STUDENT GUIDE

Building the skeleton of your shark's cranium and jaws

Text and images by Aaron M Olsen, PhD

Description

In this module, you will identify the skeletal cartilages that make up the cranium and jaws of the spiny dogfish shark (*Squalus acanthias*) and figure out how they fit together by building a 3D model of the skull.

Introduction

If you've ever watched a nature documentary featuring sharks, you've seen the quintessential shot of a shark breaching the surface of the water, jaws gaping wide with row after threatening row of razor edged teeth to engulf some prey.

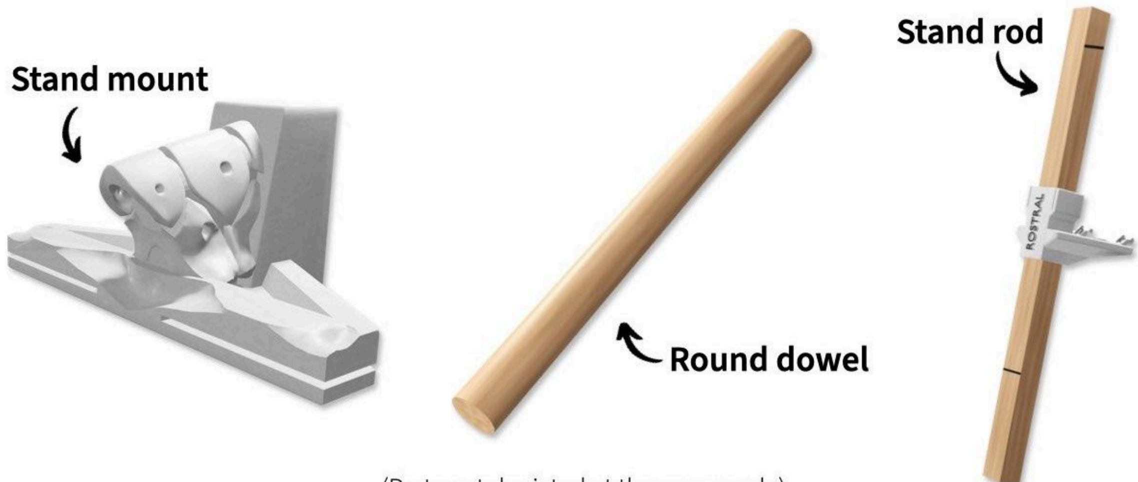
A white shark (*Carcharodon carcharias*) feeding at the surface by Fallows, Gallagher, & Hammerschlag 2013 and licensed under CC BY 2.5.

If you thought it looked like the shark was shooting its jaws out of its skull, you weren't imagining things! Many sharks have the ability to **protrude** their upper and lower jaws forward as they are opening their mouth, allowing them to "reach" their jaws toward their prey to take a bite (Wilga & Motta 1998). How is it possible for sharks to do this? In this module, you will figure out for yourself by building the skeleton of a shark skull, using your model spiny dogfish shark.

Materials needed

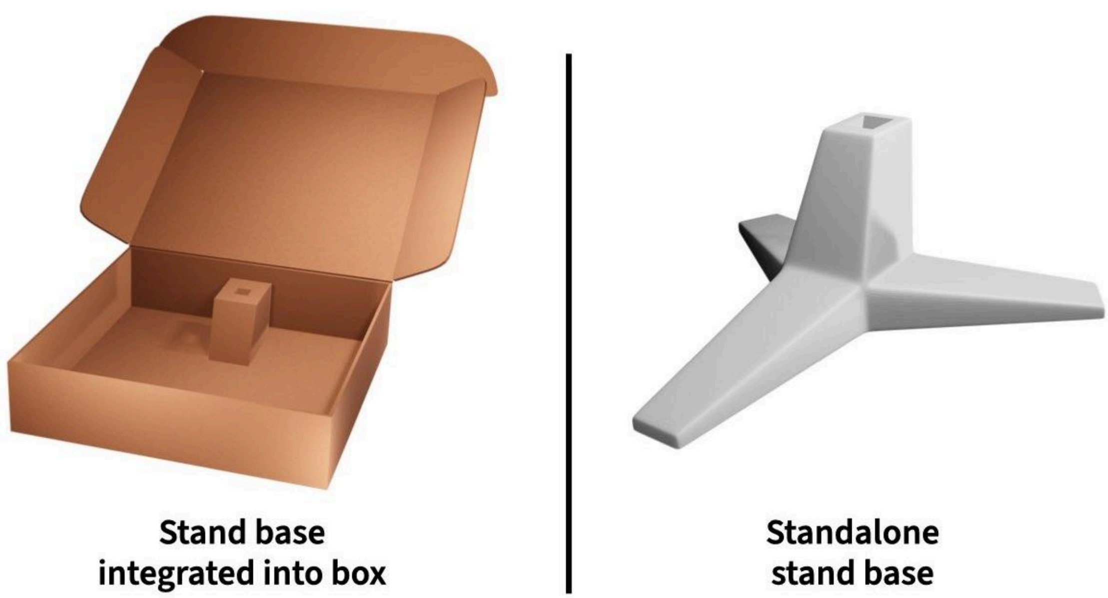
For this module, you'll need:

- The **Student Notebook** for this module (SA01).
- The following pieces from your kit:



(Parts not depicted at the same scale)

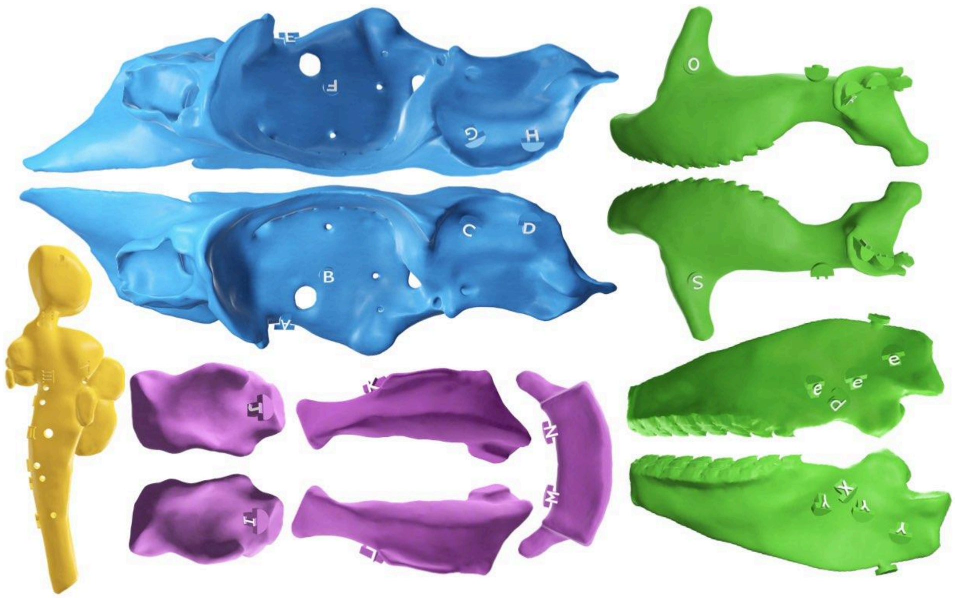
- The stand base from your kit. This could either be the box itself (for kits with the stand base integrated into the box) or a standalone 3D printed piece:



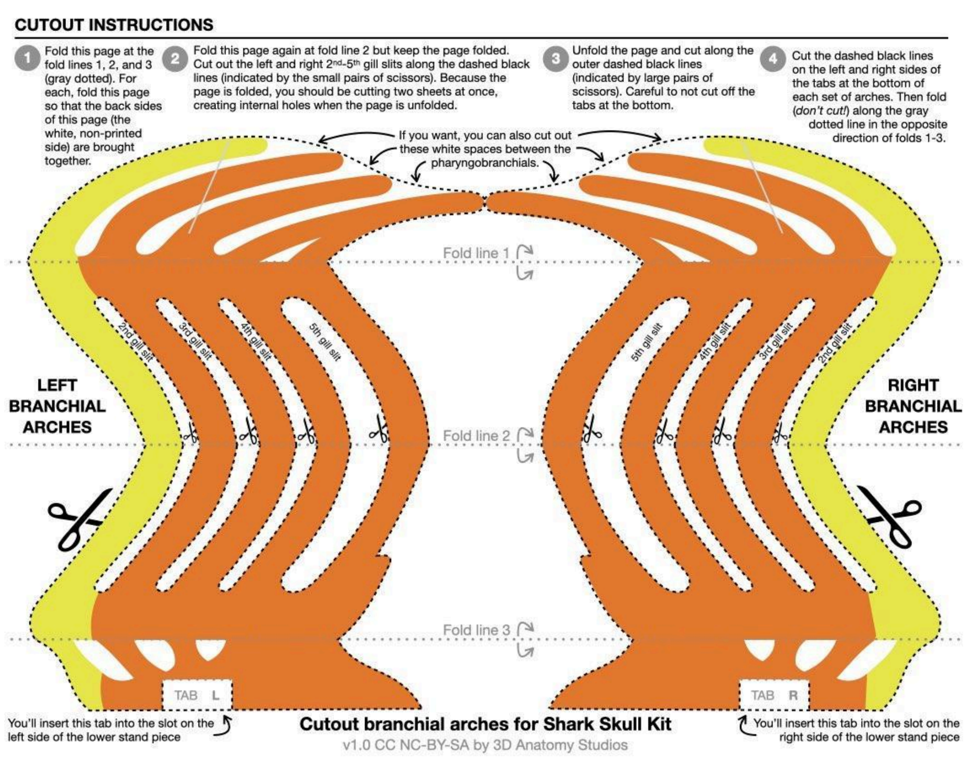
(Parts not depicted at the same scale)

Materials needed (continued)

- The following 3D printed pieces from your kit (you don't need to get them all out yet):



- The **left and right branchial arches** from your kit. If the branchial arches are not yet cut out, follow the instructions on the sheet to fold and cut them out.



- "Office" scissors for cutting out the branchial arches (if not already cut out)

BUILD NOTE: Those hooks with letters

Each of the 3D printed pieces in your kit has small hooks and pegs with raised letters on them. You'll use these in other modules to attach muscles (rubber bands) and ligaments (ribbons) but in this module they'll just help you to identify the pieces. These raised letters may be white or black in the images for easier visibility but they are the same color as the piece on the actual 3D printed pieces.

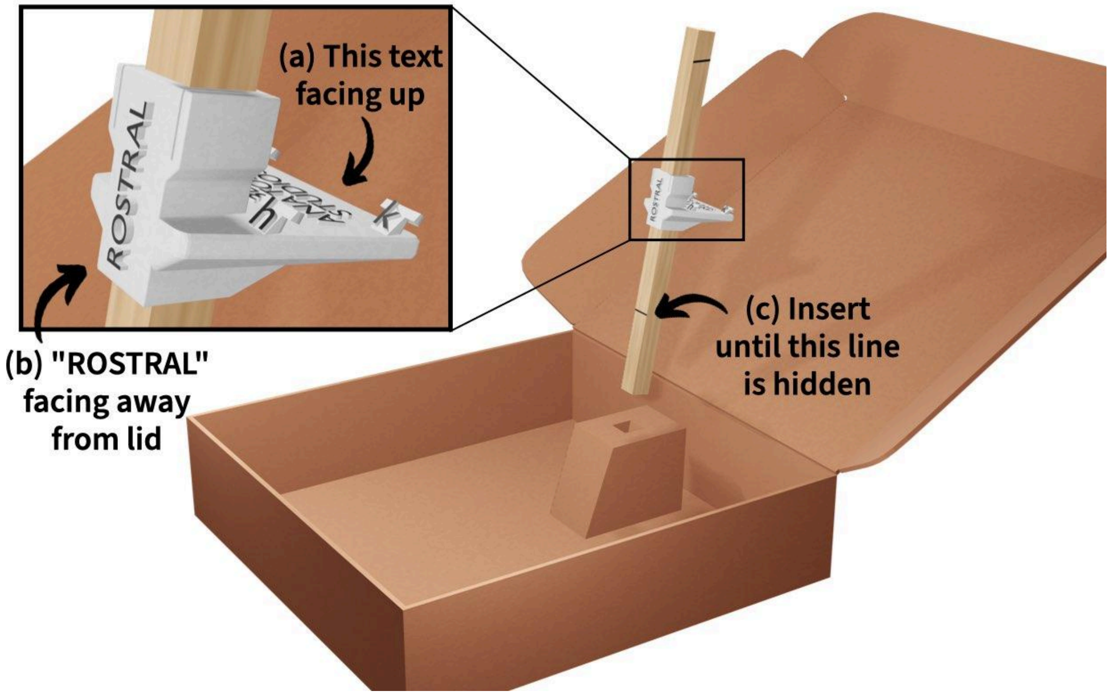
Preparing the stand

Before you start building, you'll need to prepare the stand that will hold your shark to free up your hands for building. In your kit, find the stand rod; it's the wooden square dowel rod with a 3D printed "shelf" in the middle (see image to the right).

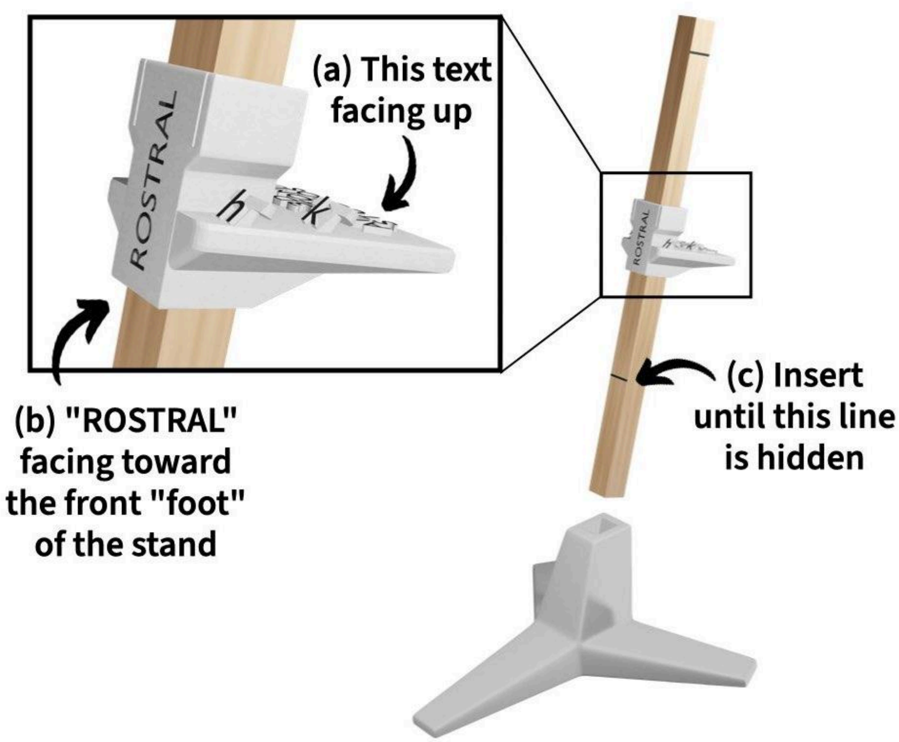
Insert the rod into the stand base as shown in the images on the next page (choose the image corresponding to the type of base your kit has). It may take a bit of force. Be sure to:

(a) orient the rod so that the "3D ANATOMY STUDIOS" text on the shelf is facing up,
(b) insert the rod into the base so that the "ROSTRAL" text is facing in the direction indicated in the image,
(c) and push the rod down into the base until the line is hidden within the base.

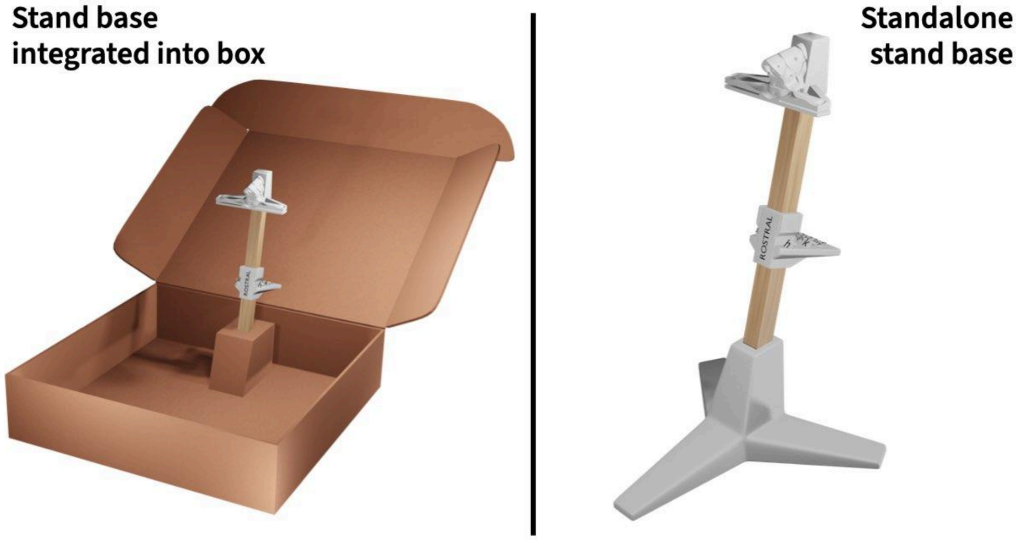
Inserting the stand rod with the box-integrated base



Inserting the stand rod with the standalone base



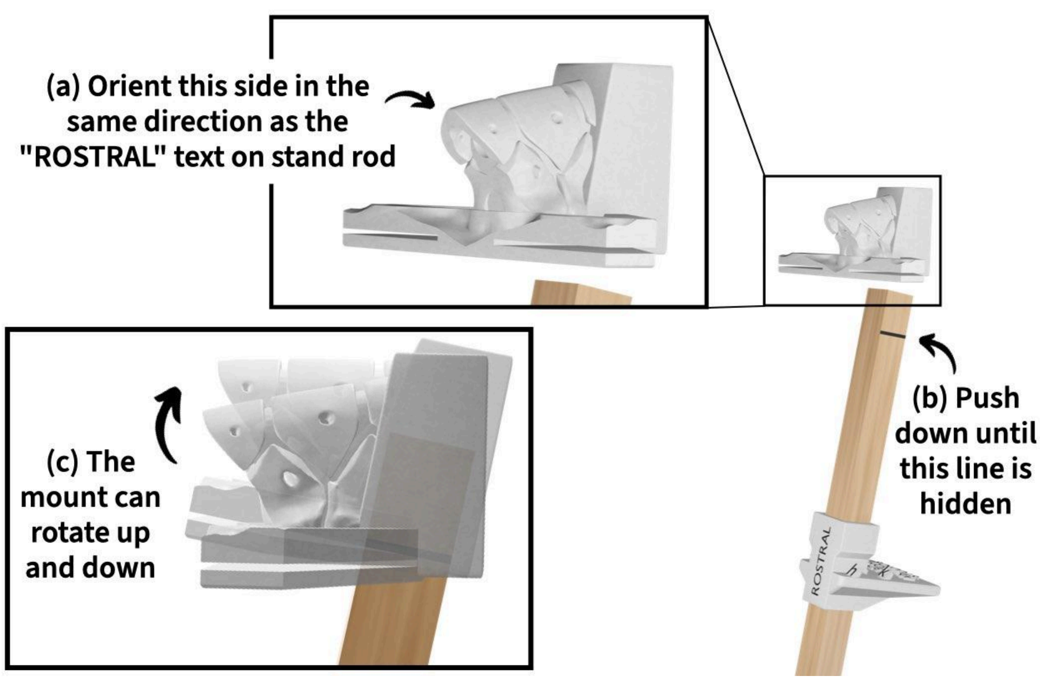
Once you've inserted the stand rod, it should look like the image below.



Fully inserted stand rod
(Parts not depicted at the same scale)

Next, find the stand mount (see right). Push the stand mount onto the rod as shown in the image below. As you do, be sure to:

(a) orient the part with the vertebrae rostrally,
(b) push the mount until the line is hidden,
(c) and not worry that the mount can rotate up and down - it's supposed to do that.



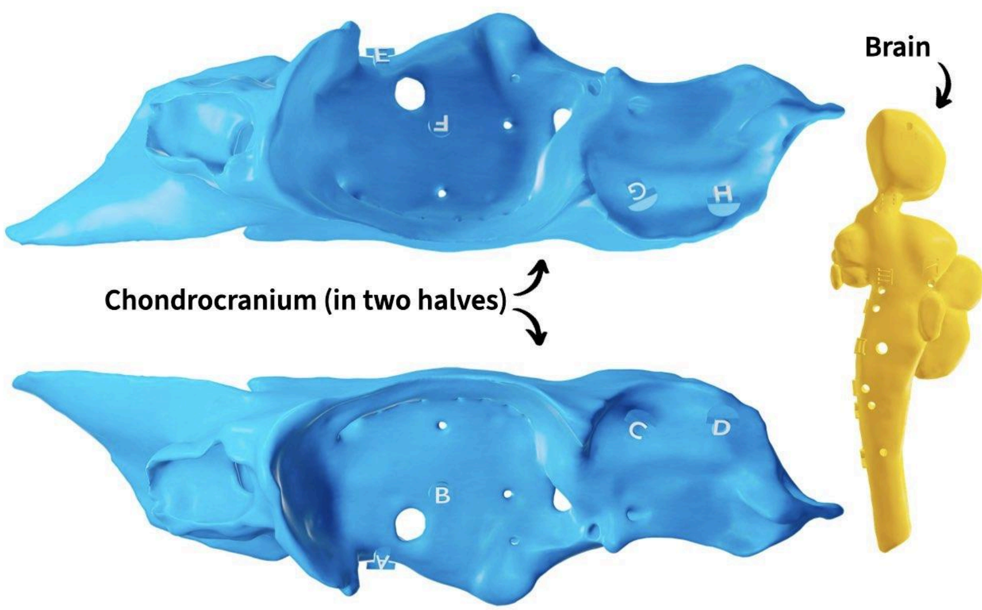
Section 1. What is the anatomical orientation of the chondrocranium and brain?

One odd thing you may have noticed about sharks is that their skeletal elements are referred to as **cartilages** rather than *bones*. This is because over the course of their evolution, sharks have lost nearly all of their bony tissue and, in its place, they've evolved specialized types of flexible and resilient cartilage (Dean & Summers 2006). This includes the skull, which is made up of various cartilages split into two groups: the **chondrocranium** and the **splanchnocranium**.

The chondrocranium (meaning, "cartilaginous skull"), also known as the **braincase**, *encases* the brain whereas the splanchnocranium, also known as the **viscerocranium**, includes all the cartilages derived from the **gill arches** (all the other cartilages of the skull). The names "splanchnocranium" and "viscerocranium" come from the association between the gill arches and the gut: "viscero-" and "splancho-" both mean intestines in Latin and Greek, respectively. You'll start building with the chondrocranium, since this forms a foundation for the skull.

Orientation of the braincase and brain

In your kit, find the two halves of the chondrocranium and the brain (see the image below).



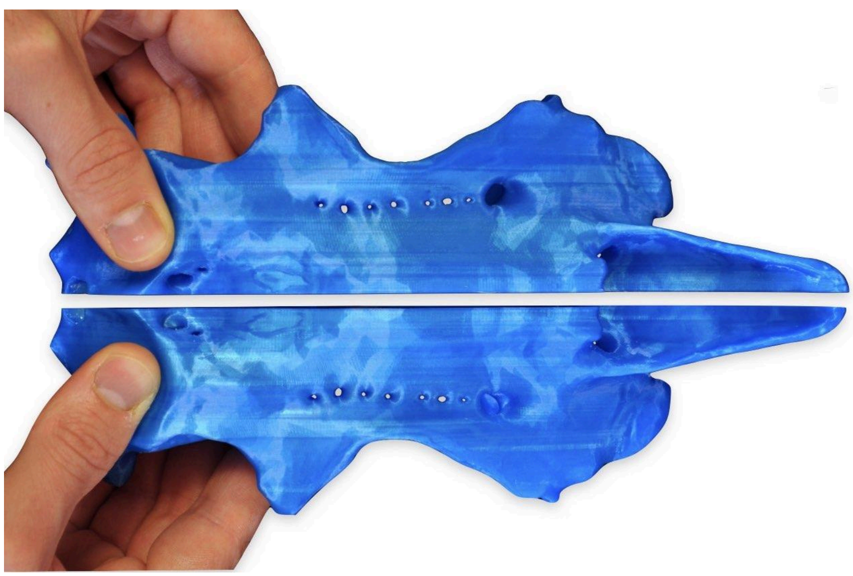
If the two halves of the chondrocranium are not already snapped together as a whole piece, how do they fit together? If you get stuck, use the hint at the top of the next page.

HINT: Find the flat surface

Find the completely flat surface of each half; this is where the two halves fit together.

ASSESS: Braincase made whole

The two halves of the chondrocranium, with the help of embedded magnets, should snap together like in the image below.

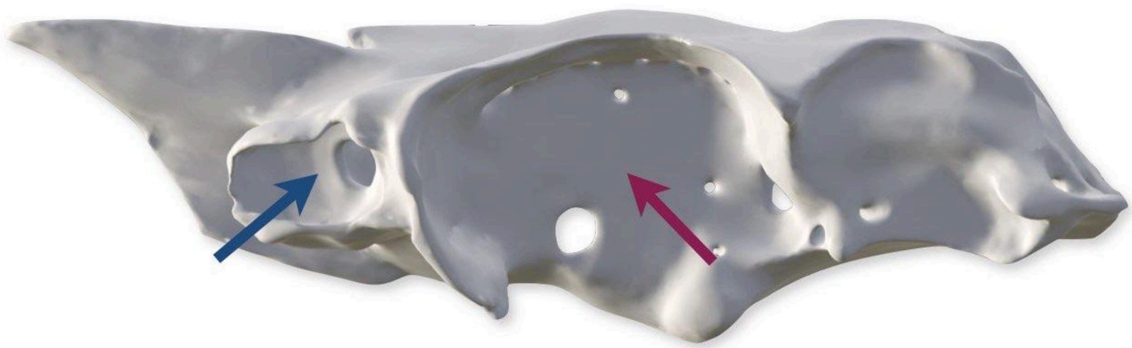


Now that you've solved how the two halves fit together, which end is **rostral** (toward the shark's snout or front end) and which end is **caudal** (toward the tail or back end)? Which side is **dorsal** (the shark's back) and which side is **ventral** (the shark's belly)?

Fill in the blanks on page 1 of your **Notebook** with these directional terms. When you think you've got it correct, use the following three hints to check your work.

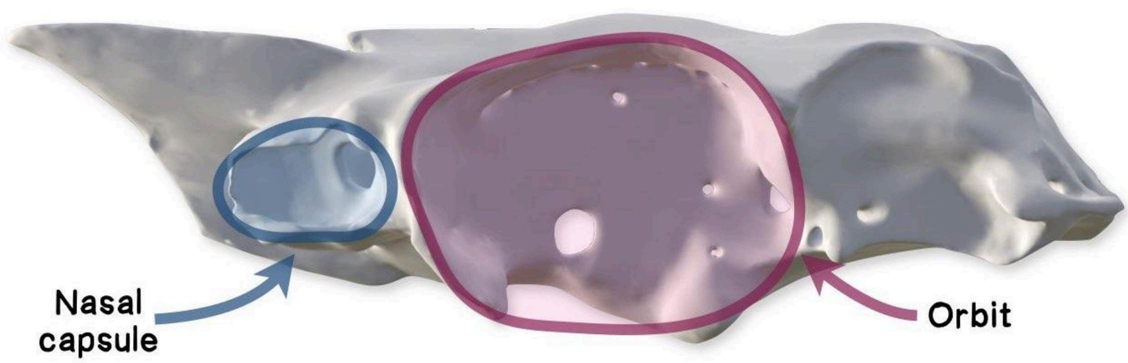
HINT: Where are the nose and eye?

The arrows below show the positions of the **nasal capsule** (which houses the olfactory organ) and **orbit** (which houses the eye). Which do you think is which? Do you need to change any of your answers?



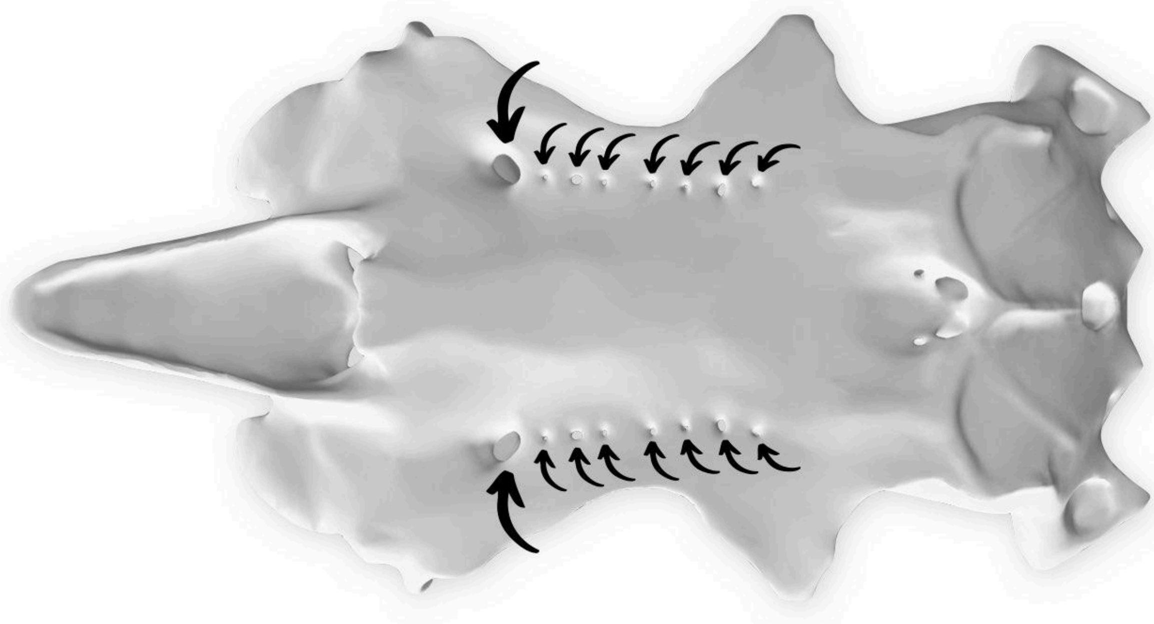
HINT: Nose in front

The labeled arrows in the image below indicate the nasal capsule (more rostral) and the orbit (more posterior). Do you need to change any of your answers?



HINT: Dorsal foramina

The holes indicated in the image below are for nerves that travel out to sensory structures in the skin on the dorsal aspect of the head. Do you need to change any of your answers?

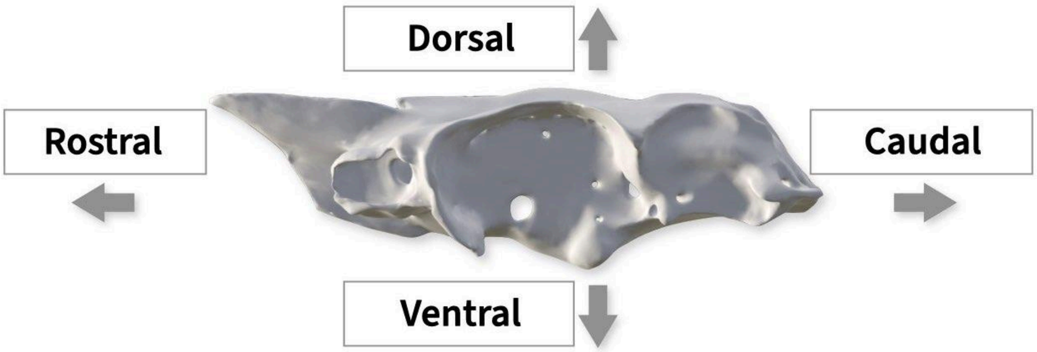


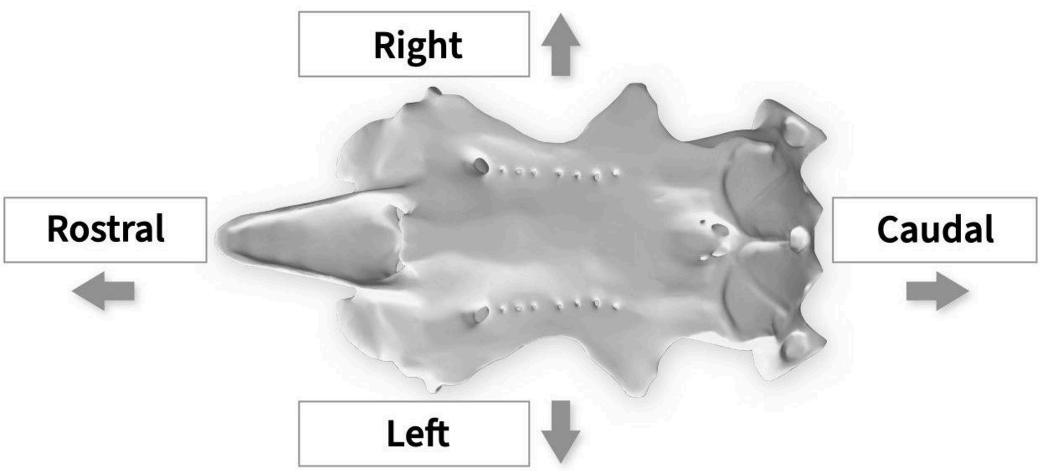
HINT: Determining left vs. right

If you've figured out which ends are rostral and caudal, and which sides are dorsal and ventral, you should then be able to determine which sides are left and right.

ASSESS: Chondrocranium oriented

Compare page 1 of your **Notebook** with the image below to check your work.





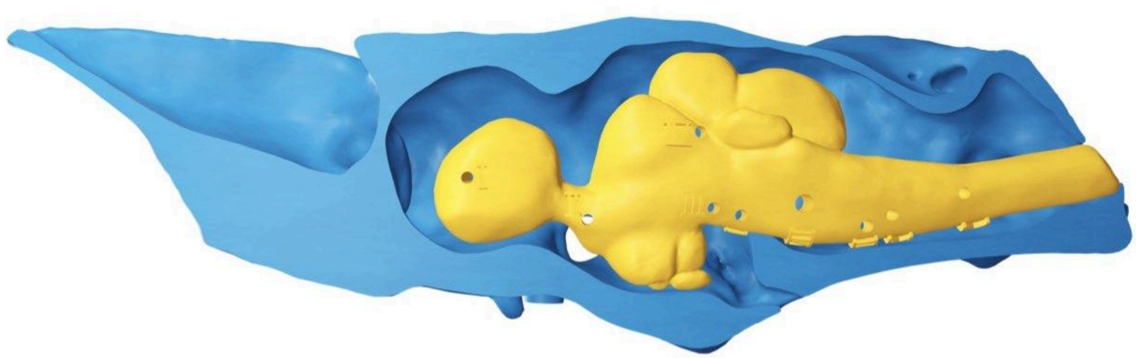
Now that you have the orientation of the chondrocranium figured out, how does the brain sit inside the **endocranial cavity** (the space inside the chondrocranium that holds the brain)? If you get stuck, check out the hint on the following page.

HINT: The braincase encases the brain

If you have the brain properly oriented within the chondrocranium, you should be able to bring the left and right halves together completely with the brain inside.

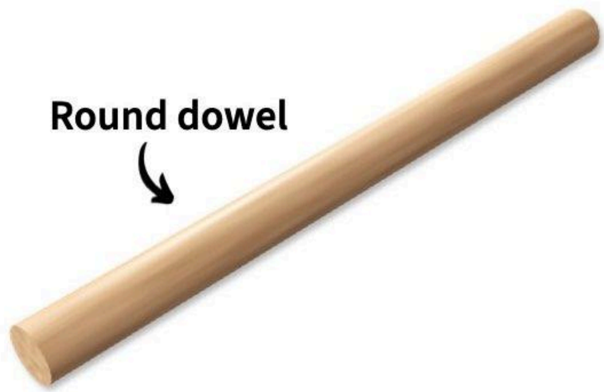
ASSESS: Brain in a case

Your shark's brain should fit inside the endocranial cavity as shown in the image below.



Mounting your brain and braincase

To mount your brain and braincase to the stand, you'll use the round dowel. Find this part in your kit (see the image to the right).



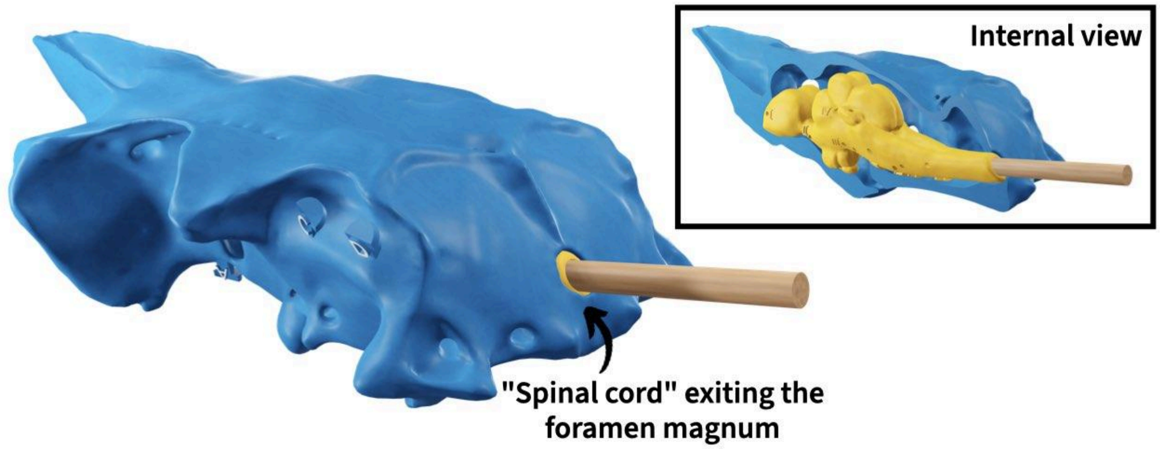
Your round dowel represents a segment of your shark's **spinal cord**, a bundle of nerves that is continuous with the brain but exits the skull to reach the rest of the body. The spinal cord exits the skull via the **foramen magnum** (meaning "big hole") so insert your spinal cord segment (round dowel) through the foramen magnum so that it connects into the brain. Can you find this hole on your chondrocranium? If you get stuck, check the hint below.

HINT: The big hole

The foramen magnum is the largest hole in the chondrocranium that is **unpaired** and at the **midline**, meaning there are not left and right holes (only one) and it is positioned in the middle of the left and right sides of the chondrocranium. You can also use the brain to help you.

ASSESS: Spinal cord inserted

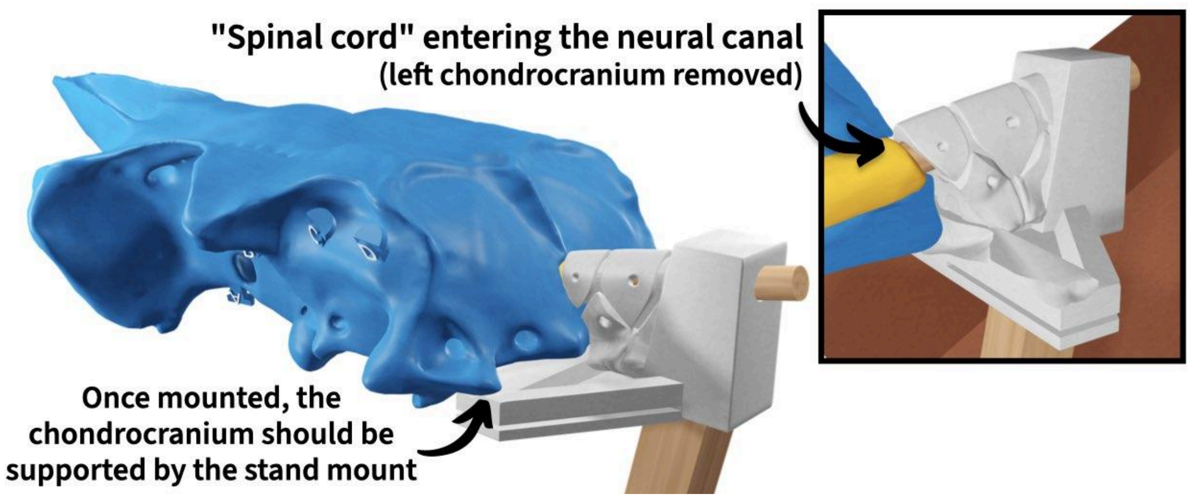
If your spinal cord segment is properly inserted, it should look like the image below.



You may need to “open” the chondrocranium, insert the spinal cord into the brain, and then “close” back up the chondrocranium. Make sure the dowel is fully inserted into the brain.

Once the spinal cord exits the skull, it immediately enters the **neural canal**, a hollow tube within the **vertebral column** that protects the spinal cord. The stand mount has a couple of vertebrae to show the position of the vertebral column relative to the chondrocranium.

Find the neural canal within the vertebrae and insert the spinal cord (plus brain and chondrocranium) as far as you can into the canal as shown in the image below.



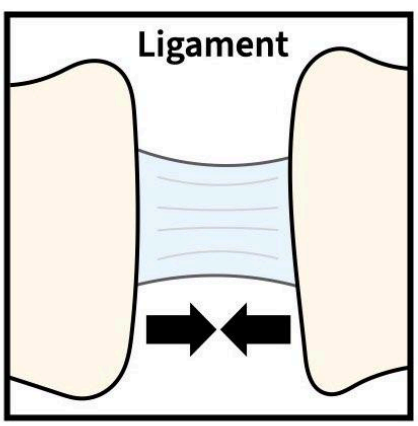
Section 2. What are the shark splanchnocranium cartilages and how do they articulate?

With your stand and braincase prepared, it's time to add your shark's splanchnocranium!

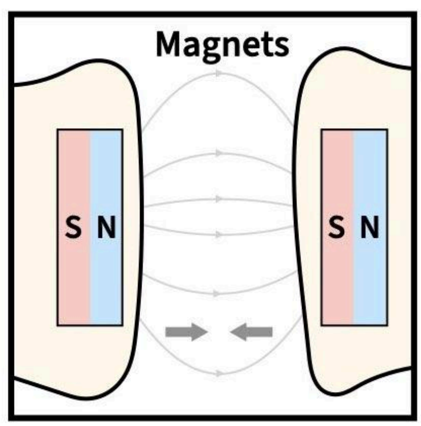
BUILD NOTE: Magnets as ligaments

All the 3D printed components of your splanchnocranium have magnets so that you can easily snap them together. Of course, the cartilages in a real shark skull are not held together by magnets. Rather, they are joined by *over 40* **ligaments**, tough bands of connective tissue that are flexible but not particularly stretchy (think rope).

Each pair of attracting magnets in your 3D printed splanchnocranium pieces corresponds to one or more ligaments in the actual spiny dogfish shark skull, giving your model structure and mobility similar to the real thing. However, there are a few key differences you should be aware of in making comparisons between your model and a real shark:



- *Much* stronger than magnets
- Produces a tensile force only when taut (pulled tight)

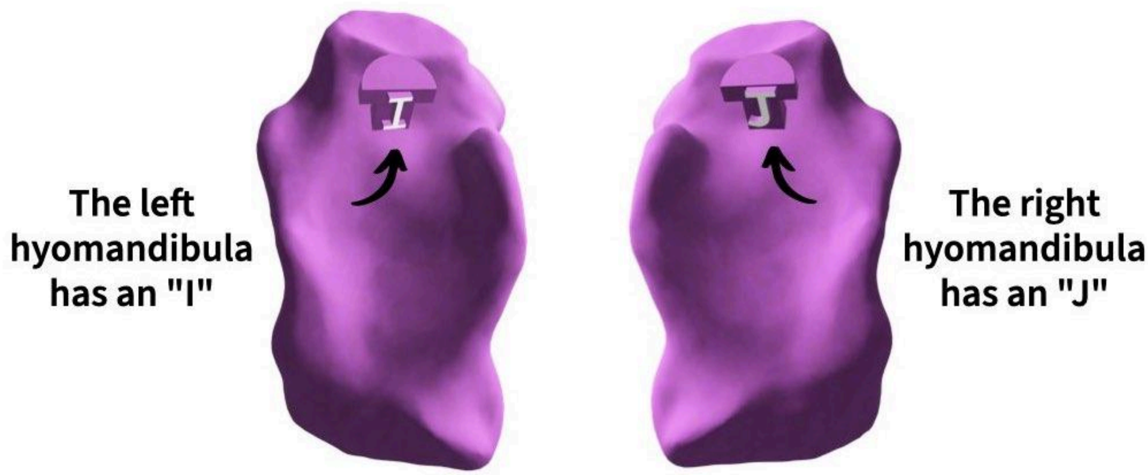


- *Much* weaker than a ligament
- Consistently produces an attractive force that decreases in strength with distance

Given that magnets are *much* weaker than ligaments, your model's cartilages will detach from one another much more easily than if they were joined by ligaments.

Adding the hyomandibular cartilages

The first splanchnocranium elements you'll add are the **hyomandibular cartilages** (also called the **hyomandibula**, singular, and **hyomandibulae**, plural). Find these in your kit; they're the stubby pieces and are purple if your kit is color-coded.



To distinguish the left versus right hyomandibula, use the letters printed on the small hooks: The left hyomandibula has the letter "I" (as in the first letter of "Intestine") and the right hyomandibula has the letter "J."

Can you guess approximately where they attach to the chondrocranium? Don't worry about the orientation, just their position. If you get stuck, see the hint below then check your work on the next page.

HINT: Think about the name

The name "hyomandibula" combines portions of the words **hyoid** and **mandible** because the hyomandibula articulates with:

- hyoid elements (elements that support the throat) and
- mandibular elements (elements of the jaw)

What might this tell you about the position of the hyomandibula along the **rostrocaudal axis** (the body axis running from rostral to caudal)?

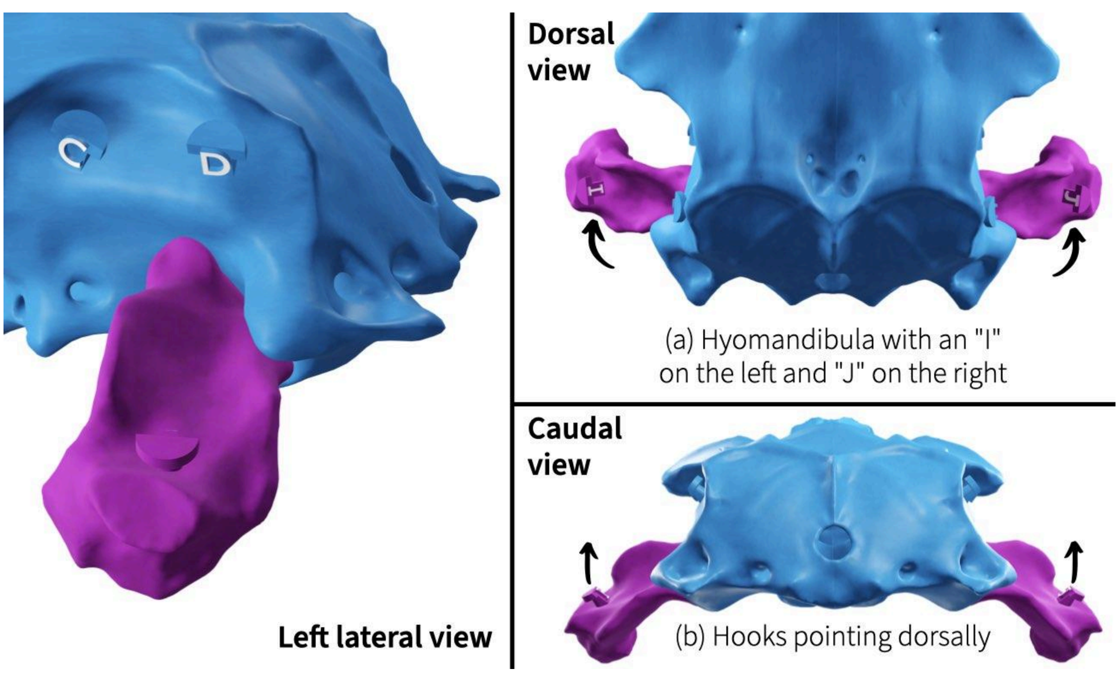
ASSESS: Hyomandibulae articulated

If you guessed that the hyomandibulae attach at the position shown below, you guessed correct!

By attaching at a caudal position on the chondrocranium, the hyomandibulae are able to articulate with elements of both the throat and mandible.

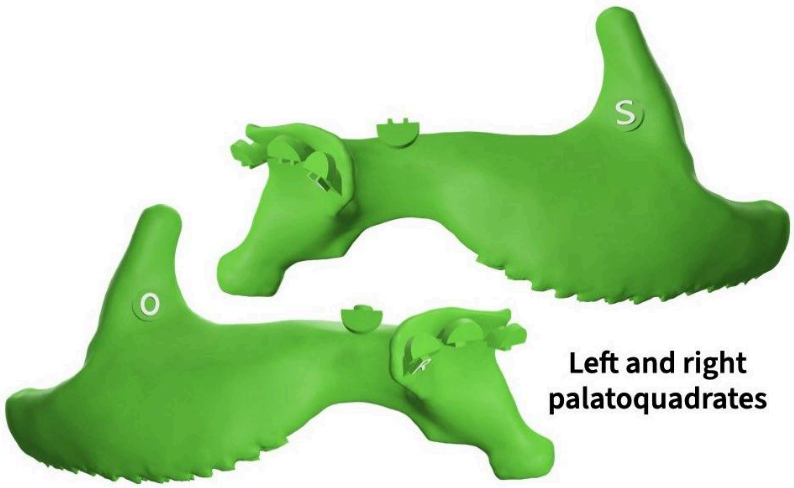
Attach the hyomandibulae as shown in the image below, making sure:

(a) to attach the left hyomandibula (hook with an "I") on the left and the right hyomandibula (hook with a "J") on the right
(b) and that the hooks are pointing dorsally.



Adding the upper jaws

Next you'll add the upper jaws. In sharks, this element is called the **palatoquadrate** because it is a fusion of a palatal bone (the epipterygoid or, in mammals, the alisphenoid) and the quadrate (the incus bone in mammals). Find the left and right palatoquadrates in your kit (don't worry which is which yet) using the image below to help you. The palatoquadrates have teeth and, if your kit is color-coded, they're green.



Left and right palatoquadrates

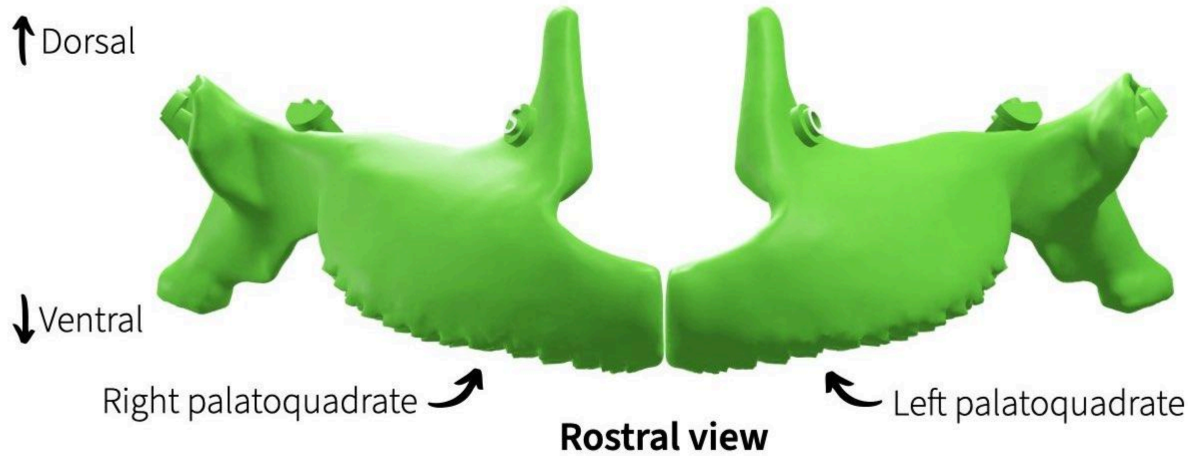
Can you figure out which piece is left versus right? If you need help, see the hint below then check your work on the next page.

HINT: Form continuous tooth rows

Snap the two palatoquadrates together so that the teeth form continuous rows. Knowing that these are the *upper* jaws, how would these two elements (snapped together) be oriented relative to the chondrocranium?

ASSESS: Palatoquadrates oriented

If you identified left versus right as shown in the image below, you're correct!



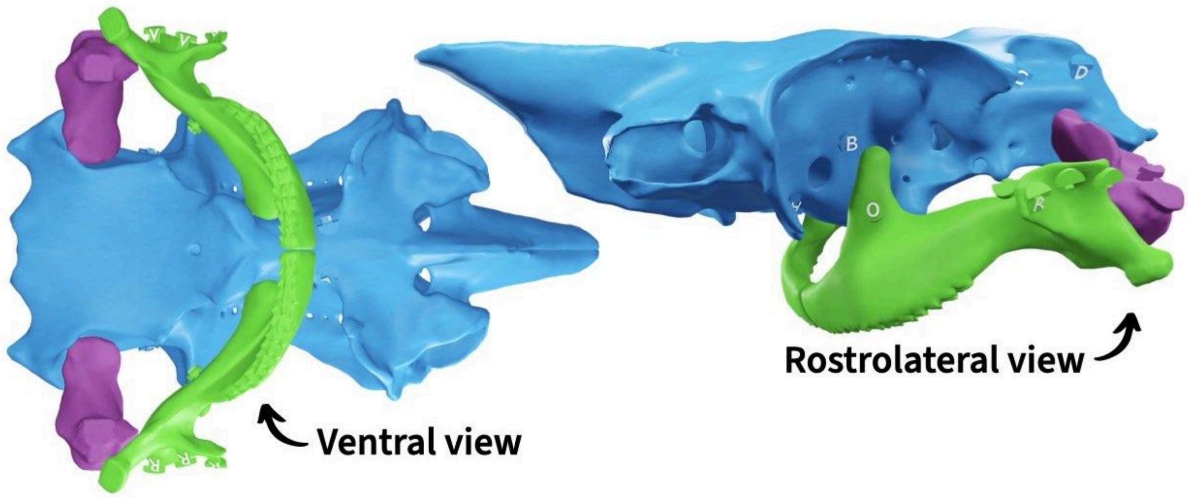
Now that you know the proper orientation of the palatoquadrates, can you add them to your skull? See the hint below, if you need help, and check your work on the next page.

HINT: A hyomandibular connection

Besides articulating with each other at the midline, each palatoquadrate also articulates with both the chondrocranium and the **ipsilateral** hyomandibula ("ipsilateral" means on the same side). Your model has magnets for both of these articulations.

ASSESS: Palatoquadrates articulated

If you added the palatoquadrates as shown in the image below, nice work!



Adding the lower jaws

To complete your jaws, you'll next add the lower jaws or **mandibles**. In sharks, the left and right mandible are each composed of a single element, **Meckel's cartilage**, named after anatomist Johann Friedrich Meckel, 1781-1833. Although he made valuable contributions to the field of anatomy, Meckel was also one of several anatomists of his time who drew inaccurate, biased, and racist conclusions from dissections of Black people. These conclusions were used to perpetuate chattel slavery, the slave trade, and the inferior treatment of Black people (Gates & Curran 2021). For this reason, and for consistency with the naming of all the other cartilages of the skull, these modules will use the terms "mandible," "mandibular cartilage," or "lower jaw" instead of "Meckel's cartilage."

Find the left and right mandibles in your kit (don't worry which is which yet) using the image below to help you. The mandibles are the remaining pieces with teeth and are green, if your kit is color-coded.

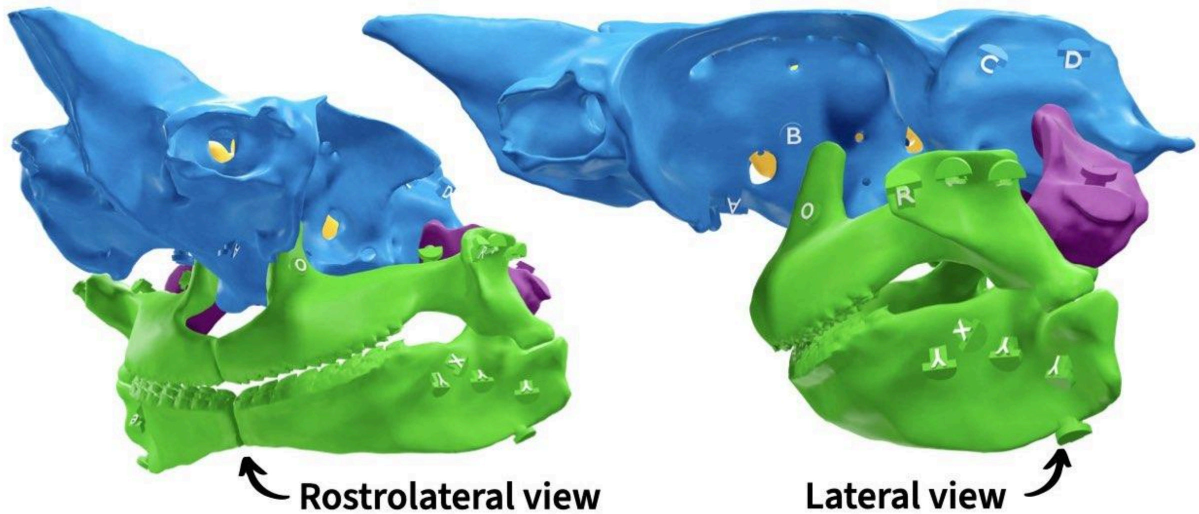
Can you figure out which piece is left versus right? If you need help, see the hint below then check your work on the next page.

HINT: An opposing continuous tooth row

The teeth of the left and right mandibles form continuous rows of teeth that come into contact with the upper jaw tooth rows during biting.

ASSESS: Mandibles articulated

If you added the mandibles as shown in the image below, nice work!



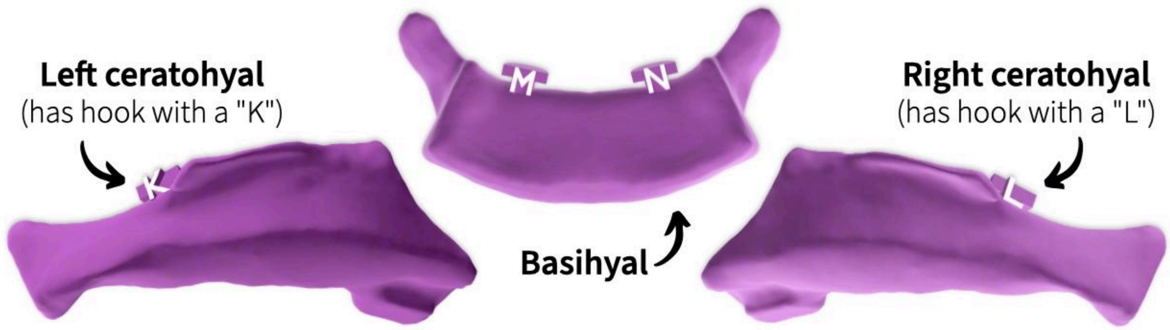
The palatoquadrate and lower jaw are both embryonically and evolutionarily derived from the **first gill arch**, also known as the **mandibular arch**. If your kit is color-coded, both of these elements are green to indicate this common derivation.

Adding the hyoid arch

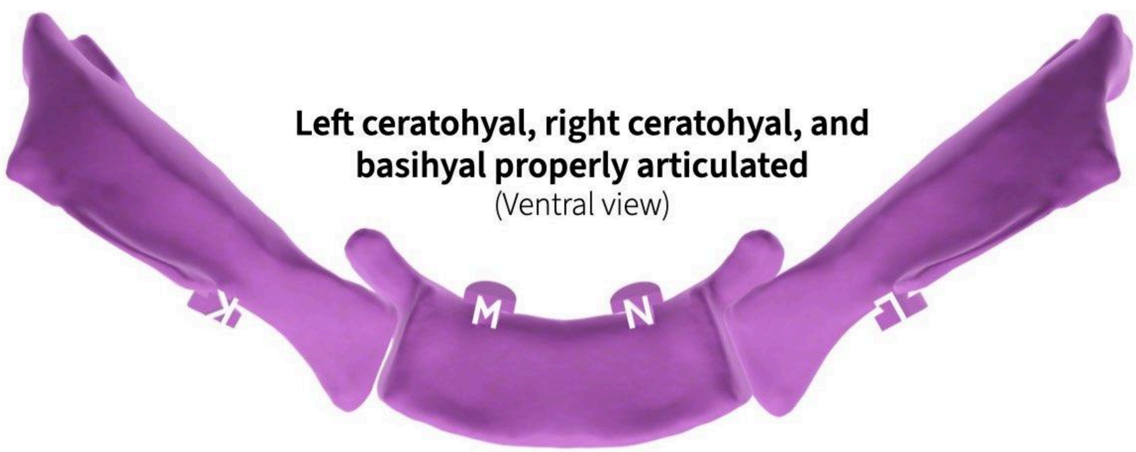
With the jaws added to the chondrocranium, your skull should now be more recognizable as a shark! However, you're not done yet- you still need to add the remaining cartilages of the **second gill arch**, also known as the **hyoid arch**. In sharks, the hyoid arch is made up of the left and right hyomandibular cartilages (which you've already added), the left and right **ceratohyals**, and the **basihyal**.

In humans and other mammals, the **hyoid bone** is located between the jaw and the **pectoral girdle** (shoulder), but closer to the jaw. Although the structure, function, and even development of the hyoid in sharks differs from that in humans, its relative position is the same. In sharks, the hyoid arch sits between the mandibular arch and pectoral girdle, but closer to the mandibular arch.

In your kit, find the left and right ceratohyals (don't worry which is which) and the basihyal, using the image below to help you. If your kit is color coded, all of these elements are purple, like the hyomandibulae, to indicate the derivation of all these elements from the hyoid arch.



The name "hyoid" comes from the Greek for "U-shaped" (well, "Upsilon-shaped" in Greek) because, as you'll see, the elements of the hyoid arch form a "U." Connect the ceratohyals and basihyal as shown in the image below to form a wide "U."



Knowing how these three elements connect together, can you figure out how to add them (as a single unit) to your shark skull? If you need a hint, check the top of the next page. Then check your work at the bottom of the next page.

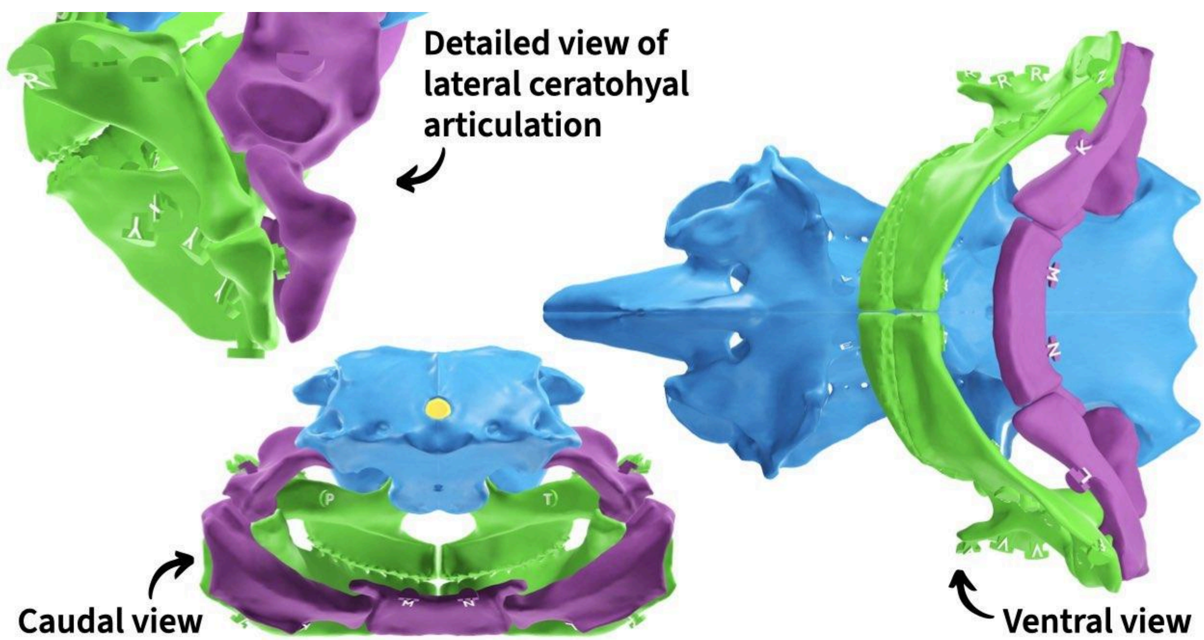
HINT: Complete the arch

As you add the ceratohyals and basihyal to you shark, keep the following in mind:

- Recall that the left and right hyomandibular cartilages articulate with the hyoid arch
- The left ceratohyal (with a "K") should be on the left and the right ceratohyal (with an "L") should be on the right.
- The "angle" of these elements in a lateral view of the skull is similar to the angle of the mandible

ASSESS: Hyoid arch completed

If you added the ceratohyal and basihyal cartilages as shown in the image below, nice work! If it's helpful, you can slide the entire skull off the stand to add the hyoid arch and then slide it back on.



Adding the branchial arches

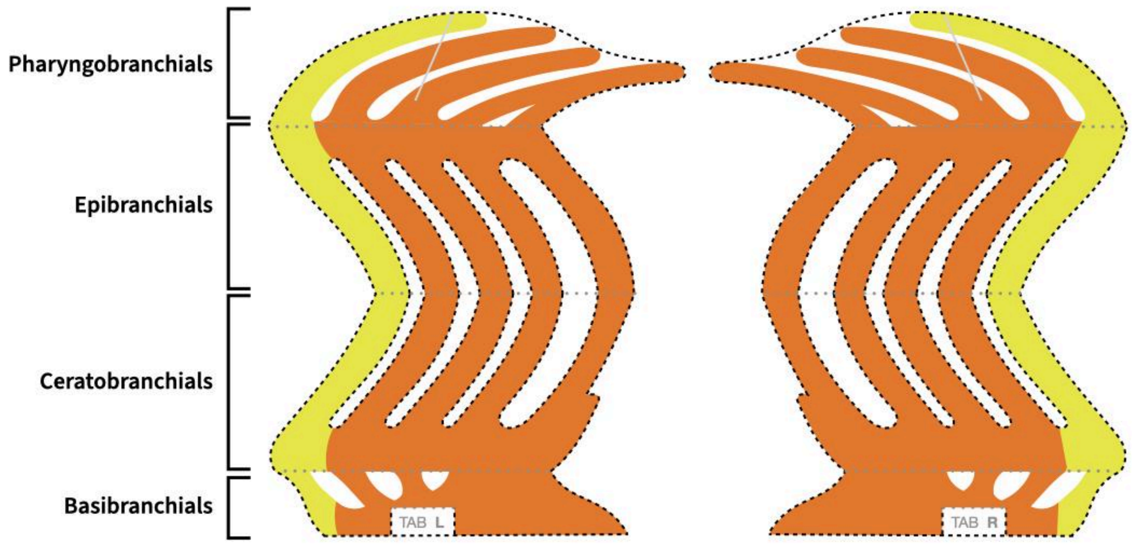
You've now added all the cartilages of the first (mandibular) and second (hyoid) gill arch to your shark! However, there are still some remaining gill arches to add. If you look at the side of most sharks behind the head, you'll see a series of **external gill openings**, also called **gill slits**. This is where water exits the body after traveling over the **gills**. The process by which fish pump water over the gills for exchange of ions and water (including exchanging CO_2 for O_2) is called **gill ventilation**.

Lateral view of a spinner shark (*Carcharhinus brevipinna*), showing the external gill openings, modified from a photograph by Jean-Lou Justine licensed under CC BY 3.0.

Most sharks, including spiny dogfish, have five gill openings and these are supported internally by five cartilaginous **branchial arches** (Wegner 2015). Since the mandibular and hyoid arches are the first two arches, these branchial arches are referred to as the **third through seventh gill arches**.

In your kit, find the left and right branchial arches.

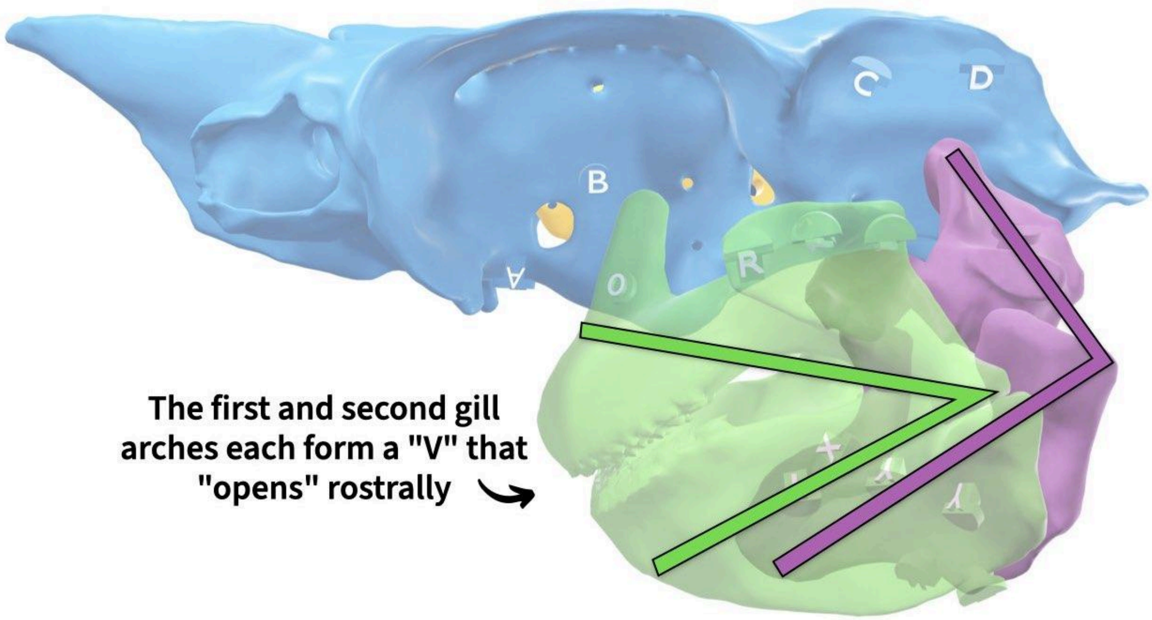
They're the yellow and orange cardstock paper pieces. You can tell the left and right side by looking at the small white tab: the left side has an "L" and the right side has an "R." Each branchial arch is composed of four parts: a **pharyngobranchial**, an **epibranchial**, a **ceratobranchial**, and a **basibranchial**.



Starting with the left side, can you figure out the proper position and orientation of the branchial arches? Don't worry about securing them to the stand yet, just hold them in place with your hand. If you need help, check the hint at the top of the next page and then check your work at the bottom of the next page.

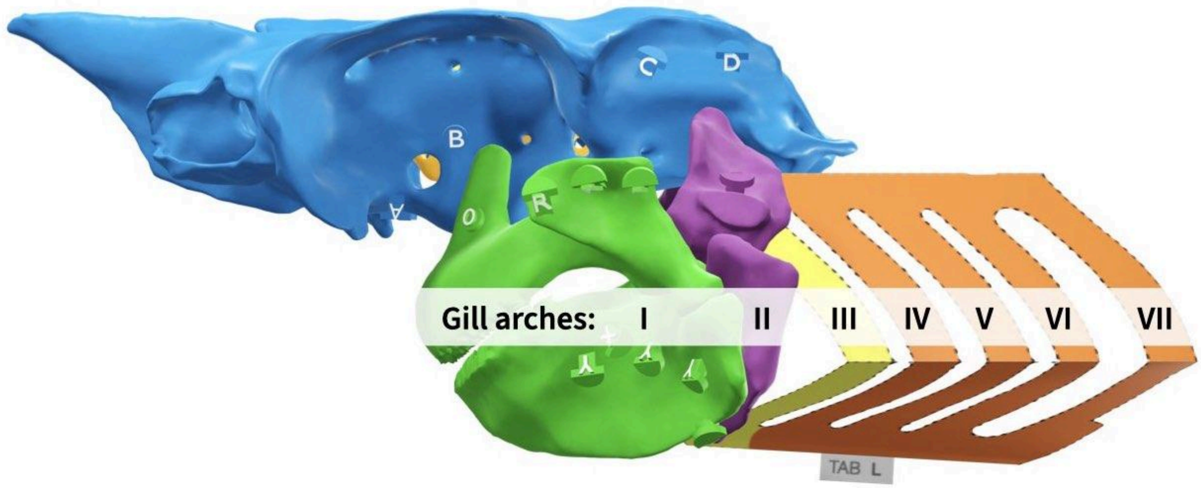
HINT: Continue the angle

The branchial arches (gill arches 3-7) continue the angle formed by the top and bottom halves of the first two gill arches.



ASSESS: Branchial arches oriented

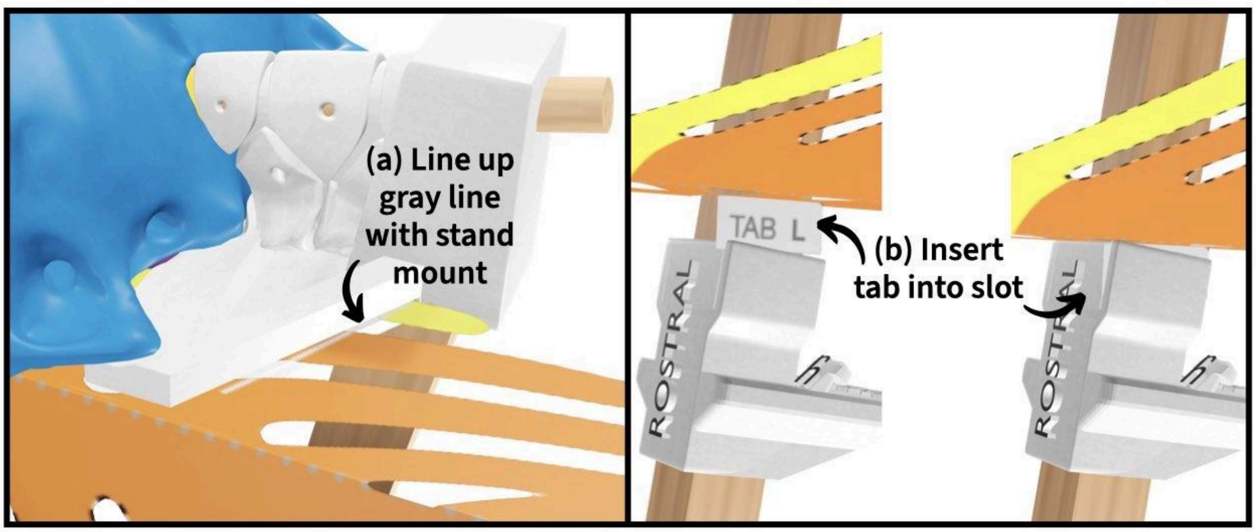
The position and orientation of the left branchial arches should look like the image below. Note that in the proper orientation, the yellow branchial arch is the third gill arch and the remaining four orange branchial arches are the fourth through seventh gill arches.



Secure the top and the bottom of each set of branchial arches to the stand by:

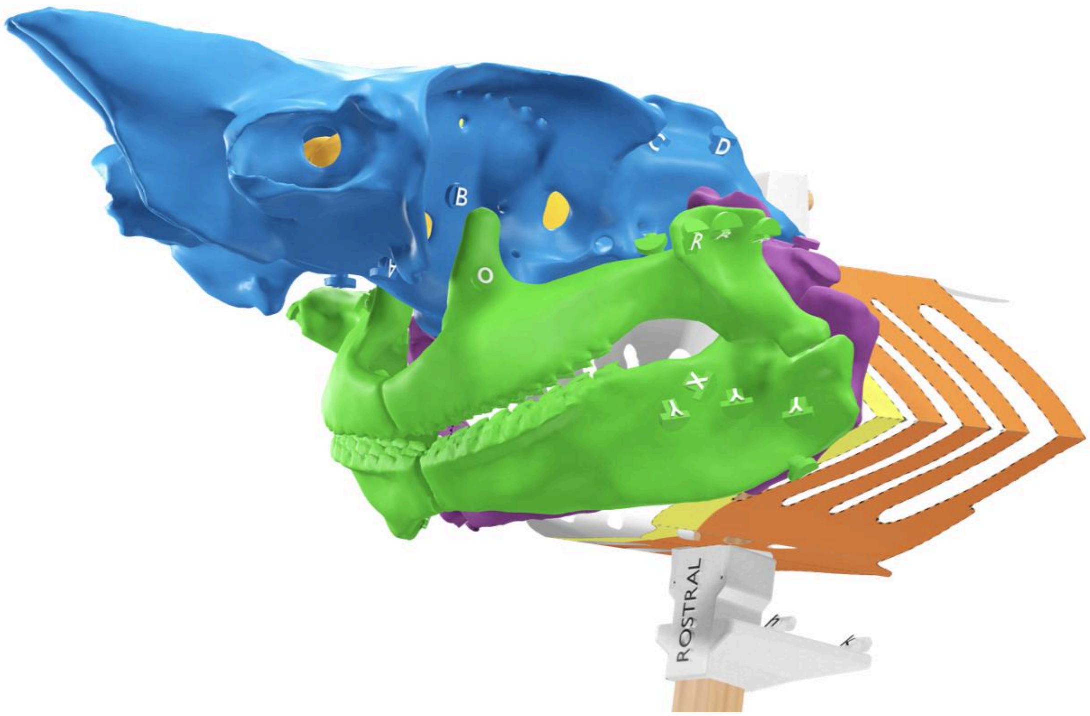
(a) sliding the pharyngobranchials into the slit of the top, stand mount piece until the gray line drawn across the first three pharyngobranchials reaches the mount,

(b) and inserting the tab into the slot on the piece in the middle of the stand rod.

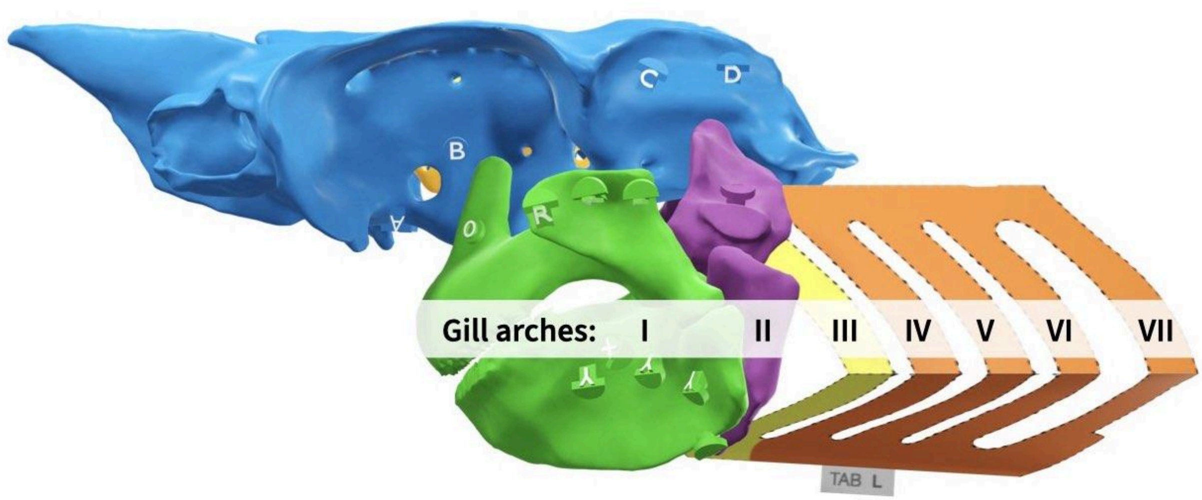


Add the right branchial arches, repeating the previous steps to attach them to the stand.

You've now fully constructed the skeletal elements of your shark skull! Take a moment to observe the splanchnocranium. Can you stick a pen or pencil through the mouth of your model to indicate the path of food into the gut? What about the path of water that enters the mouth to flow over the gills?



Also, do you notice how the structures of the splanchnocranium follow a sequence from rostral to caudal? This sequential arrangement of structures that have a common developmental origin is called **serial homology** (vertebrae are another example).



Throughout vertebrate evolution, the development of the gill arches has been modified to form a diverse array of structures. However, their sequential arrangement and identity has remained evolutionarily conserved.

Section 3. How are sharks able to protrude their jaws?

Now that you've finished building, use your shark to answer the question posed at the start of this module: how is it possible for sharks to protrude their jaws away from the rest of the skull during feeding? Write your explanation on page 2 of your **Notebook**. If you need help, use the hints below.

HINT: Manually simulate protrusion

Since your shark's cartilages are held together by magnets, you can use your hands to move the pieces and simulate motion. However, be careful that you don't move them too far or else the cartilages could detach from one another - remember, the magnets are strong but they are much weaker than ligaments! It's best if you use one hand to move the cartilages and another to support them in case they detach.

HINT: How are the jaws attached?

As mentioned previously, the magnet pairs in your shark represent ligaments. How many ligaments attach the jaws to the chondrocranium? How might the location and number of attachments affect the ability of the jaws to move relative to the chondrocranium?

References cited

- Dean, Mason N., and Adam P. Summers. "Mineralized cartilage in the skeleton of chondrichthyan fishes." *Zoology* 109.2 (2006): 164-168. DOI: 10.1016/j.zool.2006.03.002.
- Gates Jr, Henry Louis, and Andrew S. Curran. "Inventing the science of race." *The New York Review of Books* 68.20 (2021): 52-57. URL: https://www.nybooks.com/articles/2021/12/16/inventing-the-science-of-race/.
- Fallows, Chris, Austin J. Gallagher, and Neil Hammerschlag. "White sharks (*Carcharodon carcharias*) scavenging on whales and its potential role in further shaping the ecology of an apex predator." *PloS one* 8.4 (2013): e60797. DOI: 10.1371/journal.pone.0060797.
- Wegner, Nicholas C. "Elasmobranch gill structure." *Fish Physiology*. Vol. 34. Academic Press, 2015. 101-151. DOI: 10.1016/B978-0-12-801289-5.00003-1.
- Wilga, Cheryl D., and Philip J. Motta. "Conservation and variation in the feeding mechanism of the spiny dogfish *Squalus acanthias*." *Journal of Experimental Biology* 201.9 (1998): 1345-1358. DOI: 10.1242/jeb.201.9.1345.