INQUIRY & INVESTIGATION

The Mystery of the Skulls: What Can Old Bones Tell Us about Hominin Evolution?

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Abstract

In this activity, students examine nine hominin skulls for specialized features and take measurements that will enable them to determine the relatedness of these species. They will ultimately place each specimen on a basic phylogenetic tree that also reveals the geological time frame in which each species lived. On the basis of their data, and using similar scientific methods as paleoanthropologists, students will come to evidence-based conclusions about hominin evolution similar to those accepted by the scientific community (e.g., Tattersall & Schwartz, 2001; Sawyer et al., 2007; Palmer, 2010).

Key Words: *Hominin evolution; bipedalism; foramen magnum; cranial capacity; geological time scale; phylogenetic tree; scientific inquiry.*

This classroom activity was developed to teach hominin evolution in an investigative way – *CSI* style. Through examination and measurements, students are tasked with determining the identity of a collection of hominin skulls that, in this simulation, were recently unearthed (for the difference between hominid and hominin, see http://australianmuseum.net.au/Hominid-and-hominin-whats-the-difference/). This assignment relies on the availability of a set of nine teaching-quality casts of skulls (see Table 1) that span 4 million years of hominin evolution. The skull replicas needed for this activity can be obtained from Bone Clones (Canoga Park, California; catalog nos. BH-007, BH-021T, BH-020, BH-005, BH-002, BH-015, BC-178, BH-009, and BH-012) or as a customized kit borrowed from the Cornell Institute for Biology Teachers (CIBT) after attending one of the Summer Institutes in Ithaca, New York. Although the cost of purchasing the skulls may be prohibitively expensive for a single teacher or school, we encourage regional collaboration among multiple schools, teacher centers, science museums, and community colleges in acquiring one or two sets as loaner kits.

Through examination and measurements, students are tasked with determining the identity of a collection of hominin skulls.

The activity is modeled after the scientific method and is not too dissimilar from what today's paleoanthropologists do when they find a new hominin fossil. Because the focus of this activity is on hands-on data collection of skull features, we provide the students with a single template of a basic phylogenetic tree that represents but one of multiple interpretations of the current body of evidence for human evolution. Other approaches to teaching hominin evolution may also include evaluation of postcranial features (Senter, 2010) or focus on various phylogenies as working hypotheses (DeSilva, 2004), which are beyond the scope of this hands-on investigation of hominin skulls. In our experience, the students' deeper understanding of our ancestry is dramatically enhanced by actually holding and assessing a hominin skull – a two-dimensional reproduction, no matter how professionally done (e.g., Zihlman, 2000; Walker & Hagen, 2002; Ahern, 2004), cannot provide this level of perspective.

In addition to exploring the identity of the nine skulls, the students will pursue guiding research questions of the following nature:

- What is the relationship between the location of the foramen magnum and the type of locomotion a species exhibits?
- What is the chronological sequence of two of the most distinguishing characteristics in hominin evolution: the development of bipedalism and increasing cranial capacity?
- Even questions of paleo-ethological importance will be addressed: Throughout human evolution, was having only one single hominin species alive, as is the case today, the norm or the exception?

To explore these and other questions, students embark on a scientific journey of discovery and inquiry that includes collection, organization, and analysis of data, followed by conclusions based on their investigations. In order to facilitate such an investigative approach, we initially withhold the species names and only provide the students with a single-letter code marked on the underside of each skull (Table 1).

Throughout the activity, students are frequently challenged to review what they learned and to analyze their data by sets of

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Table 1. Teacher version of groups of skulls as presented in the classroom with skull letter codes and scientific names. The students' ultimate task in this inquiry-based activity is to establish the scientific identity of the nine skulls through quantitative and qualitative assessments.

Station 1	Station 2	Station 3
S = *H. **s**apiens*	**G** = *H. er**g**aster*	**B** = *Paranthropus **b**oisei*
N = *H. **n**eanderthalensis*	**H** = *H. **h**abilis*	**K** = ***K**enyanthropus platyops*
E = *H. **e**rectus*	**A** = *A. **a**fricanus*	**L** = *A. afarensis* (**L**ucy)

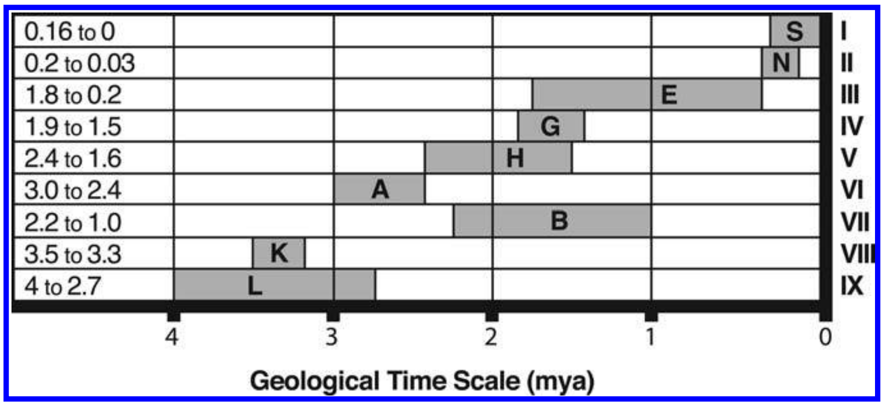

Figure 1. Teacher's version of Geological Time Scale. Roman numerals represent geological layers associated with each of the nine skull specimens represented by their letter codes.

questions. These questions are designed to foster a deeper understanding of how the data are related to the central concepts of this activity. The questions also help the instructor gauge students' understanding of the concepts, and the time needed to devote to explanations of scientific evidence and its implications where weaknesses are evident. Here, we provide selected examples to illustrate such inquiries.

The classroom should be set up with four work stations through which students rotate (Table 1). At the fourth station, students will create a geological time scale. Their task is to designate various periods that represent geological layers associated with each of the nine skulls by shading them in the graph. At this point, the students will not have enough information to match those periods with individual skulls' letter codes (unlike in the completed time scale in Figure 1). We want students to investigate the characteristics of the skulls without any preconceptions about fossil age.

○ Data Collection

Students will make observations and measurements at work stations 1–3, which they will record in the Master Data Table (Table 2) and use later to determine the identity and relatedness of the respective specimens. The quantitative measurements were intentionally kept at a basic level, using simple tools such as a metric ruler. We decided not to introduce unfamiliar calipers, in order to maintain focus on the characteristics of the various skulls. To keep the emphasis on the comparative nature of the investigation, we also opted for semiquantitative assessments using fingers for lengths and a novel use of fists for cranial volumes, rather than "accurate" measurements of those parameters.

The semiquantitative assessments include forehead length, presence or absence of sagittal crest, brow ridge, prognathism, and elongated canines (see Skull Assessment Guide [Appendix]). All these assessments require "hands-on" student participation, as students are asked to use their fingers to evaluate the skulls. To estimate the cranial capacity (CC) using their fists, each student team first selects a "model fist" that approximates 300 ccm by choosing the hand closest to 80 mm in width measured flat on a table, from pinky to index finger across the knuckles. To encourage speedy and discrete assessments of the cranial capacity, we limit the choices to 2, 3, or 4 fists (see Figure 2).

The quantitative assessments include measuring with a ruler the skull length (SL) and the distance from the posterior end of the foramen magnum to the back end of the skull (FB) as shown in the Appendix and Figure 3.

○ Data Organization

Once students have completed their data collection in the Master Data Table (Table 2), the class will begin exploratory analysis of the data by computing class averages for FB and SL, thus offering the opportunity to compare individual data with aggregate data. To quantify the relative position of the foramen magnum, they will then calculate the ratio of the class averages for FB and SL to determine the foramen magnum index (FMI) for the nine hominin species. Students will also convert their fist estimates (CC) into an approximate metric for a calculated cranial capacity (CCC) by using the formula CCC = CC × 300 ccm (the volume of a "model fist"). At this point in the investigation, students will be provided with the age of the individual letter-coded fossils based on Klein and Edgar (2002) and will complete the Geological Time Scale graph (Figure 1). Students are also provided with the actual cranial capacity (ACC), which is a range for each species based on reports from the scientific community (e.g., Zimmer, 2005; Potts & Sloan, 2010). Now students are asked to evaluate the quality of their data with a set of focused questions (*acceptable answers are provided in italics*):

1. Compare your data for FMI to the class FMI, which is based on average class data. Why is the class FMI usually a better indicator of the location of the foramen magnum than your individual calculation?

   Increased sample size provides more reliable data.

2. Compare the data that you calculated for CCC to the ACC, which has been determined by scientists, in Table 2. Which of your calculations have overestimated the cranial capacity?

   A, B, K, L

3. Which of your calculations have underestimated the cranial capacity?

   S, N

Table 2. Teacher version of the Master Data Table that students use to record their data and begin exploratory analyses.

Skull Letter Code	FL (S, L)	SC (+,–)	BR (+,–)	P/S (+,–)	CL (+,–)	FB (mm)	Class AVG FB	SL (mm)	Class AVG SL	FMI (FB/SL)	Class FMI (AVG FB/ AVG SL)	CC (2, 3, 4 "fists")	CCC (CC × 300 cm^3)	ACC (cm^3)	Age
S	L	–	–	–	–	55		180		0.286		4	1200	1300–1400	160,000 to present
N	L	–	+	–	[redacted]	55		210		0.262		4	1200	1400–1500	200,000 to 30,000 years ago
E	S	–	+	+	–	48		190		0.253		3	900	850–1200	1.8 to 0.2 mya
G	S	–	+	+	–	45		190		0.237		3	900	700–1100	1.9 to 1.5 mya
H	S	–	+	+	–	34		154		0.221		2	600	600–700	2.4. to 1.6 mya
A	S	–	+	+	[redacted]	38		175		0.217		2	600	400–500	3 to 2.4 mya
B	S	+	+	+	–	43		207		0.208		2	600	400–500	2.2 to 1.0 mya
K	S	–	+	+	[redacted]	34		165		0.206		2	600	300–500	3.5 to 3.3 mya
L	S	–	+	+	–	30		158		0.190		2	600	375–550	4 to 2.7 mya

Note: Abbreviations are defined in the Appendix. Fields in the CL for N, A, and K are blacked out because there are no canine teeth present in the specimens.

Figure 2. Student using his fists to estimate cranial capacity of a *Homo erectus* skull.

Figure 3. Students preparing to acquire quantitative measurements of the skulls.

4. Which of your calculations are within the range of the ACC?

   E, G, H

5. What could you do to get your CCC value closer to the actual value?

   Use better/more accurate measuring tools than your fist.

The final part of data organization consists of completing Figure 4 to illustrate the shift of the foramen magnum toward the center of the skull during the course of hominin evolution. Students will

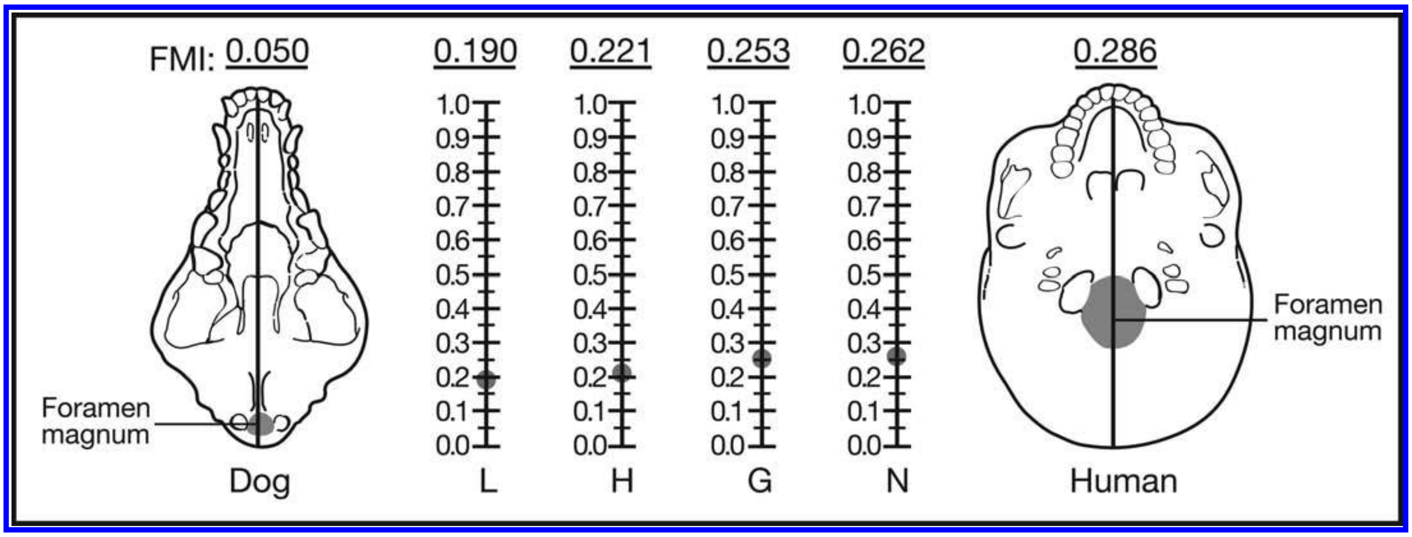

Figure 4. Visualization of the shift of the foramen magnum in hominin evolution as compiled by students' foramen magnum index (FMI) assessments.

compare their FMI assessments for four representative hominin species with that of a familiar quadruped (dog) and the modern bipedal human. We chose four skulls from different time periods to illustrate the change in FMI over time. The FMI value of 0.286 for the "Human" in Figure 4 is based on the perfectly bipedal *Homo sapiens* skull "S" in this activity and, thus, it is inferred that the closer the FMI is to 0.3, the better adapted a species is to bipedal walking.

Once students have plotted their data in Figure 4, they will then engage in data analysis using inquiry-based questions that lead to a deeper understanding of the role of FMI in the evolution of bipedalism in hominins:

1. Examine the FMI graph. Do you notice any trend in the FMI as you look from left (dog) to right (human) among the hominin skulls? If so, describe it.

   Trend is increasing toward 0.3.

2. Determine which of the skulls in this graph is the oldest by looking at the Geological Time Scale graph (Figure 1). Now compare the FMI of this oldest species to that of the dog and the human. Do you think that this species walked on two legs or four? Why?

   Acceptable answers would be "bipedal" or "partially bipedal," as long as the student provides adequate reasoning for the answer (e.g., lower than the FMI value for human, but not as low as that of the dog).

3. Which of the four species (L, H, G, or N) is best adapted to upright walking? Why?

   N, because the FMI is 0.262, which is close to the modern human.

4. One of the species in the graph (L, H, G, or N) walked on two legs, but not in the same perfectly upright manner that today's humans do. Which one do you think it is? Why?

   L (Lucy) with the lowest FMI of 0.190.

○ Data Analysis

To illustrate how cranial capacity and the central location of the foramen magnum evolved in hominins, students will plot those

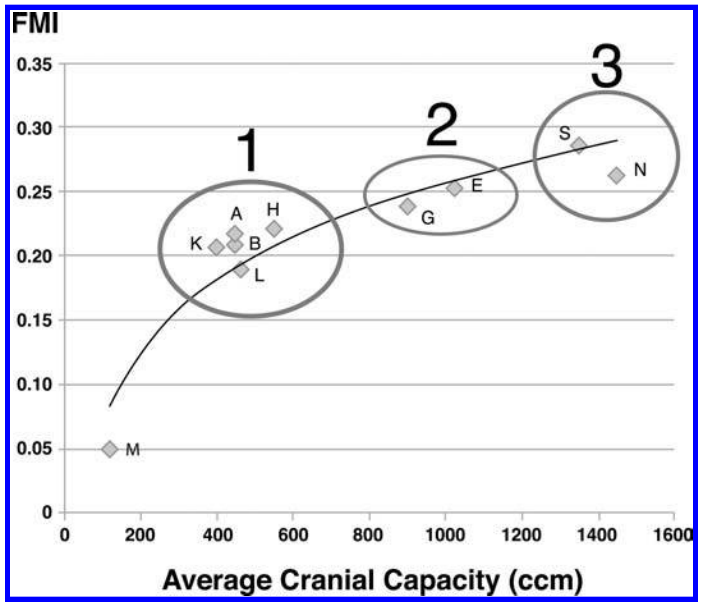

Figure 5. Graph of foramen magnum index (FMI) and average cranial capacity, showing the relationship between the shift of the foramen magnum (estimated by FMI) and increased cranial capacity during hominin evolution.

two parameters in the graph of FMI and average cranial capacity (Figure 5). For this exercise, the student version includes a graph that is prepopulated with one data point, M, which represents the macaque, an Old World monkey species that plays the role of a place holder for the dog we used for the FMI graph (Figure 4). We did this mostly because dogs' cranial capacity varies enormously among breeds. Macaques are quadrupedal and also spend a lot of their time on the ground; thus, their foramen magnum is far to the back of their skull, similar to that of a dog. Students will use the class average FMI and average cranial capacity (based on the range of actual cranial capacity, ACC) for their graph (Figure 5), and then draw a best-fit curve to illustrate the trend in FMI and cranial capacity across all species. Students are next encouraged to further analyze the graph with the following series of questions and instructions:

1. Excluding the macaque (M), group the nine species into three clusters of two or more points that are near each other. Draw a circle around each cluster and list the letters for each of these clusters.

   Cluster 1: A, B, H, K, L; cluster 2: E, G; cluster 3: S, N.

   Note: *These clusters are relatively robust across different classrooms because they are heavily based on the ACC, not the students' fist estimates.*
2. Comparing cluster 1 (with 5 data points) to M (macaque), which variable accounts for the major difference between them, FMI or cranial capacity?

   FMI.
3. Using the Geological Time Scale graph as a reference, list the three clusters in order of their relative age:

   Cluster 1 is older than cluster 2, which is older than cluster 3.
4. As you look from oldest to most recent cluster of hominin species, which factor (FMI or cranial capacity) changed more?

   Cranial capacity.

○ Putting It All Together

In this final part of the activity, students will combine their results with data that scientists have collected. Specifically, the ultimate goal of this investigation is to have students place the nine skulls that they studied in a basic phylogenetic tree that shows how all these hominins are related to each other, and how paleanthropologists concluded that they have evolved (Klein & Edgar, 2002; Prothero, 2007). This phylogenetic tree (Figure 6) contains many more species than the nine that were part of this activity to illustrate the diversity of species during hominin evolution (Sawyer et al., 2007). All the hominins are correctly placed with regard to their ages and labeled with their scientific names. The students' task is to fill in the Skull Letter Codes from their nine skulls into the correct gray-shaded squares, utilizing the various pieces of information available to them such as the Geological Time Scale, skull shapes, etc. Their collected and analyzed data should also be taken into consideration when making the final determination. Once all gray-shaded squares have been filled in, the identity of the nine skulls can be entered in the Master Data Table (Table 2). In the final analysis of their data, students are asked to scrutinize the available data with a set of questions that promotes critical thinking and culminates in a synthesis of the importance of the characteristics of the skulls that they have investigated.

1. According to the phylogenetic tree, what is the greatest number of hominins that coexisted?

   5.
2. List the names of these species (your answer may include species that were not represented by skull specimens in this investigation).

   Homo rudolfensis, Homo ergaster, Homo habilis, Paranthropus boisei, Paranthropus robustus.
3. What is the approximate period during which these multiple species coexisted?

   1.9–1.8 mya (but anything between 2.0 and 1.7 mya will do).
4. Based on your FMI–average cranial capacity graph, what were the driving forces in hominin evolution?

   FMI or, more specifically, the movement of the foramen magnum toward a more forward position in favor of bipedalism AND the increase in cranial capacity.
5. According to the phylogenetic tree, which species is the oldest ancestor of *Homo sapiens*?

   Sahelanthropus tchadensis.
6. Looking at the oldest fossil in the tree and based on the evidence you collected during this investigation, which of the nine species that you studied would you predict is most similar to this old hominin with regard to cranial capacity?

   Kenyanthropus platyops (K), with the lowest cranial capacity of the nine skulls.
7. And with regard to FMI?

   Australopithecus afarensis (L), with the lowest FMI of the nine skulls.
8. Does the phylogenetic tree support your hypotheses?

   Yes.

   Note: Both species are very old and low on the hominin evolution tree, so they are to be expected to have a rather low FMI and cranial capacity according to the trends discussed in the interpretation of the FMI–average cranial capacity graph. *Australopithecus afarensis* (L) is the oldest species studied in this activity, and its FMI is also the lowest, as expected. The cranial capacity is a little bigger than that of *K. platyops* (K), even though the latter appeared later in hominin evolution. However, *K. platyops* seems to be a branch that resulted in a dead end, whereas *A. afarensis* seems to have existed longer and given rise to more modern hominins.
9. Go back to the FMI–average cranial capacity graph that you completed earlier. Place a mark (use a big "X") on the best-fit curve for *Sahelanthropus tchadensis*. Explain your reasoning for the placement of your X in the graph.

   Note: *The "X" should be placed anywhere on the best-fit curve between the datapoint M (macaque) and Cluster 1, but closer to Cluster 1 than to M because Sahelanthropus is considered a hominin (or close to the last common ancestor of humans and chimpanzees), with a cranial capacity of 350 ccm and an FMI of 0.17 (measured by the authors in the described way using Bone Clones skull BH-029).*

After checking with their teacher to see if they have correctly named the skulls, congratulations are in order for solving the Mystery of the Skulls!

○ Teacher Implementation Suggestions

A nice way to conclude this activity is to go back to the skull replicas and have the students create a tree by laying them out in roughly chronological order and on a scale where 1 m represents 1 million years. The entire class may participate and engage in discussions as to how the tree of skulls should look, thereby revisiting what they learned in this activity. This would also be the time for a teacher-guided discussion on evolution of hominins or primates in general.

Human evolution is a topic that teachers tend to avoid or dread teaching, and students often object to it because of their own

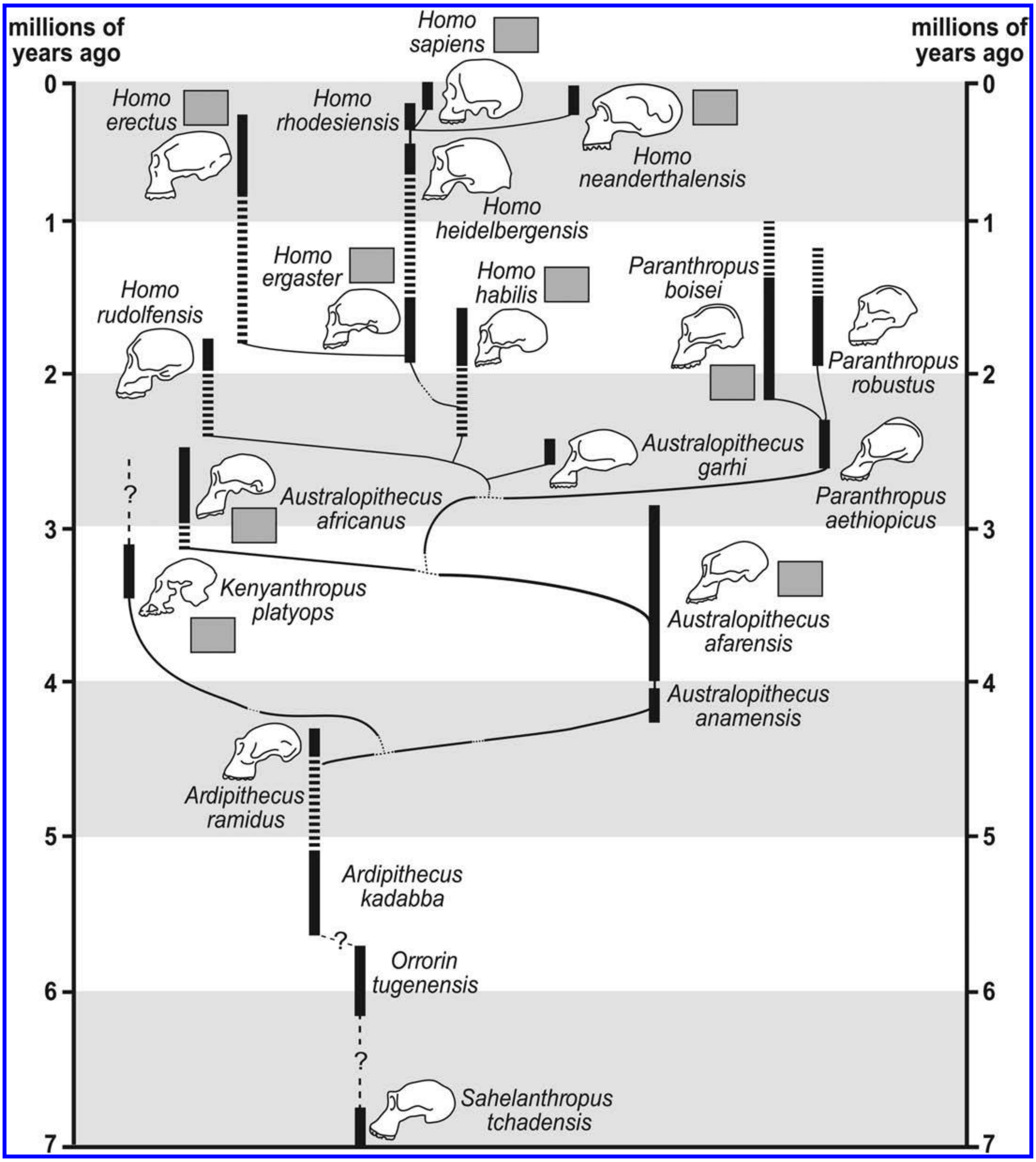

Figure 6. Students' version of the hominin phylogenetic tree. Solve the Mystery of the Skulls by filling in the correct letter codes!

misconceptions that are commonly rooted in religious beliefs. Our experience with this activity has been that students are willing to accept humans as organisms that have evolved when they can touch and compare skulls of different hominin species. Furthermore, they are more open to accepting conclusions that they have reached on their own through inquiry, rather than passively being presented with the "correct" answers. This *CSI* approach to teaching evolution feeds into the young minds' inquisitive nature and its success is evidenced by the popularity of the "skull kits" in the CIBT lending library. With the addition of this activity, teachers are inspired and willing to take the challenge of teaching human evolution head-on – as a consequence, this kit went from "collecting dust" to now being in constant use by teachers across New York State and beyond, so much so that we added two more skull kits to satisfy the demand.

○ Acknowledgments

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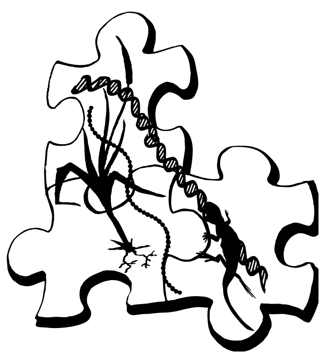

Appendix. Skull Assessment Guide: detailed explanation of the semiquantitative and quantitative measures that students are asked to take for each skull.

FL - Forehead Length: Look at the front of the skull and determine if the forehead is Long (L) or Short (S). The forehead is roughly the area from the top of the eye socket to the part of the skull that begins to flatten. Visualize your own forehead and imagine the part between your eyebrows to where your hairline begins. This is the forehead. If this length is at least the length of the average thumb, we consider it to be Long (L) (Figure 7).

SC - Sagittal Crest: Look at the top of the skull and determine if a sagittal crest is present (+) or absent (–). A sagittal crest is a ridge of bone that protrudes from the skull and runs on top of the skull from front to back (Figure 8).

BR - Brow Ridge: Look at the front of the skull and determine if a brow ridge is present (+) or absent (–). A brow ridge is a bone that runs the entire width of the skull just above the eyes (see arrow in Figure 8).

P/S - Prognathism/Snout: Look at the front of the skull and determine if it exhibits prognathism (+) or not (–). Prognathism refers to the protrusion of the mouth from the front of the skull. Animals with prognathism are thought of as having a 'snout'. To determine if a skull exhibits prognathism, press your fingers along the base of the nose opening (Anterior Nasal Spine) and rest it on the top of the maxilla (where the top teeth attach). If this area is greater than 1 index finger in width, then we consider the skull to exhibit prognathism (Figure 9).

L - Canines Long (and sharp): Look at the teeth in the top of skull and determine if the canines are long and sharp (+) or (–). The canines are sometimes referred to as 'fangs'. They are the third pair of teeth from the front – in your mouth, your 2 front teeth and the next one in each direction are called 'incisors'. The next tooth on either side is slightly pointy and called 'canine', but in many animals, like dogs and cats, these canines are very long and sharp. If the canines are not present in the skull, the cell in the table has been blackened out. If you notice that the canines are 'fang-like', we consider them to be long and sharp (+).

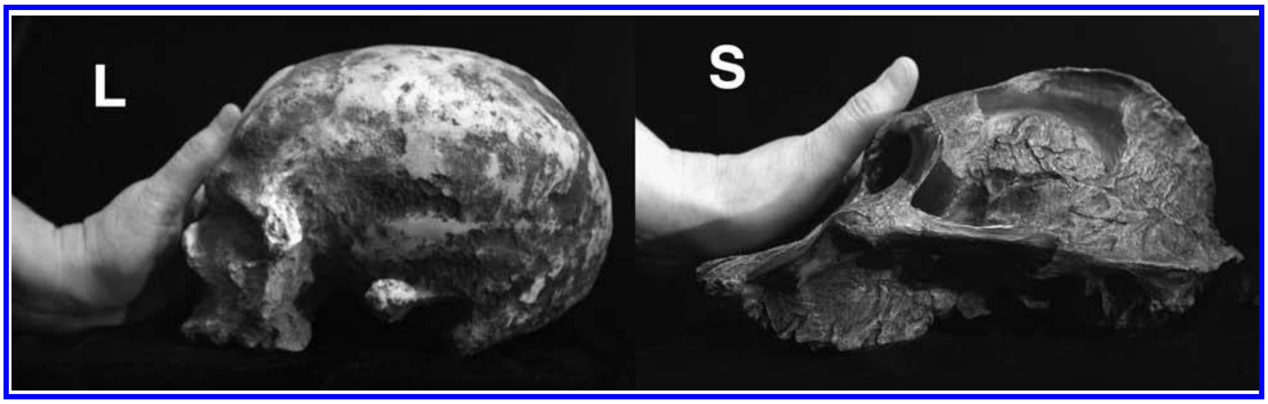

Figure 7. Forehead length.

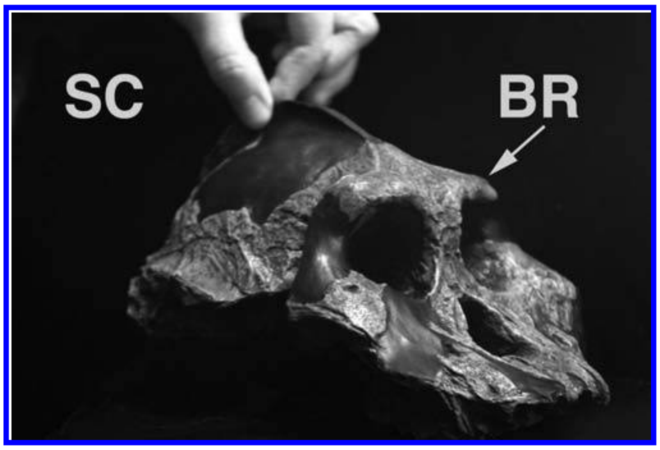

Figure 8. Sagittal crest and brow ridge.

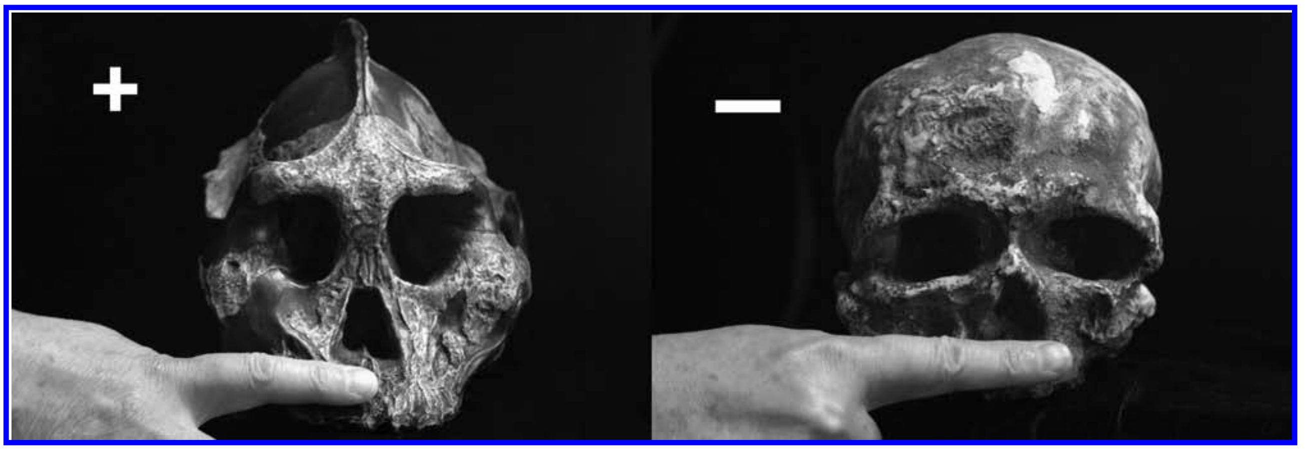

Figure 9. Prognathism/snout.

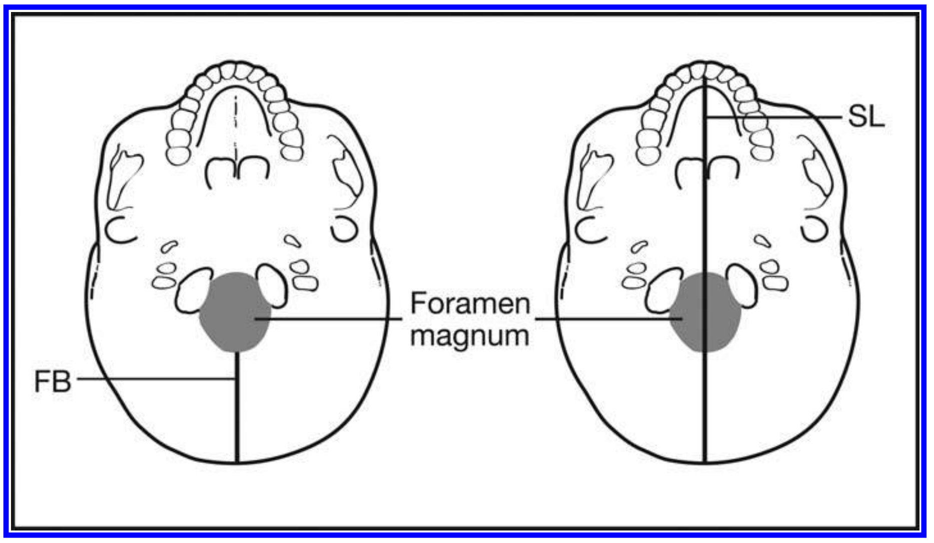

Figure 10. Foramen magnum distance to back (mm).

FB - Foramen Magnum Distance to Back (mm): Look at the underside of the skull and determine the distance between the foramen magnum and the back of the skull (measured in mm). The foramen magnum is the hole in the skull through which the spinal cord attaches to the brain. To determine this distance, place a ruler on the base of the skull, starting at the back most edge of the foramen magnum and measure the distance to the end of the skull (see Figure 10). Be sure to demonstrate this measurement to your students.

SL - Skull Length (mm): Look at the underside of the skull and determine the length of the skull (measured in mm). Place a ruler on the base of the skull (see diagram below) and measure the distance from the back of the skull to the end of the palate (roof of the mouth). Be sure to demonstrate this measurement to your students.

FMI - Foramen Magnum Index: Calculate the ratio using the Foramen Magnum Distance to Back (FB) and the Skull Length (SL). To do this for each skull, divide the value that you recorded for FB by the value that you recorded for SL, and fill in the corresponding box to the 3rd digit after the decimal point.

CC - Cranial Capacity: Look at the skull from the top and sides and estimate the number of average fists that would fit inside the cranium (the area of the skull where the brain is located). For these skulls, limit your estimate to 2, 3 or 4.