lands.

1. Native Latin culture itself developed and displaced the older borrowed Greek culture. The aristocracy changed as well, and the taste and fashionability for Greek learning waned.
2. The division of the empire into Eastern and Western halves further separated the West from the remains of Hellenistic culture.
3. Combined with the lack of Roman interest in theoretical and advanced natural philosophy, the loss of the knowledge of Greek meant that only the popularized Latin versions of Greek natural philosophy survived the fall of the empire in Western Europe.
4. The consequence was that the Latin Middle Ages received very little intellectual inheritance from the Romans.

B. Boethius (c. 480–524) is considered the last bilingual philosopher of the empire.

1. He translated some of Aristotle's logical works and other Greek texts into Latin (thus preserving them for the Middle Ages).
2. He showed little interest in specifically natural philosophical issues.

C. Disintegration of administrative and organizational systems and disruptions due to increased barbarian incursions undercut the maintenance of Roman technology.

1. An illustrative example is the inability of Constantine's engineers (fourth century) to redredge the silted Roman harbor at Ostia, even though this had been done during the early empire. As a result, the city of Rome itself was left without an adequate port.

2. Similarly, aqueducts and other sanitary waterways fell into disrepair, and their original purpose was eventually forgotten (they tended to be used merely as bridges in the Middle Ages).
3. The construction of large stone buildings could rarely be accomplished by the sixth century. Knowledge of glassmaking and other material techniques (often originally for the luxury trade) disappeared.

II. Even in the Eastern (Greek) half of the Roman Empire, the ancient schools and institutions that had been host to natural philosophy dwindled away or were closed.

III. The rise of Christianity introduced major new ways of thinking to the empire, including new values and requirements. The relationship between young Christianity and the pagan world in which it developed is complex (and will be treated by itself in Lecture Thirteen).

IV. In the West, some Christians attempted to preserve or extend the traditions of Roman learning.

A. Cassiodorus (485–580), a civil servant and officer under Ostrogothic rulers, retired from governmental life to found a monastery at his villa (the Vivarium) in southern Italy. His expressed goal was to preserve ancient learning, which he saw as imperiled.

1. Cassiodorus' *Institutiones* continues the Roman encyclopedia style by enumerating the seven liberal arts and showing their importance to Christians.
2. Cassiodorus' monks copied selected works of antiquity—again, not a great deal from natural philosophy. The works of Greek theorists were already out of their reach.

B. St. Benedict of Norcia (480–547) retired as an ascetic to a hermitage but eventually founded the monasteries bound by the *Regula* (*Rule*). The *Rule* stipulated daily work and reading (*lectio divina*), which required the presence of books.

1. Although the early Benedictines did not pursue scholarly aims, the copying and preservation of texts was soon adopted (probably from Cassiodorus' model).
2. Benedictine *scriptoria* spread as centers of literacy and scholarship throughout Western Europe.

C. The Roman encyclopedia tradition was carried on in a Christianized context in the *Etymologies* of St. Isidore of Seville (c. 600 A.D.), a bishop in Visogothic Spain.

V. In the end, the Latin West was able to hold on to very little of ancient culture, including natural philosophy and technology.

A. More was preserved in the east, where Greek was still spoken, but the decline of ancient science was dramatic there as well.

B. In the broad view, the Roman Empire bequeathed three invaluable gifts to posterity—the idea of a unified Europe, the universality of the Latin language, and the memory of former greatness.

C. Specifically, in natural philosophy, however, the Latin Middle Ages began with scarcely more than a dozen works from all of antiquity, and these were predominantly Roman popularizations, recensions, and encyclopedic works.

Essential Reading:

David C. Lindberg, *The Beginnings of Western Science*, pp. 149–159.

Supplementary Reading:

G. E. R. Lloyd, *Greek Science after Aristotle*, chapter 10.

Questions to Consider:

1. The world of learning is crumbling (how do you recognize this fact?). You are seriously concerned (like a late imperial scholar) with trying to preserve some remnants of your culture. You can choose any twelve books to preserve. What twelve would they be and why?
2. Reconsider the above question. How are your choices of what you are going to save conditioned by your own interests, those of your current culture, and those of the future culture you imagine? How does this exercise help to explain the situation and actions of fifth- and sixth-century scholars?

