INQUIRY & INVESTIGATION

Investigating "Humanity": Reconstructing Human Evolution Using Skulls, Maps, Tools, & the History of Science

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Abstract

Although the central principles of evolution by natural selection can feel both abstruse and culturally fraught for learners of all ages, evolutionary logic is at the core of biological science: once students have a solid understanding of evolution, they can better understand everything else in biology. We present here a hands-on experience, coupled with intentional questioning strategies, that inspires students to use high-level evolutionary thinking and to begin asking excellent questions about what we know and how we know it. This activity leverages skull replicas of humans, chimps, and hominins to tap into young people's natural curiosity about where we come from and what it means to be a person—fundamental topics of inquiry for young people just coming into their own identities. Along the way, students are also exposed to important data and create arguments about what the archaeological record can currently tell us about the story of how people like us came to be.

Key Words: *evolution; human evolution; inquiry.*

○ Introduction

Human evolution can be a challenging topic to broach in many classrooms. In a 2016 poll reported by the National Science Board, only 52 percent of Americans were found to agree with the statement that "humans, as we know them today, descended from earlier species of animals" (National Science Board, 2018). Additionally, the teaching of human evolution has been the focus of numerous legislative bills that would restrict educational opportunities in public schools. Due to repeated controversy in courts, classrooms, and school board meetings, many biology teachers have felt hesitant to introduce the topic of human evolution, fearing local pushback and public scrutiny. However, we've had success working through the lesson described below with students of all ages who come from a wide range of political and religious backgrounds.

For this activity, students use a set of full-sized skull replicas along with a binder that has discussion prompts, graphs, and pictorial data. In our experience, the lesson design allows instructors to act as guides, directing the flow of discussion with relatively minimal prompts as students themselves generate questions and ideas. In the process, students will be engaging in authentic, collaborative scientific work—both when cooperatively investigating within small (2 to 8 person) groups and when sharing their small group's findings with the class at large—all while reinforcing general evolutionary principles and imparting some important information about human evolution, climate science, and the archaeological record.

Given that non-specialists often have difficulty applying the same type of logic to their understanding of human or non-human animals (de Waal, 1997), and the importance of high-quality evolution learning before college (Mead & Branch, 2011), we particularly wanted to design a learning experience focused on human evolution that could be highly flexible and amenable to learners of a wide range of ages, contexts, science knowledge, and life experiences. Other teams of educators have published excellent modules for using ancient skull replicas to investigate this topic, including "Mystery of the Skulls" (Yerky & Wilczynski, 2014), "Be a Paleoanthropologist for a Day" (Bayer & Luberda, 2016), and more. We've incorporated insights from their work, but we are presenting a significantly different exercise that better accomplishes our goals of student-led inquiry; authentic collaborative scientific practice; and the analysis, interpretation, and synthesis of diverse data sets. Our lesson ties the skill of argumentation from evidence to the core concept of evolution, addressing the standards shown in Table 1. We feel that our lesson has two additional important features: (a) demonstrating that many of the traits that we intuitively feel make us "most human" emerged long ago in beings whom we might not even recognize as human, and (b) demonstrating the ways in which our understanding of the world shifts as we gain access to more information, especially when this information spans many different types of data.

In conjunction with the National Center for Science Education (NCSE), a version of this activity has been tested in over 200 classrooms, including at many schools in the politically divided American Midwest and in college courses at Indiana University. With some modifications, we've also conducted this activity at retirement homes, at public science fairs, and for people who are incarcerated at the Monroe (Indiana) County Jail. In the process, we've worked with people from elementary-school age to post-retirement

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Table 1. National standards addressed by this lesson.

Next Generation Science Standards	
Science and Engineering Practices: • 1: Posing questions • 4: Analyzing and interpreting data • 7: Engaging in argumentation from evidence • 8: Obtaining, evaluating, and communicating data	Crosscutting Concepts: • 1: Patterns • 2: Cause and effect • 6: Structure and function • 7: Stability and change
Supported NGSS standards: • HS-LS4-1: Communicating scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence. • HS-LS4-5: Evaluating the evidence supporting claims that changes in environmental conditions may result in (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species. • HS-ESS3-1: Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity.	
AP Biology	
Science Practices: • 1: Using representations and models to communicate scientific phenomena and solve scientific problems • 5: Performing data analysis and evaluation of evidence • 7: Connecting and relating knowledge across various scales, concepts and representations in and across domains	AP Biology Big Ideas: • 1: Evolution/Natural selection
Vision and Change	
Core Competencies: • 1: Apply the process of science • 4: Tap into the interdisciplinary nature of science	Core Concepts: • 1: Evolution

age, including (especially in the jail classes) people who have not previously had much success in traditional academic settings, and who have professed a wide range of non-scientific conspiratorial beliefs. However, the hands-on, learner-led, qualitative-inquiry-based nature of this activity gives people an opportunity to authentically engage with difficult ideas that they might find threatening if encountered in a lecture-based setting (see Figure 1). We've discovered that when students are given the opportunity to direct the flow of their inquiry and act as spokespeople to share their burgeoning expertise, they are more likely to approach ideologically sensitive data with an open mind and perhaps even integrate newfound knowledge with their pre-existing beliefs.

We want to stress that you do not need to be an expert in human evolution or archaeology to guide students through this activity. Our online resources, hosted on NCSE's website (NCSE, n.d.), include answers to some frequently asked questions, but we've also found that in most sessions of this activity, students will generate questions that no one yet knows the answers to. This topic is an area of active research by professional scientists across the globe: future discoveries made during your students' lifetimes are likely to clarify some of our theories, and may force us to revise others. This is, after all, an essential tenant of scientific research. As students progress through this activity, they will be encouraged to ask "How do we know what we know?" "How confident can we be?" and "What critical information is missing?" In the notes below, we've included italicized notes on the sort of answers that we might give in response to these questions, but the answers your students generate will likely differ. Throughout the exercise, please encourage students to articulate the reasoning behind their ideas.

By the end of the exercise, your students will have gained a better understanding of how to engage in collaborative scientific pursuits, both in terms of working with a small team and in communicating their findings to others. They will have practiced applying evolutionary logic: that over long periods of time, natural selection can increase the frequency of traits that are beneficial within a particular environment, where each individual's environment consists of the climate, nearby plants and animals, as well as potential allies, enemies, or mates from among their own species. We also hope that your students will begin to formulate answers to the following specific questions:

- What did our ancestors look like?
- Where did they live?
- Which human traits evolved first, and which followed?
- When and where did changes occur? Under what circumstances? Why?
- Who among our ancestors seems "human" to you, who does not, and why?

Figure 1. This lesson is engaging in a variety of settings, from science classrooms to retirement homes. Photos courtesy of Armin Moczek.

○ The Activity

This lesson can be conducted in class periods ranging from 45 minutes to 70 minutes in length, although it is easier to guide students through the entire experience when you have access to the longer end of that range. You will need to prepare the binders in advance, five copies of the file found in the supplemental materials featuring 13 black and white pages and 2 color pages. You will also need a set of skull replicas: five contemporary chimpanzee skulls, five contemporary *Homo sapiens* skulls, and one skull each for five ancient hominins: *Ardipithecus ramidus, Australopithecus afarensis, Homo habilis, H. erectus,* and *H. neanderthalensis*. We've included a purchasing guide on the NCSE website. As of 2023, this set costs approximately $4,000, but because the materials are portable and the lesson requires only a single day of instructional time, it's quite feasible to share a set among an entire school district/department or even multiple districts, or to request to share with (other) institutions of higher education. Distinct sets of materials held at both Indiana University Bloomington and the WonderLab Museum of Science, Health, and Technology are available for loan and have been used widely around our state.

If it is impossible for your district to jointly purchase or borrow this set of skull replicas, or if you are working with remote students, the activity can be done with digital tools available at the National Center for Science Education's website that allow students to see rotated and magnified skulls. However, we have found that the visceral, hands-on impact of working with full-scale skull replicas dramatically increases the memorability of and engagement with the activity. Especially when working with students who are dubious about the validity of this branch of scientific research, it is crucial to provide resources that will allow the students to draw their own insights from authentic skull casts that they can hold and inspect in the real world. A superb hypothesis-testing activity by Price [2012], in which students graph changes in fetal chimpanzee skulls and then compare the adult skulls of other species to their graph, could serve as an excellent follow-up to the lesson described here. We also note that Price's lesson works well with paper pictures of all the skulls rather than casts/models.

Preparation

Before the activity, as outlined in Figure 2, prepare the room with five stations that divide your students into equal-sized groups, between two and eight students each. At each station, provide at least one copy of the printed binder with discussion prompts and data, plus a set of three skull replicas: one contemporary human, one contemporary chimpanzee, and one of the five ancient hominins. We often choose to "nickname" the skulls with students rather than use the scientific nomenclature because many students may already have preconceived notions about *Homo habilis*, for instance, that might inhibit them from engaging as inquisitively as with a skull named "HH." Finally, you may want to have students add traits sequentially to an initial model, resulting in the figure shown in Figure 3; both the blank and completed model are available in the supplemental materials accompanying the online version of this paper.

In a brief introduction, remind students of the general principles of evolution and speciation. You may choose to gradually zoom in on a phylogenetic tree to indicate the split between the ancestors of contemporary chimpanzees and the ancestors of contemporary *Homo sapiens*, diverging from our last common shared ancestor six million years ago (Prado-Martinez et al., 2013). Remind students that contemporary chimpanzees are also a product of these six million years of evolutionary change—no contemporary organism exactly replicates our ancestors as though frozen in time. But because we believe that the ancestral lineage of contemporary chimpanzees continued to live in environments that at least partly resembled the likely habitats of our last common shared ancestor, we can use the morphological features of a contemporary chimpanzee skull as an initial reference for many of the changes that occurred during human evolution.

Then present students with the overarching goals for today's activity, in which they will attempt to formulate answers to the overarching questions articulated above. Also remind students that as they work through the activity, they should bear in mind these core scientific principles:

- How do we know what we know?
- How confident can we be in these results?
- What critical information is missing?

Step 1: Observing the skulls
- Describe brain volume, tooth size, mouth protrusion, brow ridges, prominence of cheek bones, and the location of the *foramen magnum*, the hole in the back of the skull.

Step 2: Ages and geographic ranges
- Where do most species appear to have originated?
- When did upright posture first arise in the human lineage?

Step 3: Skeletal anatomy
- How has body size changed over evolutionary time?
- When did ancient hominins appear to have developed proportions similar to contemporary humans (even if they were still smaller in overall size)?
- When did ancient hominins develop brain volumes in the range of contemporary humans?

Step 4: Observations pertaining to diet and feeding habits
- What conclusions can be drawn from available data?

Step 5: Artifacts found with ancient hominin remains
- What might each artifact have been used for?
- How difficult might these artifacts have been to make?
- What might it mean for an ancient hominin to have created these types of things?
- What creations might be less likely to be found by contemporary archaeologists?

Step 6: Historic climate change
- What was the climate was like during the time period(s) when each ancient hominin species was living?
- What might have been the consequences for each ancient hominin (who may have experienced changes in vegetation, desertification, food availability, etc.)?
- What sorts of traits might help an animal—including ancient hominins—survive during periods of change and instability?

Lesson synthesis
- Where does "being human" begin?
- How recent are these discoveries?

Figure 2. Lesson overview.

The subsequent data and prompts are presented in order in the student binders (see Figure 4); we discuss each in more detail below and include sample teacher responses in italics.

Step One: Observing the Skulls

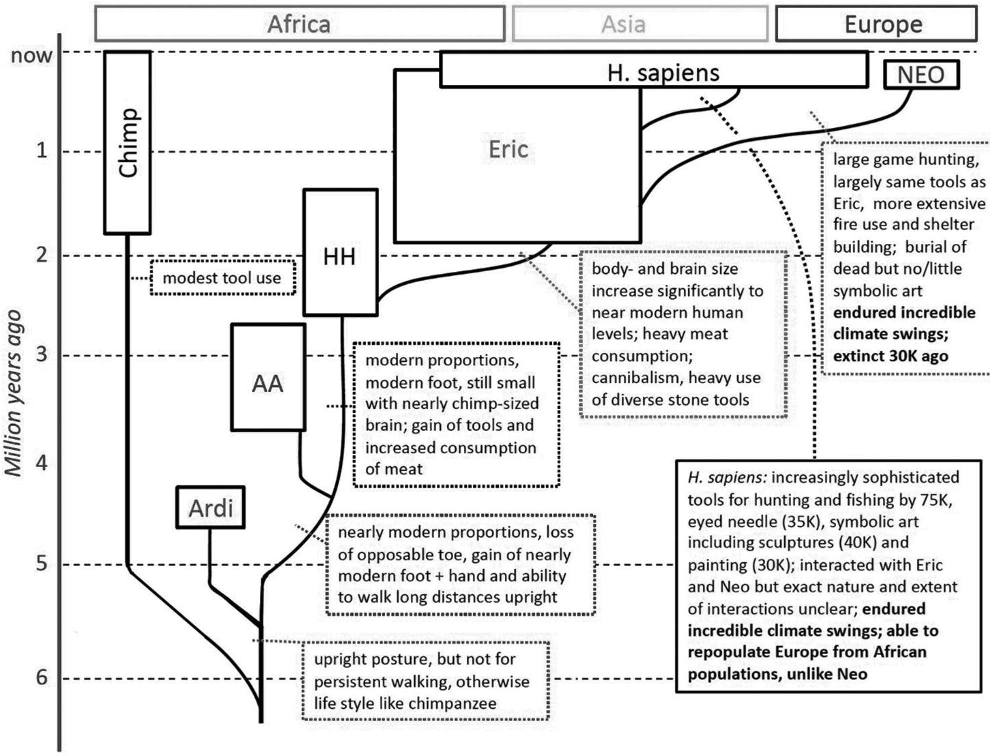
Encourage each team, working within their small group, to compare their unique set of three skulls. Provide enough time for each student to have a chance to hold and manipulate all three skulls at their station. Explain that the ancient hominin skulls are color-coded, with the brown regions indicating portions of the skull that were actually recovered by scientists, and the gray regions indicating missing fragments of the skull that had to be reconstructed (based on expected symmetry between the right and left sides, or in some cases based on the morphology of skull fragments found from other individuals of the same species who appear to have lived at similar times, with the exception of AA, in which the color-coding is reversed). When comparing the skulls, each team should pay special attention the characteristics listed in the binder: brain volume, tooth size, mouth protrusion, brow ridges, prominence of cheek bones, and the location of the *foramen magnum*, the hole in the back of the skull.

After a few minutes of inspection and discussion within their small groups (we typically allow no more than 5 minutes for this first small group discussion when leading this activity within a 45-minute class period, approximately 7 minutes for longer classes), you'll call on small groups in turn to explain some of their findings to the whole class. For a 70- to 90-minute class, you should invite each group to present their findings to their classmates, but for a 45-minute class, you'll want to have only two or three groups present their findings during this step, preferably from ancient hominins that span a wide range of time (e.g., Ardi, HH, and Eric). Encourage each small group's spokesperson to let everyone know which ancient hominin their team is investigating, explain a few similarities and differences among their set of skulls (e.g., brain volume, mouth protrusion, brow ridges, tooth size) and perhaps give a speculative guess as to which contemporary skull (human or chimpanzee) the ancient hominin skull seems more similar to.

Then, as an entire class, discuss what the location of the foramen magnum, a prominent hole in the back of each skull, might tell you about an animal's posture and style of locomotion. *This hole should be underneath the brain case for an animal that walks upright and balances its head on top of its spine, and more toward the back of the skull for an animal that walks on all fours and holds its head in horizontal extension of its spine.*

Step Two: Ages and Geographic Ranges

In Step Two of the binder, students have a chart that lists the geographic ranges where similar archaeological specimens (presumed to be from the same species of hominin over time) have been found, as well as the range in ages for these archaeological specimens. Because the archaeological record is inherently incomplete, we cannot be certain when each species arose or went extinct (Du et al., 2020); for consistency's sake, we have used the time and geographical range estimates from the Smithsonian Museum of Natural History (Smithsonian, 2022). The estimates for the timing of arrival of anatomically modern *Homo sapiens* to various geographical regions



modest tool use

large game hunting, largely same tools as Eric, more extensive fire use and shelter building; burial of dead but no/little symbolic art **endured incredible climate swings; extinct 30K ago**

body- and brain size increase significantly to near modern human levels; heavy meat consumption; cannibalism, heavy use of diverse stone tools

modern proportions, modern foot, still small with nearly chimp-sized brain; gain of tools and increased consumption of meat

H. sapiens: increasingly sophisticated tools for hunting and fishing by 75K, eyed needle (35K), symbolic art including sculptures (40K) and painting (30K); interacted with Eric and Neo but exact nature and extent of interactions unclear; **endured incredible climate swings; able to repopulate Europe from African populations, unlike Neo**

nearly modern proportions, loss of opposable toe, gain of nearly modern foot + hand and ability to walk long distances upright

upright posture, but not for persistent walking, otherwise life style like chimpanzee

Figure 3. Hominin tree annotated with information highlighted in this lesson. Herein, "Ardi" stands for *Ardipithecus ramidus*, "AA" stands for *Australopithecus afarensis*, "HH" stands for *Homo habilis*, "Eric" stands for *Homo erectus*, "Neo" stands for *Homo neanderthalensis*, "Chimp" stands for *Pan troglodytes*, and "H. sapiens" for *Homo sapiens*.

were compiled from several sources (Skoglund & Reich, 2016; Clarkson et al., 2017; Hershkovitz et al., 2018). These estimates are by no means definitive; for example, the age of stone tools found in Shangchen, China, suggest that *Homo habilis* populations may have reached East Asia (Zhu et al., 2018), whereas the qualitative data we are presenting students mirrors the Smithsonian summary and indicates a geographical range isolated to Africa for this species. Our goal here is not to oversimplify, but rather to give students access to a good working model that many scientists would currently agree on, so that students can focus on the most salient aspects of this evolutionary story.

Each team of students should identify the ancient hominin whose skull they have been inspecting from among these data, and discuss what the geographical ranges of the archaeological finds might indicate. Each team should also double-check the location of the foramen magnum of their ancient hominin, comparing it with both the contemporary chimpanzee and contemporary human skulls.

Then, as a class, draw the age ranges onto a timeline on the board where everyone can see. (Our online materials include a reference timeline that also indicates the oldest fossil evidence for skulls that we can definitively categorize as ancestors to contemporary chimpanzees.) Then ask each team to tell the entire class about the location of the foramen magnum on their ancient hominin skull. As a class, discuss the following questions:

- Where do most species appear to have originated?
- When did upright posture first arise in the human lineage?

Whereas more recent fossils have been found in Africa, Asia, and Europe, older fossils have been found exclusively in East Africa, suggesting that East Africa may be the geographic center of origin for hominin evolution. The oldest hominin fossil found to date, that of "Ardi," already possesses a foramen magnum positioned for upright posture.

If time permits (for hour-long class periods or longer), you should also discuss:

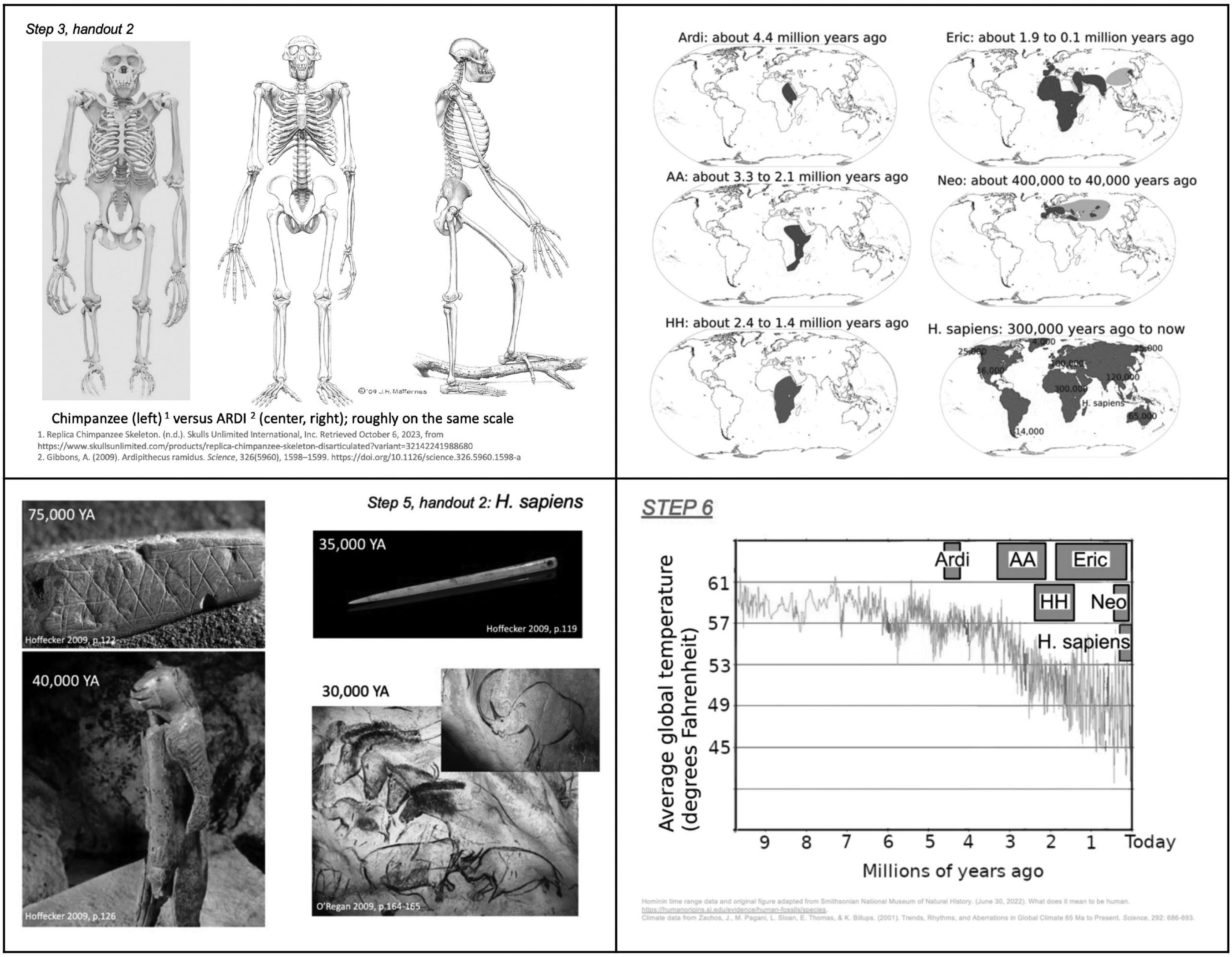
- If we didn't have these archaeological data, how might we collect data from modern-day humans to estimate where humans first originated?

Geneticists believe that we should find the greatest genetic diversity between people near the ancestral ranges of our species, because subgroups that departed this region may have experienced population bottlenecks (Cann et al., 1987). Linguists believe that we should find the greatest diversity of phonemes among languages near the ancestral ranges where human language first originated, as unique vocal sounds (such as clicks, glottal stops, or even the rolled "R" sounds that some students might struggle to pronounce in language classes) may have been dropped over time (Atkinson, 2011).

Step Three: Skeletal Anatomy

On the Step Three pages of their binders, students will find estimates for the height, weight, and brain size of each ancient hominin, as well as images of their entire skeletons (for each hominin where an entire fossilized skeleton has been found). Within their small groups, students should discuss how body size changed over evolutionary time, when ancient hominins appear to have developed proportions similar to contemporary humans (even if they were still smaller in overall size), and when ancient hominins developed brain volumes in the range of contemporary humans.

As a class, invite the small groups to share a few of their insights. Together, discuss what we can speculate based on the proportions



Chimpanzee (left) [1] versus ARDI [2] (center, right); roughly on the same scale

1. Replica Chimpanzee Skeleton. (n.d.). Skulls Unlimited International, Inc. Retrieved October 6, 2023, from https://www.skullsunlimited.com/products/replica-chimpanzee-skeleton-disarticulated?variant=32142241988680
2. Gibbons, A. (2009). Ardipithecus ramidus. *Science*, 326(5960), 1598–1599. https://doi.org/10.1126/science.326.5960.1598-a

Hominin time range data and original figure adapted from Smithsonian National Museum of Natural History. (June 30, 2022). What does it mean to be human. https://humanorigins.si.edu/evidence/human-fossils/species.
Climate data from Zachos, J., M. Pagani, L. Sloan, E. Thomas, & K. Billups. (2001). Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. *Science*, 292: 686-693.

Figure 4. Sample binder pages from this lesson. The complete set is available in the supplemental materials accompanying the online version of this article.

and hand and foot shape of "Ardi," especially when compared with modern day chimpanzees and humans

Upright posture, as indicated by the position of the foramen magnum, appears to have arisen before persistent walking (Lovejoy et al., 2009). "Ardi" may have had an upright posture, yet several features of their hand- and foot-shape resemble those of contemporary arboreal (tree-living) primates, including feet with opposable toes that appear more suitable for gripping tree limbs than for long-distance walking across hard ground (Prang et al., 2021).

Step Four: Observations Pertaining To Diet And Feeding Habits

As a class, show the Step Four set of slides with five observations about diet and read these aloud. Lead students in a discussion about what conclusions we might draw from each of these observations.

1. *Contemporary chimpanzees and "Ardi" likely had similar diets. (Chimpanzees are omnivores and while meat does not make up a large portion of their diet, they will sometimes eat other mammals.)*
2. *HH likely used tools and ate meat (Pante et al., 2018); more ancient ancestors may not have.*
3. *ERIC likely ate meat, used tools, and used fire (Gowlett, 2016). There was reduced emphasis on chewing as a form of "cooking." (Your students may be interested to learn that chewing, which increases the amount of nutrition that can be extracted from food by beginning its breakdown before it reaches the digestive tract, seems to be an evolutionary innovation that was temporally linked with a rapid increase in brain volume among the earliest mammals (Rowe et al., 2011). Fire complemented chewing leading to even more efficient nutrient extraction, likely precipitating the further increase in brain volume among ancient hominins.)*
4. *NEO likely ate meat from animals much larger than themselves, perhaps indicating cooperative hunting (Smith, 2015).*
5. *NEO likely practiced cannibalism (Rougier et al., 2016).*

Step Five: Artifacts Found With Ancient Hominin Remains

On the Step 5 pages of their binders, students will find pictures of various artifacts that have been found in association with ancient hominin remains. In their small groups, students should compare these artifacts, discussing what each might have been used for and how difficult they may have been to make. Also consider what it might mean for an ancient hominin to have created these types of things.

As a whole class, students should also speculate about the sorts of creations that would be less likely to be found by contemporary archaeologists.

Wooden tools, skin bags, organic glues, and seaweed nets are much more likely to decompose before forming fossils. Rocks and hard clay endure most easily, although occasionally even footprints can form fossils. Some cave paintings have survived until the present day, but the ones we've found recently began to fade as soon as they were exposed to humid air from the surrounding environment or human exhalations. Although we haven't yet found compelling evidence that any hominins other than Homo sapiens *made symbolic art, we aren't sure that they didn't.*

Step 6: Historic Climate Change

On the Step 6 pages of their binders, students have graphs of average global temperatures spanning several timescales: 500 million years (Voosen, 2019), 10 million years (Westerhold, 2020), and 24,000 years (Marcott & Shakun, 2021). These temperature data are necessarily approximate, and even so, a global average temperature may not reflect the local temperature of any particular habitat. Additionally, there is no direct way to measure ancient temperature: instead, scientists have analyzed the ratio of atmospheric chemical isotopes that have been preserved trapped in ice (for roughly ten-thousand-year time scales) or the fossils of ancient aquatic lifeforms (for million- and billion-year time scales). While we cannot know for certain that the absolute temperatures presented here are accurate, it is likely that the variations we see reflect real changes in the past climate, and these variations have often been extreme.

Although only the 10-million-year time span has direct bearing on this lesson, we feel strongly that students benefit from exposure to all three, time permitting. The longest timescale helps students appreciate the wide range of temperatures that have existed on our planet, the way positive feedback loops have caused switchlike behavior in global climate, and also the dire ramifications, such as mass extinctions (Sepkoski, 1996), typically associated with dramatic changes in temperature. The shortest timescale helps students appreciate the atypical climate stability that our ancestors experienced during entire history of civilization, and indicates the sudden shift that began shortly after modern industrialization and its attendant release of ancient carbon into the atmosphere (many students may have seen this graph before, but we feel that this is important for students to see again because the 10-million-year data primarily indicates a steady *decrease* in global temperatures). In classes with more advanced students or longer class periods, we often pause here to emphasize the shifting time scale(s) at which this lesson's data sets have originated, connecting the scales of the graphs in Step 6 back to the data table of Step 2 and/or the *y*-axis of Figure 3.

Next, students will find a magnified view of the past 10 million years of the global climate data. Ask them to consider what the climate was like during the time periods when each ancient hominin species was living. What might have been the consequences for each ancient hominin (who may have experienced changes in vegetation, desertification, food availability, etc.)?

As an entire class, invite students to speculate about what sorts of traits might help an animal—including ancient hominins—survive during periods of change and instability.

Perhaps instability would favor adaptability, flexible lifestyles, and learning instead of instinctual behaviors. Students might be aware that intelligent, highly adaptive species such as crows and raccoons are thriving in urban areas of the contemporary world, despite many other species being forced to the margins of expanded human populations. The use of ancient climate data to model the likely migration patterns of ancient hominins is an active field of research (Beverly, 2023).

○ Ending the Lesson

The final 5–10 minutes of your class period should be devoted to synthesis. Place human and chimpanzee skulls next to each other and reiterate that although chimpanzees are not our ancestors—contemporary chimpanzees have been evolving to better fit their environments for as long as we have—as our closest living relatives, chimpanzees provide a good reference for comparison. Then invite your student groups to place their ancient hominin skulls on a timeline at the front of the room, so they can see the relationships between each fossil.

During this discussion, you should provide your students with some important information about each of the ancient hominins that they've been investigating.

ARDI: "Ardi" stands for *Ardipithecus ramidus* and is the most ancient hominin for which we have found fossil evidence, dating from approximately 4.4 MYA (million years ago) in East Africa. Fossils of Ardi were first reported in 1994, and the first complete analysis of its skeleton was published in 2009. Ardi possessed climbing hands and feet that resemble those of contemporary arboreal primates, and yet also had an upright posture. Our current data suggests that Ardi is not our direct ancestor, but instead a representative of a separate hominin lineage that went extinct.

AA: AA stands for *Australopithecus afarensis*, and we have found fossils of AA dating from 3.85 to 2.95 MYA in Eastern Africa. Following their first discovery in 1974, more than 300 skeletons of AA have been found. AA walked upright and had hands and feet similar to those of modern humans. Like Ardi, we believe that AA was not our direct ancestor, but rather a representative of a hominin lineage that went extinct.

HH: HH stands for *Homo habilis*, and we have found fossils of HH dating from 2.4 to 1.4 MYA in Eastern and Southern Africa. The first HH fossils were discovered in 1960. HH was a prolific producer of stone tools, and these tools were presumably responsible for the scrape marks present on fossilized animal bones often found near fossilized HH remains. HH had similar relative proportions, hand shape, and foot shape compared to contemporary humans. HH is believed to be the most ancient of our own direct ancestors for whom we have found fossils, which is why scientists have given them the same genus name *Homo*.

ERIC: Eric stands for *Homo erectus*, and we have found fossils of Eric dating from 1.89 MYA to 110,000 years ago. The first Eric fossils were discovered in 1891. Eric was the first of our direct ancestors to have brains and bodies nearly as large as contemporary humans, and over time some groups of *Homo erectus* migrated from Africa into Europe and Asia, where they established significant subpopulations.

NEO: Neo stands for *Homo neanderthalensis*, and we have found fossils of Neo dating from 400,000 to 40,000 years ago. The first Neo fossils were discovered in 1829. In Europe, the isolated subpopulation of *Homo erectus* gave rise to the Neo lineage, while *Homo erectus* remaining in Africa gave rise to the *Homo sapiens* lineage (i.e., our own) beginning 300,000 years ago. As an ice age waned, approximately 50,000 years ago, some groups of *Homo sapiens* migrated from Africa into Europe, and there was a significant overlap between *Homo sapiens* and *Homo neanderthalensis* in Europe for approximately 10,000 years until *Homo neanderthalensis* went extinct. As best we can tell, Eric, Neo, and ancient *Homo sapiens* all crafted tools, used fire, built shelters, hunted cooperatively, buried their dead, and practiced cannibalism.

While viewing the ancient hominin skulls on a timeline from most ancient to most recent, students should consider who counts as human to them, and why? Does being human begin with upright posture (Ardi), long distance walking (AA), complex tool crafting (HH), art and burial practices (Eric), metaphorical language (our only proof is for *Homo sapiens*, but we should recognize that the oldest preserved writing is only 5,000 years old, and metaphorical language use among hominins may be much older), or something else? These questions cannot be definitively answered but are instead intended to stimulate discussion.

Also, note that HH, AA, and Ardi were first discovered during the lifetimes of current scientists, and new fossils are found every year. We don't know what new discoveries will be made during our students' lifetimes.

Lastly, there is a chance that some students may ask about the scientific fraud known as "Piltdown Man," in which a research team intentionally assembled a contemporary human skull with an orangutan jaw and chimpanzee teeth, then used a rock tumbler and chemical treatments to give their creation the illusion of antiquity. We've chosen not to include this example in the main body of our lesson, choosing instead to provide an unfabricated data set to build confidence in students about our current scientific understandings.

It's true that students benefit from a discussion of the ways that our understanding of fossils has changed over time. For instance, current high-school students might be aware of museum displays of dinosaur skeletons that assembled the bones in inaccurate postures, such as the upright T-Rex; in recent years, many curators have been painstakingly dissolving glue from bones in order to display postures more accurately. Similarly, students may have seen recent newspaper articles about how cave paintings that scientists originally assumed were created by *Homo sapiens* have been re-identified as the work of *Homo neanderthalensis*. These are good-faith errors and come from the natural process of scientific models shifting as we discover additional data.

But the "Piltdown Man" story is different. Unfortunately, numerous scientists throughout history (and still today) have intentionally fabricated data. Each such case might have a unique story—the perpetrators might be motivated by financial gain, career aspirations, nationalistic pride, or even racism, as in the case of the "Piltdown Man" fraud—but the harms caused are depressingly similar. Fabricated data stalls scientific progress and often damages the public at large (e.g., the anti-vaccine movement, climate-change denial, not to mention a variety of psychology findings that have been widely reported in the popular press before the underlying studies were retracted) (Lewandowsky et al., 2013). The perpetrators of the "Piltdown Man" fraud were inspired by their pre-existing belief that human evolution must have begun with large brains and that Europe was the likely site of human origins. This 1912 fraud was intended to mislead the public, but we now have a preponderance of real evidence allowing us to address the questions of where human ancestors first lived and when our various traits arose.

○ Conclusion

While working through this lesson, students will inevitably ask many questions. In our experience, we are able to answer only a fraction of these: some questions that students generate will be philosophical (such as the question of which ancient hominins we might consider to be human), some questions will have answers that depend on data that no archaeologists have yet uncovered, and some questions will have answers present in the scientific literature that we don't remember in the moment or have not yet read. Within this qualitative exercise, such unanswered questions are perfectly acceptable. Students should be encouraged to think about what sort of experiments might help them discover answers to their questions, and to recognize that the future of science includes room for their own curiosity. In our experience, in addition to imparting important facts and encouraging high-level evolutionary thinking, the best aspect of this exercise is that the physical presence and hands-on manipulation of these skull casts helps that curiosity bloom.

Both the students and teachers we've worked with have found this lesson engaging and meaningful. Here are four comments from members of Kirstin's 2016 AP Biology class:

- "It was so engaging and intriguing. Making and using data to solve which trait came first was super interesting and I learned a lot. The real data and skulls made it hands on and interactive."
- "I really enjoyed the presentation and how it was organized—how we were asked to draw our own conclusions from given data and therefore better understand how scientists discover the things we know and hypothesize about evolution."
- "I was completely fascinated by the lesson. The lesson got me excited about evolution and the ways we can study it. I actually had my mom pull me out of lunch [at school] so we could grab coffee and talk about it."
- "I usually don't like sitting and just listening because it ends up making me sleepy, but I really liked the presentation yesterday. It's not really something I believe in, but I'm open to learning new things."

One teacher in the NCSE pilot of this lesson says, "I've found that using 3D replicas of fossils is much more impactful on student learning than simply having students look at pictures. Giving students the opportunity to handle the fossils, measure their dimensions, and observe them closely created an engaging learning environment in which they could more easily make comparisons and come up with their own questions. When students were able to compare the skull and anatomical structure of extinct hominid species with the structure of a modern human skull, the relatedness between humans and ancient hominids became irrefutable. Students who were skeptical about human evolution before the lesson became much more confident in the fact of shared ancestry."

We're hopeful this lesson will help you and your students to dig into human evolution to foster authentic scientific inquiry in high-interest, humane, collaborative ways. Equally importantly, we hope this work will inspire you to build your own lessons that leverage fun and wonder to grow learners' understandings of the natural world and its history.

○ Supplemental Materials

Available on the *American Biology Teacher* website:

- A digital copy of the complete student binder
- Complete annotated tree summarizing the lesson (Figure 3), plus a blank template

○ Acknowledgments

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References

Atkinson, Q. D. (2011). Phonemic diversity supports a serial founder effect model of language expansion from Africa. *Science*, *332*, 346–349.

Bayer, C. N., & Luberda M. (2016). Measure, then show: Grasping human evolution through an inquiry-based, data-driven hominin skulls lab. *PLoS One*, *11*(8), e0160054.

Beverly, E. J. (2023). Using climate to model ancient human migration. *Science*, *381*, 605–606.

Cann, R., Stoneking, M. & Wilson, A. (1987). Mitochondrial DNA and human evolution. *Nature 325*, 31–36.

Clarkson, C., Jacobs, Z., Marwick, B., Fullagar, R., Wallis, L., Smith, M., Roberts, R. G., Hayes, E., Lowe, K., Carah, X., Florin, S. A., McNeil, J., Cox, D., Arnold, L. J., Hua, Q., Huntley, J., Brand, H. E. A., Manne, T., Fairbairn, A., Shulmeister, J., … & Pardoe, C. (2017). Human occupation of northern Australia by 65,000 years ago. *Nature*, *547* (7663), 306–310.

de Waal, F. (1997) Are we in anthropodenial? *Discover*, *18*(7), 50–53.

Du, A., Rowan, J., Wang, S. C., Wood, B. A., & Alemseged, Z. (2020). Statistical estimates of hominin origination and extinction dates: A case study examining the Australopithecus anamensis-afarensis lineage. *Journal of Human Evolution*, *138*, 102688.

Gowlett, J. A. J. (2016). The discovery of fire by humans: A long and convoluted process. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *371*(1696), 20150164.

Hershkovitz, I., Weber, G. W., Quam, R., Duval, M., Grün, R., Kinsley, L., Ayalon, A., Bar-Matthews, M., Valladas, H., Mercier, N., Arsuaga, J. L., Martinón-Torres, M., Bermúdez de Castro, J. M., Fornai, C., Martín-Francés, L., Sarig, R., May, H., Krenn, V. A., Slon, V., Rodríguez, L., … & García, R. (2018). The earliest modern humans outside Africa. *Science*, 359(6374):456-459.

Lewandowsky, S., Oberaur, K., & Gignac, G.E. (2013). NASA faked the moon landing – therefore (climate) science is a hoax. *Psychological Science*, *24*(5), 622–633.

Lovejoy, C. O., Suwa, G., Simpson, S. W., Matternes, J. H., & White, T. D. (2009). The Great Divides: *Ardipithecus ramidus* reveals the postcrania of our last common ancestors with African Apes. *Science*, *326*(5949), 73–106.

Marcott, S. A., & Shakun, J. D. (2021). Global temperature changes mapped across the past 24,000 years. *Nature,* 599: 208-209.

Marshall, C. R., Latorre, D. V., Wilson, C. J., Frank, T. M., Magoulick, K. M., Zimmt, J. B., & Poust, A.W. (2021). Absolute abundance and preservation rate of *Tyrannosaurus rex. Science* 372 (6539): 284-287.

Mead, L.S., & Branch, G. (2011). Overcoming obstacles to evolution education: Why bother teaching evolution in high school? *Evolution Education Outreach*, *4*, 114–116.

National Science Board. (2018). *Science and Engineering Indicators 2018*. NSB-2018-1. Alexandria, VA: National Science Foundation. Available at https://www.nsf.gov/statistics/indicators/.

"No More Monkeying around: National Center for Science Education." *NCSE*, National Center for Science Education, https://ncse.ngo/no-more-monkeying-around.

Pante, M. C., Njau, J. K., Hensley-Marschand, B., Keevil, T. L., Martin-Ramos, C., Franco Peters, R., & de la Torre, I. (2018). The carnivorous feeding behavior of early Homo at HWK EE, Bed II, Olduvai Gorge, Tanzania. *Journal of Human Evolution*, 120: 215-235.

Prado-Martinez, J., Sudmant, P. H., Kidd, J. M., Li, H., Kelley, J. L., Lorente-Galdos, B., Veeramah, K. R., Woerner, A. E., O'Connor, T. D., Santpere, G., Cagan, A., Theunert, C., Casals, F., Laayouni, H., Munch, K., Hobolth, A., Halager, A. E., Malig, M., Hernandez-Rodriguez, J., Hernando-Herraez, I., … & Prüfer, K. (2013). Great ape genetic diversity and population history. *Nature 499*, 471–475.

Prang, T. C., Ramirez, K., Grabowski, M., & Williams, S. A. (2021). *Ardipithecus* hand provides evidence that humans and chimpanzees evolved from an ancestor with suspensory adaptations. *Science Advances*, *7*(9), eabf2474.

Rougier, H., Crevecoeur, I., Beauval, C., Posth, C., Flas, D., Wißing, C., Furtwängler, A., Germonpré, M., Gómez-Olivencia, A., Semal, P., van der Plicht, J., Bocherens, H., & Krause, J. (2016). Neandertal cannibalism and Neandertal bones used as tools in Northern Europe. *Science Reports*, *6*, 29005.

Rowe, T. B., Macrini, T. E., & Luo, Z. -X. (2011). Fossil evidence on the origin of the Mammalian brain. *Science*, *332*(6032), 955–957.

Sepkoski, J. J. (1996). Global events and event stratigraphy in the Phanerozoic. In O. H. Walliser (Ed.), *Global events and event stratigraphy in the Phanerozoic* (pp. 35–51). Springer.

Skoglund, P. & Reich, D. (2016). A genomic view of the peopling of the Americas. *Current Opinions on Genetics and Development*, *41*, 27–35.

Smith, G.M. (2015). Neanderthal megafaunal exploitation in Western Europe and its dietary implications: a contextual reassessment of La Cotte de St. Brelade (Jersey). *Journal of Human Evolution*, *78*, 181–201.

Smithsonian National Museum of Natural History. (June 30, 2022). What does it mean to be human. https://humanorigins.si.edu/evidence/human-fossils/species.

Voosen, P. (2019). A 500-million-year survey of Earth's climate reveals dire warning for humanity. *Science*, 05–22.

Westerhold, T., Marwan, N., Drury, A.J., Liebrand, D., Agnini, C., Anagnostou, E., Barnet, J.S.K., Bohaty, S.M., De Vleeschouwer, D., Florindo, F., Frederichs, T., Hodell, D.A., Holbourn, A.E., Kroon, D., Lauretano, V., Littler, K., Lourens, L.J., Lyle, M., Palike, H., Rohl, U., Tian, J., Wilkens, R.H., Wilson, P.A., & Zachos, J.C. (2020). An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science*, *369*(6509), 1383–1387.

Yerky, M. D., & Wilczynski, C. J. (2014). The mystery of the skulls: What can old bones tell us about hominin evolution? *The American Biology Teacher*, *76*(2): 109–117.

Zhu, Z., Dennell, R., Huang, W., Wu, Y., Qiu, S., Yang, S., Rao, Z., Hou, Y., Xie, J., Han, J., & Ouyang, T. (2018). Hominin occupation of the Chinese Loess Plateau since about 2.1 million years ago. *Nature*, 559: 608–612.

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