

Bones, Stones, and Genes: The Origin of Modern Humans
Lecture 4 – Hominid Paleobiology
Tim D. White, Ph.D.

1. Start of Lecture 4 (0:00)

[Music][ANNOUNCER:] From the Howard Hughes Medical Institute...The 2011 Holiday Lectures on Science. This year's lectures, "Bones, Stones, and Genes: The Origin of Modern Humans," will be given by Dr. John Shea, Professor of Anthropology at Stony Brook University; Dr. Sarah Tishkoff, Professor of Genetics and Biology at the University of Pennsylvania; and Dr. Tim White, Professor of Integrative Biology at the University of California, Berkeley. The fourth lecture is titled "Hominid Paleobiology. "And now, a brief video to introduce our lecturer, Dr. Tim White.

2. Profile of Dr. Tim White (1:10)

[Music][DR. WHITE:] The traditional image I think of the paleoanthropologist is sort of an amateur who rides off into the desert on a camel, kicks some skull out of the sand, exclaims eureka, publishes a headline, and then a personal book about how wonderful it was to find the fossil, and then goes on a lecture circuit. That is not the way modern paleoanthropology proceeds. Modern paleoanthropology is a multidisciplinary effort. So you can come to be a paleoanthropologist through all kinds of different disciplines. To give you a far-out one, space sciences: today, that's how we find the sites. We don't find them from the top of a camel; we find them from satellites, satellite imagery, digital imagery. And we don't control where we are from looking around at an aerial photograph the way it was, say, 25 years ago when I started in this field; we go out with differential GPS and we can code that and put it right into our field logs. And so, computer scientists have a role to play in this. It's... human evolutionary studies really is an integrative science, and it's a science that needs specialists from all different walks of science, bringing together their joint expertise. And I hope that students exposed to this incredible adventure, this intellectual adventure of learning how we became human, I hope that some of them will become interested, even passionate about this and go on and contribute themselves. Whether it's in the biomedical area of human evolutionary studies, or the geological area, or the anthropological area, or the ecological area, there are many different ways that one can contribute to the understanding of how we became human.

3. Introduction to Part 1: Our Last Four Million Years (3:12)

[Applause][DR. WHITE:] Hello again, and thanks again to the Howard Hughes Medical Institute for providing this venue and this opportunity we have to talk about hominid paleobiology. I've broken this into two modules. The first one we're going to go with is our last four million years, and we're going to have to proceed pretty quickly to cover four million years in 40 minutes. Let me give you a preview where we're going. First we're

going to go into the Afar Rift; this is an area in the Horn of Africa, right there at the target. We're going to drill down at a study area that I working called the Middle Awash. We're going to climb back up through time, first in Africa, and then across the entire Old World, to give us a more global sense of our evolution, and then we're going to look at hominids in the tree of life. Where do we fit?

4. Video: Rift Valleys of Africa and Plate Tectonics (4:10)

Let's start with the African continent because we are all Africans. That's where we began, multiple times, it turns out. And when we fly across this great vast continent, we find only a couple of places that are not erosional, where there is deposition going on, where fossils are being trapped. In South Africa in limestone caverns, in eastern Africa, these long narrow lakes are filling the East African rift system, and as we go further north up toward the Red Sea, coming into view right here, below us we have the Gulf of Aden; it's full of seawater. It's a gulf, but it's also a rift valley, and so is the Red Sea. The continental rift valley joins those other two rift valleys in a country called Ethiopia, right in the Horn of Africa. Look at all the vegetation there; it's because it's a highland. And the water there runs to the north; it goes down the Nile, past the pyramids, and into the Mediterranean. So that's where we do this work. There's another view of this. And let me explain why this place looks the way it does. What conditions that topography? It's really all about tectonics: the movement of Earth plates. And this happens almost imperceptibly, about that much a year in some of the fastest moving plates out here in the Afar Triangle of Ethiopia. And it's that triangular area, where those three rift valleys come together, that we call the Afar Depression. Now, anywhere along this rift valley, if you look at what's going on, these great plates are pulling apart. They're not slipping on one another like the San Andreas where I live. They're pulling apart. They're tensional forces. And the rocks drop and form valleys; this is very important. The rocks actually fracture and they slide past one another. The water that falls up on those highlands, if it doesn't go one way into the Nile, it goes the other way into the Afar. And as it comes into the Afar, it forms rivers and lakes in the floor of this rift valley. These will become important.

5. Geography of the Afar Rift (6:25)

Let's start here: the Ethiopian highlands. It's covered with the cloud. You can actually see even in a global view from space, you can see the Afar Triangle; it's a large lowland depression, the Afar Rift. Up here on the shoulder of the rift, we see some ancient ceremonies going on; they're ancient in historical terms. There are churches carved into the volcanic rock at a place called Lalibela that were carved when Europe was in medieval times. Orthodox Christianity is very ancient in this part of Ethiopia, and the water that comes down will flow out past those lava flows, ancient lava flows that built up into that big pile, and it'll flow eventually past the pyramids. But if we go a little bit further down, just a bit more to the south and to the east, we come to the edge of the Afar Rift, and we're peering into that triangular depression. Now, if you wanted to become a fossil, it really

doesn't matter which way you fall; you fall forward into the Afar, you fall backward into the Nile, you're not going to become a fossil. Your body will rot, hyenas will get it, tough luck; not a good place to become a fossil. You say, well, what if I build a concrete bunker and reinforce it with steel? Well, it might last 10, 000 years, but then that rift edge will crumble, you'll tumble down, eventually your bones will come out, tough luck; not a good place to become a fossil. So what I propose to do is take you to a place where fossils have formed and we've collected many of them.

6. A tour of the Middle Awash study area (8:00)

We're here in the Middle Awash study area; it refers to the middle section of the Awash River, which is flowing out through that Afar Depression. We don't need our cartoon anymore; this is an actual satellite image. That blue body of water out there is a lake. We see the swampy area with vegetation next to it, and we saw that stripe, it goes up to the north; that's the riverine forest. Most of the rock out there, because it's a desert, is bare; the whitish rock, all that is sediment. So what I propose to do is take you on a trip. We're going to start on the edge of the rift. We're going to go from Point A to Point B, down in elevation, down into this depression, and see what we see along the way. Up here on the rift margin, we have a lot of precipitation; that means a lot of vegetation. And a lot of that vegetation today, of course, is agricultural; people can grow crops up there, and they do. What happens when we get the cars down a little bit further into the rift? Well, it gets dustier, and the agriculture disappears because you can't do it here: no irrigation. When you go down even further, it gets spottier and spottier. Now you're almost out on the floor of the rift, and you see that mountain out in the distance, that little peak over on the right-hand side? That's a volcano. Two million years ago, that volcano was not there; that's a new volcano. Two thousand meters it rises today above the Afar Plain, all built in the last two million years. Two million years ago...see these great big cobbles that are on the road there? They didn't bring those in in dump trucks; those are there naturally. And yet, they're way up above. There's no river to bring these big rounded cobbles into place. How did those get there? Well, the secret to all of this goes back to the tectonics; it's all of those Earth movements that are going on. And we have to pay attention to that when we're working in this area. Now, we finally...we manage to get down that escarpment, we get our cars out onto the flats, you're on the floor of the Afar now, you're about 800 meters, and we're in a rain shadow, not much vegetation out there. It's kind of a grassland savannah. We turn and we look back at the margin and we see these blocks. See those stair steps off in the distance? Those are the fault blocks. Those are the big, big pieces of rock that have dropped as this rift valley extended through time. And finally we get the cars out. This is how we go into the field every year. It's a very remote area with a pretty big crew of people. So we're almost now, almost to Point B by the shore of that lake. This is what the lake looks like from an airplane. We look across, we see the volcano rising above the Afar Valley floor. The river's running right down the axis of the rifting. Now, if you wanted to become a fossil and have your body transported across a million years of time, face plant right here [laughter] and stay. And actually, you don't have to face plant; this is kind of a dangerous place. The Afar people bring their cattle down there. You have to watch behind you; this lake is absolutely full of crocodiles and people die there. And we

find their bones right in these swamps. They're our fossils of the future. We go into the field, and as you can see here, we call this a shovel-ready project. We have to build our own roads; we do so to campsites that we set up. We import everything. We try to put these in shady areas, which is good when you're in the desert to try to find some shade. We have to make our shade in the middle of the day when we have lunch.

7. Video: Floods Supply Sediments for Fossil Formation (11:18)

And when we wake up in the morning, this is the last thing we want to see. You might think, well, you're in a desert, you want to see clouds; no, no, no. This is the last thing you want to see because when it rains out here, it gets really ugly. So this is a Ford truck. It's kind of a fossil in the making except it's not going to preserve very well, not as well as the bones of this man if he were to die there and become buried in this sand. That's an interesting concept, that deep time concept we have to go back to. So how did this happen? And by the way, I was not the driver here. Neither was he. This is not our project car; it's an Afar government car. And the driver was inexperienced at driving in conditions like this. This is a flash flood. There have been rains on the escarpment; these rains are bringing things in. If you stand on the bank of this river and watch it for about five minutes, you'll see dead camels go by. They're going to become fossils down by that lake someday. Standing waves: do not take your car across this river. We look a little bit upstream and we see that this river has a lot of capacity; it can move pretty big things. No big boulders like we saw way up on the hill, but little clads just like the ones that you used as hammer stones when you were making the stone tools, rounded river stones right there. And hominids have been exploiting these kinds of rivers coming into the Afar for 2.5 million years to make these sharp-edged stone tools, an amazing thing. Now, let's see what happens when this river gets even more water in it. It goes, what we call, overbank. There are natural levees, and it goes out into something called a floodplain. And the reason they call it a floodplain is because it's flat, it's a plain, and it floods when the river goes over-bank. And if you walk out there, for example, to say, well, let's divert some of this water to keep it from going into the camp, and we'll dig a trench, and you set the shovel down and you turn around and you turn back to the shovel, it's likely that... This creature, it lives on a floodplain. It does not have an internal skeleton, but it will climb up your pant leg. So when you're on a floodplain in a rainstorm, tuck your pants into your socks. Now we go to camp. This is bad news in a camp. Gotta pick the tents up, move 'em out of the water. The shade was nice, but the trees were there because that's where the water ends up pooling. It ponds. That water brings in sediment, not sand. It can't move it, it's too slow. Not big cobbles: can't move it, too slow. It brings in silt, clay, suspended matter, and when this water evaporates, after we're gone, this water will evaporate and that particulate matter will deposit about that much this year.

8. "Drilling down" in the Middle Awash (14:00)

And it turns out that this is just the top of the fossil record. This guy's shoe could become the most recent fossil in the entire record here. We actually know that this has been going

on in this region for millions of years, and if we drill down, we'd find about a kilometer worth of sediment right below us. And that's what we're going to do. We're going to drill down in the Middle Awash. Except the problem is if we use a drill rig, we're only going to get a window about that big into the past, and it's not very likely that we're going to even hit a hippopotamus with a drill only that big. So what we want to do is we want a bigger window. We can take advantage of the tectonics. Look back into the margin, you see those fault blocks. We're looking right here into the blocks where the faults have exposed the ancient sediments. The sediments today are forming at the bottom of the lake. Those are the modern sediments. And out on these floodplains, out in the axis of the rift, the ancient ones have moved to the side with tectonics, up come the rocks, and they're scattered around this area right there. They're the whitish patches. You can actually go up, climb up on one of those patches, these rocks are five to six million years old and they have fossils in them, and you can find the fossils.

9. Using Volcanic Rocks to date sediment (15:12)

And a key part of what we do is to look for volcanic rocks. Now, remember that rifting process has weakened the Earth's crust, so magma under pressure exploits that, and it comes in the form of volcanoes, both lava flows, very viscous, and explosive volcanic that blow huge amounts of ash all over the landscape. These are very useful things. And this is going on today; we can watch the process. This is an eruption, November 2008. You didn't hear about it here, it wasn't widely publicized, but this is a big plume. It looks like a cloud, but actually it's not; it's an exploding volcano. And that's the ash plume, and that's it from the side. This is venting, up to cubic kilometers of materials volcanic ash, and it rains out across the landscape. And a volcanic eruption happened there 3.8 million years ago. And actually, it had been erupting all the way through time. And we can use those, and I've got a sample of the 3.8; we call this is the cindery tuff. I'm just going to pass this around so everybody can have a look at it. That rock 3.8 million years ago was so hot, it was coming from a volcano, and it came out, landed in a lake, and you can see the layers as the little sediment was washed around, and all of a sudden, frozen, perfect. We're looking for that. Our project geologists go out and find those rocks in places just like this: eroding sediments. And the geologists keep time and determine environmental settings by going to these rocks and sampling them. So this man is taking a rock hammer and knocking off a chunk of rock from one of these volcanic ashes. We can use our reading of these rocks, our geology, to understand the structure of this region, how it's changed through time; the stratigraphy, that is, how the layers accumulate; the sediments, whether sand or silt or big boulders, we understand how the water moved; we can look to geochronology. As John Shea mentioned yesterday, we have tools that we can use on these volcanic rocks that are kind of timekeepers. In fact, we've used it on that one there; that's why we know it's 3.8 million years old. We've used this decay of potassium into argon to determine that. We can even do more. It turns out some of these ashes are so well preserved; you can actually see the glass shards in them. And if you take these glass shards and use an instrument called a microprobe, you can find out what the chemical composition is of this volcanic ash. And it turns out that every magma chamber has a different composition, so we can fingerprint each volcanic eruption and tie these things together across the landscape. And

since the volcanoes were so explosive, material went stratospheric. It went over the Gulf of Aden, fell down, and the Deep Sea Drilling Program found the same eruption fingerprint down in the sea sediments in the marine record. So we can know what's happening with global climate change, and we can check that versus what we're finding on land. It's an amazing story that can be told, but it can only be told with the combined effort of all of these scientists.

10. Scope of Middle Awash project (18:10)

So we've been working on this since 1981 with two basic things in mind: one, conducting scientific research to get these answers about the past, and second, building local capacity. We have specialists from lots of different disciplines. We have arranged this here alphabetically. Archaeology is not necessarily the most important thing we do, but it is a very important thing that we do. Countries: people from around the world do these studies. It's truly international. We've recovered thousands of vertebrate fossils, geological samples, artifacts, and we share the data, as scientists do, through peer-reviewed publication in different journals. We've published, for example, on this project over 6,000 pages, and there are online resources you can go to learn more about the project and paleoanthropology in general.

11. Sites and findings of the Middle Awash project research area (18:59)

Now, let's think about these geological samples. Here's a plot; there's our lake. We looked at it before; it's 15 km long for scale. And we're looking out here at a whole series of geological samples taken over the last 30 years. That rock is one of those samples. Those samples are taken to control, to understand the context of these stone tools, shown in the blue, and hominid fossils, shown in the yellow. But we're not there only for hominid fossils. In fact, most of those 20,000 fossils are animal fossils of different kinds that are not hominid. And we found that from this layer cake of rocks that's a kilometer thick, and that's the distribution. Now, right away, you see the distribution is kind of interesting. The stone tools only go back not even halfway. They only go back to two-and-a-half million years ago; that's an interesting finding in itself. We've never found a stone tool in any older bed or horizon in this stratigraphy. Now, we shouldn't think of it as a marine record with a slow gradual accumulation. This is more like a snapshot, more like the flash flood. We have to be kind of lucky that in the past at some time, there were hominids, stone tools, flushed in, sedimented in place, and they've transported through time, and we can find them. All of these things have to come into being. Here are the sites in blue with the archaeology and hominids, and below that, only hominids and other animal fossils. This is the total fossil count; it's actually a couple years old. It gives you a rough idea. Some of these sites are very rich, other ones not so rich. The archaeology, we talk about the various kinds of stone tools that John introduced yesterday, and now look at the hominid numbers. What do these data tell you? They tell you that hominids are really, really rare; they're really, really hard to find. And there are many reasons for that, but they tend to be the things that get attention. And we'll talk about that this afternoon, but we've published

in a number of different places, and these publications get picked up. Here's one at 0. 16 million years ago, 160, 000 years ago.

12. Zooming into Herto Village, a sire of hominid fossil discovery (21:01)

Let's take sort of a big view of this, a global view. There is the fossil from 10, 000 km out, courtesy of Google Earth. Let's zoom in: there's our Awash River; we're in the Afar Triangle. That's 1, 000 km above the surface. A hundred kilometers above the surface, we can see where these geological sample points are. We superimpose on that the fossil localities, a lot of localities, and some of these localities have hundreds of fossils. The locality boundaries are seen at 5 km out, and we zoom in to 1 km, you're 1 km above the surface and you look down and you say, what in the world? Are we looking at fossils there? No, not at a kilometer, but you're looking at some interesting things. Now, if you ask a cell biologist to identify these things, they'll say, well, you know, it's a nuclear membrane, the mitochondria, and so forth, [laughter] but not at a kilometer, all right? At that resolution, this is a ground view, a side view, of what you just saw. This is an Afar village called Herto. This is where the Afar people live, and they live in houses like this; those are the white reflective things in that satellite image. This is a woman throwing the cat out. The guy in the back is standing in front of a corral; that's where they keep their animals, domestic animals. Individual fossils are seen, the localities anyway, from this kilometer out. We go right down on the ground now, you're a meter away from a fossilized hippopotamus eroding out of the sand. And that's how we find these things usually, through erosion. We notice them on the surface, and then sometimes we excavate to find out the details surrounding, in this particular case, the hippopotamus skull. In the meantime, the geologists are taking samples, they're dating the samples, and we find out that this particular hippopotamus is that old.

13. Paleoanthropology: From discovery to publication (22:42)

Now, before we get much further, I want to take you down the paleo pipeline so you have an understanding of how all these different sciences are integrated in the search, recovery, preparation, analysis, and publication of fossils. So let's go back into space again, big picture kind of stuff, Google Earth; we can print it out. And we could let the cat walk around on the map [laughter] and mark it, and just go randomly out there and stumble across fossils, and you often see this in the media: "the team stumbled across the cranium of a hominid." "Well, we don't stumble across the cranium of a hominid; we identify the localities from satellite imagery. We go out to those localities and we survey them, and we look carefully on the surface for what's eroding out of those sediments. Sometimes we look really closely; we crawl across the ground. And this guy with the antenna out there, he's got the GPS unit that tells us exactly where we are in space. The geologists are watching where we are in the layers because right here is a jaw. Now, we're going to track this jaw all the way from the moment of discovery by this Afar man, all the way to the time it was published, and it's quite a long period; it's quite a pipeline that we go through. These fossils are very fragile; they don't have any more organic material left, so they

shatter when they come out on the surface, and they get scattered around. Goats walk over them, the wind blows and scatters them, and it's important to get all the pieces. So we do that by putting the soft sediment through a sieve. Sometimes if we're really lucky, we still find a bit of the fossil in place; we call it in situ, in the deposit. Now, if we just grabbed this and said, hallelujah, eureka, we'd have a bunch of crumbs in our hand and some teeth because it's extremely fragile. So we want to put preservative on it, harden it up, put it in a vehicle, take it back to the National Museum of Ethiopia, catalog it, curate it, clean it if necessary, put it back together again. In this particular case, nearly 100 pieces of that jaw were found; they're put back together with sophisticated material such as duct tape and glue. But it takes time and patience; you have to know what you're doing, obviously. That's why anatomists do this work. We photograph it. We mold it in a very high-resolution silicone rubber. We also do kind of digital molding of it; we use CT to look inside the bone. We measure the bone, compare the bone, and then when we're satisfied that our results are accurate, we make our interpretations, we write them down, we send them in for peer review. Now, what's peer review? Well, it goes to colleagues, often they're anonymous, and they look at the paper we submitted, and they give suggestions, or they say this paper is really bad, don't publish it, or publish it right away, it's perfect the way it is; that never happens. But they make comments, and then we authors get the comments back. This goes through cycles, and then eventually, things get published. This is how science works, and eventually, you see the publication. In this case, now that jaw is finally published, and there it is on the left compared with two other species of hominid. And this was published in 2009, so it's available to you. You can go online to the *Science* website, and download that scientific paper where that jaw is described. And then, of course, when that happens, often, the media, if it's an important discovery, they will cover that, and so, you'll get a worldwide distribution, particularly now with the Internet. But museums are also important repositories. This is the National Museum of Ethiopia. And so, in these museums, things can be observed by the public.

14. Building research capacity in Ethiopia (26:12)

But how do these scientists do that work? Who puts that infrastructure together? Who trains these people to do this kind of work? Well, that's a big building process. One of the things that have been happening in Ethiopia is recognizing the importance of these antiquities. The Ethiopian government constructed over the last five years on that foundation a very big building, and that's pretty much what it looks like today, except it's just been occupied and we're starting work there. This building has been equipped. It's fantastically organized: all of these fossils, all catalogued, curated, cleaned, available for study by other scientists right now. So this is an Ethiopian, one of the poorest countries on the planet recognizes how important this is, and has invested these resources to protect its antiquities. That's impressive. Here's the other thing that's happening: this is part of education in that country. There's great pride in these antiquities. Students come and learn about this, and this is, of course, the next generation. But before we go any further, we want to stop and tip our hat to the people who do the fieldwork, sometimes the most difficult, the most dangerous, certainly the most dirty part of the whole operation. These are the people. This is the Middle Awash team, and this is a different look for research in

Africa. This is not the colonial look. This is the Ethiopian look. This is the African look. This is the international look. We have people here from Turkey, from Tanzania, from Ethiopia, from the Afar government, the local people, and we all work together to generate this information. So when we look at this information, let's keep those people in mind.

15. Testing a hypothesis by comparing skulls (27:50)

Now, let's go back to our geological samples, and we'll go to the very top of the sediment stack, and we'll meet this man. His name is Abdullah, and he obviously has an AK-47. And he uses the AK to protect his animals in those pens behind him. He lives in a different village called Aramis. And here is Abdullah. Now, when you look at Abdullah and you compare him to me, we'll do the profile here, of course, I look pretty different from this guy, right? I mean, this guy has got a lot more hair than I have, so it makes it hard to compare his skull with mine, so we have to do this. And [laughter] pretty much, when you look at his head, it looks like my head, it looks like the head on this human, it looks like this human head over here; we can turn it sideways. That's a human cranium. So there are some predictions in the world, and one of the predictions is that humans were created exactly the way we look today, 6, 000 years ago, and we haven't changed since. Well, that prediction has consequences. If we drill down through time in this place through this stack of sediment, we should find humans from top to bottom. So, testable: let's take a look at what we found, start on the top, drill down in time. We should find, according to that hypothesis, human crania all the way down the stack.

16. Earliest *Homo sapiens*; Herto (29:10)

Well, we start on the top of the stack and so far, so good. This is exactly like what you guys were trying to make yesterday with obsidian, except I don't think anybody, even John Shea probably would say that he might not be as good as this Middle Stone Age stone knapper that made this point about 80, 000 years ago. And we have some skeletal remains of these people, and they're anatomically modern. So far, so good. Let's go down the rock record. Hmm, New York Times headline: "In Ancient Skulls from Ethiopia, Familiar Faces. "This cranium, some important facts, basic ones, is 155, 000-160, 000 years old. This man lived 6, 500 generations ago, and this is the earliest *Homo sapiens*. That's this cranium from the Middle Awash; it's known as Herto. It was found right outside that village we zoomed in on. That's an impressive cranium. Is it a human? Well, that's where it was in space; that's where it is in time. We're pretty much close to the top of the stack of rocks. We've got a pretty complete cranium, so we ought to be able to do something with this. And there it is. You can come after the lecture and handle it and take a look yourself. But we did some comparative work on this, and

17. Video: The Delicate Process of Excavating and Cleaning Fossils (30:31)

I want to show you how it comes out of the ground because there is a misconception. These things on the table have been specially selected; they're our most complete crania from this sequence in the Middle Awash. You don't get to do this very often as a paleoanthropologist. It's not a weekly occurrence. It's not a monthly occurrence. It's not a yearly occurrence. A few times in your lifetime, if you are lucky enough to find something, and it's not really luck as we know from the fossil pipeline, right. We didn't stumble across it, we found it intentionally. If you're fortunate enough to be able to remove this cranium in a plaster jacket, that's that cranium coming out of the ground, we've hardened the sand with Super Glue to keep it together, keep it intact, we lift it out of the ground and that's great; doesn't happen very often. Now, we're faced with cleaning it. It's extremely fragile. The cranial structure: at the base of the cranium, there's a bone called the vomer, very thin like a razor. We've got to work around it, one sand grain at a time, to clean this from the adhering sediment before we can even start to study it. We finish the cleaning process. But that's not the only one we found. We found one that we got to a little bit later, a little bit too late; it shattered and was scattered all over the surface. So we got all the pieces, Dr. Berhane Asfaw, Ethiopian PhD, 1980s, University of California at Berkeley, put that back together again. It's the skull of a child, about a seven-year-old child who died at the same time 160, 000 years ago.

18. Herto skull compared with modern human skull (31:59)

So we took the adult-- and there's a big series of measurements from all over the world, a man from Harvard did this, 3, 000 modern human crania--and we did a comparison, measurements of that skull, and look where that falls. Here are 3, 000 humans in the cloud, and this man lies just at the edge of that cloud. You could argue, well, that's kind of extreme *Homo sapiens*. In fact, if you took this cranium into a CSI lab and went to a forensic anthropologist and said, "Where did this man come from?" And didn't tell him that you had found it in Africa, you know what they'd tell you? They would say, it looks most like an Australian aboriginal, but not quite. That's interesting. No forensic anthropologist would say it's an African, but we found it in Africa, in the Horn of Africa. Fascinating.

19. Evidence of stone tool use by Herto man (32:44)

What else can we learn about these people? Well, we can learn through archaeology using the tools that John described yesterday. Where we found the cranium, we brush more of the sand away. Luckily, there wasn't very much rock on top, so we were able to find... each one of the flags indicates a pin position of an artifact, a stone tool. Remember the hippopotamus? We dug it up; here are the guys digging it up. Look at what we found when we took it out of the ground: a huge chopping mark made by one of the stone tools left on a bone which is now completely stone; it's turned to stone. There's no way you could even make this mark with a metal tool today; it's been there for 160, 000 years ago when this guy, or somebody like him, butchered a hippopotamus on the shore of a freshwater lake in Ethiopia at a time that there were Neanderthals living in Europe.

20. Bodo man from 0.5 Myr and Daka man from 1 Myr (33:38)

Let's go down the stack of rocks. We have to move a little bit to the north to do that. We move a little bit further down in time. Now we're at a half a million years. We have a specimen known as the Bodo man, a half a million years old; that's the next one in the line over there. We rotate this man into view, and now it's not a human anymore. We're looking at something that nobody would mistake for an anatomically modern human. What is it? Is it an ape? No. Is it a human? No. What is it? Well, we can put labels on these things, but biologically, it is an intermediate fossil in the record of human evolution. This man studied the record of the archaeology; his name was Desmond Clark, and he founded the project many years ago. And he found thousands of these hand axes at a million years, down a little bit further in the record. And then finally, one of the graduate students from Berkeley, doing a survey found this cranium eroding from the surface. We took it out, we cleaned it up, and this is this cranium. This one is about two-thirds as large as the one, that's the next one in line there. This is *Homo erectus*. It's well known; it was discovered, the species was discovered in Java many, many years ago.

21. Invention of stone tools affected human evolution (34:49)

In the Middle Awash then, just to see what we've already done, we've tested the hypothesis, we've falsified it, we see already that there is a succession of forms. What happens if we go down in time? Before we do, let's think about what's happened just in the last million years. We've gone through a tremendous series of changes in Earth history: glacial, interglacial, glacial, warming, cooling, warming, cooling, polar ice caps coming and going. And yet, the hyena fossils that we find with this *Homo erectus* are pretty much like modern hyenas, but certainly, *Homo erectus* is not pretty much like *Homo sapiens*. These are very different. What happened? And the answer is culture in our lineage became a selective force. When did that happen? Well, as John explained, we can trace culture through stone tools, at least part of culture, a little bit of culture. We move over there, we move down in time to two million years ago, and there we have a Mode 1 tool pretty much like what you guys were doing yesterday, if you'd have broken those cobbles up correctly. Now we have the opportunity to go and see, just like the debris that you made yesterday, we can go and excavate--this is two million-year-old debris, and this is the place where people made those stone tools. But we don't know who those people are, because we haven't found their bones at this horizon in the Middle Awash. We know from other places in Africa, though, but

22. *Australopithecus* from 2.5 Myr used stone tools (36:12)

let's drilldown again, going down to two-and-a-half million years ago. Interesting: next cranium on the table. Smaller braincase, bigger face, bigger teeth; we call this *Australopithecus*, and this is a very, very interesting hominid, interesting not just because

of the anatomy, but also interesting because of what we found nearby. The cranium was found up by the Land Rover on the right, and right there, we excavated and we found things like this: a wildebeest jawbone with stone-tool-made cut marks. Somebody took the tongue out of this animal two-and-a-half million years ago, and that's a really radical difference from what chimpanzees do. Yes, chimpanzees hunt, but they don't do...they don't butcher large mammals, and this was going on a very long time ago. We find evidence of this not only at our locality but to the north at a place called Gona, beautifully made cut marks on a hippopotamus rib; that places hominids in a very different selective environment, competing with carnivores. But that's also where the stone tool record stops. From thereon, we can move to sites, and we have lots of them, but we've never found any stone tools.

23. "Lucy" and other australopithecines, 4.1-3.2 Myr (37.25)

We find hominids. In fact, just to the north of our study area, the famous Lucy fossil was found, 3.2 million years ago. In our study area, we have the same species at Maka. A little earlier in time, 4.1, we have the direct ancestor, it appears, of that species, all *Australopithecus*. So it's not all humans all the way back to 4.1 million years ago, even in one valley in Ethiopia.

24. *Australopithecus* lineage, 2.7-1.2 Myr (37:51)

What about globally? Well, let's climb back up through time, first in Africa, then across the Old World. We expand our field of view to Africa. We ask what happened? Early *Australopithecus*, the Lucy species: it evolved from an earlier variety, *anamensis* into *afarensis*. We call this in paleontology, we call this a chronospecies: one species lineage arbitrarily divided into labels that are called chronospecies. We know these forms well; we have their fossilized footprints in Tanzania, in freshly fallen volcanic ash. Later *Australopithecus*, between three and two million years ago, we have things like the one we found. It evolved from the Lucy species apparently as a chronospecies. We don't know what it evolved into. In South Africa, we have a form known as *Australopithecus africanus*, a different species. It looks like a species line down there, and we have it pretty well represented, actually since the 1920s, *Australopithecus africanus*. Now, just less than a month ago, published in the scientific journal *Science*, was *Australopithecus sediba*, its direct descendant, lived two million years ago. And they finally found a site where whole bodies have been preserved down in one of these limestone caverns in South Africa.

25. Robust *Australopithecus* lineage, 2.7-1.2 Myr (39.12)

Now, there's a fascinating creature: robust *Australopithecus*, very strange, not an ancestor; it seems to have evolved in Eastern Africa at least, from our *afarensis* into this form, *boisei*. Let me show you something about *boisei* just to give you the flavor of this. This is its jaw.

The back teeth are about as big as a quarter. That's a huge modern human jaw; it's an Eskimo. Huge, huge cranium: we have one of these up on the table here. What I've done, you see I've broadened the field of view so we're looking at things that never lived, or at least we haven't found in the Middle Awash, but these things, like this robust *Australopithecus*, lived in other places in Africa. Now, there are other things that lived in other places and also went extinct. These forms were bipeds, very closely related to us, but they're not here anymore. Much closer to us than chimpanzees but they're not here anymore. They're extinct.

26. *Homo erectus* expands from Adrica 1.8 Myr (40:12)

What about us? Well, it turns out if you look in the area just outside Africa at a place called Dmanisi, deep down underneath this medieval settlement, we find two million-year-old, nearly, fossils, and these are *Homo erectus*. And we're smiling because they give us a look at the first people to have expanded from Africa. And this expansion took place along that lineage that we're pretty familiar with because we see it in the Middle Awash.

27. Neanderthal lineage in Europe, 0.6-0.03 Myr (40:39)

But at the same time, something was going on in Europe: Neanderthals. Sarah talked about that yesterday. We call the earlier chronospecies *heidelbergensis*, the latter one *neanderthalensis*. These Neanderthals are very well known, been known since the 1800s, all around the Mediterranean. They lived in caves, and from the beginning, they were compared with humans. And now, we actually have genetic evidence from these now-vanished hominids, the Neanderthals.

28.H. *Florensiensis*: An 18,000-year-old extinct species (41:11)

There is one more, one more very interesting one, as we move up through time, very recent, *florensiensis* from the island of Flores, 2004 discovery. We don't know exactly what it is yet; people are working on it. How do we explain something that's only 18,000 years old that is contemporary with this human that is only that big? What do we do with that? Well, as scientists, what we do is we come up with hypotheses, and there are various ones out there that are being tested by new excavations and all kinds of other work. Some people say maybe it's a pathology. Others say maybe something like Lucy, the early hominid, got all the way to Flores and stayed there in isolation for about two to three million years. Other people say, You know what? Sometimes when mammals get to insular island environments, they can dwarf, or get very large. Komodo dragons live on these islands: big lizards. Island dwarfing is a common thing in mammalian evolution.

29. How many species are in the human family tree? (42:16)

Is it possible that that hominid represents this phenomenon? Well, to answer that question, and to answer the question about the shape of the family part of the bush, we go to a whole bunch of species names that I'm not going to ask you to remember the spelling on, or anything else. But I'm going to ask you to pay attention to this because some people are claiming these days that our family tree, and we shouldn't call it our family tree, our family branch was very, very bushy. But the problem is many of these names are not really new; they belong to already-named fossils. So we've got to get rid of those names. And the other thing is this chronospecies problem. Remember the chronospecies are merely segments of an evolving lineage. Now, if we indicate these in the same color, we see, for example, in South Africa that *africanus* evolved into *sediba*. We see that in Europe, *heidelbergensis* evolved into Neanderthals. These are not two species in any real species diversity sense. The diversity of labels, and they're labels we apply, doesn't equal biological species diversity, and the fact of the matter is there's no evidence for some 25 hominid species lineages in the past. Now, what went wrong here? Steve Gould, 1976, the great evolutionary biologist, said, "We know about three coexisting branches of the human bush. "He called it a bush; he used a metaphor. "I will be surprised if twice as many more are not discovered before the end of the century. "By the end of the century, the New York Times is saying, "The human family tree has become a bush with many branches. "Okay, good, fine, let's examine the metaphor. That's a bush. We slice across it, many branches. What's in the foreground? That's a cactus. Slice across it, whole bunch of branches. It doesn't look like that, either. If we're looking for a botanical metaphor for the shape of the hominid family tree, we have to go to a saguaro forest in Arizona, and we have to consider this. This is pretty much what we have just looked at, these representatives on the table. We have *flores* at the very end. We have early-in-time forms. We have side branches, robust *Australopithecus*, the South African forms. We have Neanderthals as this part of the cactus. And finally, we're the only remaining species. But if we slice across this tree, as a good zoologist would, and ask, What about the species diversity? We find that, maximally, there are only about four at any one time.

30. Did adaptive radiation occur in human evolution? (44:38)

So why is it-- and here's where I want to bring your critical sense to play on this question-- why is it that within the last month, this scientific journal published a statement that this *Australopithecus* from South Africa "conceivably implies an adaptive radiation of hominids"? What's an adaptive radiation? Are we, our own part of the family tree, which is really the tree of life, did we have an adaptive radiation like the Galapagos finches? An adaptive radiation is the exceptional extent of adapted diversification into a variety of ecological niches with such divergence happening rapidly. Did that really happen in human evolution? No. Why was species diversity limited among hominids? Actually, it's been known for quite a while: hominids were large terrestrial generalists with increasingly broad ecological niches. Intelligence and culture increased this niche breadth and reduced opportunities for sympatry. What it means is at any one place at any one time slice at any one savanna or forest or other environment, you wouldn't find 20 or 30 different species as you do fruit bats or rats or all kinds of other organisms, not in humans.

31. The Big Picture L Hominid evolution from ~4.2 Myr to the present (45:55)

So the big picture: we start with *Australopithecus* at 4.2; 2.7, our own clade is established, Oldowan tools, large mammal butchery at 2.7; by around 1.8 million years ago, the first hominid expansion from Africa; 1.2, large robust *Australopithecus*, that one there with the big face and the big teeth, they go extinct; 600,000 years ago, this European clade is established, it becomes Neanderthals; anatomically modern people appear in the Herto here, consistent with the genetic evidence that Sarah talked about yesterday; 30,000 years ago, Neanderthals go extinct and this little, apparently dwarfed lineage on the island of Flores persists for a little bit, but doesn't make it. And so, at the end of that journey, we're the lone species standing. And our closest relatives, these and these and these, they're all extinct. So what's...what about next? What happens before this on our way back to that fork point with the chimpanzees? That's the topic of Module 2. So let's take a minute and ask any questions that you might have about this, and then we'll move more deeply into our past.

32. Q&A: How has our diet changed from our ancestors' diet? (47:22)

[DR. WHITE:] Yes?

[STUDENT:] How has our diet changed from our ancestors'?

[DR. WHITE:] Our diet has changed because it diversified, and our diet was able to diversify largely because of the introduction of culture. As those stone tools, for example, at the beginning of our clade, came into play, we were able to broaden our niche and compete with carnivores. We didn't have the dental apparatus for this, but the kinds of stone tools that you made yesterday with those sharp edges are very good for cutting into carcasses through the thick hide and removing meat, taking that and getting out of there before the carnivores come and eat you, too. And in some cases, like this one from Georgia that I talked about, this is a pretty small-brained hominid, stone tools are left around this place. They were probably coming and raiding a carnivore lair, and some of them didn't make it back with the meat. So natural selection can be a pretty strong force in these kinds of situations. So it's that culture, and as culture went on through time, look at the other end of time with humans, what Sarah talked about yesterday, the adaptation toward drinking the milk of domestic animals. There's a biological adaptation, but it depended on other cultural things happening to domesticate those animals in the first place. So basically, that's why this niche broadened through time in our own ancestors.

33. Q&A: How can you tell the age of individuals? (48:48)

[DR. WHITE:] Yes?

[STUDENT:] How do you know the facial structure of these animals when the bones aren't complete? And my other question was, How can you tell the age?

[DR. WHITE:] Okay, let's take them in reverse order. How do we know the age? Well, remember John Shea's lecture yesterday, we can get the dating, but I think you're talking about the individual age of this. What we look for are developmental things. For example, we know in humans the third molar tooth comes in at 18 years of age. When we find a tooth, a third molar tooth, that's pretty heavily worn, we know this individual is much more than 18 years old; it's a full adult and all the bones are fused up in the skeleton. So we can do individual age pretty easily through dental eruption and fusion of the long bones and so forth.

34. Q&A: How can you reconstruct a skull from an incomplete fossil? (49:32)

When you say, What about the facial structure? What about when it's broken? Well, that's why we hope to find things that have whole faces, so that they're not broken, and we brought some good examples here of that. I like this one because when you turn it to the side, its face is actually dished. And the reason for that is its cheekbones come so far forward, and the reason they come so far forward is this is the one with the big back teeth. That's run by a muscle that you can feel right here on the side of your jaw when you clench your teeth, that's your masseter muscle; that's elevating your mandible against your maxilla. This animal was capable of spreading that across a very large tooth platform and running the apparatus with these huge muscles. Another muscle here on your temporal comes up from both sides, and it forms in adults a crest across the top of the head. It won't happen here no matter how big the muscles get, because the cranium is so large, but this cranium is only a third the size. This extinct hominid, therefore, is a dietary specialist. We see that adaptation in the face.

35. Q&A: Advantage of a small brain for our most recent relative? (50:36)

[DR. WHITE:] Yes?

[STUDENT:] What do you think the advantages are of having a smaller brain size for the more closely, the more recent relative?

[DR. WHITE:] The question is about what is the advantage of having a smaller brain size for the most recent relative? And that has to do with the energetics of island populations. And that's why we see dwarfing. For example, off the coast of California, we have very small-sized, body-sized fossil elephants; they're called pygmy. And so, it's possible that that is what this is all about. But it's also possible those other hypotheses are true, that it's some form of a specialized, like a pathological manifestation. So there are these different competing hypotheses, and the bottom line is we don't know what happened here. But because the fossil was found, we can start to ask those questions and examine them from all different points of view, from a genetic point of view, if we can extract DNA. So far, they've been completely unsuccessful at extracting DNA from this.

36. Intro to Part 2: *Ardipithecus* and Our Place in Nature (51:37)

Okay, let's get back to the past because we have to go more deeply in time. What we're going to have to do is drilldown in the Middle Awash, and it's actually the only place on the planet that you're able to do this. We're going to look at *Ardipithecus* and our place in nature. To preview the module, we're going to look at the historical context of this discovery, and we're going to look at how we found this thing, how we came to understand it, and what it all means, and being evolution minded.

37. Lamarck's ideas as the roots of the savanna hypothesis (52:05)

What about that? Well, here was a man who was evolution minded, a man named Lamarck. He was an evolutionist. He wrote a book about evolution the year that Charles Darwin was born. And in the book, he said this about the bimana because in those days, the anatomists classified things according to a different kind of classification system. They put bimana, meaning two-handed humans, apart from the quadrumana like this chimpanzee, who has four appendages that can grasp. So bimana, quadrumana. About bimana, he knew about humans. None of these fossils were available to this Frenchman. None had been found. It's 1809, and what he says is interesting. "Moreover, if the individuals I'm talking about, moved by the need to grow higher so as to see all at once far and wide over the grasses of the savanna, " I added that, "were forced to hold themselves upright, " forced, "and acquired from that constant habit from one generation to the next, "you could turn something like this, a chimpanzee, into something like this, a human being. Now, we know 50 years later when Darwin published *On the Origin of Species*, this inheritance of acquired characteristics no longer became a sufficient explanation. We now had natural selection to explain why things happened in evolution. But the roots of the savannah hypothesis were therein the early 1800s, the idea that something like a chimp, when exposed to open grassland environments, would turn into something like a human.

38. Darwin knew chimpanzees did not evolve into humans (53:49)

Now, Darwin appreciated very clearly that chimpanzees did not evolve into humans. He appreciated common ancestry. In fact, if you go to his notebook in 1837, this is his depiction of the process. The terminal things that we call species today are all linked through a series of common ancestors as we go into the past. Unfortunately, Darwin got it, but a lot of his contemporaries didn't. Darwin appreciated that a common ancestor must have given rise to the line that ended up with a common chimpanzee and the line that ended up with a human. Now, what about that line that ended up on the human side? Well, Darwin didn't address that question until 1871, in *The Descent of Man*, and he warned us; he was very, very cautious. He said, "We have to, we must not fall into the error of supposing that the early progenitor of the whole simian stock, including humans, was identical with or even closely resembled any existing ape or monkey. "Darwin knew we didn't evolve from living primates, and yet, Darwin was immediately cartooned by people skeptical of his ideas in this implausible restoration of a human head on the body of a chimpanzee. There weren't any of these fossils in those days. This stays with us today. You've heard of the Monkey Trial in the 1920s? Many people across the world imagined

that Darwin suggested that we evolved from living primates. He didn't. We evolved from common ancestors, and our quest is to find out how that happened now.

39. *Ardipithecus*: A hominid close to the common ancestor (55:37)

And we go back to this diagram, this branching diagram. Now, we've looked at fossils of the genus *Homo*. We know about the last part of that journey. We know that there are forms of *Australopithecus*, small-brained, completely bipedal forms. One of them became technological and eventually became us; other ones went extinct because of their specializations. And now, finally, we've been able to move beyond *Australopithecus* with some new evidence from that drill hole. It's not really a drill hole; it's exposed sediment. And it happens in Africa, and it happens in Kenya, Ethiopia, and Chad. And what we have are the first windows into this time period. It is a chronospecies set; it's an evolving lineage apparently. It is older than what we left the last lecture with, *Australopithecus*; we traced it back a little bit beyond four million. Now, we're moving to *Ardipithecus* over herein the geography, down here in time, 4.4 million years ago, the first time we've been able to look through that window. And what a window it is.

40. Central Awash Complex: Where *Ardipithecus* was found (56:47)

For scale: our landscape, that's a Land Rover; imagine finding a tooth out there. We have to go up in the air even to have a sense of what this place is like. Turn a video camera on it, and we actually did this. We put an HD camera on the nose of a stable helicopter, flew it around, took footage; you can watch this on the website that's here. But when we get up in that helicopter and look down on the ground, we see a couple of cars down there, and we see this long stripe, you can trace it around the landscape; that's actually one of these volcanic ashes, very much like the one that I handed around. And that's dated to 4.4 million years ago. Now, you see these people? Let's take a better look. Now, bring the helicopter around, we're looking down. What in the world? Here are a bunch of people crawling on their hands and knees across the burning desert floor. What are they doing? Well, they're picking up anything biological, anything that's eroding out of these sediments, ancient floodplain sediments, below this volcanic ash horizon that's up here just at the top of the screen. And they find them like this. This is a tooth of an animal called a kudu, an antelope.

41. Video: Dung Beetles and Their Fossilized Evidence (57:55)

Occasionally, as you're crawling across, you run across something like this. And you say, whoa, I'm getting out of the way of that. That's not a fossil; that one's alive. And what is that anyway? That's a dung beetle. You know how many species of dung beetle there are? About 5,000. A little different from the human saguaro cactus. We don't pick these up, but

we pick these up. This is a 4.4-million-year-old fossilized dung beetle ball. Dung beetle is long gone, but the ball is there, fossilized, calcite on the inside. This is a rock. We find fossilized nests of these animals.

42. Fossils of many types of animals found at the “Ardi” site (58:34)

We find snails, we find wood, we find millipedes, seeds, bird's eggs. That's a tooth of a mouse. These are the jaws of bats, a carnivorous bat on the left, a fruit bat on the right. All from sediments coming out from that volcanic, under, right underneath that volcanic ash, and this is what it looks like. Can you spot the fossil? Pretty tough work, huh? Got to get down on your hands and knees. All right, now can you spot the fossil? Yeah, you can kind of see that white thing there. You reach down, you pick up that thing in the middle of the frame, and this is what it is. Wow: it's the lower jaw of a monkey who lived there 4.4 million years ago. This is what we do;

43. Discovery of hominid bones from 4.4 Myr (59:21)

this is how we recover the primary data. And that was happening one afternoon, late in the afternoon in 1994; that's a long time ago. Yohannes Haile-Selassie was a graduate student, Ethiopian fellow who was at the University of California, Berkeley, and he was crawling across this landscape seeing eroding sediments very much like this. And here is a case, a fantastic case in science of the right person being at the right place at the right time. Not stumbling across a fossil; this is not chance, this is not luck, this is paleoanthropology, modern paleoanthropology. And he finds these two fragments, and he recognizes them right away as bones from the palm of the hand of a hominid, except we're missing the middle piece. So what do we do? Well, you know the pipeline, you know the drill. We've got to excavate, we've got to sieve. So we start sieving, we sieve some more, and we start finding other pieces. Yohannes is getting pretty happy now: another piece. Could it be the same individual? We start an excavation. We mark these fossils with a yellow flag so we maintain their position. The base of the yellow flag is actually the horizon, the level the fossil is found at. So here's this little hill. We've got to keep it wet because if we don't keep it wet, the clay expands and contracts. These are floodplain sediments, and it'll shatter the bones inside. If it rained on this little hill for another ten years, we would have a handful of isolated teeth; that's the timing. Amazing. This thing has been in the deposit 4.4 million years old and Yohannes comes around just at the time that these things are coming out of the ground? Wow. We take off the top of the hill, look what we find: a dense concentration of these fossils. Here's how they come out of the ground. Another bone from the palm of the hand: we expose it. That's the head, that's a knuckle, a finger bone, a shin bone; we have to put hardener on these things.

44. Video: Hardening Fragile Fossils for Extraction (61:11)

Here's the lower jaw just as it's coming out. We take a syringe and we inject a hardener into this sediment. You can't touch the bones at this stage. You have to solidify them, let them harden, and take them out, so we're dripping the preservative into place. Eventually, we take this out

45. Returning solidified fossils to museums (61:29)

and we do that, remove all of those fossils to the camp table. Now we've got, we can't see what they are yet because they're embedded in these blocks, rigidified with plaster, and now we've got to remove them. We've got to get them two days' drive over camel trails, and then asphalt, back to the capital in Addis Ababa to that museum. So we load them in the car, take the car across the river. Note that the river doesn't have standing waves, it's not very deep, good thing. We would not try to cross the river that you saw before. Finally, they get to the museum. Now the work begins. Now we fast-forward through time. 15 years later, we're at Washington, D. C., the American Association for the Advancement of Science, October 2009. There's Yohannes. Looks a little bit different now: he's got...he's older, he's now a Ph. D., Cleveland Museum of Natural History. One reporter asks, Why did it take you so long? Yohannes looks at me. [laughter] Blame your professor, right? Well, look, these fossils are Ethiopian and world heritage. Different time period, we know nothing...it was the only one that's ever been found. We screw this up, maybe nobody will ever find another one. This is an awesome responsibility, and opportunity. We had to restore this hominid; we wanted to understand its biology.

46. Reconstructing past environment form (63:00)

We started that not with the hominid; well, the hominid work was going on. We started with the broad question: What about the ecology here at 4.4 million years ago? How do we get back to what it was like when that animal, or human ancestor or whatever it is, whatever it turns out to be after study, died and was buried there on the floodplain? Well, that's where the context information becomes important because by this time, and we go back to the field, again and again, we excavate three more years at that site to try to make sure we get every piece of this hominid. We go back again and again to get more bats and more rats and more birds and more turtles and more everything we can. We bring it back, 150,000 vertebrate fragments, invertebrates, soil isotopes, phytoliths, pollen, wood, seeds, fantastic, a 4.4-million-year-old world, and we can put it back together again with the right people. And this takes some time. In this case, 17 years, 47 authors, 10 countries, 11 papers published in *Science*. All of these people are project members. They're specialists. Here's one specialist. This is the guy who does the bird bones. He faces bones like this that have been recovered from the field, and he can tell you what kind of bird those bones belong to. And what he finds out is that over half of the birds from this layer that held *Ardipithecus* are parrots and peacocks, birds that live in wooded environments,

not open savannas. We know it's not a lake margin because we hardly have any ducks at all. What are these? These are the ankle bones of mammals. Can you guess the one at the upper left? There's your scale down below; it's about 8 cm. Anybody with a guess? Take a wild guess. What animal would have an ankle bone that big? It could be a giraffe, that's true. We don't have a giraffe here. That happens to be a rhino. What about the little dot down on the right? Let's magnify it. That's an ankle bone, same bone, ankle bone. Insectivore: a shrew. Wow, we've got the whole fauna. *Ardipithecus* was there in the middle somewhere. We'll come back to that. Abundance. Remember that kudu tooth? Well, we've got thousands of specimens now from all different kinds of mammals. Kudus are very abundant. Monkeys, the monkey jaw, very abundant at this site. Three-toed horses: very, very rare. Interesting thing: monkeys live in trees, eat leaves for the most part. These are leaf-eating monkeys mostly that we find. We find very rare horses. Horses graze on grass. We can actually find out about an animal's diet, where it comes from, by using the isotopes in its enamel that are trapped there for 4. 4 million years, and we do this in the laboratories. And we find out that *Ardipithecus*, we analyzed that hominid tooth, and it patterns out herewith the kudus, with the monkeys, with creatures that live in the closed ha...and of course, they're the most abundant ones. What are these telling us about *Ardipithecus*? Faunal and floral associations, tooth anatomy and proportions, microscopic tooth wear on the hominid itself, enamel isotopes, masticatory apparatus, that just means the chewing, it's not at all like that big robust thing we saw over there, and locomotor adaptations; we'll talk about in a minute. The hands, the feet, and the pelvis, they all add up to one thing. Multiple convergent lines of evidence adding up to the same picture, and it's not the picture Lamarck drew us. This is a woodland.

47. Early hominid skeletons (66:17)

What about what eventually came out of that little hill? What about this creature, *Ardipithecus ramidus*? Well, we give these creatures names, and we just shortened the genus name in this case and called her Ardi. She's a female. This is the Turkana Boy, at 1. 6 million years ago. These are the new skeletons from Malapa. One of them has a name; I forget what it is now. There is Lucy, at 3. 2 million years ago. Yohannes has his own skeleton, quite a big guy that he found at 3. 4, belongs to the Lucy species, a male individual. And then we have Ardi; there's that skeleton. I want you to pay attention here. Look at the hands and the feet. Look at the preservation of the hands and the feet just by what elements are there, and compare that with Lucy. That's fantastic for a paleontologist because you can get at biology here. You've got one individual from 4. 4 million years ago with the biologically key parts. You've got skull, teeth, pelvis, hands, and feet; that's going to tell you a lot. But that's not just that individual.

48. Comparing "Ardi" with "Lucy" (67:17)

Remember crawling all over those surfaces? We have found parts of 36 additional males, females, and children from this hominid species among all those other mammals. So now we can compare Ardi with Lucy. We can compare tooth size to body size. We find out

Lucy, relative to her small body size--she's three-and-a-half feet tall, a full adult--she has pretty big back teeth compared to Ardi. But before we could do those comparisons, we had to put the teeth back together again. They had been exploded, damaged. We had to take little pieces of these teeth and put them back together again before we could even measure the tooth.

49. Digitally reconstruction “Ardi: skull and what it tells us (67:53)

What about the skull? Well, we saw this in the lecture yesterday. If you compare a chimpanzee skull with a human skull, you can see they're different in size. We knew that Ardi was pretty small; we didn't know how small. The problem was before her bones came to be preserved there, what happened is that the cranium, something stepped on it, maybe the rhino; we really don't know, but it was not good news for us. It was good news we found the cranium, but we had a big job in front of us. How do we deal with this? How do we take these pieces? Now, on a normal fossil, we take a very fine needle and take the pieces apart and put them together again properly. But the problem was this bone is so soft that you'll damage the fossil when you do that, and this is a unique fossil. So you don't want to do it. We can use technology: micro-CT scanning. Gen Suwa from the University of Tokyo was able to take a whole series of slices right through that crushed cranium. And you can see these slices on the CT scan here. We can freeze it, we can segment these slices out, and we can take the bones out, 60 digitally separated parts in the final reconstruction. And finally, we can add from the Middle Awash, we can add the 4.4-million-year-old cranium of *Ardipithecus ramidus*. It came before the Lucy species. And there is Ardi, thanks to that computer reconstruction, the original still pancaked, but we have the digital material generated through resin, and you can come and take a look at that after the lecture. So Ardi's skull features a very small braincase, one of the smallest hominids ever found; an unspecialized chewing apparatus; weaker facial projection--it doesn't have the expanded projecting face of a chimpanzee; a very short cranial base, more like a human cranial base.

50. Comparing pelvises: “Ardi” and “Lucy,” human, and chimpanzee (69:42)

The pelvis didn't look very good when we found it. Took it out of the jacket, cleaned it up. When we looked at how broad that pelvis was, we realized that it compared very favorably in that part of the anatomy with the Lucy pelvis: a biped. That's Lucy in the gold. That's the Ardi restoration; And compare that to a chimp. One of the things that allowed Lucy to walk, allowed her species to make those footprints, allows us to walk, is the shape of our pelvis. Our pelvis wraps around. Looks at the chimpanzee's pelvis. It comes up over the back and it locks in the lumbar vertebrae; incredibly stiff spine. These animals, when they stand up, are incredibly uncomfortable. They can walk bipedally and you see this in the circus, but only for a couple of hundred meters, then they fatigue. This organism with the blades very broad and low, wrapped around the side of the body, gives good leverage

hereto stabilize the trunk during bipedal locomotion, and we see that already in Ardi. And yet, when we look at this region and the bone that you sit on, what we find is it's very extended, as we find in the climbing chimpanzee. So even within a single bone, we're looking at a mosaic.

51. Comparing hands: "Ardi," human, and chimpanzee (70:49)

What about the hand and wrist? Remember the Darwin caricature based on the chimpanzee? These hands of the apes are adapted to walking on their knuckles. This is a gorilla. It's asleep right now, so we're safe. And you can see that the animal is adapted to walking on its knuckles. That's the pose of this, of the chimp because they do the same thing. And this requires a lot of rigidity in the wrist. John talked about that yesterday, goes actually all the way up the forearm. They're knuckle walkers. And so, many people predicted that we would find something like that as we went back on the hominid lineage looking at these adaptations. Humans, of course, are not knuckle walkers, and they're very different from chimps. We have short palms, and we have longer relative thumbs. The Ardi hand, nobody ever saw a hand like that before. You couldn't even really imagine it until we found it. It's not the hand of a chimp; look how short the metacarpals are. It's not the hand of a human; look how long these bones are, the phalanges. It's a mosaic. It's different. That's why we gave it a different genus name.

52. Comparing feet: "Ardi" and primates (71:59)

The foot. Remember the quadrumana? They were named that because of four-handedness. The gorilla: look what's missing. What's missing from the gorilla foot? Where did it lose its toe? The answer is the gorilla's not the weird one; we're the weird ones. We humans have feet like that; all other primates have feet like this. This chimp up here, divergent big toe. Gorillas, orangutans, gibbons, monkeys, lemurs, all the way back to the base of the primate tree, it's a defining characteristic of the primate order; we have grasping feet, except for us. We don't. That evolved. That's what those footprints in the volcanic ash at 3.7 million years ago tell us; they tell us that we had evolved a fairly modern-looking foot even before our braincase expanded. And now with Ardi, we see something new. We go beyond *Australopithecus*, we see a foot that maintains that grasping ability of the big toe. But the lateral foot, the rest of the foot is functioning as a rigid lever, not a hand. It doesn't have that grasping adaptation of the rest of the foot that the chimpanzee had. The chimpanzee went its own way.

53. Making sense of "Ardi's" characteristics (73:13)

Now, what are we going to do with all these characteristics to make sense of all of this? We've got all kinds of things. We've got spine and cranium and so forth. We evolutionists pay attention to the new things in evolution. What are the new things? Where can we place this creature in the phylogeny, in the relationships? A part of the foot is like a human foot, the pelvis is more human, a long lumbar spine, a very flexible back, not the solid rigid back of the chimp, a short cranial base, and feminized male canines, all of these features answer the question of whether or not this creature is on our side of that fork with our last common ancestor, the chimp. The features uniquely shared with all later hominids, from the teeth, the skull, the pelvis, and the foot, allow us to make that placement. So you're asking a question now, well, okay, that's fine, you can get a yes to that one, it's a hominid. But is it the direct ancestor of things like Lucy, an *Australopithecus*? That's a tougher question to answer for the paleontologist. Let me explain why. We have these early forms. They're not well represented yet; we're just beginning to find them. *Australopithecus anamensis* evolves into *afarensis*; it's a chronospecies. We looked at that in the last lecture. But look at the fossil record. Despite all of our success in the field, it's still mostly gaps. There are pretty big gaps that remain to be filled. We have fossils from Tanzania, Kenya, and Ethiopia, so we have a geographic gap on the rest of the continent. And we have time gaps: *Ardipithecus ramidus* is possibly the direct ancestor of *Australopithecus*. It's pretty close in time. But evolution can happen very rapidly with the right selection and the right genes.

54. Teeth as indicators of behavior (74:52)

And classification and phylogenetics, in fact, they're useful, people pay a lot of attention, but there are much more interesting biological questions to be asked. What about this? We know the human palm is very short compared to the ape palm. But what about what's under the table? Now we get to a quiz. This is a common chimpanzee. It's an autopsy photo. It turns out, there's a chimpanzee very much like this male chimpanzee, killed a human child, so the local people killed the chimpanzee. And they autopsied it, and they took the organs out in the autopsy. Please identify organ A: Brain, easy. Please identify organ B. That's a testicle. Now, the problem is with the fossil record, testicles don't fossilize. [laughter] They're soft tissue. It's a problem. But we kind of have a proxy in the canine tooth. You can see it in the animal up here. Male chimpanzees have these very long projecting fanglike canines that sharpen as they come down across the lower dentition; even females have this. This is called C/P3, upper canine, lower P3 honing, sharpening, and these animals used these teeth in threat, bluff, and display, largely the male against male in chimpanzee society. Why are they fighting? What are they competing for? Estrus females, females that can be impregnated. So these teeth can stand in as an indicator of the kind of social behavior going on. What about humans? Well, we see that humans compete for females, but we humans don't really know when the females are ovulating most of the time. There are all kinds of products developed to help that, but it's kind of concealed from us. And what about *Ardipithecus*? Well, this is not Ardi. Ardi's a female, But fortunately, since we have those other individuals, we can take the largest male canine from the collection, and this is what it looks like. It's a tiny, short, blunt tooth, completely different from a chimpanzee. It's not functioning like a chimpanzee. What do we read from

that? Well, we have to think as biologists because these are systems under evolution. What we're talking about here is a creature that is at the beginning of bipedality; it's not a full adaptation like in *Australopithecus*. It doesn't have the honing canine; that may be a signal that the males in this species are not competing over estrus females. It may be a signal that this ovulatory cryptis is very deep in human evolution. It's a fundamental part of our biology; maybe it started off way back then. Maybe it has something to do with bipedality. We can generate hypotheses; more fossils can test them.

55. Chimpanzee-human common ancestor was not a chimpanzee (77:59)

So *Ardipithecus*: a woodland hominid, not a savanna chimp, not a link between modern apes and modern people, but it really reveals chimpanzee evolution. It shows how specialized these apes are. After all, they've been evolving for the same seven million years since we split from them: chimpanzee evolution in one trajectory, human in another. And it shows that common chimpanzees today, like this one or the one that was shot in Uganda, their behavior is highly specialized. Their diet, highly specialized. Their locomotion, highly specialized. And their habitat preference, tropical forest. The common ancestor we shared with chimpanzees was not a chimpanzee. How can we explain that? If you're looking for insight into this, turn to evolutionary developmental biology. That's what Sean Carroll does, Professor Carroll's book, a good place to start, *Endless Forms Most Beautiful*. Great quote from this book: "Nature invents by teaching very old genes new tricks." That common ancestor had genes. We haven't found that common ancestor. We've gotten pretty close through Ardi; the Ardi species had genes. These genes, those old genes learned different tricks, in a sense. It's really not like that; it's natural selecting. Natural selection operating on those genetic materials on the evolutionary endpoint, which is the chimpanzee, make a chimpanzee, and make a human a human. So, another book, same topic, it's called *Your Inner Fish* by Neil Shubin...has a couple great lines in there. "The zoo in you." "You are linked to the rest of the tree of life." "The zoo in you," and "why history makes us sick." "What's he talking about? Is he talking about we don't like history class? No. He's talking about evolutionary history.

56. Why human medicine must be evolution minded (79:57)

What is it? Why, to come back to that question in the initial lecture, why is it that human medicine must be evolution-minded? Well, because evolutionary biology is the science that has proven to unify medicine. Humans all grow, and we all get sick, and we will all die in a world of other evolving organisms, other species' lineages, parasites, bacteria. They will kill many of us ultimately, so we'd better understand that. Our genetic diseases were forged through this evolutionary process; we'd better understand it. The biological variation within *Homo sapiens*, the reason that Abdullah looks different from me, that is the result of evolution; we'd better understand it. Human bodies, behaviors, and

physiologies were shaped by evolution because humans evolved, and now we have all of this evidence that Darwin didn't have.

57. Evolution's perspective: Geographic range and preferred habitat (81:00)

But to move even beyond human health and disease, to move beyond medicine...this gives us a perspective on our existence on this planet. We have seen just in terms of geographic range, over this six-million-year time period, we've moved with *Ardipithecus*, a woodland creature, barely bipedal, through *Australopithecus* that expanded its range all across Africa, a couple different species of it arose and then went extinct. It led to early *Homo* that expanded the range, expanded the geography of hominids beyond Africa. And then finally *Homo sapiens*, that is planetary. Fascinating because what's happened just over the last little bit of geological time over 2.6 million years ago, technology-driven niche expansion has happened. And what are the consequences? The consequences are real, and the consequences are fatal to creatures like that one. These are, of course, the extant apes, very-well-adapted through natural selection to tropical forest environments, tropical forest environments that are being destroyed by *Homo sapiens* with chainsaws, not stone tools. That's interesting. It turns out that this species, this bizarre species, *Homo sapiens*, is now-- and this has never happened before in the history of life on this planet, it has never happened before that a single evolutionary lineage, one species, is bringing about the extinction of so many contemporary species. And these primates, the extant apes, within your lifetimes may well be extinct in the wild because of the activity. And that's not the only organism; there are many others.

58. Humans are the sole surviving hominid species (82:45)

We are, in fact, the sole surviving hominid species. I'm going to leave you with three images. This is Michelangelo's masterpiece on the ceiling of the Sistine Chapel. This is the hand of *Ardipithecus ramidus*, 4.4-million-year-old hominid that we have just found, that Yohannes was skillful enough to come across in the desert and recover almost intact. And this, of course, is the view of Planet Earth given to us through the Apollo astronauts. Right now, we're seven billion living individuals in this one species, *Homo sapiens*. We're having global impacts on biodiversity and on human health. After six million years of human evolution, evidence and reason, much as Darwin predicted, have illuminated where we came from. What will you do with that knowledge? And what will we do with that knowledge? I'll take questions.

59. Q&A: Procedures to be followed to get permission to dig? (84:23)

[Applause]

[DR. WHITE:]In the very back.

[STUDENT:] When you go to locations and sites to dig, what are some of the procedures that you have to follow to get permission from the local governments and communities to dig there?

[DR. WHITE:] Good question. The question is when we go out to these places, what kind of permissions are needed? We need permission at the federal government level, so we go to the national government of Ethiopia, and then we go down to the local level, which is under the Afar administration. That's why the Afar man was in the photograph; he is the cultural representative who comes with us to do the work. And then we have a, sort of a cultural interaction with these local people, the people with the AK-47s and the goats and the camels and so forth; these are the Afar people. They are nomadic pastoralists. They've had no education, they don't have running water, electricity, a lot of other things; well, they've actually got a couple wells now. We've put a couple wells into this area; they have clean water and so forth. The Afar people have a traditional justice system, and they have their own governmental system. And so, we negotiate with them. So if we get hassled by some bad boy with a gun, for example, and it can happen, we'll go to the elders in that society, in that clan, where we're working, and we'll talk to the elders, and they have their own justice system. And so, they'll deliberate and they may say, whoa, you know, our 14-year-old child's been a bad boy; he pointed one of the guns at one of the geologists on the outcrop. Bad, bad boy, we're going to take a goat away from his father to give it to the geologist. That's justice, right? And of course, the elders usually also say, and we'll also take a goat for ourselves.

60. Q&A: Why should validity of our beliefs be based on theory? (86:05)

[DR. WHITE:] Yes, in the back again.

[STUDENT:] Charles Darwin said in his book, *Origin of Species*, that two things need to happen, otherwise evolution is just a theory. He said that there needs to be the transition fossils, and he said that there needs to be simple building blocks, and in all living things. And clearly, as science has evolved, we see that cells are not simple. So my question is, Why should we base the validity of all of our life's beliefs on a theory?

[DR. WHITE:] Well, that's a pretty big question, and it's a good question. I would start with actually contesting what you said that Darwin said; that's number one. I don't think he said it in those words, but let's not quibble over that. Let's go directly to the last word you used because people use it all the time. Evolution is just a theory, right? That's basically, that's the crux of it. Okay, have you ever heard of gravitational theory?

[STUDENT:] Yes.

[DR. WHITE:] Works pretty well. How about the germ theory of disease? You see, in science, we use the term "theory" in a different way. It's not somebody's wild idea. You could even argue that it was Darwin's, but it's been tested scientifically. It's been demonstrated to have happened. Evolution is a fact; it's not a theory. There is evolutionary theory, and that is the body of fact and observation that we can impose, we can bring to bear on the question of how things evolved. Let's take your building block example for that, right? I'm not sure that Darwin said that, but I am damn sure that Darwin didn't know what DNA was, and I am certain that he didn't know what a nucleotide is. Sarah has informed us all about nucleotides; those, I think, are the building

blocks, right? We're getting this fantastic understanding, and let's bring this back to medicine now. Howard Hughes Medical Institute: many of the Howard Hughes Medical Institute investigators around this country at the top universities--and believe me, they pick the very best people in the world to do this research--| these people are working on those building blocks because those building blocks sit at the fundamental foundation of things like cancer. Now, if you're given a choice between an evidence-and reason-based interpretation of your cancer, of those cells, out of control, and, well, let's think about it and psychically go after it. What are you going to take? I'm going with the Howard Hughes Medical Institute investigator every single time, right? That's pretty much demonstrated to be the way to go. And so it is with evolutionary biology. That is a part, medicine is a part of this grander overarching evolutionary biology. It just means that we scientists have looked at this from every angle, and as you can see from listening to us during these lectures, we're pretty critical people. That critical element of science is always there because you can always level it a colleague and say, whoa, you blew it there; Darwin blew it there. And Darwin did blow it in a number of cases. He didn't know anything about heredity; he thought it was blending. We now know it's particulate. It's the particles; those are the building blocks. But look how beautifully that merges into his understanding of natural selection. Look at the predictions that are made. Look at the prediction we made about a single valley in Africa, where we start with Abdullah on top and we step back through time, through a series of forms with smaller braincases and bigger faces, all the way back to a creature that is not a chimp and not a human. You could say that we tested the hypothesis there, and by so doing, we have demonstrated that evolutionary theory applies well in this case, much as it does in the biomedical basis of cancer.

61. Q&A: What will the chimpanzee-human common ancestor be like?

[DR. WHITE:] Another question, in the back again.

[STUDENT:] You said that *Ardipithecus* is not the common ancestral link between chimpanzees and *Homo sapiens*.

[DR. WHITE:] Correct.

[STUDENT:] What do you think the characteristics will be of that common ancestor?

[DR. WHITE:] Okay, very good question. At some point in time, somewhere around seven million years ago, we think, the lineage, the DNA leading to this species, *Homo sapiens*, and the DNA leading to chimpanzees, was all within a common ancestral species. What was that like? Now, for many, many years, in fact, all the way back to the time of Darwin, people have said, well, it's going to look just like a chimp. You follow it back, you find more and more chimpanzee-like forms. That's why *Ardipithecus* was the surprise, because it's so not like a chimp. And so, that's the best thing we have to predict what the last common ancestor is like. But the one great thing about paleontology, the thing that keeps us going, is that we need to find the evidence for that, and nobody has found it. And the real question is, when we do find it, not just what it's going to look like, how are we going to recognize it? We can barely recognize that this one is on our side of the split; some people actually disagree with that. They are critical of the interpretation that I gave you here. That's how science proceeds. So in about three weeks, I am going to go to a place called N'Djamena in Chad, Central Africa. Remember that star on the map? My colleague, a

Frenchman, Michel Brunet, in Chad, found a cranium very much like *Ardipithecus*, same size teeth, same short face, same...but he didn't find a skeleton. So a bunch of us are going to a conference in N'Djamena, and then after that, we're heading out to the Sahara. This is a place that is so barren, not a bush, not a tree, no water, you can see the Earth's curvature. And the sand dunes sit on top of deposits that are yielding seven-million-year-old fossils. We don't know what we're going to find. What a voyage of discovery that is. Whether it's in the field, in the desert, the molecular biology laboratory, the archaeological excavation, all of these dimensions of human evolution, we're actually able to look into the past and understand where we came from and how we got here. Thank you very much for your attention. [Applause][Music]