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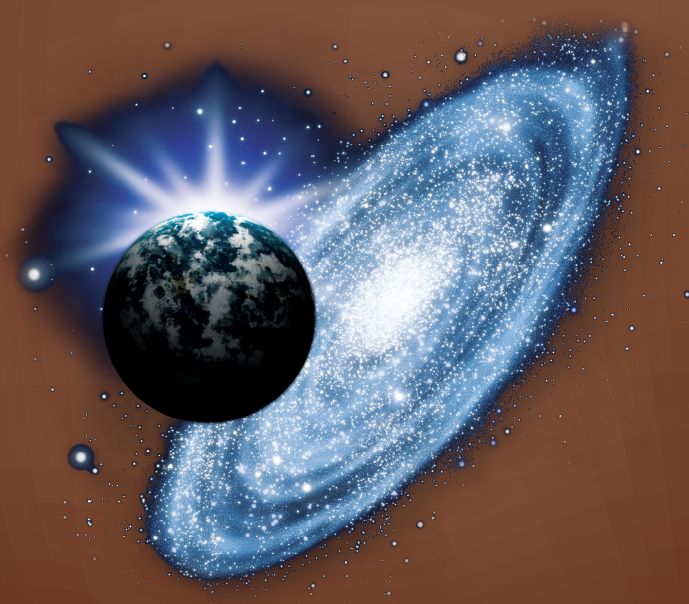
Big History: The Big Bang, Life on Earth, and the Rise of Humanity

Course Guidebook

Professor David Christian
San Diego State University



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Professor David Christian is Professor of History at San Diego State University, where he teaches courses on big history, world environmental history, Russian history, and the history of Inner Eurasia. From 1975 to 2000, he taught Russian history, European history, and world history at Macquarie University in Sydney.

Professor Christian was born in New York and grew up in Nigeria and Britain. He completed his B.A. in History at Oxford University, his M.A. in Russian History at The University of Western Ontario, and his D.Phil. in 19th-Century Russian History at Oxford University. As a graduate student, he spent a year in Leningrad (now St. Petersburg) during the Brezhnev era.

In the late 1980s, Professor Christian developed an interest in understanding the past on very large scales. With the help of colleagues in astronomy, geology, biology, anthropology, and prehistory, he began an experimental history course that started with the origins of the Universe and ended in the present day. Within two years, after his students persuaded him that it was a shame not to deal with the future after studying 13 billion years of history in 13 weeks, he introduced a final lecture on prospects for the future. In 1992, he wrote an article describing this approach as "big history." The label seems to have stuck, as similar courses have independently appeared elsewhere, and there are now several courses in big history at European, Russian, Australian, and North American universities.

In addition, Professor Christian has written on the social and material history of 19th-century Russian peasantry, in particular on aspects of diet and the role of alcohol. In 1990, he completed a study of the role of vodka in Russian social, political, and economic life. Professor Christian's recent publications include: *Imperial and Soviet Russia: Power, Privilege and the Challenge of*

Modernity (Macmillan/St. Martin's, 1997); *A History of Russia, Central Asia and Mongolia, Vol. 1: Inner Eurasia from Prehistory to the Mongol Empire* in *The Blackwell History of the World* (Blackwell, 1998); *Maps of Time: An Introduction to Big History* (University of California Press, 2004), which won the 2005 World History Association Book Prize and has been translated into Spanish and Chinese; and *This Fleeting World: A Short History of Humanity* (Berkshire Publishing, 2007).

Professor Christian is a member of the Australian Academy of the Humanities and the Royal Holland Society of Sciences and Humanities. He is Affiliates Chair for the World History Association and was one of the editors of the *Berkshire Encyclopedia of World History*. He also participated in the creation of the world history website World History for Us All (http://worldhistoryforusall.sdsu.edu/dev/default.htm). ■

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SUPPLEMENTAL MATERIAL

Big History: The Big Bang, Life on Earth, and the Rise of Humanity

Scope:

Big history surveys the past at all possible scales, from conventional history, to the much larger scales of biology and geology, to the universal scales of cosmology. It weaves a single story, stretching from the origins of the Universe to the present day and beyond, using accounts of the past developed within scholarly disciplines that are usually studied quite separately. Human history is seen as part of the history of our Earth and biosphere, and the Earth's history, in turn, is seen as part of the history of the Universe. In this way, the different disciplines that make up this large story can be used to illuminate each other. The unified account of the past assembled in this way can help us understand our own place within the Universe. Like traditional creation stories, big history provides a map of our place in space and time; but it does so using the insights and knowledge of modern science.

At first, the sheer scale of big history may seem unfamiliar—after all, historians usually focus on human societies, particularly those that had states and left documentary records. Until the mid-20th century, "history," in the sense of a chronologically structured account of the past, meant "human history" because we could only date those parts of the past for which we had written records. Since World War II, however, new dating techniques have allowed us to determine absolute dates for events before the appearance of written records or even of human beings. Radiometric dating techniques, based on the regular breakdown of radioactive materials, were at the heart of this chronometric revolution. These new chronometric techniques have transformed our ideas of the past, enabling us for the first time to construct a well-structured, scientifically rigorous history extending back to the origins of the Universe!

Telling this story is the daunting challenge taken up by big history; however, we have so much knowledge today that no single individual can be an expert on it all. Thus, you will not find in this course detailed analyses of the functioning of DNA, the causes of the French Revolution, the myths of ancient Greece, or the artistic innovations of the Renaissance—plenty of other courses offer more detailed accounts of such topics. What you *will* find is an attempt to weave stories told within many different historical disciplines into a larger story so that, instead of focusing on the details of each period or discipline, we can see the larger patterns that link all parts of the past. I am a historian, so this course inevitably reflects the expertise and biases of a historian. The same tale can also be told, with varying emphases, by astronomers and geologists. But at the heart of any such account is a core story, one that enables us to see the underlying unity of modern knowledge.

The first modern courses in big history appeared in the 1970s and 1980s. I began teaching big history in 1989; in 1991, I published an article in which (somewhat whimsically) I coined the term "big history." Though far from ideal, the name seems to have stuck, which is why we use it here in this course.

The unifying theme adopted in this course is the idea of increasing complexity. Though most of the Universe still consists of simple empty space, during almost 14 billion years new forms of complexity have appeared in pockets, including stars, all the chemical elements, planets, living organisms, and human societies. Each of these new forms of complexity has its own distinctive "emergent" properties, which is why each of them tends to be studied within a different scholarly discipline.

The introductory lectures describe the origins and aims of big history, the vast scale of the modern creation story, the central idea of complexity, and the large body of scientific evidence on which this account of big history is based. Eight major thresholds of increasing complexity provide the basic framework for this course.

The first threshold we cross is the creation of the Universe itself about 13.7 billion years ago during the big bang. This group of lectures summarizes some of the main insights of modern cosmology. We move from cosmology to astronomy in the second threshold with the creation of stars, which were the first really complex objects to appear in our Universe as well as the source of energy and raw materials for later forms of complexity. The third threshold is the creation of the chemical elements, which laid the foundations for the new forms of complexity studied within the discipline of chemistry. In the fourth threshold, where we cross from chemistry to geology, we zoom in on our own tiny corner of the Universe: the solar system and the creation of the planets, including Earth.

Earth provided an ideal environment for the fifth threshold, which takes us from geology to biology and describes the appearance of life; we survey the history of life on Earth and the evolution of our own species. The sixth threshold in this course is the appearance of human beings between 200,000 and 300,000 years ago, leading us from biology to history and marking the beginning of the first of three major eras of human history. The seventh threshold is the appearance of agriculture about 10,000 to 11,000 years ago, which supported larger and denser populations and made possible the creation of more complex human societies. Finally, the eighth threshold concerns the modern world within the last few centuries; during this period, the pace of innovation increased, creating human societies vastly more complex and integrated than those of the Agrarian era.

The final lectures of the course will peer into the future, and the course will end with a discussion of the place of human beings within the Universe.

I hope you will find the sheer scale of the course exhilarating, and I hope you will be persuaded—as I am—that each of the different time scales surveyed in this course has something important to teach us about our distinctive place within the Universe. ■

The Structure of the Course

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What Is Big History?
Lecture 1

Big history assembles accounts of the past from many different disciplines into a single, coherent account of the past.

In this lecture, I introduce myself and describe how I began teaching such a course. Then I discuss what big history is and some of the challenges it poses. I end by describing the structure of this course. I will begin by describing my own path to "big history." My own, somewhat confused background is relevant here. I was born in Brooklyn, lived as a child in Nigeria, went to school and university in England, married in Canada, studied as a graduate student in Russia during the Brezhnev years, then taught Russian and Soviet history at Macquarie University in Sydney, Australia, for 25 years before coming to the U.S. in 2001. That background may explain my interest in global approaches to the past!

The French Annales School of historiography insisted on seeing history within a larger spatial and temporal context. It had an immense impact on historians of my generation. The leading *annaliste*, Fernand Braudel, famously argued that historians needed to explore the past at multiple scales, including what he called the "*longue durée,*" or very large time scales. Only at these scales could you tackle the history of important but often neglected features of life such as diets, which seemed to change hardly at all at smaller scales. To fully understand the past, he argued, you had to see it at multiple scales.

These ideas encouraged me to undertake research on the daily life of 19th-century Russian peasants, and led to a study on the vital role of vodka in 19th-century Russia. As a history teacher, I was also concerned about the *significance* of history. Why did we always seem to be teaching fragments of the past rather than trying to convey a sense of the past as a whole? In the 1980s, I took up these twin challenges in the most ambitious way I could imagine, by creating a history course that began at the beginning—with the origins of the Universe.

I began teaching big history with a wonderful team of astronomers, geologists, biologists, anthropologists, and historians. Such courses are rare, so we made up the rules as we went along. We soon found that big history was exhilarating for both teachers and students because it allowed us to explore fundamental questions about the meaning of history and our place in the cosmos.

In 1992, I wrote an article on the course using the whimsical label "big history." It's not the ideal label but … it seems to have stuck! Since then, I've discovered that in the U.S., the rapidly emerging field of "world history" is also aiming at a larger vision of the past. So, big history can be thought of as an expansion of the world history approach to the past.

Threshold 6 is the creation of our own species, *Homo sapiens*, about 250,000 years ago.

Because of its large scale and the many disciplines it touches on, many will find this vision of the past unfamiliar. We do not try to cover everything! Instead, we will focus on large patterns of change. This means familiar historical topics, such as the French Revolution or the Renaissance, may seem to sail past in a blur. Though we will touch on many disciplines, from cosmology to biology to history, my expertise is as a historian. So this is not the course in which to study the specialist details in each discipline. Others are better qualified to explain the intricacies of DNA or the nuances of Confucian philosophy. Instead, you will find an attempt to link the insights of these different disciplines into a single, coherent vision of the past, in which each discipline can provide its own distinctive illumination.

Though such courses are unusual today, they belong to a long and ancient tradition. Though it uses modern, scientific information, big history has many similarities with traditional creation stories. These also used the best available information to construct credible and powerful stories that gave people a sense of their bearings in space and time. Similar attempts to map space and time have been made within all the great religious and cultural traditions. This was the aim of Christian writers such as Augustine (354–430 C.E.), who constructed a universal history that began about 6,000 years ago and would shape Christian historiography for more than 1,000 years. H. G. Wells's *Outline of History*, published just after WWI, is perhaps the most famous 20th-century attempt at a universal account of the past.

Despite this long tradition of "universal histories," modern education focuses on specialized knowledge, which inevitably leads to a fragmented vision of reality. Erwin Schrödinger (1887–1961), one of the pioneers of quantum physics, wrote a famous book on the nature of life in which he argued that it was vital for scholars to cross discipline boundaries, despite the risks this involved, if we are to move toward a more unified understanding of reality. That is the spirit in which I have approached this course.

What follows counts as just one attempt to tell the story of big history. There are other courses in big history taught by geologists and astronomers, and their emphases differ. However, historians may be in a particularly good position to tell such stories because historians are used to dealing with phenomena of extraordinary complexity, and they are also used to weaving stories from complex information.

This course is organized around the central idea of eight thresholds of increasing complexity. These eight thresholds provide the scaffolding for this course. Threshold 1 is the creation of our Universe about 13 billion years ago. Threshold 2 is the creation of the first complex objects, stars, more than 12 billion years ago. Threshold 3 is the creation inside dying stars of the chemical elements that allowed the formation of chemically complex entities, including planets and living organisms. Threshold 4 is the creation of planets, such as our Earth, bodies that are more chemically complex than the Sun. This group of lectures also surveys the history of our home planet.

Threshold 5 is the creation and evolution of life on Earth from about 3.8 billion years ago. This group of lectures also surveys the evolution of our own ancestors, the hominines, from about 6 million years ago.

Threshold 6 is the creation of our own species, *Homo sapiens*, about 250,000 years ago. This section of the course discusses what makes us so distinctive and describes the Paleolithic era of human history.

Threshold 7 is the appearance of agriculture (about 11,000 years ago). Agriculture accelerated the pace of change, leading to the emergence of larger and more complex societies and introducing the Agrarian era of human history.

Threshold 8 is the "Modern Revolution," the vast social, economic, and cultural transformations of recent centuries that introduced the Modern era of human history and created today's world.

The concluding parts of the course look to the future of humans, of the Earth, and of the Universe. They also offer an overview of the entire course.

Here are some of my more important objectives in this course.

- I hope you will find this huge journey exhilarating.
- I hope you will gain a clear understanding of the overall shape of this modern origin story.
- I hope you will gain a better sense of the underlying unity of modern knowledge. ■

Essential Reading

Christian, "The Case for 'Big History.'"

———, *Maps of Time,* Introduction.

Supplementary Reading

Christian, "World History in Context."

Questions to Consider

1. What are the main difficulties we face in trying to construct a "modern creation story"?

2. How can big history help us to better understand who and what we are?

Moving across Multiple Scales

Lecture 2

Tigers are dangerous; galaxies are not. Bump into a tiger, you have to be able to understand it, you have to be able to deal with it. Bump into a galaxy and, quite frankly, you're not going to need to deal with it. Either it's going to obliterate you and all of us, or it's not.

We saw that big history surveys the past at many different scales. Indeed, one of the unifying ideas of big history and one source of its intellectual power is the idea that what we see at any one scale illuminates what we see at other scales. That makes it very different from most history courses, which normally concern themselves with scales of a few decades to a few centuries. So big history requires an understanding of large spatial and temporal scales. But how can we possibly grasp how big (or how old) our solar system is—or the entire Universe? This lecture tries to help you deal with multiple scales in both space and time.

Understanding such scales is both difficult and extremely important. There's a biological reason why it's difficult. Our brains evolved to deal with the scales familiar in our daily lives, the "biological scale." Tigers are dangerous; galaxies are not! So we're not really designed by nature to grasp larger spatial or chronological scales. As Stephen Jay Gould writes: "An abstract, intellectual understanding of deep time comes easily enough—I know how many zeroes to place after the 10 when I mean billions. Getting it into the gut is quite another matter" (Gould, *Time's Arrow, Time's Cycle*, p. 3).

But getting a feeling for these large scales is important. Like ants on an elephant, we can see only the wrinkles up close. If we don't stand back, we'll never see the elephant. Each scale within big history brings new things into focus, even if it also hides other things. Though we can never really grasp the largest scales, like geologists and astronomers, we can find ways of dealing with them. The rest of this lecture starts the process of helping you become more comfortable with large scales.

To get a sense of spatial scales, let's go on a journey through the solar system. We begin with the human scale, then widen the lens. On April 12, 1961, at 9:07 am Kazakhstan local time, Yuri Gagarin blasts off aboard a Vostok 1 rocket from the Baikonur Cosmodrome to become the first human being to enter space.

We can picture the lift-off because we're still at the human scale. Almost 6 miles up we see Baikonur as if from an international jet. That's a view familiar to many of us. Gagarin reached 188 miles, close to the orbit of the International Space Station (220 miles). From here you can see large, clearly geographical features—seas and mountains—and also the Earth's curvature. But you can no longer see Baikonur. From 6,000 miles up we can see the Earth as a ball drifting in space. The first pictures of Earth from space had a powerful impact because they reminded people of the Earth's fragility and isolation.

Courtesy NASA.

Neil Armstrong became the first man on the moon.

What does the Earth look like from the Moon? Neil Armstrong landed on the Moon at 10:56 pm (EDT) on July 20, 1969, becoming the first human to step onto another world. As he stepped on the Moon his interest was focused (naturally) on whether he was stepping into quicksand; yet he was also aware of the momentousness of the occasion. He was thinking at multiple scales.

So far, no human has traveled further—though two human-made objects, the Voyager satellites, have now passed the outer planets of our solar system. To appreciate the scale of the solar system, imagine flying in a modern passenger jet at roughly 550 mph. To cross the continental U.S., it takes about 5 hours. To reach the Moon, it would take 18 days. To reach the Sun, it would take 20 years; to reach Jupiter, about 82 years; and about 750 years to reach Pluto, at the edge of our solar system. These are distances our minds can no longer grasp.

Stellar scales take us to entirely new orders of magnitude. How long would it take to reach the nearest star, Alpha Centauri, which is about 4.3 light years, or 25 trillion (25,000,000,000,000) miles away? The answer is about 5 million years. Cosmologically, that's a walk next door!

How many of these stellar neighbors do we have? There are about 100 billion stars in our stellar "city," the Milky Way. Most are separated by a plane flight of at least 5 million years. How many galactic "cities" are there in our Universe? About 100 billion. This means, as Cesare Emiliani writes, that there are "about as many stars in the Universe as there are sand grains in all the deserts and beaches of the Earth" (Emiliani, *The Scientific Companion*, p. 9). Another way of appreciating these different spatial scales is by going to one of the many "Powers of 10" websites. These offer images of the Universe at different scales, from the very large to the very small.

There are about 100 billion stars in our stellar "city," the Milky Way.

The temporal scales of the modern creation story are equally daunting. But they are not unique. Almost 2,500 years ago, the Buddha described even larger time periods in a delightful parable about how long it would take to wear down an entire mountain just by dragging a silken cloth across it. Our modern time scale, with a Universe just over 13 billion years old, seems modest in comparison. We can grasp it more easily if we shrink it one billion times, so that the whole history of the Universe can fit into just 13 years. On this scale, our Earth would have been formed about 5 years ago. The first multi-celled organisms would have evolved about 7 months ago. After flourishing for several weeks, the dinosaurs would have been wiped out by an asteroid impact about three weeks ago. The first hominines would have appeared about three days ago, and our own species just 53 minutes ago. The first agriculturalists would have flourished about 5 minutes ago, and the first Agrarian civilizations would have appeared just 3 minutes ago. Modern industrial societies would have existed for just six seconds.

At first sight, these huge scales may seem to deprive human history of any significance. But we will see in the next lecture that this is not quite the end of the story. By some criteria, such as that of "complexity," we humans and our history are significant even on cosmological scales. The French philosopher Pascal wrote: "For what is Man in nature? A nothingness in respect to infinity, a whole in respect to nothingness, a median between nothing and everything" (Delsemme, *Our Cosmic Origins*, p. 1). ■

Essential Reading

Christian, *Maps of Time*, chap. 2, 53–55; app. 1.

———, "World History in Context."

Supplementary Reading

Calder, *Timescale*.

Delsemme, *Our Cosmic Origins*, Introduction.

Gould, *Time's Arrow, Time's Cycle*.

Kelley, *The Home Planet*.

Power of 10 Websites

http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/

http://www.powersof10.com/

http://www.wordwizz.com/pwrsof10.htm

Questions to Consider

1. Do the huge spatial and temporal scales of modern cosmology diminish the significance of human beings?

2. Is it possible that, by placing humans in a larger context, they can help to illuminate the nature and meaning of human history?

Simplicity and Complexity

Lecture 3

You could study the properties of hydrogen and the properties of oxygen as long as you liked without being able to predict the properties of water, which is what you get when you combine two hydrogen atoms and an oxygen atom in a very specific way.

What thematic coherence can we possibly find across all the scales and disciplines included within big history? This lecture discusses the unifying idea of increasing complexity. We must begin by exploring what we mean by "complexity."

Here are some basic properties of complex entities. Complex things, like stars, planets, or living organisms, consist of diverse components bound into larger structures. These structures display "emergent" properties: features that are not present in the components from which they are constructed, but appear only when those components are assembled in specific ways. For example, the properties of water are not apparent in its component atoms, hydrogen and oxygen. They emerge only from a particular arrangement of those atoms. Emergent properties can appear magical because they do not reside in particular things but only in particular arrangements of those things. The idea of "emergence" is present in many different religious and scholarly traditions.

Complex entities have a certain stability. Molecules or stars survive for billions of years; butterflies survive for just a few days. But eventually they all break down. Energy flows are needed to bind simple components into more complex structures. Without these flows the structures break down. We study complex things because we are complex. But there are also good biological reasons for our fascination. To survive, we must be good at detecting complex patterns in our surroundings (such as tigers or tax inspectors!).

Over 13 billion years, the upper level of complexity appears to have increased. Intuitively, this is reasonably clear. The early Universe consisted of little more than hydrogen and helium; today's Universe contains many more interesting objects, such as ourselves! There may be more rigorous ways of demonstrating that complexity has increased. Astronomer Eric Chaisson (who teaches an astronomer's version of big history in Boston) argues that if it takes energy flows to sustain complexity, we ought to be able to measure levels of complexity by estimating the size of those energy flows in different complex entities. To test this idea, Chaisson has estimated the amount of energy (in ergs) flowing through a given amount of mass (in grams) in a given amount of time (seconds) within several complex entities. He finds that these energy flows increase significantly as we move from stars to planets to living organisms to modern human society.

Complexity ought to be decreasing, not increasing!

Chaisson's results suggest conclusions of fundamental importance for big history. Most of the Universe has remained simple. Yet the upper level of complexity has increased. Chaisson's calculations suggest that living organisms are more complex than stars, and modern human societies may be among the most complex things we know. Perhaps we are not as insignificant as the previous lecture might have suggested. However, more complex objects also appear to be rarer and more fragile than simpler objects. Stars, for example, are more common and survive longer than butterflies. The simplest thing of all—the vacuum—is more common than either!

Curiously, the idea that complexity has increased may seem to contradict one of the most fundamental laws of physics: the second law of thermodynamics. The laws of thermodynamics describe the relationship between energy and work (the ability to make things happen, to cause change). The first law states that the total amount of energy available in any closed system (such as the Universe) is fixed. Yet at any particular point in the Universe, the form, distribution, and intensity of energy can change. This matters because work can be done only when energy is distributed unevenly, so that it can flow from one level to another: from the top to the bottom of a waterfall, or from the boiler to the condenser of a steam engine.

However, as energy flows its distribution evens out, thereby reducing the capacity of energy to perform work. Like a battery, electrons flow from one terminal to the other until the distribution of electrons has evened out, and we say the battery has "run down." Energy has not disappeared; it is simply distributed more evenly so it cannot flow or do work. The level of simplicity or disorder (known as "entropy") has increased.

The second law of thermodynamics was formulated by a German physicist, Rudolf Clausius (1822–1888). It generalizes these principles, stating that differences in energy levels tend to diminish as work is done, so that entropy increases. Applied to the Universe as a whole, the second law of thermodynamics implies that energy flows ought to decrease over time.

As Stuart Kauffman puts it:

> The consequence of the second law is that … order—the most unlikely of the arrangements—tends to disappear. … It follows that the maintenance of order requires that some form of work be done on the system. In the absence of work, order disappears. Hence we come to our current sense that an incoherent collapse of order is the natural state of things. (Kauffman, *At Home in the Universe*, pp. 9–10)

Complexity ought to be decreasing, not increasing!

How can the upper levels of complexity increase if energy flows in the Universe are constantly being run down? There have been several attempts to solve this apparent paradox. Nobel Prize–winning chemist Ilya Prigogine (1917–2003) suggested there may exist a spontaneous tendency toward "self-organization" wherever there are large energy flows. As yet, though, it has been impossible to identify such laws.

A simpler answer is that even if energy differentials are diminishing over the entire Universe, they may increase locally. For example, gravity packs energy and matter into smaller spaces, thereby creating the local differentials in density and temperature from which stars are built. In turn, the heat generated in stars creates new energy flows within their hinterlands. This is why planets are good places for complex beings such as us. (*Inside* stars, however, the energy flows may be too intense for the building of new forms of complexity.)

Eric Chaisson has suggested a third possible source of free energy (or "negentropy"). The expansion of the Universe itself may constantly create new energy imbalances, ensuring that work can always be done somewhere in the Universe! These conclusions do not contradict the second law of thermodynamics because in the long run local energy flows diminish energy differentials in the Universe as a whole.

Wherever there are local energy gradients allowing energy to flow, it is possible, in principle, for complex entities to appear. The rest of this course will trace the astonishing creative process of increasing complexity, a process eventually leading to modern human societies, one of the most complex entities we know of. In the next lecture we ask: How do we know these things? Why should we trust the claims made by modern scientific accounts of the past? ■

Essential Reading

Chaisson, *Cosmic Evolution*, Prologue and Introduction.

Christian, *Maps of Time*, app. 2.

Supplementary Reading

Christian, "World History in Context."

Spier, *The Structure of Big History*.

Questions to Consider

1. What properties are shared by all complex entities?

2. Does the idea that modern human society may be among the most complex things you know alter your idea of the place of humans within the Universe?

Evidence and the Nature of Science

Lecture 4

The second position we'll describe as "relativism." And it goes something like this. We can never really know if what anyone says is true or not. We can't even know whether to trust our own senses, because they may be conveying inaccurate impressions about the real world.

In this lecture we ask: Why should we trust the claims of modern science (including the modern scientific discipline of history)? We discuss the nature of truth, in particular "scientific truth." We illustrate the discussion by surveying the evolution of modern techniques for dating events in the past.

Whatever society you live in, you need to ask the same fundamental question: Why should I believe the stories the experts tell me? The idea of "truth" is explored in the branch of philosophy known as "epistemology."

In principle, there are two extreme positions one can adopt to the idea of "truth." "There is a real world out there and with a bit of effort we can get real knowledge of that world." This is epistemological "absolutism." "We can never really know if what anyone says is true or not because even our senses can deceive us." This is epistemological "relativism." (Descartes [1596–1650] famously asked how you could prove that all the impressions you had about the world were not placed there by an evil demon.)

In practice neither position is tolerable in its extreme forms. Extreme relativism is intolerable because, as I live my life, I have to act, and to do that I need to trust some statements about the world I live in. Extreme absolutism is intolerable because we all know that some information is unreliable and our senses sometimes deceive us. So the real question is: How do I decide what claims about reality to trust?

To the question of trust, there are also two broad types of answers. The first is to trust authority. We trust a priest, or a sacred text such as the Koran, or the president of the U.S., or a scientist. Every time we fly in a plane we place our trust in those who built it, maintained it, and fly it. Or we can decide to trust no claims unless they are based on strong evidence. Descartes famously decided to distrust everything for which he did not have firm evidence, and concluded that the only thing of which he could be certain was that he was thinking, so therefore he must exist: "*Cogito ergo sum*." In practice, life is too short to get direct evidence about everything, so we always have to rely on both evidence and authority.

Modern science bases its claims as much as possible on evidence. This rule applies to all modern scholarship, from historical scholarship to geology or astronomy. In this sense all historical disciplines, from cosmology to human history, can be described as "scientific." Even if you cannot always check out the evidence yourself, you must be assured that the evidence is available so that, if you had the time, you could check it yourself. All scientific scholarship makes some concessions to relativism. As in a court of law, we know that the evidence is rarely perfect, so there is always the possibility of error. Yet modern science does not believe that all stories are equal. The story based on good evidence should always be preferred to the story based on none. As in a court of law, claims based on no evidence will be thrown out. Science has this advantage over the courts of law, that it can change its mind so it can evolve and improve. Over time, the story should slowly get more trustworthy, as more evidence accumulates. In summary, scientists are generally confident that they are on the right track because their claims rest on a vast amount of carefully tested evidence accumulated over many centuries and subjected to multiple tests. That is why in this course we will discuss evidence a lot.

The rest of the lecture will illustrate these features of modern science by surveying the evolution of "chronometry," the techniques used to date past events. To construct a well-structured account of the past, we must be able to assign dates to past events. How? In societies without writing, history depended on oral traditions. But oral tradition tends to lose precision within a few generations of the present.

The first "chronometric" revolution was the appearance of writing, about 5,000 years ago. Written documents made it possible to assign objective dates to events many generations earlier. But written documents also distorted the past. They highlighted the activities of the literate and could say nothing about the history of the natural world or of anything that existed before the invention of writing. The idea that history could only be based on written documents created a sense of separation between human history and the history of the natural world. Written evidence could also deceive. Christian theologians, such as Eusebius of Caesarea (who died c. 340 C.E.), used written evidence from the Old Testament to date the moment of creation to about 4000 B.C.E. Their evidence-based calculations would dominate Christian cosmology for 1,500 years.

From the 17th century, new evidence began to undermine this chronology. Seventeenth-century geologists already doubted the traditional Christian timescale of 6,000 years. For example, the finding of marine fossils in mountains suggested that mountains had once been under the sea, which suggested they had been created over vast periods of time.

The first "chronometric" revolution was the appearance of writing, about 5,000 years ago.

In 1795, James Hutton (1726–1797) argued that the Earth's surface had been formed by slow processes such as erosion and uplift, acting over unimaginably long periods of time. By his time, it was possible to generate relative dates for the Earth's history (saying what order things occurred in by using the fossils in different strata), but he despaired of constructing an absolute chronology. As late as the early 20th century, written records remained the basis for chronology. When, just after World War I, H. G. Wells attempted a form of big history in his *Outline of History*, he knew that he had no precise dates before the 1st millennium B.C.E.

The situation was transformed in the middle of the 20th century by a second "chronometric" revolution. The discovery of radioactivity provided the crucial breakthrough. Marie (1867–1934) and Pierre (1859–1906) Curie discovered radioactivity, and both eventually died of cancer caused by handling radioactive substances. A New Zealand–born physicist, Ernest Rutherford (1871–1937), showed that radioactive materials break down with great regularity, so that in principle they could be used as clocks. In the 1950s, at the University of Chicago, Willard Libby (1908–1980) developed practical ways of using these techniques of "radiometric dating" in archaeology. In 1953, Clair Patterson of the California Institute of Technology used similar "radiometric" techniques to show that the solar system was about 4.5 billion years old. These and other new dating techniques, most developed since the Second World War, provide the evidence for the chronologies we use in this course.

We have seen that science makes strong, but not absolute, claims on the truth, and that its claims are based on evidence. We have also seen how, in just the last century, revolutionary new dating techniques have provided the evidence needed to construct a rigorous account of the past extending back well before the appearance of written records. ■

Essential Reading

Calder, *Timescale*.

Christian, *Maps of Time*, app. 1.

Supplementary Reading

Bryson, *A Short History of Nearly Everything*.

Toulmin and Goodfield, *The Discovery of Time*.

Questions to Consider

1. How can nonscientists best decide whether or not to trust the claims made by modern science?

2. How did the evolution of modern dating techniques, such as radiometric dating, transform our understanding of the past?

Threshold 1—Origins of Big Bang Cosmology
Lecture 5

As far as we know, all societies have asked this question: How did everything begin? And as far as we know also, many societies have offered deep, rich, and powerful answers to that question.

How did everything begin? We have seen that evidence is fundamental to modern scientific knowledge, so this lecture describes the slow accumulation, over many centuries, of the evidence that provided the foundations for modern answers to this most fundamental question.

We focus on the Western Christian tradition of knowledge within which the modern answers emerged. Christian cosmology was dominated by a theology that saw God as the creator of the Universe, coupled with an Earth-centered model of the Universe created by a Roman/Egyptian astronomer, Ptolemy of Alexandria (c. 90–168 C.E.).

Though alternative, Sun-centered models of the Universe also existed, Ptolemy's model succeeded partly because it was based on rigorous astronomical observation and partly because it was backed by the church. The Earth rested at the center of Ptolemy's Universe. Around it were several transparent crystalline spheres. They carried the Sun, stars, and planets, and inhabited a perfect, heavenly realm that contrasted with the imperfect "sub-lunar" realm of the Earth. Ptolemy's model could explain most of the movements of heavenly bodies, and also the fact that the Earth appeared to be still. It also enjoyed the authority of the Catholic Church.

In the 16th century, it was challenged by new evidence and new theories. Polish-born astronomer Nicolaus Copernicus (1473–1543) showed that some problems of the Ptolemaic system (including the "retrograde" motions of the planets: their apparent reversal of direction in each orbit) could be resolved if we put the Sun, rather than the Earth, at the center of the Universe. A German astronomer and mathematician, Johannes Kepler (1571–1630), showed that the planets move in elliptical orbits, not in the perfect circles required by Ptolemy's system.

Galileo Galilei (1564–1642) used a new instrument, the telescope, to show that heavenly bodies contained blemishes (such as sunspots). This disproved Ptolemy's claim that the heavens were a realm of perfection, and hinted that the same fundamental laws might apply on Earth as in the heavens. Galileo also showed that we do not experience the Earth's motion through space because, like passengers on a ship, we share in that motion.

Assuming that our part of the Universe was typical, Hubble's discovery suggested that the entire Universe was expanding.

During the "Scientific Revolution" of the 17th century, a new model of the Universe was constructed. In the *Principia Mathematica*, published in 1687, Isaac Newton (1642–1727) explained the elliptical orbits of the planets as the result of a universal force of attraction (or "gravity") that existed between all objects, both in the heavens and on Earth. Newton's cosmology had no obvious limits in time or space, suggesting that the Universe might be infinitely large and infinitely old. But the idea of an infinitely large Universe raised new problems. Kepler had pointed out that if the Universe was infinite it ought to be bathed in an infinite amount of heat and light, which was patently not true. The second law of thermodynamics (see Lecture Three) suggested that the amount of usable energy in the Universe was constantly diminishing. For 19th-century astronomers this posed a fundamental problem, for in an infinitely old Universe there should be no usable energy left.

These problems were resolved early in the 20th century with the appearance of an entirely new model of the Universe. In the late 1920s, American astronomer Edwin Hubble (1889–1953) showed that the entire Universe was expanding. His achievement rested on 19th century attempts to map the position and movements of the stars. First, astronomers tried to estimate the distances to the stars and the size of the Universe.

Hold your finger up at arm's length, then move your head from side to side. Your finger will seem to move against the background. That is "parallax." By measuring those movements you could, in principle, calculate the distance to your finger using basic trigonometry. The same principle applies to stars, for as the Earth orbits the Sun, the closest stars should appear to move against the background stars. The Greeks understood these principles, but even the nearest stars are so remote that detecting their movements requires very delicate observation. Not until 1838 were the first accurate measurements made.

In the first decade of the 20th century, American astronomer Henrietta Leavitt (1868–1921) found that variations in the light from stars called Cepheid variables could be used to calculate their true brightness. Comparing this with their apparent brightness on Earth made it possible to estimate their true distance even if they were well beyond the range of parallax measurements. In 1924, Hubble showed that at least some Cepheids existed outside our galaxy, the Milky Way—proving for the first time that the Universe consisted of many galaxies, not just one.

Second, astronomers tried to determine the motions of the stars. In 1814, German glassmaker Joseph von Fraunhofer (1787–1826) invented the spectroscope, a device like a prism, which splits light into its component wavelengths. Fraunhofer identified dark "absorption lines" in the spectra of starlight. These correspond to particular elements in the stars themselves, because each element absorbs light energy at different frequencies.

In the late 19th century, Vesto Slipher, at the Lowell Observatory in Flagstaff, Arizona, showed that some stellar absorption lines were shifted away from their expected frequencies. Slipher interpreted these shifts as the results of a Doppler effect, an apparent change in wavelengths caused by the relative movements of the two bodies. (We experience the Doppler effect when the pitch of an ambulance siren appears to change as it passes us.) As Slipher showed, this meant that changes in absorption lines could tell us whether distant objects were moving toward us or away from us, and at what speed.

Using these findings, Hubble showed that all remote objects are shifted to the red end of the spectrum, which meant they were moving away from us. Furthermore, the more remote they were, the greater was the red shift, or the rate at which they were moving away from the Earth.

Assuming that our part of the Universe was typical, Hubble's discovery suggested that the entire Universe was expanding. As Belgian astronomer Georges Lemaître pointed out, this implied that in the distant past everything in the Universe must have been crushed into a single, tiny, dense hot point, a "primeval atom" as he called it. This meant that the entire Universe had a history. These ideas solved the problems posed by an infinite Universe, for an expanding Universe had to be finite, containing finite amounts of light and heat, and plenty of usable energy. The idea of an expanding Universe also fitted Einstein's recently formulated general theory of relativity, which appeared to show (though Einstein initially resisted this conclusion) that the Universe must be either expanding or contracting. The name "big bang" was coined by Fred Hoyle (1915–2001), who had worked with Gamow but would become a fierce critic of the theory. He used the label derisively in a 1950 radio broadcast.

We have seen how, early in the 20th century, new evidence and new arguments accumulating over several centuries generated a new model of the Universe. This model suggested that the Universe had been created at a specific date and had been expanding ever since. In other words, the Universe had a history! ■

Essential Reading

Bryson, *A Short History of Nearly Everything*, chap. 8.

Christian, *Maps of Time*, chap. 1.

Supplementary Reading

Coles, *Cosmology*, chaps. 1, 4.

Questions to Consider

1. Why did it take so long for astronomers to take big bang cosmology seriously?

2. What were the three most crucial steps in the creation of a modern cosmology?

How Did Everything Begin?

Lecture 6

"There was neither non-existence nor existence then." What we're talking about is a sort of state in which there's not quite nothing, but there's not quite something; there's sort of potential. That, in fact, is very like modern accounts of the vacuum.

—Rigveda, the basic Hindu scriptures

How was the Universe created? This lecture summarizes the modern answer to this fundamental question and explores the evidence on which it is based. All human societies have asked how everything began, and they have all offered answers of some kind. Traditional answers rested on limited evidence. Yet they were often poetically rich and philosophically deep, and they mattered because they helped people map their place in space and time. Most assumed that the Universe had been created by a deity or deities. Modern scientific answers do not posit a divine creator, because such a claim cannot be supported with scientific evidence. Besides, it raises the awkward question of how the creator was created. However, like all other accounts, the modern account also faces the "paradox of beginnings": the challenge of explaining how something can come from nothing. And it offers no solution. We just don't know what there was before the moment of creation. We do not even know if time or space existed. In such cases, scientists will generally admit their ignorance, while continuing to search for new forms of evidence.

Yet from a moment after the creation, astronomers can tell a well-grounded scientific story based on masses of carefully tested evidence. It begins 13.7 billion years ago. To explain this story, we need some very large and very small numbers, for which we use "exponential" notation. A figure 1 with two zeroes (100) represents two 10s multiplied together. The figure 1,000 (with 3 0s) represents three 10s multiplied together. In exponential notation we write these numbers as 10^2 and 10^3. We can do the same with fractions. One hundredth (1/100 or 0.01) is 0.1 multiplied by itself. So we write 10^{-2} for 1/100, and 10^{-3} for 1/1000.

From about 10^{-35} of a second after the moment of creation, we can tell a good scientific story. Something appeared. It was tiny (the size of an atom perhaps) and inconceivably hot. It was expanding rapidly and cooling fast. At this point, energy and matter were indistinguishable. As this “something” cooled, “things” and “forces” appeared, in a series of “phase changes,” rather like the change steam undergoes as it turns into water. Gravity appeared from the chaos, as did the “strong” and “electromagnetic” forces.

From 10^{-33} to 10^{-32} seconds, the Universe expanded faster than the speed of light, growing from the size of an atom to the size of a galaxy. This phase is known as “inflation.” Within the first second, quarks—the building blocks of atomic nuclei— were created in positive and negative forms. These then proceeded to annihilate each other, leaving just a few survivors. These forlorn survivors formed protons (which are positively charged) and neutrons (which are electrically neutral).

Electrons (lighter than protons and negatively charged) were created in an equally violent process. A few minutes after the big bang, the Universe consisted of a hot “plasma” (a mixture of energy and charged subatomic particles, a bit like the center of the Sun today).

About 380,000 years later, the Universe was cool enough for positively charged protons to capture negatively charged electrons, creating the first, simple atoms of hydrogen and helium. Because the positive charges of protons are cancelled by the negative charges of electrons, atoms are electrically neutral, so electromagnetic radiation (of which light is just one form) could now travel freely through the Universe without getting tangled in networks of electromagnetism. The Universe cooled, entering a “dark age” that lasted several hundred million years.

Other entities and forces were created that we don’t understand. We call this missing stuff “dark matter” or “dark energy.” We know it’s there because studies of the movements of galaxies show that something is exerting a powerful gravitational pull. This stuff may account for up to 95% of the Universe’s total mass. Seventy percent of that total may consist of undetected forms of energy. Twenty-five percent may consist of matter in forms we cannot detect because they emit no radiation (such as cold, dead stars or planets) or because they are too small (such as the subatomic particles known as neutrinos).

Why should anyone believe this bizarre story? Because it rests on a colossal amount of carefully tested evidence. The earliest evidence came from Hubble's studies of the "red shift," which showed that the further away an object was, the faster it was moving away from us. This meant that the Universe must be expanding; so at some time in the past it must have been infinitely small.

Models of the big bang suggest that hydrogen and helium were created in huge amounts, and other elements in smaller amounts.

What clinched the new theory was the discovery of "cosmic background radiation" (CBR). Until 1965, big bang cosmology had a rival, the "steady state" theory, supported by Fred Hoyle and others. They argued that the apparent expansion of the Universe was caused by the continuous creation of new matter. Supporters of the "big bang" theory suggested that when energy and matter separated 380,000 years after the big bang, there must have been a huge flash of energy that should still be detectable as a weak energy source coming from all parts of the Universe.

In 1964, two engineers, Arno Penzias and Robert Wilson, were trying to construct an extremely sensitive radio antenna. They could not eliminate a persistent background hum. Eventually, they realized they were hearing the cosmic background radiation. That clinched it for the big bang theory because no other theory could explain the source of this universal energy.

There are other powerful reasons for accepting big bang cosmology. No astronomical objects older than 13 billion years have ever been detected. As telescopes (like the Hubble space telescope) probe deeper in space they are also probing further into the past. What they find is that the early Universe was different in several respects from today's Universe, which is what big bang cosmology predicts in an evolving, historically changing Universe. Models of the big bang suggest that hydrogen and helium were created in huge amounts, and other elements in smaller amounts. Observed distributions of chemical elements fit this prediction very well. Hydrogen accounts for about three-quarters of all matter, and helium for almost all the rest.

Despite its bizarre conclusions, big bang cosmology offers a scientific, well-tested explanation of how the Universe was created. But the early Universe didn't yet contain anything of much interest. In the next lecture we ask: How were the first stars and galaxies created? ■

Essential Reading

Brown, *Big History*, chap. 1.

Chaisson, *Epic of Evolution,* Prologue, chap. 1.

Christian, *Maps of Time*, chap. 1.

Supplementary Reading

Bryson, *A Short History of Nearly Everything*, chap. 1.

Coles, *Cosmology*, chap. 5.

Delsemme, *Our Cosmic Origins*, chap. 2.

Questions to Consider

1. How persuasive is the evidence for big bang cosmology?

2. Why did it take astronomers so long to accept the implications of Hubble's evidence that the Universe was expanding?

Threshold 2—The First Stars and Galaxies

Lecture 7

So, here's the problem. How can you move from something this simple to the vastly more varied and beautiful world that we inhabit today? How can you generate complex things with such simple components?

This lecture leads us across the second major threshold of this course by describing how the early Universe created the first complex objects. How do you make a star? The early Universe contained vast clouds of hydrogen and helium atoms with energy pouring through them. Enter gravity. Gravity is a force, so it can rearrange things in interesting ways. Gravity began the process of sculpting more complex things. Newton described gravity as a universal force of attraction acting between all forms of matter.

Einstein showed that it also acted on energy, because energy and matter are different forms of the same underlying "stuff." He also showed that gravity is caused by the changing geometry of "space-time." Here, we stick with Newton's simpler idea of gravity as a "force," because it is easier to grasp and can explain all the phenomena we need to understand in this course.

Newton showed that the strength of gravity (1) increases with the mass of the objects involved and (2) declines as the distance between objects increases. This means that if the early clouds of matter had been distributed perfectly equally, gravity would have acted equally on everything, leading to a sort of cosmic traffic jam in which nothing could move and nothing could happen. But gravity can magnify even the tiniest unevennesses, because its power increases where matter is more concentrated. So, where matter and energy are *not* distributed evenly, gravity can rearrange them in more interesting ways.

In 1992, George Smoot used the COBE (Cosmic Background Explorer) satellite to detect tiny variations in the temperature of the cosmic background radiation. He showed that there *were* tiny differences in density and energy within the clouds of hydrogen and helium that filled the early Universe.

Gravity magnified these differences, splitting vast clouds of matter into billions of smaller clouds. As each cloud contracted, the pressure and temperature at its center rose, and atoms collided with increasing frequency and violence.

Eventually, in a sudden phase change, the violence of these collisions overcame the positive electric charges between protons. Hydrogen nuclei fused to form helium nuclei, and the first stars were formed. Once the center of a cloud of matter reached a minimum of about 10 million degrees Celsius, hydrogen nuclei collided so violently that some fused together, forming helium nuclei. As they did so, a tiny amount of matter was transformed into huge amounts of energy, in accordance with Einstein's formula $E = mc^2$. (The energy released when matter is converted into pure energy is equivalent to the mass of the converted matter multiplied by the speed of light *squared*—a colossal amount!) Hydrogen bombs use the same fusion reaction.

The colossal energy produced at the center of each star created a sort of furnace, which prevented any further gravitational collapse and stabilized the newborn star. From now on, its stability would depend on a constant negotiation between the heat at its center, which prevented further contraction, and the force of gravity that pressed it together. Fusion at the center explains why stars emit energy. Heat and light travel from the star's core until eventually they are released into nearby space. Suddenly, the Universe lit up with billions of hot spots, each pumping energy into the cold of surrounding space. Fusion can continue within a star until it has used its stores of hydrogen. This may take millions or billions of years. The next lecture describes what happens when a star runs out of fuel. Recent evidence suggests that the first stars lit up about 200 million years after the big bang.

As billions of stars lit up, gravity herded them together into larger "societies" of stars. First they formed into galaxies of hundreds of billions of stars. Gravity herded galaxies into clusters, and herded clusters into even larger membrane-like structures known as superclusters. However, at scales of millions of galaxies, gravity is too weak to overcome the expansion of the Universe. Only at these colossal scales can we observe the expansion of the Universe. Stars represented a new level of complexity. They are structured, they have stability, they show emergent properties, and they are sustained by energy flows.

How do we know about the birth and death of stars? Our understanding of star formation depends largely on our theoretical understanding of processes such as fusion (which is very well understood by nuclear physicists) and the operations of gravity. But observational astronomy can also identify regions of our own galaxy where huge clouds of matter appear to be collapsing and forming new stars, such as the famous Horsehead Nebula.

Gravity began the process of sculpting more complex things.

Studying the life cycle of stars is tricky because they last so long that we can never observe an individual star evolving. Instead, we have to study millions of individual stars and assume that they represent different parts of a star's life cycle. How do we do this?

Lecture Five mentioned the invention of the spectroscope by Joseph von Fraunhofer in 1814. Spectroscopes can help us identify the relative amounts of different chemical elements within a star because of the "absorption lines" they leave in the star's spectrum. Spectroscopic studies show that stars consist overwhelmingly of hydrogen and helium. We can measure a star's apparent brightness, and if we know its distance, we can measure its real brightness—the amount of energy it emits. As larger stars generate greater pressures and temperatures, a star's brightness effectively tells us its mass. We can estimate the temperature at its surface from its color.

Using such observations, astronomers built up a massive database of information on different stars. Finally, in 1910, Danish astronomer Ejnar Hertzsprung and American astronomer Henry Russell distilled this information into a simple graph that identified the key factors in a star's life cycle. They plotted two features of each star: first, its brightness (effectively a measure of its mass), and second, its surface temperature. They found a simple correlation: For most stars, the more massive they were, the higher their surface temperature. Stars in this area of the graph (the "main sequence”) generate energy by hydrogen fusion. They also found stars that did not fit this correlation. These were stars at the end of their life cycle. We will discuss them in the next lecture. What the graph shows is that the key determinant of a star’s life is the size of the initial cloud of matter from which it is formed. This determines the pressure in its core and the temperature and speed at which it burns its fuel. This determines how soon it will run through its fuel and die.

Why are stars so important in the modern creation story? First, they represent the first large, complex objects created by our Universe. Second, stars create the preconditions for new forms of complexity. They do so in two main ways. They pump energy out into the cold empty spaces between them, creating powerful energy flows. These provide the energy needed to create even more complex entities (including planets and even ourselves). They also create new chemical elements needed to form more complex entities (including ourselves). How they do so is the main subject of the next lecture.

This lecture has described how gravity sculpted stars from the simple raw materials of the early Universe. But how did the Universe create even more complex entities such as ourselves? To do that, it had to create more elements. That was the task of dying stars. ■

Essential Reading

Chaisson, *Epic of Evolution*, chap. 2.

Christian, *Maps of Time*, chap. 2.

Supplementary Reading

Brown, *Big History*, chap. 1.

Croswell, The Alchemy of the Heavens.

Delsemme, Our Cosmic Origins, chap. 2.

Questions to Consider

1. How does the force of gravity sculpt matter and energy into new forms?

2. Why do stars play such an important role within big history?

Threshold 3—Making Chemical Elements

Lecture 8

[Russian chemist Dmitrii Mendeleev] found that the elements known in his time could be arranged in such a way that the vertical columns contained elements with similar features, features such as differing degrees of chemical reactivity. And he also showed something else. These features recurred at surprisingly regular intervals.

Most of the chemical elements from which we are constructed were formed in dying stars. So stars laid the foundations for a new, chemical, level of complexity. The chemical elements are the 92 most elementary forms of matter. The modern understanding of chemical elements really goes back to the work of Russian chemist Dmitrii Mendeleev (1834–1907).

In 1869, Mendeleev did for the chemical elements what Hertzsprung and Russell had done for stars. He arranged all elements known in his time in a way that revealed new and hitherto unsuspected regularities. He arranged them in rows according to their atomic weight. (Modern versions of his table arrange them by their "atomic number," the number of protons in their nuclei.) He arranged them in columns by their chemical properties and was able to show that similar properties recur at regular intervals. Remarkably, this enabled him to accurately predict the chemical properties of some elements that had not yet been discovered. Mendeleev's table is known as the "periodic table of the elements."

How were the different elements created? Most elements were *not* formed in the big bang because, by the time protons and neutrons had been created—within seconds of the big bang—temperatures were too low to forge elements heavier than hydrogen and helium. Temperatures high enough to forge heavier elements would not be re-created until the appearance of stars. To understand how stars created heavier elements, we need to understand their life cycles.

Let's return to the Hertzsprung-Russell (H-R) diagram. The diagram is a scatter graph. It ranks stars according to two types of measurement. The first parameter is their brightness, or the amount of light they emit. This is usually measured on the vertical axis, with brighter stars higher on the graph. In effect, a star's brightness tells us its real mass, because a large star generates more density and more energy. The second parameter is a star's surface temperature, which can be estimated from its color. Blue stars are hot, and normally appear on the left of the graph; red stars are cooler and appear to the right. Most stars appear on a diagonal band, the so-called main sequence, running from the top left to the bottom right. Stars on the main sequence are normal mature stars doing what stars do best: turning hydrogen into helium.

The exact position of a star on the main sequence depends on one factor: its mass. Small stars generate less pressure at the center and burn at lower temperatures, so they burn their fuel slowly and may live for billions of years. They appear at the bottom right of the main sequence. Our Sun is in the middle of the main sequence. It will burn for about 9 billion years. Stars more than 10 times larger than our Sun have much higher internal temperatures and burn their fuel much faster. The biggest stars, such as Rigel in Orion, shine with a bluish light and appear at the top left of the main sequence. They may live for just a million years or so.

The death of a star begins when it runs out of hydrogen. At this point, it leaves the main sequence on the H-R diagram. When our Sun has used up all the hydrogen in its core, it will cool and collapse quite suddenly. This violent collapse will compress the star's center so that its temperature will rise again. At about 100 million degrees Celsius, helium atoms will start to fuse, eventually forming carbon. The Sun will expand again, reaching beyond the orbit of Mercury and turning into a "red giant," like Aldebaran in the constellation of Taurus. As it burns helium, it will move from the main sequence to the upper right of the H-R diagram.

Once all the helium in its core has been used up, the process will repeat itself. The Sun will collapse again, temperatures will rise, and it will expand again until this time it includes the orbits of Mars and Earth, vaporizing both planets as it does so. The Sun will have become a "red supergiant," like Betelgeuse in the constellation of Orion. Eventually, it will shed its outer layer and collapse around its carbon core, turning into a "white dwarf" about the size of the Earth. It will move across the main sequence of the H-R diagram toward the bottom left of the diagram. It will become smaller and less bright but with a high surface temperature. Over billions of years, it will cool until eventually any surviving astronomers will start calling it a "black dwarf." Smaller stars than the Sun will burn much longer. When they run out of fuel, they may simply collapse into a white dwarf, or they may briefly burn helium and then collapse into a white dwarf.

If you're wearing a gold ring, it was forged in a supernova and is on very temporary loan to you!

The death of really large stars is much more spectacular. When they run out of hydrogen they, too, become unstable. They start burning helium, and when that's gone, temperatures will still be high enough for them to burn their way through carbon and a number of other elements including oxygen and silicon. Eventually, they start producing iron (which has 26 protons in its nucleus), and the temperature at their core reaches 4 billion degrees Celsius. Cesare Emiliani describes this dramatic phase in the death of a large star:

> A star 25 times more massive than the Sun will exhaust the hydrogen in its core in a few million years, will burn helium for half a million years, and—as the core continues to contract and the temperature continues to rise—will burn carbon for 600 years, oxygen for 6 months, and silicon for 1 day. (Emiliani, *The Scientific Companion*, p. 61)

When its iron core shuts down, the star will collapse catastrophically in just a second, before exploding in a "supernova." Most of its mass will be hurled into space. Its core will collapse into a "neutron star," a ball of matter so dense that all its atoms are crushed into their nucleus. If the supernova is large enough the collapse will go even further, to form a "black hole." A black hole is an object so dense that not even light can escape its gravitational pull. In the extreme temperatures of a supernova, the remaining elements of the periodic table can be manufactured in just a few seconds, all the way through gold and lead, to uranium. Then they will be scattered throughout nearby space.

In summary, it has taken three steps to create the chemical elements from which we are constructed. Hydrogen and helium, the simplest atoms in the periodic table, were created during the big bang. In their death throes, medium to large stars create elements such as carbon (6 protons), nitrogen (7 protons), oxygen (8 protons), silicon (14 protons), and up to iron (with 26 protons). As dying stars throw off their outer layers, these elements are scattered through space, which is why, though not as common as hydrogen and helium, these elements are more common than the other elements of the periodic table. The remaining elements were manufactured and scattered through space in supernova explosions. (If you're wearing a gold ring, it was forged in a supernova and is on very temporary loan to you!) The first stars provided the energy flows and the chemical ingredients needed to make even more complex entities such as our Earth. ■

Essential Reading

Brown, *Big History*, chap. 1.

Christian, *Maps of Time,* chap. 2.

Delsemme, *Our Cosmic Origins*, chap. 3.

Supplementary Reading

Chaisson, *Epic of Evolution*, chap. 3.

Croswell, *The Alchemy of the Heavens.*

Questions to Consider

1. What were the three main stages in which the chemical elements were forged?

2. Why are chemical elements crucial to the emergence of new forms of complexity?

Threshold 4—The Earth and the Solar System

Lecture 9

Life, we'll see, is too delicate to exist on stars, which are extremely violent places. Planets, though, provide a perfect environment.

We're beginning to see that everything, including chemicals, even including the Universe itself, has a history. So, too, does our solar system and our Earth. This lecture describes the fourth great increase in complexity: the appearance of planets. To understand how planets were formed, we must shift scales, from the cosmological scale to the scale of a single star, our Sun. Our temporal scale shrinks slightly. We begin 4.5 billion years ago, when the Universe was about 9 billion years old.

Our spatial scale shrinks drastically as we focus on one tiny part of the Universe. We have seen that there are as many stars as there are grains of sand on all the beaches on Earth. Now we look at one of those grains of sand, and the stuff around it. Yet from a human perspective, this is still a huge scale. Remember, an airliner that takes five hours to cross the U.S. would take 80 years to reach Jupiter, 750 years to reach Pluto, and about 5 million years to reach the nearest star, Alpha Centauri.

In the 1990s, improved observational techniques let astronomers observe other planetary systems for the first time. So far, 10% of all stars surveyed have turned out to have planetary systems, which suggests that such systems are very common. Soon we may know a lot more about solar systems, but in the meantime most of what we know is based on our own system. Planetary systems are created as by-products of star formation, but only in regions that are chemically rich because of previous supernova explosions.

Our Sun was created like all other stars, by the collapse of a cloud of matter, a "solar nebula." Planets formed because this particular cloud was chemically rich. Hydrogen made up about 70% of the matter in the solar nebula, and helium another 27%. Carbon, oxygen, and nitrogen (all vital ingredients of living organisms), accounted for about 1.5%, and the remaining 1.5% included all the other elements of the periodic table.

What followed should be familiar by now. Gravity drew the cloud together. As it became denser, it heated up—particularly in the center. When the center reached 10 million degrees Celsius, hydrogen fusion began and our Sun lit up. It acquired the typical structure of stars, with fusion reactions in the center, a middle layer containing reserves of hydrogen, and a surface from which energy radiates into space. We can see areas of star formation in our galaxy even today. Similar processes occur even at smaller scales. For example, Jupiter is mainly gaseous and is large enough for its center to be extremely hot, but not quite hot enough for fusion. It is almost a star, but not quite.

We cannot determine the age of the solar system by dating Earth rocks because the Earth is so geologically active that its original surface is now unrecognizable.

Now we shift away from the Sun to the debris surrounding it. Through a process known as accretion, the planets and other bodies of our solar system were created from the 0.1% of the solar nebula that was not incorporated in the Sun. As it contracted, the solar nebula spun faster, like an ice skater doing a pirouette. Centrifugal force flattened the spinning nebula into a disk, so that the material not gobbled up by the Sun orbited the Sun in a single plane. Saturn's rings consist of orbiting debris, so they may give us a good idea of the shape and structure of the solar nebula.

In each orbit, particles of matter were drawn together by electrostatic forces or crushed together in the course of violent collisions. Gradually, larger objects appeared and began colliding with each other and sometimes merging with each other. They grew like large snowballs. Stray bodies in the solar system, such as comets, are thought to be remnants of these early stages of accretion. Within a few million years, the large bodies in each orbit formed "planetesimals." The largest planetesimals drew in most of the remaining material through their gravitational pull until a single large body appeared in each orbit.

Differences in the materials in different orbits explain the differences between the planets. The young Sun's heat drove more volatile elements away from the center, so they collected further out. As a result, the inner planets contained less matter and were dominated by rocky materials while the outer planets were larger and consisted mainly of gassy materials. The asteroids, at the border between these two regions (between Mars and Jupiter), may represent a failed planet that was broken up by the powerful gravitational force of Jupiter, the largest planet in our solar system. The Earth's Moon was probably created by a collision between the young Earth and a Mars-sized protoplanet. This would have gouged material from the Earth's outer layers, forming a small, dusty nebula from which the Moon formed by accretion. Material not swept up inside planets formed the other bodies of the solar system—its comets, asteroids, meteorites, and many of its moons—some of them orbiting in strange patterns because of erratic collisions.

What's the evidence for this story? The idea that the Sun and solar system had all condensed from a single solar nebula that collapsed under the pressure of gravity was first proposed by German philosopher Immanuel Kant in 1755. It fits what we know of the workings of gravity and the shape and structure of the solar system. It also fits recent observations of other regions where planetary systems appear to be forming.

We cannot determine the age of the solar system by dating Earth rocks because the Earth is so geologically active that its original surface is now unrecognizable. However, the surface of the Moon, like that of most meteorites and asteroids, has changed little since the time of accretion. The fact that all these objects yield similar dates increases the confidence of astronomers that the entire solar system was formed more or less at the same time, about 4.5 billion years ago.

This lecture has described how planetary systems form, including our own, the solar system. Now we focus on our home planet, the Earth. What was the early Earth like? How different was it from the Earth we know today? ■

Essential Reading

Brown, *Big History*, chap. 1.

Christian, *Maps of Time*, chap. 3.

Delsemme, *Our Cosmic Origins*, chap. 4.

Supplementary Reading

Bryson, *A Short History of Nearly Everything*, chap. 2.

Chaisson, *Epic of Evolution*, chap. 4.

Questions to Consider

1. What are the main constituents of the solar system?

2. What were the crucial processes and forces that created the objects in our solar system?

The Early Earth—A Short History

Lecture 10

But what I would really like you to notice is how natural the crossing can be. There are no border patrols, and there are no geologists saying: "You've been traveling in astronomy. You need a visa to enter geology."

The previous lecture described the origins of our Sun and solar system about 4.5 billion years ago. Now we cross from astronomy to geology as we focus on our own planet, the Earth. We'll look at the Earth in its early days. What was it like? How friendly an environment was it for life? And how different was it from today's Earth?

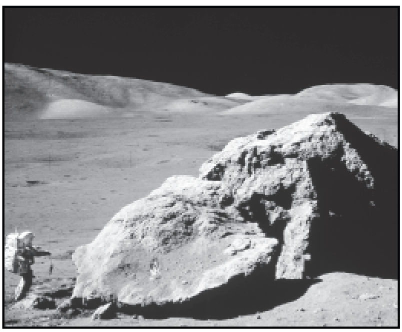
The early Earth would have seemed an unlikely home for life. The earliest era (strictly "eon") of Earth history is known as the Hadean (or "hellish") eon. It lasted from about 4.5 to about 3.8 billion years ago. It is the first of four eons in the Earth's history. (The others are the Archaean eon, from 3.8 to 2.5 billion years ago; the Proterozoic eon, from 2.5 billion years ago to 550 million years ago; and the Phanerozoic eon, or "eon of multi-celled organisms," from 550 million years ago to today.)

As the young Earth formed through accretion, it heated up and melted. It was heated by three different forces. The first was repeated violent collisions. The early solar system was much like a cosmic demolition derby. The second force was radioactivity, because the early solar system contained many radioactive materials created in supernovae. The third force was pressure. As each planet grew in size through accretion, pressure and temperature built up at its center.

Then what took place was a sorting of elements by their density in a process known as "differentiation." Heavy materials sank to the center, and lighter materials rose to the surface. Differentiation gave the Earth the internal structure it has to the present day. Metals (mainly iron and nickel) sank to the center to form the core, with a solid center and a liquid outer layer. The core generated the Earth's magnetic field. Lighter materials formed the semimolten middle layers of the mantle. Even lighter materials such as granites formed the eggshell-thin crust, which cooled most rapidly. Gases and water vapor bubbling up through volcanoes formed the Earth's earliest atmosphere, which was dominated by water vapor, nitrogen and carbon dioxide. (An earlier atmosphere of hydrogen and helium had probably drifted into space when the Earth was too small to hold them through its gravitational pull.)

The Earth also acquired a satellite of its own, the Moon. The fact that the Moon contains few metallic elements suggests that it was gouged out of the Earth's upper layers by a violent collision with a Mars-sized object just after differentiation, when most metals had sunk to the core.

During the Hadean eon, the Earth cooled. Eventually, water vapor rained down to form the first seas. As we will see, water in liquid form appears to be vital for the complex chemical reactions that gave rise to life. At the end of the Hadean eon, the Earth would still have seemed an extremely hostile environment to modern humans.


Courtesy NASA.

Apollo 17 astronaut Harrison Schmitt collects lunar rock samples.

The Archaean eon, the eon of the earliest life forms, lasted from 3.8 billion to 2.5 billion years ago. There were two important changes during this era. Asteroid impacts diminished as more and more stray objects were absorbed within existing planets, and the solar system became a less violent place. However, as we will see in Lecture Seventeen, occasional impacts could still play a critical, and catastrophic, role in the Earth's history.

The Earth's atmosphere began to change. Most important for us, there appeared increasing amounts of free oxygen. Oxygen is an extremely reactive element that eagerly combines with other elements, a fact we observe whenever we light a fire. So the appearance of free oxygen must mean that oxygen was continually being freed by some process occurring on or near the Earth's surface. That process, as we will see later, was photosynthesis: Free oxygen was produced by plant-like organisms, a first hint of how living organisms could transform the Earth's surface.

How do we know about the early history of the Earth? The Earth has changed so much that we have little direct evidence from the Hadean eon. The oldest Earth rocks date to about 4 billion years ago. Our understanding of the Hadean eon depends on a combination of theoretical inference and the indirect evidence described in the previous lecture.

Capturing the gases released by volcanoes today can tell us much about the constituents of the Earth's early atmosphere, as we know that volcanoes generated much of that atmosphere.

At present, we cannot drill deeper than about 7 miles into the Earth, which is just 0.2% of the distance to the center (4,000 miles). To understand what's inside the Earth we have to use indirect methods. One of the most important techniques depends on seismology, the study of earthquakes. Different types of seismic waves travel in different ways and at different speeds through different types of rock, so careful comparisons of their movements, using seismographs placed at many different parts of the Earth, can tell us much about what is inside the Earth. Seismographs have played a similar role in study of the Earth's interior to spectroscopes in studies of the stars.

How can we know what was in the ancient atmosphere billions of years ago? Capturing the gases released by volcanoes today can tell us much about the constituents of the Earth's early atmosphere, as we know that volcanoes generated much of that atmosphere. We can observe and date the buildup of free oxygen in the atmosphere from the appearance of increasing amounts of rusted iron in the Archaean eon.

This lecture has described the early Earth and some of the more important changes it underwent during its early years through accretion, differentiation, and early changes in its atmosphere. We saw that the early Earth was very different from today's Earth. How did its surface change to create the familiar geography that has done so much to shape human history? The next lecture will tackle this question by describing the fundamental geological paradigm of plate tectonics. ■

Essential Reading

Chaisson, *Epic of Evolution*, chap. 4.

Christian, *Maps of Time*, chap. 3.

Supplementary Reading

Delsemme, *Our Cosmic Origins*, chap. 4.

Macdougall, *A Short History of Planet Earth*.

Questions to Consider

1. How and when did the Earth acquire the layered structure it has today, with a metallic center, a semimolten mantle, a thin but rigid crust, and an atmosphere?

2. What have been the crucial stages in the history of the Earth's atmosphere?

Plate Tectonics and the Earth's Geography

Lecture 11

You look at a map of the world, and what you see is what looks like a jigsaw puzzle whose pieces have been slowly moved apart.

In the previous lecture, we saw that the early Earth was very different from today's Earth, and distinctly less friendly to life. How did the Earth acquire today's geography, a geography that has profoundly shaped the course of human history? Two figures, one German and one American, will play vital roles in our understanding of how the geography of today's Earth was constructed. What they showed was that the Earth's surface also has a history and has changed profoundly over time.

To understand modern ideas about the history of the Earth's surface, it will help to contrast them with more traditional ideas. Traditionally, geologists assumed that, though mountains might rise (through processes such as earthquakes or volcanic activity) and fall (by erosion), the basic geography of the Earth's surface was fixed.

The idea that the Earth's surface had changed was first proposed seriously by a German meteorologist, Alfred Wegener (1880–1930). In 1912, Wegener published a book called *The Origins of Continents and Oceans*, in which he proposed a theory that would come to be known as "continental drift." Wegener argued that the Earth's continents had once been joined in a single supercontinent called Pangaea. What evidence did he offer for this revolutionary idea, which contradicted most of the basic assumptions of contemporary geologists?

The first modern world maps, created early in the 16th century, showed that the continents seemed to fit together like pieces of a jigsaw puzzle, particularly across the Atlantic Ocean. Wegener identified geological formations of a similar date and composition in West Norway, East Greenland, much of Britain, Northwest Africa, and the eastern seaboard of the U.S. This made sense only if all these regions had once been joined together. An Austrian geologist, Eduard Suess (1831–1914), had already proposed that the southern continents of South America, Africa, Antarctica, Australia, and India had once been part of a single supercontinent that he named Gondwanaland. Wegener expanded this idea to suggest that *all* the world's continents had once been joined together. Wegener showed that fossil species, such as the ancient plant *Glossopteris*, could be found on most of the continents of Gondwanaland.

He also found evidence of ancient glaciers in tropical regions of Africa, and of ancient tropical forests in Antarctica, which suggested that both continents had traveled huge distances. But how could whole continents possibly move? Wegener could not explain this. As a result, most geologists rejected his ideas from the 1920s to the 1960s. However, they had to get very creative to ignore the powerful evidence he had presented. For example, it became fashionable to argue that there had once been thin land bridges linking the continents.

New research after World War II suggested a solution to Wegener's dilemma and revived interest in his ideas. In the 1960s, the new theory of plate tectonics emerged as the core idea of modern geology. American geologist Harry Hess (1906–1969), who was a naval commander during World War II, used the technology of sonar (developed to detect submarines) to survey the Pacific seafloor. Like most geologists, he assumed the ocean floors would consist of a huge, flat ooze, from sediments washed into the seas. Instead, he was astonished to find underwater chains of volcanic mountains. These turned out to be one section of a chain linking all the major oceans.

In 1962, studies of the deep seafloor showed that while regions close to the mid-oceanic ridges had normal magnetism, further out, the magnetism was reversed, and further out it was reversed again. In 1966, it was shown that the Earth's magnetic field periodically reverses, so that each band represented seafloor laid down in a different period. Improved dating techniques eventually confirmed that the bands closest to the ridges consisted of new oceanic crust and those further away were much older.

This evidence confirmed an idea Hess had proposed in 1962: that molten magma rose from the Earth's interior at the oceanic ridges, creating new seafloor and pushing existing seafloor aside. Where did the old seafloor end up? Hess suggested that millions of years later it plunged back into the interior. This idea explained why oceanic crust consisted mainly of volcanic basalts, and why it was so much younger than most continental crust.

These discoveries laid the foundations for the modern theory of plate tectonics. (The term "plate tectonics" is used to distinguish this theory from Wegener's theory of "continental drift.") According to plate tectonics, the Earth's crust consists of a dozen or so plates, like sections of a cracked eggshell.

Convection currents in the semimolten regions beneath them move the plates around. Most geologically interesting events occur at the plates' edges. At "divergent margins," such as suboceanic ridges, magma from the interior rises and forces adjacent plates apart. This is why the Atlantic Ocean is widening by about 2 cm each year, about the speed at which your fingernails grow.

Elsewhere, at "convergent margins," plates are forced together. There are two main types of convergent margins. If both plates are continental, they may buckle up at "collision margins" to form mountain chains such as the Himalayas, which were formed when the Asian and India plates collided. If an oceanic plate, consisting of heavy basaltic materials, meets a lighter continental plate, the oceanic plate will dive under the continental plate at "subduction margins." As it does so, the plates will grind together and

Corel Stock Photo Library.

Harry Hess, a geology professor at Princeton and World War II naval commander, used sonar to detect submarines—and volcanoes on the seafloor.

generate colossal heat, which can melt rock and drive up mountain chains. The Andes were formed above a subduction margin created as the Pacific plate dove beneath the South American plate.

Where plates slide past each other at "transform margins," such as the San Andreas Fault in California, friction builds before being suddenly released in earthquakes. Satellite images now enable us to measure tectonic movements with great precision. Driving the entire machinery is heat from the center of the Earth, created when the Earth was first formed 4.5 billion years ago.

It is now clear that the Earth's plates have joined periodically to form supercontinents such as Pangaea. Here, we summarize changes in the Earth's geography over the last two of these cycles. About 540 million years ago, as the first multi-celled organisms formed in the Cambrian period—the oldest period of the Phanerozoic eon—the ancient supercontinent of Rodinia was breaking up. About 420 million years ago, in the Silurian period, most continental plates were gathered in the south; the first bony fishes and the first trees appeared. About 300 million years ago, in the Carboniferous period, continental plates were reassembling. This is the period of the first reptiles, winged insects, and amphibians, and the period in which fossilized trees began to lay down huge beds of coal. About 180 million years ago, in the Jurassic period, most continental plates joined to form the supercontinent of Pangaea. The dinosaurs flourished during this period, as did ferns and conifers—and early forms of mammals, which (disappointingly) probably looked a bit like shrews! About 60 million years ago, Pangaea was splitting into two large continents, Laurasia and Gondwanaland. This is just after an asteroid impact wiped out most species of dinosaurs, allowing the mammals to flourish in the niches they left behind. Today, the Earth is as fragmented as it has ever been, a geographical reality that has had a profound impact on human history. ■

Essential Reading

Christian, *Maps of Time*, chap. 3.

Redfern, *The Earth*.

Supplementary Reading

Bryson, *A Short History of Nearly Everything*, chap. 12.

Macdougall, *A Short History of Planet Earth.*

Questions to Consider

1. What evidence did Wegener have for his idea of continental drift, and why was his idea rejected in the 1920s?

2. What are the main differences between Wegener's idea and the modern theory of plate tectonics?

Threshold 5—Life

Lecture 12

Most of the Universe as I've described it so far is still technically dead. It's not alive. It can do lots of interesting things, as we've seen, but it's not—strictly speaking—alive, not alive in the sense that you and I are alive.

We have described the creation of our Universe, our Sun, and our Earth. This lecture crosses a new threshold with the appearance of life. What is life? Life is one of those things that may seem easy to define until you try. Traditional accounts have often seen life as a divine gift, dependent on some kind of life force. But it has proved impossible to demonstrate scientifically the existence of a creator-deity, and as we have seen, deistic theories always generate a new question: How was the creator created?

Until the early 19th century, many scientists argued that there was a basic difference between the "organic" chemicals from which living organisms were made and the "inorganic" chemicals from which nonliving things were made. This idea was disproved in 1828 when German chemist Friedrich Wöhler (1800–1882) synthesized a simple organic chemical (urea) in a laboratory. Just as Newton has argued that the same physical laws applied in the heavens and on Earth, so this suggested that the same chemical laws applied to living and nonliving things. This implies there is a continuum between life and non-life, which may be why it is so hard to distinguish rigorously between life and non-life.

Nevertheless, living organisms are different. First, they count as a higher level of complexity. Like all complex things, their existence depends on very specific ways of organizing matter. Get the plan wrong and the organism dies. They have a degree of stability but eventually die. They display new, emergent properties. And they depend on flows of energy to maintain their complexity. Indeed, these flows seem to be denser than in all the other complex things we have seen, which justifies the claim that living organisms represent a higher level of complexity. Eric Chaisson has argued that energy flows more densely through living organisms than through nonliving entities. The complex structures of living organisms seem exquisitely designed to maintain and handle these dense energy flows. The energy flows, in turn, help living organisms maintain a high level of complexity.

Three distinctive “emergent” properties distinguish living organisms from non-life and contribute to their complexity. (Some of these properties are present in nonliving entities; it is the combination that really distinguishes life from non-life.) These properties are metabolism, reproduction, and adaptation.

- Metabolism means the ability to use and process energy from the environment. All living things require a constant flow of energy to maintain themselves, and their metabolism consists of the chemical reactions through which they extract energy. Humans extract energy mainly by eating and breathing. Plants extract energy directly from sunlight through photosynthesis. (In a sense, of course, even stars and planets depend on energy flows; the difference is the astonishing variety of ways in which living organisms extract energy from their environments.)

- Reproduction is the ability of living organisms to make multiple copies of themselves.

- Adaptation is the ability of living species to change over time so as to find new ways of extracting energy from their environments. What is remarkable is that adaptation allows organisms to keep extracting energy from their environments even if their environments change. Adaptation is the ability, unique to living organisms, to change over time so as to fit better into their surroundings.

Even this list of features does not define the borderline between life and non-life completely. Viruses are little more than bundles of genetic material with no metabolism of their own. What they *can* do is hijack the metabolism of other organisms in order to reproduce. And because they can reproduce, they can also adapt. This is why viruses such as the AIDS virus can survive even in the hostile environment humans create for them by using antiviral drugs.

Now we focus on life's astonishing capacity to change, so as to generate new levels of complexity. How does life adapt? The key is the synergistic way that metabolism, reproduction, and adaptation work together. The metabolism of living organisms supplies the energy needed to maintain their complex structures. Reproduction allows them to copy structures that work. Adaptation enables living organisms to tweak their structures so as to explore new ways of extracting energy from their environments. Through adaptation, living organisms are constantly exploring the possibilities of their environment.

Though there seems to be no intrinsic drive toward greater complexity, some adaptations will inevitably be more complex than others, which is why, over time, the upper level of complexity has slowly increased. Of course, more complex organisms will need more energy, so they will have to develop a more powerful metabolism. For example, the first organisms that learned to extract energy from oxygen suddenly had access to new forms of chemical energy not available to other life forms. Clearly, adaptation is the key. So, to explain how more complex life forms have appeared, including ourselves, we must explain how adaptation works.

Only "inherited characteristics" are passed on. A fattened pig will not necessarily produce fat piglets, but a pig with fat parents may.

Explaining adaptation proved surprisingly difficult. The most common traditional answer was that living organisms did not change. They were adapted to their environments because that was how their creator made them. This explanation is present in the sacred texts of the Judeo-Christian-Muslim tradition, and in the works of Carl Linnaeus (1707–1778), the founder of modern taxonomy (the system by which living organisms are classified).

Yet even when Linnaeus wrote, there were good reasons for thinking that living organisms did change. By the 18th century many fossils had been found of creatures that no longer existed. Why should God have destroyed his own creations? Besides, animal breeders understood that animals *do* change. Indeed, they can be *deliberately* changed. Darwin quoted a famous breeder of pigeons, Sir John Sebright, who boasted that "he would produce any given feather in three years, but it would take him six years to obtain head and beak" (Christian, *Maps of Time*, p. 87).

By the 19th century, growing evidence that species really did change made it necessary to explain how. In 1809, French naturalist Jean-Baptiste Lamarck proposed that species change, in effect, because they *want* to change. Thus, in an environment where the tastiest leaves were high up, browsing animals would naturally stretch, and over time they might even lengthen their necks. Over many generations, they might even turn into giraffes!

Unfortunately, any animal breeder could point out what was wrong with this argument. Qualities acquired during one's lifetime ("acquired characteristics") are not passed on to one's offspring. Only "inherited characteristics" are passed on. A fattened pig will not necessarily produce fat piglets, but a pig with fat parents may.

We have seen that life represents a new level of complexity with three critical emergent properties: control of energy, the capacity to reproduce, and the ability to adapt to changing environments. We have also seen that, in the middle of the 19th century, the riddle of adaptation—the key to understanding what made life different from non-life—remained unsolved. Charles Darwin solved the riddle in a book published in 1859. What was his answer? ■

Essential Reading

Christian, *Maps of Time*, chap. 4.

Delsemme, *Our Cosmic Origins*, chap. 5.

Supplementary Reading

Chaisson, *Epic of Evolution*, chap. 6.

Maynard Smith and Szathmáry, *The Origins of Life*.

Questions to Consider

1. What are the most important features distinguishing life from non-life?

2. Why did it prove so difficult to explain the ability of living organisms to “adapt”?

Darwin and Natural Selection

Lecture 13

The result of being born into a family that had money and a commitment to research was that [Darwin] was able to spend most of his life studying the one thing he most wanted to study, which was the natural world. You really do have to envy him. How many of us would love to be so privileged?

We've seen repeatedly that modern scientific accounts of the Universe are historical; they tell a story of change at all scales, from the scale of the Universe to the scale of human history. Darwin's great achievement was to show that this is also true of living species. This lecture describes Darwin's elegant solution to the riddle of adaptation. One of Darwin's grandfathers, Erasmus Darwin, was a doctor who was intrigued by how living organisms seemed to change over time. His other grandfather, Josiah Wedgwood, was a well-known scientist, a friend of James Watt and chemist Joseph Priestly, and the founder of the Wedgwood pottery works.

As a child, Darwin (1809–1882) was fascinated by the natural world. His father despaired of him, writing, "You care for nothing but shooting, dogs and rat-catching, and you will be a disgrace to yourself and all your family" (Eldredge, *Darwin*, p. 22). Darwin resisted pressure to become a surgeon (he was appalled by the screams of patients undergoing operations without anesthesia) or a clergyman. He wrote in his autobiography, "No pursuit at Cambridge was followed with nearly so much eagerness or gave me so much pleasure as collecting beetles" (Eldredge, *Darwin*, p. 24). Darwin described as the most important event of his life an invitation that he received in 1831 from Captain Robert Fitzroy to travel around the world as the naturalist on a ship called the *Beagle*. The voyage lasted from 1831 to 1836. It took Darwin to South America, around Cape Horn, across the Pacific via the Galapagos Islands, Tahiti, and New Zealand, to Australia, Mauritius, around South Africa, to Cape Verde Island, and back to Britain. Darwin collected specimens and fossils and took detailed biological and geological notes.

When Darwin left on the *Beagle*, he shared the orthodox belief that living species had been made by the creator, more or less in their existing forms. What he saw on his travels undermined this conviction. First, he observed the staggering variety of living organisms and the many subtle variations between species. Second, he noted many examples of similar but not identical species living close to each other, such as the finches, tortoises, and iguanas of the Galapagos Islands. In South America, he also found fossils (such as those of armadillo-like creatures) that were similar but not identical to species still living in the same areas. He concluded that all species, including humans, must be the products of slow, continuous change. In a letter to a friend, he wrote, "I am almost convinced (quite contrary to the opinion I started with) that species are not (it is like confessing a murder) immutable" (Eldredge, *Darwin*, p. 58). Third, Darwin understood that few would accept this conclusion unless he could explain *how* species changed. In other words, he had to solve the riddle of adaptation.

Darwin stumbled on the solution two years after returning home, after reading Thomas Malthus's *Essay on the Principle of Population* (1798). Malthus was a pioneer of demography, or the study of populations. He pointed to the terrifying fact that in every generation and every species, most individuals die before they can reproduce. Darwin immediately saw an analogy with pigeon breeding. Breeders only allowed individuals with particular features to breed, in the expectation that these features would become more common in subsequent generations. Darwin concluded that nature "selected" individuals to breed in a similar way.

But what were the criteria for selection used by nature? His answer was "fitness"—how well they fitted their environment. Those individuals whose features best fitted them for their environment would survive and reproduce just as those best fitted to the specifications of the breeder survived in the artificial world of pigeon breeding. In his autobiography, he wrote, "it at once struck me that under these circumstances favorable variations would tend to be preserved, and unfavorable ones to be destroyed. The result would be the formation of new species" (Eldredge, *Darwin*, p. 52). Repeated over many generations, this mechanism could explain why species changed and why those changes that were preserved tended to be "adaptive": They tended to aid the species' survival.

Though his ideas had crystallized by 1838, Darwin didn't publish for fear that many would find them offensive. He published only after another naturalist, Alfred Russel Wallace (1823–1913), sent him a letter in 1858 that made it clear that he had stumbled on the same explanation. Darwin's friend, geologist Charles Lyell, arranged for the ideas of Darwin and Wallace to be presented together at a meeting of the Linnaean Society in London on July 1, 1858. The society's journal published the two presentations in August. Darwin then set to work to complete the book he had been thinking about for 20 years, and in 1859, he published *On the Origin of Species by Means of Natural Selection*. Priced at 15 shillings, it sold out immediately.

Though quite simple, the idea of natural selection is slippery because it is statistical. This explains why it is so easily misunderstood. This section will summarize the argument, step by step, emphasizing that natural selection is about change not in *individuals*, but in the *average qualities of entire species*.

- Species. Species are groups of organisms that can breed with each other.

- Variations. Though members of the same species are similar, there are always tiny differences, as you can see by looking at the faces of those around you.

- Heredity. Individuals inherit features from their parents.

- Fitness. Some features may increase or reduce an individual's chances of surviving and reproducing. Poor eyesight is a serious problem for an eagle!

- Differential reproduction. Because of fitness, some individuals have less chance of surviving and reproducing.

- Gradual change. The qualities of individuals with a lesser chance of reproducing will vanish in subsequent generations while the qualities of those with greater chances of reproducing will tend to increase. In this way, the average qualities of entire species will slowly change.

Why were these ideas so shocking in Victorian Britain? First, they implied that all species are related. Perhaps humans were related to apes—or even to plants and bacteria! In class-conscious Britain, this was a serious problem. Second, the idea of natural selection implied that complex organisms such as human beings could be created by blind, statistical processes acting over huge periods of time. Natural selection ("Darwin's dangerous idea," as philosopher Daniel Dennett has called it) seemed to leave no room for a divine creator. This terrified Darwin's wife, Emma, who feared her husband's impiety would ensure that they were separated in the afterlife! A third consequence was that biological change was endless, because environmental change ensured that adaptation would continue forever. This meant there were no perfect organisms, despite the claims of some contemporaries that humans (particularly British humans) were clearly the "fittest" of all organisms.

We have summarized Darwin's idea of natural selection. But what evidence is there that Darwin was right? The next lecture describes why Darwin's idea remains at the center of modern biological thought. ■

Essential Reading

Christian, *Maps of Time*, chap. 4.

Mayr, *One Long Argument.*

Supplementary Reading

Darwin, *On the Origin of Species.*

Eldredge, *Darwin.*

Questions to Consider

1. What was the crucial insight that allowed Charles Darwin to solve the problem of adaptation?

2. Why do so many people still find Darwin's solution to the riddle of adaptation unpalatable?

The Evidence for Natural Selection
Lecture 14

If you look at a lot of species, one of the strange things you find is you can often find very similar features across a wide range of different species.

Because his ideas seemed so radical to his contemporaries, Darwin defended them with great care. Yet he did so in language accessible to a general readership, which is why *On the Origin of Species* is one of the most readable of all scientific classics. We will find that many of Darwin's arguments are easier to understand if we appreciate that he was arguing against an alternative theory of life: the idea that all living things had been created by a deity. This lecture discusses the evidence available in Darwin's time, as well as the evidence that has become available since his death.

For Darwin himself, the first argument for his theory was that it made sense of what he had encountered on his travels. Darwin was repeatedly puzzled by finding many neighboring species that were clearly related but also slightly different. These differences were particularly striking among the birds, tortoises, and lizards of the Galapagos Islands, a group of 19 small volcanic islands in the Pacific Ocean about 600 miles west of Ecuador. For example, there seemed to be 14 distinct species of finches, each exquisitely adapted to one of the islands. In 1846, Darwin wrote, "Seeing this gradation and diversity of structure in one small, intimately related, group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends" (Eldredge, *Darwin*, p. 89).

Only on his return did Darwin realize how similar the different species of finch were. This suggested they had all once belonged to a single species. Yet in each island, slightly different beaks must have been favored because of slight differences in the trees and fruit of the island. Over many generations, those individuals with the best-adapted beaks would have fed and bred more successfully—and left more offspring, with similar beaks. Eventually, such processes would have generated new species, closely related, yet each adapted to its own island. The Galapagos finches offered a paradigm of the working of natural selection. Natural selection could explain both why the finches were well adapted and why they were closely related. Deistic arguments could offer no reason why they should be related.

The rapid evolution of disease vectors such as AIDS also provides direct evidence of natural selection, as does the declining effectiveness of antibiotics as new, resistant strains of bacteria have evolved.

What direct evidence did Darwin offer for his theory? First, he pointed to the fossil record. It was already clear that the fossil record contained many species that no longer existed. But there were so many gaps in the fossil record that to refute the argument that God had repeatedly created new species, Darwin needed to show the existence of "transitional" species, demonstrating the slow evolution of one species into another. While a deistic theory of life did not need transitional species, the theory of natural selection did. Fortuitously, such a fossil was found in 1861, just two years after his book was published. It belonged to a bird-like species now known as *Archaeopteryx*, which lived about 150 million years ago. It was about the size of a magpie and had feathered wings and a wishbone, features one would expect of a bird. But it also had some distinctly reptilian features, including teeth and a bony tail. These made it similar to a small dinosaur. *Archaeopteryx* was the perfect "transitional" fossil.

Second, Darwin pointed to "homologies," or unexpected similarities between species. Many striking features can be found across many different species, such as the fingers of mammals. A deistic theory of life naturally supposed that homologies reflected good design. But not all homologies could be explained in this way. For example, whales have fingers, though they have no use for them. There was no reason why a rational creator should have given whales fingers. But natural selection, which worked by constantly tweaking existing species, provided a natural explanation for such "survivals." It suggested that such species were similar because they were related. (We now know that whales are indeed descended from mammal ancestors.)

Third, Darwin argued that the geographical distribution of species supported his theory. Why did most marsupials live in Australia? Why were there no wolves in Australia, even though there was a "marsupial wolf," the *Thylacinus*, living in environments that would have suited wolves very well? Darwin argued that this was because Australian species were descended from local ancestors. Yet a deistic theory of life could offer no reason why a deity should not have placed species such as wolves in all parts of the world for which they were designed.

As a scrupulous scientist, Darwin was also painfully aware that there were gaps in his evidence. However, most of the gaps have been filled in since his death. The fossil record is now much richer. Even today, it is impossible to produce a series of fossils showing all the links between one species and another because so few organisms are ever fossilized. However, many more "transitional" fossils have been found. Modern dating techniques also enable us to date fossils precisely, putting them on timelines that demonstrate clearly how species have changed over time. A particularly striking example is the detailed reconstruction of the evolution of modern horses from a small, fox-sized animal—*Hyracotherium*—that lived about 60 million years ago. Darwin feared that contemporary estimates for the age of the Earth (20–400 million years, according to Lord Kelvin) allowed too little time for natural selection to generate the many species present in the modern world. As we have seen, modern estimates give an age of more than 4 billion years for the Earth, providing plenty of time for natural selection to create new species.

Darwin and his contemporaries had little understanding of how heredity works. Darwin assumed that qualities inherited from parents were normally blended in their offspring. Unfortunately, this seemed to mean that unusual but advantageous mutations, far from being preserved, would be diluted generation by generation. And that suggested that species ought to remain stable over time. Modern genetic studies began with the work of Gregor Mendel (1822–1884), whose work was not widely known before the 20th century. Mendel showed that many features, such as the colors of eyes, were *not* blended. The discovery of DNA in 1953, and subsequent clarification of how genes work, has demonstrated that heredity works in just the ways required by Darwin's theory. While some parental features are blended, many are not. Furthermore, though the copying of genes is almost perfect, there are occasional errors, which create the tiny variations that provide the raw material on which natural selection works.

Darwin feared that we could never observe natural selection directly because it was such a gradual process. In the 20th century, work on rapidly reproducing species such as fruit flies (*Drosophila*) has allowed us to observe evolution at work in great detail. The rapid evolution of disease vectors such as AIDS also provides direct evidence of natural selection, as does the declining effectiveness of antibiotics as new, resistant strains of bacteria have evolved.

Since Darwin's time, the evidence that living organisms adapt and evolve through natural selection has become overwhelming, which is why Darwin's idea is the key to modern biological science, with applications in many different areas of life—from the design of pharmaceuticals to the use of DNA in the courtroom. But how were the very first living organisms created? That is the question tackled in the next lecture. ■

Essential Reading

Christian, *Maps of Time*, chap. 4.

Mayr, *One Long Argument.*

Supplementary Reading

Darwin, *On the Origin of Species.*

Jones, *Almost Like a Whale.*

Watson, *The Double Helix.*

Questions to Consider

1. How did Darwin counter contemporary objections to the theory of natural selection?

2. What new evidence in support of Darwin's theory has emerged since his death?

The Origins of Life

Lecture 15

And it's now very, very clear—it's been repeated using different gases—that creating these simple chemicals is really not a huge problem in an environment without free oxygen.

Even the simplest living organisms are extremely complicated, so explaining how the first organisms were created is a tough challenge. Fred Hoyle (1915–2001), one of the pioneers of modern cosmology, put it like this:

> A junkyard contains all the bits and pieces of a Boeing-747, dismembered and in disarray. A whirlwind happens to blow through the yard. What is the chance that after its passage a fully assembled 747, ready to fly, will be found standing there? (Hoyle, *The Intelligent Universe*, p. 19)

> Hoyle made this comparison because both Boeing 747s and yeast cells contain about 6 million parts. Hoyle's solution to the puzzle of life's origins was to argue that life must have evolved somewhere else in the Universe before arriving on Earth. Yet most modern biologists are convinced that life did evolve on Earth, and that the idea of natural selection provides part of the explanation. This lecture summarizes some of the main ideas of modern explanations of the origins of life on Earth.

Traditional explanations for the origins of life can be divided into the divine and the naturalistic. Divine explanations suppose that life was created by a divine being. As we've seen before, modern science excludes such theories because they beg further questions (who created the creator?) and they cannot be tested scientifically. It does not assert that such theories are wrong, but merely that they cannot be tested scientifically. Naturalistic explanations suppose that life can be generated spontaneously from existing materials and forces. The Greek philosopher Aristotle (384–322 B.C.E.) saw the appearance of maggots in rotting meat as an example of spontaneous generation.

During the Scientific Revolution, scientists began to test such ideas more rigorously. In 1765, Lazzaro Spallanzani (1729–1799) claimed to have refuted Aristotle's idea by showing that if a meat broth was sterilized by boiling and then placed in an airtight container no microorganisms appeared. Opponents argued that there might be a "life force" in the air that "animated" living things, and Spallanzani's containers had merely excluded that life force.

Though we don't yet know all the details, we understand enough to know that life can be assembled from nonliving ingredients.

In 1862, Louis Pasteur (1822–1895) refuted the notion of a life force in a remarkably simple and elegant experiment. He boiled a broth in a flask with a long swan-necked outlet, open to the air. He argued that if there was a life force, it could enter, while seeds or spores would get trapped in the bend. His retorts can still be seen today in the Pasteur Institute in Paris, and they remain sterile. Pasteur's experiment seemed to prove that life could only come from previous life forms, from eggs or spores. Spontaneous generation was impossible. If so, how were the first living organisms created?

Biologists began to get a grip on this knotty problem early in the 20th century. Modern approaches explain the origins of life in distinct stages. First, we must explain the creation of the simple molecules present in all living organisms: the amino acids that make proteins, the nucleic acids that make DNA, the carbohydrates that make sugars and starches, and the lipids that make fats and hormones. Today, atmospheric oxygen destroys such molecules, which is why, as Pasteur claimed, life can no longer be generated spontaneously. However, in the 1920s, Alexander Oparin in Russia and J. B. S. Haldane in Britain pointed out that such molecules could have thrived in an oxygen-free atmosphere, such as that of the early Earth. How could you test such an idea?

In 1952, a graduate student, Stanley Miller, filled a glass tube with gases such as methane, ammonia, and hydrogen that might have been present in the early atmosphere, while carefully excluding oxygen. He added water, because complex chemical reactions are much easier in liquids than in gases (where atoms are usually too far apart to react) or in solids (where atoms are locked so tightly together that there can be little change). He added energy in the form of heat and electric charges. Within days a dark red sludge appeared containing amino acids, nucleotides, and phospholipids. Later versions of the experiment, using different gases, have shown that all life's basic chemicals could have formed spontaneously on the early Earth.

Second, we must explain the evolution of the much larger and more complex molecules found in living cells. The Urey-Miller experiment generated simple molecules with just a few atoms. Yet even the simplest viruses contain billions of atoms in complex configurations, many arranged in huge chains. How could such huge and complex molecules have formed? As Fred Hoyle argued, it was unlikely that such molecules would be assembled by pure chance. Yet there is an answer to Hoyle's riddle, and it involves natural selection. Though random changes are unlikely to create living organisms, if each successful step toward life can be locked into place, then the odds improve drastically. This is precisely how natural selection works, by locking into place random variations that create viable life forms. The idea that chemicals can "evolve" through a chemical version of natural selection ("chemical evolution") underlies modern theories of the origins of life.

In the 1950s and 1960s, Sydney Fox (1912–) showed how "chemical evolution" might work. Under certain conditions, organic molecules spontaneously form long chains similar to those in living organisms. Some of these molecules naturally curl up to form cell-like spheres with semipermeable membranes through which they can ingest chemicals from outside (eating?). They can also divide (reproduction?). With a metabolism and the ability to reproduce, they can also adapt over time, giving them all the "emergent properties" of life. Where might such reactions have occurred in the early Earth? Darwin assumed they might have occurred in a "warm pond," perhaps on the edge of the seas. Yet early in the Earth's history, its surface would have been extremely dangerous, so today it seems more likely that life evolved under the seas, near mid-oceanic vents. Here there was energy, a rich mix of organic chemicals, and protection from ultraviolet radiation. Today, rich colonies of chemical-eating bacteria thrive in such environments.

Third, we must explain the creation of the exquisitely organized billion-atom molecules of DNA (deoxyribonucleic acid), the "software" that controls reproduction. This is the toughest part of the puzzle. Without DNA, reproduction was inaccurate, and "chemical evolution" would have been slow and unreliable. DNA consists of two linked chains of nucleotides, linked by bonds like rungs on a ladder. Each bond consists of two "bases" (small clusters of atoms) that come in only four types and can only fit together in certain ways. They are known as Adenine, Thymine, Cytosine, and Guanine. A (Adenine) links only with T (Thymine), and C only with G. So, along each chain, you have a sequence of the four bases, each linked to its complement on the other chain. The exact sequence of these bonds codes the information used to construct each organism. When DNA reproduces, the bonds split in two and the two chains separate. The bases seek out their complements from the chemicals surrounding them (A looks for T and so on), and in this way two new chains of DNA appear, identical to the originals.

This mechanism is the key to accurate reproduction. But there's a problem. DNA cannot exist on its own, yet cells cannot survive without DNA—so which evolved first, the software of DNA or the hardware of the cell? At present, the best bet is that RNA (ribonucleic acid), a single-stranded variant of DNA, may have acted as both "hardware" and "software." Because it is similar to DNA, RNA can code for genetic information, but it can also act like an enzyme and help manufacture the molecules that cells need. However it was done, life seems to have appeared quickly on Earth, for living organisms existed by 3.8 billion years ago. This suggests that life may appear everywhere in the Universe that conditions are right. Though we don't yet know all the details, we understand enough to know that life can be assembled from nonliving ingredients. ■

Essential Reading

Christian, *Maps of Time*, chap. 4.

Delsemme, *Our Cosmic Origins*, chap. 5.

Supplementary Reading

Cairns-Smith. *Seven Clues to the Origin of Life.*

Davies, *The Fifth Miracle.*

Dyson, *Origins of Life.*

Questions to Consider

1. Why did the arguments of Haldane and Oparin shift discussions of the origin of life in new directions?

2. How satisfactory are modern naturalistic explanations of the origins of life?

Life on Earth—Single-celled Organisms

Lecture 16

Life for the best part of 3 billion years of the Earth's history consisted of single-celled organisms. Not until about 600 million years ago would the first multi-celled organisms appear.

We don't know how many species of living organisms there are today. There could be 10 million, or perhaps as many as 100 million. Only about 1 million have been described and catalogued. How, from simple beginnings, did this staggering variety of organisms evolve through natural selection? This and the next lecture describe how living organisms evolved to create the modern biosphere: the thin film of living organisms that covers the Earth's surface. We will survey eight stages in the history of the biosphere, each of which created one of the elements that define our own species. This lecture describes the first four of these stages. It describes how life evolved and changed during the first 3.5 billion years of the Earth's history, before the appearance of multi-celled organisms.

The first organisms on Earth were single-celled "prokaryotes." Prokaryotes are extremely simple cells. They are invisible to the naked eye. Indeed, countless billions live in or on our bodies. However, they are not the simplest of organisms. We have seen that viruses have evolved in the direction of greater simplicity, by shedding the capacity to generate energy on their own. They survive by hijacking the metabolic machinery of other organisms—something we experience, painfully, every time we come down with the flu.

Like all cells, prokaryotes have a fatty membrane through which chemicals can flow inward (for nutrition) and outward (for excretion). Within the cell there are free-floating molecules of DNA. Though simple by some standards, even prokaryotes are immensely complex entities, full of constant frenetic chemical activity. The earliest prokaryotes probably got most of their food from chemicals near the seafloor or by consuming other prokaryotes.

The second transition is the evolution of the complex chemical reaction known as "photosynthesis." Photosynthesis is an extremely complex chemical reaction found, today, in all plants and plant-like organisms that contain chlorophyll. Organisms capable of photosynthesis can capture and store energy directly from sunlight, in a reaction whose main inputs are carbon dioxide and water and whose main outputs are sugary molecules such as glucoses, which can store energy, and free oxygen. The first photosynthesizing prokaryotes appeared as early as 3.5 billion years ago. Photosynthesis marks a fundamental threshold in the history of life because it enabled living organisms to tap the colossal energy flows generated in the core of the Sun by hydrogen fusion.

Today, all plants practice photosynthesis, capturing energy from the Sun using green molecules of chlorophyll. As plants are consumed by other organisms, this captured energy diffuses throughout the biosphere via the "food chain." Some of the oldest microfossils (3.5 billion years old) are photosynthesizing algae, like modern "cyanobacteria." They created coral-like structures called stromatolites, some of which still exist today. Photosynthesis produces oxygen as a by-product. By 2.5 billion years ago, free oxygen started building up in the atmosphere. For many prokaryotes, oxygen was poisonous, which is why Lynn Margulis and Dorion Sagan described this change as the "oxygen holocaust" in their book *Microcosmos*. This revolutionary change in the atmosphere provides one marker for the beginning of the Proterozoic eon, from about 2.5 billion years ago.

Photosynthesis marks a fundamental threshold in the history of life because it enabled living organisms to tap the colossal energy flows generated in the core of the Sun by hydrogen fusion.

The third crucial transition is the appearance of "eukaryotic" cells more than 1 billion years ago, during the Proterozoic eon. Lynn Margulis (1938–) showed that eukaryotes evolved through the merging of once independent species of prokaryotes. Evidence for this is the presence in all eukaryotes of internal "organelles," some of which have their own DNA, which suggests they had once existed quite independently. Internal organelles include mitochondria, which can extract energy from oxygen, and chloroplasts, which can extract energy from sunlight through photosynthesis. The merging of these entities through "symbiosis" anticipates the later creation of multi-cellular organisms, though in the case of eukaryotes all the organisms coexisted within a single cell. Most eukaryotes are 10 to 1,000 times larger than prokaryotes; some can be seen just with the naked eye. The DNA of eukaryotes is protected within a special container, the nucleus, which limits the damage to genetic material and increases the accuracy of reproduction.

Many eukaryotic cells contain mitochondria, special "organelles" that can generate energy from oxygen—a more powerful source of energy than "fermentation," the reaction used to generate energy in prokaryotes. So eukaryotes flourished in an oxygen-rich atmosphere. The appearance of eukaryotes marks a significant increase in the complexity of life. Lynn Margulis and Dorion Sagan write, "The difference between the new cells and the old prokaryotes in the fossil record looks as drastic as if the Wright Brothers' Kitty Hawk flying machine had been followed a week later by the Concorde jet" (Margulis and Sagan, *Microcosmos*, p. 115).

The fourth crucial transition is the appearance of sexual reproduction about 1 billion years ago. Prokaryotes regularly exchange genetic material, but they normally reproduce simply by splitting into two identical individuals or "clones." In most eukaryotes, two organisms exchange genetic material before reproduction, so that offspring contain a mix of genetic material from two parent individuals. As a result, offspring are no longer simply clones of their parents. Sexual reproduction introduces greater variation between individuals. As natural selection "selects" from such variations, the result of sexual reproduction is to speed up the rate of evolution. This is why evolution seems to have accelerated during the last 1 billion years.

This lecture has surveyed the first 3.5 billion years of the history of life on Earth, during which all organisms were single-celled. How were multi-celled organisms created, and how did they evolve over the last 600 million years? That is the subject of the next lecture. ■

Essential Reading

Brown, *Big History*, chap. 2.

Christian, *Maps of Time*, chap. 5.

Fortey, *Life: An Unauthorised Biography*.

Supplementary Reading

Gould, *The Book of Life*.

Margulis and Sagan, *Microcosmos*.

Questions to Consider

1. What were the most important changes in the history of life before the appearance of multi-celled organisms?

2. Why does photosynthesis count as such an important development in the history of life on Earth?

Life on Earth—Multi-celled Organisms

Lecture 17

There's a sense in which we have to remind ourselves that we, too, from a certain point of view, are merely vast crowds of billions of single-celled eukaryotic cells, organisms.

This lecture traces the evolution of multi-celled organisms during the last 600 million years. It describes four more transitions on the evolutionary pathway leading to our own species, *Homo sapiens*. The first transition we discuss in this lecture is the appearance of multi-cellular organisms almost 600 million years ago. As late as the 1950s, most biologists thought that life itself first appeared on Earth only in the Cambrian era, about 570 million years ago, because that was when the first naked-eye fossils appeared. We now know that single-celled organisms had already existed for almost 3 billion years. What the Cambrian era really marks is the appearance of the first *multi-cellular* organisms.

The evolution of multi-cellular organisms was a complex process. For such organisms to work, billions of cells had to cooperate and communicate with great precision. It was also necessary for them to be able to communicate with each other in some way, and for each cell to know its place and role in the functioning of the organisms as a whole. These are staggering organizational challenges. However, as we have seen, such challenges were not entirely unprecedented, for evolution can involve cooperation as well as competition. In fact, simpler forms of cooperation that do not count as multi-cellularity had already evolved. Even eukaryotes formed through a symbiosis between distinct types of prokaryotes.

Early forms of collaboration took several forms. Stromatolites, like coral reefs, formed from huge colonies of individual prokaryotes in which the colony provided some protection to each individual cell. Some sponges that look like single organisms will reassemble if passed through a sieve, so we must assume that each cell retains its independence. Particularly fascinating are slime molds, colonies of amoeba that can come together to form a single entity when times are tough and then break apart again when conditions improve. None of these species count as multi-cellular organisms. Nevertheless, the growing interdependence and specialization of their cells point toward multi-cellularity.

Genuine multi-cellularity requires that all participating cells have identical genetic material in order to avoid competition between cells. In human beings, for example, a fertilized cell will create billions of clones, each with the same genes. Yet each cell can develop in different ways, depending on the chemical environment in which it finds itself, for different chemicals can activate different parts of a cell's genetic code. In this way, genetically identical cells can develop into any of the 210 distinct types of cells in human bodies, from bone cells to liver cells to brain neurons. Specialization allows multi-cellular organisms to handle a wider range of functions than single-celled organisms.

About 67 million years ago, right at the end of the Cretaceous period, an asteroid impact (the "Cretaceous event") destroyed most large species, including dinosaurs.

Multi-cellularity allowed the construction of gigantic organisms. To a prokaryote, you or I might look like a vast, mobile version of the Empire State Building. Indeed, our bodies contain as many cells as there are stars in the Milky Way. Once the first multi-celled organisms appeared, they evolved rapidly in an "adaptive radiation." Adaptive radiations occur frequently in evolutionary history, when a new type of organism appears and rapidly evolves into a wide range of different species.

The art of classifying these different species ("taxonomy") was pioneered by Carl Linnaeus in the 18th century. Taxonomy groups living organisms into many nested categories. Today, the largest generally recognized category divides all living organisms into two "superkingdoms," prokaryotes and eukaryotes. Below that come the "kingdoms," which include animals, plants, and fungi. Then come "phyla" (such as the chordates), "classes" (such as mammals), "orders" (such as primates), and finally "species" (such as human beings). Now we will discuss the evolution of those categories of organisms that included our own ancestors.

The second major transition on the road to modern humans is the appearance of the first vertebrates. We belong to the phylum of chordates, or vertebrates—organisms with backbones. The first vertebrates evolved about 500 million years ago, in the Ordovician period, from worm-like ancestors. They were probably unimpressive fish-like creatures with no heart or brain, a bit like modern "lancelets." All vertebrates have a front and back end, and a complex system of internal communications through nerve cells running along the spine. The vertebrates include fish, amphibia, reptiles, birds, and mammals.

The third major transition leading to humans is the movement of some multi-cellular organisms from the sea to the land. Plants and insects probably reached the land first about 500 million years ago, during the Ordovician period. The first vertebrates to leave the sea did so about 400 million years ago, during the Devonian period. Leaving the sea posed huge challenges. You needed a strong skeleton as water no longer supported your weight. You needed a tough skin to avoid drying out. You needed special apparatus enabling you to breathe oxygen directly rather than through the water. And you needed some way of reproducing in a watery environment so your offspring would not dry out. The first vertebrates to live for prolonged periods on land were probably a bit like modern lungfish, which can survive for some periods on land if the ponds they live in dry out. Two important "classes" of vertebrates were:

- The amphibia, which lived on the land permanently but returned to the water to lay eggs, and which evolved during the Devonian period; and

- The reptiles, which evolved about 350 million years ago, during the Carboniferous period, and laid their young in eggs protected within tough skins.

The fourth transition on the path toward modern humans is the appearance of the class of mammals about 250 million years ago, during the Triassic period. As the supercontinent of Pangaea was forming, the majority of living species vanished during the Permian period, from about 290 to 250 million years ago. This mass extinction may have been caused by an asteroid impact, though at present this is by no means certain. Another possibility is that it was caused by the coming together of many once-separate regions to form a supercontinent within which many different species had to compete for fewer niches. The removal of so many earlier species created space for a rapid "adaptive radiation" of new species. Two important new groups of vertebrates were the dinosaurs and mammals, both of which appeared in the Triassic period, between 250 and 210 million years ago. The class of mammals contains furry, warm-blooded organisms that nurture their young within their mother's body and feed them with milk. (Even humans have fur, though not much!) The earliest mammals were probably small, shrew-like animals that foraged for insects at night.

About 67 million years ago, right at the end of the Cretaceous period, an asteroid impact (the "Cretaceous event") destroyed most large species, including dinosaurs. That there was such an impact was demonstrated only in the 1980s by geologist Walter Alvarez. Mammal species diversified rapidly in a new adaptive radiation, filling niches vacated by the dinosaurs. As part of this mammalian radiation there appeared a new order of mammals, the primates: tree-dwelling mammals with stereoscopic vision, hands designed to grasp, and larger brains. We'll cozy up to the primates in the next lecture because we, too, are primates.

We have seen four crucial stages in the evolution of multi-celled organisms like ourselves. Each of the eight stages of evolution described in this and the last lecture contributed something to the makeup of our own species, *Homo sapiens*. We will see how in the next lecture. ■

Essential Reading

Brown, *Big History*, chap. 2.

Christian, *Maps of Time*, chap. 5.

Fortey, *Life: An Unauthorised Biography.*

Supplementary Reading

Alvarez, *T. Rex and the Crater of Doom.*

Gould, *The Book of Life.*

Lovelock, *Gaia.*

Questions to Consider

1. Why did multi-celled organisms evolve so late in the history of life on Earth?

2. How great a role was played by chance in the evolution of the life forms that exist today?

Hominines

Lecture 18

Many of the crucial differences between plants and animals arise from this simple but fundamental difference: They can photosynthesize; we can't.

The last two lectures described evolution in general, focusing on those evolutionary lines that would eventually lead to our species. Now we are ready to ask how our ancestors evolved from the primates. First we must be clear about our place in the biological world. We have seen that modern systems of biological classification (or "taxonomy") build on the work of Carl Linnaeus (1707–1778). The multiple levels of a taxonomy (from superkingdom to species) allow us to define each species uniquely so as to reveal its position in the huge family tree of life. You and I belong to the "superkingdom" of eukaryotes (we're made from eukaryotic cells); the "kingdom" of animals (we're not single-celled, nor are we plants or fungi); the "phylum" of vertebrates, or "chordata" (we have backbones); the "class" of mammals (we're furry, warm-blooded, and our young develop within the womb); the "order" of primates (lemurs and monkeys); the "family" of hominoids (great apes); the "subfamily" of hominines (bipedal apes); the "genus" *Homo*; and the "species" *Homo sapiens*. (Note that classification systems differ in details.) In short, we are eukaryotic, multi-celled mammals from the order of primates.

The order of primates appeared about 65 million years ago, at about the time of the Cretaceous asteroid impact. The primates include all monkeys and lemurs, from tarsiers to gorillas, as well as humans! Primates share some distinctive features. Because early primates lived in trees, they developed stereoscopic vision and grasping limbs. Perhaps because visual information requires a lot of processing capacity (for brains as for computers), primates have disproportionately large brains for their size. (Elephants have huge brains, but their bodies also use a lot of computing capacity so it's brain size *relative* to body size that really counts.) Larger brains generally imply longer lives to take advantage of the brain's capacity to learn. The sense of smell is less important, so most primates have small snouts and flattish faces.

The “great apes” are a “family” within the “order” of primates. They are large, intelligent, tailless primates. The family includes chimpanzees, gorillas, orangutans, gibbons, and humans as well as many extinct species. The great apes evolved in Africa about 18 million years ago, though some eventually migrated to other parts of Eurasia. Only in recent decades have we begun to realize how complex their social lives are, through the pioneering work of researchers such as Jane Goodall (1932–) and Dian Fossey (1932–1985), who studied the great apes in their own environments. The striking similarities between us and the great apes persuaded Darwin that we were closely related.

In short, we are eukaryotic, multi-celled mammals from the order of primates.

The “hominines” (or “hominids”) are a “subfamily” of apes that walked upright. They evolved 7 million years ago. This date is based on comparisons of the genetic material of modern great apes, because we have few fossils from this era. Genetic evidence suggests that the human line split from the chimp line about 7 million years ago, and from the gorilla line about 8–10 million years ago. The hominines diverged rapidly in a new “radiation” that may have included 20 or 30 distinct species. However, today, we are the only survivors of this diverse group of great apes. In recent decades many hominine fossils have turned up, and these show that the first hominines were characterized not by large brains, but by bipedalism—the ability to walk on two legs.

Why bipedalism? We have no conclusive answers. The creation of the African Rift Valley beginning 15 million years ago raised mountains that left much of East Africa in a rain shadow and reduced forest cover. French researcher Yves Coppens suggested that bipedal species would have found it easier to travel through the resulting grasslands and to see dangers and opportunities as they did so. Unfortunately, the recent discovery of hominine species in forested environments has undermined this promising idea.

In what follows, we will focus on just three major groups of hominines. The “australopithecines” were a large and varied group of hominines that lived from about 4 million to about 1 million years ago. They include Lucy, whose remains are described in the next lecture. Australopithecines were bipedal, though they may still have used trees as refuges. They were shorter than humans, the tallest being less than five feet tall. At about 400–500 cubic centimeters (cc), their brains were slightly larger than those of chimps (300–400 cc) but about one-third the size of human brains (which average about 1,350 cc). Some may have made stone tools, but there is no sign of significant technological ability or enhanced linguistic ability. Though we are probably descended from one branch of the australopithecines, we would probably not think of them as humans if we were to meet one in the street today.

Homo habilis ("handy man") appeared about 2.3 million years ago. *Homo habilis* were probably just under 5 feet tall and had brains of 600–800 cc. Louis Leakey regarded them as the first real humans because they made stone tools. (This is a powerful reminder of how paleontologists can shape such stories. Leakey belonged to a generation that regarded the use of tools as the key marker of humanity.) Tool use implies considerable intellectual ability and may have improved diets by making it easier to scavenge meat. But today few paleontologists share Leakey's view that they were the first true humans. This is partly because they had small brains, partly because other ape species have been shown to use tools, and partly because their technologies did not evolve significantly.

Another species, *Homo ergaster*, evolved about 1.8 million years ago. They were as tall as us, and their brains (at about 1,000 cc) were almost as large as ours. They made more sophisticated "Acheulian" stone tools, often in the form of carefully manufactured stone "axes." Members of this species were the first hominines to migrate out of Africa. As these migrants entered the colder lands of southern Eurasia, reaching as far as modern Beijing, they may have learned to use fire. Nevertheless, their stone tools changed little over 1 million years, which suggests that they too lacked the technological creativity that distinguishes modern humans.

By 1 million years ago most of the features that define us as a species were already present, but there was no sign yet of the technological and ecological creativity that makes us so different. Clearly some sort of threshold still had to be crossed. But before we describe the crossing of that critical threshold, we must examine the evidence used to trace the evolution of our species. ■

Essential Reading

Brown, Big History, chap. 3.

Christian, Maps of Time, chap. 6.

Fagan, People of the Earth, chap. 2.

Supplementary Reading

Johanson and Edey, Lucy.

Jones, The Cambridge Encyclopedia of Human Evolution.

Lewin, Human Evolution.

Questions to Consider

1. What features do humans share with other primates?

2. Was Louis Leakey wrong to regard *Homo habilis* as humans?

Evidence on Hominine Evolution

Lecture 19

It gives you some sense of the extreme excitement of finding 40% of a skeleton. Paleontologists are used to meager rations. They can get very excited if they can find one tooth or one knucklebone.

Like many parts of this course, the modern story of human evolution is very recent. Even 50 years ago, we had far less information than we have now. Before completing the story of human evolution, we need to survey the evidence on which it is based. The evidence falls into three main categories: archaeological evidence, evidence based on the study of modern primates, and evidence based on genetic comparisons between modern species of primates, including ourselves. The most important evidence comes from surviving remains of our ancestors and the objects they left behind. Such evidence can tell us much about the physiology of our ancestors and their diets and lifeways. Some of the most exciting hominine remains have come from the African Rift Valley, the tectonic tear running from Mozambique through Tanzania and Kenya to Ethiopia.

In 1974, in Hadar, Ethiopia, Don Johanson and his colleagues found almost 40% of the remains of a hominine individual about three and one-half feet tall. This is one of the most complete hominine skeletons ever found. Johanson christened the remains "Lucy," because his team had been listening to the Beatles song "Lucy in the Sky with Diamonds."

Study of the pelvis and the base of the skull proved that she was bipedal. In quadrupedal species, the spine enters the skull from behind, not from below.

Lucy illustrates well what skeletal remains can tell a skillful team of archaeologists. Radiometric dating of nearby materials determined that Lucy lived about 3.2 million years ago. Study of the pelvis showed that Lucy was female. Study of the teeth and other anatomical features suggested Lucy belonged to the genus of australopithecines (genus is the next taxonomic level above species) and that she died in her twenties.

Study of the pelvis and the base of the skull proved that she was bipedal. In quadrupedal species, the spine enters the skull from behind, not from below. Yet her brain (at about 450 cc) was only slightly larger than that of a chimp (chimp brains average 350 cc). Clearly, bipedalism evolved before large brains. In 1978, Mary Leakey discovered fossilized footprints left by three australopithecines who had walked through still-warm lava, in Laetoli, Tanzania (also in the rift valley), about 3.6 million years ago. They confirmed that australopithecines were bipedal. Skeletons can tell us much more. For example, paleo-dentists can tell whether a tooth was used to eat plants or meat, and knowledge of diets can tell us a lot about lifestyles.

Louis Leakey (1903–1972) and his family made Olduvai gorge, also on the rift valley, one of the most famous of all sites for human paleoanthropology. Like the South Dakota badlands, this is an area where geological processes break open the Earth's crust for us, revealing large numbers of fossil remains. In 1964, Leakey's son Jonathon found a 2.3-million-year-old skull that was about half the size of a human skull (about 600 cc). Despite the smallness of the skull, Louis Leakey announced that a new species had been found, and he classified it as *Homo habilis*, placing it within the same genus as us.

Leakey insisted on classifying these remains within the genus *Homo* because *habilis* made tools. Their tools are known as "Oldowan," after the Olduvai Gorge. Oldowan stone tools were made from pebbles of quartz, flint, or even obsidian that were struck together to remove flakes that could be used as cutting edges. The leftover cores may have been used as crude hammers. Leakey was impressed because these tools, though unsophisticated by later standards, suggested the sort of technological creativity he expected from humans. Modern attempts to manufacture Oldowan tools suggest considerable skill was needed for their manufacture. Microscopic study of stone tools can suggest what materials they were used on, and this can tell us something about diets and lifeways. For example, *Homo habilis* seem to have had an omnivorous diet dominated by plant foods such as leaves and fruits. Microscopic studies of cut marks and scratches on animal bones at hominine sites can determine whether hominines hunted for themselves or scavenged animals killed by others. The cut marks inflicted by the stone tools of *habilis* often lie *over* the teeth marks of carnivores, which suggests that they generally scavenged from animals already killed by other carnivores.

A second vital type of evidence for understanding hominine evolution comes from studies of closely related species that are still alive today. Richard Leakey's former students, Jane Goodall and Dian Fossey, pioneered the study of apes in the wild. They showed that the great apes have complex and clearly defined social relationships that differ from species to species: For example, males compete for dominance. They also showed that humans are not the only great apes to use tools. For example, chimps often strip leaves from sticks to fish out termites from termite mounds. Though no apes make tools as sophisticated as those of *habilis*, this finding undermined Leakey's claim that *habilis* was the first great ape species to use tools.

The most recent technique for studying human evolution uses genetic evidence from living species. The evolution of genetic dating techniques counts as one part of the "chronometric revolution" described in Lecture Four. Genetic dating was pioneered by Alan Wilson and Vincent Sarich in the 1960s. How does it work? Many genes are not expressed in the physical body, so they do not all affect a species' "fitness." Such genes can therefore change randomly, so we can use statistical methods to estimate how much random genetic change there has been between two different species. By calibrating these differences against other evidence (such as the knowledge that mammal species diverged rapidly after the Cretaceous extinctions of 65 million years ago), we can estimate when two species may have shared a common ancestor. When they first proposed the idea, Wilson and Sarich met with great skepticism, but since then, genetic dating has become a fundamental tool for the study of evolution in general. Genetic dating techniques have revolutionized our understanding of human paleontology by showing that the DNA of humans and chimps differ by little more than 1%. This suggests that the two species had a common ancestor about 7 million years ago, rather than 15–20 million years ago as suggested by earlier studies of skeletal remains. This date establishes a clear time frame for the history of human evolution. Such techniques are particularly important because so few fossil remains survive from this era. We've seen some of the evidence used to construct the story of human evolution, and now we can complete the story. The next lecture asks: What was it that made our species so different? ■

Essential Reading

Christian, *Maps of Time*, chap. 6.

Fagan, *People of the Earth*, chap. 2

Supplementary Reading

Johanson and Edey, *Lucy.*

Jones, *The Cambridge Encyclopedia of Human Evolution.*

Lewin, *Human Evolution.*

Questions to Consider

1. What are the most important forms of evidence used to reconstruct the evolution of our species?

2. How have techniques of genetic dating transformed our understanding of hominine and human evolution?

Threshold 6—What Makes Humans Different?

Lecture 20

[Big history] encourages us to think seriously about questions such as the meaning of being human. And it encourages us to think that they are not just metaphysical or philosophical questions, but they are questions to which there may be good, rigorous, evidence-based scientific answers.

What does it mean to be human? The previous lectures described the history of life on Earth and the evolution of our own ancestors through the adaptive mechanism of natural selection. The next group of lectures takes us across a new threshold, describing the creation of our own species and the earliest stages of human history. But before we can determine when our species appeared we need some clear ideas about the features that distinguish us from other hominines. The differences, we will see, are fundamental.

We have seen how similar we are to other living organisms. Now we must ask: What makes us so different that our evolution counts as a fundamental turning point in the history of our planet? One distinctive feature is the amount of energy we control. Eric Chaisson has calculated that about 20,000 ergs per second per gram flow through large-bodied animals such as apes. He calculates that modern humans use on average 25 times as much energy (500,000 ergs/sec/gram; calculated by dividing total energy consumption by the number and mass of human beings; Chaisson, *Cosmic Evolution*, pp. 136–39). Though approximate, these figures clearly point to a profound difference between us and all other animal species.

Human control of energy increased slowly at first, then accelerated. In the Paleolithic era, more than 10,000 years ago, humans probably used enough energy to stay alive with a small surplus, perhaps 3,000 to 5,000 kilocalories a day. Early agriculturalists may have used up to 12,000 kilocalories a day. Today, each of us uses on average 230,000 kilocalories a day. In contrast, chimp use of energy, like that of most other species, has remained stable. More energy allowed humans to multiply. Today, there are a few hundred thousand chimps (and their numbers are dwindling rapidly). But there are 6 billion humans. More people and more energy help explain why modern human society is so complex.

Why does our species control such extraordinary amounts of energy? We have seen that all living organisms explore their environments in the search for the energy they need. But humans apparently do this peculiarly successfully. Indeed, we seem to continually find new ways of getting energy and materials from our environment. Our adaptability was apparent even in the Paleolithic era, the oldest era of human history, as migrations took our ancestors into many different environments and to all continents except Antarctica, because each new environment required new ways of controlling energy.

If chimps function mostly like stand-alone computers, modern humans are networked.

In summary, most species, like the Galapagos finches, develop a way of exploiting their environment and survive only as long as their technique works. In contrast, humans constantly develop new ways of extracting resources from their environments.

Our extraordinary ability to adapt, and to keep adapting, makes us very powerful. Our astonishing control of the planet's resources is now affecting other species. According to some estimates, we may be controlling 25%–40% of all the energy that enters the biosphere through photosynthesis. This leaves less energy for other species, which may explain why other species are dying out at a rate comparable to the five or six greatest extinction episodes of the last billion years. We may be strange even on cosmological scales. For almost 50 years, astronomers have searched, without success, for evidence of other organisms with a similar level of technological creativity. Perhaps we are unique on galactic scales!

Why are we so good at adapting? There is no universally accepted answer. However, lines of argument in several disciplines, from psychology to anthropology and archaeology, seem to be converging on some revealing answers. What follows is based on some of this scholarship. I will argue that our species is endowed with a unique and extraordinarily powerful adaptive mechanism: "collective learning." That's a term I'll use a lot so I need to explain it carefully.

Adaptation by natural selection is slow. Because it depends on genetic changes, it can take hundreds or thousand of generations for changes to evolve and spread. But there are other ways of adapting. Organisms with brains can change how they relate to their surroundings within a single lifetime. This is "individual learning." It works faster than natural selection, but it has limitations. Individual learning is costly because brains consume lots of energy and have to be fed. Emperor Hirohito, who was a biologist, once studied a species of sea slug that illustrates the point nicely by eating its brain once it no longer needs it. Individual learning is not cumulative. Most of what an individual learns cannot be passed on to others, so each individual has to start from scratch.

Now imagine a species in which individuals could pass on most of what they learned to other members of their species. Here we would have a third, and much more rapid, way of adapting—because what each individual learned would then be stored within the entire community. This is the unique gift humans acquired with human language. Simple forms of communication depend on one-to-one correspondence, like the warning call of a vervet monkey: A bark-like call means a leopard, while a sort of stutter means a snake. Such utterances can communicate about as much information as an ambulance siren. Most animal languages seem to take this form.

However, humans are capable of using "symbolic language." Symbols are arbitrary signs that can group many observations or ideas within larger categories and can therefore rearrange information in many new ways. While a vervet can say "leopard," it cannot say exactly where the leopard is or what it is doing. Symbols *can* convey such information. They can even refer to things that are not present (such as the leopard I saw yesterday) or things that may not exist (pink elephants or Santa Claus).

Human languages also have elaborate grammatical systems that greatly enhance their efficiency. Grammar lets us arrange symbols in almost infinite configurations so humans can use word pictures to convey large amounts of complex information with great precision. Unlike a vervet, a human could explain, for example, that: “My cousin was killed by a cat-like predator at the water hole one mile away to the south of the volcano.”

Symbolic language allows humans to exchange so much information so precisely and so rapidly that more information is transmitted than is lost. As a result, large stores of information can begin to accumulate within the community as a whole. If chimps function mostly like stand-alone computers, modern humans are networked. Each of us has access to a vast communal database of information about how to adapt to our environment.

I call this unique form of adaptation “collective learning.” If this line of argument is correct, it suggests that collective learning is what explains our exceptional ability to adapt. It is what makes our species unique on this planet, and it explains why human history represents a new level of complexity. Note that this argument does not yet count as an established orthodoxy, though many researchers are converging on some form of it.

Note, also, that it does not depend on individual humans being smarter than individual apes. It is the *sharing* of information that makes us different. Humans, unlike apes, face their environments armed with a vast amount of information accumulated by millions of individuals over many generations. Collective learning explains why only humans have a history of constant change, as humans have accumulated more and more information about the world they inhabit. Indeed, human history is all about the many changes made possible by our capacity for collective learning. Collective learning explains why we have gotten better and better at extracting energy and resources from the environment and why, collectively, we have become one of the most complex entities in the Universe.

This lecture has argued that we are different because we have access to a new and uniquely powerful adaptive mechanism: collective learning. How and when did our ancestors first acquire this unique ability? That is the question tackled in the next lecture. ■

Essential Reading

Christian, *Maps of Time*, chaps. 6, 7; pp. 171–76.

Lewin, *Human Evolution*.

Supplementary Reading

Deacon, *The Symbolic Species.*

Pinker, *The Language Instinct.*

Tomasello, *The Cultural Origins.*

Wright, *Nonzero.*

Questions to Consider

1. What evidence is there that our species is radically different from other hominines?

2. What is "collective learning," and why does it give our species such a striking ecological advantage?

Homo sapiens—The First Humans

Lecture 21

Recent analyses of DNA extracted from Neanderthal skeletons suggest something very, very clear indeed. It suggests that Neanderthal and human lines split more than 500,000 years ago—maybe 600,000 or 700,000 years ago. And what that suggests is that we really are talking about different species. We're not talking about minor variations on the same species. And that evidence also seems to rule out any possibility that humans and Neanderthals interbred.

So, here we are. Though tantalizingly close to us, neither *ergaster* nor Neanderthals display quite the technological creativity that is the birthmark of our species, nor apparently the ability to communicate with the fluency, precision, and speed of modern humans. Both species disappeared about 20,000 to 30,000 years ago, probably under pressure from our species.

The last lecture suggested that our astonishing ecological creativity arises from our capacity for "symbolic" language, which allows us to learn collectively. If this argument is correct, how can we tell when the first real humans appeared? What evidence could show the presence of symbolic language and a new level of ecological and technological creativity?

Unfortunately, the evidence is so sparse and hard to interpret that we have few unambiguous answers. This makes it important to be clear about the sort of evidence we are looking for. In principle, we can imagine two main types of archaeological evidence that might show that the threshold to collective learning has been crossed. The first is evidence for symbolic language. Of course, language leaves no direct archaeological traces. But it may leave indirect traces. Studies of the base of the skull show how the larynx was placed, which can suggest how well a species could manipulate sounds. Sculpture or cave (or body) painting may indicate that a species was capable of symbolic thought and language.

The second type of evidence is anything that might show an acceleration in innovation or adaptation, or increasing variety in the technologies used by different human communities. Unfortunately, early evidence of accelerating technological change is scarce and ambiguous, particularly from Africa, where our species probably evolved.

Fossil evidence for most of the last million years is dominated by two other hominine species, *Homo ergaster* and *Homo neanderthalis*. Could they speak? And could they adapt with the virtuosity of modern humans? We saw in Lecture Eighteen that *ergaster* evolved almost 2 million years ago. Some migrated to Indonesia and China. They probably used fire, and certainly used "Acheulian" stone tools, which were better made than the "Oldowan" tools of *Homo habilis*. This is evidence of technological creativity but not of *exceptional* creativity. Other species (including apes such as orangutans) had migrated from Africa to Asia; evidence on *ergaster* control of fire remains limited, and their stone tools barely changed over 1 million years.

Homo neanderthalis seem even closer to us. Neanderthals lived in ice age Europe and Russia. They were as tall as us and had brains as large as ours (perhaps even larger). They also manufactured more delicate and precisely made stone tools described by paleontologists as "Mousterian." They probably used fire and hunted large ice age mammals such as mammoth and woolly bison, which was no small feat!

Yet their technologies show limited variation over 200,000 to 300,000 years, and there is no proof that they had symbolic language. Indeed, studies of Neanderthal skulls suggest that their larynx would not have allowed them to speak like we do. (However, there is somewhat controversial evidence that Neanderthals buried their dead, which might imply a capacity for symbolic thought.) Recent analyses of DNA extracted from Neanderthal skeletons suggest that Neanderthal and human lines split more than 500,000 years ago.

Though tantalizingly close to us, neither *ergaster* nor Neanderthals display the technological creativity that is the birthmark of our species. Both species disappeared about 20,000 to 30,000 years ago, probably under pressure from *Homo sapiens*.

Currently, there are two competing explanations for the origins of *Homo sapiens*. The "multi-regional hypothesis," defended by Milford Wolpoff and Alan Thorne, argues that our species evolved gradually throughout Africa and Eurasia from *Homo ergaster*. It implies that most hominines in this era belonged to a single, evolving species, with regional variants that show up today in racial differences. However, most anthropologists are skeptical that individuals could remain sufficiently interconnected over such large distances to remain a single species.

At present, most paleontologists prefer the "Out of Africa" hypothesis, according to which our species evolved quite rapidly in Africa within the last 250,000 years. This theory builds on recent developments in evolutionary thought and dating techniques. In their theory of "punctuated equilibrium," Stephen Jay Gould and Niles Eldredge showed that the pace of evolution can vary significantly, so that sometimes new species can evolve within thousands rather than millions of years.

I will argue in the rest of this course that human history really begins between 200,000 and 300,000 years ago, somewhere in Africa.

One mechanism for rapid evolutionary change is "allopatric speciation." If individuals at the edge of a species' range get cut off for many generations, they may diverge rapidly from a parent population because variations can spread rapidly in small populations. Besides, such groups may already be statistically atypical. Allopatric speciation may explain the rapid species formation Darwin observed on the Galapagos Islands and the sudden appearance of modern humans.

Modern genetic dating techniques show that modern humans are closely related and probably evolved within the last 250,000 years. The fact that the greatest variation appears within Africa suggests that that is where humans have lived longest. Finally, the earliest fossil evidence of anatomically modern humans comes from Africa, and the oldest remains of modern humans are about 160,000 years old.

Perhaps we appeared even more recently? Archaeological evidence seems to show an acceleration in technological change in Europe and Russia about 50,000 years ago. Improved stone tools appeared, as did new materials including bone and skins. Cave paintings and carved objects provide evidence of symbolic thought. Some specialists argue that this "Revolution of the Upper Paleolithic" proves that even if *Homo sapiens* evolved earlier, modern human *behaviors* appeared only 50,000 years ago, perhaps as a result of tiny changes in the wiring of the brain. If this is correct, then the critical threshold may have been crossed—and human history would have begun—just 50,000 years ago.

I am not a paleontologist, but recent work by two paleontologists, Sally McBrearty and Alison Brooks, has convinced me that the good money is on the "Out of Africa" hypothesis. So, with a warning that opinion could change if new evidence appears, I will argue in the rest of this course that human history really begins between 200,000 and 300,000 years ago, somewhere in Africa. What's the evidence for this conclusion?

McBrearty and Brooks argue that the "Revolution of the Upper Paleolithic" is an illusion, created simply because much more archaeology has been done in Europe than in Africa. Their detailed survey of the scanty archaeological evidence from Africa suggests that the technologies that appear in the Upper Paleolithic had already evolved in Africa. From almost 300,000 years ago, new technologies, and even hints of symbolic activity (such as the use of ocher), appear in association with a new hominine species, *Homo helmei*, which they regard as an early version of *Homo sapiens*. Blombos cave in South Africa offers a good illustration. It was occupied from 70,000 years ago. Its inhabitants used ocher (presumably to paint their bodies) and made fine stone tools. They used shellfish and may have fished.

The details of how our species evolved remain unclear, but currently the bet is on a rapid appearance of modern humans about 200,000 to 300,000 years ago, somewhere in eastern or southern Africa. The next lecture asks: How did the first humans live during the earliest phase of human history—the Paleolithic era? ■

Essential Reading

Christian, *Maps of Time*, chap. 7.

———, *This Fleeting World*, chap. 1.

Fagan, *People of the Earth*, chap. 3.

Supplementary Reading

Lewin, *Human Evolution*.

McBrearty and Brooks, "The Revolution That Wasn't."

Ristvet, *In the Beginning*, chap. 1.

Questions to Consider

1. What are the most powerful reasons for thinking that our species appeared between 200,000 and 300,000 years ago in Africa?

2. What reasons are there for arguing that Neanderthals were not fully human?

Paleolithic Lifeways

Lecture 22

When historians say: "I don't do the Paleolithic because I do written evidence," it's a bit as if Sherlock Holmes were to say, in the middle of one of his investigations: "Sorry, chaps, I can't pursue this case any further because there are blood stains, and I don't do blood stains."

Genetically, the earliest human beings were more or less identical to you and me. If the arguments of the previous lecture are correct, their emotional lives were as rich as ours, they were as intelligent as humans today, and they communicated as fluently. Yet their lives were, of course, very different. How did our ancestors live during the 250,000 years or so of the Paleolithic era? Though we have no detailed records about particular communities of the Paleolithic era, no precise dates, and of course no names, we have enough evidence to sketch out some very general answers to these important questions.

In this course, we will divide human history into three main eras: the Paleolithic, the Agrarian, and the Modern. The Paleolithic era (or "Old Stone Age") is the first and by far the longest era of human history. The idea of classifying historical eras by surviving tool types was the brainchild of 19th-century Danish archaeologist C. J. Thomsen. In the mid-1860s, English naturalist John Lubbock further subdivided the Stone Age into an "Old Stone Age" (the *paleo*-lithic era), and a "New Stone Age" (the *neo*-lithic era). The term "Paleolithic" is often used for the entire period since *habilis* made stone tools 2 million years ago. But in this course, we confine it to the period from the first appearance of *Homo sapiens* (about 250,000 years ago) to the earliest appearance of agriculture (about 10,000 years ago). The Paleolithic era laid the foundations for human history, so it is a shame that historians often ignore it.

To get a preliminary sense of the distinctive features of the Paleolithic era, it will help to compare it very broadly with the other two eras: the Agrarian era (from 10,000 years ago to about 500 years ago) and the Modern era (the last 500 or so years). The Paleolithic era occupies about 96% of the time that our species has existed, and the Agrarian era occupies most of the remaining 4%. However, Paleolithic populations were small. Of the 80 billion humans estimated to have lived since our species first appeared, only about 12% lived in the Paleolithic era, while about 68% lived in the Agrarian era and about 20% in the Modern era.

We have two main types of evidence on Paleolithic lifeways. Most important are archaeological remains. Almost as valuable are studies of modern societies that still use Paleolithic technologies. However, such studies can be misleading, because today no foraging societies remain untouched by the modern world.

Modern studies of foraging societies suggest that people often survived on just 3–6 hours of work a day.

Taken together, these forms of evidence can help us construct tentative sketches of Paleolithic lifeways. Our Paleolithic ancestors almost certainly lived in small, family-size groups, so that relations were personal, more like those in a modern family than those in a modern city. Their basic technology can be described as "foraging" (or sometimes as "hunting and gathering"). Paleolithic humans used stones, plants, insects, or animals from the environment more or less in their natural form. What distinguishes Paleolithic foraging from the foraging of many other animals is that our ancestors foraged using the knowledge accumulated within each community through collective learning. This meant they could exploit their environments in a much greater variety of ways.

To survive, foragers needed to use large areas. So Paleolithic communities were usually small and nomadic, traveling regularly to different parts of their home territory. In the jargon of economists, this was an "extensive" way of exploiting the environment—it depended more on using a large area than on using a small area more "intensively."

Family groups that traveled together probably met periodically with neighbors and relatives, usually in special places with enough food for large gatherings. Here, they exchanged marriage partners, gifts, and of course, information. We have modern descriptions of what these gatherings may have been like. These were "do it yourself" societies. Justice, for example, was a family affair.

It is a mistake to think our ancestors were unsophisticated. To survive using Stone Age technologies, they needed detailed "scientific" knowledge of their environments, accumulated through millennia of "collective learning" and stored in stories and myths. Southwestern Tasmania was one of the most remote environments on Earth in the Paleolithic era. Yet modern archaeological studies of Kutikina Cave, which was occupied from 35,000 years ago to perhaps 13,000 years ago, have revealed hundreds of stone tools, ancient hearths, delicate spear points of wallaby bone, and knives made from natural glass (Mithen, *After the Ice*, pp. 306–07). The first Tasmanians exploited their environment with great efficiency.

We have little access to the spiritual world of our Paleolithic ancestors. Yet Paleolithic art, such as cave paintings, hints at a rich artistic and spiritual life. Paleolithic religions were probably based on the "animistic" assumption that the world contains many different types of living beings. In 2006, in a cave in Botswana, archaeologists found evidence dating back more than 70,000 years that delicate stone tools were presented as gifts to a python god whose shape had been carved from a large boulder.

How well did people live? This question matters, because if Paleolithic lives were desperately hard, we may conclude that human history is a story of progress. But if their lives weren't too bad, we may have to question our assumptions about progress.

To many, it may seem obvious that Paleolithic lifeways were harsh, brutal, and unpleasant. Yet in 1972, American anthropologist Marshall Sahlins wrote a famous article, "The Original Affluent Society," in which he questioned these assumptions. Sahlins argued that in some ways Paleolithic life was not too bad. Being nomadic, people had little desire to accumulate goods. This, he describes as the "Zen" path to abundance: a feeling that everything you need is all around you. Diets were often healthy and varied. Modern studies of foraging societies suggest that people often survived on just 3–6 hours of work a day. Because there was little accumulated wealth, Paleolithic societies were more egalitarian than those of today (though this does not mean there were no conflicts between individuals, or divisions by age, lineage, and gender).

On the other hand, studies of Paleolithic skeletons suggest that most people died young, usually from physical trauma of some kind. Sahlins may have overstated the case, and we can be sure that someone reared in a modern society would struggle to survive in a Paleolithic society. Nevertheless, Sahlins's article reminds us that we should not *assume* without question that history is a story of progress.

This lecture has sketched some of the most general features of life in the Paleolithic era as if nothing changed. But we are a dynamic species, so in fact there was plenty of change. The next lecture asks: What were the main historical changes in the Paleolithic era? ■

Essential Reading

Christian, *Maps of Time*, chap. 7.

Fagan, *People of the Earth*, chaps. 4–6.

Ristvet, *In the Beginning*, chap. 1.

Supplementary Reading

Gamble, *Timewalkers*.

Mithen, *After the Ice*.

Sahlins, "The Original Affluent Society."

Questions to Consider

1. What are the most striking differences between Paleolithic lifeways and those of today?

2. Was Marshall Sahlins right to describe Paleolithic communities as "The Original Affluent Society"?

Change in the Paleolithic Era

Lecture 23

Today, we're at the end of an interglacial that's already lasted 10,000 years—and that's something worth thinking about.

One of the reasons why history texts rarely discuss the Paleolithic era is that things changed so slowly that it is easy to think of this as an era in which nothing happened. Indeed, Paleolithic peoples themselves may have seen history as a cyclical pattern **of** seasonal and life changes within an essentially unchanging world. This is a view of history that Romanian historian of religion Mircea Eliade called the "Myth of the Eternal Return." Yet, with the benefit of hindsight and with modern techniques for tracking and dating long-term changes, we can see that this view is illusory. At large scales, a lot happened in the Paleolithic era, so the astonishing adaptability of our species is already evident in the Paleolithic era. Though change was much slower than today (too slow to be observed by the people who lived through it), it was much faster than in any pre-human community.

This lecture will describe three main types of long-term change. First, we discuss the dramatic climatic and environmental changes associated with the ice ages. Second, we discuss the migrations that took Paleolithic humans to all parts of the Earth (except for Antarctica and the Pacific). Third, we describe the increasing impact of our Paleolithic ancestors on the natural environment.

The study of climate history has advanced rapidly in recent decades, driven partly by research into global warming. An example is the analysis of ratios of different oxygen isotopes in bubbles of air from ice cores. These ratios vary depending on the amounts of ice locked up in glaciers, so they can indicate changes in global temperatures.

Such techniques have revealed dramatic climatic changes. For 50 million years, global climates have slowly gotten cooler. This has reduced evaporation from the oceans and increased aridity. During the Pleistocene era (the last 2 million years), ice sheets spread in polar regions, generating a series of ice ages. In the last million years, ice ages have normally lasted about 100,000 years, with warmer "interglacials" of about 10,000 years in between. Our species has already survived two ice ages. Today, we are at the end of an interglacial that has already lasted 10,000 years.

At the coldest phases, tundra-like steppes and deserts spread, forests retreated, glaciers covered much of North America and northern Eurasia, sea levels fell as water was locked up in glaciers, and plant growth was less vigorous in middle and upper latitudes. These changes may have shaped the evolution of our ancestors because, with their brains and their increasing ability to network, they were ideally suited to survive such rapid environmental changes. In summary, for most of the Paleolithic era, global climates were generally colder and more arid than today, though these differences were less marked in tropical regions than in higher latitudes.

The most striking *historical* change in the Paleolithic era was the migration of modern humans around the world. Humans were good at adapting to new environments because, through collective learning, they kept generating new technologies as they explored the environments at the edges of their home ranges. Until about 100,000 years ago, all humans lived in Africa. During this "African" era of human history, which includes at least half of human history, humans settled new environments *within* Africa, adapting to deserts, forests, and sea shores.

In the last 100,000 years, some humans left Africa. Entering southern Eurasia was not hard; indeed, other species (including *ergaster*) had made similar migrations. But migrating further afield required more ingenuity. At the height of the last ice age, when sea levels were lower than today, Australia, Papua New Guinea, and Tasmania were joined in the single ice age continent known as "Sahul." Humans first entered Sahul about 50,000 years ago, from what is today the archipelago of Indonesia. Reaching Sahul required exceptional maritime skills, for migrants had to cross at least 40 miles of open water. When they arrived, they encountered completely unknown environments, animals, and plants. No other species had made this crossing successfully.

From 40,000 to 30,000 years ago, humans entered the tundra-like environments of ice age Ukraine, Russia, and Siberia. Plant life was less abundant here, so they had to learn to hunt large mammals such as mammoth, to tailor well-fitting skin clothing, and to manage fire. Sites from this era suggest how they lived. At Pushkari, in Ukraine, 19,000 years ago, where temperatures could fall to −30°C in winter, people lived in round houses built using mammoth bones. Though humans may have entered North America earlier, we know they crossed there from eastern Siberia by about 13,000 years ago.

By 13,000 years ago, the range of our species was already much wider than that of any other large mammal species, a clear sign that our remarkable ecological and technological prowess was already apparent in the Paleolithic era. These dates also suggest that the pace of innovation accelerated during the last 50,000 years. This is the archaeological reality behind the idea of an "Upper Paleolithic Revolution."

As humans migrated, their numbers increased, and so did the number of archaeological remains they left behind. Though estimates of Paleolithic populations are largely guesswork, Italian demographer Massimo Livi-Bacci suggests there were several hundred thousand humans 30,000 years ago and 5 or 6 million humans at the end of the Paleolithic era, about 10,000 years ago.

The dominant form of change in the Paleolithic era can be described using the ugly word "extensification" (as opposed to "intensification"). By "extensification," I mean technological change that allowed migration to new environments without permitting more intensive exploitation of existing territories. Extensification explains why the size and complexity of individual human communities did *not* increase during the Paleolithic era, though the total number of communities *did* increase.

As Paleolithic humans explored more environments and developed new techniques to deal with them, they began to have an increasing impact on their environments. Here are two striking examples. Humans transformed the environments of entire continents by systematically firing the land. Australian archaeologist Rhys Jones (1941–2001) coined the phrase "firestick farming" to describe how Australian aboriginal communities used fire to manage their environments. By regularly firing the land, they limited uncontrolled fires and stimulated new plant growth, which attracted prey species such as kangaroo. Similar practices were used in other parts of the world, including North America. Over thousands of years, firestick farming transformed entire landscapes. In Australia, for example, it encouraged the spread of fire-resistant species such as eucalypts. This means that the landscapes observed by the first Europeans to encounter Australia were not "pristine" at all; in their way, they were as manicured as the gardens of 18th-century Europe.

In Australia, 70% of mammals over 44 kg in weight may have vanished (about 60 species).

Humans may also have driven many large mammal species to extinction in a series of "megafaunal extinctions." In the last 50,000 years, many large mammal species have died out, including mammoth, giant kangaroos, saber-toothed tigers, and North American horses. Most extinctions occurred in newly colonized lands such as Australia and the Americas. In Australia, 70% of mammals over 44 kg in weight may have vanished (about 60 species).

The dates of these extinctions suggest that they coincided with the arrival of humans and may have been caused by overhunting, though climatic changes may also have played some role. "Megafaunal extinctions" transformed the biota of entire continents. However, there still remains disagreement about the precise contribution of humans to these extinctions. Among the earliest victims of our increasing ecological power were our closest relatives, *Homo ergaster* and *Homo neanderthalis*, both of which vanished about 20,000 to 30,000 years ago.

We have seen that a lot happened in the Paleolithic era, a clear sign of our species' remarkable capacity for adaptation and innovation. By the end of the last ice age, 10,000 years ago, humans had spread to all parts of the world, and there was no room left for further "extensification." Then, in several quite separate parts of world, a new type of technology appeared: agriculture. ■

Essential Reading

Christian, *Maps of Time*, chap. 7.

Fagan, *People of the Earth*, chaps. 4–6.

Ristvet, *In the Beginning*, chap. 1.

Supplementary Reading

Christian, *This Fleeting World.*

Flannery, *The Future Eaters.*

Mithen, *After the Ice.*

Questions to Consider

1. Does human history during the Paleolithic era support the claim that we are, indeed, radically different from all other animals?

2. What enabled our ancestors to settle almost all of the world during the Paleolithic era?

Threshold 7—Agriculture

Lecture 24

Humans transformed the environments of entire continents by systematically firing the land.

Threshold 7 of this course introduces a new type of technology: agriculture. The appearance of agriculture set human history off in entirely new directions by increasing human control of food, energy, and other resources. Rather as gravity pulled together clouds of hydrogen and helium atoms to form the first stars, so agriculture generated denser and denser human communities until, eventually, entirely new forms of complexity began to emerge, including cities, states, and entire civilizations. This lecture describes the appearance of agricultural societies, defines agriculture, and discusses agriculture's impact on human history.

The "early Agrarian era" is the first of two subdivisions of the Agrarian era of human history. It began with the appearance of agriculture, slightly more than 10,000 years ago, and ended with the appearance of the first cities, about 5,000 years ago. That marks the beginning of the second subdivision of the Agrarian era, which we will call the "later Agrarian era." The early Agrarian era was the first era of human history in which there were communities that supported themselves mainly from agriculture.

Seen globally, the early Agrarian era lasted from the appearance of agriculture, more than 10,000 years ago, until the appearance of the first Agrarian civilizations, just over 5,000 years ago. However, in many parts of the world agriculture appeared later, and so did Agrarian civilizations, so dates for the era vary significantly in different regions. To understand global changes during this era, it will help to think of the world as divided into four major "world zones," whose histories were so different that they might as well have taken place on different planets. These were Afro-Eurasia (Eurasia and Africa), the Americas, Australasia (including Papua New Guinea), and the Pacific.

Agriculture evolved independently in at least six separate parts of the world, scattered throughout the three oldest world zones, within just a few thousand years. (Note that the dates I will give are approximate, and new evidence could modify them in the future. They are mostly based on radiometric dating techniques, which are generally given as dates “BP,” or “before present.” Strictly speaking, “the present” means about 1950 C.E., the date when radiometric techniques first began to be widely used, but for our purposes we can ignore this minor difference.)

The earliest evidence of agriculture comes from the Fertile Crescent, between modern Turkey, Iran, and Egypt. Here, agricultural villages appeared as early as 11,000 BP. Their main domesticates were wheat, barley, peas, and lentils; sheep, goat, pig, and cattle. Agriculture based more on animal domesticates may also have appeared in parts of the Sahara, which was then wetter than today. Between 9,000 and 6,000 years ago, agriculture based on taro, sugar cane, and banana appeared in the highlands of Papua New Guinea, in the Australasian zone. By 9,000 BP, agriculture based on rice, millet, pigs, and poultry had appeared in China. By 9,000 BP, agriculture was well-established along the Indus River in modern Pakistan, perhaps as a result of Mesopotamian influence. From Pakistan, it spread to much of the Indian subcontinent. By 5,000 to 4,000 BP, agriculture based on millet, yams, African rice, and cattle had appeared in sub-Saharan Africa, though it may have appeared earlier in the Sahara and Sudan.

By 5,000 to 4,000 BP, agriculture based on maize, beans, squashes, manioc, tubers such as potatoes, and small animals such as guinea pigs was present in Central Mexico and the Andes, in the American world zone. By 4,000 to 3,000 BP, agriculture based on squashes and local crops such as sumpweed may have appeared independently in the eastern parts of today’s U.S.

What is agriculture? Defining agriculture turns out to be tricky. From a biologist’s point of view, agriculture is an intense form of “symbiosis,” or cooperation between different species. “Mutualism” is a type of symbiosis involving relations between species that seem to benefit both species. For example, honeypot ants keep herds of aphids. They protect them, help them reproduce, and extract “honeydew” by stroking them with their antennae. Other examples include the relationship between flowering plants and pollinators such as bees and birds. Symbiotic relationships can become so close that the species start to "coevolve": If one changes the other has to change, too, because neither can survive any longer on its own.

So here's a preliminary definition of agriculture: Agriculture is a symbiotic relationship between humans and the species we call "domesticates." Domesticates benefit because they receive protection from humans, which is why their populations are so large. Many domesticates could no longer survive without human help. Maize cannot seed itself, and domestic sheep are helpless against predators. Humans benefit because they receive food and other services from their domesticates. If maize or sheep were to vanish overnight, millions of humans would die of starvation.

Agriculture is a symbiotic relationship in which humans help favored species reproduce in return for food and other services.

We and our domesticates coevolve, but in distinctive ways. Domesticates have mostly changed genetically. Domestic cattle, for example, are smaller and more tractable than their wild ancestor, the fearsome aurochs. Humans have mostly changed culturally. Farmers are genetically more or less identical to their Paleolithic ancestors but have very different lifeways. However, even humans have undergone some genetic changes. For example, genes allowing adults to digest raw milk are common among livestock herders. In summary, agriculture is a symbiotic relationship in which humans help favored species reproduce in return for food and other services.

Agriculture transformed human history by increasing human control of energy and resources. How? Agriculturalists clear away species they cannot use ("weeds" or "pests") in order to increase production of those they *can* use (domesticates). These activities usually reduce total biological productivity but channel more of the Sun's energy, captured through photosynthesis, toward species that humans can use. The result is an increase in our species' share of biospheric resources. In other words, agriculture counts as a successful grab for a larger share of the biosphere's resources by a single species, our own.

Another way of putting this is to say that agriculture implies "intensification." While the extensive technologies of the Paleolithic era allowed human populations to spread to new regions, the intensive technologies of the Agrarian era allowed more humans to live in a given area. This is why agriculture was able to start increasing the social "pressure" of human communities, just as gravity increased the pressure within the solar nebulae of early stars.

Larger, denser communities posed new problems and created new opportunities. Human populations grew rapidly as humans acquired more energy and resources. Human communities became larger. Even the earliest forms of farming could support 50–100 times as many people as foraging technologies from the same area (Christian, *Maps of Time*, pp. 208–09).

Larger, denser communities generated new forms of power and hierarchy because they required new rules to prevent conflict. They also stimulated collective learning and innovation by increasing the amount of people exchanging information and ideas. These changes accelerated change and transformed human societies. Niles Eldredge writes, "Agriculture represents the single most profound ecological change in the entire 3.5 billion-year history of life" (Eldredge, "The Sixth Extinction").

This lecture has discussed what agriculture is and why its impact was so revolutionary. The next lecture tries to explain why it appeared when it did in a number of different parts of the world, from about 10,000 years ago. ■

Essential Reading

Christian, *Maps of Time*, chap. 8.

Fagan, *People of the Earth*, chaps. 7, 8.

Ristvet, *In the Beginning*, chap. 2.

Supplementary Reading

Bellwood, *First Farmers.*

Mithen, *After the Ice.*

Questions to Consider

1. What is agriculture?

2. Why does the appearance of agriculture count as one of the fundamental thresholds of complexity in this course?

The Origins of Agriculture

Lecture 25

Normally, tributary rulers, tribute-taking rulers, the kings and emperors of this world, were more interested in capturing wealth than in producing it. A successful war could generate wealth much more quickly and much more effectively than investment in infrastructure.

The previous lecture defined agriculture and explained why its impact was so revolutionary. This lecture discusses the evidence used to trace the origins of agriculture and asks why agriculture appeared. Why did humans in so many different parts of the world suddenly start getting the food and energy they needed in entirely new ways? Agriculture appeared at least 6,000 years before there were written records, so we must study it through archaeology. Rather than discussing the evidence abstractly, it may help to focus on a particular cluster of sites associated with the "Natufian" peoples, who lived in the Fertile Crescent (in modern Jordan and Israel) from about 14,000 to about 12,000 years ago. (The Fertile Crescent is a loop of highlands running from the Nile along the eastern shore of the Mediterranean, then west and south along the border between modern Iraq and Iran.)

Natufian sites are strikingly different from those of most foragers. Their dwellings were more substantial, often built into the ground for warmth, with well-built drystone walls. Natufians hunted gazelle, but growth bands on gazelle teeth show that they did so year-round from the same place. That and the presence of rodent bones suggest they lived in their houses year-round. Other surprises include the presence of grindstones for grains such as emmer, a type of wheat, and sickles made by setting flint blades into bone handles. Microscopic study of the blades shows they were used to harvest grains. In short, these look like agricultural villages.

However, by studying grain pollen, archaeologists can distinguish between wild and domesticated species, and it turns out that the Natufians were harvesting wild grains. They were not farmers, but sedentary or semi-sedentary foragers. Below, we will see how study of the Natufians has helped solve some of the puzzles that surround the "agricultural revolution."

In Lecture Twenty-Four, we saw that agriculture appeared within a few thousand years in many different parts of the world. How can we explain this odd near-simultaneity? Let's begin by clearing away some popular misconceptions. The first is that extraterrestrials did it. In *2001*, Stanley Kubrick hinted that aliens gave humans periodical technological nudges. This idea might explain the timing (lots of monoliths?), but historians will rightly reject it until hard evidence of aliens turns up!

More influential has been the idea that agriculture appeared as a brilliant one-off invention, like the steam engine, whose benefits were so obvious that it spread rapidly from a single point of origin. This is what archaeologists call a "diffusionist" view. In the 19th century, such views were popular, at least in part because they fitted an imperialist view of civilization as something brought from advanced to less-advanced societies. Diffusionism in some form was the orthodox explanation for the origins of agriculture until recently. It is now rejected for several reasons.

- Agriculture was not one invention but a cluster of linked innovations requiring entirely new lifeways.

- Agriculture did not necessarily improve living standards, which is why many foragers who knew about farming rejected it. Archaeological evidence suggests they may have been right, for many early farmers suffered from poor health and nutrition. This idea encourages us to look for "push" rather than "pull" explanations, for factors that forced people to take up agriculture whether they wanted to or not.

- Finally, agriculture was invented not once, but many times. Diffusionist arguments cannot explain this odd timing, though they can help explain how agriculture then spread from a number of distinct centers.

Modern explanations include several interlocking factors. First, foragers already knew how to increase the productivity of favored species. Firestick farming was just one of many such techniques. The knowledge was there, so the problem is to explain why foragers in different parts of the world suddenly started using such techniques more intensively. Second, the geographical distribution of easily domesticated species may help explain the geography of early farming. As Jared Diamond has pointed out, the Fertile Crescent, where the Natufians lived, had many species like wheat, which can be domesticated with only minor changes, while other regions had species less amenable to domestication.

Third, as foragers migrated around the world, population pressure may have built up as less land was available for new migrations. Larger populations might have forced humans to use the knowledge they already had to extract more energy from a given area, to "intensify" production by introducing at least some agricultural techniques. But this argument is tricky because modern foragers often limit population growth (for example, by prolonging breast-feeding, which limits fertility, or by more violent means such as killing twins or allowing the old to die). So overpopulation should not have been a problem. Fourth, the Natufians may help us solve this last riddle, for their population began to grow fast once they settled down. This was probably because sedentary communities, which do not have to carry the old or the very young, have less need to limit population size. But why should foragers have settled down?

But for foragers sedentism can be a trap, because it may encourage population growth, making it necessary within just a few generations to start intensifying food production.

The fifth factor, climatic change, may help solve this puzzle. The last ice age reached its coldest stage about 20,000 years ago, and then climates began to get warmer. By 11,500 years ago, after a 1,500-year cold spell, they had reached temperatures similar to those of today. During the "interglacial" of the last 10,000 to 11,000 years, climates were generally warmer, wetter, and more stable than those of the ice ages. How might these changes have encouraged early forms of agriculture? Peter Richerson and Robert Boyd have argued that agriculture was simply impossible during the last ice age because climates were too unstable. If they are right, it is the stability of interglacial climates that explains the appearance of sustainable agriculture. Warmer and wetter climates may also explain why some foragers settled down, for improved climates would have stimulated plant growth, creating regions of great abundance, or "Gardens of Eden." Modern anthropological studies suggest that in such environments, foragers often become more sedentary. (Sedentary foragers are often described as "affluent foragers," because they are found in regions of exceptional abundance, such as the northwestern coast of North America.) But for foragers sedentism can be a trap, because it may encourage population growth, making it necessary within just a few generations to start intensifying food production. As populations grew, sedentary foragers would soon find it necessary to tend their crops more carefully, to water them and weed around them—in short, they would have to become farmers! In this roundabout way, pressure may have played as powerful a role in the appearance of agriculture as it did in the appearance of the first stars!

Arguments like these work well in the Fertile Crescent. Natufians almost certainly had a good understanding of natural plants and how they reproduced. They lived in a region with many promising potential domesticates such as wheat. We know from archaeological evidence that, as they became sedentary, populations grew rapidly. We know that warming climates may have encouraged them to become more sedentary by increasing the abundance of domesticable grains such as emmer. Finally, we know that farming villages appeared quite rapidly after a period of cooler climates (the "Younger Dryas," c. 13,000–11,500 BP) forced sedentary foragers to start intensifying. When climates warmed again, farming villages appeared rapidly. Elsewhere, the mix of elements was different. In Mesoamerica, nomadic foragers probably cultivated crops such as early forms of maize before they became fully sedentary. There are also tantalizing hints that root crops were farmed early in coastal regions in the tropics, but we know little of these regions because most coastal sites were flooded as sea levels rose. So, though we lack a complete explanation of agricultural origins, we know many of the factors involved, even if they may have interacted in slightly different ways in different regions. ■

Essential Reading

Christian, *Maps of Time*, chap. 8.

Fagan, *People of the Earth,* chap. 8.

Ristvet, *In the Beginning*, chap. 2.

Supplementary Reading

Bellwood, *First Farmers.*

Diamond, *Guns, Germs, and Steel.*

Mithen, *After the Ice.*

Questions to Consider

1. How can we explain the fact that agriculture appeared within a very short time in parts of the world that had no contact with each other?

2. What can study of the Natufians tell us about the origins of agriculture?

The First Agrarian Societies

Lecture 26

The encounter between newly arrived humans and indigenous species that had no experience of humans and no understanding of how dangerous they could be may help explain the massive extent of the die-off of large mammals in Sahul in the millennia after the arrival of humans.

This lecture surveys the 5,000 years of the "early Agrarian" era, a period that is often neglected by historians because it left no written records and lacks the glamour of the great civilizations. We will see that in reality many important changes occurred during this era. We will also discuss how most people lived during the early Agrarian era. We define the "early Agrarian" era as the period beginning with the appearance of agriculture and ending with the appearance of cities and states. Globally, it lasted for 5,000 to 6,000 years, but locally, its duration varies. For example, it never began in Australia, while in neighboring Papua New Guinea, it began early and has lasted to the present day. Historians often neglect this era, but this is a mistake. It embraced at least half of the last 10,000 years and laid the foundations for the eventual appearance of Agrarian civilizations. During this era, the largest and most powerful communities were villages or small towns.

Many important changes occurred in the early Agrarian era. The most important large-scale change was the spread of agriculture in the Afro-Eurasian and American world zones. For the most part, agriculture seems to have spread by diffusion from a few initial centers.

- About 10,000 years ago, agriculture was confined to the Fertile Crescent and maybe Papua New Guinea.

- About 8,000 years ago, it could be found in China, in Southeast Asia, and along the Nile.

- About 5,000 years ago, it could be found in West Africa, Mesoamerica, the Andes, Central Asia, and parts of Europe. By then, most humans lived as small peasant farmers, and that way of life would dominate the history of the next 5,000 years.

- Within just 5,000 years, agriculture had become the dominant technology of most human societies on Earth. This was a revolutionary change in human history.

Agriculture did not necessarily spread because it was attractive to foragers. It spread, rather, because agricultural communities could generate more resources than foraging communities and could therefore support larger populations. Even the simplest farming communities could support 20–30 times as many people per square kilometer as most foraging communities. As agriculture spread, world populations rose from about 6 million to 50 million between 10,000 and 5,000 years ago. The population of Southwest Asia alone may have increased from 100,000 to 5 million between 10,000 and 6,000 years ago (Bellwood, *First Farmers*, p. 15). This meant that, though Agrarian and foraging societies often traded and lived together peacefully, when there were conflicts, Agrarian societies had more people and more resources than their foraging neighbors. This is why the Agrarian frontier slowly advanced at the expense of foragers, as farmers began to cultivate more and more regions with easily worked soils and adequate rainfall and sunlight.

Agriculture introduced a new technological dynamism into human history because it stimulated collective learning. How? With larger populations, there were more people to exchange ideas within and between communities. Population growth forced those at the margins of society to experiment with new techniques and crops. Population growth generated conflicts over land and resources, and warfare began to drive technological and social change in new ways.

For the most part, technological change took the form of micro-innovations, each adapted to particular environments. Two fundamental Agrarian techniques in this era were horticulture and swidden agriculture, each of which evolved with many local variations. "Horticulture" means farming based purely on human labor power using implements such as hoes or digging sticks, mortars, and sickles. Many horticultural communities exist even today in regions such as the Amazon basin or Papua New Guinea. In forest regions, "swidden" (or "slash-and-burn") farmers used stone axes and fire to clear trees before planting crops in the rich, ashy soil. As fertility declined within a few years, the process had to be repeated in a slow, Agrarian version of nomadism. So swidden farming initiated global deforestation.

Jericho may be the oldest known Agrarian settlement. Lying about 20 kilometers east of Jerusalem, it has been excavated since the mid-19th century by archaeologists looking for its famous walls.

Most early Agrarian communities can be thought of as villages, but some were large enough to be thought of as small towns. Villages and small towns were the most important and complex types of communities throughout the early Agrarian era. Jericho may be the oldest known Agrarian settlement. Lying about 20 kilometers east of Jerusalem, it has been excavated since the mid-19th century by archaeologists looking for its famous walls. Jericho's first occupants were Natufians. But by 11,000 years ago, about 1,000 people lived in 70 mud-brick dwellings, supporting themselves by farming. Few permanent communities this large had ever existed before.

Even more densely settled was Catal Huyuk in Anatolia, which flourished 9,000 years ago. Here, mud-brick houses were built with adjoining walls, a bit like cells in a beehive, so houses were entered from the roof. Each house contained a hearth, a storage area, and exotic bull-headed statues. The inhabitants exported the tough volcanic glass known as obsidian, which was used to make fine blades. Most early Agrarian villages were smaller. Modern anthropological studies of regions such as the Papua New Guinea highlands or the Amazon basin today may give an impression of how most people lived in the early Agrarian era.

How well did the first farmers live? Did agriculture necessarily mean "progress"? We saw in Lecture Twenty-Two that, by some criteria, Paleolithic foragers lived quite well. The evidence on early farmers is mixed. The first generation or two probably lived well, enjoying improved food supplies. However, within a few generations, population growth created problems that nomadic foragers had never faced. Sedentary villages attracted vermin and rubbish, and diseases spread more easily with a larger pool of potential victims to infect, particularly after the introduction of domesticated animals, which passed many of their parasites on to humans. Studies of human bones from early Agrarian communities hint at new forms of stress, caused by the intense labor of harvest times, or by periodic crop failures, which became more common because farmers generally relied on a more limited range of foodstuffs than foragers. Periodic shortages may explain why skeletons seem to get shorter in early Agrarian villages. On the other hand, early Agrarian communities were probably fairly egalitarian. Relative equality is apparent even in large sites such as Catal Huyuk, where buildings are similar in size, though differences in burials show there were some, possibly hereditary, differences in wealth.

The early Agrarian era transformed a world of foragers into a world of peasant farmers. Within these denser communities new forms of complexity would begin to emerge. Yet by some criteria, living standards may have declined. Complexity does not necessarily mean progress! ■

Essential Reading

Brown, *Big History,* chaps. 4–5.

Christian, *Maps of Time*, chap. 8.

Fagan, *People of the Earth*, chaps. 9–13.

Supplementary Reading

Bellwood, *First Farmers.*

Coatsworth, “Welfare.”

Mithen, *After the Ice.*

Questions to Consider

1. What were the most revolutionary developments during the "early Agrarian" era of human history?

2. Why have historians often neglected the "early Agrarian" era of human history?

Power and Its Origins

Lecture 27

Power from below can exist without power from above. It doesn't work the other way around. And what that means is that to explain the slow buildup to institutionalized power over 5,000 years, we must begin by looking at forms of power from below.

If you study the past using written records you will soon encounter states, empires, and civilizations. This is why the history of these immense, highly institutionalized power structures has been one of the central themes of historical scholarship and teaching from ancient times to the present day, in all literate traditions. States created new forms of oppression as well as new opportunities, and they would dominate the "later Agrarian" era from the moment they first appeared, about 5,000 years ago. Yet so far, we have not talked much of such things because we have been describing societies in which hierarchies were embedded in personal relationships or the rules of kinship rather than in large institutional structures such as states. Now we must try to explain the emergence of large, institutionalized power structures. We will see that their roots lay in the early Agrarian era.

To clarify the nature of the problem, we need to be clear what states are. So we will move forward to the later Agrarian era before returning to trace the roots of institutionalized power in the early Agrarian era. Following Eric Wolf, we will use the terminology of "tribute-taking" states. The word "tribute" is used here to mean resources extracted through the threat of organized force. Tribute-taking states often enjoy the genuine support of many of their subjects because, though they can coerce, they can also provide real services, just as farmers provide valuable services to their domestic crops and animals. The great world historian William McNeill has captured this ambiguous relationship well by describing tribute-taking states as "macroparasites." Like parasites, they may hurt their prey, but they must also protect their prey if they are to survive. Nevertheless, the defining quality of tribute-taking states is the ability, when necessary, to impose their will by force.

The appearance of the first tribute-taking states marks a new level of social complexity. Indeed, though I have not classified this as one of our eight major thresholds, one could make a case for doing so. States were larger, more internally varied, and more complex than the village communities of the early Agrarian era or the small, kin-based communities of the Paleolithic era. They all achieved a certain degree of stability (though eventually they all broke down). To maintain their complex structures, they mobilized the resources and energy of millions of individuals. Large projects such as the building of pyramids or the formation of armies demonstrated their power to mobilize energy, resources, and people. Tribute-taking states also generated new "emergent" properties, such as organized warfare, monumental architecture, the management of markets, and an unprecedented power to coerce.

"Power from above" depends on the capacity to make credible threats of coercion.

To understand the emergence of tribute-taking states, we need a clear definition of institutionalized (as opposed to personal) power. I will define institutionalized power as the concentration in the hands of a few people of substantial control over considerable human and material resources. Note that this definition has two components: control and the resources being controlled. The distinction matters because where there are few people and resources to control, power has limited reach. This is why power structures were less significant and less institutionalized in the Paleolithic era. As populations—as well as the goods they produced—multiplied, power began to matter more as leaders gained control over more people, more resources, and more energy.

Now we return to the early Agrarian era to trace how power structures became more significant and more institutionalized. It will help to imagine two distinct ways of mobilizing power. Though intertwined in reality, we can distinguish them analytically. "Power from below" is power conceded more or less willingly by individuals or groups who expect to benefit from subordination to skillful leaders. People expect something in return for subordination, so power from below is a "mutualistic" form of symbiosis. As societies became larger and denser, leadership became more important in order to achieve group goals, such as the building of irrigation systems or defense in war. Familiar modern examples of power from below include the election of club or team officials or captains. When we think of power as "legitimate" (e.g., the right to tax in a democratic society), we are generally thinking of it as power from below, even if it is backed by the threat of force.

"Power from above" depends on the capacity to make credible threats of coercion. That depends on the existence of disciplined groups of coercers, loyal to the leader and able to enforce the leader's will by force when necessary. In such an environment, people obey because they will be punished if they do not. This aspect of power highlights the coercive (or "parasitic") element in power relationships. The existence of jails, police, and armies is evidence that such power exists. Yet no state can depend entirely on coercion because maintaining an apparatus of coercion is costly and depends on maintaining the willing support of the coercers. No individual can single-handedly coerce millions of others. In practice, the two forms of power are intertwined in complex ways. "Protection rackets," for example, offer a service. Yet it is often the racket itself that is the likely source of danger, so does the payment of "protection money" count as a form of power from below or above? Building coercive groups is complex and costly, and the earliest forms of power emerged before such groups existed. That is why the first power elites depended mainly on power from below.

This lecture has discussed the nature of institutionalized power to help us explain how it first emerged in human history. The next lecture will ask how this analysis of power can help us understand the simple forms of power that emerged during the early Agrarian era. ■

Essential Reading

Christian, *Maps of Time*, chap. 9.

Fagan, *People of the Earth*, chap. 14.

Supplementary Reading

Harris, “The Origin of Pristine States” (in *Cannibals and Kings*).

Johnson and Earle, *The Evolution of Human Societies*.

Questions to Consider

1. What is power?

2. Is it possible to analyze power relations in today’s world using the categories of “power from above” and “power from below”?

Early Power Structures

Lecture 28

If you find infants that are buried with a lot of wealth around them, then you know not only that there were wealthy people in that society, but you know something else as well. You know that wealth could be inherited. In other words, this is not just one individual who built up their wealth during their lifetime; they could pass on their wealth to their children. And that suggests the existence of institutionalized hierarchies of wealth and power.

The previous lecture described the appearance of the first tribute-taking states and offered a simple definition of power. Now we ask: How did the first and simplest power structures evolve? The evidence we need to answer this question comes mainly from archaeology and anthropology. Archaeological research offers many indirect hints about early power relations. The relative size and wealth of houses and burials hints at inequalities of wealth and power. An example is the huge burial mount of Arzhan in the Inner Asian steppes, dating from the 8th century B.C.E. Such structures demonstrate the presence of a very significant degree of institutionalized power, enough to mobilize the resources of many hundreds of people, some of whom were required to sacrifice their own lives to honor a dead leader. Rich infant burials demonstrate the presence of inherited wealth and status. Evidence such as the terra-cotta army buried with the first ruler of a unified China, or extensive fortifications and walls, shows the presence of armies and organized coercion. The stone figures (or ahu) of Easter Island, or Britain's Stonehenge represent more modest forms of "monumental architecture." Anthropological studies of modern "early Agrarian" societies, such as those of Melanesia or the Amazon basin, suggest ways of interpreting the archaeological evidence. But we must always remember that these are modern models and we may be missing important differences between them and the first early Agrarian societies.

Why did power relations develop so rapidly in the early Agrarian era? The key was population growth. As communities became larger, more productive, and more interdependent, new problems arose, and also new forms of

Corel Stock Photo Library.

The Stonehenge in Britain is a modest example of "monumental archaeology."

wealth, which created new opportunities and temptations for would-be leaders. Whenever complexity increases, new coordinating mechanisms are needed, like the nervous systems in multi-celled organisms. Like modern families, Paleolithic communities could deal with conflicts face-to-face, or simply by splitting. In early Agrarian villages, relations were often less personal and splitting was more difficult because households had invested labor and resources in crops and farmed land. Leaders were needed to resolve disputes within the community or with neighboring communities. As communities expanded, their gods generally became more magnificent and specialist priests took on the role of communicating with them. Their privileged relations with the gods gave them influence and prestige that could be parleyed into real power. In large communities, new tasks arose such as garbage collection, wall building, or the maintenance of temples and irrigation systems. These, too, required leadership. The appearance of specialists, such as warriors or artisans or scribes, made it necessary to organize exchanges of goods and services between them and the groups that produced the food and other resources they needed. The first rulers ruled because they could offer services to those they ruled. So power relations arose as a form of symbiosis.

How were leaders selected? Some acquired followers through their charismatic personalities or their skills in dispute resolution, warfare, organization, or mediating with the gods. As communities expanded in size, ideas of kinship began to be used to create hierarchies of birth. In large communities, those who traced descent to founding ancestors (real or mythical) through senior ancestral lines claimed the deference due to seniors in all kin-based systems. High birth provided a seemingly natural basis for authority. The decoration of ancestral skulls, evident even in Natufian communities, suggests how important lineage was even in the very earliest Agrarian communities.

Males dominated leadership roles in most early Agrarian communities, laying the foundation for the asymmetrical power relations known as "patriarchy." What were the sources of patriarchy? Clearly, they reflect no innate differences in political ability, for in many different societies women have shown themselves as capable as men of wielding power. The key may lie in the demographic rules of peasant societies. In peasant communities, having many children was vital to a household's success. But this demand tied women to their roles as reproducers and child rearers. Consequently, men generally found it easier to take on specialist roles, including power roles. In turn, the overrepresentation of males in public power roles encouraged the presumption that males were natural leaders, even if in most households power relations were quite variable.

The decoration of ancestral skulls, evident even in Natufian communities, suggests how important lineage was even in the very earliest Agrarian communities.

Modern anthropological studies offer helpful models of how power roles may have been constructed within small communities. One influential model is that of the "big man." In a classic 1955 study, Douglas Oliver described the "big men" or *mumi*s of the Solomon Islands, which are east of Papua New Guinea. Ambitious young men collected food from relatives and allies and then threw huge feasts of pigs, coconut pies, and sago puddings for local men. Those whose feasts were judged impressive enough could acquire enough of a following to become *mumis*. As in modern "pork-barrel" politics, gift-giving was a form of political investment because it created loyal followers. *Mumi*s could become powerful war leaders. One old man in Oliver's study remembered that, "In the olden times there were greater *mumi* than there are today. Then they were fierce and relentless war leaders. They laid waste to the countryside and their clubhouses were lined with the skulls of people they had slain" (Harris, *Cannibals and Kings*, p. 106). As this suggests, the move from "power from below" to "power from above" could occur very swiftly.

A widely used model of authority at regional scales is that of the "chief." Chiefs normally rule over local leaders and may have little direct contact with most of their "subjects." Their power is often based on high lineage, and they may achieve god-like status. Polish anthropologist Bronislaw Malinowski once witnessed "all the people present in the village of Bwoytalu [in the Trobriand Islands] drop from their verandas as if blown down by a hurricane at the sound of a drawn-out cry announcing the arrival of an important chief" (Harris, *Cannibals and Kings*, p. 375). Archaeologists suspect the presence of chiefs when they find large structures such as pyramids or earthen mounds that required control over not just single villages but over hundreds or thousands of workers. These early forms of power rested largely (though not exclusively) on support from below, so they were too volatile to provide the basis for durable tribute-taking states. Loss of support or defeat in war led too quickly to loss of power. How was it possible to construct more durable power structures? That question leads us into the "era of Agrarian civilizations." ■

Essential Reading

Christian, *Maps of Time*, chap. 9.

Fagan, *People of the Earth*, chaps. 14, 15.

Supplementary Reading

Harris, "The Origin of Pristine States" (in *Cannibals and Kings*).

Johnson and Earle, *The Evolution of Human Societies.*

Questions to Consider

1. What evidence do we have on the early history of power, and how reliable is it?

2. How did early leaders establish their authority without an apparatus of coercion?

From Villages to Cities

Lecture 29

The appearance of Agrarian civilizations, from about 5,000 years ago, marks an important subordinate threshold in this course.

With Agrarian civilizations we get, for the first time, cities, states, and … writing! This means that for the first time we have written evidence, precise dates, and even some names. In short, we enter the realm of what many historians might regard as "real history." Suddenly, we have a mass of information and ideas. This creates new problems. Whereas in discussing biology or geology there was a broad consensus about the main ideas, historians debate endlessly about the main lines of historical development, so there is more room for controversy here than in any earlier part of this course. From now on, our main challenge will be to avoid getting too caught up in the details or the controversies of historians and try to keep our eye on the overall shape of human historical development.

Lectures Twenty-Nine through Thirty-Seven survey the 5,000 years or so during which "Agrarian civilizations" dominated the history of most people on Earth. This is the largest single group of lectures in this course. This lecture defines Agrarian civilizations and offers a brief chronology of their initial appearance. Then we turn to Mesopotamia, located in modern Iraq, to describe how increasing productivity created the foundations for some of the earliest Agrarian civilizations.

The term "civilization" can be used in many different ways, so I need to explain that I use it neutrally, as a label for a particular type of human community. I do not use it to imply any value judgments about these communities. However, I will argue that Agrarian civilizations were more complex than all earlier human societies. Agrarian civilizations had distinctive characteristics.

- They had large, networked communities of many millions of people.

- These communities contained cities and tribute-taking states with bureaucracies and armies.

- Most of their resources came from agriculture, and most of their inhabitants (often as many as 90%) were small-holding peasants living in villages.

Like agriculture, Agrarian civilizations evolved independently in different parts of the world. But because they depended so much on agriculture, they appeared in regions where agriculture was well established.

- Just over 5,000 years ago, the first Agrarian civilizations appeared in Mesopotamia and Northeast Africa/Egypt.

- About 4,500 years ago, the first Agrarian civilizations appeared in North India/Pakistan.

- Just over 4,000 years ago, the first Agrarian civilizations appeared in northern China.

- About 2,500 years ago, the first Agrarian civilizations appeared in Southeast Asia, sub-Saharan Africa, around the Mediterranean, and also in a new world zone, the Americas.

- During the last 1,500 years, states appeared by diffusion in one or two islands of the Pacific zone, but none were large enough to count as fully developed Agrarian civilizations.

The emergence of Agrarian civilizations was driven mainly by increasingly productive technologies that generated more resources and larger populations. Two clusters of innovation were particularly important in Afro-Eurasia: the "secondary products revolution" and irrigation. Archaeologist Andrew Sherratt (1946–2006) identified a cluster of innovations he called the "secondary products revolution." When first domesticated, animals were used mainly for their meat and hides, which meant you had to slaughter them to make use of them. From about 5,000 years ago, new methods of exploitation evolved over a wide area reaching from Northwest Africa to the

Eurasian steppes. These made it possible to exploit animals throughout their lifetime by using their "secondary products," or resources they generated while alive. These techniques included the use of milk for food and wool for cloth-making. They also included exploitation of the draft power of large animals for riding and transportation or for pulling plows. Oxen or horses can deliver up to four times as much power as human beings, so this change counted as an energy revolution. Animal power allowed farmers to plow soils more deeply and to farm soils with tougher surfaces. It also revolutionized transportation in both commerce and warfare. In arid steppe regions, these innovations laid the foundations for pastoralist communities, which were largely nomadic, relying primarily on the exploitation of domestic animals that they grazed by traveling to different sites through the year. Pastoral nomadism would create new types of communities, which because of their mobility and military skills would play a vital role in the history of Afro-Eurasia.

As we have seen, some of the earliest farming communities appeared in the Fertile Crescent, around the edges of Mesopotamia.

A second group of innovations was linked to irrigation. Irrigation means artificially introducing water to regions with limited natural rainfall but fertile soils and plenty of sunlight. Such regions can often be found in arid lands with alluvial plains (regions that are regularly flooded by large rivers). Mesopotamia, the land within the loop of the Fertile Crescent, was such a region. Literally, "Mesopotamia" means "land between the rivers," the rivers being the Tigris and Euphrates. Most of it is within modern Iraq.

Archaeologists have lavished much attention on Mesopotamia, so here better than anywhere else, we can see how increasingly productive technologies prepared the way for the first Agrarian civilizations. As we have seen, some of the earliest farming communities appeared in the Fertile Crescent, around the edges of Mesopotamia.

By 9,000 years ago, some farming communities were starting to settle the arid plains of Mesopotamia itself, but only in better-watered regions. As they pushed into the arid lowlands, they developed simple forms of irrigation.

By 8,000 years ago, there were many villages of irrigation farmers settled along the major rivers north of modern Baghdad. Some were beginning to build substantial canal systems.

By 7,000 years ago, villages were multiplying, particularly along the Euphrates to the south of modern Baghdad, in the lands of what would later be known as "Sumer." Villages of the Ubaid culture often appear in small clusters near small towns with up to 4,000 people. They dug canals sometimes several kilometers long, grew barley and dates, and kept cattle and sheep. They also fished and caught water birds.

Rising productivity encouraged population growth and the emergence of larger towns that provided markets and other services to surrounding villages. Some, such as Eridu, contained large temples from perhaps as early as 6,000 years ago.

As populations increased, trading systems began to link entire regions into networks of trade. Catal Huyuk, in Turkey (see Lecture Twenty-Six), owed its wealth to the trade in obsidian, a volcanic glass that is extremely hard and can be used to make sharp and durable blades. Obsidian from Catal Huyuk and other sites was traded over many hundreds of miles. Other trade goods in early Agrarian Mesopotamia included shells, precious stones such as turquoise, and eventually pottery. By 8,000 years ago, the spread of distinctive forms of pottery such as Halafian ware and the presence of other goods such as obsidian, traded over hundreds of miles, shows that significant exchange networks were evolving between the multiplying villages of Mesopotamia.

The multiplication of villages, the appearance of an increasing number of larger towns, and the development of extensive trade networks had created the largest concentrations of people and resources and the most active systems of regional exchanges ever known. Now we're ready to describe the appearance of the first Agrarian civilizations in ancient Sumer. ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chap. 2.

Brown, *Big History*, chap. 6.

Christian, *Maps of Time*, chap. 9.

Supplementary Reading

Nissen, *The Early History of the Ancient Near East.*

Ristvet, *In the Beginning*, chap. 4.

Trigger, *Early Civilizations.*

Questions to Consider

1. What features distinguish "Agrarian civilizations" from the communities of the early Agrarian era?

2. Why did the size of the largest human communities grow significantly in the early Agrarian era?

Sumer—The First Agrarian Civilization

Lecture 30

And one more detail that actually strikes a very modern ring. Around the edge of these cities, archaeologists have found evidence of sort of shantytowns—as immigrants from the countryside tried to make a living, often without great success, in the big cities.

How did the buildup of human and material resources described in the last lecture generate the first tribute-taking states, the first Agrarian civilizations, and the first real cities? All these developments occurred, with surprising suddenness, just before 3000 B.C.E., in Sumer, at the southern edge of Mesopotamia. As with earlier thresholds, many different components were suddenly arranged into something new. Before we go further, we need to clarify dating systems. For several lectures, I have given dates as archaeologists do, in years "BP" or "before present." However, historical scholarship is dominated by a different convention, derived ultimately from the Christian calendar, and from now on we will shift conventions, giving dates in years "B.C.E." (before the Common Era) or "C.E." (Common Era). This system is essentially identical to the older convention of dates "B.C." (before Christ) and "A.D." (*anno domini*) but reflects a (not entirely successful) attempt to be less culturally specific. For better or worse, the convention now dominates scholarship in world history. To get from dates "BP" to dates "B.C.E." or "C.E.," you deduct 2,000 years. So 4000 B.C.E. is the same as 6000 BP. That's where we start, somewhere near modern Basra.

In 4000 B.C.E., Sumer was a swampy backwater. However, lively trade networks traversed the region, and its rich soils attracted increasing numbers of immigrants. Between 4000 and 3000 B.C.E., climates became drier. This made it easier to farm the land as swamps began to dry out, but eventually it forced more and more people to settle in the region's rapidly growing towns. These towns controlled increasingly scarce water supplies through large irrigation systems. In the centuries before 3000 B.C.E., 10–20 powerful cities appeared quite suddenly. They included Ur (Abraham's home city, according to biblical tradition), Uruk, Nippur, Lagash, and Eridu. By 3000 B.C.E., Uruk may have had 20,000 to 50,000 inhabitants. They lived in whitewashed mud-brick houses along narrow streets. At the center, on an artificial mound 12 meters high, stood the "White Temple," dedicated to the goddess Inanna, a goddess of both love and war. Around the main part of the city was a massive wall, more than 7 meters tall in some places. The *Epic of Gilgamesh*, the world's oldest recorded epic, includes a description of Uruk, which though written down only around 1200 B.C.E., may capture something of the city's appearance in the reign of King Gilgamesh, at about 2750 B.C.E. Modern archaeology also allows us to imagine what life in ancient Uruk may have been like. We have an ancient map of nearby Nippur dating from about 1500 B.C.E. The map shows the city's walls, gardens, and canals, as well as a large temple complex.

Indeed, in Sumer, the earliest rulers may have been priests of some kind, as many of the earliest large buildings seem to have been temples rather than palaces.

Sumer's first cities were the densest and most complex communities that had ever existed. Uruk's 20,000 to 50,000 people lived in just 2.5 square kilometers, an area that would barely have supported a single individual using the foraging technologies of the Paleolithic era. Unlike foraging communities or the villages of the early Agrarian era, cities were not self-sufficient, as many of their inhabitants were not farmers. So cities had to control nearby "hinterlands" of peasant villages. They also traded along Mesopotamia's great rivers and across the seas.

Now we discuss some of the distinctive "emergent" properties of the earliest Agrarian civilizations. Many city dwellers were specialists, dependent on markets for essential supplies. A document from about 2500 B.C.E., the "Standard Professions List," mentions many different professions, including soldiers, farmers, priests, gardeners, cooks, scribes, bakers, coppersmiths, jewelers, snake charmers, and even the profession of king! Markets were also vital because southern Sumer lacked basic materials such as wood. So rulers supported merchants who traded within a "world system" reaching to Egypt, North India, Central Asia, and Anatolia. (A world system is a large region unified by extensive trade networks.)

Cities needed defensive walls and irrigation systems. These could be built and maintained only by powerful rulers capable of organizing huge labor levies. Rulers controlled labor through slavery or "corvée" (forced labor). Forced labor was important because in societies without modern energy supplies human beings were the most easily exploitable stores of energy. (From the point of view of rulers, humans were living, intelligent, "batteries," a perspective that helps explain the pervasiveness of forced labor and slave labor in all Agrarian civilizations.) The discovery of crude, mass-produced beveled-rim bowls in Sumerian cities is evidence that the government provided rations for workers or slaves. To maintain the favor of the gods, it was necessary to build and supply temples. Indeed, in Sumer, the earliest rulers may have been priests of some kind, as many of the earliest large buildings seem to have been temples rather than palaces.

Rulers ruled through literate bureaucracies, powerful taxation systems, and paid armies, features that would reappear in all tribute-taking states. Just as farmers extracted ecological "rents" from their domesticated crops and animals, the rulers of Sumer's city-states collected resources from their subjects. We call these "tributes" because, like modern taxes, they were raised in part through the threat of coercion. New, institutionalized hierarchies emerged, with the wealthy and powerful at the top and slaves and war captives at the bottom.

To keep track of their growing wealth, rulers needed new methods of accounting. These eventually evolved into the first writing systems. At first, accounts were kept using tokens representing objects. Then, marks were cut into clay using wedge-shaped papyrus stalks to represent objects such as sheep or units of grain. The step from accounting to a writing system that can imitate spoken language is associated with the "rebus" principle. The Sumerian symbol for an arrow looked like an arrow. But the word for "life" happened to sound like the word for "arrow" ("*ti*"), so the symbol for arrow could be used for the more abstract idea of "life." By early in the 3rd millennium, such changes meant that writing could record chronicles and even poetry, some of which can still be read today. With such huge resources, rulers could hire paid enforcers or armies. This is the crucial step from "power from below" to "power from above." Much early Sumerian writing describes wars fought by well-organized armies, and a Sumerian mosaic of

2600 B.C.E., known as the *Standard of Ur*, depicts the army of Ur, with its donkey-drawn chariots and large convoys of captives.

Inspiring awe by lavish displays of power was one of the keys to statehood. The royal tombs of Ur, from the late 4th millennium B.C.E., show the spectacular riches rulers could accumulate and the extraordinary expense lavished on tombs, temples, and palaces. As in the royal burials of many early Agrarian civilizations, servants of the ruler were often killed and buried to serve in the afterlife. From late in the 3rd millennium B.C.E., the typical form of monumental architecture in Mesopotamia would become the ziggurat, a stepped pyramid-like temple dedicated to the gods, of which the best preserved today is that of Ur.

Two more significant changes occurred about 1,000 years after the appearance of the first states. Sumer's city-states were united under a single ruler, Sargon, who ruled from c. 2370 to 2316 B.C.E. from a city called Akkad in northern Sumer. This pattern of imperial expansion would recur many times in later Agrarian civilizations. In the centuries after Sargon, Sumer's population crashed, apparently as a result of over-irrigation, which led to salination and undermined the region's fertility. This pattern, too, would recur many times in the history of Agrarian civilizations.

Voilà! A whole series of linked features came together to establish the first tribute-taking city-states in ancient Sumer. In the next lecture we ask: How similar was the process of state formation in other early Agrarian civilizations? ■

Essential Reading

Christian, *Maps of Time*, chap. 9.

Fagan, *People of the Earth*, chap. 15.

Ristvet, *In the Beginning*, chap. 4.

Supplementary Reading

Fernandez-Armesto, *The World*, chap. 3.

Nissen, *The Early History of the Ancient Near East.*

Trigger, *Early Civilizations.*

Questions to Consider

1. What were the most important "emergent properties" of the earliest Agrarian civilizations?

2. What were the crucial preconditions for the appearance of the first tribute-taking states about 5,000 years ago?

Agrarian Civilizations in Other Regions

Lecture 31

The Nile was a wonderful river along which to trade. Trade winds heading south and river currents heading north made sailing up and down the river relatively easy. And we know that Egyptian rulers sent expeditions for ivory and gold, for example, to Nubia and Punt, in modern Ethiopia, and also to Lebanon for its famous cedars. We still have fine illustrations of a fleet that was sent by Hatshepsut—one of the few female pharaohs, who ruled soon after 1500 B.C.E.

How typical was Sumer of Agrarian civilizations in general? Agrarian civilizations were constructed using the huge human and material resources generated in regions of flourishing agriculture, so each civilization was shaped to some degree by the cultural traditions and ecology of the regions in which it emerged. This lecture briefly surveys six different areas in which Agrarian civilizations appeared early. The main exception to the general rule that agriculture generated civilizations is in tropical areas such as Papua New Guinea (and perhaps the Amazon basin). Here, agriculture may have appeared early, but it was based on root crops that could not be stored for long periods. As William McNeill argues, the lack of storable wealth may explain why these regions never supported Agrarian civilizations.

Within the Afro-Eurasian world zone, Agrarian civilizations emerged along fertile river systems in four different regions. We have seen how Sumerian civilization arose in the Euphrates-Tigris basin, in the form of a cluster of competing city-states all dependent on irrigation. Nearby, in modern Sudan and Egypt, an Agrarian civilization appeared at about the same time, based on the remarkable natural irrigation system of the Nile River. The annual floods of the Nile, the world's longest river, brought nutritious silts from the south. After about 5000 B.C.E., the Sahara desert became drier, and more people settled in the Nile Valley. As in Sumer, populations grew rapidly, but here most settled in a long ribbon of villages along the Nile. Wheat and barley, introduced from Mesopotamia around 5000 B.C.E., flourished.

So did watermelons and other crops from Sudan. By 4000 B.C.E., village communities stretched from the Nile Delta to Nubia, in modern Sudan.

Small kingdoms appeared and were rapidly united within a single large state. Around 3100 B.C.E., a southern ruler called Menes (or Narmer) unified the region north of Aswan into a single empire. The *Narmer Palette*, probably engraved by a contemporary, shows the pharaoh smiting his enemies. Cities were less important than in Mesopotamia, though Menes established a capital at Memphis, south of modern Cairo. Unlike the rulers of Sumer, who were either priests or kings, Egypt's "pharaohs" were treated as gods. Their tombs, the pyramids, reflect their high status. The largest, the pyramid of Cheops, was built between 2500 and 2600 B.C.E., using 2.3 million limestone blocks.

The annual floods of the Nile, the world's longest river, brought nutritious silts from the south.

Despite occasional periods of political breakdown, Egyptian dynasties ruled the Nile region for almost 2,600 years. The regularity of the Nile floods may explain why Egyptian civilization avoided the sort of ecological collapse experienced in many other early Agrarian civilizations. A hieroglyphic writing system developed early here, possibly under indirect Mesopotamian influence. Trade winds heading south and river currents heading north encouraged trade along the Nile. Egyptian rulers sent expeditions for ivory and gold to Nubia and Punt and for timber to Lebanon. We still have fine illustrations of a fleet sent by Hatshepsut.

Early in the 3rd millennium, cities and states appeared in the north of modern Pakistan and India. The Indus river brought rich Himalayan silts but flooded less predictably than the Nile. By 2500 B.C.E., there were many small towns and at least two huge cities, now known as Harappa and Mohenjo Daro. Each had about 40,000 inhabitants. Houses and streets were built along a carefully planned grid system using prefabricated bricks. There were water and sewage systems, uniform systems of weights and measures, specialized crafts, markets, and extensive trade with Mesopotamia and Central Asia. Here, too, a writing system evolved. Unfortunately, it has not yet been deciphered, so our knowledge of this civilization depends entirely on archaeology. The absence of obvious palaces or royal tombs limits our understanding of the political system. The Indus Valley civilization collapsed early in the 2nd millennium. Overpopulation may have caused ecological collapse through deforestation, erosion, flooding, and desertification.

The earliest Agrarian civilizations in China emerged along the Yellow River, whose fertile “loess” soils formed from dust blown in from Inner Asia. Agriculture was productive, but flooding was a perennial problem. Chinese traditions describe two ancient dynasties, the Xia and Shang. Cities and states appeared along the eastern Yellow River late in the 3rd millennium. The Xia dynasty was probably one of several regional kingdoms. Its capital, at Erlitou, has been recently excavated. The Shang dynasty ruled for much of the 2nd millennium B.C.E. Bronze metallurgy and horse-drawn chariots, as well as wheat and barley, may have arrived from the West. The Shang controlled many cities. They had large armies equipped with mass-produced weapons and armor, and they built massive royal tombs and palaces. There may have been other similar kingdoms in other regions of China. Shang writing, using symbols carved on tortoise shells or other bones, can still be read today. Here, writing was linked to divination, a skill highly valued in rulers. Rituals were important, but deities and priests played a smaller role than in Mesopotamia or Egypt.

Agrarian civilizations appeared later, but quite independently, in two regions in the Americas. We will survey these civilizations in more detail in Lecture Thirty-Seven. “Mesoamerica” includes southern Mexico and parts of Central America. The first incipient civilizations appeared among the “Olmec” during the 2nd millennium B.C.E. In the 1st millennium, cities and states also appeared in the Oaxaca valley, in modern Mexico. By the 1st millennium C.E., there were cities and states throughout Mesoamerica. Here, great river valleys played a lesser role than in Afro-Eurasia, though techniques for increasing agricultural productivity included forest clearance and the creation of large artificial swamplands. In the Andes, state systems emerged in the 1st millennium B.C.E. along the arid coasts of Peru (where they relied largely on fishing) and in the Andean uplands around Lake Titicaca (which relied on maize, potato, and quinoa). Exchanges of crops and other goods between lowland and upland regions laid the foundations for the first large empires.

The Inka Empire, which flourished in the 15th and early 16th centuries C.E., was the first to link these centers into a single political system.

This brief tour of some of the earliest Agrarian civilizations hints at their variety. But there were also some remarkable similarities, which we return to in the next lecture. ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chaps. 3–6.

Christian, *Maps of Time*, chap. 9.

Fagan, *People of the Earth*, chaps. 15–18, 21, 22.

Supplementary Reading

Brown, *Big History*, chap. 6.

Fernandez-Armesto, *The World,* chap. 4.

Mann, *1491*.

Questions to Consider

1. What were the most important differences between the earliest regions of Agrarian civilization?

2. How important was religion in the appearance of Agrarian civilizations?

The World That Agrarian Civilizations Made
Lecture 32

So, the many striking similarities between Agrarian civilizations, even where there were no significant contacts, count as one of the most interesting and important factors about human history because they provide powerful reasons for thinking that human history is in some sense directional—that it was shaped by large, general factors that you could only see if you look at human history on a large scale.

Why were all Agrarian civilizations so similar despite the limited contact between them? Why did human societies in different parts of the world not evolve in utterly different ways? The fact that they did not suggests that there are large forces, perhaps related to our astonishing adaptability as a species, that drive human history in particular directions despite local differences in geography and cultural traditions. It is tempting to think that, ultimately, those similarities derive from the human capacity for collective learning, which ensured that, over time, human societies—wherever they might appear—would acquire increasing resources that would allow the appearance of larger and more complex societies. In short, it may be collective learning, the defining feature of our species, that helps explain the apparent directionality of human history. This lecture concentrates on general features of the 4,000-year era dominated by Agrarian civilizations. Instead of discussing each civilization in turn, we will discuss Agrarian civilization in general. As Robert Wright puts it, "if we relax our vision, and let these details go fuzzy, then a larger picture comes into focus: As the centuries fly by, civilizations may come and go, but civilization flourishes, growing in scope and complexity" (Christian, *Maps of Time*, p. 283).

Though labels for eras and types of societies are artificial, we need them because to understand the past we have to break it into manageable chunks. Chronologically, we will use two interchangeable labels for the epoch from 3000 B.C.E. to about 1000 C.E.: the "later Agrarian" era and the "era of Agrarian civilizations." This epoch was dominated by Agrarian civilizations.

Spatially, it is helpful to divide the world before modern times into four separate world zones. The Afro-Eurasian world zone includes the African and Eurasian continents and offshore islands such as Britain and Japan. It was the most ancient zone because this is where humans evolved. It was also the largest and most varied world zone, which may explain its dominant role in world history. It was where agriculture and Agrarian civilizations first appeared. The American world zone was the second-largest world zone, though it was settled late, probably within the last 13,000 to 15,000 years. This was the second zone in which Agrarian civilizations evolved independently. The Australasian world zone includes modern Australia and Papua New Guinea, as well as offshore islands such as Tasmania. Though agriculture did appear in Papua New Guinea, Agrarian civilizations did not evolve independently in this world zone. The Pacific zone was settled within the last 4,000 years by seafaring communities from Southeast Asia, who brought agriculture with them. Here, some elements of Agrarian civilizations did appear by diffusion on some of the larger islands such as Hawaii. But no island was large enough to support large Agrarian civilizations.

At the core of all Agrarian civilizations were tribute-taking states. States exacted resources in labor, goods, or cash.

Not everyone lived within Agrarian civilizations even in the era of Agrarian civilizations. Beyond their borders were regions inhabited by peoples regarded, at least by the rulers of Agrarian civilizations, as "barbarians." In some regions, such as Australia, most people continued to live in foraging communities like those of the Paleolithic era, and many lived in such communities until the 20th century. Many people lived in small farming communities with rudimentary political structures like the villages of the early Agrarian era. In arid regions of Afro-Eurasia, there were communities of pastoral nomads, some of which, like the Mongols, posed serious threats to neighboring Agrarian civilizations. Finally, there appeared the Agrarian civilizations that are the main subject of this lecture. This list provides a rudimentary, four-part typology of pre-modern human societies that reminds us of the great variety of adaptations developed by our species.

Now we focus on some of the shared features of the largest and newest of these communities: Agrarian civilizations. Agrarian civilizations were huge and complex, with hundreds of thousands, or millions, of inhabitants linked by religion, trade, economics, and politics. They were supported by the surplus labor and produce of peasant farmers, who made up most of the population. (As a rule of thumb, in most Agrarian civilizations, it took about nine peasants to support one city dweller.) Peasant life was tough. Egyptian documents from late in the 2nd millennium B.C.E. provide a vivid description of peasant life and the many trials caused both by natural disasters and the demands of tribute-takers. Elite groups, particularly in towns and cities, supported themselves by exchanging specialist skills as artisans, traders, warriors, priests, and rulers.

At the core of all Agrarian civilizations were tribute-taking states. States exacted resources in labor, goods, or cash. Tributary rulers claimed the right to exact resources but backed up their claims with the threat of force. We call such exactions "tributes." Their coercive power depended on organized armies that could defend against external attacks and suppress internal resistance. Administrative tasks, such as the collection and storage of tributes, or the administration of justice and law, were handled by organized groups of literate officials. The documents we have used earlier in this lecture provide a vivid account of the attractions of being a scribe and official. Writing appears in all Agrarian civilizations, though in some cases (e.g., the Inka), it assumed rudimentary forms. Tributary rulers built "monumental architecture": tombs, palaces, and temples designed to display their majesty and power. At lower levels, rulers depended on local nobles or officials, who duplicated their power on smaller scales.

Within Agrarian civilizations there were steep, and relatively rigid, hierarchies of wealth and power. Class hierarchies ranked groups by their lineage and social status. Aristocracies were distinguished by their lineage, power, lifestyle, and wealth. Members of the ruling elites generally despised the peasants who generated most of society's wealth. They also tended to regard those outside Agrarian civilizations as inferior or subhuman. And they normally despised merchants, whose wealth came not from tributes but from entrepreneurial activity. Power hierarchies shaped gender hierarchies. As most rulers were men, women rulers were generally regarded as exceptional (which is why the Pharaoh Hatshepsut is often represented wearing a fake beard). However, women often ruled indirectly, through husbands, lovers, or fathers. And women rarely lacked rights entirely. The oldest surviving legal code, compiled by Mesopotamian emperor Hammurabi (who reigned circa 1792–1750 B.C.E.), recognizes their right to divorce abusive husbands.

This lecture has surveyed some general features of Agrarian civilizations. In the next lecture, we ask: How did Agrarian civilizations change during the 4,000 years after their first appearance? ■

Essential Reading

Christian, *Maps of Time*, chap. 10.

Ristvet, *In the Beginning*, chap. 4.

Supplementary Reading

Ehrenberg, *Women in Prehistory.*

Trigger, *Early Civilizations.*

Questions to Consider

1. Did Agrarian civilizations share enough features to justify treating them as a major "type" of human community?

2. Of all the features shared by Agrarian civilizations, which do you regard as the most important?

Long Trends—Expansion and State Power

Lecture 33

By 5,000 years ago, by 3000 B.C.E., there were probably about 50 million people on Earth. Now, what this means is that in the early Agrarian era, human populations had multiplied by about 10 times. Then by 1,000 years ago, at the end of the later Agrarian era, there may have been about 250 million people on Earth.

The previous lecture described some general features of Agrarian civilizations. The next three lectures ask: How did Agrarian civilizations change during the 4,000 years of the later Agrarian era? They focus on Afro-Eurasia, the largest and most influential of the four world zones. This lecture describes two ways in which Agrarian civilizations in Afro-Eurasia expanded during almost 4,000 years. First, Agrarian civilizations occupied larger areas and incorporated more people. Second, as rulers got more skillful at their craft, and knowledge of "governance" accumulated within elite groups, the power and reach of states increased.

In the course of 4,000 years, Agrarian civilizations spread to incorporate most of the population of the Afro-Eurasian world zone. Five thousand years ago (in 3000 B.C.E.), Agrarian civilization existed only in Sumer and Egypt. Four thousand years ago (in 2000 B.C.E.), Agrarian civilizations also existed in the north of the Indian subcontinent and along the Yellow River in northern China. By 2,000 years ago, Agrarian civilizations were also flourishing around the Mediterranean basin, in southern China, and in parts of Southeast Asia. By 1,000 years ago, Agrarian civilizations had spread to sub-Saharan Africa, and to both western and eastern Europe.

Estonian American scholar Rein Taagepera has tried to quantify these changes by estimating the areas included within states in "megameters." A megameter is approximately the size of modern Egypt. Though very approximate, these calculations do seem to indicate some clear trends. In 3000 B.C.E., states controlled just 0.2 megameters, which is almost 0.2% of the area of Afro-Eurasia that is controlled by modern states. (Today, of course, states control virtually the entire landmass of Afro-Eurasia, so this is a reminder of how exotic and unusual the first Agrarian civilizations were when they appeared.) In 1000 B.C.E., Agrarian civilizations controlled almost 2.5 megameters (about 2% of the area of Afro-Eurasia that is controlled by modern states). By 1 C.E., with the appearance of huge empires in Persia, China, and the Mediterranean, Agrarian civilizations covered 8 megameters (about 6% of the area under modern states, and about 40 times the area controlled by the very first states). By 1000 C.E., Agrarian civilizations covered about 16 megameters, which is still only about 13% of the area controlled by modern states.

What do these figures suggest? First, they imply population growth. Agrarian civilizations included the most flourishing and productive regions on Earth, so they were the regions in which populations grew most rapidly, and their growth is therefore a key ingredient in the growth of world populations. Ten thousand years ago there were 5–6 million people on Earth. By 5,000 years ago, there were about 50 million people, so the population had multiplied by about 10 times in the 5,000 years of the early Agrarian era. By 1,000 years ago, there were about 250 million people on Earth, so the population had multiplied by about 5 times in the 4,000 years of the later Agrarian era. These figures suggest that, though populations continued to grow in the later Agrarian era, they grew no faster than in the early Agrarian era. Taagepera's figures also remind us that even quite recently many people in Afro-Eurasia still lived outside Agrarian civilizations, in small communities of pastoralists, foragers, or independent peasants. However, Taagepera's figures also chart a fundamental transformation in human history because they suggest that within just 4,000 years most humans on Earth lived within Agrarian civilizations. Agrarian civilizations had become the normal type of community for human beings in Afro-Eurasia (and probably throughout the world).

The area under Agrarian civilizations expanded, in part, because tributary rulers learned to control larger areas. In 3000 B.C.E., states were novelties, and their rulers were unsure of the best ways of managing such vast and complex communities. Over 4,000 years, their political, military, and economic skills improved, and so did their reach and power. The basic challenge was to maximize the resources rulers extracted from populations consisting mainly of small-holding peasants. We call resources extracted in this way "tributes," to contrast them with "gifts" (which are given freely) and "profits" (which are generated through exchanges in competitive markets). The trick was to maximize resource extraction without exhausting the capacity of peasants to keep paying.

Roughly speaking, we can track increasing power by charting the increasing size of states. Rein Taagepera has estimated changes in the areas controlled by particular states. His calculations highlight four main eras in the expansion of state power. The first city-states covered tiny areas. Uruk covered about 2.5 square kilometers (a tiny fraction of 1 megameter), though its rulers also controlled nearby villages. The first Mesopotamian state to include several city-states, that of Sargon of Akkad (2371–2316 B.C.E.), may have controlled 0.6 megameters. In the 2nd millennium B.C.E., the largest states—those of Egypt at its height and Shang China—controlled about 1 megameter of territory, and most controlled much less. So 1 megameter seems to have been a rough upper limit for empires formed before the 1st millennium B.C.E. The Persian Achaemenid Empire, founded by Cyrus II in 560 B.C.E., marks a sudden increase in the size of large states. It covered about 5.5 megameters. For the next 1,500 years, the largest states ranged from about 4 megameters (the Roman Empire) to about 10 megameters (the earliest Islamic empires). In the last 1,500 years, much bigger empires have appeared, starting with the Mongol Empire, which briefly controlled about 24 megameters. These estimates hide eras of collapse and decline, such as the decline of Mesopotamian states early in the 2nd millennium through ecological collapse. Nevertheless, with the benefit of hindsight the long trend toward increasing state power is unmistakable.

How did states expand their power and reach? Rulers increased their military authority partly by recruiting larger armies and equipping them with increasingly sophisticated weapons, such as chariots and siege weapons. Some of the more important innovations, particularly in cavalry warfare, came from the pastoral nomads of the Eurasian steppes. Road building and the establishment of courier or post-horse systems allowed rulers to send armies, supplies, and messages over large distances. We have a wonderful description by Herodotus of the Persian "Royal Road" built between 550 and 486 B.C.E. between southern Persia and modern Turkey. As bureaucracies expanded, they became more effective at managing tax collection over large areas by supervising the activities of local power brokers. The Achaemenid Empire, for example, set quotas in silver for each of its main provinces, and police spies checked up on tax collection. States also developed subtler ways of mobilizing resources. As their reach increased, states created large zones of relative stability within which peasants and merchants flourished, so both populations and available resources increased. In such times, the interests of rulers, peasants, and merchants came closest together, and the most farsighted rulers understood that protecting the interests of those they ruled was often the most effective way of generating taxable wealth. Rulers became increasingly adept at using tributes: first, to bind the ruling elites together through the sharing of privilege; and second, to overawe their subjects by displays of power such as military triumphs or the building of religious monuments that displayed their closeness to the gods.

Rulers increased their military authority partly by recruiting larger armies and equipping them with increasingly sophisticated weapons, such as chariots and siege weapons.

This lecture has surveyed the spread of Agrarian civilizations and their increasing power over almost 4,000 years. The next lectures will ask about rates of innovation in the later Agrarian era. Did Agrarian civilizations encourage or discourage the capacity for innovation that is such a distinctive feature of our species? ■

Essential Reading

Brown, *Big History*, chaps. 6, 7.

Christian, *Maps of Time*, chap. 10.

Supplementary Reading

Taagepera, "Size and Duration of Empires."

For details on particular civilizations, see Bentley and Ziegler, *Traditions and Encounters;* and Fernandez-Armesto, *The World.*

Questions to Consider

1. What evidence is there that, broadly speaking, the power of tribute-taking states increased in the 4,000 years after the appearance of the first states?

2. What new techniques and methods enhanced the power and reach of Agrarian states?

Long Trends—Rates of Innovation

Lecture 34

One more example [of micro-innovations] may be the slow spread of windmills. We first get evidence of them in Persia late in the 1st millennium C.E. And then they start to spread quite widely throughout the Mediterranean, eventually in Europe.

By modern standards, change was slow in the era of Agrarian civilizations. So it is all too easy to think of this as an era of stagnation. Yet we have also seen that there was considerable long-term growth in this period, and that suggests that there must have been a continuous trickle of innovations. What factors encouraged innovation in the era of Agrarian civilizations? Earlier lectures argued that collective learning—the ability to share and accumulate learned information—is what makes our species different. Ultimately, collective learning is the source of all innovation in human history. Indeed, collective learning can generate cycles of positive feedback, as innovations allow population growth, which increases the number of people contributing to innovation. But specific features in each era and region can also accelerate or slow the pace of innovation. This lecture discusses four features of Agrarian civilizations that could stimulate innovation.

- Population growth.
- Expanding networks of exchange.
- Increasing market activity.
- The role of states.

Danish economist Ester Boserup (1910–1999) argued famously that population growth can stimulate innovation, as those at the edges of society are forced to seek new ways of feeding and supporting themselves. During the 4,000 years of the later Agrarian era, human populations multiplied by about five times, growing from about 50 million to about 250 million people.

Feeding these growing populations depended on a constant trickle of mini-innovations, some of which were almost certainly driven by population pressure. Peasants or their masters sought out new lands to farm and encouraged settlement in new regions. That meant adapting to new soils, climates, and neighbors and adopting new farming techniques and crops. Examples include new crops such as the strains of rye that allowed farmers migrating from eastern Europe to begin settling the lands of modern Russia some 1,500 years ago, or the slow spread of windmills, which are first recorded in Persia late in the 1st millennium C.E.

Despite their hostility to commerce, tribute-taking rulers could also stimulate innovation and growth.

The increasing size and variety of exchange networks could also stimulate the spread of innovations. Roughly speaking, the larger and more diverse the networks of exchange, the larger the pool of ideas they contained, and the greater the chances for the spread of significant innovations. In the later Agrarian era, the most important large exchange networks were the "silk roads," which crossed most of the Afro-Eurasian world zone.

As early as 4,000 years ago, innovations such as horse-riding and the use of chariots may have diffused from the steppelands to the Mediterranean region and also to China, while Indo-European languages, which probably originated in modern Russia, were spreading toward China, India, and Mesopotamia. Two thousand years ago, trans-Eurasian exchanges became more common. Chinese governments traded with Central Asia, Chinese silks entered Mediterranean markets, and Buddhism traveled from India to China. The travels of Chinese envoy Chang Ch'ien to Central Asia in the reign of Han Emperor Wu-ti (141–87 B.C.E.), or the astonishing military campaigns of Alexander the Great (365–323 B.C.E.), provide vivid illustrations of how Agrarian civilizations from different ends of the Eurasian landmass came into closer contact with each other. Sea trade also increased between the Mediterranean, India, Southeast Asia, and China, as mariners learned to exploit the monsoon winds of the Indian Ocean. By 2,000 years ago, and perhaps earlier, most of Afro-Eurasia belonged to a single "world system." (The term "world system" is derived from the work of Immanuel Wallerstein and refers to a large region linked within a single network of exchanges.) This meant that goods, ideas, religions, and technologies were now being exchanged across the largest of all the world zones.

The expansion of commerce and trade was also a crucial source of innovation. Since Adam Smith (1723–1790), economists have understood that competitive markets encourage innovation. Unlike tributary rulers, merchants lacked the power to generate wealth by force; instead, they had to use finesse. They had to produce and sell goods as efficiently and cheaply as possible. That required a constant openness to innovation. This is "Smithian" growth. Tributary rulers normally despised commerce, but they also needed goods such as rare stones or silks, or horses that only merchants could supply, so they often protected commerce. But merchants flourished best in the cracks between Agrarian empires, such as in small city-states that traded with wealthy neighbors. Venice and Genoa in Renaissance Italy and ancient Phoenicia are good examples of such highly commercial city-states. Urbanization stimulated commerce because cities sucked in goods, techniques, and people from large hinterlands. In 3000 B.C.E., few cities had more than 30,000 inhabitants, and most were in Mesopotamia or Egypt. By 100 C.E., there may have been over 70 large cities spread throughout Afro-Eurasia, some with populations of several hundred thousand (Christian, *Maps of Time*, p. 326).

Despite their hostility to commerce, tribute-taking rulers could also stimulate innovation and growth. Generally, tribute-takers had less incentive to innovate than merchants, because they could extract resources coercively. Indeed, in an era when growth was painfully slow by modern standards, it often made more sense to capture wealth through war, than to produce wealth through investments that could take generations to mature. That is why most rulers in the later Agrarian era thought of themselves primarily as warriors rather than producers. They admired warfare, found fulfillment in it, and spent much time preparing for it. Nevertheless, to succeed as tributary rulers, they sometimes had to encourage innovation. Heavy taxation encouraged innovation, as peasants were forced to raise production in order to feed themselves and pay taxes. The most farsighted rulers understood that they could increase tributes by stimulating production and maintaining infrastructure. That meant protecting peasants, building and maintaining irrigation systems, and avoiding excessive taxation. Military and strategic factors encouraged rulers to undertake large projects that often encouraged trade and commerce. In the Roman Empire, military needs stimulated innovation in road building, bridge building, the construction of aqueducts, and the building of elaborate military catapults and siege engines. Such innovations had significant "trickle-down" effects. Joel Mokyr writes, "The Rome of 100 A.D. had better paved streets, sewage disposal, water supply, and fire protection than the capitals of civilized Europe in 1800" (Christian, *Maps of Time*, p. 321). The building of monuments such as the pyramids could also provide employment and encourage innovation in areas such as architecture, engineering, and mathematics.

We have seen that there were several features of Agrarian civilizations that tended to encourage innovation and growth. Yet we also know that in this era, innovation was much slower than in the Modern era. Why? There must have been other factors that retarded innovation and growth, and indeed there were. We will describe some of them in the next lecture. ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chap. 12.

Christian, *Maps of Time*, chap. 10.

Fernandez-Armesto, *The World*, chaps. 7, 8.

Supplementary Reading

Brown, *Big History*, chaps. 7, 8.

Chase-Dunn and Hall, *Rise and Demise*.

Mokyr, *The Lever of Riches*, Introduction, chap. 1.

Questions to Consider

1. What evidence is there that significant innovation occurred during the era of Agrarian civilizations?

2. What were the main forces that stimulated innovation in the era of Agrarian civilizations?

Long Trends—Disease and Malthusian Cycles

Lecture 35

Tribute-taking states, we've seen, could encourage growth in several ways, but they could also discourage it. So, their overall impact on growth was rather contradictory. They stifled growth in many subtle and not-so-subtle ways.

The previous lecture described some of the ways in which Agrarian civilizations could stimulate innovation. Yet if this is true, why were rates of innovation so much slower than in the modern world? Why were there such regular famines, and why did entire civilizations seem periodically to collapse? We will see that sometimes the same features that stimulated growth and innovation could also act as checks to growth. These factors help explain why ancient society did not show the productive dynamism of the most productive of modern societies. Exploring these features will eventually help us to better appreciate some of the distinctive features of the Modern era.

Because we have been focusing on long-term trends, we have focused on growth. But at smaller scales, and to thoughtful contemporaries, what stood out more sharply was a pattern of rise and fall that made history seem cyclical rather than directional. Peasants, too, were more aware of the cycles of the seasons and of years of feast and famine than of the long-term trend toward growth. Why did growth in this era always seem to be followed by collapse? Two main types of collapse stand out: political collapse (such as the decline of the Roman Empire) and demographic collapse (such as the Black Death), and often the two went hand in hand.

Shelley's poem *Ozymandias,* written in 1817, provides a powerful symbol of political decline. As it happens, we know more or less who "Ozymandias" was. Shelley wrote his poem after hearing of the imminent arrival in the British Museum of a bust of Pharaoh Ramses II, "The Great," who ruled Egypt for much of the 13th century B.C.E. What factors tended to undermine the power of rulers such as Ramses?

There is also a demographic oddity about this era. We have seen that, despite improved forms of agriculture and irrigation, populations grew no faster in the later Agrarian era than in the early Agrarian era. Indeed, in the 1st millennium C.E. there appears to have been hardly any growth at all in Afro-Eurasia. What factors checked population growth?

There was plenty of innovation in this era, but it was never rapid enough to keep pace with population growth.

One of the curiosities of the later Agrarian era is that the same factors that stimulated innovation could also check growth. The political structures of tribute-taking states could certainly encourage growth in some areas, but they also stifled growth in many subtle and not-so-subtle ways. Normally, tribute-taking rulers were more interested in capturing wealth than in producing it. A successful war could generate wealth much more quickly than investment in infrastructure. Seeing themselves as capturers rather than producers of wealth, tribute-taking elites generally despised producers and merchants and took limited interest in how goods were produced and traded. Such activities discouraged policies that actively supported production and commerce. The structures of tributary power also stifled growth in subtler ways. As Marx pointed out, tribute-taking states had to ensure that peasants had access to land. However, this limited wage-earning employment. It also deprived peasants of any incentive to raise productivity, as they knew that any surpluses would be skimmed by their overlords. In summary, those who produced society's wealth generally lacked the education, the capital, and the incentive to innovate; while the elites, who had the education and the wealth, generally despised productive or commercial activities and preferred to take wealth rather than to generate it. Outside the specialist domains of warfare and administration, tribute-taking rulers took little interest in improved efficiency or innovation.

Patterns of disease frequently checked population growth. Two factors stand out, both closely linked to factors that, in other ways, could stimulate growth. While cities could stimulate growth by encouraging commerce, they could also stifle demographic growth (itself a key driver of growth, as we have seen) by creating lethal disease environments, so urban populations had to be constantly replenished by immigration from rural areas. Diseases spread rapidly in filthy city streets; human and animal wastes accumulated in public places and waterways; rivers were treated as sewers and dumps; and city air was often polluted by fires and manufacturing processes such as smelting or tanning. The expansion of exchange networks, another important driver of growth in this era, also encouraged the spread of disease. As William McNeill showed in his classic study *Plagues and Peoples*, diseases spread along trade routes, along with goods and ideas. As exchange networks expanded, they spread diseases to new regions. Indeed, he argues that both the Roman and Han empires may have declined, in part, because of the spread of devastating plagues along Eurasia's expanding trade routes.

While humans are very good at finding new ways of exploiting their environments, they are not as good at identifying the limits of ecological exploitation. Time and again, Agrarian civilizations grew so rapidly that they began to overuse their forests, their rivers, and their crop lands to the point where entire civilizations collapsed. Estimates of populations in Mesopotamia over 7,000 years show two periods of sudden decline. The sudden collapse early in the 2nd millennium B.C.E. was almost certainly caused by over-irrigation leading to salination and declining harvests. According to one estimate, Mesopotamian populations fell from over 600,000 in 1900 B.C.E. to about 270,000 by 1600 B.C.E., not to rise again for at least a millennium. A similar pattern of growth and decline would be repeated again early in the second millennium C.E.

These and other factors meant that, alongside the positive feedback cycles that drove innovation and growth, there were also negative feedback cycles that inhibited growth. This balance shaped the fundamental rhythms of historical change throughout the later Agrarian era. A typical cycle began with innovations that stimulated population growth, which in turn stimulated growth in other sectors. Eventually, though, populations began to press against ecological constraints. Shortages appeared, as did growing evidence of malnutrition, which encouraged disease. States increasingly began to fight over scarce resources; and finally, through warfare, disease, or famine, populations crashed. These rhythms are very clear on a graph of Eurasian populations over the last 2,000 years.

We will call these rhythms, which dominate the history of the later Agrarian era, "Malthusian cycles." Thomas Malthus was one of the pioneers of modern demography. He argued that in all species, populations tend to grow geometrically while resources tend to grow arithmetically. Eventually, this means that population growth is bound to outstrip the available resources, leading to disease, famine, and demographic collapse. Economic historian Robert Lopez describes these cycles as "an alternation of crest, trough and crest … [that] can be observed not only in the economic field, but in almost every aspect of life" (Christian, *Maps of Time*, p. 309). As French historian Le Roy Ladurie puts it, these cycles were like the "respiration," the in-breaths and out-breaths, of an entire social structure (Christian, *Maps of Time*, p. 309). Explaining these cycles takes us to the heart of the issue of innovation in Agrarian civilizations. There was plenty of innovation in this era, but it was never rapid enough to keep pace with population growth. This fundamental fact explains the persistence of Malthusian cycles over several millennia despite a long term tendency toward growth throughout the later Agrarian era.


Corel Stock Photo Library.

Rameses, Egyptian ruler for much of the 13th century, built this tomb, Ramesseum, for himself outside of Thebes.

We have seen that in the later Agrarian era many of the factors that stimulated growth in some ways could also inhibit or help to stifle growth and innovation. This balance of forces that encouraged and stifled growth explains why, eventually, each phase of expansion ended in collapse. In the last three lectures we have concentrated on Afro-Eurasia. But how typical was the history of the Afro-Eurasian zone of humanity as a whole? To answer that question we shift our focus to the Australasian, Pacific, and American world zones and ask what was happening there. ■

Essential Reading

Christian, *Maps of Time*, chap. 10.

Fernandez-Armesto, *The World*, chaps. 4, 8, 14.

Supplementary Reading

Mann, *1491*.

McNeill, *Plagues and Peoples.*

Questions to Consider

1. What forces inhibited innovation in the era of Agrarian civilizations?

2. Why did Malthusian cycles play such a dominant role in the history of all Agrarian civilizations?

Comparing the World Zones
Lecture 36

The ice age continent of Sahul included modern Australia, Papua New Guinea, and Tasmania. It was unified because lower sea levels at the height of the last ice age filled the bridges between these areas—so, it was a single landmass.

How typical was Afro-Eurasia of the sort of historical changes that occurred in other parts of the world? To answer this question, the next two lectures survey developments in the American, Australasian, and Pacific world zones. At first sight, what stand out are the huge differences between these different worlds. But as we look more carefully, we will also begin to see some surprising and important similarities.

Comparisons between world zones are important for two main reasons. First, the differences mattered. They shaped the diverse histories of each region; but they also shaped the history of the world as a whole in the last 500 years, since the coming together of the world zones. Second, if we find important similarities between the zones despite the lack of significant contact between them, this may hint at some deep patterns in human history as a whole.

Here, I will summarize information on the early history of the various world zones. During the ice ages, modern Australia, Papua New Guinea, and Tasmania were united within the continent of Sahul. The Australasian zone was smaller in area than the Afro-Eurasian or American zones, and less diverse, with relatively arid climates and flat landscapes (except in modern Papua New Guinea). Its soils were old and relatively infertile. Sahul inherited the marsupial fauna of the supercontinent of Gondwanaland, of which it was a fragment, but it had separated from Gondwanaland almost 100 million years ago, so its plant life and animal life were quite distinctive. The human history of Sahul began 40,000 to 50,000 years ago, during the last ice, when it still formed a single continent. To reach Sahul from Outer Eurasia, humans had to cross at least 60 kilometers of open sea and adapt to entirely new flora and fauna. No other large mammal made this crossing, so it provides clear evidence of our ancestors' unique ecological adaptability. Megafaunal extinctions and the widespread use of firestick farming demonstrate that even where agriculture did not appear, humans could have a significant impact on their environments.

The American world zone formed just 3 million years ago, when a large fragment of the supercontinent of Laurasia (North America) touched a large fragment of Gondwanaland (South America) at the isthmus of Panama. As a result, this zone (uniquely) stretches from the Antarctic to the Arctic and spans all major ecological and climatic zones. As Jared Diamond has pointed out, this north-south orientation means that when humans arrived they found that most migrations led them into new and unfamiliar environments, in contrast to Afro-Eurasia, where it was possible to migrate huge distances east or west while remaining in regions of roughly similar climate and ecology. Did the north-south orientation of the Americas slow the pace of change here? Humans entered the Americas from East Siberia, certainly by 13,000 years ago and maybe several millennia earlier. As in Sahul, the sudden entry of humans into unfamiliar territory may help explain the massive megafaunal extinctions. The removal of so many large species of mammal may have had a significant impact on American history because it meant that there could be no American equivalent of the "secondary products revolution."

Estimates of the population of the Americas 500 years ago range widely from about 40 million to as high as about 100 million.

The Pacific world zone formed a huge island archipelago whose communities were separated by hundreds or thousands of miles of open sea. Each island had distinctive features and therefore a distinctive history. But all (except New Zealand) were small. (As Jared Diamond has pointed out, the diverse ecologies of different Pacific islands set up a wonderful series of natural experiments in the impact of environment on human history.) The Pacific world zone was not occupied until the later Agrarian era. It was settled by migrants who brought knowledge of farming and superb navigational skills. It used to be assumed (for example, by Norwegian scholar and adventurer Thor Heyerdahl) that the Polynesians came from the Americas. However, the similarity of their Austronesian languages, and the spread of a distinctive type of pottery (Lapita ware), has shown that the Pacific islands were settled by people whose ancestors probably came from the mainland of Southeast Asia. The islands of Melanesia (to the east of Papua New Guinea, reaching as far as Fiji and Tonga) were settled over tens of thousands of years by migrants traveling in huge, oceangoing double-hulled canoes, carrying taro, yam, breadfruit, coconuts, and sugarcane as well as chickens, dogs, and pigs. The remoter islands of eastern Polynesia were mostly settled during the 1st millennium C.E. New Zealand, one of the last regions to be settled, was probably colonized between 1000 and 1200 C.E.

How did the agricultural revolution play out in each of these zones? In the Australasian zone, agriculture appeared early, but only in modern Papua New Guinea. In Papua New Guinea, agriculture was based on root crops such as taro that did not store well, which may be why no Agrarian civilizations emerged here. However, there did emerge flourishing and highly competitive "early Agrarian" village communities, which have survived to the present day. Agriculture flourished because Papua New Guinea was at the leading edge of the Australian tectonic plate as it plowed north so that, unlike other parts of Australia, its landscapes were warped to form a great variety of different soils and terrains. In Australia and Tasmania, landscapes were older and flatter, and soils were poorer. Foraging technologies survived to modern times. However, even in Australia there was significant change within recent millennia. Indeed, in some regions there appeared semi-sedentary communities that are reminiscent of the affluent Natufian foragers of the Fertile Crescent 12,000 years ago. By 500 years ago, when the world zones would at last be joined, the population of Sahul cannot have been more than about 2 million.

In the American zone, agriculture evolved later than in the Afro-Eurasian zone, and in different ways. Though maize and squashes may have been cultivated earlier, the earliest dated samples of domesticated maize were grown about 3500 B.C.E., in the Tehuacán valley southeast of Mexico City. In South America, guinea pigs, llamas, and alpacas were domesticated by 2000 B.C.E. The relatively late development of cultivation in the Americas may reflect the absence of "easy" domesticates. Crops such as maize had to undergo significant changes before they could support large populations, and many large mammals had been driven to extinction. Estimates of the population of the Americas 500 years ago range widely from about 40 million to as high as about 100 million. In the Pacific zone, migrants brought agricultural technologies with them. However, on some of the smaller islands, including Easter Island, agriculture eventually failed, leading to a return to modified forms of foraging. The total population of the zone is unlikely to have exceeded 1–2 million.

We have seen some striking differences in the historical trajectories of the different world zones, including a very significant demographic imbalance. Five hundred years ago, populations ranged from about 400–500 million in Afro-Eurasia to 50–100 million in the Americas, to just 1 or 2 million in the Australasian and Pacific zones. Nevertheless, there are also important similarities. In each zone, human numbers increased as innovations allowed humans to extract more resources from a given area. Even in Australia, populations increased significantly in recent millennia. So differences in the histories of each region were at least in part a matter of timing rather than of substance. Many of the differences reflect differences in natural endowment, in the size of local populations, and therefore in the "synergy of collective learning" in each region. Differences in the pace and timing of change would matter profoundly when the four zones were finally joined in the last 500 years.

We have seen that, despite important differences, there were also striking parallels in the histories of the four world zones. The most important was a universal long-term trend toward "intensification": innovation characterized by the possibility of larger populations per given area and increasing complexity. ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chaps. 6, 21.

Christian, *Maps of Time*, chap. 10.

Diamond, *Collapse*

———, *Guns, Germs, and Steel*.

Supplementary Reading

Bellwood, *The Polynesians*.

Flood, *Archaeology of the Dreamtime.*

Mann, *1491*.

Questions to Consider

1. What were the most important geographical differences between the four major world zones?

2. How did geographical differences shape the histories of the four major world zones?

The Americas in the Later Agrarian Era

Lecture 37

Market relations and warfare seem to have linked all these areas of evolving Agrarian civilization into a large network of exchanges and warfare. So, it may be appropriate to talk of an evolving Mesoamerican "world system."

How similar was the evolution of Agrarian civilizations in the American and Afro-Eurasian world zones? And what were the crucial differences? In the Americas, Agrarian civilizations evolved in Mesoamerica and the Andes. In both regions, evidence of embryonic Agrarian civilizations began to appear from the 2nd millennium B.C.E. In Mesoamerica, incipient Agrarian civilizations appeared in the middle of the 2nd millennium B.C.E. They appear among the Olmec of Southeast Mexico, near modern Veracruz, on the Gulf of Mexico. Improved varieties of maize, beans, and squash allowed rapid population growth in regions of heavy rainfall, where drainage was more important than irrigation. Towns such as Lorenzo (with a population of about 2,500 people) and La Venta appeared. They had large ceremonial centers, with pyramid-like tombs up to 33 meters high. The Olmec made huge and distinctive basalt stone heads. With no large domestic animals, these had to be transported by humans, presumably under compulsion. The small size of these towns suggests that they represented polities perhaps at the level of chiefdoms. The presence of obsidian and other precious goods at Olmec sites shows the existence of extensive exchange networks. La Venta was destroyed violently in about 400 B.C.E., clear evidence of the importance of warfare. An inscribed stone found in 2006 in Veracruz suggests that the Olmec had already developed a writing system, though it has not yet been deciphered.

After 1000 B.C.E., larger communities evolved in the Oaxaca valley of South Mexico, with evidence of craft specialization, canal building, markets, and writing. By 500 B.C.E., there existed a cluster of city-states, reminiscent of 3rd-millennium Sumer. By 500 C.E., the region's largest settlement, Monte Alban, may have had 20,000 or more inhabitants; it is often thought of as the first large city of the Americas. Carved stone engravings found nearby depict enemies slaughtered in war. Olmec and Oaxacan civilizations created many durable features of Mesoamerican civilizations. By the 1st century C.E., towns, cities, and states could be found near modern Mexico City. Teotihuacán (25 miles northeast of modern Mexico City) had massive pyramids and a population of 100,000 people from many different parts of Mesoamerica. Market relations and warfare linked much of Mesoamerica into a large network of exchanges: a Mesoamerican "world system." In 378, for example, an army from distant Teotihuacán conquered Tikal, in modern Guatemala, and probably killed its king. Distinctive features of Mesoamerican civilizations include religious beliefs requiring the letting of blood, and extremely accurate calendrical systems that were of great religious and political significance.

The Maya are particularly interesting and, now, since the decipherment of their writing system, they are better known than any other American civilization from before 1500. Mayan civilization emerged as early as 1000 B.C.E., in the lowland rainforests of the Yucatan peninsula in South Mexico, Belize, and Guatemala. Villagers initially practiced swidden agriculture, but by the end of the 1st millennium B.C.E. large temple complexes appeared, with pyramids, causeways, and public squares. In the "classical period," in the middle of the 1st millennium C.E., the Maya were organized in competing city-states that formed complex and shifting alliance systems reminiscent of Sumer in the 3rd millennium B.C.E. The Maya developed remarkably accurate calendars, with a sacred year of 260 days and a secular year of 365 days. As in China, calendars had great political significance, as rulers were expected to identify auspicious dates for political acts such as wars, coronations, or religious celebrations. In conjunction with the calendar, the Maya developed a hieroglyphic script that was used to record political and religious events and royal genealogies. Mayan hieroglyphic, like Sumerian cuneiform, developed into a highly expressive medium by using the "rebus" principle. Mayan civilization declined in the 8th and 9th centuries C.E. in a classic Malthusian collapse. The causes included

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increasing warfare triggered by overpopulation (the heartland, near Tikal, may have been more densely settled in 800 C.E. than today), deforestation, erosion, and declining soil fertility. But Mesoamerican civilizations would revive. By 1492, there existed in Central Mexico a huge imperial civilization based on Tenochtitlán (now Mexico City). The Aztec rulers of Tenochtitlán exacted tributes from neighboring regions and cities. Tenochtitlán was one of the most magnificent cities in the world; with nearby towns, it may have had a population of 2 million people. We have a wonderful description of it in the writings of Cortés's lieutenant, Bernal Díaz.

In the Andes region, Agrarian civilizations evolved in modern Ecuador, Peru, and Chile. The main crops were maize, potatoes, and quinoa, and the main animal domesticates were llama, alpaca, and guinea pig. Along the coast, substantial communities emerged in the 2nd millennium B.C.E. They built irrigation systems and ceremonial pyramids.

Incipient Agrarian civilizations emerged in the 1st millennium B.C.E. They exploited different ecological zones extending from the coast, with its arid climates and rich fisheries, to the mountain highlands, with their crops of peanuts, potatoes, cotton, and beans. Towns flourished with populations of more than 10,000 and large public buildings. In the 1st millennium C.E., the Moche state, near the coast of northern Peru, integrated highland and lowland regions, organizing irrigation and managing exchanges between regions using humans, llama, and alpaca. Images show evidence of class hierarchies, warfare (once again we find pictures of rulers inspecting captives), and organized labor. The Moche state collapsed sometime in the 7th century C.E., after a series of spectacular natural disasters ruined irrigation systems and El Niño–driven climate changes ruined the rich anchovy fisheries. No writing is known from these early states. However, by 1500 C.E. the Inka had developed a system based on knotted strings, or "quipu." This worked well for accounting, but probably less well for recording history or literature.

Were the two major American zones of Agrarian civilization as integrated as those of Afro-Eurasia? Maize diffused to South America from Mesoamerica by about 2000 B.C.E. and, when the Spanish arrived, their diseases reached Peru before any of their soldiers did, so there were clearly contacts of some kind. Nevertheless, contacts were much less intense than those linking different regions of Afro-Eurasia through the silk roads. One reason was that, with few animal domesticates, transportation systems were less developed in the Americas. Here, humans were the primary beasts of burden.

How similar are the histories of Agrarian civilizations in Afro-Eurasia and the Americas? The timing of major thresholds is clearly different. In the Americas similar phenomena appeared, but with a time lag of approximately 3,000 years. For example, we have seen that the city of Monte Alban emerged late in the 1st millennium B.C.E., almost 3,000 years after the first large cities had appeared in Afro-Eurasia. By 1500 C.E., large imperial structures had appeared that may be comparable with the political systems of Afro-Eurasia in the 2nd millennium B.C.E., though they were never as large as the Achaemenid Empire at its height. Nevertheless, the general trajectory of change is similar.

In both zones, agriculture appeared independently in several regions and led to population growth; increasing exchanges; and the evolution of cities, states, and empires. As a result, within just two to three millennia of their appearance, Agrarian civilizations incorporated most of the people living in these two world zones. Agrarian civilizations in both zones shared the same emergent properties: cities, militarized states, writing systems, monumental architecture (pyramids seemed to crop up everywhere!), tribute-taking systems, and extensive networks of exchange. American civilizations also displayed a Malthusian pattern of rise and fall. As in Afro-Eurasia, there was plenty of innovation in the Americas, but never enough to avoid eventual demographic collapses. These similarities suggest that similar drivers operated in both zones. Collective learning drove innovation, leading to population increase, which generated a common set of problems and opportunities that yielded parallel solutions and outcomes. There is indeed a shape to human history, and the comparison between these regions illustrates that fundamental truth about human history.

We have seen that, despite many important differences, there were striking similarities in the histories of the different world zones. These suggest that in all zones similar forces were at work. Now we start to explore how these forces shaped the Modern era of human history. ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chaps. 6, 21.

Christian, *Maps of Time*, chap. 10.

Supplementary Reading

Brown, *Big History*, chap. 9.

Mann, *1491*.

Questions to Consider

1. What are the most striking similarities in the histories of the American and Afro-Eurasian world zones?

2. What were the most striking differences in the histories of these two zones, and why did they matter?

Threshold 8—The Modern Revolution

Lecture 38

Then, things seemed to suddenly go very strange. From 1500 onwards, the pace of change accelerates. Suddenly, the isolation of the different world zones is broken in the first phase of what today we call "globalization." The world suddenly comes together. It's interlinked for the first time in human history. Then, from about 1700, changes appear that within 300 years will have transformed the entire world. Population numbers go crazy.

In the last millennium, the pace of change accelerated sharply and decisively. The isolation of the world zones was breached in the 16th century. Then, from 1700 the pace of innovation began to accelerate so rapidly that, within just three centuries, the entire world had been transformed. Global population rose from 250 million in 1000 C.E. to about 700 million in 1700 C.E. and more than 6 billion in 2000 C.E. As Lynn Margulis and Dorion Sagan put it, humans had become a sort of "mammalian weed." Yet productivity rose even faster, so (so far!) there has not yet been a global Malthusian collapse. These transformations mark the eighth threshold of increasing complexity in this course. They lead us into the "Modern era" of human history.

The Modern era is the third major era of human history. So far, it has lasted just a few hundred years. Though all periodizations are somewhat arbitrary, here is the periodization we will use. We will date the beginning of the Modern era to about 1700 C.E., because that is when we first begin to see, in some regions of the world, a transition to radically different types of society capable of extraordinary rates of innovation and change. However, the roots of change lay in the previous millennium, so our explanations of the Modern era will begin more than 1,000 years earlier, in the 1st millennium C.E. I will divide the period after 1700 into two main periods. Between 1700 and 1900, parts of the world—particularly in the Atlantic region—were transformed, acquiring unprecedented wealth and power in the process. During the second period, beginning in about 1900, the Modern Revolution transformed the rest of the world.

What are the most distinctive features of the Modern era? Above all, modern human societies are much more complex than those of all previous eras.

First, they have more structure: For example, the variety of roles available to individuals is vastly greater than it was in the Agrarian world, where most people were peasants. Second, modern societies mobilize energy flows many times greater than those typical of earlier eras of human history. Total human energy use today is almost 250 times what it was just 1,000 years ago (mainly due to the use of fossil fuels). Third, associated with the Modern Revolution is a spectacular range of new, emergent properties—from the ability to communicate instantly across the globe, to the existence of cities of 20 million people, to weaponry capable of obliterating these same cities in a few minutes.

However, identifying the most critical changes is extremely difficult. This is partly because there have been so many different types of change, partly because the changes are still continuing today, and partly because, as yet, there exists little scholarly consensus about the nature of modernity. The discussion that follows represents an attempt to pick out the crucial features of the Modern Revolution, as seen through the wide lens of big history. We try to see this threshold as one in a sequence that reaches back to the very origins of our Universe. Our discussion builds on a long tradition of debate about modernity that includes major thinkers from Adam Smith to Karl Marx and Max Weber. So we have plenty of ideas! But the big history perspective has certain consequences for our view of modernity. The first is that some familiar landmarks (e.g., the French Revolution or the Renaissance or the Enlightenment) may vanish entirely at these scales. A second consequence of the big history perspective is that we will try to see the Modern Revolution as a global phenomenon, generated by global exchanges of ideas, technologies, goods, and people. Though many of the crucial changes first became apparent in the Atlantic region, they were the product of global forces.

Four features of the Modern Revolution explain why in this course we treat it as a new threshold of complexity. Rates of innovation accelerated sharply. Accelerating innovation increased the pace of historical change. It took 200,000 years for foraging lifeways to spread around the world, about 10,000 years for agriculture to do so, and just 200 to 300 years for the Modern Revolution to transform the entire world. Innovation increased human control over the energy and resources of the biosphere. Modern forms of education and science have created formal structures that encourage and sustain innovation.

Rapid innovation drove many other changes. It increased available resources, allowing humans to multiply—creating larger, denser, and more complex societies than those of the Agrarian era. Human numbers rose from about 250 million in 1000 C.E., to about 950 million in 1800 C.E., to about 6 billion in 2000 C.E. Larger and denser communities meant new lifeways and new power structures. Wage-earning replaced peasant farming as the normal way of earning a living. Governments became larger, more powerful, and more intrusive, but also more responsive to the needs and capacities of their subjects. Human history became global. Since the 16th century, human societies have exchanged goods, ideas, diseases, and people within a single global network, and rapid improvements in communications and transportation have steadily tightened these links.

The dominant groups are not tribute-takers but entrepreneurs, who make their wealth by trading efficiently on competitive markets.

Our species has begun to transform the biosphere. By some estimates, humans now control 25% to 40% of all the energy that enters the biosphere through photosynthesis (Christian, *Maps of Time*, p. 140). Modern weaponry is so powerful that humans could, if they chose, destroy much of the biosphere within a few hours. Increasing human control of biospheric resources has affected other species through loss of habitat and increasing extinctions, and it is beginning to transform the global climate system. John McNeill writes, “For most of Earth’s history, microbes played the leading role of all life in shaping the atmosphere. In the twentieth century, humankind stumbled blindly into this role” (McNeill, *Something New Under the Sun*, p. 51).

How can we explain these vast transformations? I will focus on accelerating innovation, because this is the key to most other aspects of the Modern Revolution. So why did innovation accelerate so sharply? Economists and historians have discussed the main drivers of innovation at least since the publication in 1776 of *The Wealth of Nations*, by Adam Smith (1723–1790). Though historians have identified many possible drivers of change in the Modern era, we will concentrate on three drivers of growth that played only a limited role in the era of Agrarian civilizations: (1) commercialization and the spread of competitive markets, (2) the spread of capitalism, and (3) the expansion of global exchange networks.

Driver 1 is commerce. Adam Smith argued that specialization raises productivity, and specialization depends on the extent of market competition. Smith's idea that the spread of competitive markets drives innovation remains fundamental in modern economic thought.

Driver 2 is the spread of capitalist social structures. Karl Marx (1818–1883), though determined to overthrow capitalism, also admired it because he believed it encouraged innovation. His ideas expand in important ways on those of Smith. Marx offered a "social structure" theory of growth, arguing that different social structures affect innovation differently. We have seen how social structures of the Agrarian era limited innovation because neither peasants nor tribute-taking elites had a sustained interest in generating innovation. Capitalism is different. The dominant groups are not tribute-takers but entrepreneurs, who make their wealth by trading efficiently on competitive markets. The majority class consists not of self-sufficient peasants but of wage earners who have to work hard and efficiently to "market" their labor. Capitalism forces both major social groups to concern themselves with productivity so the spread of capitalist social structures should encourage innovation.

Driver 3 is a sudden expansion in the size and reach of exchange networks. The coming together of the four world zones from the 16th century stimulated commerce and capitalism by expanding the scale and intensity of both entrepreneurial activity and information exchanges. This sudden rearrangement of global networks of exchange also shifted the center of wealth and power in the world away from its traditional centers (in the Afro-Eurasian world) toward a region that had previously been somewhat marginal—the Atlantic seaboard! That would prove one of the most radical of all the changes associated with the Modern Revolution.

This lecture has described some major features of the Modern Revolution and described the strategy we will use in the next three lectures to explain this remarkable transition. ■

Essential Reading

Christian, *Maps of Time*, chap. 11.

Supplementary Reading

Cipolla, *The Economic History of World Population.*

McNeill, *Something New Under the Sun*, Introduction.

Mokyr, *The Lever of Riches*, chaps. 1, 2.

Questions to Consider

1. What features distinguish the "Modern era" most decisively from the "era of Agrarian civilizations"?

2. Is it possible to find a better label than "Modern Revolution" to summarize the major transformations of the Modern era?

The Medieval Malthusian Cycle, 500–1350

Lecture 39

As in all Malthusian cycles, growth began with innovations that stimulated population growth. New technologies included improved strains of rice in China and improved plows and yokes in Europe.

When did the Modern Revolution really begin? The next two lectures tackle this question using the ideas sketched out in the previous lecture. They will survey world history over the last 1,500 years through two "Malthusian cycles" to see if we can detect elements of modernity falling into place. This lecture describes the medieval Malthusian cycle, which lasted from about 500 C.E. to about 1350 C.E.—from the decline of the Roman and Han empires to the time of the Black Death. We will focus on Afro-Eurasia, the largest and most significant of the four world zones and the region that drove change in the early stages of the Modern Revolution.

We will focus on the central problem of accelerating innovation. Consequently, we will keep our eyes on three crucial drivers of innovation: commercialization, the spread of capitalism, and a rapid expansion in the extent of exchange networks. Can we detect any evidence of an increase in the importance of these drivers of innovation? Did commercialization raise productivity by encouraging specialization and innovation? Did entrepreneurial activity and wage earning (two key features of capitalism) become more important, and if so, did they accelerate innovation? Did exchange networks expand, and if so, did they stimulate commercial activity and information exchanges?

Second, we will look for signs of a shift in wealth and power to a new hub region, around the Atlantic. Can we detect the beginnings of this shift? Third, we must note one more crucial factor: "accumulation." During the 4,000 years of the later Agrarian era, despite many fluctuations, populations increased, markets expanded, and new technologies emerged in much of the world. Without this slow accumulation of skills and resources, the Modern Revolution could not possibly have occurred.

The medieval Malthusian cycle ran from about 500 C.E. to 1350 C.E. Population graphs show the overall shape of the cycle, as populations slowly rose throughout Eurasia from the middle of the millennium before crashing in the middle of the 14th century. Commerce developed so quickly during this cycle that historian Robert Lopez claimed there was a "commercial revolution" in the later Middle Ages.

Populations grew fastest in regions such as South China or eastern Europe that had previously been underpopulated frontier regions. Population growth stimulated commerce, urbanization, and cultural efflorescence. The number and size of cities increased throughout Eurasia. Baghdad and Cairo were among the largest cities in the Muslim lands that dominated the Eurasian heartland; but by the end of the cycle, China was probably the most urbanized region in the world. Hangzhou, the capital of the Southern Song dynasty in China, may have been the world's largest city, with at least a million inhabitants.

Commerce developed so quickly during this cycle that historian Robert Lopez claimed there was a "commercial revolution" in the later Middle Ages.

Trade networks reached further than ever before. Muslims dominated the silk roads, but Europeans were increasingly active. By 1300, the Vikings had reached Iceland, Greenland, and North America (where they established a short-lived colony in Newfoundland in 1000 C.E.), while Venetian traders such as Marco Polo had reached China.

Capitalism flourished as wage earning and entrepreneurial activity expanded. Everywhere, peasants made up most of the population. Yet in many regions, peasants were sucked into capitalist networks. Government demands to pay taxes in cash, land shortages, indebtedness, and the need to buy goods on markets, all forced peasants to earn cash. They earned money by selling surplus produce, by selling goods such as textiles manufactured in the household, or by seeking wagework as laborers or in nearby towns. In such an environment, entrepreneurs flourished. Their power was particularly striking at the edges of the great empires, in Southeast Asia, or the Mediterranean, where powerful small trading states flourished. Some, such as Venice, were ruled by merchants.

The history of Song China (960–1279) illustrates the transformative power of these changes. Since it was first unified in 221 B.C.E., China had been the very epitome of a traditional Agrarian era tribute-taking empire. Its rulers controlled huge revenues produced mostly from the land, and like most Agrarian elites, they despised commerce even though markets were vital to the Chinese economy.

In the 10th century, northern China was conquered by dynasties originating in Manchuria and Tibet. Suddenly, China was divided into three large warring states. Confined to the south, rulers from the Song dynasty faced huge defensive problems and shrinking revenues, so they had to seek revenues from new sources, including commerce. In just 200 years, the share of revenues from foreign trade rose from 2% to 20%. Not surprisingly, the Song began to back traders and encourage trade.

As our model predicts, in such a highly commercialized environment, innovation accelerated. In a now-classic study, Marc Elvin described the remarkable acceleration of innovation in this era. There were innovations in agriculture (including the introduction of new strains of rice from Vietnam, with active government support), in manufacturing (government factories produced 32,000 suits of armor each year in the late 11th century), and in weaponry (this was when gunpowder first began to be used in war). Was China perhaps on the verge of an early industrial revolution? Particularly striking were advances in naval technology in this period. These would make possible an astonishing series of state-sponsored voyages to India, Arabia, and Africa in the early 15th century, under the command of the Muslim admiral and eunuch Zheng He. In 1279, a Mongol dynasty, the Yuan, reunited China under a ruler named Kublai Khan, and in 1368 the Yuan were overthrown by a new Chinese dynasty, the Ming. With fewer rivals and a much larger tax base, government practice slowly reverted to the anticommercial, tribute-taking methods of earlier times, and governments stopped backing commerce and trade. The Ming even tried to ban foreign trade.

Innovation slowed partly because reunited Chinese governments had less need to support commerce, and partly because the world was, as yet, too disconnected for innovations to spread rapidly (though some, such as gunpowder and the compass, did diffuse slowly across Eurasia).

In the mid-14th century, the medieval Malthusian cycle ended in a crash that affected most of Eurasia. Overpopulation and malnutrition were widespread before the plague spread from China, through Central Asia, to the Mediterranean world. In many regions, it killed off a third of the population. The crash suggests that rates of innovation, though impressive in some regions, were not yet rapid enough to match population growth, so the Malthusian pattern would continue. In 1350, the main structures of Agrarian civilizations, including tribute-taking elites and peasant farmers, remained firmly in place, and Eurasia was still dominated by the traditional hub regions.

Though commerce, capitalism, and international exchanges flourished during the medieval Malthusian cycle, they could not yet overcome the technological inertia of Agrarian civilizations. The next lecture surveys changes during the "early Modern Malthusian cycle," which lasted from about 1350 to 1700 C.E. ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chaps. 15, 17, 18, 20.

Christian, *Maps of Time*, chap. 12.

Fernandez-Armesto, *The World*, chaps. 10, 12, 13, 14.

Supplementary Reading

Abu-Lughod, *Before European Hegemony.*

Elvin, *The Pattern of the Chinese Past.*

McNeill, *Plagues and Peoples.*

Questions to Consider

1. What were the most important changes during the medieval Malthusian cycle?

2. What reasons are there for concluding that the world in 1500 had not yet crossed the threshold into modernity?

The Early Modern Cycle, 1350–1700

Lecture 40

The first and most spectacular change probably of all in this period was in exchange networks. And this has to count as one of the most spectacular changes in all of human history. What happens after the voyages of Columbus is that the four world zones are linked, over the next 200 years, for the first time in human history.

The "early Modern" Malthusian cycle lasted from about 1350 to about 1700. By 1500, most areas of Afro-Eurasia had recovered from the Black Death and continued to rise. In the 17th century, populations stagnated or declined slightly in some areas, but there was no population crash similar to that of the 14th century. Is this a hint that rates of innovation were beginning to accelerate? How rapidly did commerce and capitalism expand in this period? The evidence is contradictory.

The most spectacular change in this period was the unification of all four world zones into a single global network of exchange. This change stimulated commerce and capitalism throughout the world as goods, crops, ideas, and people began to circulate on a larger scale than ever before.

The linking of the four world zones was the work of European mariners, using highly maneuverable ships equipped with cannons and backed by aggressive, commercially minded governments. The first captain known to have circumnavigated the globe was Juan Sebastian del Cano, a commander in Ferdinand Magellan's fleet who returned to Spain in 1522. The sudden expansion of world markets stimulated commerce and capitalism so decisively that Karl Marx described this as one of the great turning points in human history.

American crops such as maize, potatoes, manioc, and tomatoes stimulated population growth in China, Europe, and Africa, where they could be grown in regions unsuitable for local staples. Between 1400 and 1700, the populations of China, India, and Europe all doubled. Increasing trade stimulated commerce and capitalism. As China's population and economy expanded, it sucked in silver for coinage. This benefited European middlemen who used brutal methods to extract silver by force from American mines such as Potosi in modern Bolivia. Increasing commercialization began to transform the lives of China's peasants.

The emergence of a global network of exchanges transformed the global geography of wealth and power. For most of the Agrarian era, the Atlantic region was marginal to world history. In Afro-Eurasia, the major centers of economic and political power were in the eastern Mediterranean, North India, and China; in the American world zone, they lay in Mesoamerica and the Andes. Suddenly, Europe found itself at the center of the first global world system. European merchants not only pioneered the first transoceanic exchange networks but also maintained control of them for several centuries. A durable pattern of small- or medium-sized states, engaged in constant competition, forced European rulers to seek commercial sources of revenue. So European states were generally more supportive of commerce than the great empires of the Muslim world or China.

Between 1400 and 1700, the populations of China, India, and Europe all doubled.

With supportive governments and a central position in global commercial networks, European societies became increasingly capitalistic, and their governments became more supportive of entrepreneurial activity. In Britain, these changes are evident from the remarkable statistics assembled by Gregory King (1648–1712), one of the pioneers of modern statistics.

According to King, in 1688, 43% of the British population consisted of "cottagers and paupers" or of "laboring people and out servants." In other words, almost half of Britain's population had no land and had to survive entirely from wage labor. Modern studies suggest that in the late 17th century, more than half of British national income came from commercial activities (Christian, *Maps of Time*, p. 413). By the early 18th century, most of the revenues of the British government came from commercial sources, which ensured that the government would aggressively back commerce. The importance of commerce was evident from the many merchants in the British Parliament.

Yet, despite these changes, there was no sharp acceleration in global rates of innovation. There were significant improvements in shipping and military technology, and in mining and instrument building. But in general, global rates of innovation remained sluggish. Populations grew less because of significant innovations than because of changes such as the introduction of American crops or government backing for the settlement of new lands, from Siberia to South America. The European Scientific Revolution may have been a product, in part, of the torrent of new information that flowed through European societies as Europe found itself at the center of the first global network of information. But as yet, science had little impact on technological innovation.

In the smaller world zones, the initial results of global unification were catastrophic. Globalization exposed the smaller world zones to colonization and brutal exploitation by European invaders. In the silver mines of Potosi, in modern Bolivia, miners (many of them children) were routinely worked to death, or their health was destroyed by the handling of mercury, all to ensure the flows of American silver that drove global commerce.

Europeans brought diseases such as smallpox that decimated indigenous populations. In Afro-Eurasia, the widespread use of domesticated animals allowed diseases to cross species, creating a rich palette of diseases and toughening immune systems. The other world zones had smaller populations, few or no domesticated animals, smaller exchange networks, and a less rich disease environment. As a result, the introduction of Afro-Eurasian diseases such as smallpox was catastrophic, mimicking the impact of Eurasian plagues but on a far larger scale. In the more densely settled regions of Mesoamerica and Peru, populations may have fallen 50%–70% in the course of the 16th century. For Americans, this was an apocalyptic calamity.

How much had the world changed by 1700? Globalization stimulated commerce and capitalism, and it transformed some regions, particularly in Europe and (more destructively) the Americas. Yet most states were still dominated by traditional tribute-taking elites with traditional aristocratic values. Peasants, though increasingly enmeshed in market exchanges, remained the vast majority of the population in most countries. The survival of traditional social structures may help explain why, on a global scale, innovation remained sluggish.

In the early Modern Malthusian cycle, as in the medieval cycle, there was much change, yet the basic structures of the Agrarian era remained in place, and that may explain why rates of innovation remained low. When, where, and why did the breakthrough to modernity occur? ■

Essential Reading

Bentley and Ziegler, *Traditions and Encounters*, chaps. 23–26.

Christian, *Maps of Time*, chap. 12.

Supplementary Reading

Crosby, *The Columbian Exchange.*

McNeill, *The Pursuit of Power.*

Questions to Consider

1. What were the most important changes during the early Modern Malthusian cycle?

2. What were the most important consequences of the first wave of "globalization" between 1500 and 1700?

Breakthrough—The Industrial Revolution
Lecture 41

Now, something also happens to the nature of land ownership. Increasingly, the land vacated by peasants was taken over by large landowners who farmed it for profit. In Britain, this transfer of land from small pockets of peasant farming to much larger areas, farmed more commercially, was dominated by the idea of enclosures.

By 1700 many elements of modernity seemed to be in place, yet global rates of innovation remained slow. This lecture describes the breakthrough to modernity after 1700. It focuses on one country, Britain, where the transformation has been studied most intensively. To understand these changes we need statistics. First, we discuss estimates of changes in total global production from 1500–1998. What do these estimates show? First, they show an astonishing increase in total production: Between 1500 and 2000, global production increased by 135 times. Second, the increases really became evident in the 19th century and were most striking in the 20th century. Increasing production allowed population to multiply by almost 14 times in the same period. Once again, this is an accelerating process. Particularly striking is the fact that production rose faster than population. In other words, more goods and services were being produced *per person*. Production per person increased by about 10 times between 1500 and 1998. Once more, this is an accelerating trend. These figures show that in the Modern era, rates of innovation have begun to outstrip rates of population growth, promising to make Malthusian crises a thing of the past.

A second set of figures illustrates how these changes transformed the global geography of wealth and power. Here we compare the combined production of Britain and the U.S. (two major powers of the emerging Atlantic hub zone) with the combined production of India and China (the ancient economic heartlands of the pre-modern world). In 1750, India and China accounted for almost 60% of global production, while Britain and the U.S. accounted for just 2% of global production (Christian, *Maps of Time*, p. 366). In 1830, India and China still accounted for just under 50%, while the U.S. and Britain accounted for 13%. The relationship changes drastically in the mid-19th century. By 1860, each region produced about 28% of global gross domestic product. Then India and China started to fall behind rapidly. By 1900 the U.S. and UK produced about 42% of global output, and India and China produced merely 8%. By 1950, the U.S. and UK produced 53%, and India and China a mere 4%. Of course, that's not the end of the story. From the mid-20th century, the tide has started to turn once more.

The breakthrough to modernity can be seen most easily in Britain. Many historians argue that Britain was the first country to experience the sustained growth rates typical of the Modern Revolution. Patrick O'Brien writes, "Between 1750 and 1850, the long-term rate of growth of the British economy became historically unique and internationally remarkable" (Christian, *Maps of Time*, p. 411). In 18th-century Britain we can see three interrelated revolutions: a transformation in social structures that created a more capitalistic society, a revolution in the agricultural sector, and a revolution in manufacturing.

By 1700 Britain was probably the most capitalistic and highly commercialized country in the world. It was also one of the best connected, being at the center of global exchange networks. Our model suggests that in such an environment rates of innovation ought to have accelerated as entrepreneurs competed to raise output and as markets expanded, with increasing numbers of wage earners who had to purchase both basic food and clothing with cash. That is exactly what we observe. Agriculture was the fundamental economic sector in all Agrarian societies. Productivity first began to rise in this sector from the 17th century. By 1700 many British peasants had become wage earners. This rapidly growing class provided a source of cheap labor and also a rising source of demand for basic consumer goods. Much of the land vacated by peasants was taken over by large landowners who farmed for profit. Often, they were helped by Parliament, which passed "Enclosure Acts," granting them full possession of land that had once been available for communal use. On these large, consolidated plots of land, the new owners could introduce commercial farming methods, producing goods for sale rather than subsistence. Agriculture became a business.

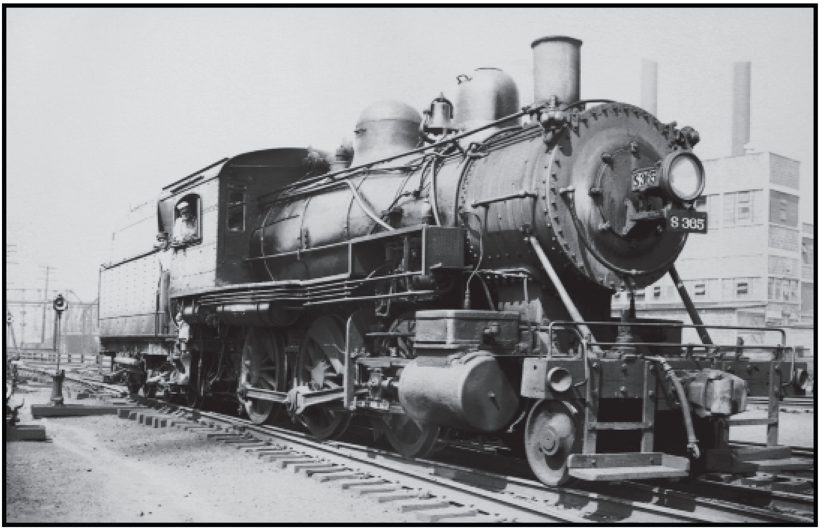
Farming for profit meant competing with other producers, and that meant increasing efficiency. British farmers raised productivity by introducing techniques that had been known for many centuries. What was new was not the techniques but the increasing incentives to apply them on a large scale. Farmers raised soil fertility by planting legumes; they improved irrigation, bred better-quality animals, and used improved methods of planting and preparing their land.

Between 1700 and 1850, British agricultural output increased 3.5 times, while the numbers employed in agriculture fell from 61% to 29% of the population. For the first time in human history, a minority of the population was feeding a majority. Expanding internal and foreign markets, a supportive government, and a stable financial system that could provide cheap capital (the Bank of England had been incorporated in 1694) encouraged investment in manufacturing as well as in agriculture.

In most Agrarian societies, textile production was the largest sector after agriculture.

In most Agrarian societies, textile production was the largest sector after agriculture. Innovations in cotton spinning reduced the time taken to spin 100 pounds of cotton from 50,000 hours to 300 hours in the late 18th century and stimulated the mechanization of weaving. A shortage of wood encouraged greater use of coal. That meant improving the technologies used to pump water out of coal mines. In the 1760s, James Watt (1736–1819) improved the efficiency of the steam engines traditionally used to pump out mines. More efficient steam engines made it economical for the first time to use coal to drive machines even well away from the coal fields. This encouraged the creation of large factories driven by steam power.

Putting steam engines on wheels early in the 19th century revolutionized land transportation and slashed transportation costs. The first steam engine designed for passengers as well as for freight was the “Rocket,” designed by George Stephenson. We have a wonderful description from the actress Fanny Kemble (1809–1893), who traveled on one of Stephenson’s trains in 1830.



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Putting steam power on wheels in the early 19th century revolutionized land transportation and slashed transportation costs.

By the early 19th century, innovation was raising productivity in many sectors of manufacturing, including textiles, coal, and metals; building; and consumer goods. Between 1770 and 1830, the value of cotton production in Britain rose over 40 times, that of coal production almost 9 times, that of iron production about 5 times, and that of building by more than 11 times.

The English Industrial Revolution provides a good illustration of the model of innovation proposed in Lecture Thirty-One. It suggests that once societies emerged that were highly commercialized, capitalistic in their social structures, and well-connected to global markets, new incentives would stimulate innovation. But the innovations themselves were also important, above all the discovery of a massive new energy source: fossil fuels. The steam engine, followed by technologies that exploited oil and natural gas, allowed humans to tap into the vast reserves of fossilized energy that had been laid down over several hundred million years. Before the steam engine, the most powerful prime mover available was probably a windmill, which could deliver about 9 horsepower. Watt's steam engine delivered 134 horsepower.

By the early 19th century, contemporaries began to notice these changes. In 1837, French Revolutionary Blanqui described the changes in Britain as an "Industrial Revolution," his way of saying that they were at least as important as the French revolution, the most momentous event in recent European history.

We have seen how, in Britain, a high level of commercialization, a highly capitalistic social structure, and multiple connections to global markets encouraged soaring innovation. The next lecture asks: How, why, and when did these innovations spread to other parts of the world? ■

Essential Reading

Christian, *Maps of Time*, chap. 13.

Supplementary Reading

Maddison, *The World Economy.*

Stearns, *The Industrial Revolution in World History.*

Wrigley, *Continuity, Chance, and Change.*

Questions to Consider

1. What evidence justifies Blanqui's claim that an "Industrial Revolution" had occurred in Britain by the early 19th century?

2. What factors did most to stimulate innovation in Britain during the Industrial Revolution?

Spread of the Industrial Revolution to 1900

Lecture 42

What made the Modern Revolution so different is that instead of dying away like this, the process of innovation continued and spread around the entire world—and it's still continuing today, more than two centuries later.

Within just two centuries industrialization had transformed the entire world. No earlier transformation in human history had been so rapid or so far-reaching. This lecture describes the impact of industrialization before 1900. There were four main waves of change before 1900. The first wave began in the late 18th century. It mainly affected Britain and the western edge of Europe. New technologies included a more productive Agrarian sector, improved steam engines, the mechanization of textile production, and increased production of coal and iron.

The second wave took place early in the 19th century. Innovation accelerated in many parts of western Europe, and also along the eastern seaboard of the newly independent U.S. Technological changes included the increased use of steam engines in manufacturing and the spread of railways and steamships. Steam transportation sped up commercial exchanges and cut transportation costs, which stimulated commerce and manufacturing, particularly in large countries such as the U.S. or Canada, where cheaper land transport had a revolutionary impact on commerce in general.

The third wave dominated the middle decades of the 19th century. Industrialization accelerated within Europe, particularly within Germany (now united economically within a common custom zone, the *Zollverein*) and in the eastern U.S. Technological innovations included the industrial production of chemicals (such as dyes and artificial fertilizers), steel-making (with the introduction of the Bessemer process), and the industrial use of electricity. Domestic lighting revolutionized patterns of work and leisure by lighting up the night. Railways, and new and more powerful weapons such as machine guns, revolutionized warfare. The American Civil War was the first major war of the industrial era. The telegraph (first introduced in 1837) and telephone (invented in 1876) revolutionized communications. In 1901, Guglielmo Marconi sent the first wireless signal across the Atlantic.

A fourth wave of innovation dominated the late 19^{th} and early 20^{th} centuries. Industrialization took off in Russia and Japan, and spread westward within the United States. The oil age launched a second phase of the fossil fuels revolution, with the invention of the internal combustion engine. The Wright brothers flew the first powered heavier-than-air plane in 1903. In 1913, Henry Ford produced the first Model T Ford in 1913, pioneering mass production for a new mass consumer market.

Library of Congress, Prints and Photographs Division, LC-USZ62-77563.

Marchese Guglielmo Marconi sent the first wireless transmission across the Atlantic in 1901.

Increasing productivity transformed the role and power of governments. Governments acquired new forms of power but also faced new and more complex challenges.

War was a major driver of change. With increasing production, states had to become more effective at mobilizing national resources of both manpower and materials. The armies of revolutionary France pioneered in the challenge of raising large citizen armies using the appeal of nationalism. But nationalism meant giving citizens a greater sense of ownership of society: a change achieved, in part, through democratic processes such as elections. To mobilize support from populations that were becoming more mobile, more urbanized, and better educated, governments had to provide new services such as policing, health services, and mass education, which few Agrarian-era states had offered. The power of modern governments depended more and more on economic growth, so they increasingly became economic managers, concerned with creating environments in which commerce could flourish.

The role and scope of government inevitably increased in societies in which most people were wage earners. This is because whereas peasants were largely self-sufficient, wage earners depend on the maintenance of markets, on education, and on the maintenance of law and order within rapidly growing towns. Inevitably, this meant that governments became more involved in the day-to-day lives of most of their citizens.

In short, the rules of political success had changed. Larger, more mobile, and better-educated societies had to be managed rather than simply coerced. In the Atlantic hub zone, the beginnings of these changes were already evident in the "democratic revolutions" of the late 18th and early 19th centuries.

Increasing productivity transformed the role and power of governments.

While modern states have become more democratic, their power to coerce has also increased. Industrialization magnified the military power of states by enabling them to transport soldiers and weapons larger distances, and by increasing the destructiveness of weaponry. Their increased military power was apparent in the astonishing speed with which, in the late 19th century, governments from the new Atlantic hub region conquered much of Africa, Asia, and the Americas.

Cultural life and popular lifeways were transformed. Everywhere, peasants slowly turned into wage earners as they were squeezed off the land by more efficient commercial farmers. Because of the variety of activities for which they had to be prepared, wage earners needed education—so, beginning in France and Germany early in the 19th century, governments began to introduce systems of mass education.

Elite culture was transformed, particularly by science. The first industrial science laboratories were created in Germany in the middle of the 19th century. As the economic, technological, and military importance of science rose, it challenged the traditional role of ancient religious traditions in education and culture by offering new materialistic accounts of the Universe that offered little room for traditional deities.

Growth in industrializing regions was accompanied by sometimes catastrophic decline elsewhere. As productivity rose in the new hub regions, regional differentials in wealth and power widened. The once awesome power of ancient tribute-taking empires evaporated. China's share of global production fell from 33% in 1800 to 6% in 1900, and in the 1840s, British gunboats forced China to trade in opium with the remarkably hypocritical argument that they were defending free trade. China was then forced to accept humiliating controls on its foreign trade. By 1900, states from the new hub regions dominated much of the world, directly or indirectly.

This sudden transformation depended in part on new industrial weaponry. The first successful machine gun, the Gatling gun, was used in the later stages of the American Civil War. It could fire 1,000 rounds a minute. The Maxim gun, the first machine gun to use a belt feed, was invented in 1884 and used by British troops in the Matabele war in 1893–1894. Hilaire Belloc wrote, with vicious irony:

> Whatever happens
> We have got
> The Maxim gun
> And they have not.
>
> —(Belloc, *The Modern Traveler*)

The vast regional differences in wealth and power that are familiar today first appeared in the late 19th century. Mike Davis has shown that it was in the late 19th century, for the first time, that differences in living standards between different parts of the world began to widen sharply. This was when the "third world" was born (Christian, *Maps of Time*, pp. 435–36).

This lecture has traced how the Modern Revolution spread around the world, transforming governments and cultures as well as economies. It also showed how industrialization created new regional disparities in wealth and power. Would these changes continue? Yes, and they would even accelerate in the 20th century. ■

Essential Reading

Christian, *Maps of Time*, chap. 13.

Supplementary Reading

Bayly, *The Birth of the Modern World.*

Davis, *Late Victorian Holocausts.*

Headrick, "Technological Change."

Questions to Consider

1. What were the main achievements of the first four "waves" of global industrialization?

2. Why was global industrialization so damaging to many societies outside the new Atlantic hub zone?

The 20th Century

Lecture 43

Nineteenth-century military innovations ensured that World War I would be particularly bloody. New weapons included machine guns, tanks, airplanes, and chemical weapons such as mustard gas, which could effectively burn out the internal organs of its victims.

Now, after 13 billion years, we enter the era of our own lifetimes! After 1900, the pace of change accelerated and the Modern Revolution began to transform societies throughout the world. A fourth, fifth, and sixth wave of change shaped the history of the 20th century. The fourth wave began in the late 19th century and continued into the early 20th century. It began to transform regions well beyond the new Atlantic core region. Russia and Japan both underwent revolutionary transformations and became major industrial and military superpowers. Then there was a slowdown for much of the first half of the 20th century as the engine of growth seemed to stall in an era of global wars and global depression. The vast casualties of these wars provided a gruesome demonstration of the increasing "productivity" of modern weapons. This violent era culminated in the Nazi Holocaust and the dropping of the first nuclear weapons.

A fifth wave of innovation began after the Second World War and ran until the last decade of the century. It launched the most sustained era of global economic growth ever known—growth built partly on wartime innovations. Atomic power, rocket technology, and the electronic transistor were developed. Some multinational corporations, such as oil companies, became as powerful as medium-sized states. From the 1920s until 1990, the world was divided into capitalist and communist regions, each of which sought to influence the rest of the world (the "third world"). Communist countries included highly industrialized societies in Eastern Europe, Russia, and (after 1949) China, which preserved many elements of tributary societies. Though their elites actively encouraged industrial growth, they rejected commercial activity and relied largely on the power of the state to engineer growth.

A sixth wave of innovation began at the end of the 20th century. Computerization and the Internet transformed communications, business, and information exchanges. Genetic engineering promised to transform medicine and agriculture. Communist societies, lacking the innovative drive of their capitalist rivals, eventually collapsed or reintroduced market economies, leaving capitalism as the dominant form of society. Accelerating globalization allowed instant global transfers of information and money. It also generated new cultural conflicts as groups with very different values and traditions were forced into closer contact with each other. When those conflicts turned violent, the availability of modern weaponry ensured that even small guerilla armies could wield significant military power. Asian economies revived, challenging the dominance of the Atlantic hub zone.

Courtesy National Archives, photo no. 342-AF-58189.

The dropping of the atomic bomb in Japan ended World War II.

The pace of change itself accelerated. Between 1900 and 2000, world population quadrupled, rising from 1.6 billion to more than 6 billion. The urban population multiplied by 13 times, and by the end of the century, almost half the world's population lived in communities of more than 5,000 people.

Population increases were made possible by increasing industrial and agricultural production. Global economic output increased by about 14 times, and industrial output by about 40 times. Global grain production rose 5 times, from about 400 million tons to about 2,000 million tons. Agricultural productivity tripled, with increased irrigation, increasing use of artificial fertilizers and pesticides, and the introduction of more productive genetically engineered crops. Because food production outstripped population growth, we have not yet seen a global Malthusian crisis in the Modern era (that is, a crisis caused by *under*production), though there have been many regional famines. Energy use increased by about 16 times, mainly through increased use of the three fossil fuels: coal, oil, and natural gas.

The lethality of weapons increased even faster. World War I artillery shells could kill hundreds; the bomb dropped on Hiroshima on August 6, 1945, killed 70,000 people, and a similar number died from wounds or radiation sickness. In the 1950s, the U.S. and the USSR developed even more powerful bombs that used hydrogen fusion, the energy that drives all stars.

Capitalism emerged as the dominant social and economic system. But it also evolved in new directions. I have argued that capitalism was a fundamental driver of the Modern Revolution. That conclusion looks even more plausible after the collapse of the communist societies that had seemed, briefly, to offer an alternative.

Yet the impact of capitalism was contradictory, for it generated unprecedented wealth as well as new forms of poverty. This is because in capitalist societies, innovation is driven by the gradient in wealth and power between entrepreneurs, who own significant capital resources, and wage earners whose main asset is their own labor. Without inequality, capitalism cannot work.

In the wealthiest societies, capitalism evolved into "consumer capitalism," in one of the most important transformations of the century. Karl Marx had argued that as capitalism developed it would impoverish most wage earners, generating huge revolutionary movements that would eventually bring about its collapse. By the end of the 20th century it was clear that this prediction had proved wrong. Why? Marx had missed something that would be seen clearly by industrialists such as Henry Ford, economists such as John Maynard Keynes, and politicians such as Franklin Roosevelt (1882–1945). As productivity outstripped population growth, producers had to work harder to find markets for the massive numbers of goods they produced. Early-20th-century pioneers such as Henry Ford saw that wage earners themselves provided a huge potential market. But they could only purchase goods if their wages rose. So it was in the interests of capitalists to raise wages and increase consumption. Such arguments were tested in the American "New Deal" and analyzed in the work of economists such as John Maynard Keynes.

In the most developed capitalist societies, led by the U.S., average consumption levels rose, creating a large, affluent middle class. Affluence deflected the revolution Marx had anticipated, as prosperous wage earners became contented supporters of consumer capitalism. Consumer capitalism also generated a new rhythm of change. For the first time in history, major economic crises (such as the Depression) were more likely to be caused by overproduction than underproduction. We can describe these new cycles of boom and bust as "Keynesian" cycles. Whereas in all earlier societies, slow growth had limited consumption, in the era of developed capitalism, consumption became the main driver of growth.

Affluence deflected the revolution Marx had anticipated, as prosperous wage earners became contented supporters of consumer capitalism. Consumer capitalism also generated a new rhythm of change.

Yet as living standards rose in the developed capitalist societies, global inequalities increased. Between 1913 and 1992, the gap between average income levels in the poorest and wealthiest countries grew from 11:1 to 72:1. Poverty affected health and life expectancies. In 2000, life expectancies in the U.S. were 74 (for men) and 80 (for women); in Burkina Faso in West Africa, they were 45 for men and women. Land shortages forced many peasants off the land, and the number living in extreme poverty increased. Paul Harrison's vivid accounts of life in Burkina Faso show what this meant to individuals. Is the widening gap a warning of new crises? Or will the living standards of the very poor slowly rise as consumer capitalism spreads to regions where, so far, it has been experienced just by elite groups?

We have seen that, far from slowing, the pace of change continued to accelerate in the 20th century, reshaping societies throughout the world in the process. This suggests that, far from the revolution of modernity being over, as some have claimed, it may be just beginning. ■

Essential Reading

Christian, *Maps of Time*, chap. 14.

Supplementary Reading

Hobsbawm, *The Age of Extremes.*

Maddison, *The World Economy.*

Questions to Consider

1. What evidence is there that change was more rapid in the 20th century than ever before in world history?

2. How and why did capitalism morph into "consumer capitalism" during the 20th century?

The World That the Modern Revolution Made

Lecture 44

And in the pace of change, this acceleration in the pace of historical change has also had a profound impact on ways of thinking, and we could even say on ways of experiencing the world.

Now, as we did with the era of Agrarian civilizations, we need to stand back and try to get a general impression of the world created by the Modern Revolution. What are the main distinguishing features of the modern world? Unfortunately, the modern world is so changeable, and we are so enmeshed in it, that it is extraordinarily difficult to see beyond the details. Still, we must try, so here is a provisional attempt.

Rapid innovation has meant a speedup. Constant innovation means constant change, so history itself moves faster. The Modern era has lasted for about a third of a millennium. So much historical scholarship is about the Modern era that it is easy to forget how short a period this is. The Agrarian era lasted 30 times as long, and human history as a whole perhaps 600 times as long. If we collapse the history of the Universe into 13 rather than 13 billion years, the Modern era accounts for no more than 6 seconds. Yet in this instant, human societies have been transformed around the entire Earth, which is why despite its brevity the Modern Revolution counts as one of the eight thresholds of this course.

Accelerating change makes it difficult to pick out stable features of our world. In the Paleolithic and Agrarian eras, we could identify features and structures that endured for thousands of years, such as the rhythms of peasant life or the basic structures of tributary states. In the Modern era, it is hard to identify any features that will certainly be present in, say, 500 years. Fundamental change now occurs on the scale of a single lifetime. This affects our personal sense of time and history. Indeed, the modern vision of a Universe in which everything has a history, including the Universe itself, is itself the product of an era of universal change. The astonishing pace of change means that today's world is extremely unstable.

Within just a few generations, the Modern Revolution has destroyed the lifeways and social structures that dominated the Agrarian and Paleolithic eras of human history. Even a century ago, viable communities of foragers and early Agrarian era villages flourished in many parts of the world. Today, none exist outside of a modern state. Particularly striking is the destruction of peasant lifeways, which had shaped the life experience of most humans for almost 10,000 years. The Modern Revolution has also destroyed traditional tribute-taking states.

In just a few generations, the Modern Revolution has also created entirely new types of community and new power structures. Modern communities are extraordinarily large. The modern world is organized into 194 sovereign states. The most populous, the People's Republic of China, had a population of 1.3 billion in 2007, or more than five times the entire population of the Earth 1,000 years earlier. Sovereign states have divided up the entire landmass of the Earth (with the partial exception of Antarctica). Even 1,000 years ago, states controlled only 13% of the Earth, because vast areas in Australia, the Americas, Africa, and Eurasia were beyond their reach. There are now 20 to 30 cities with populations of more than 5 million (the total population of the world 10,000 years ago), and several have populations of more than 10 million.

Today, more people eat well and live without chronic suffering than in any other era of human history.

Modern communities are integrated globally through exchanges of ideas, goods, diseases, and people. Indeed, today's integrated global community of 6 billion modern humans counts as one of the most striking emergent properties of the modern world. Politically, this global community is integrated loosely through international organizations such as the United Nations. These provide a modern equivalent of the meetings once held between Paleolithic communities of foragers. Collective learning is now a global process. The exchanges of information that have been the main driver of human history now take place more or less instantaneously throughout the world within a diverse and often well-educated population of 6 billion people. The increasing "synergy of collective learning" is magnified by the use of intellectual prosthetics such as computers. Global integration has been painful, as it has forced communities with diverse ethical and social norms into close proximity. Modern weaponry has ensured that such conflicts can take highly destructive forms.

Entirely new types of lifeways have evolved. Most people today are no longer foragers or self-sufficient, rural-dwelling peasants. They are wage earners, integrated into modern market systems and living, increasingly, in large towns and cities. Modern lifeways have transformed life experiences. For example, they are transforming gender relations by freeing increasing numbers of women from the lifetime of childbearing and child rearing that was their lot in peasant societies and allowing them to take on many new roles. Though many forms of gender inequality survive, traditional forms of patriarchy are being undermined. The material wealth generated by modern societies has raised the living standards of billions of people. Today, more people eat well and live without chronic suffering than in any other era of human history. The human life span has increased. As rates of child mortality have declined, average global life expectancies have risen from the Agrarian era norm of about 30 years to 65–70 years in 2000. This momentous change may prove a foretaste of future extensions in the span of a single human life.

A fourth striking feature of modern communities is the changing role of coercion. Within the tribute-taking states of the later Agrarian world, coercion was a widely accepted way of controlling behavior. Slavery, coerced labor, and domestic violence flourished. Today, behavior is steered more effectively by market forces rather than by coercion, and modern states increasingly frown on the private use of violence. Yet when they choose to do so, modern states can wield coercion far more effectively than traditional tribute-taking states. Even the most democratic states maintain significant prison populations (0.8% of the population of the U.S. was incarcerated in June 2006). And modern states maintain levels of military power that threaten the future of human society. Even after the Cold War, several thousand nuclear weapons remain on “hair-trigger” alert, and false alarms have led to several close calls.

Do these diverse changes represent "progress" or "betterment"? With their high productivity, modern societies have the ability, in principle, to provide everyone on Earth with a high material living standard. They have solved the fundamental problem of the Agrarian era: underproduction.

Less clear is the relationship between material consumption and well-being. Research into the preconditions for happiness, which has been conducted for many years, points to two clear conclusions. First, rising material living conditions clearly raise levels of well-being as they lift people out of dire poverty. Second, beyond a certain level, increasing consumption has little impact on the sense of well-being. In the U.S. and Japan in the last 50 years, surveys of "contentment" have shown no increase despite massive increases in consumption levels. Is continued growth necessarily a sign of progress? A second deep question is whether the growth of the Modern era is sustainable. Are there ecological limits to growth? And is it possible that the extraordinary complexity of modern human societies is creating new forms of fragility?

We have seen that the Modern Revolution has solved some of the most fundamental problems of the pre-modern world. But it has created new problems as well. Above all, how sustainable is it? Can it possibly endure as long as the Agrarian civilizations or the Paleolithic communities of earlier periods of human history? ■

Essential Reading

Brown, *Big History*, chap. 12.

Christian, *Maps of Time*, chap. 14.

Supplementary Reading

Harrison, *Inside the Third World.*

Held and McGrew, *Global Transformations*.

Kennedy, *Preparing for the Twenty-First Century.*

Questions to Consider

1. Why is it so hard to identify durable structural features of the modern world?

2. Should we interpret the extraordinary pace of change today as a sign of progress or unsustainability?

Human History and the Biosphere
Lecture 45

In the 20th century it became apparent for the first time that humans were beginning to have a huge and perhaps disruptive impact on many aspects of the biosphere.

In the previous lecture we tried to stand back and survey the major structural changes of the Modern era. However, we deliberately skipped one large group of changes: changes in our relationship with the biosphere. These have a direct bearing on the question of sustainability. To see these changes clearly we must widen the lens further to include all of human history.

In the 20th century, it became apparent that humans were beginning to have a huge and disruptive impact on many aspects of the biosphere. The term "biosphere" was invented by Austrian geologist Eduard Suess (1831–1914) and popularized in the 1920s by Russian biologist V. I. Vernadsky (1863–1945). It refers to the region of Earth, water, air, and living organisms at the Earth's surface that sustains life on this planet.

The major turning points in human history are all associated with humans' increasing control, or new forms of control, over the resources of the biosphere. This is what we generally mean by "growth." But setting human history in the context of the biosphere reminds us that this was really a grab for resources by a single species: our own. By the late 20th century, it was apparent that our increasing ecological power was affecting the biosphere as a whole. John McNeill argues (in *Something New Under the Sun*) that our changing relationship to the environment may have been the most important change in the 20th century. To understand these changes, we must review our relationship with the biosphere over the 250,000 years of human history.

What impact did Paleolithic humans have on their environment? The first distinguishing feature of our species was a greatly enhanced ability to adapt through collective learning. Adaptation itself implies an increased capacity to manipulate our surroundings, so collective learning necessarily implies an increasing impact on the environment.

In the Paleolithic era, the impact of this constant exploration of the environment was limited. As “foragers,” Paleolithic humans consumed natural products largely in their natural form. Populations were small and communities were scattered, so their ecological “footprint” was small.

Yet even in the Paleolithic era, the environmental impact of our species was remarkable. Our Paleolithic ancestors learned how to exploit natural environments throughout the world. As they did so, they developed new techniques for dealing with different environments, from the tropics to the tundra. Each new migration was a significant technological achievement. Some of the techniques developed in the Paleolithic era had a significant environmental impact. Foragers throughout the world fired the land regularly to increase plant growth and attract prey species. Over thousands of years, such practices could change the mix of plants and animals over entire continents. As their hunting techniques improved, our ancestors may also have helped drive many large mammal species to extinction, particularly in newly colonized lands such as Australia and the Americas, where local fauna had no experience of dealing with humans. Evidence on the “megafaunal” extinctions remains ambiguous, but the fact that these extinctions appear to coincide roughly with the arrival of humans makes it likely that humans played a significant role.

In the Agrarian era, humans began to transform their environments more systematically. Agriculture requires systematic, large-scale manipulation of the natural environment. Farmers transform environments so as to discourage species they don’t need (which they call “weeds” or “pests” or “rodents”) and encourage species they do need (which they call “domesticates”). This may mean plowing (removing weeds and exposing fertile sub-soils) or the deliberate elimination of pests such as wolves. It may require more elaborate changes such as diverting entire rivers into artificial channels to water crops in arid regions. Used badly, such methods could ruin the fertility of soils over large areas, as seems to have happened in Sumer 4,000 years ago. Swidden agriculture led to widespread deforestation. Farmers also manipulated species of plants and animals through domestication, turning wild plants and animals into “domesticated” species that were more useful to humans and were therefore encouraged to multiply rapidly. In towns and cities, humans created entirely anthropogenic environments. There was little that was not shaped by the presence of humans in even the oldest cities, such as Ur. Increasing control over environmental resources allowed humans to multiply from about 6 million people 10,000 years ago to more than 250 million people just 1,000 years ago.

The first distinguishing feature of our species was a greatly enhanced ability to adapt through collective learning.

The Modern Revolution has vastly increased human impacts on the biosphere. Each of the more than 6 billion humans on Earth today consumes approximately 60 times as much as energy as humans of the Paleolithic era. These figures suggest that the total energy consumption of our species has increased by about 60,000 times in 10,000 years. Most of this astonishing increase arises from population increase and the introduction of fossil fuels during the Modern Revolution. John McNeill estimates that in the 20th century humans became the most important movers of earth, more important even than natural erosion. Mining had the greatest impact on soil movements. As humans consume more resources, fewer are available for other species. So rates of extinction have accelerated sharply in the Modern era. Indeed, current rates of extinction may be similar to those of the five or six most spectacular extinction events in the last 600 million years. In the 20th century, humans engaged in a vicious and prolonged war with the bacterial world after the introduction of antibiotics. The outcome of this conflict remains uncertain as bacteria develop new and more resistant strains.

Finally, massive consumption of fossil fuels is increasing the levels of carbon dioxide in the atmosphere, while other activities, including cattle farming, are raising the levels of other greenhouse gases such as methane. The result is that we are beginning to alter global climate patterns. Though there is debate about many aspects of global warming, there is no doubt that the level of carbon dioxide in the atmosphere has increased significantly since the Industrial Revolution. Will global warming cause changes as drastic as those of the last ice age—but in the opposite direction? We may find the answer to such questions within our lifetimes.

In summary, evidence is accumulating that we are now using more resources than the biosphere can provide, with the risk of a serious breakdown. We have seen such breakdowns before, but this time it threatens to be global rather than local. Such conclusions suggest the folly of treating human history as separate from the history of the Earth. Human history has evolved within the complex global film of life that James Lovelock has called "Gaia." Lovelock has argued, controversially, that the entire biosphere constitutes a single feedback system that has maintained the surface of the Earth in a state suitable for life. This is a view of evolution in which cooperation seems more important than competition. Yet Lovelock argues that human activity may now be threatening the stability of the global "Gaian" system.

We have seen that in the course of human history, humans have used more and more resources at an accelerating rate. Is this a story of triumph, or a sign of danger? Where is all this going? In the last three lectures of the course we will try to answer this question by peering into the future. ■

Essential Reading

Christian, *Maps of Time*, chap. 14.

McNeill, *Something New Under the Sun*.

Supplementary Reading

Hughes, *An Environmental History of the World.*

Turner et al., *The Earth as Transformed by Human Action.*

Questions to Consider

1. Why has our species had such an extraordinary impact on the biosphere?

2. How can we assess when human impacts on the biosphere become dangerous both for the biosphere and for our own species?

The Next 100 Years

Lecture 46

As I worked on these lectures, I soon realized that historians seem to be more or less the only people who refuse to think seriously about the future.

After surveying 13 billion years, can we resist peering into the future? I think not. Indeed, I will argue that it is appropriate and necessary to do so. I was first prompted to do this by students who argued that, after surveying 13 billion years, it seemed odd to stop abruptly in the present moment. As a professional historian, I shared the historian's taboo on considering the future. So I had to think hard about how I should approach such a topic. Why and how should historians study the future? I soon realized that thinking about the future is not such a strange activity! On the contrary, all human societies have tried to predict the future, and many professionals in our own society—from stockbrokers to gamblers—make a good living by doing so.

Furthermore, we must take our thoughts about the future seriously because they may influence what we do today, and that in turn may shape the future. Besides, all organisms constantly try to predict; indeed, they are designed by natural selection to do so. Every time you act, you have to predict the likely outcome of your action, and sometimes (as in crossing a busy road) it's vital to predict wisely.

How should we think about the future? Rule 1 is that the future really is unpredictable. Nineteenth-century physicists often claimed we could predict the future if we knew the motion and position of every particle in the Universe. Quantum physics has shown this is not true. At the very smallest scales there is a certain indeterminacy in the behavior of the Universe. Rule 2 is that those who think carefully about the future get it right more often (and, if they are stockbrokers or gamblers, earn more money) than those who do not. Rule 3 is that we must begin with existing trends—in other words, with history. A horse's "form" is not a perfect guide to performance, but it's better than nothing.

We will divide the future into three distinct periods. The first period, the next century, is close enough to matter—and to be shaped by our actions. Existing trends can guide our predictions. The second period, the next thousand years, is harder to discuss. Possibilities multiply too quickly, and the outcomes are too remote to matter as much. Here, anything we say is highly speculative. The third period includes the rest of time. Oddly, in the remote future our predictions become more confident again, as we return to slower and simpler processes such as the evolution of the Sun, the galaxy, and the Universe! This lecture discusses the next hundred years.

What large patterns or trends can guide our ideas about the next century? In his *A Green History of the World*, Clive Ponting took the history of Rapa Nui (Easter Island) as a warning about the dangers of a future Malthusian crisis. Rapa Nui, a tiny Polynesian island just 16 miles long, is one of the most remote places on Earth. It was settled between 1,000 and 1,500 years ago by 20–30 colonists. They kept chickens and grew sweet potato and fished. The population grew to about 7,000, and village chiefs began building the large stone figures for which the island is famous. About 500 years ago, their society suddenly collapsed in warfare, disease, and famine.

Archaeologists have reconstructed much of the story. The stone figures were carved in the island's single quarry and moved on rollers made from trees. As villages competed to build more statues, more trees were cut down until eventually none were left. That meant no wood for boats, houses, or fuel. Islanders must have seen disaster coming as they felled the last trees, but they felled them nonetheless. Could modern consumption patterns cause a similar crisis but on a global scale?

What can this story tell us? Like the Easter Islanders just before their crash, we face some ominous trends. Populations are rising fast, carbon emissions threaten rapid climatic change, most fisheries are in decline, reserves of fresh water are shrinking, and rates of extinction are higher than for many millions of years. Consumption levels are rising fast and will rise even faster as countries like China and India begin to consume at the levels of today's richer capitalist societies.

Yet blocking rising consumption can only lock in existing inequalities and create new conflicts. And, as the U.S. learned in September 2001, modern weaponry allows even small groups to inflict terrible damage. Can global consumption slow in a capitalist world? Does not the logic of consumer capitalism require endless growth throughout the world?

There are also more hopeful trends. Global population growth is slowing as a result of the "demographic transition." As the proportion of peasants has declined and living standards have risen, fertility rates have fallen throughout the world. By the 1980s, fertility levels had fallen to the "replacement level" of 2.1 children per woman in most developed industrialized countries. But rates of population growth are also falling in poorer countries. In the 1960s, global growth rates were over 2% per annum. By 2005 they had fallen to under 1.2% per annum, according to the U.S. Census Bureau. These trends suggest that by the middle of this century, global population may level out at 8 or 9 billion people, rather than the 12–16 billion many had predicted in the 1980s.

The collective brain of modern humanity, magnified by billions of networked computers, is the most powerful problem-solving entity we know of.

Since the 1960s, ecological awareness has increased. Most governments have agencies concerned with environmental issues, there are many nongovernmental agencies concerned with environmental issues, and there have been two international environmental summits, in Rio in 1992 and in Johannesburg in 2002. There have also been some notable successes, such as the 1988 international agreement to reduce production of CFCs because they damage the ozone layer. Despite the existence of nuclear weapons since 1945, we have avoided a global nuclear war.

Capitalism may turn out to be part of the solution as well as part of the problem. Recent centuries have shown capitalism's astonishing capacity to adapt to change and generate social and technological solutions to new problems. Capitalism is particularly good at reacting to scarcities by shifting investment to alternative sources of supply. Already, investment is shifting toward technologies that may reduce dependence on fossil fuels and reduce consumption through recycling. And of course we should not forget "collective learning." The collective brain of modern humanity, magnified by billions of networked computers, is the most powerful problem-solving entity we know of. If there is a solution to the problems that face us and the biosphere, 6 billion networked humans are surely likely to find it.

Which leaves the political question: If solutions can be found, will they be implemented in time? Many would argue that we already know most of the solutions, and the first solution is to slow the rate at which we consume natural resources. Done with care, such a change might not mean a drastic reduction in material living standards, but it will certainly be painful. Will we show the political will and creativity needed to take these decisions? Perhaps the Easter Islanders saw perfectly what needed to be done (stop building ahus!) But their chiefs wouldn't let them, and anyway they wanted to build just one more ahu that was better than that of the neighboring village … Will modern humans do any better?

Though there are ominous trends in our relationship with the environment and a real threat of a global Malthusian crisis, there is also growing awareness of the dangers. Will we, unlike the islanders on Rapa Nui, show the insight and the political and moral will needed to act before it is too late? ■

Essential Reading

Christian, *Maps of Time*, chap. 15.

Supplementary Reading

Brown, *Eco-Economy.*

Ponting, *A Green History of the World.*

Questions to Consider

1. Is it legitimate for historians to consider the future? If so, how should they do it?

2. Are we overdue for a global Malthusian crisis? What steps need to be taken to avoid such an outcome?

The Next Millennium and the Remote Future

Lecture 47

Is it possible that the dangerous knowledge that accumulates within a species like ours that's capable of collective learning is bound to eventually outweigh the more creative knowledge that such species generate? Or is it simply that such a species is eventually bound to construct societies of such complexity that they're not sustainable?

Now we return to larger spatial and temporal scales. We consider first the next millennium. Then we consider the rest of time, asking about the future of the Earth, the galaxy, and the Universe as a whole. Oddly, we will see that it is easier to discuss the remote future than the next millennium. On the scale of a millennium or so, we have far more questions than answers! Human societies are so complex that, even if we can identify some trends, we know of none that are certain to continue for more than a few decades. All we can really do is to play with different scenarios.

Some scenarios are disastrous for humans and perhaps for the entire biosphere. In *A Canticle for Leibowitz* (1st published in 1959), Walter M. Miller imagined a future in which nuclear weapons were developed and used, then redeveloped and used again. Is this the fate of all species capable of "collective learning"? Is there a necessary limit to collective learning? Could that be why we have failed to detect other species like ourselves?

Geologists now understand that the Earth's history has been interrupted by periodic asteroid impacts such as those that killed off the dinosaurs. Though astronomers can now keep an eye on potentially dangerous objects, we do not yet have the means to protect ourselves adequately from such impacts.

Some scenarios are more optimistic. Perhaps, after a near brush with disaster (such as the regional nuclear wars described in the future histories written by Wagar as well as Stableford and Langford), we will avoid the fate of Easter Island. We will slow consumption levels and find new ways of living that can be satisfying without putting excessive pressure on the environment. If our ancestors avoid disaster, the "Modern era" may turn out to be the prelude to an entire new epoch of human history. Innovation may generate sustainable technologies that we can barely imagine. They may include new energy sources (such as hydrogen fusion) and biotechnologies that create new food sources, eliminate most forms of ill-health, and prolong human life. New social structures may include mechanisms for reducing violent conflict and generating more sustainable notions of progress and well-being.

In reality, of course, the future will probably fall between these extremes. What new things will we learn? Here are areas where there could be profound scientific and technological breakthroughs in the next millennium. Quite soon, we may find evidence for the existence of planets similar to the Earth. Will we also find evidence for the existence of life elsewhere in the Universe? At present, the speed with which bacterial life appeared on our planet makes it seem likely that life of some kind is widespread.

We are less likely to find evidence for creatures like us, capable of collective learning. On Earth it has taken almost 4 billion years to evolve such a species. And a lot of luck was involved. In a famous study of the Cambrian fossils of the Burgess Shale (in the Canadian Rockies), Stephen Jay Gould argued that biological evolution can take many utterly different pathways. On the other hand, Simon Conway, another specialist on the Burgess Shale fossils, has argued that the number of evolutionary pathways may be limited, which makes the evolution of species like us more probable. If our descendants survive disaster, are there new thresholds of complexity waiting to be crossed? Perhaps, like eukaryotic cells in the Cambrian era, they will become so interdependent that they will turn into a single Earth-spanning organism, capable of managing "Gaia."

Our descendants might start migrating again, leaving this Earth just as our ancestors migrated from Africa and through the Pacific. Many of the technologies already exist for migration to the planets and moons of our solar system. But we have none of the technologies needed to reach other star systems. If our descendants do migrate to distant star systems, will they create a vast archipelago like the colonies of Polynesia? If so, will collective learning occur at stellar scales? Or will the distances be so huge that human communities will become isolated culturally, and even genetically? If so, our species will split by allopatric speciation into numerous closely related successor species, just like the Galapagos finches. Will that mark the end of human history?

At larger scales we return to slower and simpler processes, such as the evolution of the Earth, the Sun, and the Universe. These we can predict with more confidence. Studying the movement of tectonic plates hints at what the Earth will look like in 100 or 200 million years' time. The Atlantic will widen; the Pacific will narrow, bringing Asia and North America together; and eventually a new supercontinent will emerge. Los Angeles will slide north and join Canada.

In the late 1990s, astronomers found that the rate of expansion of the Universe is actually increasing. We do not yet know why.

Our Sun is about halfway through its life. In 4–5 billion years it will run out of hydrogen, collapse, and then expand again to form a "red giant." The Earth will be vaporized. Eventually, the Sun will cool and shrink, becoming a "black dwarf." In its retirement, it will keep cooling for countless billions of years. Our galaxy, the "Milky Way," is on a collision course with its neighbor the Andromeda galaxy. The two will collide as our Sun enters its death throes, gliding through each other gracefully, though gravity will introduce some turbulence as they do so.

How will the Universe evolve? One idea, popular in the late 20th century, was that the gravitational pull of all the matter and energy in the Universe would eventually slow expansion until the Universe began to collapse in on itself. Time would reverse, and the Universe would collapse in a "big crunch," to be followed perhaps by a new "big bang," which would create a new Universe.

In the late 1990s, astronomers found that the rate of expansion of the Universe is actually increasing. We do not yet know why. But this suggests the Universe will keep expanding forever. What will that mean? Eventually, all stars will use up their fuel and die. The Universe will darken, and black holes will graze on what's left for countless billions of years. The space between objects will increase, and temperature differentials will narrow. With smaller energy differentials to drive complexity, the Universe will become simpler and more boring. The second law of thermodynamics will have triumphed over complexity. The Universe will continue to get more uninteresting for as many billions of years as there are sand grains on all the beaches and deserts of the Earth. And so on, forever and ever.

Where does that leave us? What is our place in this huge story? The last lecture will recapitulate the story of big history and touch on these large issues of meaning. ■

Essential Reading

Christian, *Maps of Time*, chap. 15.

Prantzos, *Our Cosmic Future*.

Supplementary Reading

Miller, *A Canticle for Leibowitz.*

Stableford and Langford, *The Third Millennium.*

Stearns, *Millennium III, Century XXI.*

Wager, *A Short History of the Future.*

Questions to Consider

1. Are there any reasonable predictions we can make about the next 1,000 years?

2. What can we reasonably say about the future of the Universe?

Big History—Humans in the Cosmos

Lecture 48

Agriculture appeared about 10,000 or 11,000 years ago. Before the appearance of agriculture, all human beings were foragers.

If asked (perhaps around a campfire) to explain how everything got to be the way it is, how might we respond? Let's begin with human history. We live in the largest and most complex human community ever created. Six billion humans, often in conflict with each other, are linked through trade, travel, and modern forms of communications into a single global community. This community was created in just a few hundred years. About 300 years ago, human beings crossed a sort of threshold as human societies became more interconnected and began to innovate faster than ever before. For 5,000 years before this, most people had lived in the large, powerful communities we call "Agrarian civilizations." They had cities with magnificent architecture and powerful rulers sustained by large populations of peasants who produced most of society's resources. Innovation was slower, so history moved more slowly, and there were fewer people than today. Two thousand years ago, there were about 250 million people on Earth.

The first Agrarian civilizations appeared in regions such as Mesopotamia, Egypt, and China. During the previous 5,000 years, humans had increasingly lived in small peasant villages governed by local chiefs. Yet many still lived by foraging, gathering what they needed as they migrated through their home territories. The appearance of agriculture, just over 10,000 years ago, counts as a fundamental historical threshold because agriculture increased the amount of resources humans could extract from a given area. By doing so, it stimulated population growth and innovation and laid the foundations for the first Agrarian civilizations.

In the preceding 200,000 to 300,000 years, all humans had lived as foragers, in nomadic, family-sized communities. Slowly, they spread through Africa and around the world. For most of this time, humans were only slightly more numerous than our close relatives, the great apes, are today. Our species, *Homo sapiens*, appeared about 200,000 to 300,000 years ago somewhere in

Africa. What made them different from all other animals, and enabled them to explore so many different environments, was their remarkable ability to exchange and store information about their environments. Humans could talk to each other, they could tell stories, and unlike any other animals, they could ask about the meaning of existence! Their appearance counts as a fundamental threshold in our story.

To understand how the first humans appeared, we must survey the history of life on Earth. Like all other species, our ancestors evolved by natural selection. They evolved from intelligent, bipedal, ape-like ancestors known as "hominines" that had appeared about 6 million years earlier. The hominines were descended from primates: tree-dwelling mammals with large brains and dexterous hands that had first appeared about 65 million years ago.

The mammals were furry, warm-blooded animals that had first evolved about 250 million years ago. They were descended from large creatures with backbones, whose ancestors had left the seas to live on the land about 400 million years ago. These were descended from the first multi-celled organisms, which appeared about 600 million years ago in the Cambrian era.

During the preceding 3 billion years, all living organisms on Earth were single-celled. The first living organisms had appeared by about 3.8 billion years ago, just 700 million years after the formation of our Earth. They were the ancestors of all living creatures on today's Earth. The speed with which they appeared suggests that life is likely to appear wherever there are planets bathed in the light and energy of nearby stars but far enough away for liquid water to form. The appearance of life is one of the most important thresholds in the big history story.

Life could evolve only after the crossing of three earlier thresholds: the creation of planets, stars, and chemical elements. Our Earth was formed about 4.5 billion years ago, along with all the other planets, moons, and asteroids and comets of our solar system, from the debris formed as our Sun was created. Solar systems probably formed countless billions of times in the history of the Universe.

Our planet, like the living organisms that inhabit it, is made up of many different chemical elements, so neither could have formed if the chemical elements had not been manufactured in the violent death throes of large stars (in supernovae) or in the last dying days of other stars. The earliest stars may have died within a billion years of the creation of the Universe. Since then, billions upon billions of stars have died and scattered new elements into interstellar space. The first stars were born, like our Sun, from collapsing clouds of gas within about 200 million years of the big bang. Today, there may be more stars than there are grains of sand on all the beaches and deserts of our Earth. And that takes us back to the beginning. Our Universe began as a tiny, hot, expanding ball of something popped out of nothingness like an explosion about 13.7 billion years ago. The explosion has continued ever since, and we are part of the debris it has created.

Trying to imagine the long, drawn-out death of our Universe suggests that we may live in the most exciting era of the Universe's history.

The story told in this course is our best shot at explaining origins of all kinds. Like all origin stories, it is far from perfect and will change in the future. Important details, including the date of the big bang, have been clarified in the last decade or two. Here are some other possible areas in which the story may change. Cosmologists will keep pushing back their understanding of the origins of the Universe. The holy grail will be a theory explaining *why* the Universe popped out of nothing, or perhaps *what* it popped out of. Cosmologists will try to understand "dark matter" and "dark energy." Biologists will acquire a better understanding of the origins of life on Earth (and perhaps elsewhere).

Anthropologists will seek new evidence on the origins of our species. To do this they will have to invest more time and energy in the archaeology of Africa in the Paleolithic period and improve their understanding of the evolution of symbolic language and collective learning. Genetic dating techniques will allow us to track human migrations with much greater precision. We also need an improved interdisciplinary understanding of complexity that can illuminate our understanding both of stars and of modern human societies and can tease out the many links between different types of complexity.

Despite the limitations of any account of big history, the story is one we need to know and tell. Telling it backward is a good way of showing how such stories can help us map ourselves onto the cosmos. We see how the modern world fits into the larger story of human history, how human history fits into the history of life on Earth, and how these stories fit into the largest story of all—that of the Universe as a whole. Like the different parts of a Russian matryoshka doll, each story is nested in and helps explain the stories surrounding it. This sort of "mapping" is closely linked to our sense of meaning. Scientists are usually reluctant to discuss meanings and prefer to concentrate on getting the story right. But as symbolic beings, most of us have to look for meaning in any universal story. So what meanings may be hidden within big history?

The suggestions that follow are personal answers prompted by teaching big history for almost 20 years. Trying to imagine the long, drawn-out death of our Universe suggests that we may live in the most exciting era of the Universe's history: its springtime, when there existed the perfect balance of energy and space to make complex things such as ourselves. We have also seen that the societies we live in today may represent the most complex structures in our part of the galaxy. Can our Universe create more complex structures? Either way, our extraordinary complexity makes us rather interesting!

We are also the only creatures we know of that are capable of seeking meaning and purpose in the Universe. In the scientific view of the Universe, in which there is no deity or conscious creator, that means that we become the Universe's bearers of purpose and meaning. It is, after all, awe-inspiring to think that blind algorithmic processes might have successfully created an organism clever enough to figure out how those blind algorithmic processes created an entire Universe!

And that's where we'll end! I hope you have enjoyed this telling of our modern creation story, and I hope you will want to encourage others to become acquainted with it. If they are young enough, they may be the ones who will help construct a new and perhaps better story in the future. ■

Essential Reading

Christian, *Maps of Time*, 497–99 (a brief synopsis of the modern creation story).

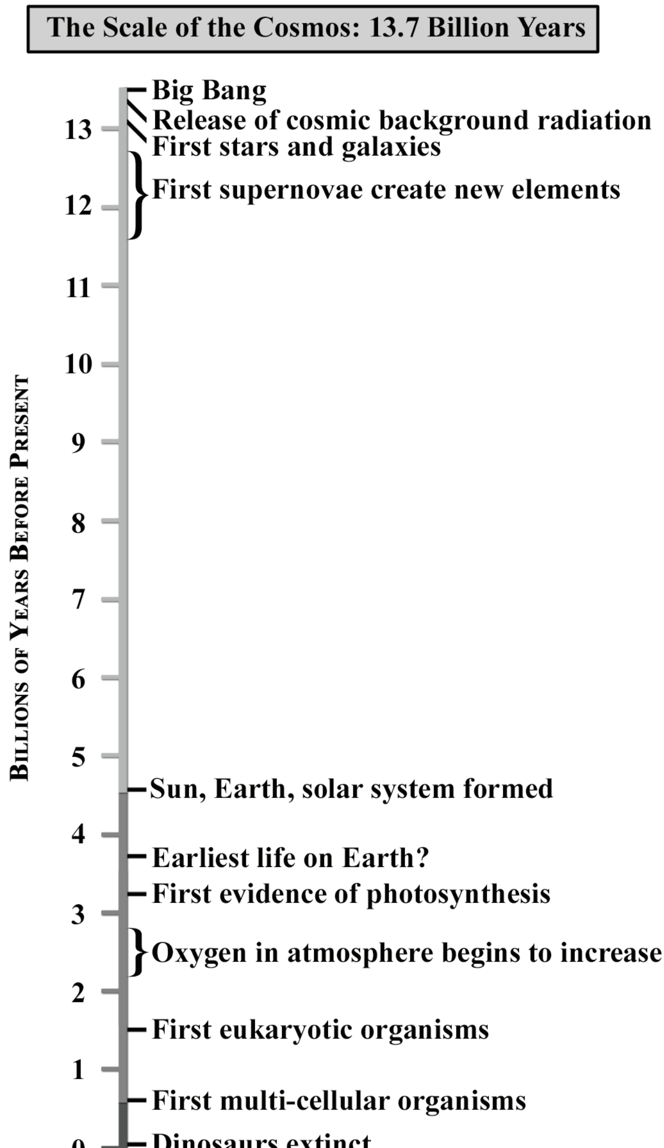
Supplementary Reading

Christian, "World History in Context."

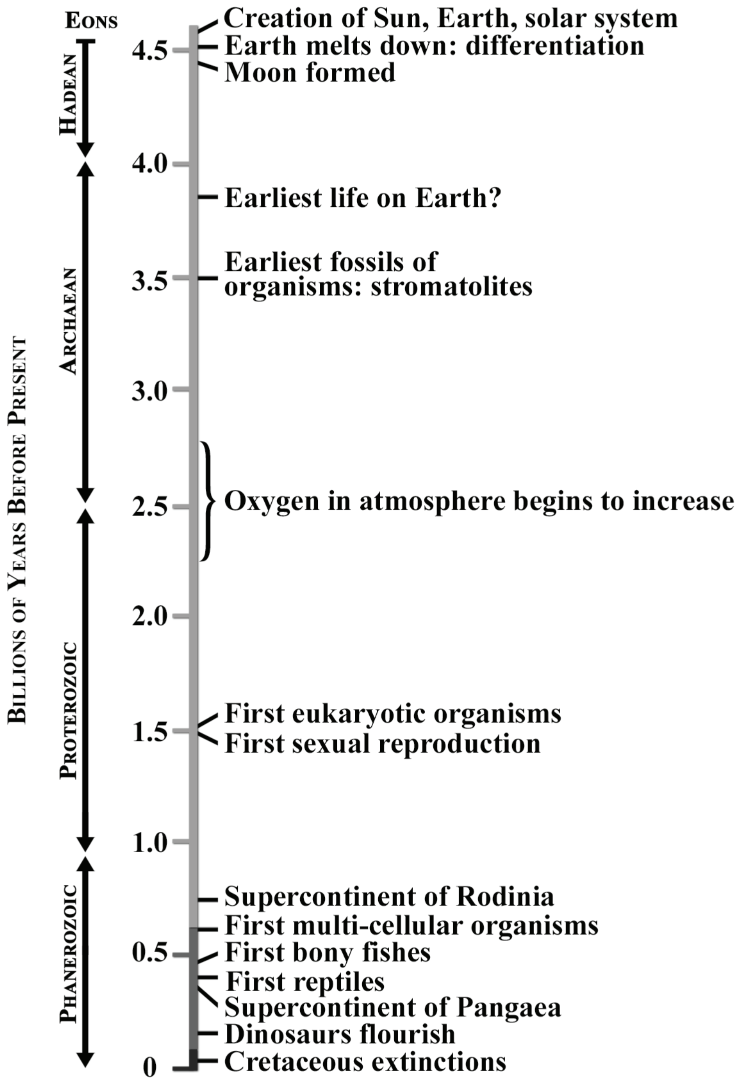
Questions to Consider

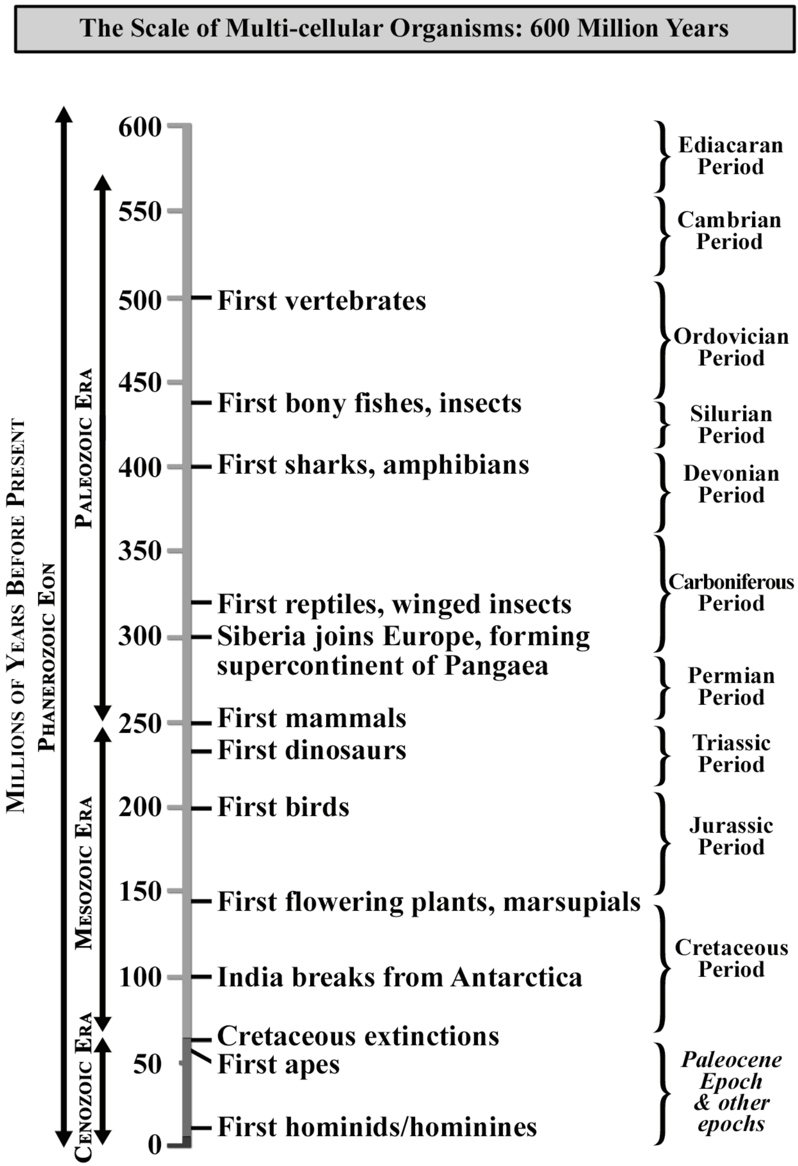
1. What do you regard as the most important themes of the modern creation story?

2. Does the modern creation story carry ethical baggage like all earlier creation stories?

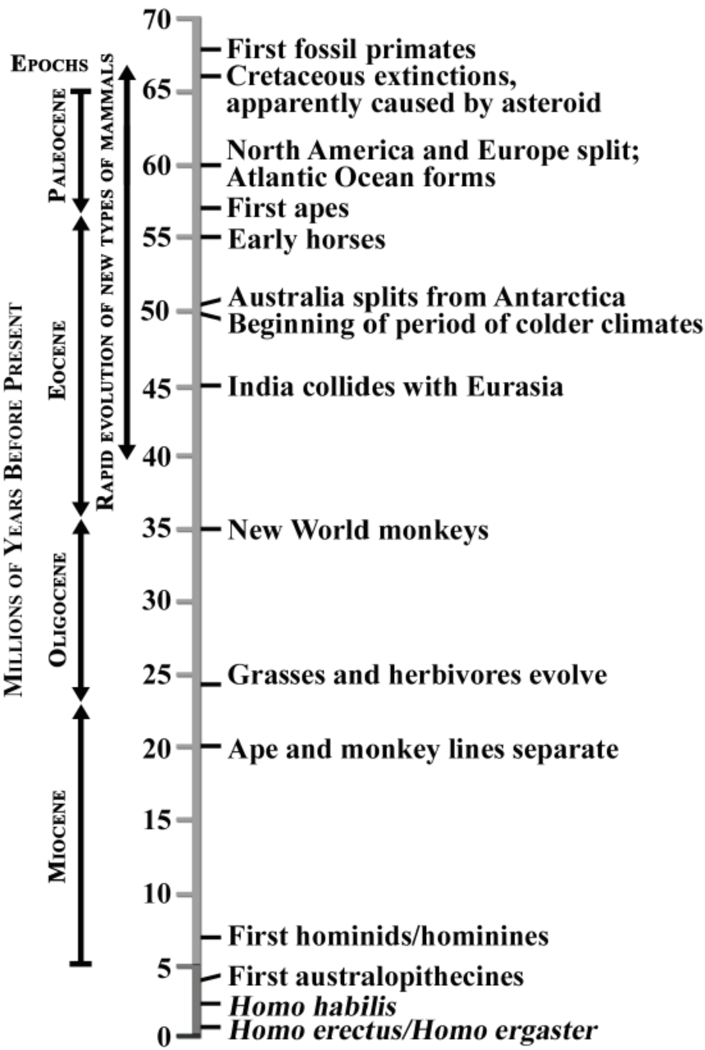

The Scale of the Cosmos: 13.7 Billion Years
Billions of Years Before Present
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Big Bang
Release of cosmic background radiation
First stars and galaxies
First supernovae create new elements
Sun, Earth, solar system formed
Earliest life on Earth?
First evidence of photosynthesis
Oxygen in atmosphere begins to increase
First eukaryotic organisms
First multi-cellular organisms
Dinosaurs extinct

The Scale of the Earth: 4.5 Billion Years

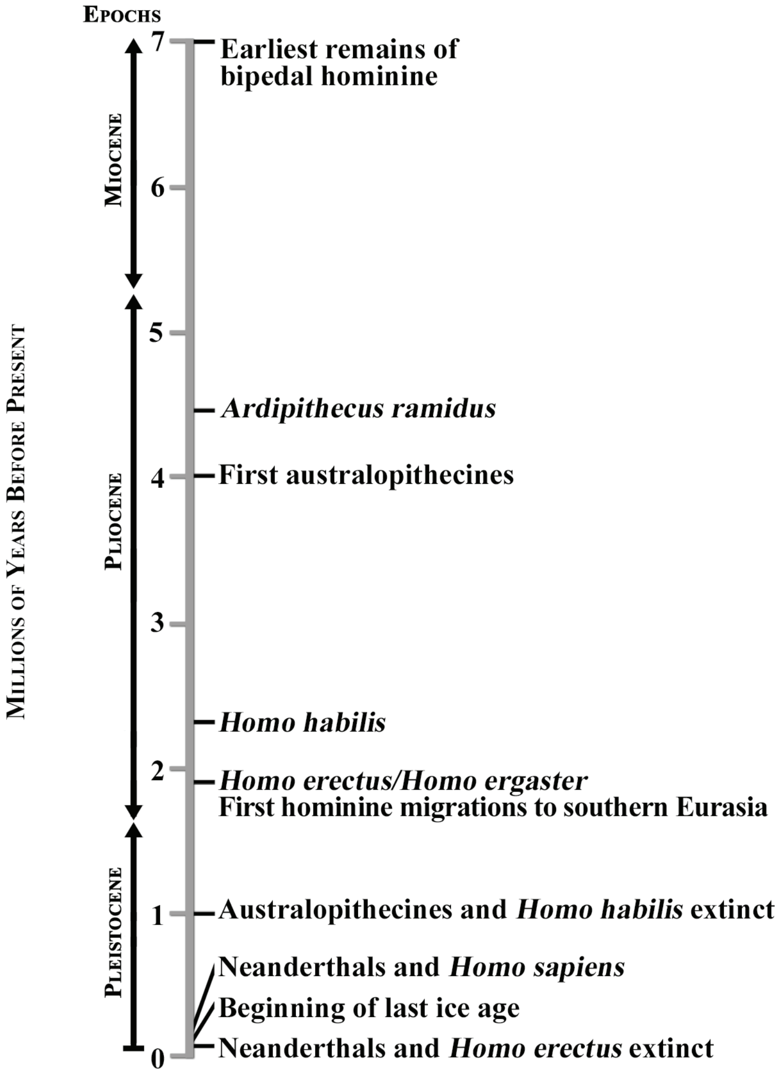


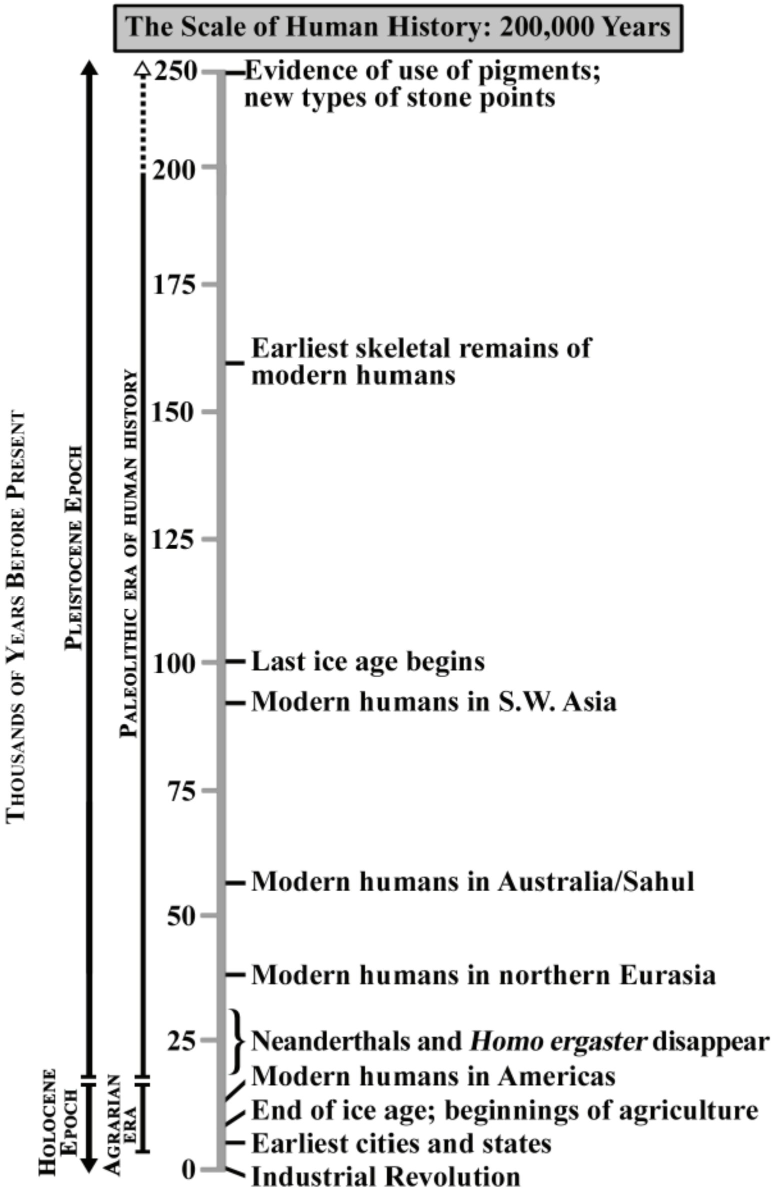

The Scale of Multi-cellular Organisms: 600 Million Years
Millions of Years Before Present
Phanerozoic Eon
Paleozoic Era
Mesozoic Era
Cenozoic Era
600
550
500
450
400
350
300
250
200
150
100
50
0
First vertebrates
First bony fishes, insects
First sharks, amphibians
First reptiles, winged insects
Siberia joins Europe, forming supercontinent of Pangaea
First mammals
First dinosaurs
First birds
First flowering plants, marsupials
India breaks from Antarctica
Cretaceous extinctions
First apes
First hominids/hominines
Ediacaran Period
Cambrian Period
Ordovician Period
Silurian Period
Devonian Period
Carboniferous Period
Permian Period
Triassic Period
Jurassic Period
Cretaceous Period
Paleocene Epoch & other epochs

The Scale of Mammalian Evolution: 70 Million Years



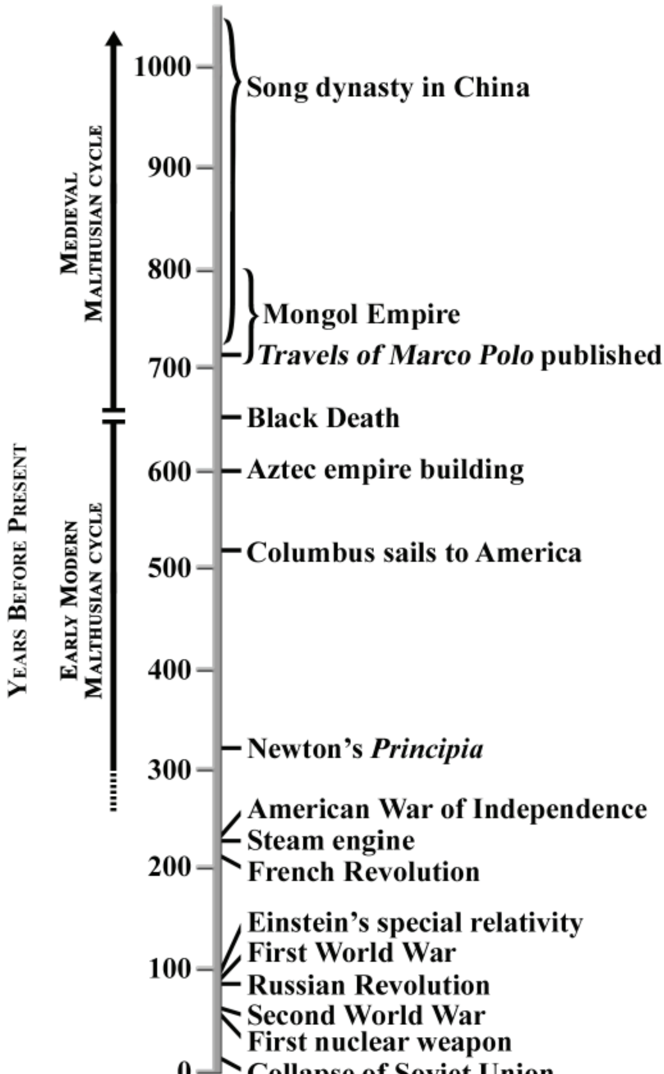
The Scale of Human Evolution: 7 Million Years




The Scale of Human History: 200,000 Years
Thousands of Years Before Present
Pleistocene Epoch
Holocene Epoch
Paleolithic era of human history
Agrarian Era
250
200
175
150
125
100
75
50
25
0
Evidence of use of pigments; new types of stone points
Earliest skeletal remains of modern humans
Last ice age begins
Modern humans in S.W. Asia
Modern humans in Australia/Sahul
Modern humans in northern Eurasia
Neanderthals and *Homo ergaster* disappear
Modern humans in Americas
End of ice age; beginnings of agriculture
Earliest cities and states
Industrial Revolution

The Scale of Agrarian Societies: 10,000 Years

The Scale of Modernity: 1,000 Years



Summary Timeline

13.7 billion years ago .... Origins of Universe.

380,000 years later .... Separation of energy and matter; cosmic background radiation.

200 million years later .... Appearance of first stars.

11–12 billion years ago (bya).......... First supernovae; appearance of new elements.

4.6 bya.. Creation of the Sun, solar system, and Earth.

c. 3.5 bya .... First life forms on Earth; single-celled "prokaryotes"; photosynthesis.

c. 2–3 bya .... Increase of oxygen in atmosphere due to photosynthesis.

c. 1.5 bya .... First complex or "eukaryotic" cells; sexual reproduction?

c. 600 million years ago (mya) .... Cambrian era; first surviving fossils of multi-celled organisms.

c. 500 mya....................................... First vertebrates; supercontinent of Rodinia breaking up.

c. 475 mya....................................... First organisms on land.

c. 350 mya....................................... First reptiles.

c. 250 mya	First dinosaurs and first mammals; supercontinent of Pangaea.
c. 67 mya	An asteroid impact destroys many species including dinosaurs.
c. 20 mya	First apes.
c. 6 mya	First "hominines" (bipedal apes).
c. 4 mya	Australopithecines.
c. 2.3 mya	*Homo habilis.*
c. 1.9 mya	*Homo erectus* evolves in Africa, but some migrate to Asia.
200,000–300,000 years ago (ya)	*Homo sapiens* evolves somewhere in Africa.
100,000 ya	Beginnings of last ice age.
40,000–50,000 ya	Humans in Sahul (Australia/Papua New Guinea).
30,000–40,000 ya	Humans in ice age Siberia.
13,000 ya	Clear evidence of humans in Americas.
11,500 ya	End of last ice age; first signs of agriculture.
6,000 ya	Earliest evidence of pastoralism; domestication in Americas?

5,000 ya	First cities and states in N.W. Africa and S. Mesopotamia.
4,000 ya	First multicity empires; cities and states in India and China.
2,500 ya	First superempire (Achaemenid Persia); first states in Americas?
2,000 ya	Roman, Parthian, Kushan, and Han Empires flourish.
800 ya	Mongol Empire, largest land empire ever created.
650 ya	Black Death.
500 ya	Different world zones linked by sea: Columbian exchange.
300 ya	Scientific Revolution.
200 ya	First industrial revolutions; first “democratic” revolutions.
100–50 ya	Western imperialism; First World War; anticolonial revolutions.
50 ya	First nuclear weapons.
0 ya	Rising consumption levels; serious damage to biosphere.
50 years from now (yfn)	Global populations stabilize?
4 billion yfn	Sun expands, destroying planets, before dying.

30 billion yfn.................................. Star formation ceases.

Many billion yfn .... Universe keeps expanding; stars die; Universe cooler and simpler.

Glossary

Note: Though some of the terms defined below are widely used, some are used in specific senses in this course. All the definitions below refer to the ways that terms are used in this course.

absolute dates: Precise dates on a universal time scale, as opposed to relative dates, which merely give a date relative to the age of some other event.

accretion: The process by which planets were formed, as materials orbiting the young Sun gathered together through collisions or gravitational or electrostatic attraction into larger and larger bodies within each orbit.

acquired characteristics: Characteristics acquired by an organism during its lifetime and therefore not inherited by its offspring.

adaptation: One of the three fundamental features of living organisms; the capacity of living organisms to slowly change from generation to generation so as to maintain their ability to fit into their changing environments (see also *metabolism*, *reproduction*).

Afro-Eurasia: One of the four major "world zones"; it includes the linked African and Eurasian landmasses.

Agrarian civilizations: Large communities of hundreds of thousands or even millions of people, based on farming, with cities and tribute-taking states.

Agrarian era: One of the three great eras of human history; the era of human history in which most people lived as agriculturalists and most resources were generated through agriculture; roughly from c. 10,000 B.C.E. to c. 1700 C.E.

agriculture: A way of exploiting the environment by increasing the productivity of those plant and animal species most beneficial for human beings. A form of symbiosis, it generally results, over time, in genetic changes in the “domesticated” species. Agriculture is vastly more productive than foraging technologies. Its appearance marks a revolutionary transformation in human history.

allopatric speciation: An evolutionary pattern in which members of a population become separated from other members of their species long enough to diverge genetically, until eventually they can no longer breed with their parent species, and they form a separate species.

amino acids: Basic chemical constituents of all proteins, the basic building blocks of living organisms.

antimatter: Particles of matter with the opposite charge to the dominant forms of matter; thus, positrons are identical to electrons except that they have a positive charge. When particles of matter and antimatter meet, they annihilate each other. It is speculated that during the big bang vast amounts of matter were annihilated in this way, leaving a tiny residue from which our Universe was constructed.

apes: Large, tailless African monkeys, a group that includes humans; members of the primate superfamily of Hominoidea.

australopithecines: A group of hominine species with brains about the size of those of chimpanzees that flourished in Africa between 4 million and 1 million years ago.

axial age: A term first used by the philosopher and historian Karl Jaspers to refer to the era during the first millennium B.C.E. and early in the first millennium C.E. when most of the major “universal” religions emerged in Afro-Eurasia.

B.C.E.: Before the Common Era; the equivalent of “B.C.”

big bang cosmology: The modern understanding of the origins of the Universe; first proposed in the 1930s but became the central idea (paradigm) of modern cosmology from the 1960s.

big history: The attempt to construct a unified account of the past at all scales from those of human history to those of cosmology; the modern, scientific equivalent of traditional creation stories; what this course is about!

big men: Anthropological term for powerful leaders in non-state societies, whose power rests mainly on their ability to accumulate and redistribute resources.

biosphere: The network of living organisms found near the surface of the Earth; the region of the Earth in which living organisms can be found (see *Gaia*).

bipedalism: Walking on two legs.

black holes: Regions in space of such high density that their gravitational pull does not even allow light to escape. Black holes can be formed by the collapse of large objects such as supernovae.

BP: Before present.

business cycle: A characteristic rhythm of expansion and contraction in capitalist societies, driven by overproduction and lack of markets.

Cambrian era: From c. 570–510 million years ago, the era in which the first large fossils appear; long thought to be the era in which life first appeared on Earth, though it is now known that single-celled organisms existed for several billion years before this.

capitalism: A type of society characterized by elite groups who generate incomes from entrepreneurial activity; a majority that generates income from wage-earning activity and exchanges on competitive markets; in Marxist thought, capitalism, though exploitative, generated higher rates of innovation than earlier social forms such as tribute-taking societies.

C.E.: Common Era; the equivalent of "A.D."

chemical evolution: Slow change in complex but nonliving chemicals, operating in a similar manner to natural selection and possibly leading to the creation of the first true living organisms.

chiefs: Anthropological term for powerful leaders in non-state societies whose power rests largely on their aristocratic birth, though they may also wield significant coercive power.

coevolution: When two species develop a close symbiotic relationship, evolutionary change in one species must be followed by evolutionary change in the other, so the two species begin to evolve together.

collective learning: The ability, unique to human beings, to share in great detail what each individual learns through symbolic language; collective learning may be the source of the unique technological creativity of our species.

collision margins: Tectonic margins where plates are driven together; either one plate dives beneath the other (as the Pacific plate is diving under South America), or both plates rise to form mountain chains at the borders between them (as in the Himalayas).

Columbian exchange: Term coined by Alfred Crosby for the exchange of diseases, crops, peoples, and goods that followed the linking of the different world zones after 1500 C.E.

complexity: Entities with many precisely linked internal components and novel "emergent" properties, whose survival depends on flows of free energy.

consumer capitalism: The most recent phase in the history of capitalism, in which productivity levels are so high that profits can only be realized by selling goods to the wageworkers who produce them; requires paying workers high enough wages to purchase and encouraging steadily raising average consumption levels. Consumer capitalism originated in the early 20th century and is typical of the wealthiest capitalist countries today.

contingency: The idea that many events (in history or the natural world) are random and unpredictable.

cosmic background radiation: Low energy radiation pervading the entire Universe, released c. 380,000 years after the big bang, when the Universe cooled sufficiently for neutral atoms to form so that energy and matter could separate; its discovery, in 1964, persuaded most cosmologists to accept the big bang theory.

cosmic evolution: A synonym for big history; history on all scales up to those of cosmology.

cosmology: Study of the history and evolution of the Universe.

creation stories: Stories found in all human societies about the origins of all things.

Cretaceous event: The term used to describe the asteroid impact about 67 million years ago that led to the extinction of many species, including the dinosaurs.

cuneiform: A type of writing, common in ancient Mesopotamia, in which symbols are made by pressing wedge-shaped cross sections of reeds into clay.

dark matter/dark energy: Studies of the movements of stars and galaxies have shown that there must exist much more energy and/or matter than we can observe; at present, astronomers have no idea what either dark energy or dark matter consist of; one of the great mysteries of contemporary astronomy.

determinism: The idea, common in the 19th century, that general laws determine the exact course of events so that if we had complete knowledge of reality we could, in theory, predict the future.

differentiation: The process by which, early in the Earth's history, the Earth melted to form a series of different layers, with the heaviest materials (mostly metals) in the core, lighter materials in the mantle, the lightest elements at the surface, and gassy materials in the atmosphere.

diffusion: The spread of ideas or innovations or people from a single center.

dissipative structures: Technical term used by Nobel Prize–winning chemist Ilya Prigogine to describe complex structures (such as stars or living organisms) that exist far from equilibrium and require flows of energy in order to survive; so-called because, by using free energy, they "dissipate" it, thereby increasing entropy.

divergent margins: Geological regions where tectonic plates are driven apart by upwelling magma; a modern example is the center of the Atlantic Ocean.

division of labor: Differentiation in human occupations so that different professions appear and individuals have to exchange goods and services in order to support themselves. There was very little division of labor in the Paleolithic era, but as populations and population densities increased in the Agrarian era the division of labor developed rapidly, generating greater social, economic, and political complexity.

DNA: Deoxyribonucleic acid, the complex, double-stranded molecule that carries genetic information in all living organisms on Earth.

domestication: Genetic modification of species by humans to make them more docile, more productive, and more amenable to human control; a form of symbiosis, in which domesticated species benefit from human protection.

Doppler effect: The stretching out or contraction of wavelengths because of the relative movement of two bodies; the Doppler effect explains why an ambulance siren seems higher when the ambulance is traveling toward you than when it is moving away; it also explains why the light from distant galaxies is displaced toward the red end of the spectrum if they are moving away from us. This is crucial evidence for the idea that our Universe is expanding.

Dreamtime: In indigenous Australian traditions this was the time of beginnings, of origins, and of the law.

early Agrarian era: The early part of the Agrarian era, which lasted, globally, from c. 8000 B.C.E. to c. 3000 B.C.E., though its dates vary in different regions; the 5,000-year-long era of human history during which there were Agrarian societies but no Agrarian civilizations, and the largest human communities were villages.

electromagnetism: One of the four fundamental forces of the physical Universe, responsible for holding positively and negatively charged particles (such as protons and electrons) together; the most important force in many chemical processes.

electrons: Negatively charged subatomic particles that orbit the nuclei of atoms.

elements (chemical): The basic constituents of chemical processes; each atomic element is defined by the number of protons in its nucleus, and elements are listed in the *periodic table*; chemical processes are dominated by the combination of different elements into larger "molecules"; only hydrogen and helium, the simplest elements (with, respectively, one and two protons in their nuclei), were created in the big bang; most other elements were created either in stars or in supernovae.

emergent properties: Properties of a complex entity that are not present within its component parts but emerge only when those parts are linked together in a particular configuration; an automobile has emergent properties that its parts lack when it is dismantled.

Enlightenment: Era of European intellectual history in the 18^{th} century; a period of optimism about the beneficial achievements of science and the necessity of progress.

entrepreneurs: Those who make money primarily by producing, buying, and selling goods or services on competitive markets (distinguished from tribute-takers, who exact resources through the threat of force).

entropy: A measure of disorder; according to the second law of thermodynamics, in any closed system (including the Universe as a whole) the total level of entropy must slowly increase as energy is distributed more and more evenly and is therefore less and less capable of performing work.

eukaryotes: Cells more complex than prokaryotes, in which there are distinct "organelles" (such as *mitochondria*), and in which the genetic material is protected within the nucleus; many single-celled organisms are eukaryotic, and so are *all* multi-celled organisms; Lynn Margulis has shown that the first eukaryotes probably arose through a symbiotic merging of prokaryotic cells.

evolution: Change over time; applied most frequently to the evolution of living organisms according to the principles of natural selection, first discovered by Charles Darwin in the 19th century; does *not* necessarily mean change in the direction of a "higher," more "advanced," or more "progressive" state.

exchange networks: The networks through which humans exchange information, goods, styles, and even diseases.

extensification: An ugly word coined specifically for this course; it describes processes of innovation and growth that lead to more extensive settlement without leading to increase in the size of individual human communities; extensification was the characteristic form of growth in the Paleolithic era; the opposite of *intensification*.

extinctions: There have been several episodes in the Earth's history in which large numbers of species have suddenly become extinct; we are living through such an episode now, and its main cause appears to be increasing human consumption of resources and habitats.

feedback loops (negative): Causal chains in which some factors reduce the impact of other causal factors, potentially leading to stability or equilibrium; a thermostat in a heating system is an example of negative feedback.

feedback loops (positive): Causal chains in which each factor magnifies the impact of other factors; can lead to accelerating or runaway change, as in a nuclear explosion, in which the breakdown of each atom triggers the breakdown of other nearby atoms.

Fertile Crescent: The arc of lands around Mesopotamia, which contain the earliest evidence of agriculture.

firestick farming: *Not* a form of farming, but a foraging strategy; foragers regularly burn the land to prevent wildfires, to encourage new growth, and to attract grazers that can be hunted. Though a form of foraging, it also counts as a way of manipulating the environment in order to increase the productivity of resources useful to humans, so it can be regarded as a step toward farming.

fission: The breaking up of large atoms, such as uranium, releases radioactive energy; when many atoms are close together, the breakup of one atom can release subatomic particles that split other atoms, in a chain reaction; this chain reaction drives nuclear weapons and nuclear reactors.

foraging: Technologies that depend on the use of natural resources more or less in their natural state; hunting and gathering; the dominant type of technology in the Paleolithic era.

fossil fuels: Fuels formed from living organisms fossilized in the remote past, they are the dominant source of energy today; fossil fuels include coal, oil, and natural gas; the "fossil fuels revolution" is the transition to dependence on fossil energy that has occurred since the Industrial Revolution.

free energy: Energy distributed unevenly so that it is capable of doing useful work; a charged battery can do work because negative charges are concentrated at one of its terminals, but as it does work, the balance of negative and positive charges evens out, increasing *entropy* and reducing its capacity to do more work.

free energy rate density: The density of free energy flowing through a complex entity, measured in units of energy passing through a given mass in a given amount of time; Eric Chaisson has argued that the free energy rate density provides a rough measure of levels of complexity.

fusion: Stars are powered for most of their lives by the fusion of hydrogen atoms into helium atoms, as a result of which vast amounts of energy are released; source of the power of hydrogen bombs.

Gaia: The Greek goddess of the Earth; the name was used by James Lovelock to describe the linked actions of all life forms on the surface of the Earth, which for some purposes can be regarded as a single, vast organism that has lived and evolved for almost 4 billion years; as Lovelock has argued, today human activity may be inflicting significant damage on Gaia, though he also argues that Gaia may prove resilient enough to survive and outlast us.

Galapagos Islands: An archipelago of 19 islands in the Pacific Ocean, owned today by Ecuador and visited by Darwin for five weeks in 1835; the many tiny variations he observed between the species on different islands helped crystallize his ideas on natural selection.

galaxies: Large "societies" of stars, held together by their mutual gravitational pull.

global history: Studies of world history since the linking of the world into a single system in the 15th century of the Modern era.

global warming: The observed increase in global average temperatures that is almost certainly due mainly to the rapid increase in the amounts of carbon dioxide in the atmosphere caused by the massive use of fossil fuels in the last two centuries.

globalization: The increasing interlinking of different regions of the world since 1492.

GNP: A standard measure of economic production; a widely calculated measure, for which there are even estimates reaching several centuries into the past. However, because it is based on market prices, it can tell little about nonmarket production or about the ecological costs of production.

Gondwanaland: The large southern supercontinent formed almost 200 million years ago by the breakup of Pangaea; included South America, Antarctica, Australia, Africa, and India; see also *Laurasia*.

grand narrative: Term used in post-modern theory to describe overarching accounts of reality (such as Marxism, or big history); points to the danger that such accounts can mislead or be put to self-interested uses.

grand unified theory: The idea of a single, unified scientific account of all aspects of physical reality; the holy grail of modern physics since the 1960s; remains elusive because of the failure to merge relativity and quantum physics or to explain the nature of dark matter/dark energy.

hafted tools: Tools attached to handles.

half-life: The period during which half of the mass of a given radioactive material decays; the precision with which half-lives can be calculated for different radioactive materials is the basis for most forms of radiometric dating.

helium: The second-simplest atomic element, with two protons and two electrons, produced, like hydrogen, soon after the big bang; helium made up about 24% of the matter in the early Universe but now makes up about 28% as fusion reactions have converted hydrogen atoms into helium.

hominids/hominines: Bipedal apes, ancestors of modern humans; first appeared 6–7 million years ago.

Hominoids/Hominoidea: The superfamily of apes (includes humans).

Homo erectus/ergaster: Hominine species that appeared in Africa almost 2 million years ago; almost as tall as modern humans, their brains were larger than those of *Homo habilis*; some *erectus* migrated into Eurasia, reaching as far as China.

Homo habilis: Hominine species that appeared in Africa between 2 and 3 million years ago; classified by their discoverer, Louis Leakey, within the genus that includes us because they made simple stone tools, they are now thought to have been much closer to australopithecines than to modern humans.

Homo sapiens: Human beings, our own species; probably evolved in Africa between 200,000 and 300,000 years ago; the only species on Earth (or anywhere else as far as we know at the moment) that can adapt by "collective learning."

hub region: A geographical region characterized by an exceptional number of exchanges of people, ideas, and goods taking place; Mesopotamia was an ancient hub region; after 1500, the Atlantic regions became a significant hub region through Europe's control of the major international sea routes.

Hubble constant: The rate of expansion of the Universe; calculating this constant precisely has been extremely difficult; modern estimates range from 55 to 75 km per second per megaparsec, implying that the Universe must be between 10 and 16 billion years old.

hunting and gathering: See *foraging*.

hydrogen: The simplest of all atomic elements, hydrogen was produced soon after the big bang; each hydrogen atom consists of one proton and one electron; deuterium is an isotope (or form) of hydrogen whose nucleus also contains a single neutron; hydrogen made up about 76% of all the matter in the early Universe and still makes up about 71% today.

intensification: The type of growth or innovation characteristic of the Agrarian and Modern eras, in which innovation allows the support of more people from a given area and therefore generates larger and denser human communities; contrast with *extensification*.

isotopes: Atoms of a given element that have varying numbers of neutrons in their nucleus and therefore varying atomic weights; carbon dating techniques depend on measuring changes in the ratio of different isotopes of carbon as carbon 14 (the only radioactive isotope of carbon) breaks down over time.

kin-ordered societies: A term used by Eric Wolf to describe all human societies in which kinship systems are the most important basis for social organization; all societies before the appearance of the first tribute-taking states can be regarded as kin-ordered.

later Agrarian era: From c. 3000 B.C.E. to a few centuries ago; the second part of the Agrarian era, in which there existed Agrarian civilizations; synonym for "era of Agrarian civilizations."

Laurasia: The large northern supercontinent formed almost 200 million years ago by the breakup of Pangaea; included Eurasia and North America; see also *Gondwanaland*.

macrohistory: Study of the past on large scales.

Malthusian cycles: Long cycles of economic, demographic, cultural, and even political expansion, generally followed by periods of crisis; warfare; and demographic, cultural, and political decline. These cycles, generally lasting several centuries, are apparent throughout the Agrarian era and were probably generated by the fact that, though there was innovation (which generated the upward swings), rates of innovation could not keep pace with rates of growth (which explains the eventual crashes).

mantle: Layer of the Earth between the core and the crust; the mantle is semimolten, and convection currents within it drive plate tectonics.

margins, tectonic: Regions where tectonic plates meet; this is where most interesting geological events occur, including mountain building, earthquakes, and volcanic activity.

matter: As Einstein showed, matter and energy are interchangeable (according to the famous formula, e [energy] = m [mass] × c [the speed of light]^2); matter can, therefore be regarded as a form of congealed energy; for much of the first second of the big bang, matter and energy were still interchangeable.

megafaunal extinctions: The extinction of large animal species in the Paleolithic era, probably as a result of overhunting by humans; megafaunal extinctions were particularly severe in lands newly colonized by humans in the Australasian and American world zones, which is why those regions had fewer large mammal species and therefore fewer potential animal domesticates.

metabolism: One of the three fundamental features of living organisms; the ability of all living organisms to take in energy from their surroundings; the methods they use to do so (see also *adaptation*, *reproduction*).

microhistory: Study of the past on very small scales, often through the biographies of individuals, or through study of particular events.

mitochondria: "Organelles" found within all eukaryotic cells, which specialize in processing the energy of oxygen; they contain their own independent DNA, which suggests, as Lynn Margulis has proposed, that they were once independent organisms incorporated with eukaryotic cells through symbiosis.

Modern era: One of the three great eras of human history, beginning within the last two or three centuries; characterized by sharp increases in innovation and productivity that rapidly transformed human societies throughout the world.

Modern Revolution: A deliberately vague label for the revolutionary transformations that have created the modern world; the "Modern Revolution" ushered in the "Modern era" of human history.

monumental architecture: Large structures, such as pyramids or large statues, that seem to appear wherever powerful leaders emerge; a feature of all Agrarian civilizations.

Natufians: A culture of affluent foragers whose remains are found in much of the Fertile Crescent; from c. 14,000 BP, the Natufians lived in villages but harvested wild grains and hunted gazelle; though they did not farm, their culture suggests some of the transitional stages between affluent foraging and early forms of agriculture.

natural selection: Key idea in the modern understanding of how living organisms change, developed in the 19th century by Charles Darwin; Darwin argued that tiny, random variations in individuals may increase or decrease their chances of survival; those whose chances are enhanced are more likely to pass on their genes to their offspring so that, eventually, more and more individuals will inherit the successful variations; over long periods of time such tiny changes lead to the emergence of new species; the central idea (paradigm) of modern biology.

Neanderthals: A hominine species that appeared within the last million years in Europe, the Middle East, Central Asia and southern Russia; genetic evidence suggests that the human and Neanderthal lines diverged from c. 500,000 years ago; though Neanderthals used more advanced stone technologies than *Homo erectus/ergaster*, it seems unlikely that they were capable of symbolic language; the last Neanderthals lived c. 25,000 years ago in Western Europe.

Neolithic era: "New Stone Age," from about 10,000 years ago; the era in which agriculture first appeared.

neotony: An evolutionary process in which juvenile features of the ancestral species are preserved into adulthood; humans can be regarded as neotenous apes because brain growth continues for much longer than in apes and we preserve into adulthood the flat faces and relative hairlessness of young apes.

net primary productivity (NPP): That portion of energy from sunlight which is used by photosynthesizing organisms and therefore enters the food chain and becomes available to support the biosphere in general; the energy income of the biosphere.

neutrons: Electrically neutral subatomic particles present in the nuclei of most atoms; unlike protons, the number of neutrons in a given element can vary slightly, giving rise to different "isotopes" of each element.

nucleotides: Basic chemical constituents of the genetic material of all living organisms.

obsidian: A hard, glass-like substance formed during volcanic eruptions and widely used in prehistory for the making of sharp and durable blades; widely traded in the Neolithic era.

Olbers' paradox: The observation that if the Universe were infinite in size, there ought to be an infinite amount of light and heat so that the night sky should not be dark.

oxygen: A highly reactive chemical element with eight protons (atomic number 8), normally a gas on Earth; because oxygen is so reactive, the oxygen in the Earth's atmosphere has to be constantly renewed by the activity of photosynthesizing organisms, so free oxygen did not appear in the atmosphere until about halfway through the Earth's history; as James Lovelock pointed out, any planet with free oxygen in its atmosphere must have some chemical mechanism (perhaps associated with living organisms?) that constantly replenishes the supply of oxygen.

ozone layer: Ozone is a molecule consisting of three oxygen atoms, in contrast to the more common form consisting of just two atoms; a thin layer of ozone high in the atmosphere shields the Earth's surface from harmful forms of ultraviolet radiation; in the 1980s it was found that the use of CFCs (chlorofluorocarbons) was breaking up the ozone layer; international treaties have led to the banning of most production and use of CFCs.

Pacific zone: The largest but least populous of the four world zones of human history; created within the last 3,000–4,000 years as migrants from the western edge of the Pacific Ocean slowly settled Pacific islands, bringing with them technologies of farming.

Paleolithic era: One of the three great eras of human history; literally, the "Old Stone Age," as most surviving evidence consists of stone tools; in this course, refers to the era of human history from the origins of our species (perhaps 200,000 years ago) to the appearance of agriculture about 10,000 years ago.

Pangaea: The vast supercontinent formed more than 200 million years ago as plate tectonics joined most of the major continental plates together; it is probable that such supercontinents have formed periodically throughout the Earth's history; the existence of a single huge landmass probably reduced biodiversity.

paradigm: The central organizing idea of a scientific discipline, such as natural selection (in biology), big bang cosmology (in cosmology), or plate tectonics (in geology); as yet, history lacks a paradigmatic idea; the term is associated with the work of philosopher of science T. S. Kuhn.

parallax: The change in the apparent relationship between two fixed objects caused by the movement of the observer; if you hold your finger up and move your head, your finger will appear to move against the background; parallax measurements can be used to measure the distance to the nearest stars.

pastoralism: A life similar to agriculture but based primarily on the exploitation of domesticated animals rather than plants; in order to allow animals to graze over large areas, pastoralists are generally nomadic; pastoralism was made possible as a result of the innovations of the *secondary products revolution* and spread widely in the steppelands of both Eurasia and Africa.

patriarchy: Ideologies and social structures that assume the superiority of males over females.

peasants: Small holding farmers, who generally pay taxes to overlords; the most numerous class in all Agrarian societies.

periodic table: A way of listing chemical elements in groups with common features; first constructed by the great Russian chemist Dmitrii Mendeleev in 1869.

photosynthesis: The use of sunlight by plants or plant-like organisms to store energy; first evidence from c. 3.5 billion years ago; the source of most of the energy that drives life within the biosphere.

planetesimals: Objects formed by accretion during the formation of the solar system; protoplanets.

planets: Chemically complex objects orbiting stars; it is now known planets orbit a majority of stars.

plate tectonics: The central idea (paradigm) of modern Earth sciences since the 1960s; based on the notion that the Earth's crust is broken into separate plates that are in constant motion.

power: Power relations in human societies can usefully be analyzed into two fundamental forms: "power from below" is power granted by followers to a leader to ensure the successful achievement of group tasks (such as the election of captains in sports teams); "power from above" is power that depends, in addition, on the ability of rulers to impose their will by force; in the history of human societies, power from below preceded power from above for the simple reason that to pay for a body of retainers that could impose one's will by force it was necessary already to have the ability to mobilize significant resources.

prestige goods: Goods such as silk or precious metals that combine high value and relatively low bulk or weight; before the Modern era, such goods were more often traded over large distances than goods of greater bulk or lesser value, such as grains.

primary producers: Those groups of people (such as peasants or foragers) who produce resources from the natural environment; elite groups exact resources from primary producers.

primates: An order of mammals that appeared about 70 million years ago, characterized by relatively large brain size, manipulative hands, and stereoscopic vision; all these features may be the result of dwelling in trees; apes (and therefore hominines and humans) belong within this order.

prime movers: Used in these lectures to refer to the most important forces driving innovation and growth in human history; they include commerce, collective learning, and population growth.

prokaryotes: Simple, single-celled organisms in which the genetic material is not bound within a nucleus.

proletarians: The term used within Marxist theory to refer to wage earners, those groups who could bring to markets nothing but their own labor power.

proton: Positively charged subatomic particle present in the nuclei of all atoms.

punctuated evolution: The idea first proposed by Stephen Jay Gould and Niles Eldredge in 1972 that the pace of biological evolution can vary significantly, so that the history of biological species consists of long periods of relative stasis "punctuated" by periods of abrupt change.

quarks: The fundamental constituents of neutrons and protons.

quipu: Knotted strings used by the Inka for accounting and as an embryonic form of writing.

radiometric dating techniques: Techniques for determining the dates of origin of materials by measuring the extent of the breakdown of radioactive materials.

Rapa Nui: A Pacific island (also known as Easter Island) owned by Chile, first settled by Polynesian navigators approximately 1,000 years ago and remarkable for the presence of many large stone figures.

rebus principle: A critical stage in the evolution of writing; if an object that could be easily depicted (say an arrow) sounded similar to a more abstract concept (such as soul), the symbol for the first could be used to refer to the second; this device greatly expanded the ability of written language to mimic spoken language.

reciprocity: Mutual exchanges of gifts; in kinship societies, one of the most powerful ways of holding communities together through the creation of mutual obligations.

red shift: In the 1920s, Edwin Hubble observed that the light from many distant galaxies appeared to be shifted toward the red end of the spectrum; he interpreted this as the result of a Doppler effect, which implied the galaxies emitting such light were moving rapidly away from us; the first piece of evidence that our Universe was expanding.

regimes: Complex structures such as stars or living organisms or entire ecosystems that achieve a certain stability but eventually break down.

relative dates: Dates that can determine the order in which events occurred (such as the order in which different geological epochs occurred) but not the time periods between them (see *absolute dates*).

reproduction: One of the three fundamental features of living organisms; the ability of all living organisms to make almost perfect copies of themselves; the occasional imperfections provide the variety from which natural selection constructs new species (see also *adaptation*, *metabolism*).

retinues: Armed retainers of political leaders; a critical step toward the creation of states capable of coercive power (*tribute-taking states*), or "power from above."

RNA: Ribonucleic acid; similar to DNA, but it comes in single strands so it can fold like a protein and engage in metabolic activity, yet it can also carry genetic information; RNA, with its ability both to encode genetic information and engage in metabolism, may have played a crucial role in the early evolution of life on Earth.

secondary products revolution: A concept developed by the late Andrew Sherratt to describe a series of technological innovations from about 6,000 years ago that made it possible to exploit domesticated animals more efficiently by using products such as their wool, their milk, and their traction power, all of which could be used without first killing the animals; these innovations revolutionized transportation, made possible plow agriculture, and led to the emergence of pastoralist lifeways.

sedentism: Living in one place for most of the year; sedentism was rare in foraging societies but became widespread with the adoption of agriculture because agriculture made it possible to produce more resources from a given area and encouraged farmers to stay in one place to protect their crops.

sexual reproduction: A form of reproduction that emerged about 1 billion years ago, in which two organisms exchange genetic material before reproduction so that their offspring are not clones of the parents; sexual reproduction increased variations between individuals and thereby sped up the pace of biological evolution.

spectrometer: A prism-like device that can split light into its different wavelengths; fundamental tool in the study of stars.

steady-state theory: An alternative theory to big bang cosmology, holding that the "red shift" was an illusion created by the constant creation of new matter in the Universe; the theory lost credibility after the discovery of the cosmic background radiation, which it could not explain.

supernova: The explosion of a large star at the end of its life; most chemical elements can only be manufactured in supernova explosions.

swidden agriculture: A form of agriculture in which woodlands are burned down, crops are planted in the ashy soil, and then, when the fertility of the newly cleared fields declines, new regions are cleared; because it is seminomadic, swidden agriculture is possible only in regions of low population density, such as the Amazon basin.

symbiosis: Relations of interdependence between different species, such as those between humans and domesticated plants and animals, which offer benefits (of different degrees) to each species; such relations are extremely common in the natural world.

symbolic language: A form of communication unique to human beings, using symbols and grammar; much more powerful and precise than the forms of communication used by all other animals; the basis for "collective learning."

synergy: Processes in which causal factors mutually enhance their combined impact so as to have a greater effect than they might have had on their own.

tectonic margins. See *margins, tectonic*.

tectonic plates: Portions of the Earth's surface or crust that move as a result of movements in the hot, semiliquid magma beneath them.

teosinte: Wild, ancestral form of maize.

thermodynamics, first and second laws of: Two fundamental laws of modern physics; the first law of thermodynamics says that energy is never lost; the second law says that "free energy," i.e., energy distributed in ways that enable it to do work, is slowly dissipated over time as energy differentials tend to even out.

tribute-taking societies: Societies dominated by tribute-taking states, in which the majority of people are small farmers; such societies are characterized by lower rates of innovation than the much more commercialized "capitalist" societies.

tribute-taking states (tribute-takers): States or groups capable of exacting resources from others, if necessary, through the threat of force.

universal Darwinism: Term coined by Richard Dawkins to suggest that change in many different domains, including cosmology and history, is similar to change through natural selection in the biological domain.

universal history: The project of constructing histories at all scales; a project pursued at least since the classical era, sometimes used as a synonym for "big history."

wage labor: Work performed in return for wages rather than under obligation or compulsion.

world history: Historical research and teaching embracing the entire world, generally focusing on the last 10,000 years of human history.

world systems theories: Pioneered by Immanuel Wallerstein, world systems theories explore large networks of interaction through trade or other exchanges.

world zones: Large regions settled by humans, between which there is no significant contact; the main world zones during the era of human history have been Afro-Eurasia, the Americas, Australasia, and the Pacific; similarities and differences in these zones provide powerful evidence of fundamental long-term tendencies in human history.

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"Big history" is a new discipline, so there are few books that attempt to tell the whole story, though there are many that recount different parts of the story. H. G. Wells's famous *Outline of History*, first published in 1920 in the aftermath of World War I, was an engaging and immensely successful attempt to write a big history. But Wells wrote before the scientific breakthroughs of the middle of the 20th century allowed us to date events before the appearance of written records. He also wrote before the breakthroughs in cosmology, evolutionary biology, and geology that transformed all these scientific disciplines into *historical* disciplines, disciplines concerned with change over time.

Here, I list some recent attempts to tell the story of big history, or significant parts of it. I have referred most of all to my own book, *Maps of Time*, because that will supplement the arguments presented, in more concise form, in the lectures. For the second half of this course, there are now many fine textbook surveys of world history, some of which are listed in the Reading section below. Fred Spier has compiled a more complete bibliography of works on big history, which is available at: http://www.iis.uva.nl/i2o/object.cfm/objectid=21E38086-9EAF-4BB2-A3327D5C1011F7CC/hoofdstuk=5.

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Useful websites:

Powers of 10. There are several "Powers of 10" websites. They survey the Universe on different scales, changing the scale by 10 times at each step. A superb way of getting a sense of the vast distance we travel as we move from the very large to the very small. For three examples, see: http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/, http://www.powersof10.com/, and http://www.wordwizz.com/pwrsof10.htm.

Big History. Fred Spier's site includes a bibliography of works on big history: http://www.iis.uva.nl/i2o/object.cfm/objectid=21E38086-9EAF-4BB2-A3327D5C1011F7CC/hoofdstuk=5.

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Global GDP per capita 1500–1998: Based on Table B-21: World GDP per Capita, 20 Countries and Regional Averages, 0–1998 A.D., *The World Economy: Volume 1: A Millennial Perspective and Volume 2: Historical Statistics*, © OECD 2006.

Global Population Growth: 1500–1998: Based on Table B-10: World Population, 20 Countries and Regional Totals, 0–1998 A.D., *The World Economy: Volume 1: A Millennial Perspective and Volume 2: Historical Statistics*, © OECD 2006.

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Ratio of Wealth in World's Richest Countries and Poorest Countries for years 1913 and 1992 based on data from *Monitoring the World Economy: 1820/1992*, © OECD 1995.

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