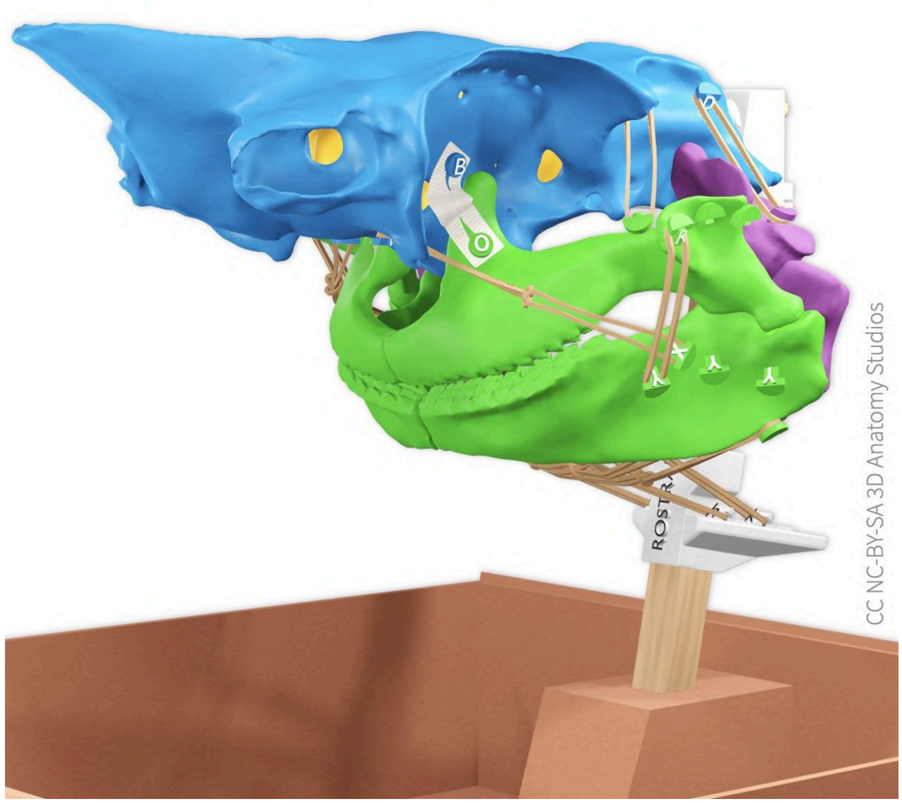
Dogfish Skull Active Learning Kit

ACTIVITY MODULES



Introduction

ABOUT THIS DOCUMENT

This is a public and open-source Google Doc with modules for the Dogfish Shark Skull Kit by 3D Anatomy Studios. Each module has its own top-level section and includes an **Educator Guide**, a **Student Guide**, and (if the activity includes any writing or drawing) a **Student Notebook**. The rest of this section lists information used in or related to all activities.

SYSTEMS, CONCEPTS, AND COMPETENCIES

The lists below are anatomical systems, core concepts, and competencies, that could be potentially addressed in these active learning modules. Subscripts indicate references (see References cited) and numbers in parentheses indicate the ID of the module(s) in this document that address(es) that system, concept, or competency.

Anatomical systems

- Circulatory
- Connective tissue
- Digestive
- Endocrine
- Excretory
- Immune
- Integumentary
- Lymphatic
- Muscular (5)
- Nervous, central (2,3,4)
- Nervous, peripheral
- Respiratory
- Reproductive
- Sensory (3,4)
- Skeletal (1,2,3,4,5)
- Urinary

Core concepts in anatomy and physiology

- Cell-cell communication[2]
- Cell membrane[2]
- Cell theory[2]
- Development[1,2] (4)
- Energy[2]
- Evolution[1,2] (4)
- Flow down gradients[2]
- Homeostasis[2]
- Humans are vertebrates[1] (4)
- Morphological integration[1] (2)
- Levels of organization[2]
- Mass balance[2]
- Properties of matter[2]
- Structure & function[1,2] (1,2,3,4,5)
- System integration[2]

Competencies

- Value of biological collections[1]
- Data integration[1] (4)
- Depiction of anatomy[1] (3,4)
- Dissection of specimens[1]
- Heteronormativity, androcentrism, and reproductive anatomy[1]
- Inclusivity in anatomy[1]
- Legacy of colonialism and slavery[1] (1)
- Legacy of racism in anatomy[1]
- Observation[1] (1,2,5)
- Scientific communication[1] (2,4)
- Scientific reasoning[2] (2,4,5)
- Tree thinking[1] (4)

References cited

- Danos, Nicole, Katie Lynn Staab, and Lisa B. Whitenack. "The core concepts, competencies, and grand challenges of comparative vertebrate anatomy and morphology." *Integrative Organismal Biology* 4.1 (2022): obac019. DOI: 10.1093/iob/obac019.
- Michael, Joel, and Jenny McFarland. "Another look at the core concepts of physiology: revisions and resources." *Advances in Physiology Education* 44.4 (2020): 752-762. DOI: 10.1152/advan.00114.2020.

LEARNING LEVELS

Bloom's taxonomy (revised)

Bloom's Taxonomy table and wheel by Quinnipiac University (PDF)
A Revision of Bloom's Taxonomy: An Overview by Krathwohl (2002)

References cited

- Anderson, Lorin W., and David R. Krathwohl. *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives* (2001) New York: Longman.
- Bloom, Benjamin S., and David R. Krathwohl. "Taxonomy of Educational Objectives: The Classification of Educational Goals, by a committee of college and university examiners." *Handbook I: Cognitive Domain* (1956) New York: David McKay.

MODULE COMPLETION TIME TESTS

The table below lists the results of completion time tests for modules or activities within modules.

Module / Activity	Time	Added	Timed By
Cutting out the paper branchial arches	11m	7-Sep-23	A Olsen
SA01 Building the skeleton of your shark skull	40m	7-Sep-23	A Olsen
SA02 Observing your shark's braincase and brain	40m	7-Sep-23	A Olsen
SA03 Wiring your shark's brain	40m	8-Sep-23	A Olsen
SA04 Mapping the functional evolution of cranial nerves	42m	8-Sep-23	A Olsen
SA05 Simulating the motions of your shark's jaws	52m	8-Sep-23	A Olsen

EDUCATOR GUIDE

Building the skeleton of your shark skull

Text and images by Aaron M Olsen, PhD

Time to complete: 40-60 min
Age level: Grades 11-12 or College
Bloom's levels: 1, 2, 3, 4 & 5
Description: In this module, your students 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.
Materials needed:

- SA01 Student Guide & Notebook v1.0
- Dogfish Shark Skull Kit v1.0
- "Office scissors" to cut out branchial arches

Systems:

- Skeletal

Core concepts:

- Structure & function

Competencies:

- Observation
- Legacy of racism in anatomy

Module ID: SA01
Module version: 1.1
Module sequence (suggested):
SA02 → SA03 → **SA01** → SA05 → SA04

How to use and edit this module

This is an open-source active learning module created by 3D Anatomy Studios and licensed under CC NC-BY-SA for use with the Dogfish Shark Skull Kit.

Module Structure

This module has an **Educator Guide**, a **Student Guide**, and a **Student Notebook** and is divided into one or more sections, each with a number, a motivating question as its heading, and a learning objective.

Educator Guide

The **Educator Guide** is intended for educators and contains a pedagogical schema for the module to help implement the module in a course (e.g., learning objectives, target Bloom's level and competencies, core concepts), an answer key for certain prompts/questions in the the **Student Notebook**, and module updates.

Student Guide

The **Student Guide** is intended for students to read as they complete the module's activities and can be read on a device or printed out.

Student Notebook

The **Student Notebook** contains worksheets or diagrams on which students can write or draw as a part of the module's activities. The **Student Notebook** can be printed out or filled in using a digital tablet.

Sharing and Editing

The CC NC-BY-SA license allows you to share and edit this module as long as you (1) do not sell the module or module derivatives ("NC"), (2) attribute the author(s) of all the content, including preserving text and graphic attributions ("BY"), and (3) share the module under the same license ("SA"). You can edit this module by copying the current Google Doc of this module (accessible at 3danatomystudios.com/guides/SA00) and editing that copy.

Purchasing Kits

To purchase kits, please visit 3danatomystudios.com/shop/dogfish-skull-kit.

Pedagogical schema

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

Learning objective	**Identify (Bloom's Level 1 - Remember)** the chondrocranium and brain and **interpret (Bloom's Level 2 - Understand)** their orientation and position relative to one another.
Activity	Observe models of the shark braincase and brain and fill in blanks on an anatomical conceptual image
Self-assessment	Compare fill-in-the-blank responses with possible responses in the student guide
Systems	**Skeletal**
Core concepts	**Structure & function**
Competencies	**Observation**

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

Learning objective	**Identify (Bloom's Level 1 - Remember)** the cartilages of the shark jaws by **matching (Bloom's Level 1 - Remember)** 3D models to 2D representations, **choose (Bloom's Level 3 - Apply)** their proper orientation by trial and error, and **solve (Bloom's Level 3 - Apply)** how the cartilages of the shark cranium and jaws attach and articulate with one another by **building (Bloom's Level 3 - Apply)** a 3D model.
Activity	Assemble 3D model of shark jaws made from 3D printed and paper pieces
Self-assessment	Compare 3D model with images in student guide
Systems	**Skeletal**
Core concepts	**Structure & function**
Competencies	**Legacy of racism in anatomy**

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

Learning objective	**Explain (Bloom's Level 4/5 - Analyze/Evaluate)** how sharks are able to protrude their jaws by observing an articulated and mobile model of a shark skull.
Activity	Observe model of shark cranial skeleton and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Skeletal**
Core concepts	**Structure & function**
Competencies	**Observation**

Answer key

Section 3. How is it possible for sharks to protrude their jaws away from the rest of their skull during feeding?

How is it possible for sharks to protrude their jaws away from the rest of their skull during feeding?

- The upper jaws are only connected to the chondrocranium at one point (on each side) and this articulation is formed by ligaments. This frees the upper and lower jaw to move together as a single unit.
- The mandibular and hyoid arches connect to the chondrocranium at only two points on each side (palatoquadrate and hyomandibula) via ligaments. By only having two articulation points that are both flexible, the jaws can move relative to the chondrocranium.
- The mandibular and hyoid arches are formed by nine separate cartilages, joined together by ligaments. The more separate parts a system has, the more ways in which it can move.

Updates

Version 1.1

- Moved self-assessment for open-ended questions from the Student to Educator Guide.

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.

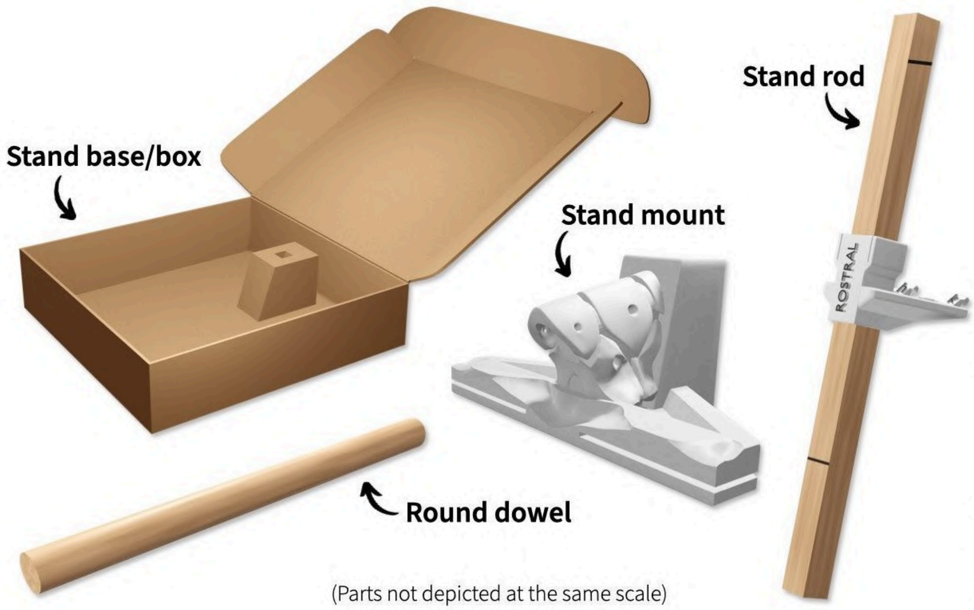
A white shark (*Carcharodon carcharias*) feeding at the surface by Fallows, Gallagher, & Hammerschlag 2013 and licensed under CC BY 2.5.

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

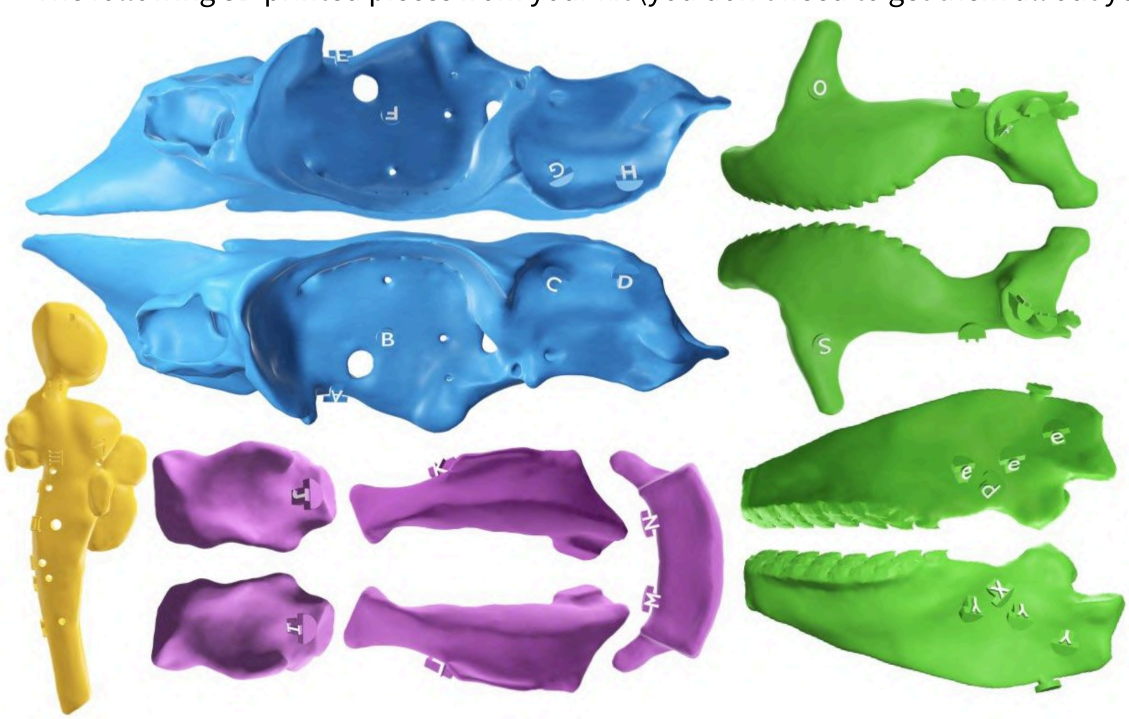
For this module, you'll need:

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



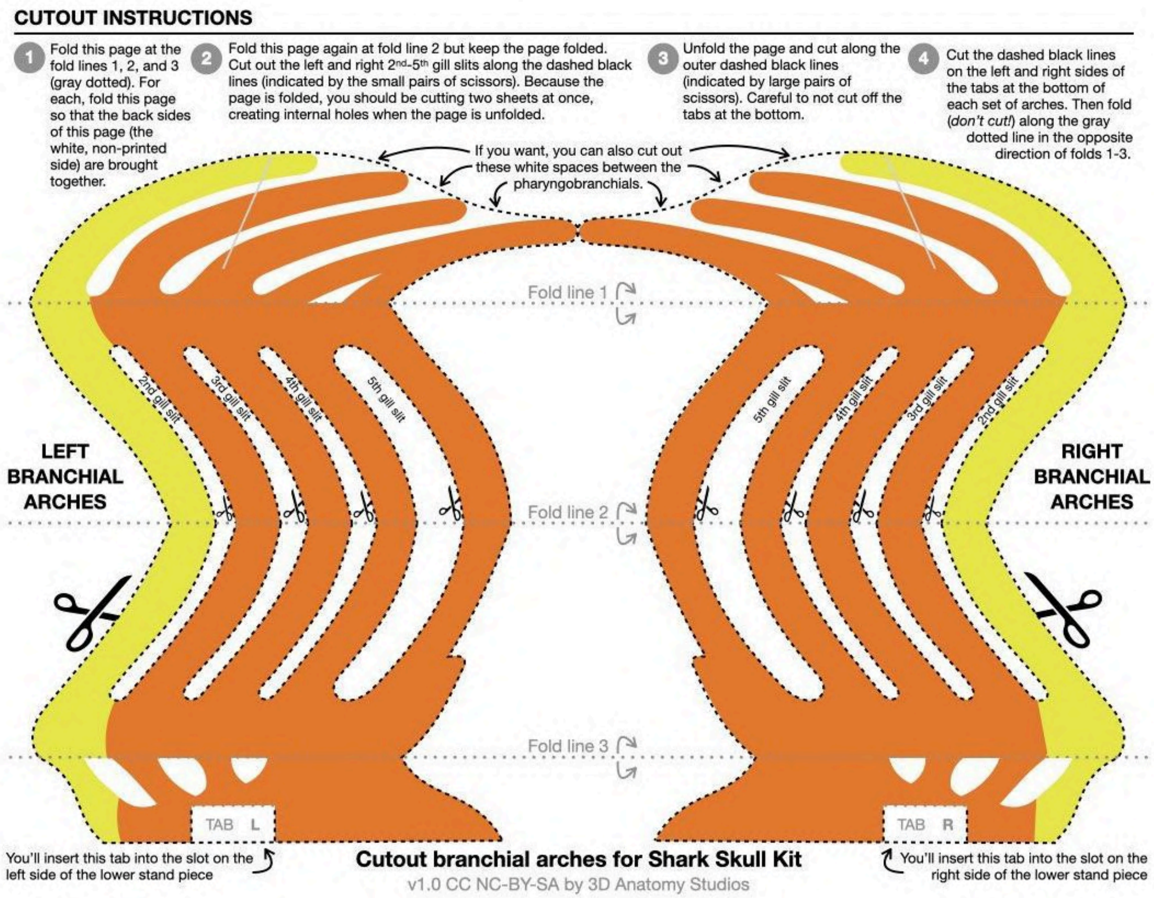
(Parts not depicted at the same scale)

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



Materials needed (continued)

- 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

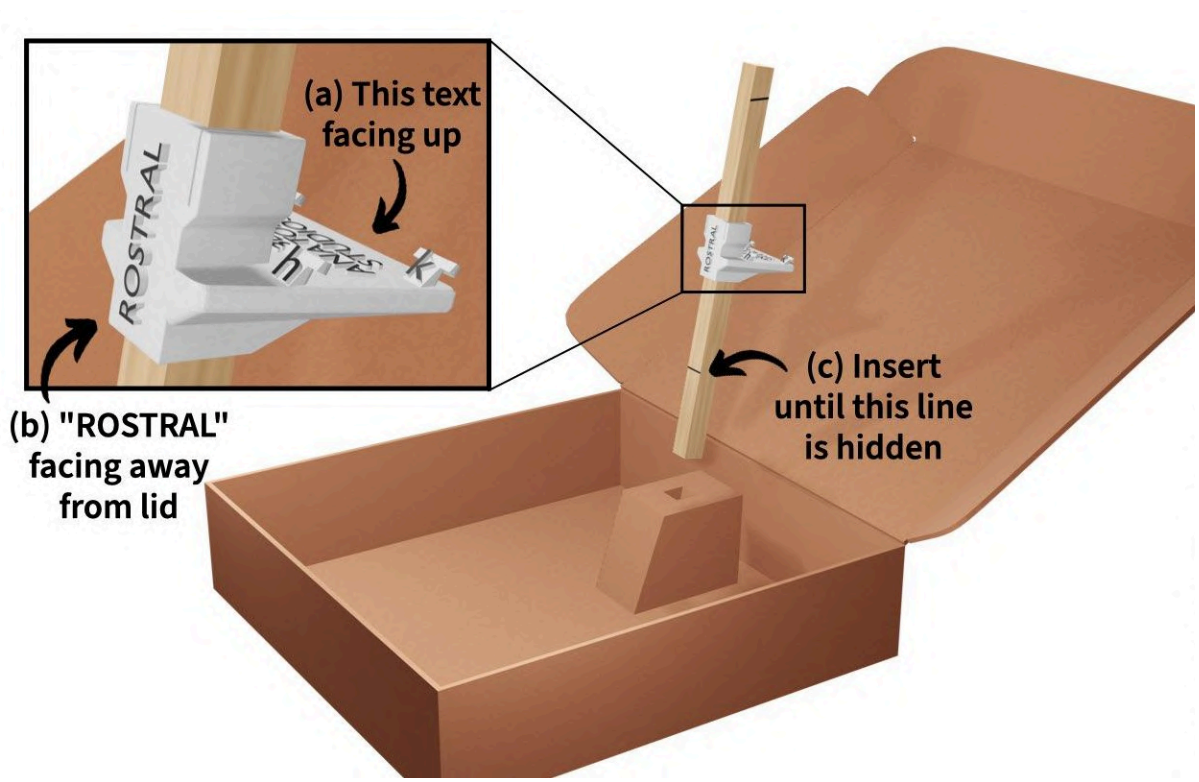
Each of the 3D printed pieces in your kit has small hooks and pegs with raised letters on them. You'll use these in other modules to attach muscles (rubber bands) and ligaments (ribbons) but in this module they'll just help you to identify the pieces. These raised letters may be white or black in the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

Preparing the stand

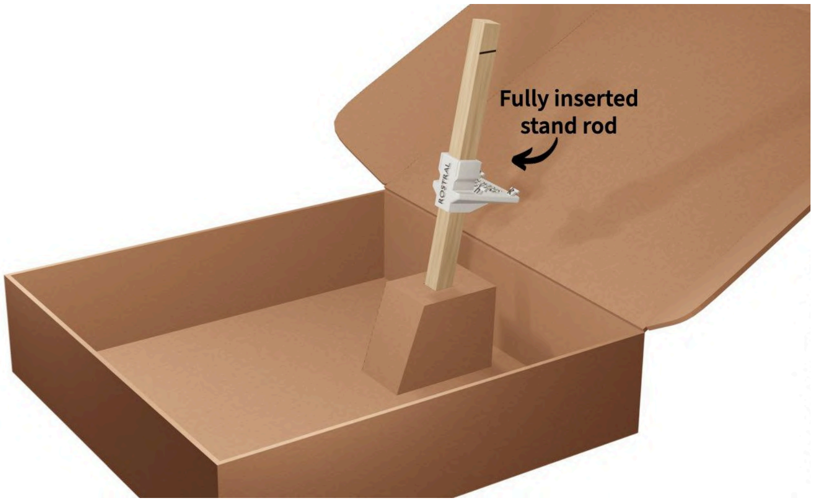
Before you start building, you'll need to prepare the stand that will hold your shark to free up your hands for building. In your kit, find the stand rod; it's the wooden square dowel rod with a 3D printed "shelf" in the middle (see image to the right).

Insert the rod into the stand base as shown in the image below. It may take a bit of force. Be sure to:

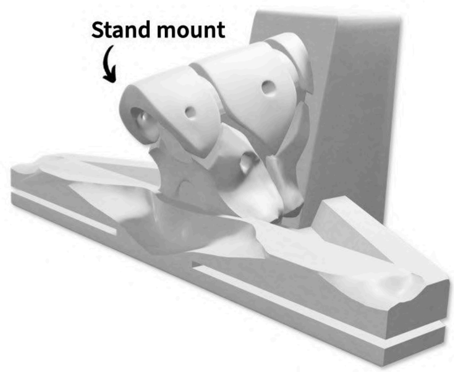
(a) orient the rod so that the "3D ANATOMY STUDIOS" text on the shelf is facing up,
(b) insert the rod into the base so that the "ROSTRAL" text is facing away from the lid of the box,
(c) and push the rod down into the base until the line is hidden within the base.



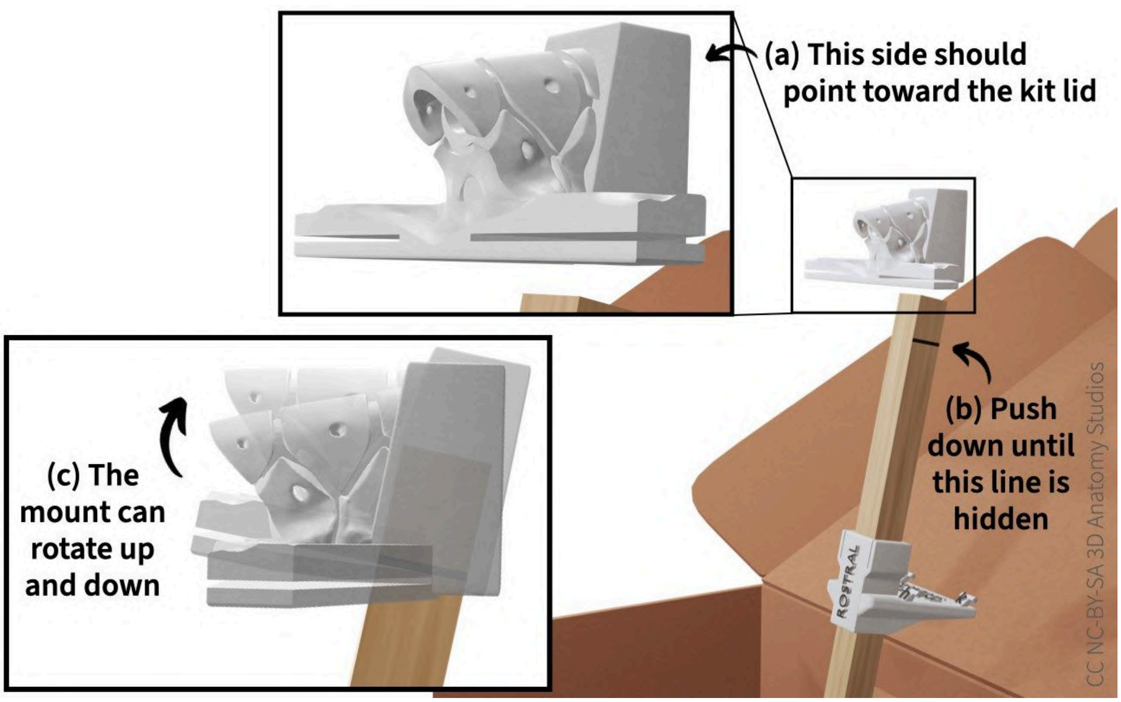
Once you've inserted the stand rod, it should look like the image below.



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 cube-ish part toward the box lid,
(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.



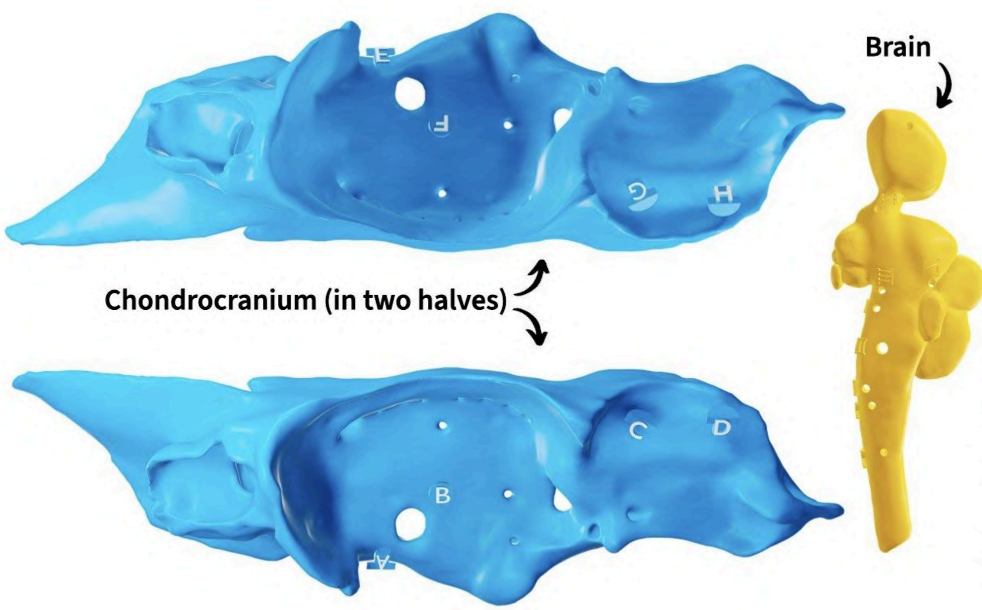
Section 1. What is the anatomical orientation of the chondrocranium and brain?

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).



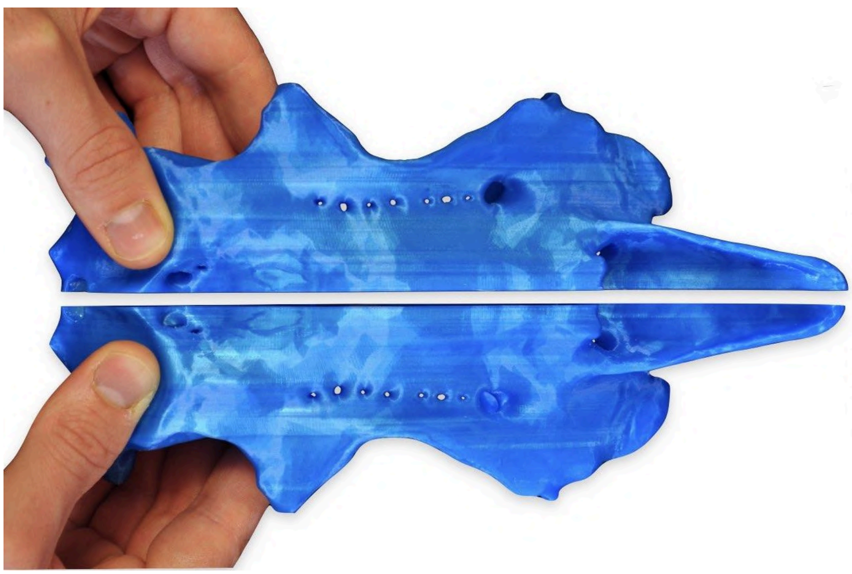
If the two halves of the chondrocranium are not already snapped together as a whole piece, how do they fit together? If you get stuck, use the hint at the top of the next page.

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.

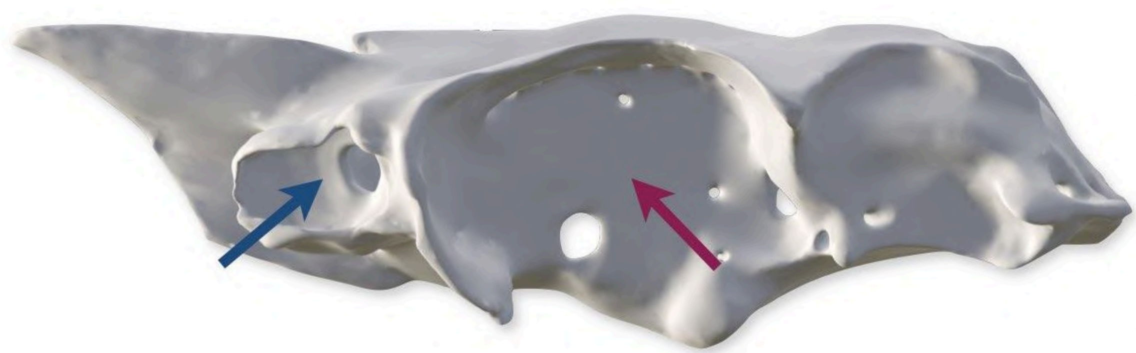


Now that you've solved how the two halves fit together, which end is **rostral** (toward the shark's snout or front end) and which end is **caudal** (toward the tail or back end)? Which side is **dorsal** (the shark's back) and which side is **ventral** (the shark's belly)?

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.

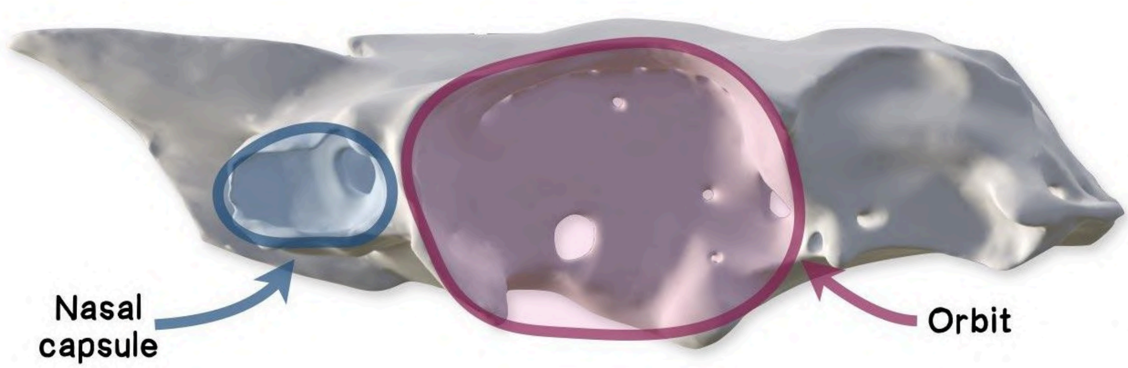
HINT: Where are the nose and eye?

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?



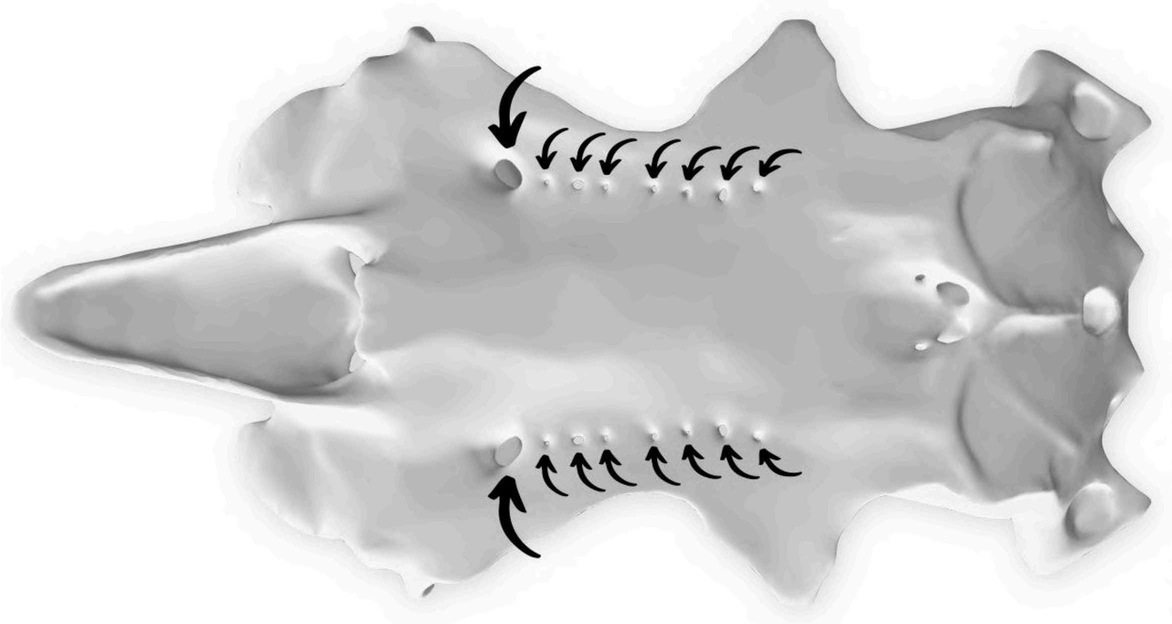
HINT: Nose in front

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?

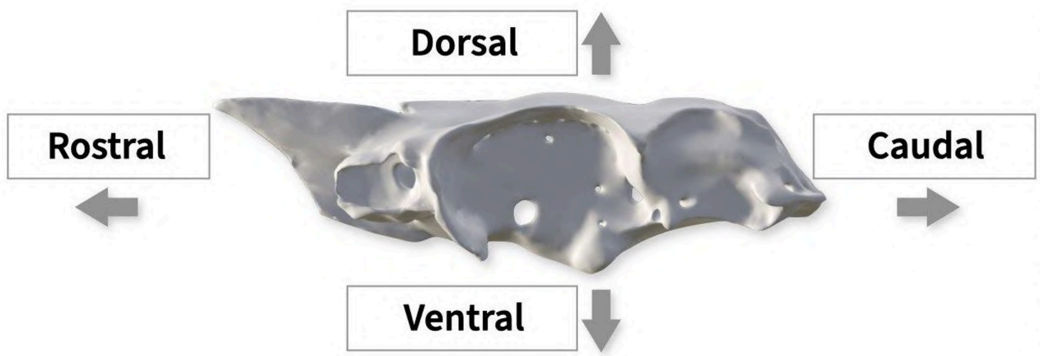


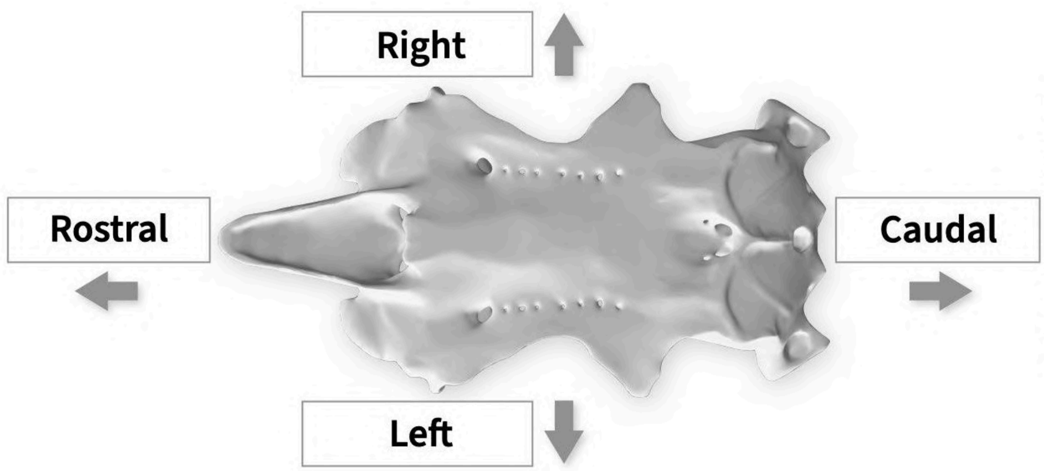
HINT: Determining left vs. right

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.





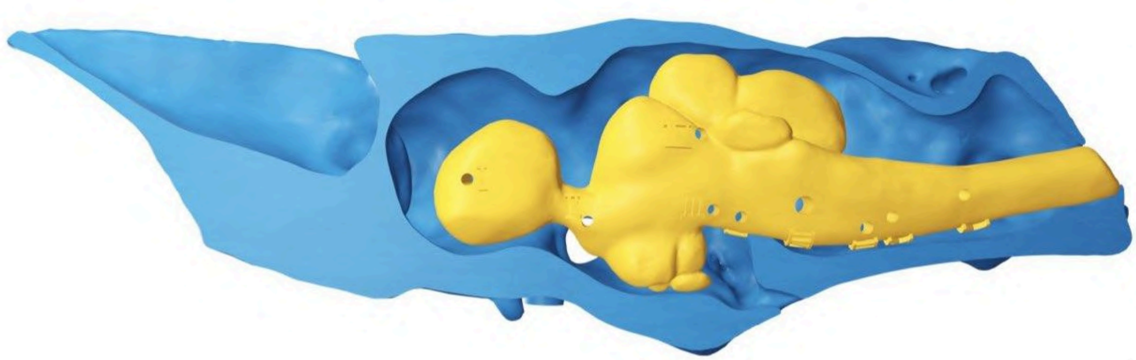
Now that you have the orientation of the chondrocranium figured out, how does the brain sit inside the **endocranial cavity** (the space inside the chondrocranium that holds the brain)? If you get stuck, check out the hint on the following page.

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.

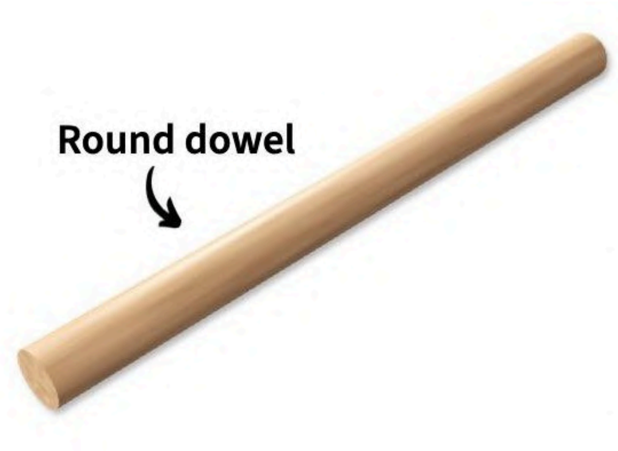
ASSESS: Brain in a case

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).



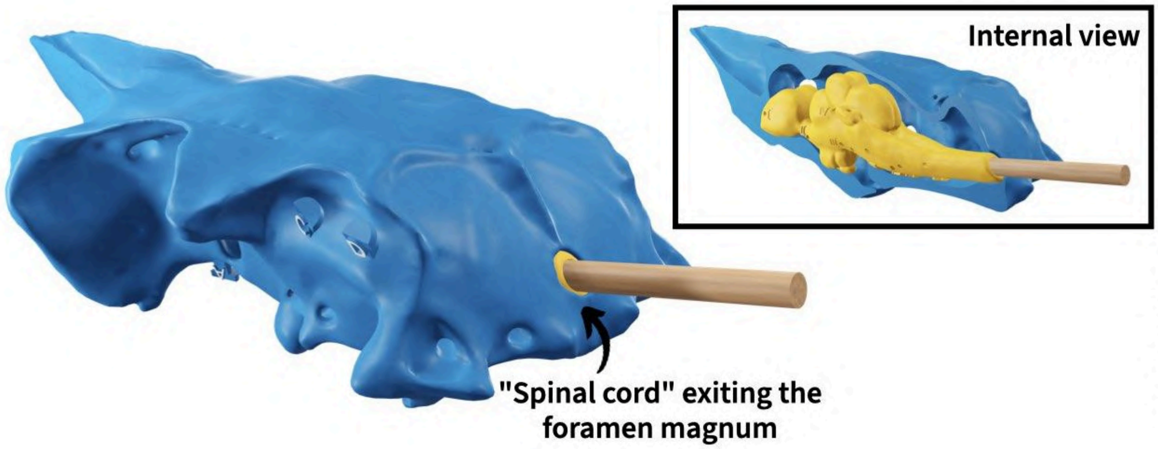
Your round dowel represents a segment of your shark's **spinal cord**, a bundle of nerves that is continuous with the brain but exits the skull to reach the rest of the body. The spinal cord exits the skull via the **foramen magnum** (meaning "big hole") so insert your spinal cord segment (round dowel) 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

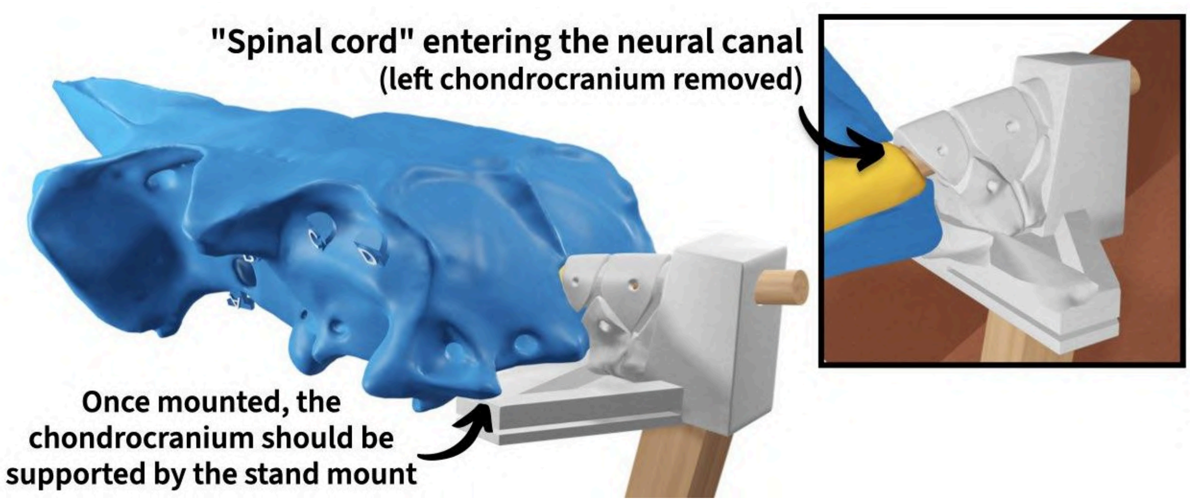
If your spinal cord segment is properly inserted, it should look like the image below.



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.



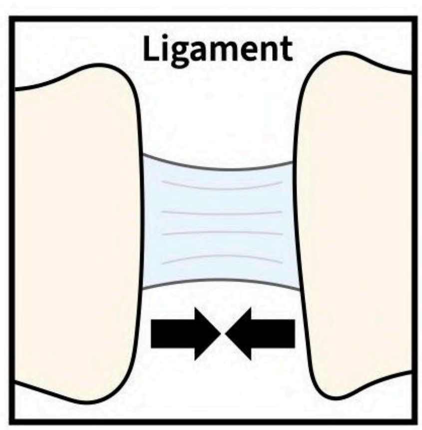
Section 2. What are the shark splanchnocranium cartilages and how do they articulate?

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

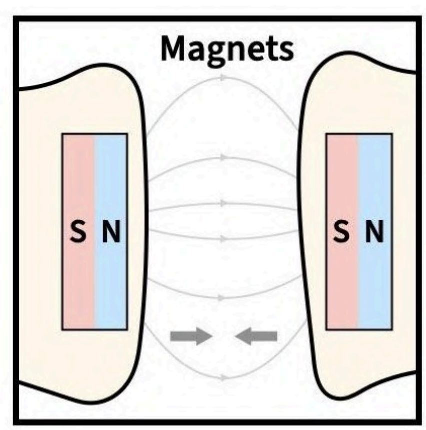
BUILD NOTE: Magnets as ligaments

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)

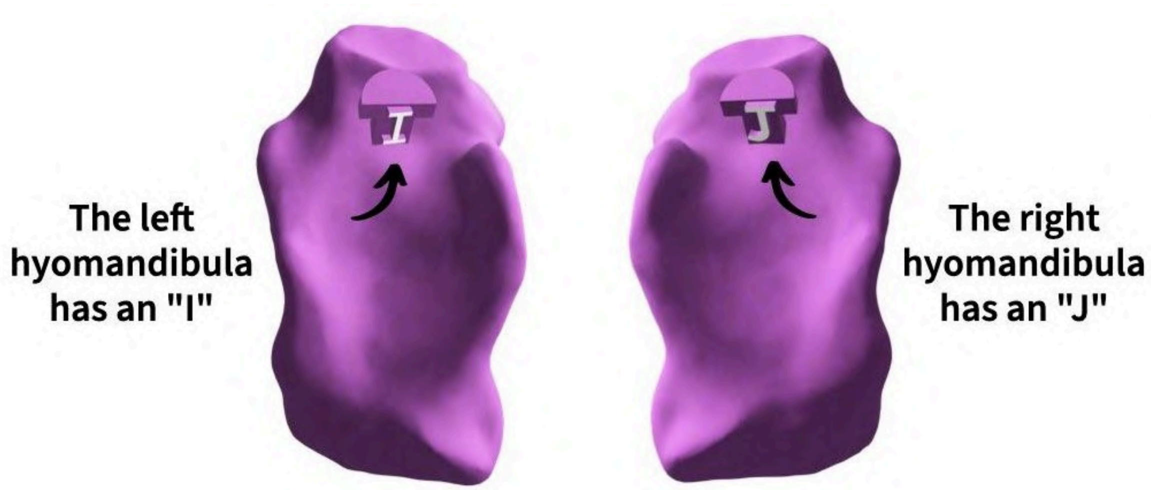


- *Much* weaker than a ligament
- Consistently produces an attractive force that decreases in strength with distance

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

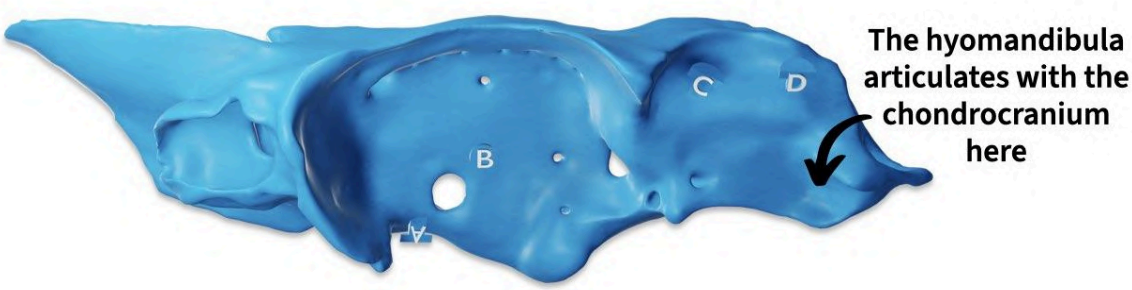
The name "hyomandibula" combines portions of the words **hyoid** and **mandible** because the hyomandibula articulates with:

- 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

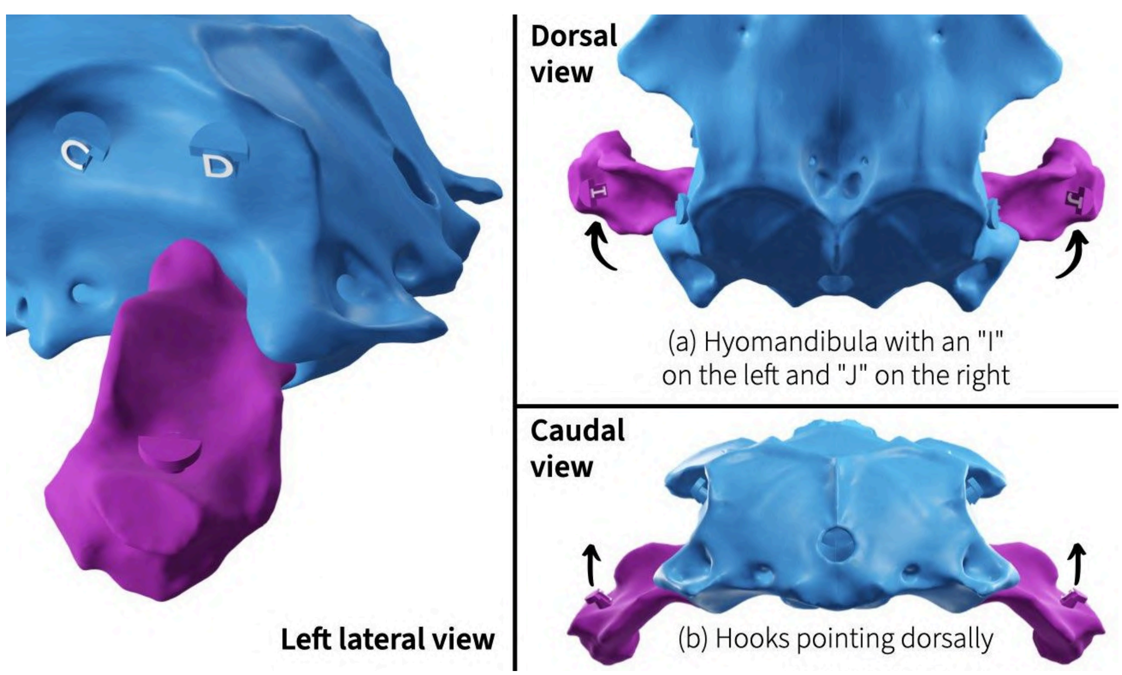
If you guessed that the hyomandibulae attach at the position shown below, you guessed correct!



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

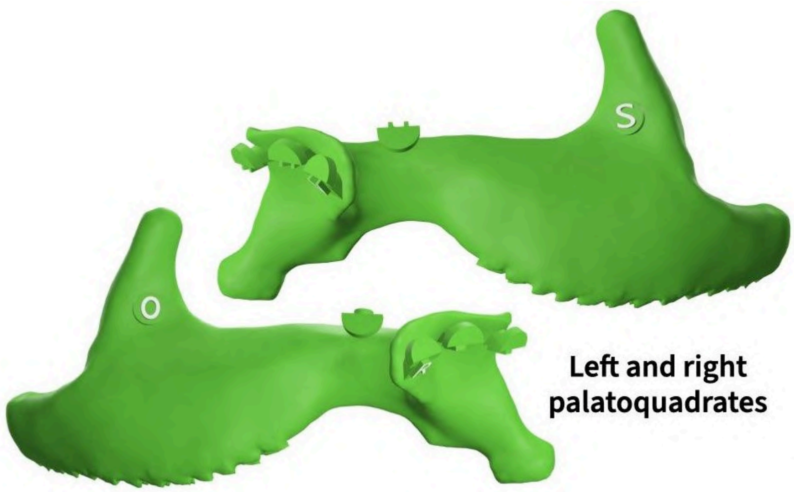
Attach the hyomandibulae as shown in the image below, making sure:

(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

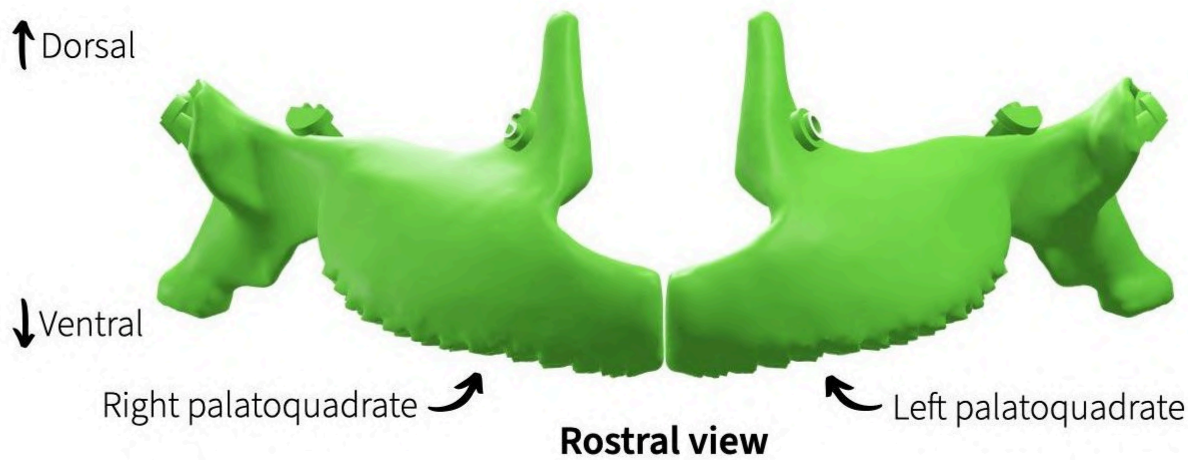
Can you figure out which piece is left versus right? If you need help, see the hint below then check your work on the next page.

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!



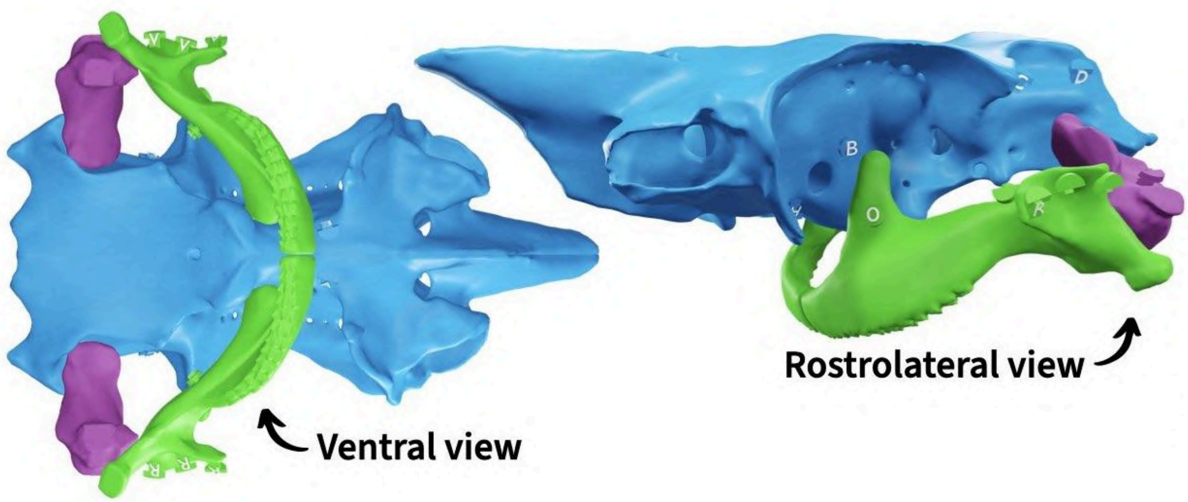
Now that you know the proper orientation of the palatoquadrates, can you add them to your skull? See the hint below, if you need help, and check your work on the next page.

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

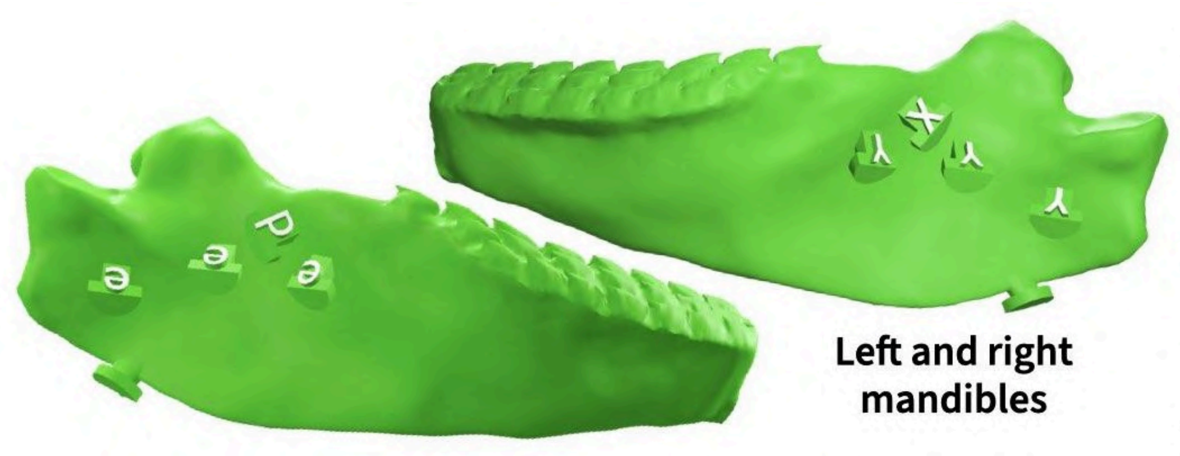
If you added the palatoquadrates as shown in the image below, nice work!



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.



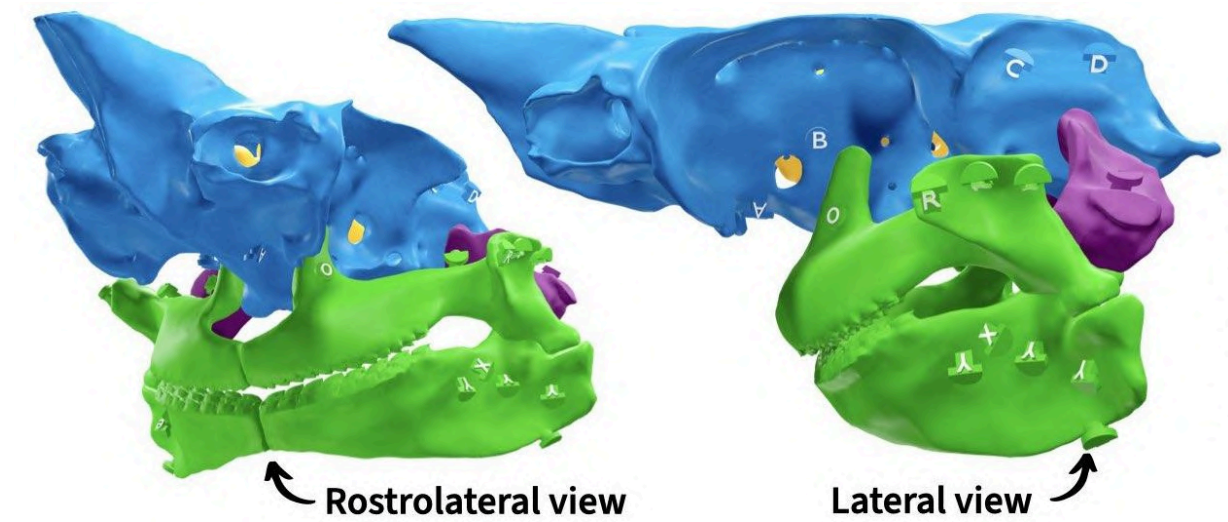
Can you figure out which piece is left versus right? If you need help, see the hint below then check your work on the next page.

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!



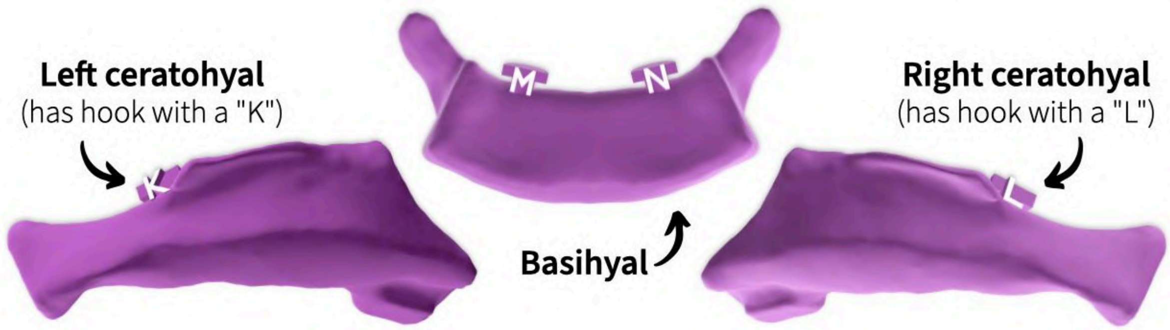
The palatoquadrate and lower jaw are both embryonically and evolutionarily derived from the **first gill arch**, also known as the **mandibular arch**. If your kit is color-coded, both of these elements are green to indicate this common derivation.

Adding the hyoid arch

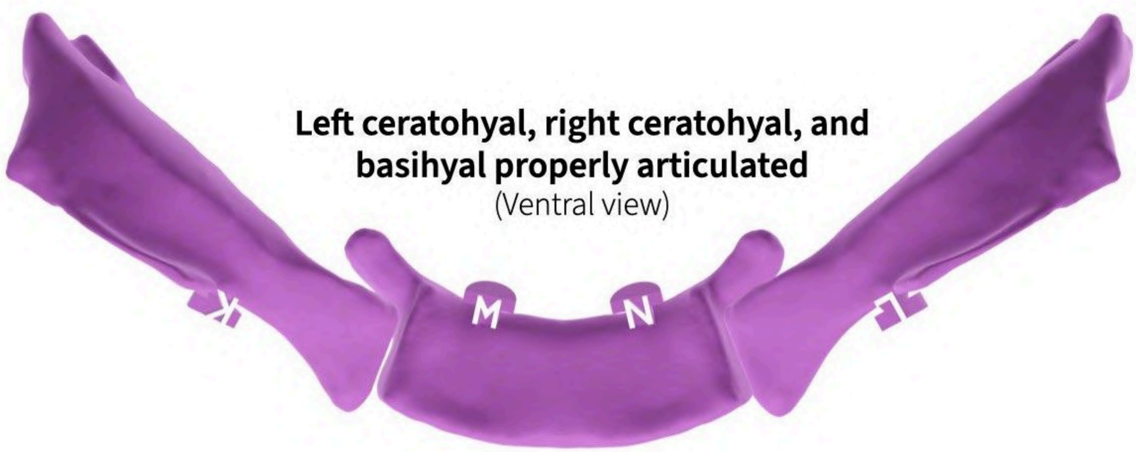
With the jaws added to the chondrocranium, your skull should now be more recognizable as a shark! However, you're not done yet- you still need to add the remaining cartilages of the **second gill arch**, also known as the **hyoid arch**. In sharks, the hyoid arch is made up of the left and right hyomandibular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

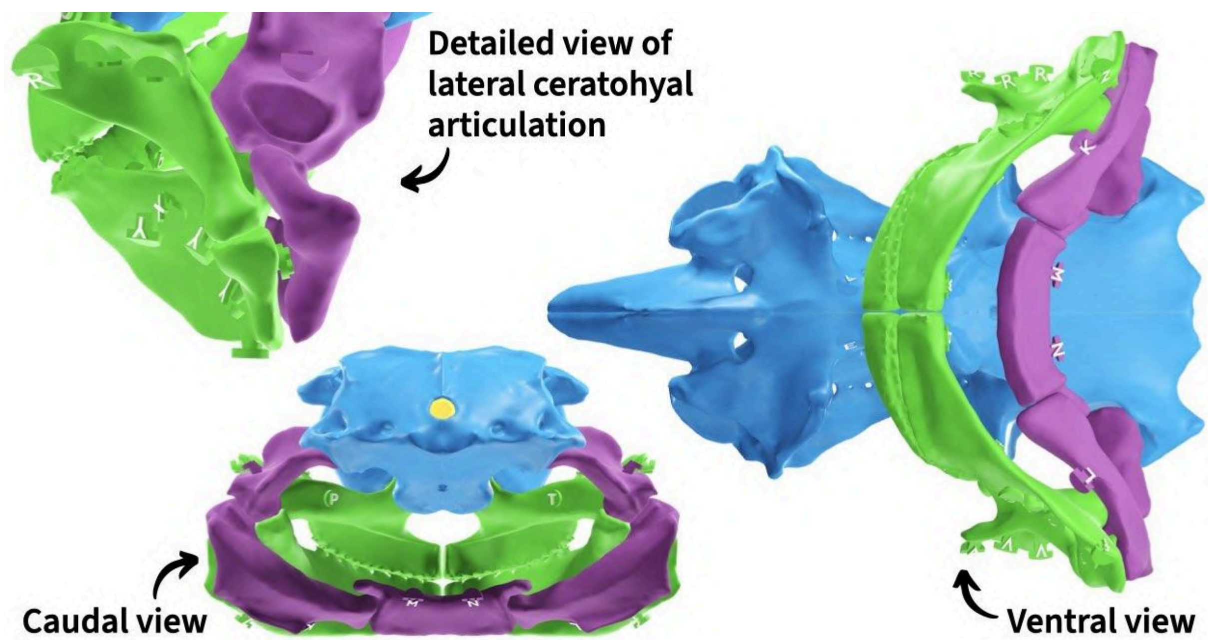
HINT: Complete the arch

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

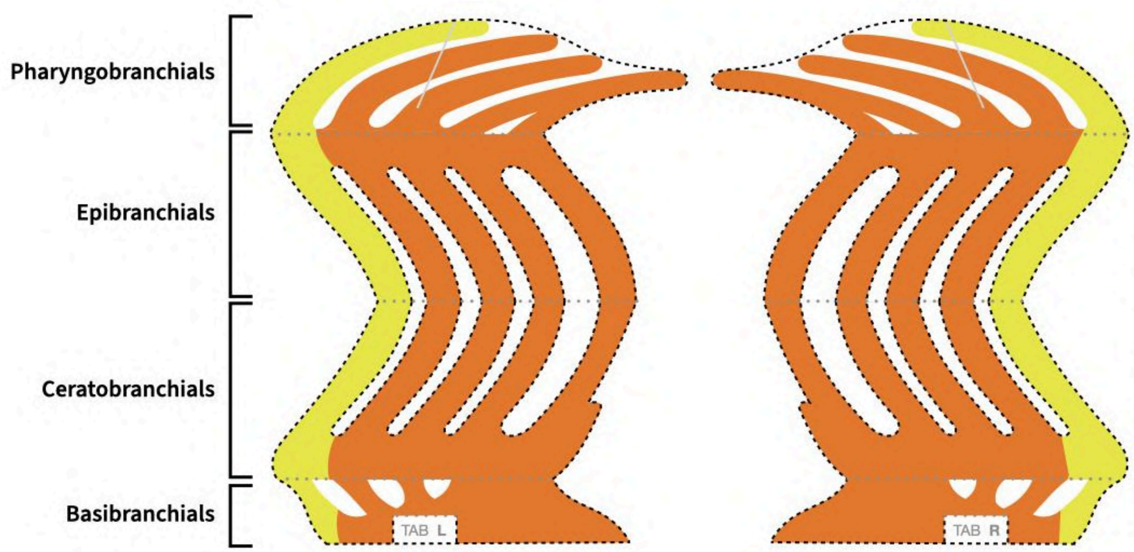
You've now added all the cartilages of the first (mandibular) and second (hyoid) gill arch to your shark! However, there are still some remaining gill arches to add. If you look at the side of most sharks behind the head, you'll see a series of **external gill openings**, also called **gill slits**. 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.

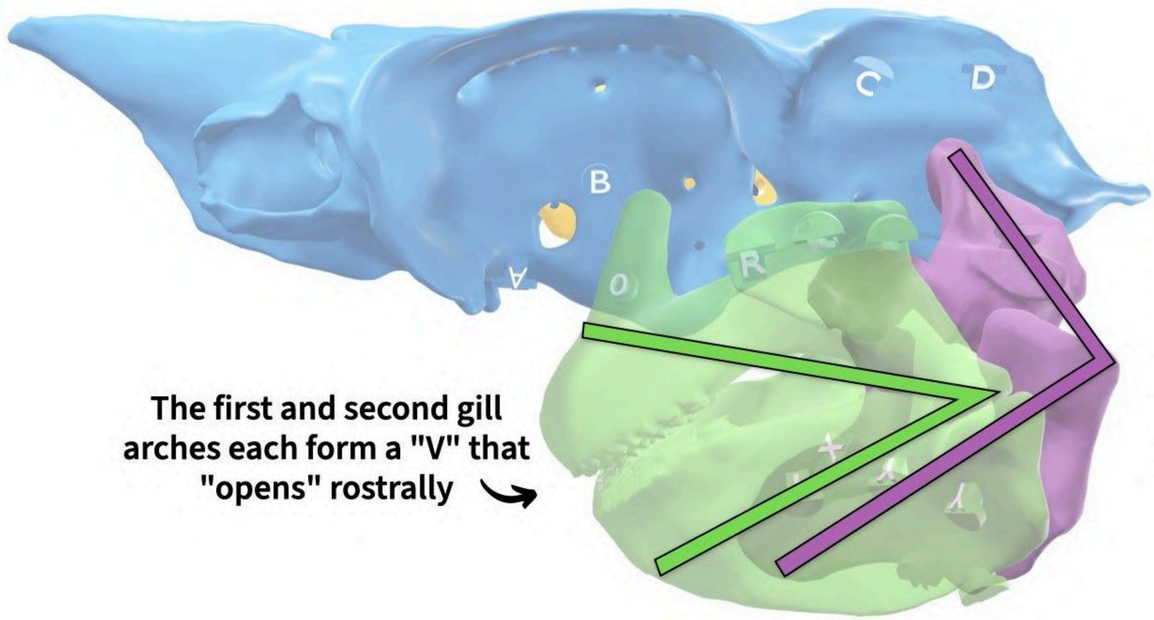
They're the yellow and orange cardstock paper pieces. You can tell the left and right side by looking at the small white tab: the left side has an "L" and the right side has an "R." Each branchial arch is composed of four parts: a **pharyngobranchial**, an **epibranchial**, a **ceratobranchial**, and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

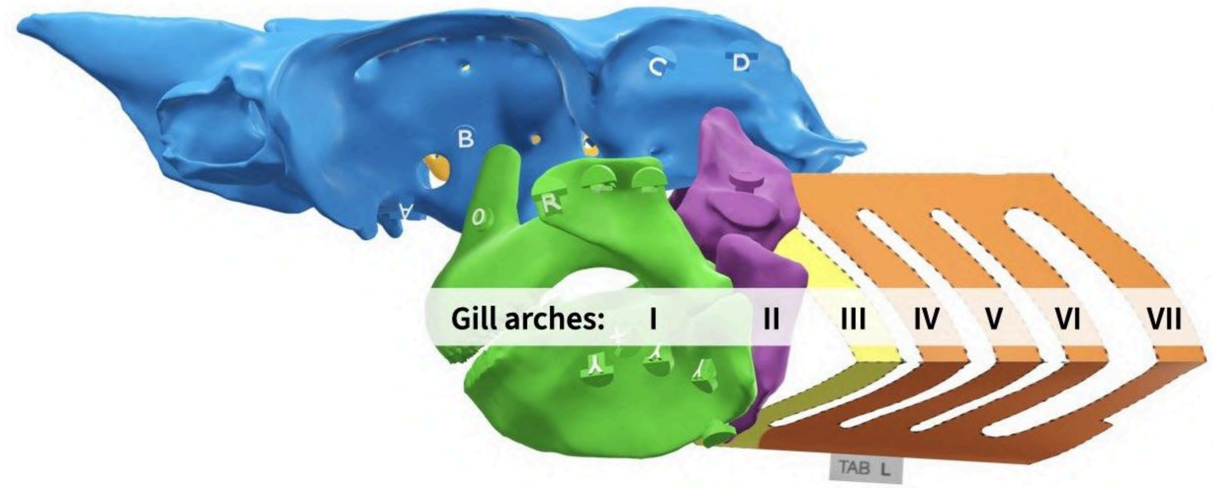
HINT: Continue the angle

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

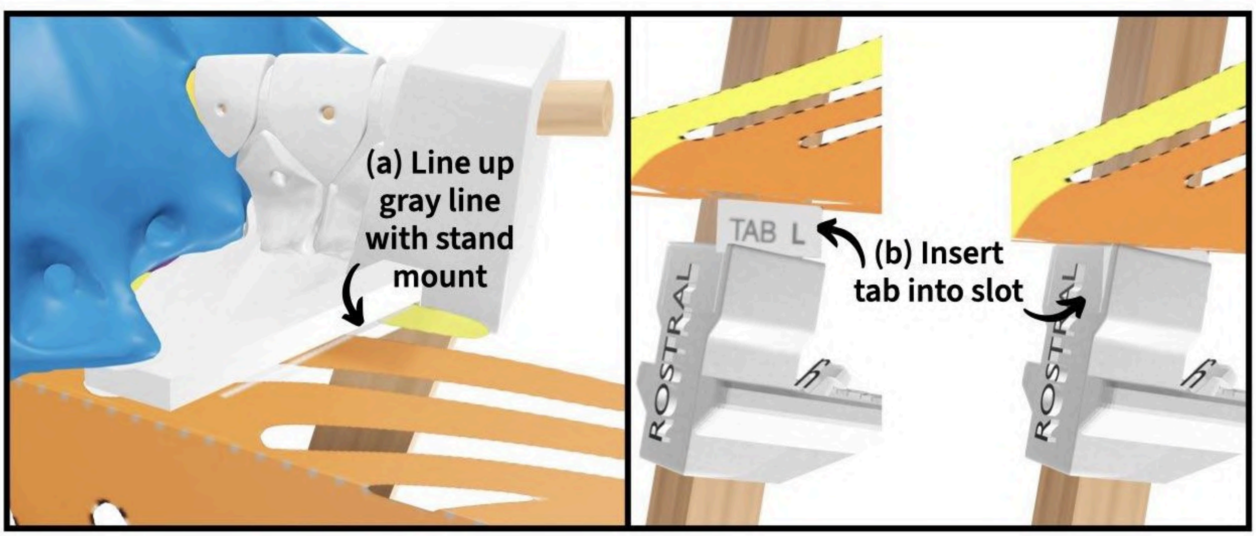
The position and orientation of the left branchial arches should look like the image below. Note that in the proper orientation, the yellow branchial arch is the third gill arch and the remaining four orange branchial arches are the fourth through seventh gill arches.



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

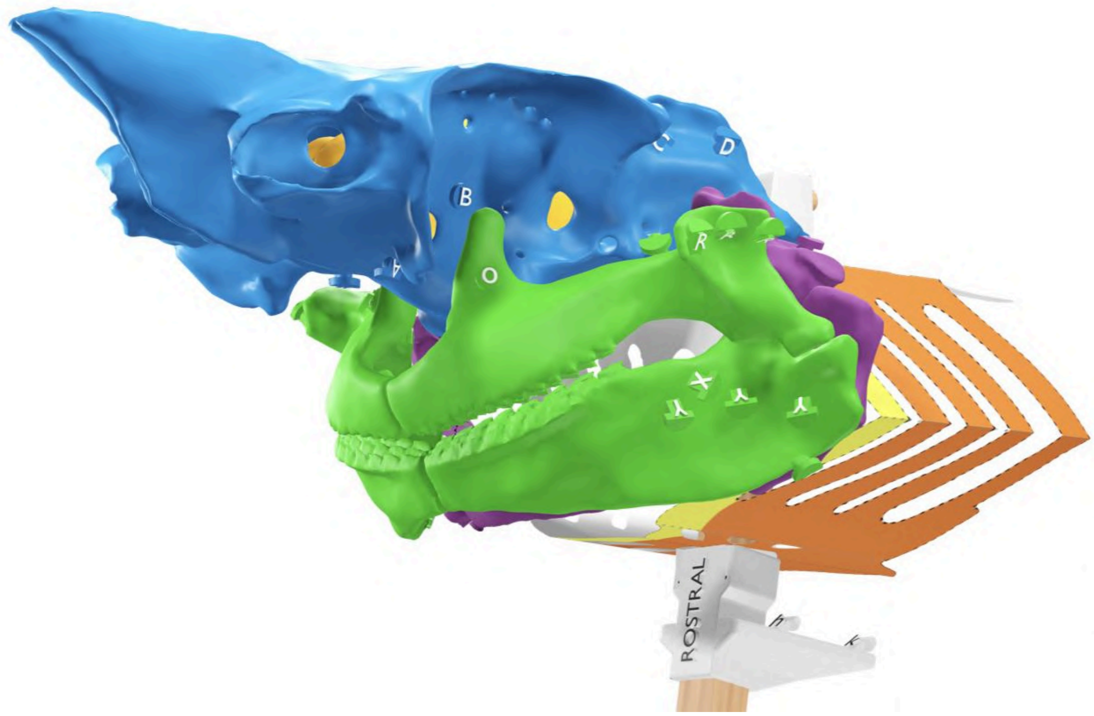
(a) sliding the pharyngobranchials into the slit of the top, stand mount piece until the gray line drawn across the first three pharyngobranchials reaches the mount,

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

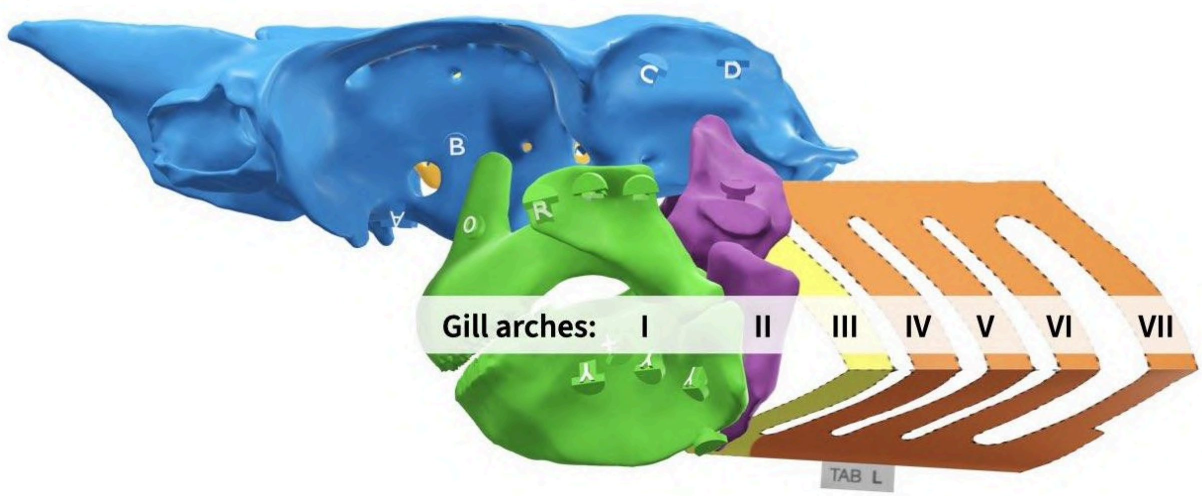


Add the right branchial arches, repeating the previous steps to attach them to the stand.

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?

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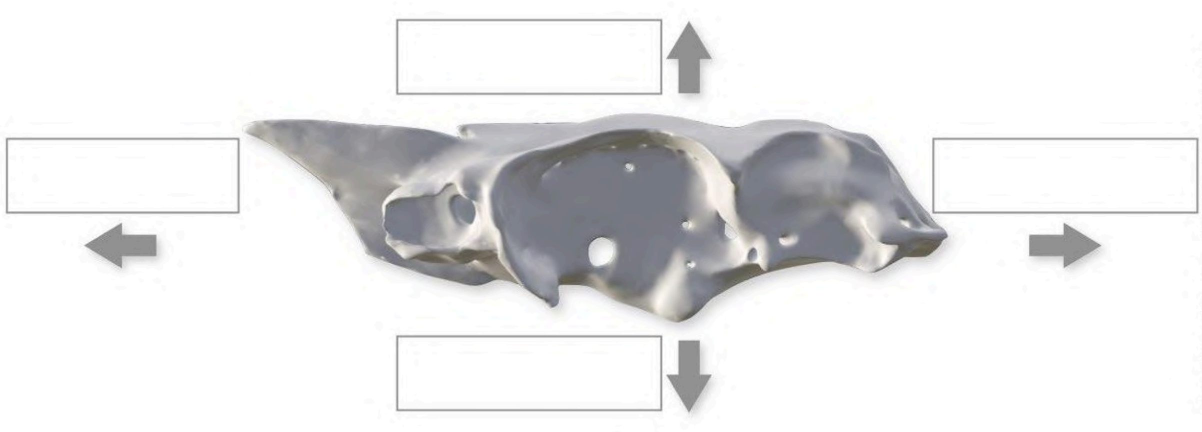
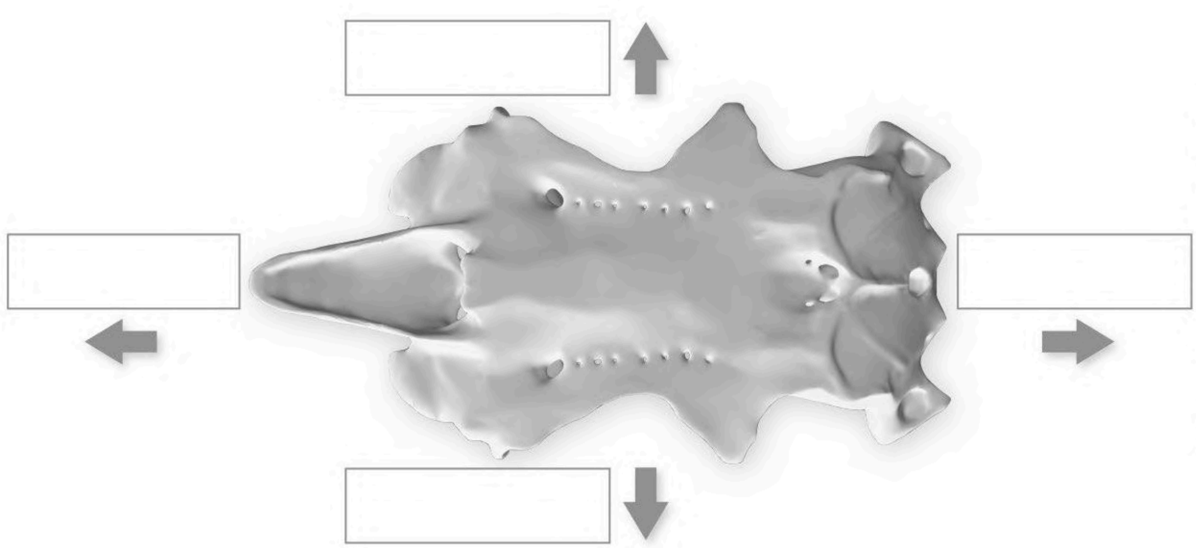
- Fallows, Chris, Austin J. Gallagher, and Neil Hammerschlag. "White sharks (*Carcharodon carcharias*) scavenging on whales and its potential role in further shaping the ecology of an apex predator." *PloS one* 8.4 (2013): e60797. DOI: 10.1371/journal.pone.0060797.
- Wegner, Nicholas C. "Elasmobranch 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.

STUDENT NOTEBOOK

Section 1. What is the anatomical orientation of the chondrocranium and brain?
Fill in the blanks in the image below using the following anatomical orientation terms (terms may be used more than once):

- Rostral (or Cranial)
- Caudal
- Dorsal
- Ventral
- Left
- Right





Section 3. How is it possible for sharks to protrude their jaws away from the rest of their skull during feeding?

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EDUCATOR GUIDE

Observing your shark's braincase and brain

Written by Aaron M Olsen, PhD

Time to complete: 40-60 min

Age level: Grades 11-12 or College

Bloom's levels: 1, 2, 4 & 5

Description: In this module, your students will become familiar with the structure of the braincase and brain of the spiny dogfish shark (*Squalus acanthias*) through observation and understand why they have the shape that they do.

Materials needed:

- SA02 Student Guide & Notebook v1.0
- Dogfish Shark Skull Kit v1.0 **OR** Dogfish Neuroanatomy Kit v1.0

Systems:

- Nervous
- Skeletal

Core concepts:

- Morphological integration
- Structure & function

Competencies:

- Observation
- Scientific communication
- Scientific reasoning

Module ID: SA02

Module version: 1.1

Module sequence (suggested):

SA02 → SA03 → SA01 → SA05 → SA04

How to use and edit this module

This is an open-source active learning module created by 3D Anatomy Studios and licensed under CC NC-BY-SA for use with the Dogfish Shark Skull Kit or Dogfish Neuroanatomy Kit.

Module Structure

This module has an **Educator Guide**, a **Student Guide**, and a **Student Notebook** and is divided into one or more sections, each with a number, a motivating question as its heading, and a learning objective.

Educator Guide

The **Educator Guide** is intended for educators and contains a pedagogical schema for the module to help implement the module in a course (e.g., learning objectives, target Bloom's level and competencies, core concepts), an answer key for certain prompts/questions in the the **Student Notebook**, and module updates.

Student Guide

The **Student Guide** is intended for students to read as they complete the module's activities and can be read on a device or printed out.

Student Notebook

The **Student Notebook** contains worksheets or diagrams on which students can write or draw as a part of the module's activities. The **Student Notebook** can be printed out or filled in using a digital tablet.

Sharing and Editing

The CC NC-BY-SA license allows you to share and edit this module as long as you (1) do not sell the module or module derivatives ("NC"), (2) attribute the author(s) of all the content, including preserving text and graphic attributions ("BY"), and (3) share the module under the same license ("SA"). You can edit this module by copying the current Google Doc of this module (accessible at 3danatomystudios.com/guides/SA00) and editing that copy.

Purchasing Kits

To purchase kits, please visit 3danatomystudios.com/shop/dogfish-skull-kit.

Pedagogical schema

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

Learning objective	**Identify (Bloom's Level 1 - Remember)** the chondrocranium and brain and **interpret (Bloom's Level 2 - Understand)** their orientation and position relative to one another.
Activity	Observe models of the shark braincase and brain and fill in blanks on an anatomical conceptual image
Self-assessment	Compare fill-in-the-blank responses with possible responses in the student guide
Systems	**Skeletal**
Core concepts	**Structure & function**
Competencies	**Observation**

Section 2. What do you notice about the brain relative to the endocranial cavity?

Learning objective	**Explain (Bloom's Level 5 - Evaluate)** why the shark brain and endocranial cavity differ in their shape if provided with the brain and chondrocranium.
Activity	Observe models of the shark braincase and brain and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Nervous** **Skeletal**
Core concepts	**Morphological integration** **Structure & function**
Competencies	**Observation** **Scientific communication** **Scientific reasoning**

Section 3. Which chondrocranium foramina could be for cranial nerves?

Learning objective	**Infer (Bloom's Level 4 - Analyze)** which foramina of the chondrocranium could convey cranial nerves out of the endocranial cavity.
Activity	Observe the foramina of a shark braincase model and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Nervous**
Core concepts	**Structure & function**
Competencies	**Observation**

Section 4. Which of these foramina isn't like the others?

Learning objective	**Infer (Bloom's Level 4 - Analyze)** which foramen in the endocranial cavity corresponds to the vestibular nerve if provided with the chondrocranium and a pipe cleaner or light.
Activity	Observe the foramina of a shark braincase model and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Nervous**
Core concepts	**Structure & function**
Competencies	**Observation**

Section 5. What differences do you notice among the cranial nerve foramina?

Learning objective	**Explain (Bloom's Level 5 - Evaluate)** the differences in relative size of the cranial nerve foramina if presented with the chondrocranium.
Activity	Observe the cranial nerve foramina of a shark braincase model and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Nervous** **Skeletal**
Core concepts	**Structure & function**
Competencies	**Observation**

Answer key

Section 2. What do you notice about the brain relative to the endocranial cavity?

What do you notice about the brain relative to the endocranial cavity?

- The brain does not completely fill the endocranial cavity
- The brain is closer to the endocranial cavity walls in some places than in others
- The brain moves a bit inside the braincase if the braincase is shaken

What are one or more potential explanations for why the brain does not completely fill the endocranial cavity?

- There are other tissues surrounding the brain that are not represented in this model
- There is fat/adipose tissue surrounding the brain to cushion the brain during head impacts
- Additional space around the brain is needed for blood vessels or other tissues
- There is fluid surrounding the brain within the braincase that allows the brain to move within the chondrocranium
- As the shark develops and gets larger, the brain does not grow at the same rate as the braincase/chondrocranium

What explanation did you find in Yopak et al. 2019? Is it contrary to or compatible with your explanation?

- In some groups of sharks, the body grows at a faster rate than the brain, resulting in a brain that does not completely fill the endocranial cavity (low level of encephalization)

Does your previous explanation work for both sharks and humans? If not, can you revise your explanation so that it does?

- Humans are well known for having a high degree of encephalization (a large brain relative to body size) due to the human brain both evolving to be larger relative to body size (within primates) and growing larger over development within an individual. So the explanation for encephalization of brain vs. body growth could also explain the degree to which the brain fills the endocranial cavity in humans.

Section 5. What differences do you notice among the cranial nerve foramina?

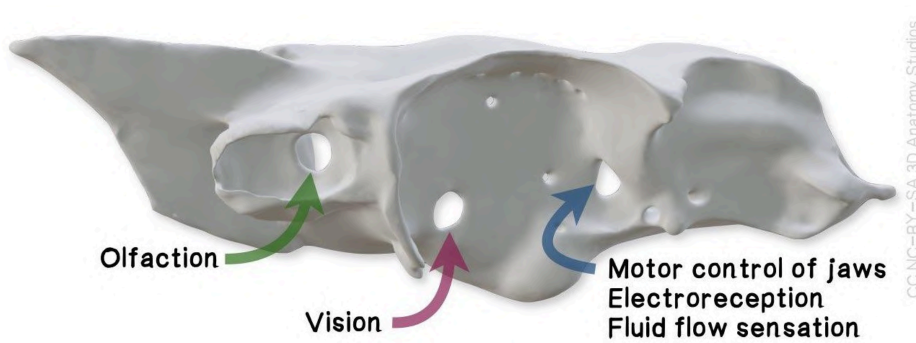
What differences do you notice among the cranial nerve foramina?

- Different sizes
- Different positions
- Different orientations
- Different path lengths through the chondrocranium (some foramina form a longer "tunnel" through the chondrocranium)

What are one or more potential explanations?
As the previous hint suggests, the diameter of a nerve is related to how much information it can carry and how quickly it can carry that information. Cranial nerves do not all need to carry the same amount of information at the same speed. Some structures send and receive more information than others and some information may be more important for quick decisions than other information. Therefore, cranial nerves differ in their diameter and thus so do the foramina that convey those cranial nerves. Note that the foramen cannot tell you the actual diameter of the cranial nerve(s) it conveys. A cranial nerve could be smaller than the foramen. However, it does tell you the maximum diameter of the cranial nerve at that point in the nerve's trajectory.

What information do you think is carried by the cranial nerves that pass through the three largest cranial nerve foramina of the braincase?
These three largest foramina convey cranial nerves that carry the following information (from rostral to caudal):

- Olfaction and chemosensation (from the olfactory organ)
- Visual information (from the retina of the eye)
- Electroreception, sensation of fluid flow on the skin, jaw motor control



Why? What do your three choices above all have in common?
All of these represent sensory information used to detect, catch, or defend against other animals, including potentially fast swimming prey or predators. A shark needs to receive a lot of this type of information and receive it quickly so that it has time to process the information, make a decision, and move accordingly. Thus, the corresponding cranial nerves, and the foramina they pass through, have large diameters.

Updates

Version 1.1

- Moved self-assessment for open-ended questions from the Student to Educator Guide.
- Added possible student responses for Section 2 to Educator Guide.

STUDENT GUIDE

Observing your shark's braincase and brain

Written by Aaron M Olsen, PhD

Description

In this module, you will become more familiar with the structure of the braincase and brain of the spiny dogfish shark (*Squalus acanthias*) through observation and gain a better understanding of why they have the shape that they do.

Introduction

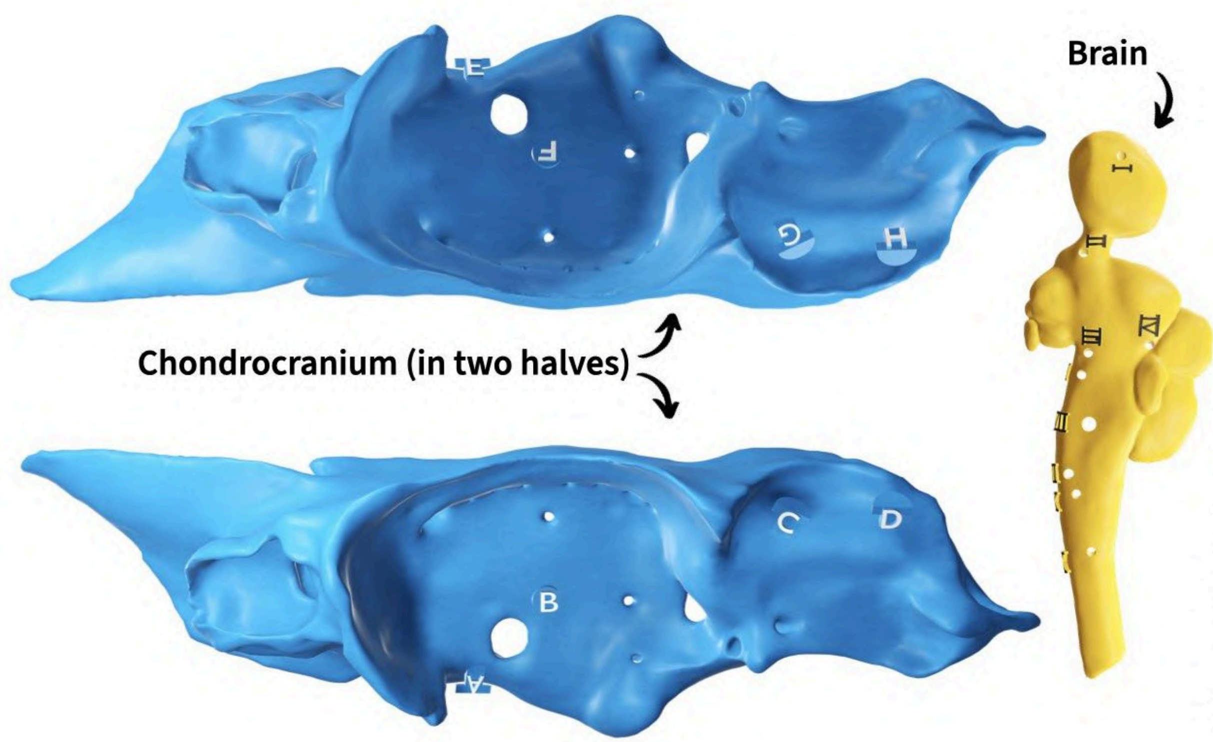
The chondrocranium of a shark will probably look like nothing you have ever seen before—like alien anatomy. However, the more you observe something, the more familiar it will become. And the more you will see, and the more you will understand. For one thing, what are all those holes for?

In this module, you will become more familiar with the structure of the braincase and brain of the spiny dogfish shark through observation and gain a better understanding of why they have the shape that they do. In particular, you'll reason through the orientation of the chondrocranium and the functions of some of its features.

Materials needed

For this module, you'll need:

- The **Student Notebook** for this module (SA02).
- The **chondrocranium** and **brain** from your shark kit (see image below). The chondrocranium comes in two parts and these are the largest parts in the kit. If your kit is color coded, the chondrocranium pieces are blue and the brain is yellow.



- **OPTIONAL** One pipe cleaner (any color) for tracing paths of cranial foramina

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

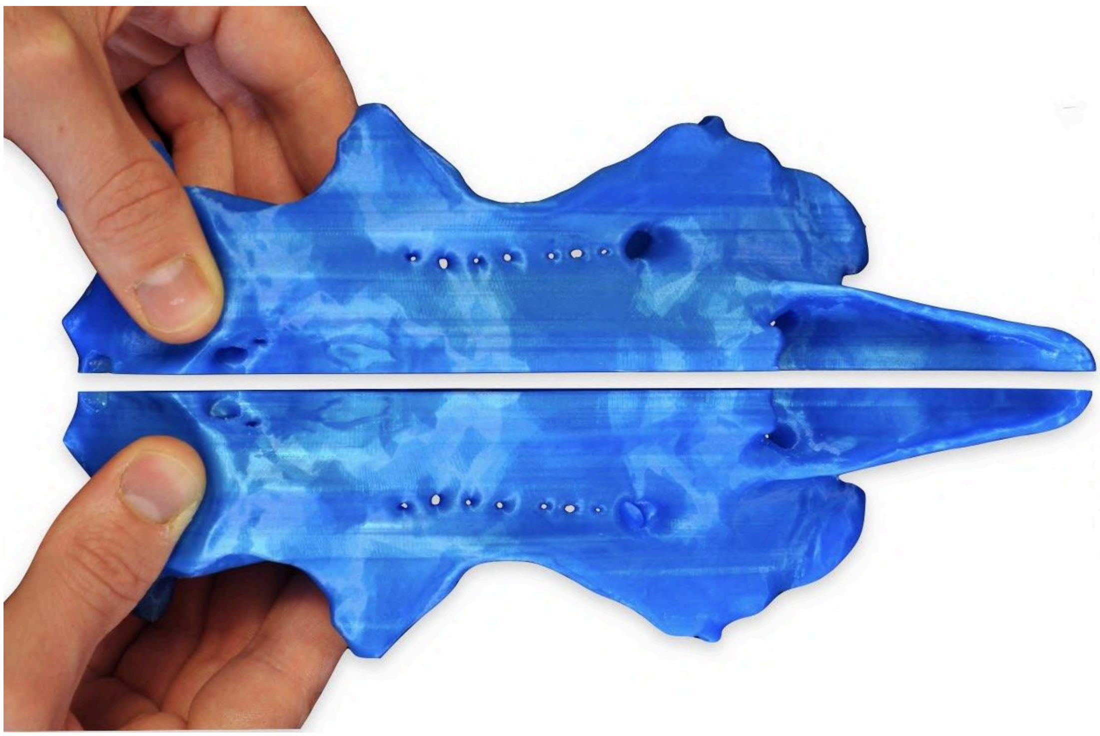
In sharks, the **chondrocranium** (meaning, "cartilaginous skull") is also known as the **braincase** because it *encases* the brain. If the two halves are not already snapped together as a whole piece, can you solve how they fit together? If you get stuck, use the hint at the bottom of this page. When you think you have it correct, check against the solution on the next page.

HINT: Find the flat surfaces

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 join together as shown in the image below.

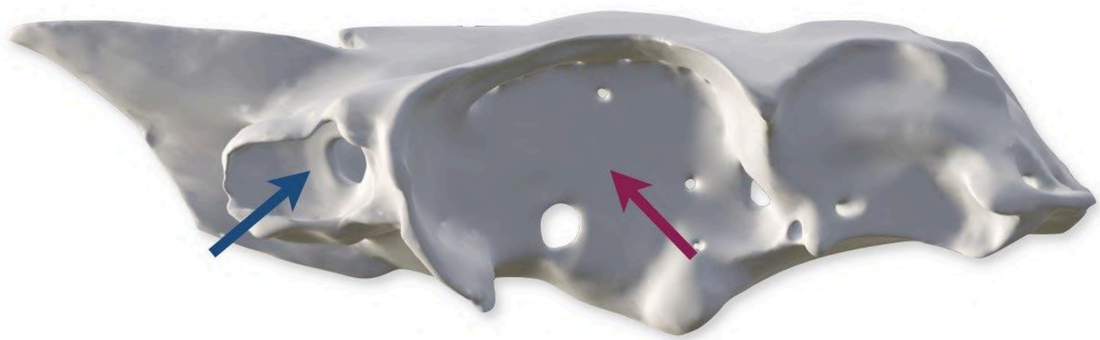


Now that you've solved how the two halves of the chondrocranium fit together, which is the left half and which is the right? Which end is **rostral** (toward the shark's snout or front end) and which end is **caudal** (toward the tail or back end)? Which side is **dorsal** (the shark's back) and which 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 right, use the following hints to check your work.

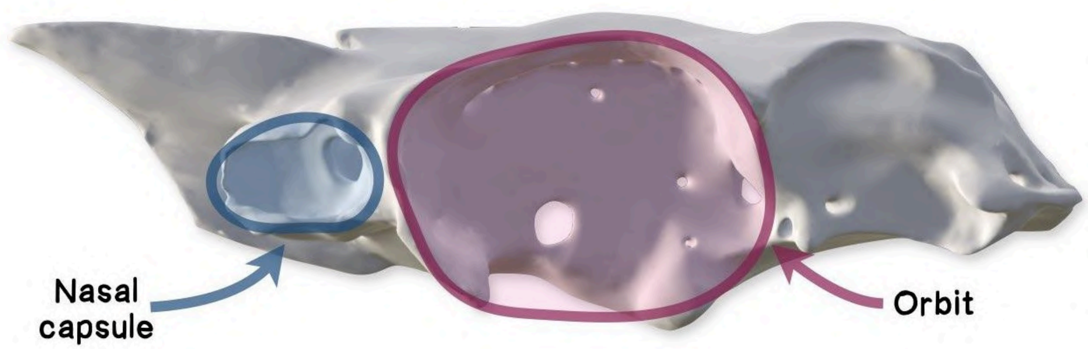
HINT: Where are the nose and eye?

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 in your **Notebook**? Check your answer in the next hint.



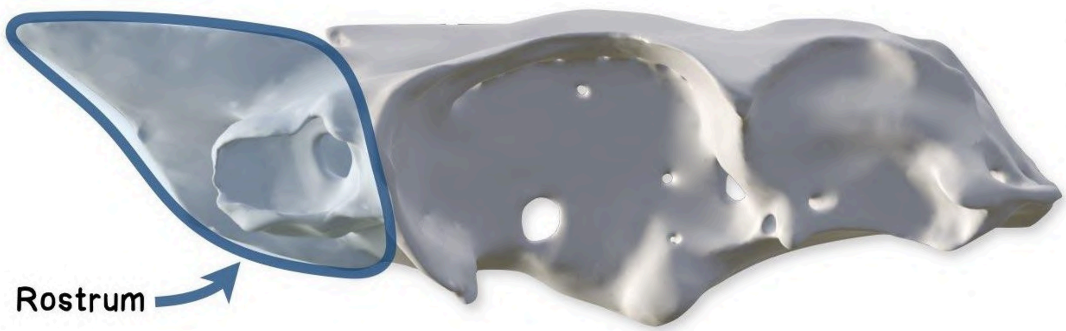
HINT: The nose is in front

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?



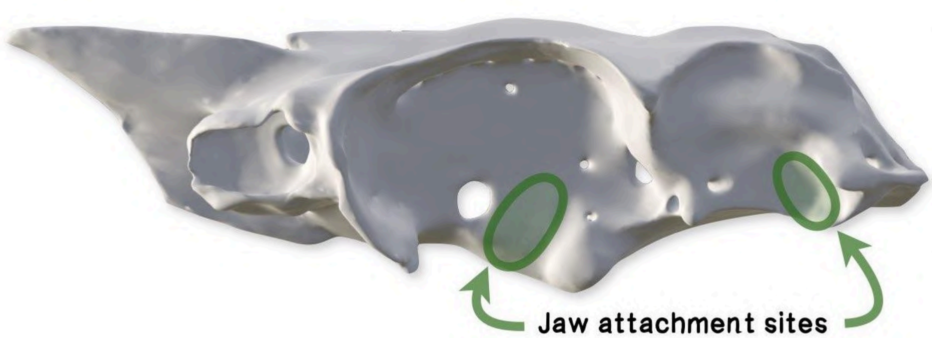
HINT: The snout of the shark

This image shows the **rostrum** (snout) of the shark. Do you need to change any of your answers?



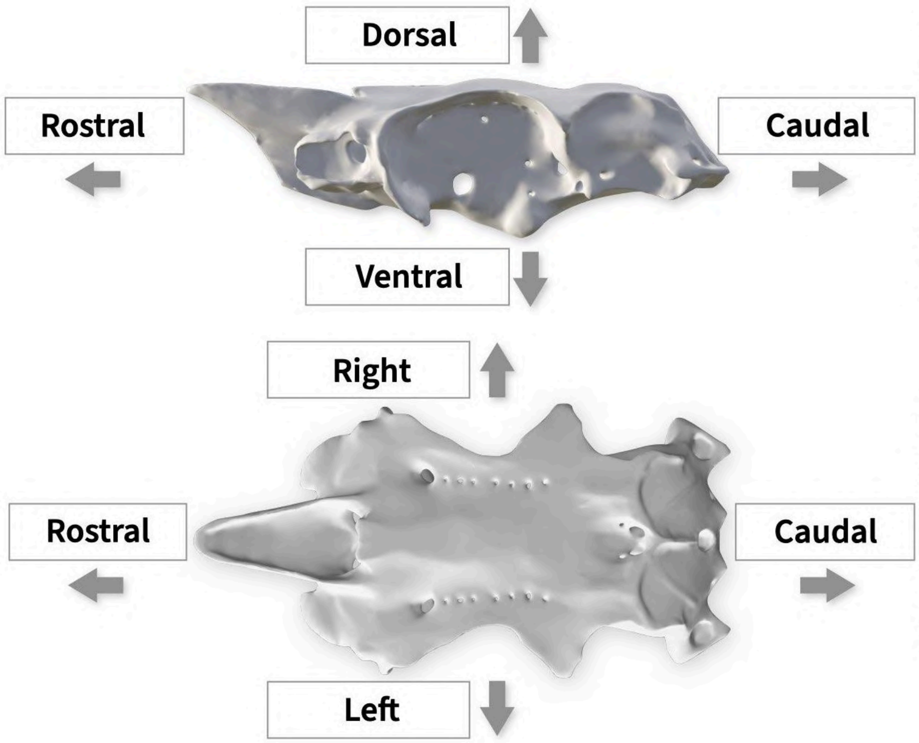
HINT: Where the jaws attach

And the circled areas in this image indicate where the jaws attach. Do you need to change any of your answers?



ASSESS: Braincase 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 is the brain oriented? Figure out how the brain fits inside the **endocranial cavity** (the space inside the chondrocranium that holds the brain). If you get stuck, check out the hint below.

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.

Section 2. What do you notice about the brain relative to the endocranial cavity?

Because the chondrocranium encases the brain, it has a close relationship with the brain. Take some time to observe the brain in relation to the endocranial cavity. What do you notice? List your observations on page 2 of your **Notebook**. If you get stuck, check out the hints below.

HINT: Is the brain a tight fit?

Are the brain and the endocranial cavity the same size? If you put the brain inside the endocranial cavity, "close" the braincase by bringing together the left and right sides, and shake the braincase, what do you notice?

HINT: A dissected brain

Here's another perspective that may help. This image is of a shark specimen, with the chondrocranium and brain cut down the middle (a midsagittal cut).

Once you've finished your observations, proceed to the next page.

One observation that you may have made is that the brain does not completely fill the endocranial cavity. *Why* do you think this is? Write one or more potential explanations on page 2 of your **Notebook**.

Other scientists have also noticed that the brain doesn't completely fill the endocranial cavity in some sharks. This 2019 research article by Yopak and colleagues, for example, discusses a potential explanation. Search that paper for their explanation and compare it with your own. Your goal is *not* to read the paper. Your goal is to find the relevant section of the paper as quickly as possible. If you get stuck, check out the following hint.

HINT: Use the search tool

Try using the "Find" feature in the browser or PDF viewer to locate relevant terms (e.g., "endocranial"). Remember that the Discussion section of research articles typically contains the authors' explanations of results or other observations.

Once you've understood their explanation, summarize it in your own words on page 2 of your **Notebook** and compare it to your own explanation.

In humans, does the brain completely fill the endocranial cavity? (If you're unsure, a Google image search can help you find an answer quickly). Does your revised explanation explain the size of the brain relative to the braincase in *both* sharks and humans? If not, come up with a revised explanation on page 3 of your **Notebook**.

Section 3. Which chondrocranium foramina could be for cranial nerves?

As you have been observing the chondrocranium, you've probably noticed that it is full of holes! These are not defects; they represent actual **foramina** (holes) of the chondrocranium.

The brain and spinal cord together form a **central nervous system** (abbreviated **CNS**), which receives, sends, and integrates information from all over the body. Think of the CNS as a continuous system: within the braincase it's called the brain, within the spine it's called the **spinal cord**. To reach the CNS, nerves need to travel in and out of the braincase and spine. The nerves that enter and exit the CNS within the chondro*cranium* are called ***cranial* nerves** whereas those that enter and exit the CNS along the *spine* are called ***spinal* nerves**.

Using observation and reasoning, can you figure out which foramina of your chondrocranium could potentially **convey** (allow passage of) cranial nerves *directly* from the brain? Circle these foramina on page 4 of your **Notebook**. Also, mark with an arrow the **foramen** (singular of foramina) you think conveys the CNS as it leaves the chondrocranium (i.e., the spinal cord).

If you need help, use the hint below. Then check your work on the next page.

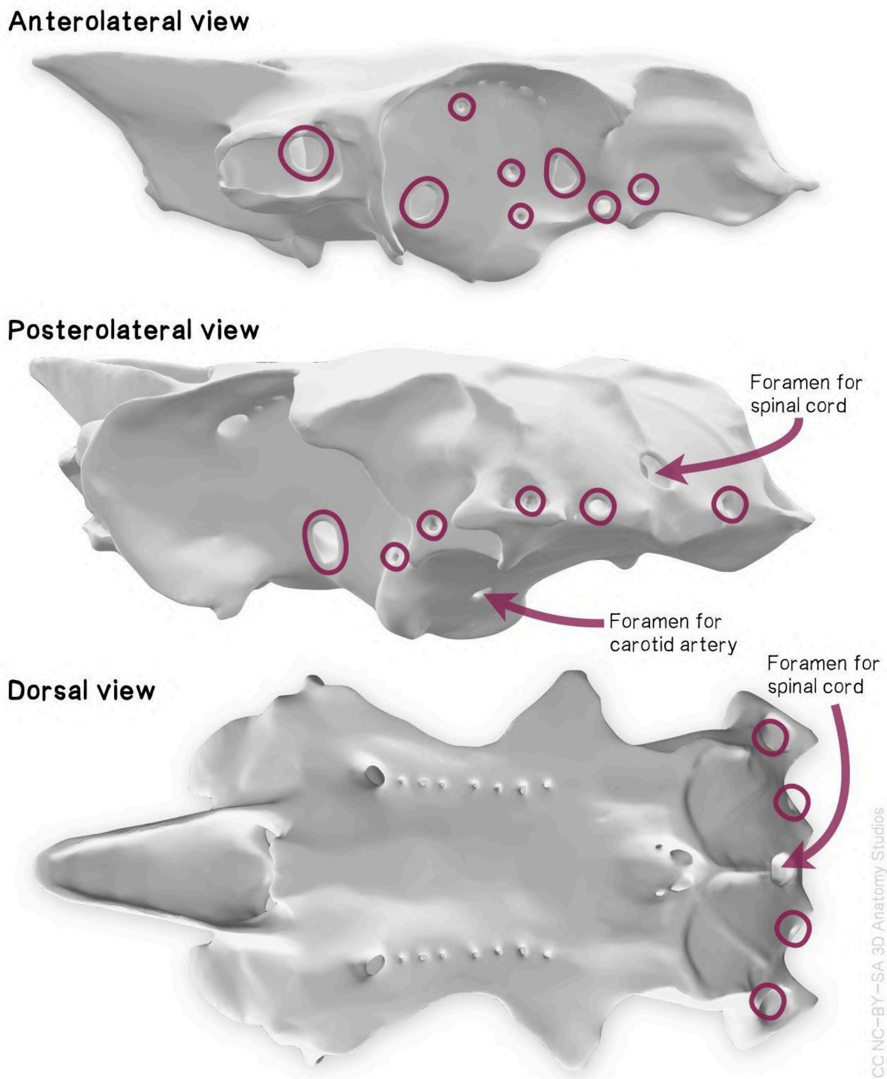
HINT: Connect the spaces

You might find it easier to make these observations with the whole chondrocranium (the two halves together). Try shining a light into the endocranial cavity through one of the foramina. Or try inserting a pipe cleaner into the foramina to see where they lead.

If a foramen could potentially convey a cranial nerve directly from the brain and out of the chondrocranium, what two spaces must it connect?

ASSESS: Cranial nerve foramina

Nearly all of the foramina that connect the endocranial cavity with the area outside of the chondrocranium carry cranial nerves directly from the brain, indicated by circles below.



A few exceptions are: the carotid artery foramen and the foramen for the spinal cord (the **foramen magnum** or "big hole"). Take a moment to appreciate the power of observation in anatomy: without any specialized knowledge and by just observing the connectivities, you were able to identify nearly all of the cranial nerve foramina!

Section 4. Which of these foramina isn't like the others?

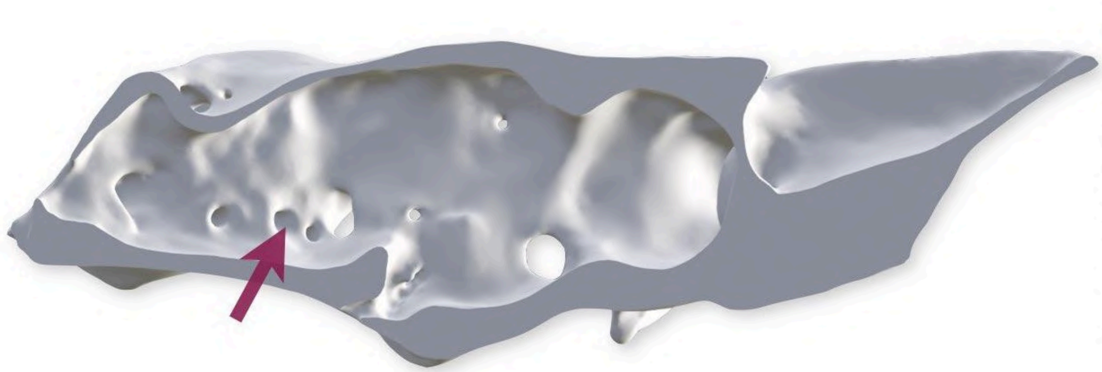
Now take some time to observe the foramina of the chondrocranium from the inside by looking at the half chondrocranium. In the previous activity, you observed the connectivities of the foramina (i.e., what spaces they connect). Observing the foramina from the inside, which foramen *inside* the endocranial cavity isn't like the others? Check out the hint below if you get stuck and check your answer on the next page.

HINT: Where does each hole lead?

Use a light or a pipe cleaner to test where each foramen leads from the endocranial cavity.

ASSESS: The dead-end foramen

Did you find the one foramen that *doesn't* connect to a space outside of the braincase? It's indicated below.



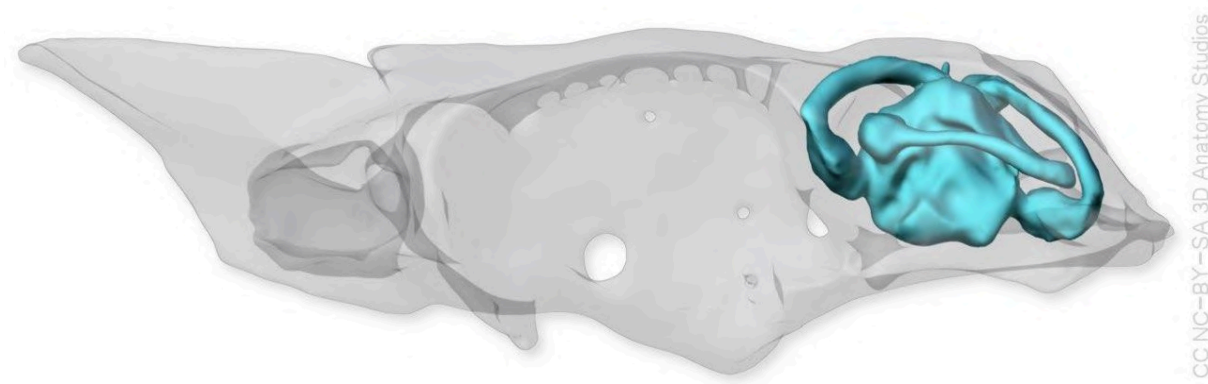
The foramen indicated by the arrow in the image above carries a cranial nerve. What structure do you think you would find at the end of this foramen/canal? That is, what structure do you think this cranial nerve is carrying information to/from? If you get stuck, check the hint below.

HINT: An internal sensory system?

What sensory structure is contained within your skull? It's not really "exposed" to the outside like the eyes or nose. It can get all the sensory information it needs within the skull. And if this structure is damaged, one of the symptoms you would likely feel is dizziness.

ASSESS: The vestibular system

This foramen that is not like the others leads to the **vestibular system**, highlighted in the image below.



The vestibular system is like a gyroscope and accelerometer all in one. It helps an organism sense orientation and acceleration to maintain balance. Since the vestibular system is contained entirely within the braincase, the cranial nerve that enters this foramen does not need to leave the braincase.

Section 5. What differences do you notice among the cranial nerve foramina?

Besides differences in connectivity, what other differences do you notice among the chondrocranium foramina that convey cranial nerves? Write your observations on page 5 of your **Notebook**. If you get stuck, check the hint below.

HINT: Group by describing

If you were to group the cranial nerves, what characteristics would you use to group them? If you were to describe them to another person, what words would you use to describe them?

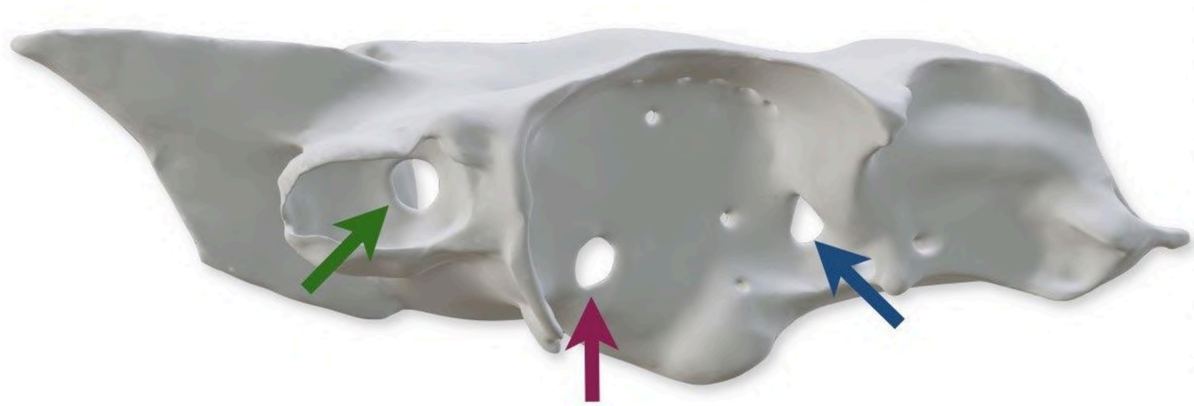
Once you've finished your list of observations, compare your list to some potential observations on the next page.

One observation you may have made is that the foramina are of different sizes. This is something you would see in all vertebrates. *Why* do you think this is? Write one or more potential explanations on page 5 of your **Notebook**. If you get stuck, check the hint below.

HINT: Diametrical analogies

A **nerve** is a bundle of many **neurons** and each neuron can carry a certain amount of information. In this way, a nerve is analogous to a bundle of fiber optic cables, electric wires, a water pipe, etc. Just as a larger diameter cable/wire/tube can carry more signals/current/water and carry them faster, a larger diameter nerve can carry more information and carry this information faster.

Based on your explanation, what information do you think is carried by the cranial nerves that pass through the three largest cranial nerve foramina (indicated in the image below) and *why*? Write your best guesses on page 5 of your **Notebook**. After you have some guesses, check the following hint to see if you're on the right track.



HINT: The information transmitted

Here's a list of the information carried by cranial nerves, grouped by the chondrocranium foramina that they pass through (in no particular order):

- Orientation and acceleration (from vestibular system)
- Motor control of a muscle that moves the eyeball
- Olfaction and chemosensation (from the olfactory organ)
- Sensation and motor control around the rostral gills
- Motor control of four muscles that move the eyeball
- Electroreception, sensation of fluid flow on the skin, jaw motor control
- Visual information (from the retina of the eye)
- Sensation and motor control around the posterior gills and gut

Your three guesses should be somewhere in this list. Use this hint to update your answer in your **Notebook**, if needed.

References cited

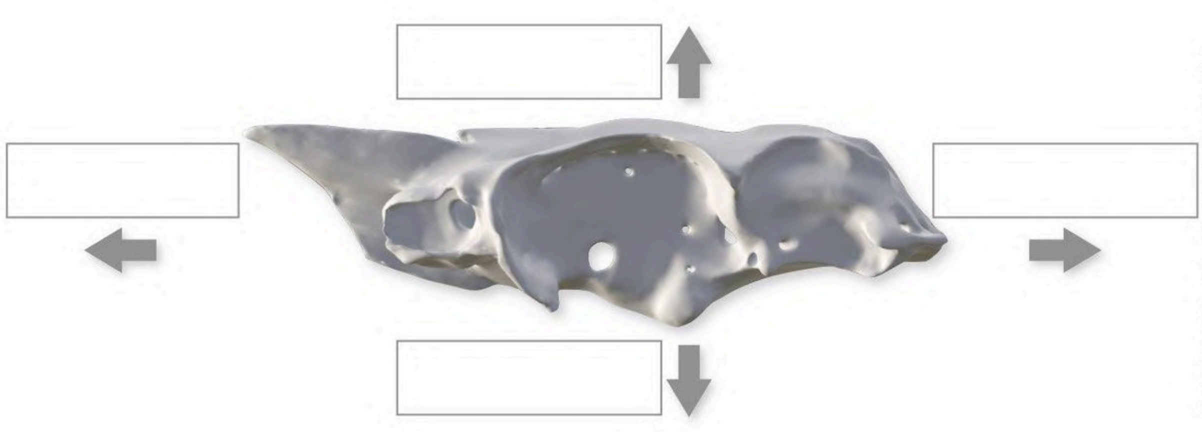
- Yopak, Kara E., et al. "Comparative brain morphology of the Greenland and Pacific sleeper sharks and its functional implications." *Scientific reports* 9.1 (2019): 1-15. DOI: 10.1038/s41598-019-46225-5.

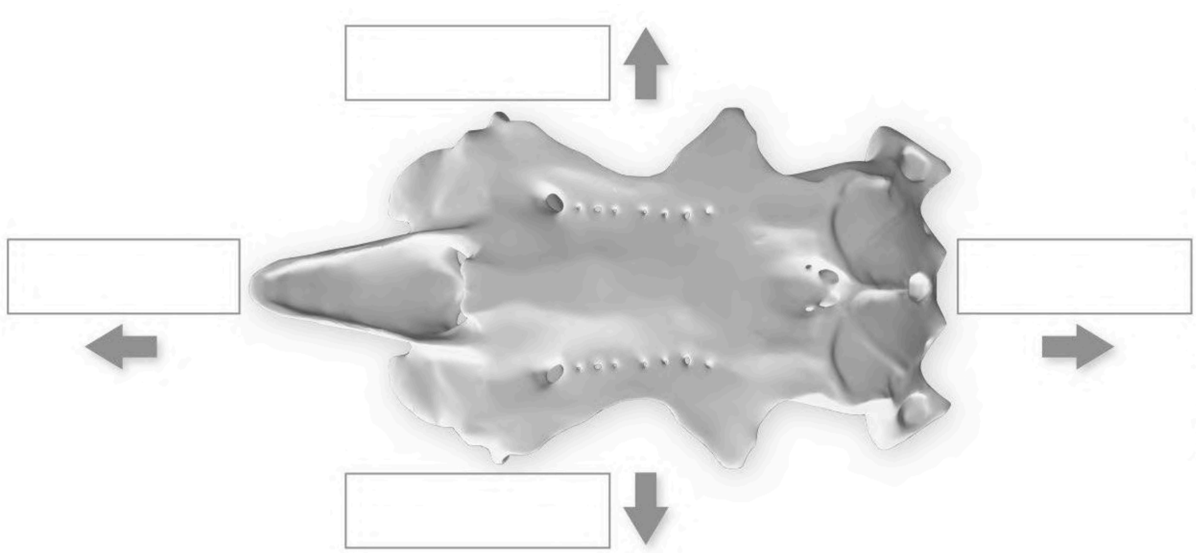
STUDENT NOTEBOOK

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

Fill in the blanks in the image below using the following anatomical orientation terms (terms may be used more than once):

- Rostral (or Cranial)
- Caudal
- Dorsal
- Ventral
- Left
- Right





Section 2. What do you notice about the brain relative to the endocranial cavity?

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What are one or more potential explanations?

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What explanation did you find in Yopak et al. 2019? Is it contrary to or compatible with your explanation?

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Does your previous explanation work for both sharks and humans? If not, can you revise your explanation so that it does?

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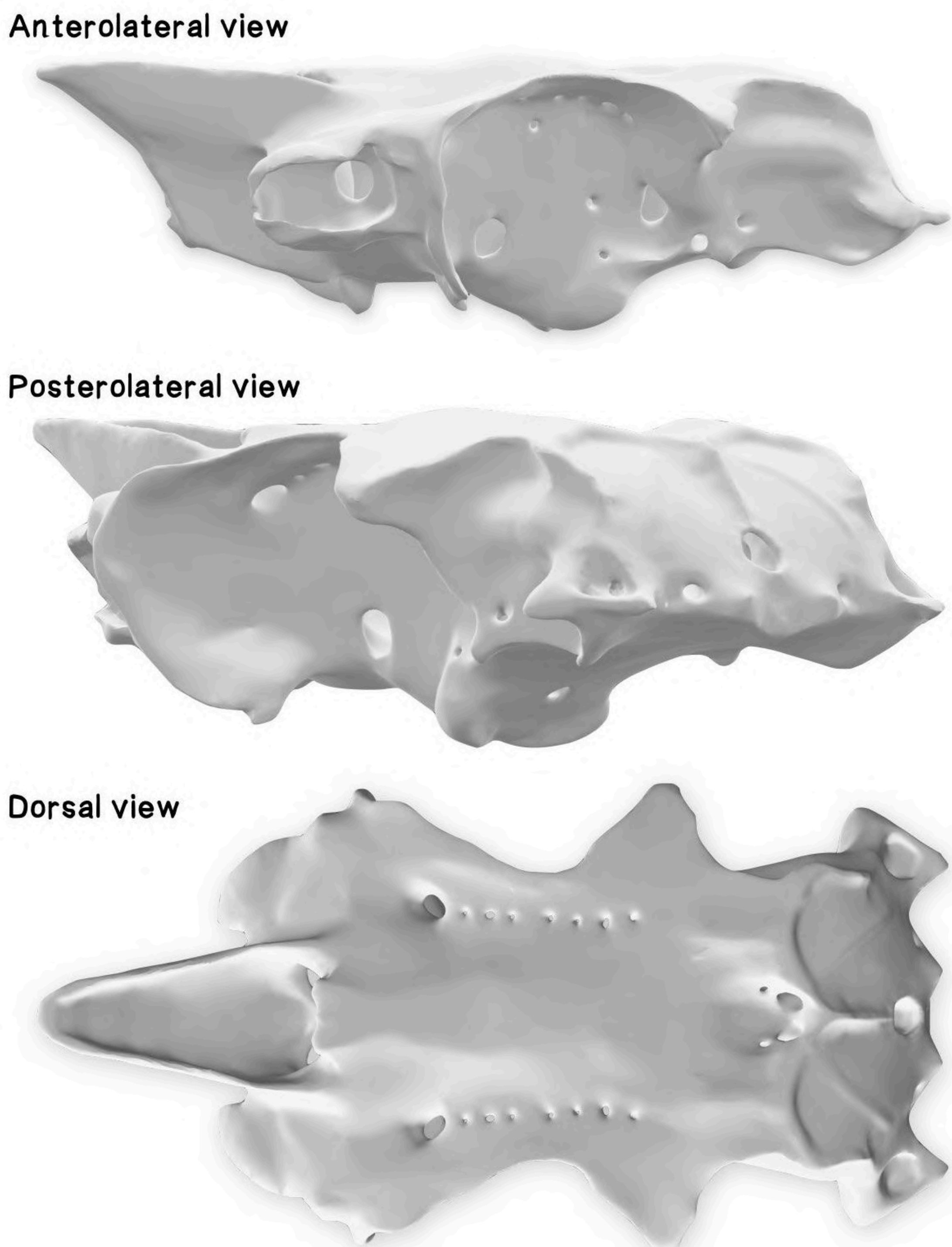
Section 3. Which chondrocranium foramina could be for cranial nerves?

Circle the foramina that could convey nerves directly from the brain.



Section 5. What differences do you notice among the cranial nerve foramina?

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What are one or more potential explanations?

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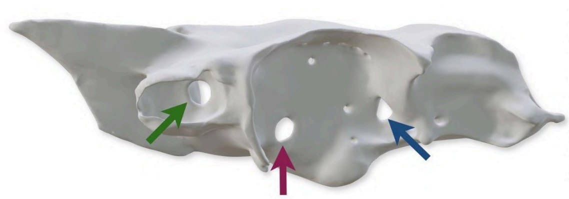
What information do you think is carried by the cranial nerves that pass through the three largest cranial nerve foramina of the braincase?

1. ________________________________

2. ________________________________

3. ________________________________



Why? What do your three choices above all have in common?

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EDUCATOR GUIDE
Wiring your shark's brain

Text and images by Aaron M Olsen, PhD

Time to complete: 40-60 min
Age level: Grades 11-12 or College
Bloom's levels: 1 & 3
Description: In this module, your students will learn the shark cranial nerves by connecting nerves to a brain model of the spiny dogfish shark (*Squalus acanthias*), tracing their paths out of the braincase, and completing a schematic diagram.
Materials needed:

- SA03 Student Guide & Notebook v1.0
- Dogfish Shark Skull Kit v1.0 **OR**

Systems:

- Nervous
- Sensory
- Skeletal

Core concepts:

- Structure & function

Competencies:

- Depiction of anatomy

Module ID: SA03
Module version: 1.1
Module sequence (suggested):

How to use and edit this module

This is an open-source active learning module created by 3D Anatomy Studios and licensed under CC NC-BY-SA for use with the Dogfish Shark Skull Kit or Dogfish Neuroanatomy Kit.

Module Structure

This module has an **Educator Guide**, a **Student Guide**, and a **Student Notebook** and is divided into one or more sections, each with a number, a motivating question as its heading, and a learning objective.

Educator Guide

The **Educator Guide** is intended for educators and contains a pedagogical schema for the module to help implement the module in a course (e.g., learning objectives, target Bloom's level and competencies, core concepts), an answer key for certain prompts/questions in the the **Student Notebook**, and module updates.

Student Guide

The **Student Guide** is intended for students to read as they complete the module's activities and can be read on a device or printed out.

Student Notebook

The **Student Notebook** contains worksheets or diagrams on which students can write or draw as a part of the module's activities. The **Student Notebook** can be printed out or filled in using a digital tablet.

Sharing and Editing

The CC NC-BY-SA license allows you to share and edit this module as long as you (1) do not sell the module or module derivatives ("NC"), (2) attribute the author(s) of all the content, including preserving text and graphic attributions ("BY"), and (3) share the module under the same license ("SA"). You can edit this module by copying the current Google Doc of this module (accessible at 3danatomystudios.com/guides/SA00) and editing that copy.

Purchasing Kits

To purchase kits, please visit 3danatomystudios.com/shop/dogfish-skull-kit.

Pedagogical schema

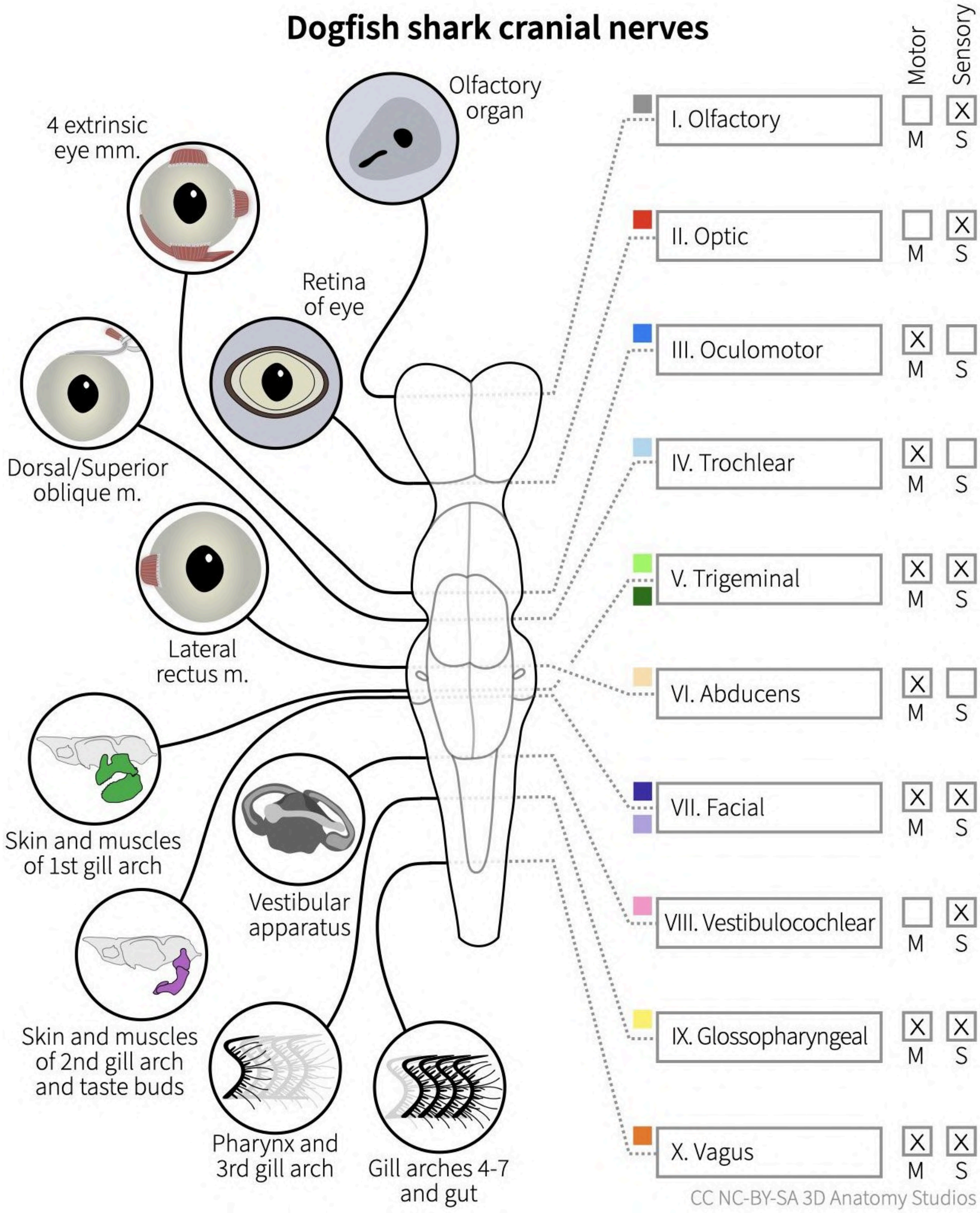
Section 1. What are your shark's cranial nerves and where do they go?

Learning objective	**Label (Bloom's Level 1 - Remember)** the name and number of each shark cranial nerve by fill-in-the-blank and **solve (Bloom's Level 3 - Apply)** the paths of the shark cranial nerves out to their target organs by **diagramming/sketching (Bloom's Level 3 - Apply)** a conceptual anatomical image of the brain and chondrocranium.
Activity	Attach pipe cleaners representing all the shark cranial nerves to a model of the shark brain, trace their paths out the foramina of a chondrocranium model, and fill in the blanks on a conceptual anatomical diagram
Self-assessment	Compare fill-in-the-blank responses with possible responses in the student guide
Systems	**Nervous** **Sensory** **Skeletal**
Core concepts	**Structure & function**
Competencies	**Depiction of anatomy**

Answer key

Section 1. What are your shark's cranial nerves and where do they go?

What are your shark's cranial nerves and where do they go?



How would you explain the structure and function of the chondrocranium in a single sentence?

The chondrocranium is structured as a series of four main "contained spaces" for the brain, olfactory system, visual system, and vestibular system and with foramina to convey nerves between the brain and each of these systems.

Updates

Version 1.1

- Moved filled-in schematic from the Student to Educator Guide.
- Added short-form summary question to Student Notebook at the end of Section 1.

STUDENT GUIDE

Wiring your shark's brain

Text and images by Aaron M Olsen, PhD

Description

In this module, you will learn the shark cranial nerves by connecting nerves to a brain model of the spiny dogfish shark (*Squalus acanthias*), tracing their paths out of the braincase, and completing a schematic diagram.

Introduction

In sharks, the **chondrocranium** (meaning, "cartilaginous skull") is also known as the **braincase** because it *encases* the brain. The brain and spinal cord together form a **central nervous system** (abbreviated **CNS**), which receives, sends, and integrates information from all over the body. Think of the CNS as one continuous system with two names: within the braincase it's called the brain, whereas within the spine it's called the **spinal cord**.

When a structure receives neural supply from a nerve, it is said to be **innervated** by that nerve. For nerves to **innervate** structures in the body, they need to travel in and out of the CNS (braincase and spine). The nerves that enter and exit the CNS within the chondro*cranium* are called ***cranial* nerves** whereas those that enter and exit the CNS along the *spine* are called ***spinal* nerves**.

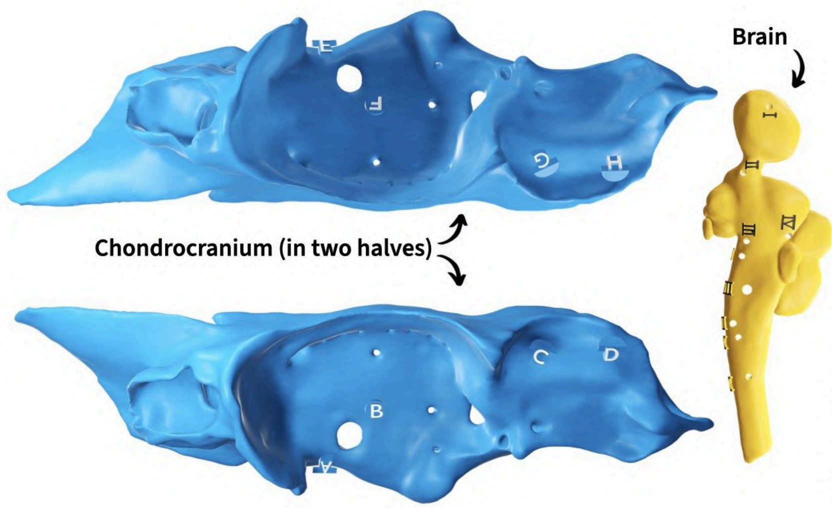
When you first learn the cranial nerves, they will just look like a long list of terms. It is always difficult to memorize a simple list of items (and you are very likely to forget them in the long term) because *your* brain doesn't have any additional context clues. If you learn the cranial nerves along with the context of their position, function, and development, you'll have an easier time remembering them.

In this module, you will learn this positional and functional context by "wiring up" cranial nerves (pipe cleaners) to the brain of your shark and tracing their paths out through the braincase toward their **innervation** targets. In the process, you'll also complete a corresponding "wiring diagram" to help you gain a conceptual understanding of the shark cranial nerves.

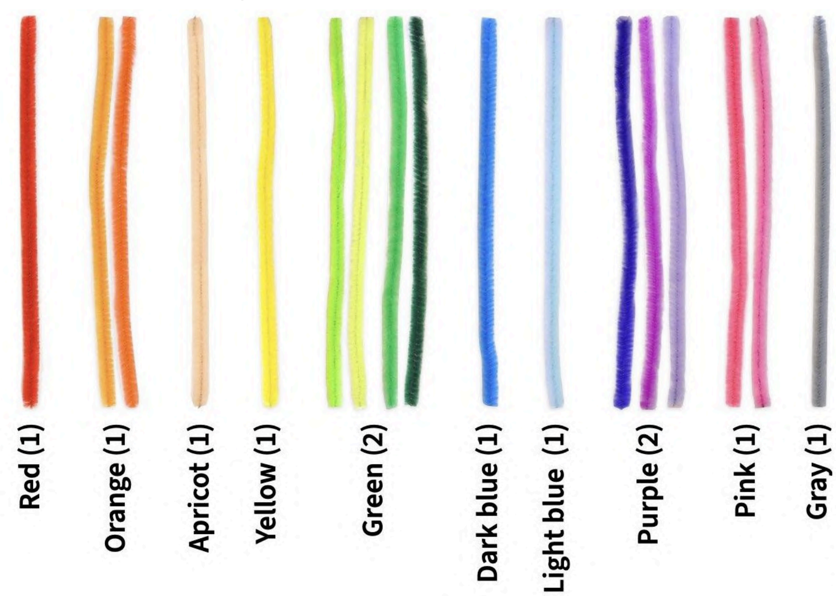
Materials needed

For this module, you'll need:

- The **Student Notebook** for this module (SA03).
- The **chondrocranium** and **brain** from your kit (see image below). The chondrocranium comes in two parts and these are the largest parts in the kit. If your kit is color coded, the chondrocranium pieces are blue and the brain is yellow.

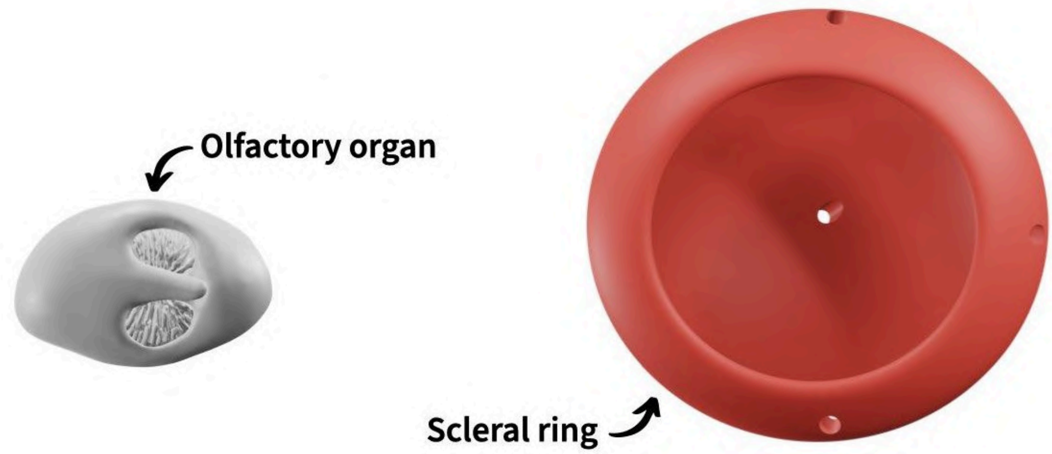


- The **pipe cleaners** from your kit. You should have 15 total but you'll only need 12 for this module (all *except* white, brown & black). Use the image below to find the 12 you need. For most colors, you'll have one pipe cleaner, indicated by "(1)" in the image. Where there are two pipe cleaners with a "(1)", you'll have one pipe cleaner matching one of the two colors. For green and purple, you'll have two pipe cleaners each.



Materials needed (continued)

- The **olfactory organ** and **scleral ring** from your kit.



COLOR NOTE: Color scheme optional

The use of particular colors for particular nerves or even different colors for different nerves is not essential for this module. If you're unable to distinguish among colors or want to use a different color scheme, feel free to disregard any color-related instructions.

Section 1. What are your shark's cranial nerves and where do they go?

The vertebrate cranial nerves are referred to by either their name, their number (as a roman numeral following "CN"), or both. For example, the first cranial nerve may be referred to in any of the following ways, where "n." is the abbreviation for nerve:

"CN I Olfactory n." or "CN I" or "Olfactory n." or "Olfactory n. (CN I)"

In this guide, the roman numeral will generally be included with the name to help you learn both the name and number for each nerve.

You'll connect your cranial nerves following the sequence of these roman numerals. As you'll see, this sequence goes approximately from the **rostral** (or **anterior**) end of the braincase (the front end, closest to the snout) to the **caudal** (or **posterior**) end of the braincase (toward the tail). This is, in part, because fish were used as a model when numbering the vertebrate cranial nerves. This fishy numbering scheme is used for *all* vertebrates, including humans.

Lateral line nerves

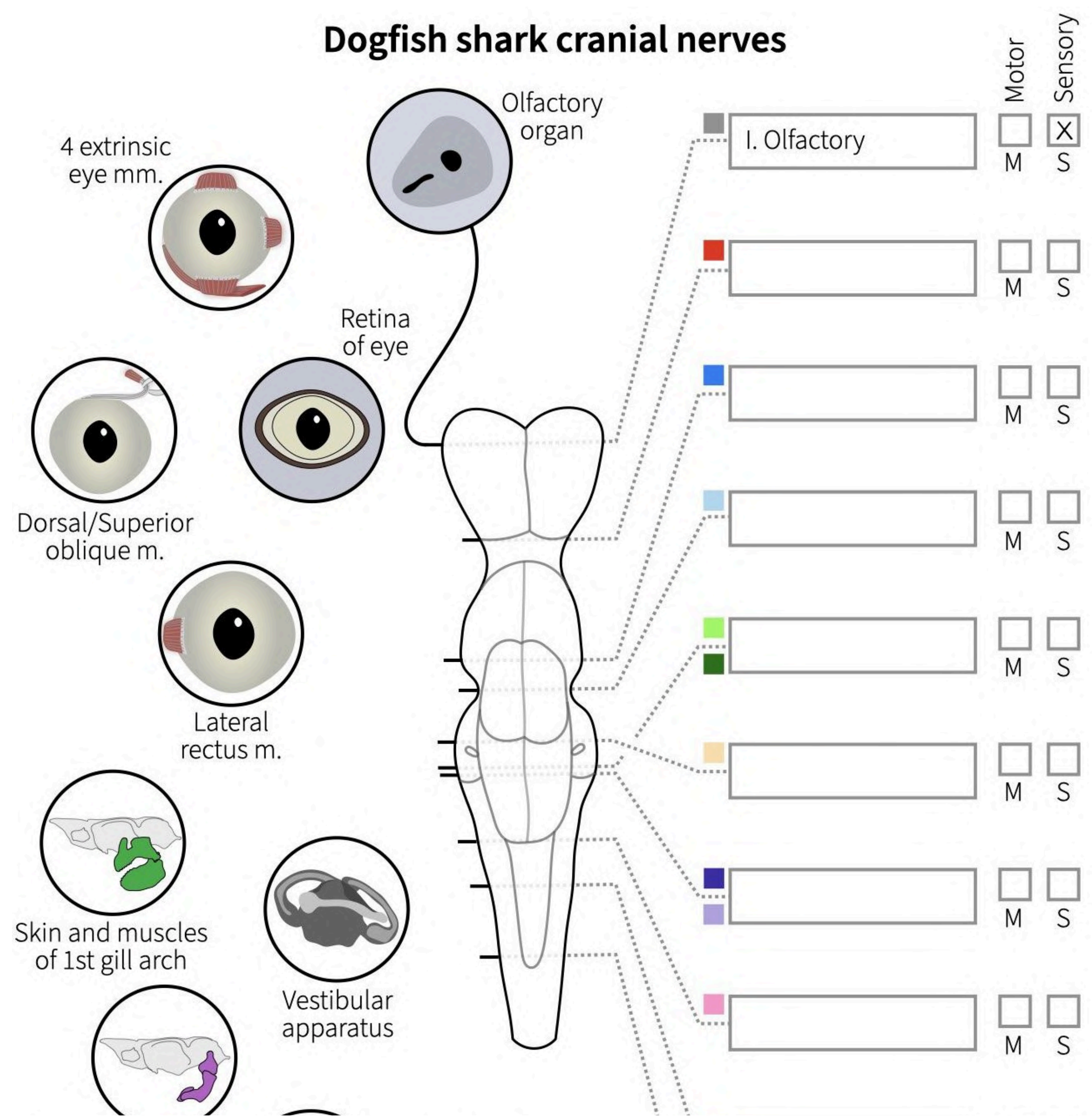
You'll often see a total of 10 cranial nerves listed for sharks, all having the same names as the first 10 cranial nerves in humans. It was previously thought that the **lateral lines** of fishes (sensory organs that can sense mechanical and, sometimes, electrical stimuli) were innervated by some of these 10 cranial nerves. However, it has recently been found that the lateral lines are innervated by a separate set of cranial nerves that connect to the brain in several different places and constitute an 11th cranial nerve. Thus, the lateral lines don't have an assigned roman numeral, like the other nerves. Additionally, since these nerves connect to the brain in many places, you won't connect any pipe cleaners representing the lateral lines in this activity. However, they are cranial nerves just as much as any other cranial nerve.

Olfactory nerve (CN I)

The first cranial nerve is the **olfactory n. (CN I)**. As the name implies (**olfaction** is the sense of smell), this nerve carries sensory information from the **olfactory organ** (or "nose"). Write in the name for this nerve on the schematic on page 1 of your **Notebook** and draw in the path of the nerve from the brain out to its target structure; also, indicate whether it carries sensory information, motor information, or both. Once you've finished, check your work against the solution on the following page.

ASSESS: CN I added

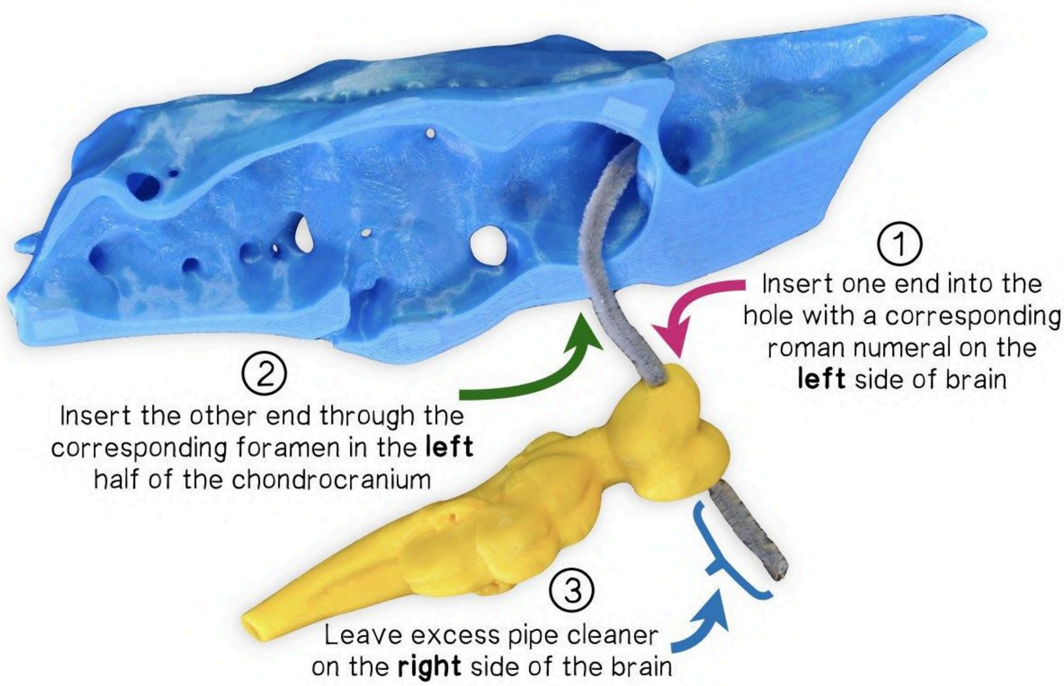
After adding the first cranial nerve, the schematic on page 1 of your **Notebook** should look like this, including a line drawn from the brain to nerve's target structure:



BUILD NOTE: Adding pipe cleaners

Use the following general steps to add each pipe cleaner (cranial nerve) to your brain:

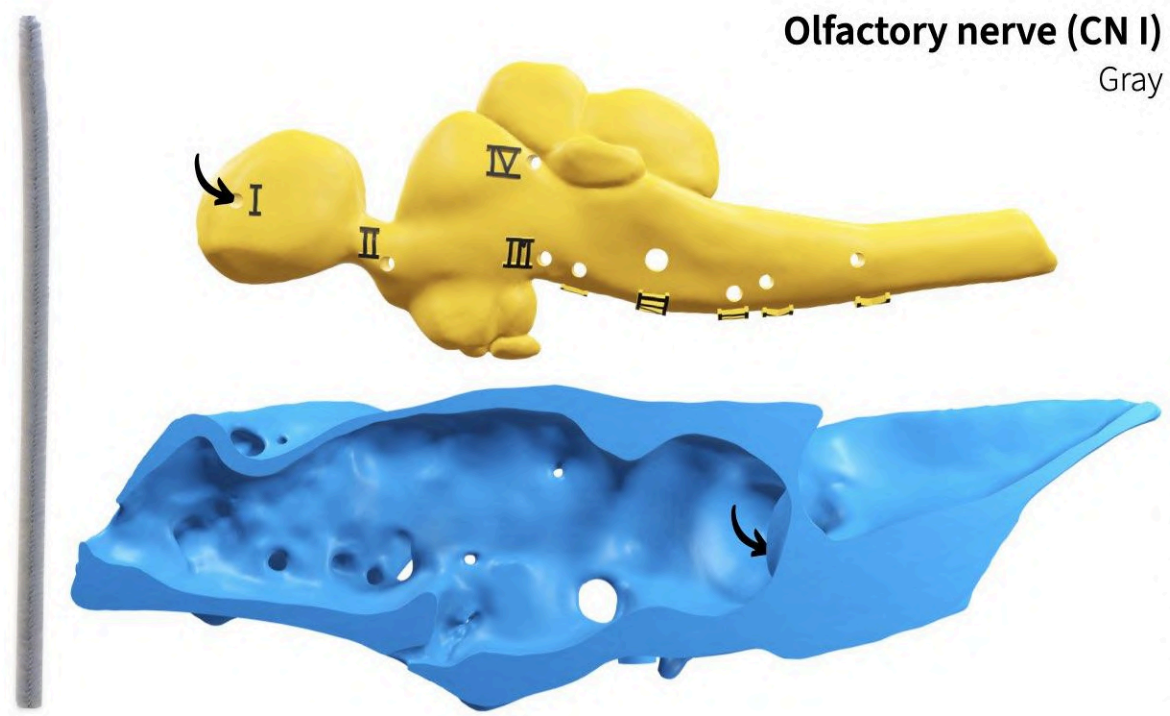
1. Insert each cranial nerve into the hole on the *left* side of the brain with the corresponding roman numeral. If your pipe cleaners are bent, straighten them out a bit; this will make them easier to insert through the holes.
2. Guide the other end of the cranial nerve out through its corresponding foramen in the *left* half of the chondrocranium.
3. Pull the cranial nerve all the way through the hole until there is some excess on the *right* side of the brain. Having this extra bit on the right side will keep the nerve from pulling out of the brain as you insert it through the chondrocranium.



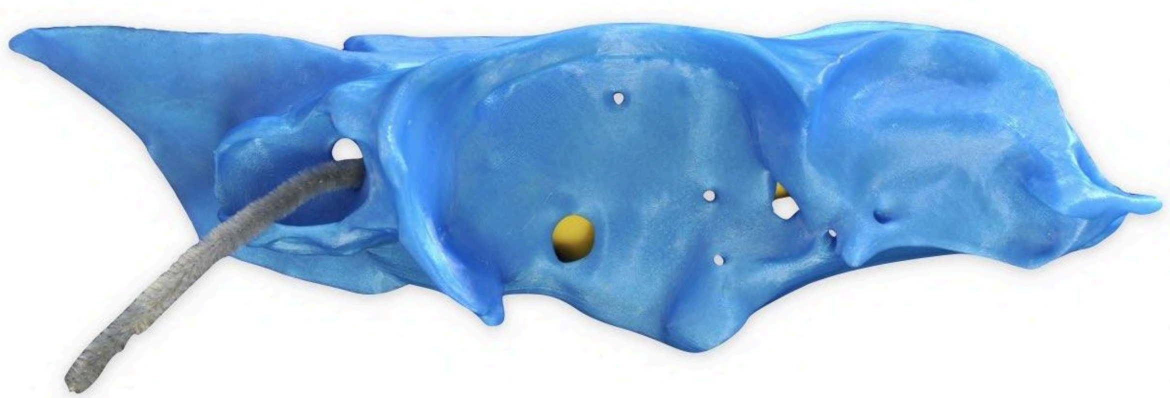
CAUTION: Pipe cleaner ends are sharp!

The pipe cleaners are made from thin wires so the cut ends can be **SHARP**. Be careful when pushing or pulling them through holes so that you don't cut yourself.

Add a pipe cleaner representing olfactory n. (CN I) to your brain by taking the gray pipe cleaner and inserting it through the rostral-most hole in the brain labeled with the roman numeral "I."



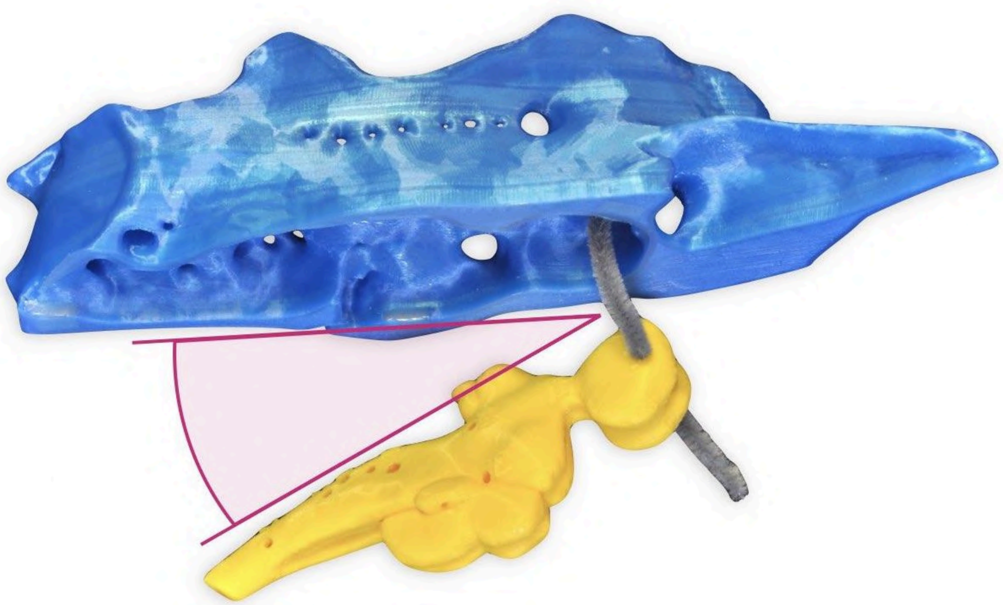
Guide the free end of the olfactory n. (CN I) out through its **foramen** (hole) in the left half of the chondrocranium: the rostral-most foramen exiting the **endocranial cavity** (the space inside the chondrocranium that houses the brain).



The olfactory n. passes through the rostral-most foramen to reach the **nasal capsule**, the cartilage encasing the olfactory organ.

BUILD NOTE: Keep space to add more

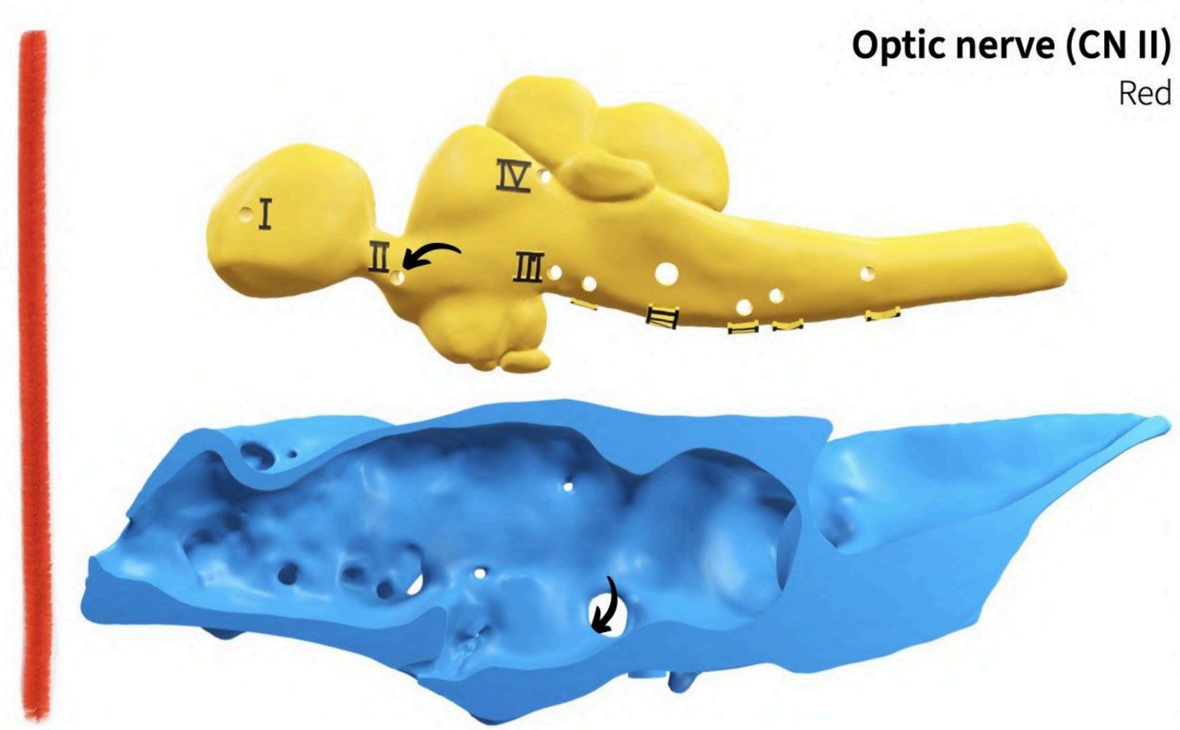
As you add more cranial nerves, it's easier to keep the chondrocranium and brain side by side with a slight angle between them, as shown in the image below. This will give you space to add additional nerves while keeping the previous nerves in place.



Optic nerve (CN II)

The second cranial nerve is the **optic n. (CN II)**. This nerve carries visual sensory information from the **retina** of the eye. On page 1 of your **Notebook**, write in the name of this nerve, draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

Connect a red pipe cleaner, representing the optic n. (CN II), to the hole in the brain marked "II" and guide it out through its corresponding foramen in the chondrocranium. Use the following image to help you.

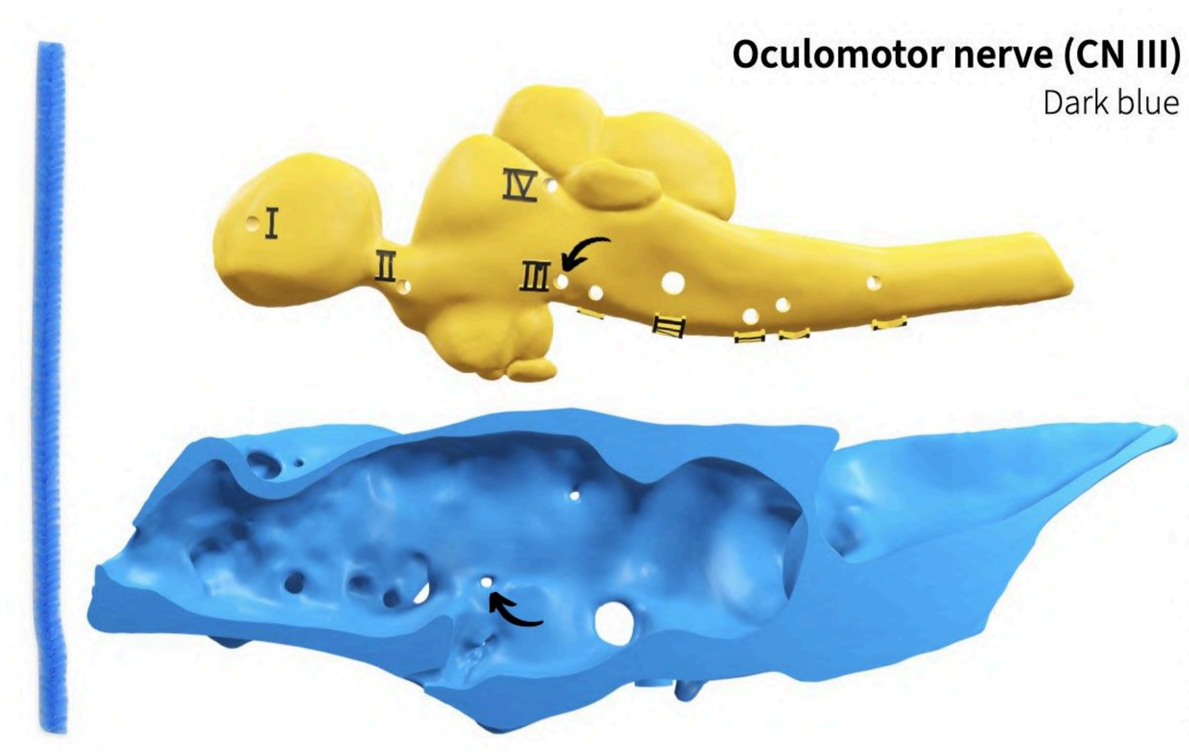


Oculomotor nerve (CN III)

Next is the third cranial nerve, the **oculomotor n. (CN III)**. As the name implies ("oculo-" means related to the eye or vision), this nerve also goes to the eye. However, it is a **motor nerve**, which means that rather than *receiving* sensory information, it *sends* information that causes muscles to contract.

Vertebrates have six muscles that attach to the outside of the eyeball to rotate it within the orbit; these six muscles are referred to as the **extrinsic eye muscles** (the muscles inside the eye, controlling the lens and pupil, are the ***intrinsic* eye muscles**). The oculomotor n. (CN III) sends motor signals to four of these six extrinsic eye muscles: **dorsal rectus**, **ventral rectus**, **medial rectus**, and **ventral oblique** (also known as **inferior oblique**). On page 1 of your **Notebook**, write in the name of the oculomotor n. (CN III), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

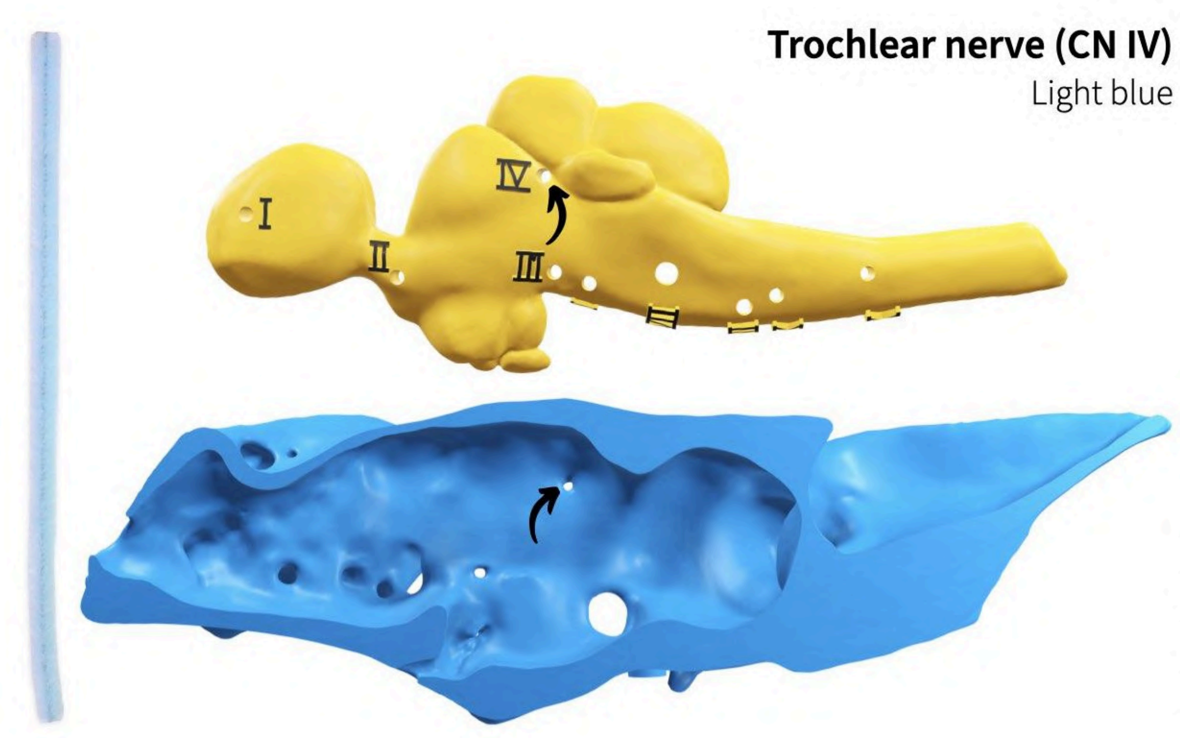
Connect a dark blue pipe cleaner, representing the oculomotor n. (CN III), to the hole in the brain marked "III" and guide it out through its corresponding foramen in the chondrocranium. Use the following image to help you.



Trochlear nerve (CN IV)

The fourth cranial nerve innervates another of the six extrinsic eye muscles: the **dorsal oblique** (also known as the **superior oblique**). On page 1 of your **Notebook**, write in the name of the trochlear n. (CN IV), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

Connect a light blue pipe cleaner, representing the trochlear n. (CN IV), to the hole in the brain marked "IV" and guide it out through its corresponding foramen in the chondrocranium. Use the following image to help you.

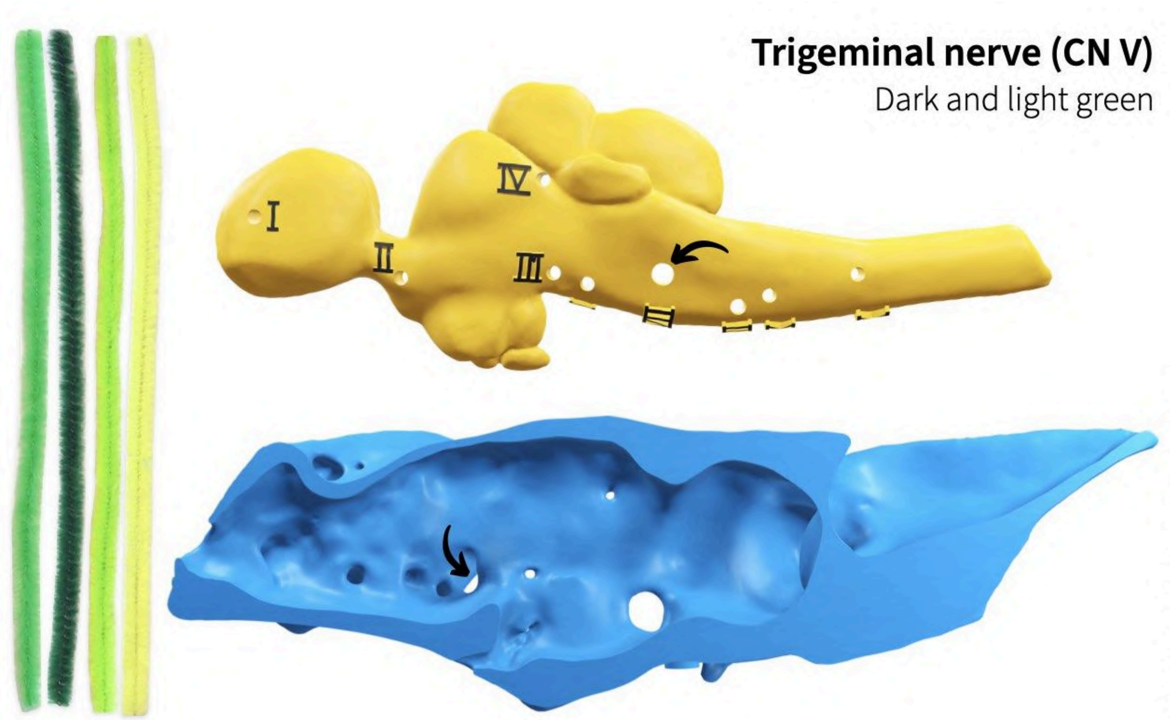


Trigeminal nerve (CN V)

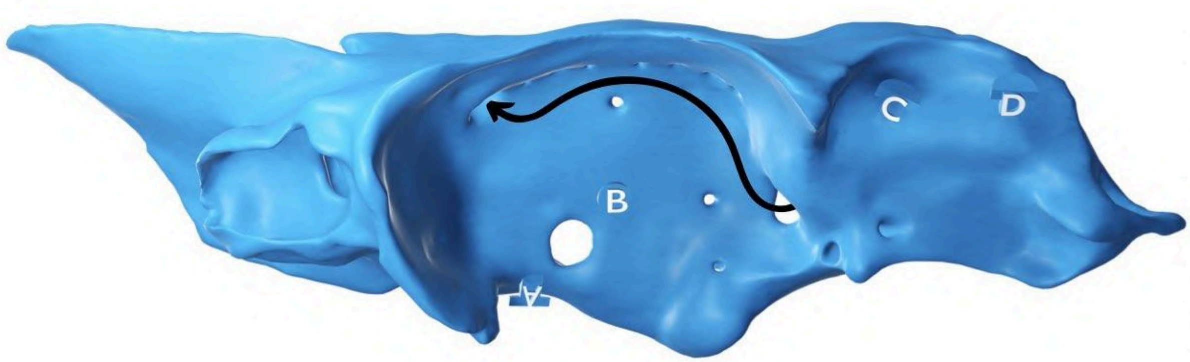
Until now, all of the cranial nerves have either been sensory (CN I and II) or motor (CN III and IV). The fifth cranial nerve, the **trigeminal n. (CN V)**, has both sensory and motor components. The sensory component receives tactile information from the skin covering the rostral-most portion of the head and around the mouth, whereas the motor component innervates the rostral-most jaw muscles.

The trigeminal n. (CN V) receives its name from the fact that it immediately splits into three branches ('trigeminus', three born at the same time). The first branch goes to the skin around the eyes and snout, the second branch to the skin and muscles of the upper jaw (**palatoquadrate**), and the third branch to the skin and muscles of the **lower jaw** (or **mandible**). In this way, all structures derived from the first of the seven **gill arches** receive innervation from the trigeminal n. (CN V). On page 1 of your **Notebook**, write in the name of the trigeminal n. (CN V), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

Connect *two* green pipe cleaners, representing two of the three trigeminal n. (CN V) branches, to the hole in the brain marked "V/VII" and guide them out through the foramen in the chondrocranium indicated in the image below. Use the following image to help you.

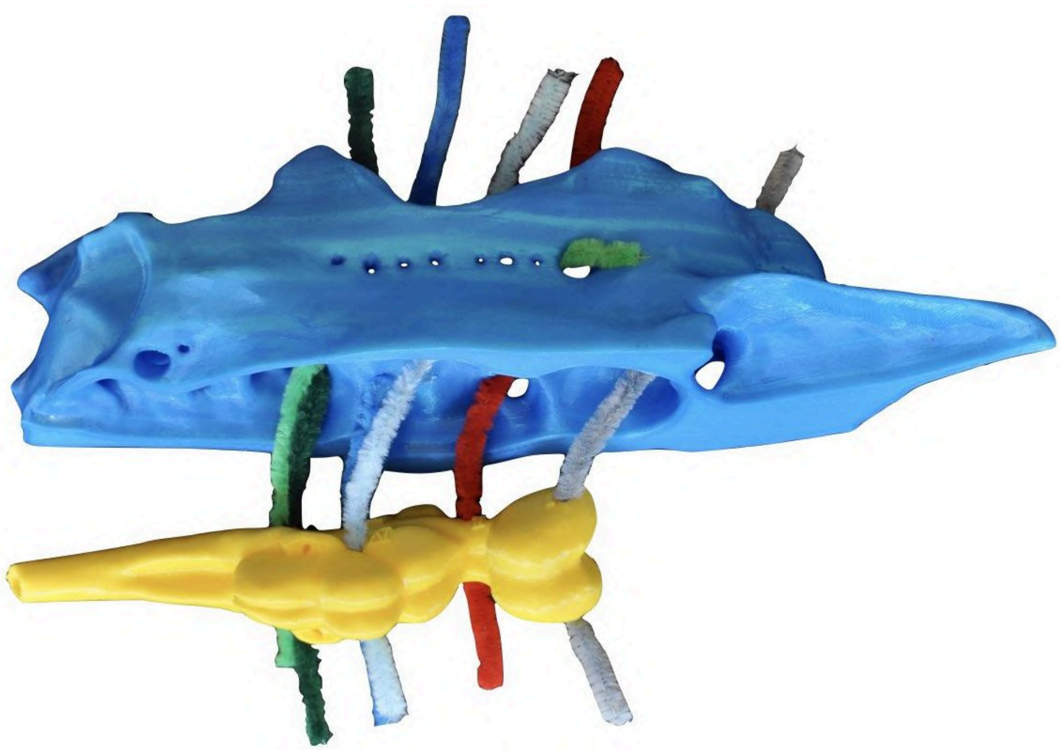


Once you've pulled your two trigeminal nerves outside of the endocranial cavity, guide one of the branches through the rostral-most foramen in the roof of the orbit. This is the branch that innervates sensory structures on the rostrum of the skull.



ASSESS: Half of cranial nerves added

You've now connected half of your shark's 10 cranial nerves! Nice job! Before proceeding, take a moment to compare your chondrocranium and brain against the following image to make sure you have everything inserted correctly.

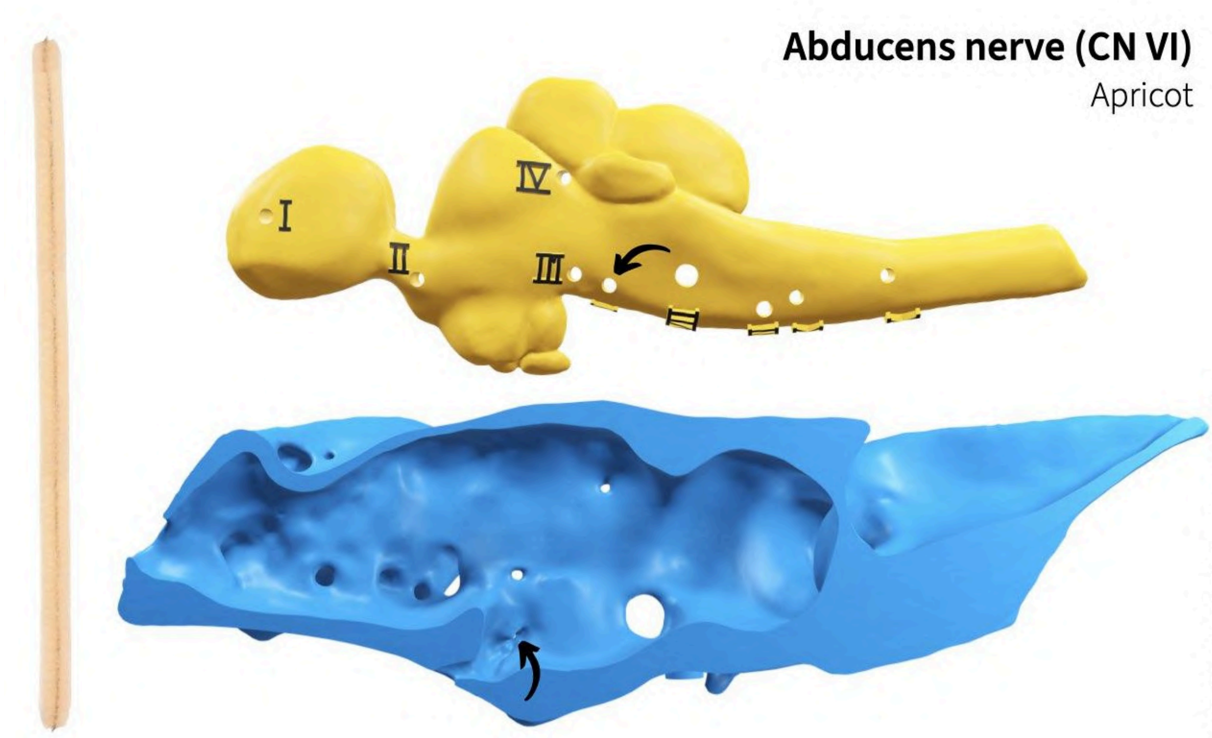


Abducens nerve (CN VI)

So far we've accounted for the innervation of five of the six extrinsic eye muscles. The sixth cranial nerve, **abducens n. (CN VI)**, provides motor innervation to the remaining extrinsic eye muscle: the **lateral rectus**. The name "abducens" comes from the fact that the lateral rectus **abducts** the eye (pulls it laterally, away from the midline).

On page 1 of your **Notebook**, write in the name of the abducens n. (CN VI), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

Connect the apricot pipe cleaner, representing the abducens n. (CN VI), to the hole in the brain marked "VI" and guide it out through its corresponding foramen in the chondrocranium. Use the following image to help you.

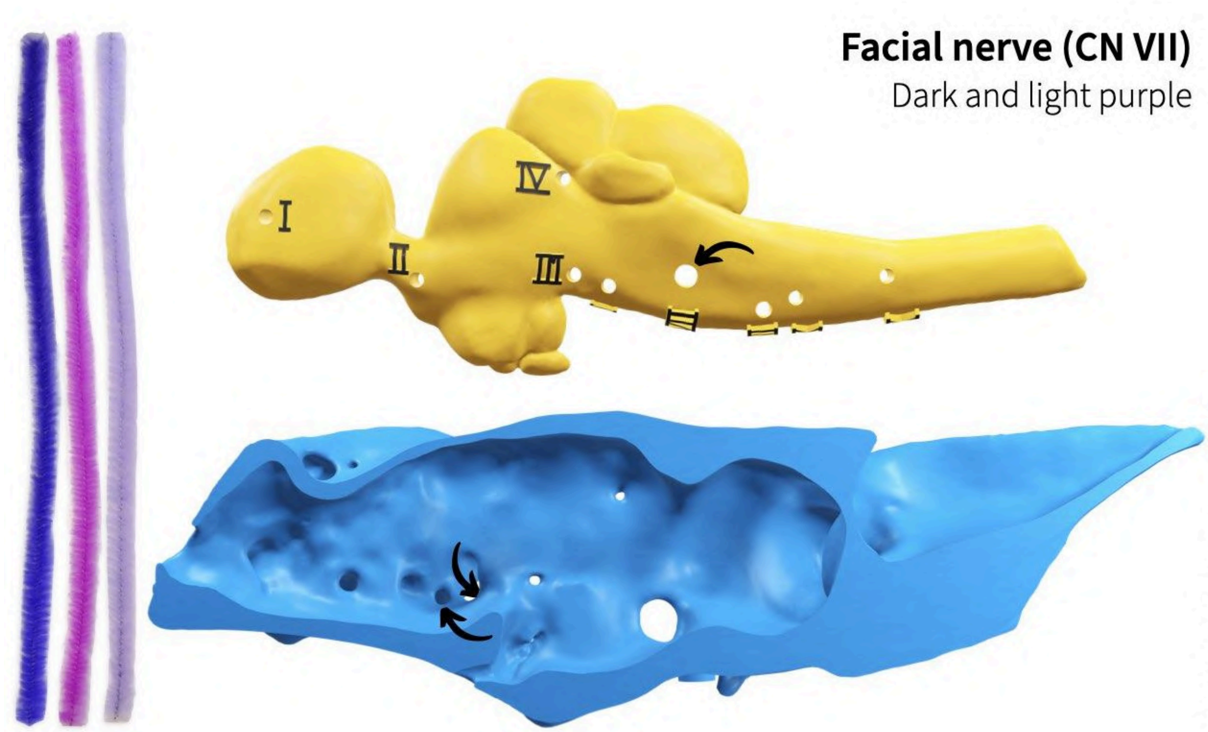


Facial nerve (CN VII)

If the fifth cranial nerve had a buddy, it would be the seventh cranial nerve, the **facial n. (CN VII)**. The facial n. (CN VII), provides sensory and motor innervation to the epithelium and muscles associated with the second of the seven gill arches. This includes sensory information from taste buds inside the mouth. On page 1 of your **Notebook**, write in the name of the facial n. (CN VII), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

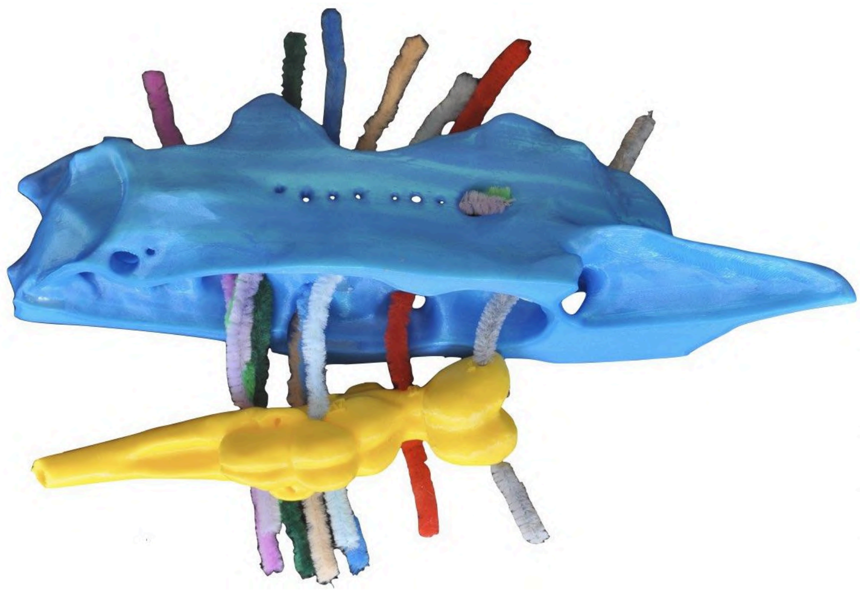
Connect *two* purple pipe cleaners, representing two branches of the facial n. (CN VII), to the brain. The close association between the trigeminal and facial nerves extends to where they leave the brain: they emerge as a single root. Thus, you'll insert the facial n. into the same hole in the brain as the trigeminal n., marked "V/VII." Guide the two pipe cleaners out through each of two foramina in the chondrocranium indicated in the image below. One of these foramina leads more rostrally while the other leads more caudally.

One of these branches travels with the trigeminal branch that exits through the roof of the orbit to also innervate sensory structures on the rostrum of the skull. Guide the more rostral of the two facial n. (CN VII) branches to follow the path of this trigeminal branch.

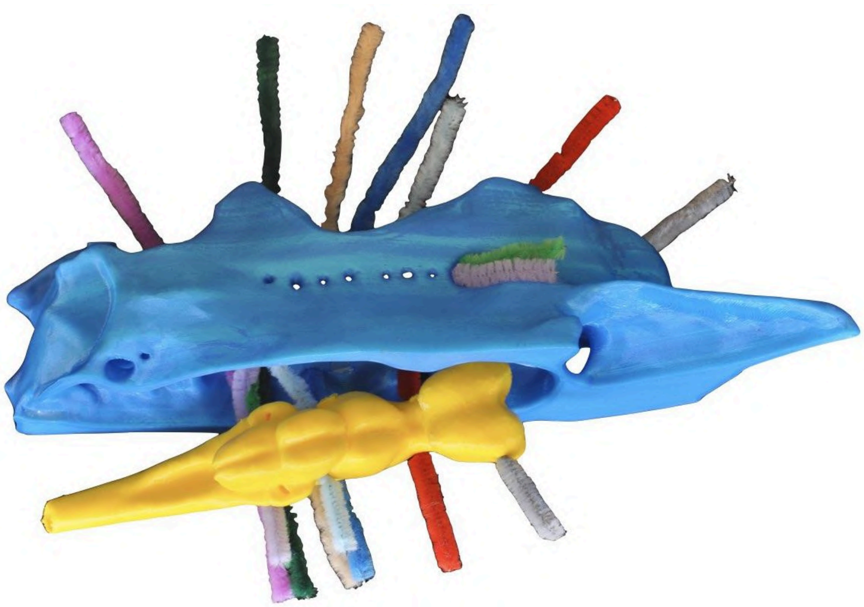


BUILD NOTE: Moving the brain in

Now that you've connected 7 of the 10 cranial nerves, it's a good time to start moving the brain into the endocranial cavity (you'll be able to pull it all the way in once you've attached all 10 cranial nerves).

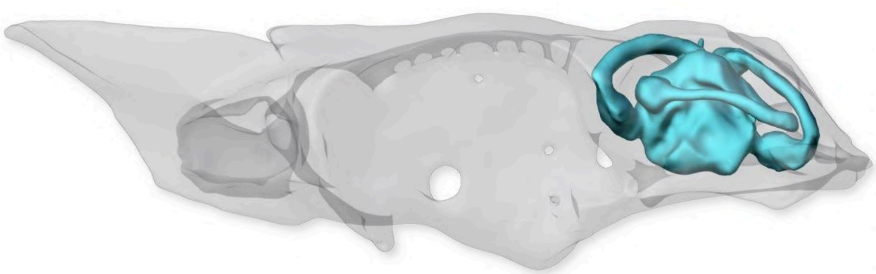


Start by pulling some of the cranial nerves through to the left side of the chondrocranium. For now, still keep the excess pipe cleaner length on the right side of the brain. Your chondrocranium and brain should look like the image below.



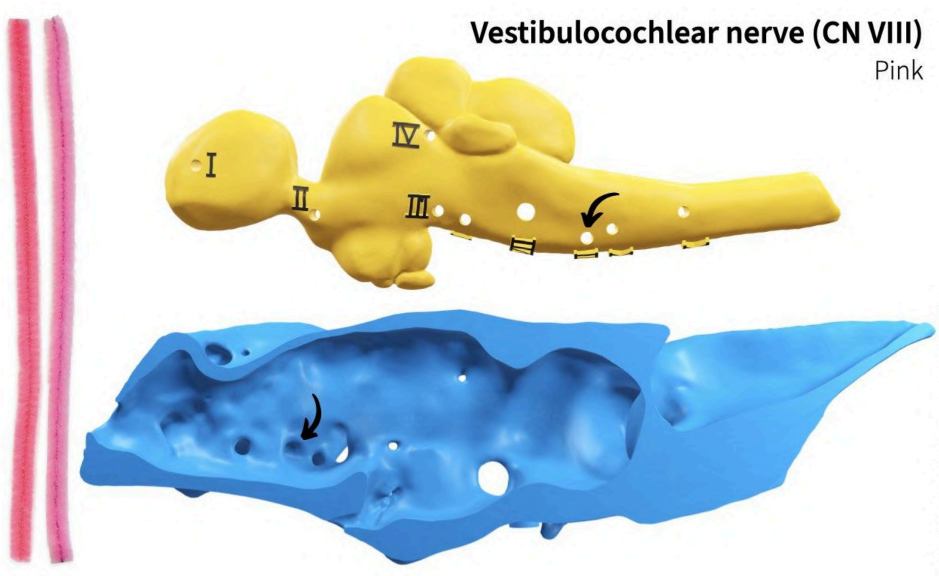
Vestibulocochlear nerve (CN VIII)

All of the cranial nerves you've seen so far leave the brain and exit the chondrocranium to reach their target. The eighth cranial nerve, the **vestibulocochlear n. (CN VIII)**, is different. It carries sensory information from a structure entirely contained within the chondrocranium, the **vestibular apparatus**, shown in the image below. The vestibular apparatus allows vertebrates to perceive their orientation and acceleration and in some sharks, including dogfish, it senses sounds transmitted through the openings of the **endolymphatic duct** (Chapuis & Collin 2022).



Although this nerve has "cochlear" in its name, sharks do not have a **cochlea**. The cochlea, also innervated by the vestibulocochlear n. (CN VIII) nerve, evolved in mammals as an outgrowth of the vestibular apparatus. On page 1 of your **Notebook**, write in the name of the vestibulocochlear n. (CN VIII) nerve, draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

Connect a pink pipe cleaner, representing the vestibulocochlear n. (CN VIII), to the hole in the brain marked "VIII" and guide it into its corresponding canal in the chondrocranium.

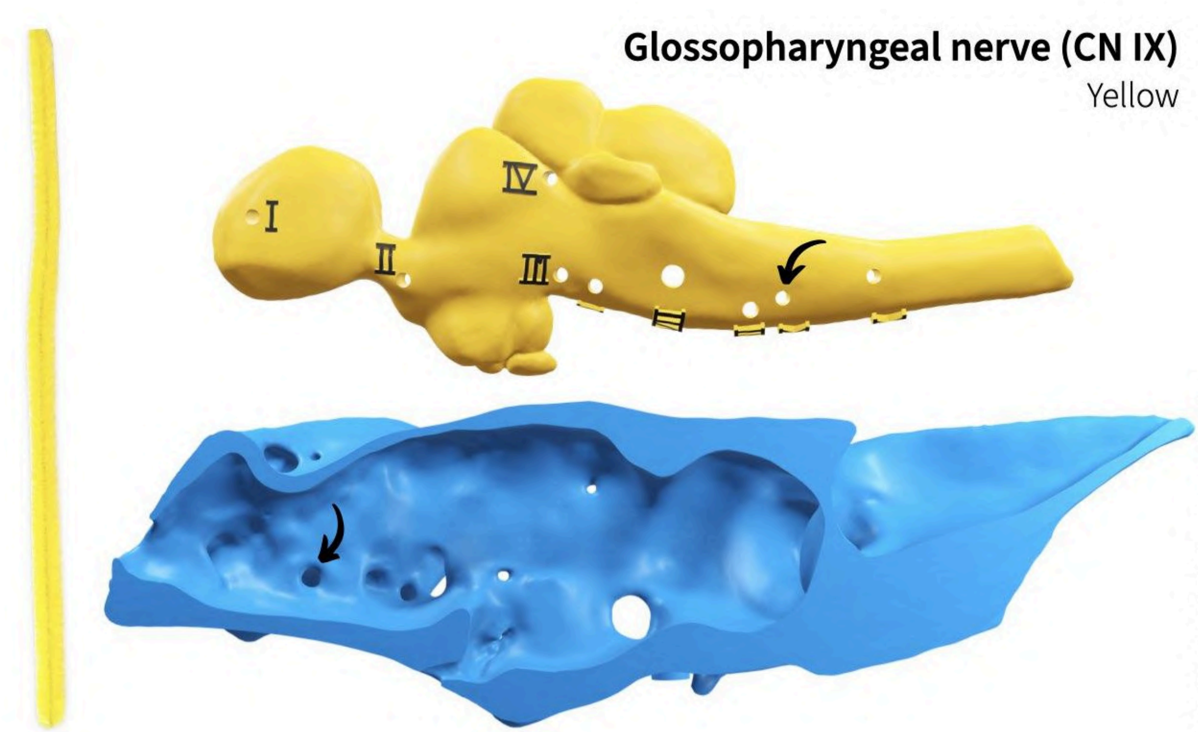


Glossopharyngeal nerve (CN IX)

You've already added cranial nerves that innervate structures derived from the first two gill arches: the trigeminal and facial nerves (V and VII, respectively). The ninth cranial nerve, the **glossopharyngeal n. (CN IX)**, innervates structures derived from the third gill arch. The third gill arch corresponds approximately to the start of the **pharynx**, the part of the digestive tract immediately after the mouth (i.e., what you might commonly call the "throat"). This innervation includes motor control of the muscles that attach to the third gill arch, sensory innervation to the skin around the third arch, and the internal epithelium of the pharynx.

The first part of the name "glosso-" ("tongue") is similar to "-cochlear" in the name of the previous cranial nerve. Although sharks don't have a tongue, the glossopharyngeal n. (CN IX) is one of the nerves that innervates the tongue in other vertebrates. On page 1 of your **Notebook**, write in the name of the glossopharyngeal n. (CN IX), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

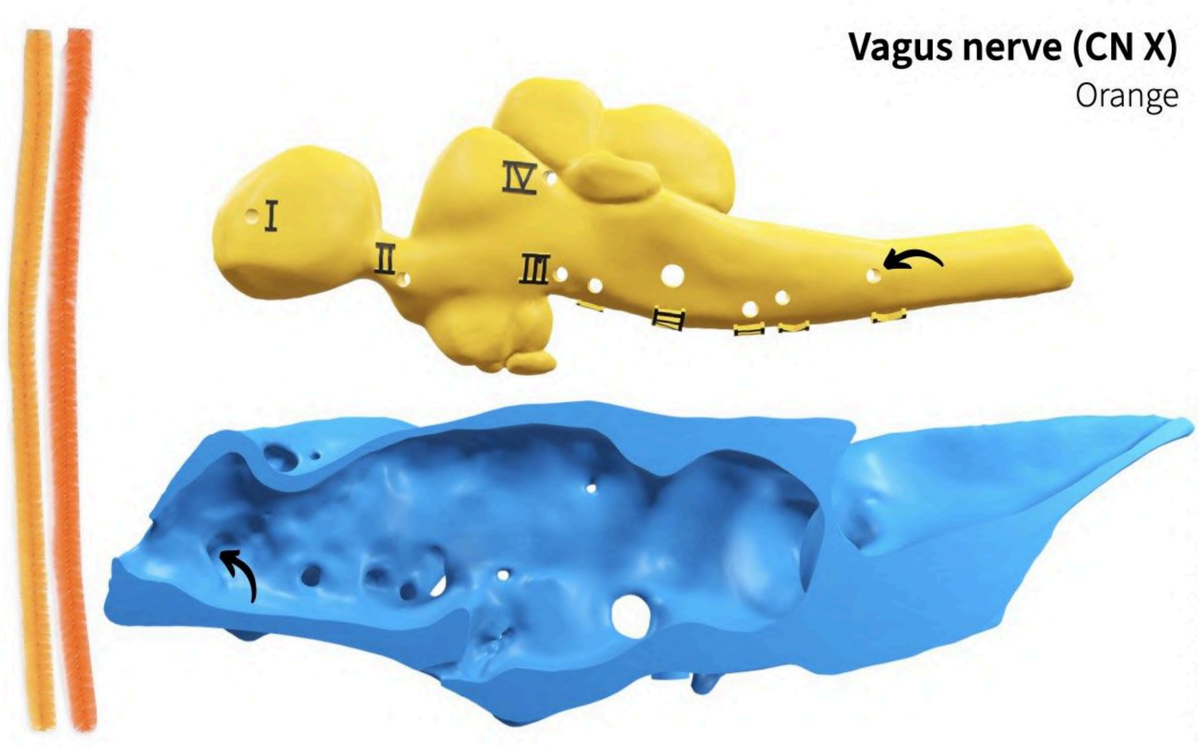
Connect a yellow pipe cleaner, for the glossopharyngeal n. (CN IX), to the hole in the brain marked "IX" and guide it through its corresponding canal in the chondrocranium. You might find it easier to insert through the chondrocranium first. Use the following image to help you.



Vagus nerve (CN X)

The tenth cranial nerve is the **vagus n. (CN X)**. The name "vagus" comes from the Latin word for "wandering" and if you were to follow this nerve's path through the body, you would indeed find it wanders: from the brain down to the esophagus, heart, stomach, and all the way to the intestines. The vagus n. (CN X) provides sensory and motor innervation to structures derived from the remaining fourth through seventh gill arches and to most of the gut. On page 1 of your **Notebook**, write in the name of the vagus n. (CN X), draw its path from the brain out to its target structure, and indicate whether it is sensory, motor, or both.

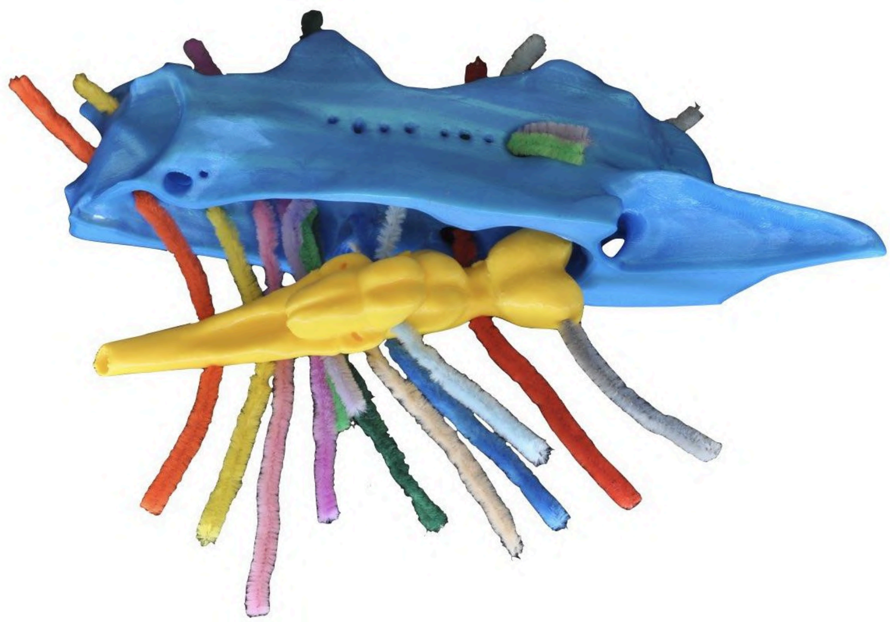
Connect an orange pipe cleaner, representing the vagus n. (CN X), to the hole in the brain marked "X" and guide it through its corresponding canal in the chondrocranium. You might find it easier to insert through the chondrocranium first. Use the following image to help you.



All the cranial nerves added

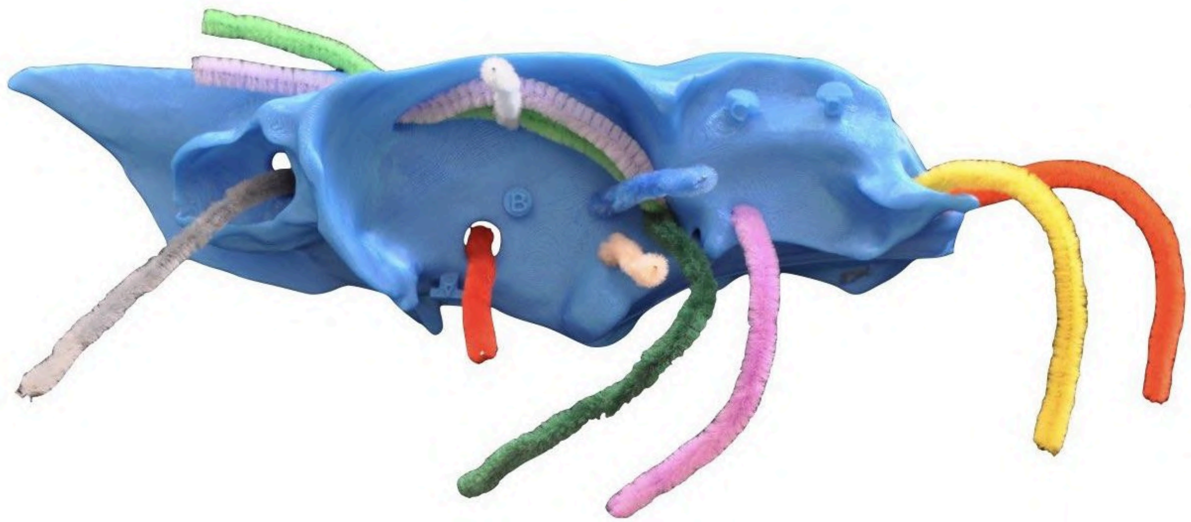
ASSESS: All cranial nerves added

Once you've added all of the cranial nerves, your shark's chondrocranium and brain should look something like this:



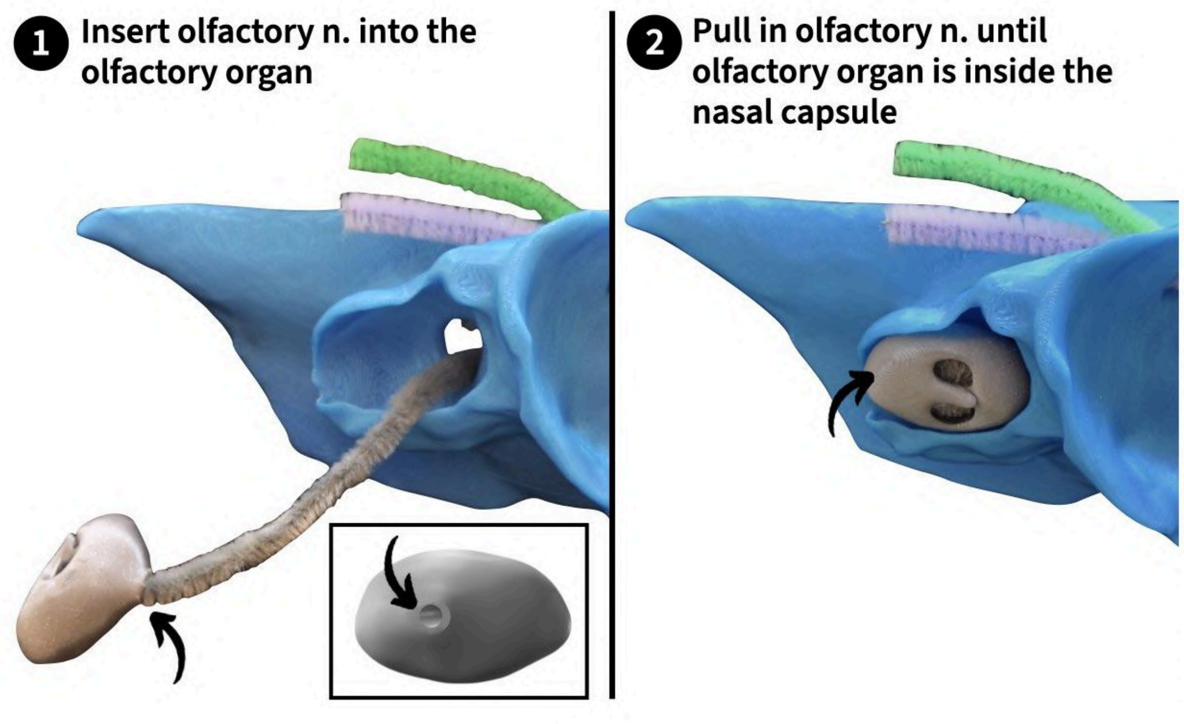
Push the brain completely into the endocranial cavity. As you do so, pull the cranial nerves I, V, VII, IX, and X from where they emerge from the chondrocranium until they're near flush with the right side of the brain. As you do, **be careful of the sharp ends of the pipe cleaners**! You don't need to pull through cranial nerves II, III, IV, VI and VIII; just fold them over the brain. When you're finished, your brain should look similar to the image below.

You should now be able to close up the chondrocranium with all of the emerging cranial nerves visible on the left side.



Adding the olfactory organ and scleral ring

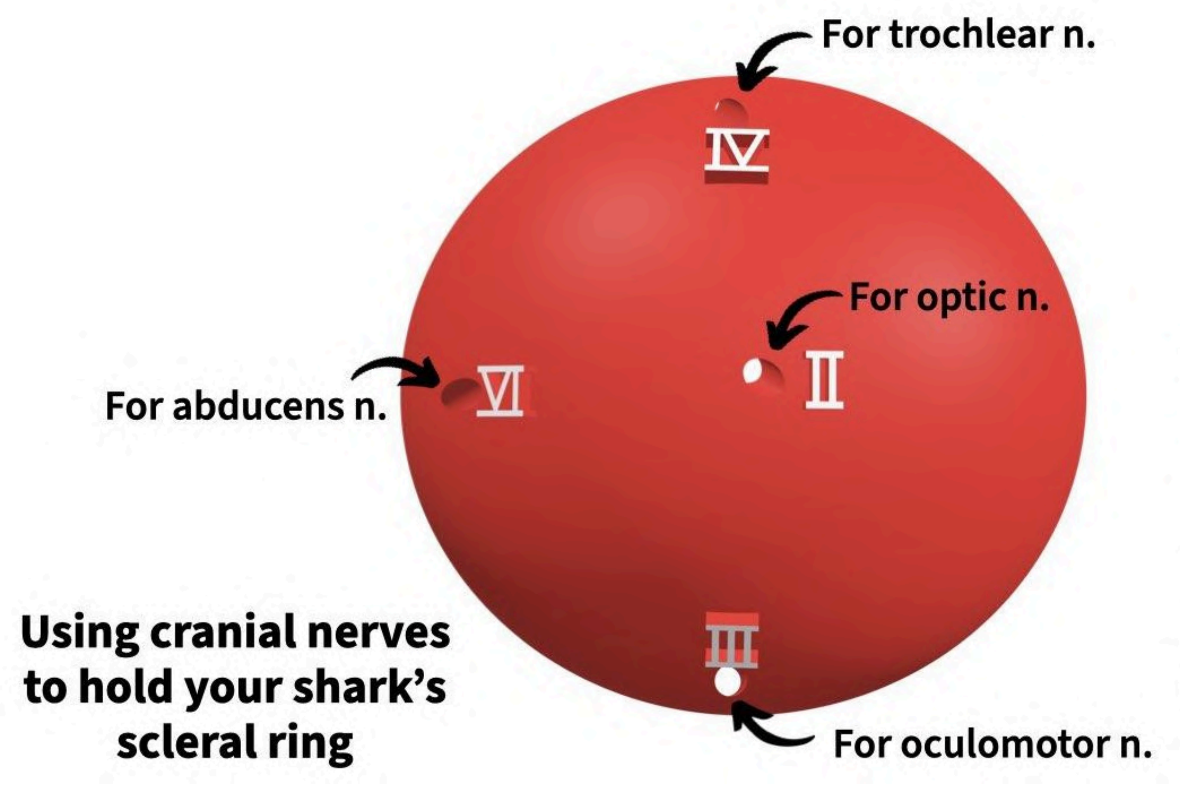
If you'd like, you can connect some of your cranial nerves to their target structures. In your kit find your shark's olfactory organ. This is the organ that your shark uses to smell. Connect the olfactory nerve to the hole in the back of the olfactory organ and then pull the olfactory nerve through the brain toward the right until the organ is fully housed within the chondrocranium.


1 Insert olfactory n. into the olfactory organ
2 Pull in olfactory n. until olfactory organ is inside the nasal capsule

Your kit doesn't include an eyeball but it does include a **scleral ring**, mineralized tissue (in this case cartilage) within the eyes of most vertebrates, the function of which isn't entirely clear (Franz-Odendaal 2020). This scleral ring represents the general shape and size of the eyeball.

The eye cranial nerves *don't connect to the scleral ring* -the oculomotor, trochlear, and abducens nerves connect to the extrinsic muscles of the eye and the optic nerve connects to the retina of the eye. However, you'll attach them here just to hold the ring in place and to represent the general locations of these nerves relative to the eye. Also, the scleral ring in your kit is *much thicker* than the actual scleral ring in dogfish sharks (so that it could be 3D printed).

Find the scleral ring in your kit (the red cup-shaped piece). Insert the four cranial nerves that innervate structures of the eye through the backside of the ring, using the raised labels and image below to help you.



Slide the scleral ring toward the chondrocranium, continuing to pull each of the four cranial nerves through the holes until the scleral ring is entirely within the left orbit.

Summing up the form and function of the chondrocranium

Take a moment to observe your chondrocranium with all of the cranial nerves. Based on what you observe, how would you explain the structure and function of the chondrocranium in a *single* sentence? Write your response in your **Notebook**.

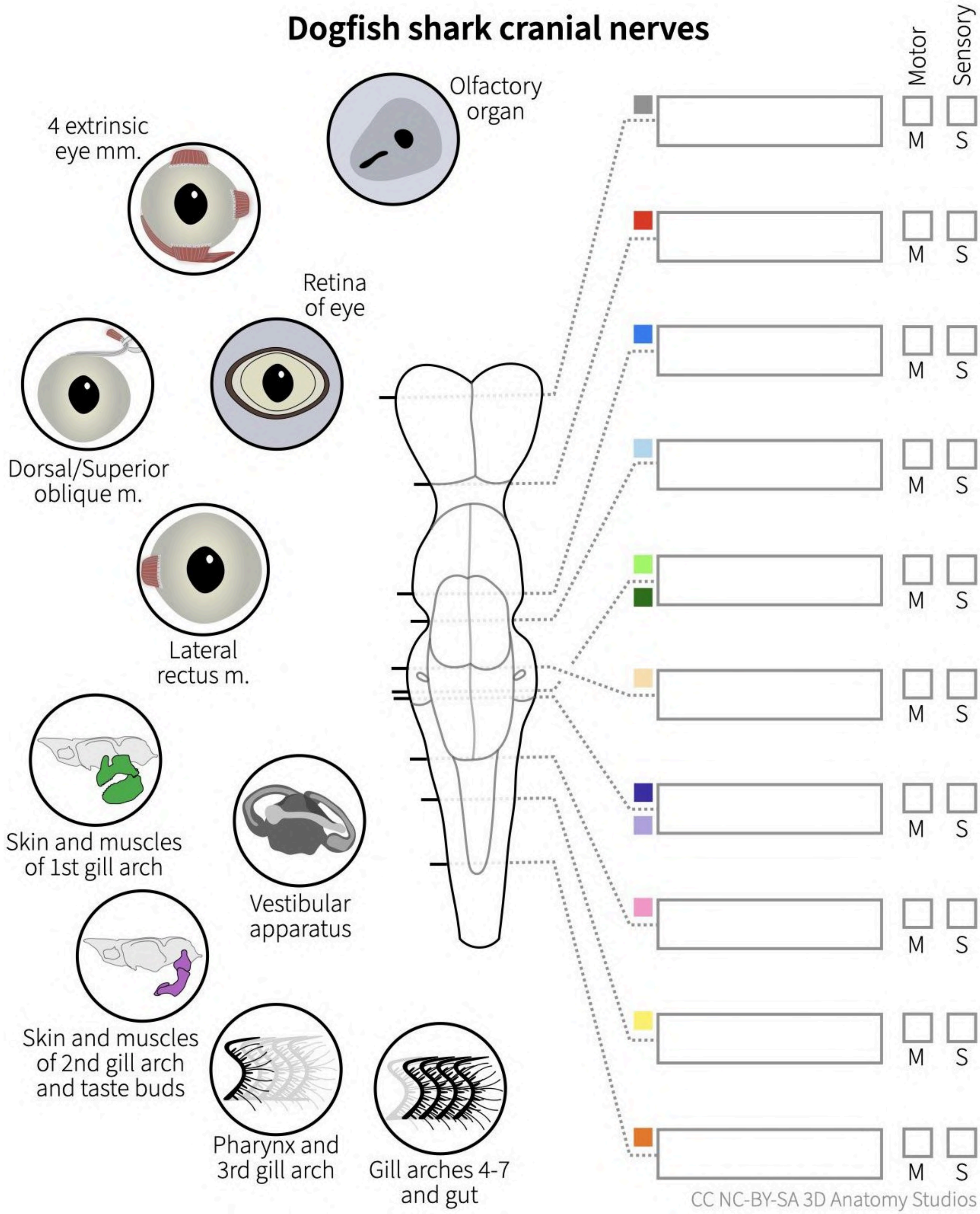
Nice work! You've added all of the cranial nerves to your shark and some of the target structures! If you're building your shark's jaws and branchial arches after this, you can keep all of the cranial nerves in place and lead CNs V, VII, IX, and X to their targets too.

References cited

- Chapuis, Lucille, and Shaun P. Collin. "The auditory system of cartilaginous fishes." *Reviews in Fish Biology and Fisheries* 32.2 (2022): 521-554. DOI: 10.1007/s11160-022-09698-8.
- Franz-Odendaal, Tamara Anne. "Skeletons of the eye: An evolutionary and developmental perspective." *The Anatomical Record* 303.1 (2020): 100-109. DOI: 10.1002/ar.24043.

STUDENT NOTEBOOK

Section 1. What are your shark's cranial nerves and where do they go?



Based on the module you just completed and observing your completed chondrocranium and brain, how would you explain the structure and function of the chondrocranium in a single sentence?

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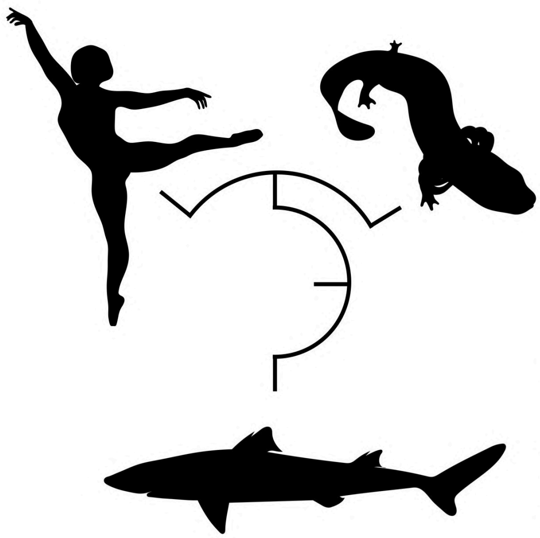
EDUCATOR GUIDE

Mapping the functional evolution of cranial nerves

Text and images by Aaron M Olsen, PhD



Time to complete: 50-70 min
Age level: Grades 11-12 or College
Bloom's levels: 2 & 5
Description: In this module your students will compare and classify the shark cranial nerves and explain the functional evolution of some of the cranial nerves in vertebrates more broadly.
Materials needed:

- SA04 Student Guide & Notebook v1.0
- **OPTIONAL** Dogfish Shark Skull Kit v1.0 **OR** Dogfish Neuroanatomy Kit v1.0

Systems:

- Nervous
- Sensory
- Skeletal

Core concepts:

- Development
- Evolution
- Humans are vertebrates
- Structure & function

Competencies:

- Data integration
- Depiction of anatomy
- Scientific communication
- Scientific reasoning
- Tree thinking

Module ID: SA04
Module version: 1.1
Module sequence (suggested):
SA02 → SA03 → SA01 → SA05 → **SA04**

How to use and edit this module

This is an open-source active learning module created by 3D Anatomy Studios and licensed under CC NC-BY-SA for use with the Dogfish Shark Skull Kit or Dogfish Neuroanatomy Kit.

Module Structure

This module has an **Educator Guide**, a **Student Guide**, and a **Student Notebook** and is divided into one or more sections, each with a number, a motivating question as its heading, and a learning objective.

Educator Guide

The **Educator Guide** is intended for educators and contains a pedagogical schema for the module to help implement the module in a course (e.g., learning objectives, target Bloom's level and competencies, core concepts), an answer key for certain prompts/questions in the the **Student Notebook**, and module updates.

Student Guide

The **Student Guide** is intended for students to read as they complete the module's activities and can be read on a device or printed out.

Student Notebook

The **Student Notebook** contains worksheets or diagrams on which students can write or draw as a part of the module's activities. The **Student Notebook** can be printed out or filled in using a digital tablet.

Sharing and Editing

The CC NC-BY-SA license allows you to share and edit this module as long as you (1) do not sell the module or module derivatives ("NC"), (2) attribute the author(s) of all the content, including preserving text and graphic attributions ("BY"), and (3) share the module under the same license ("SA"). You can edit this module by copying the current Google Doc of this module (accessible at 3danatomystudios.com/guides/SA00) and editing that copy.

Purchasing Kits

To purchase kits, please visit 3danatomystudios.com/shop/dogfish-skull-kit.

Pedagogical schema

Section 1. How are the shark cranial nerves different or similar to one another?

Learning objective **Compare and classify (Bloom's Level 2 - Understand)** the shark cranial nerves by creating a Venn diagram if provided with a conceptual diagram of all the cranial nerves and related information (e.g., name, target, sensory/motor).

Activity Create a Venn diagram

Self-assessment Compare completed diagram with possible diagram in the student guide

Systems Nervous · Sensory · Skeletal

Core concepts Development · Evolution · Humans are vertebrates

Competencies Depiction of anatomy

Section 2. What cranial nerves and functions are ancestral versus derived in vertebrates?

Learning objective **Explain (Bloom's Level 5 - Evaluate)** some of the apomorphies and synapomorphies in cranial nerve anatomy if presented with an evolutionary tree with a dogfish shark, common mudpuppy, and human

Activity Infer the trait changes on an evolutionary tree

Self-assessment Compare completed evolutionary tree diagram with one possible correct diagram in the student guide

Systems Nervous

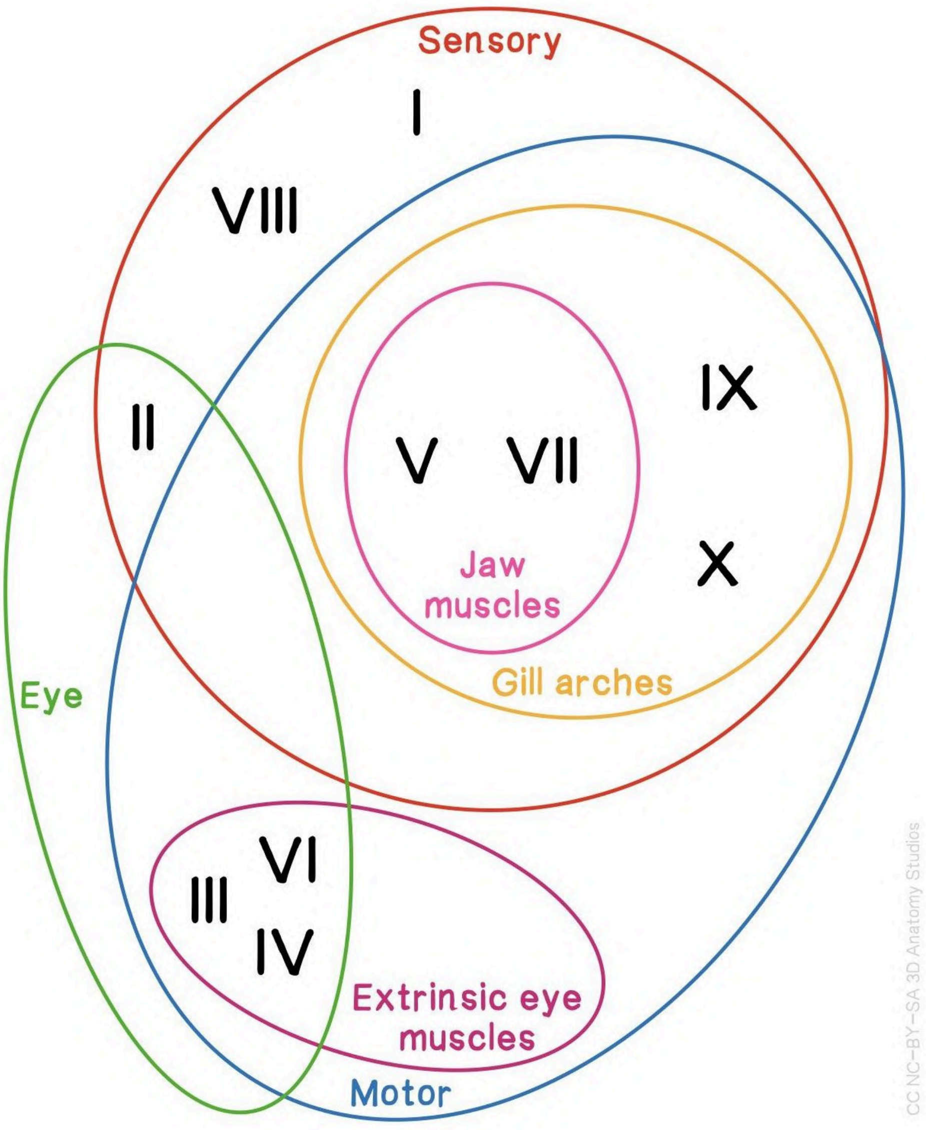
Core concepts Evolution · Humans are vertebrates · Structure & function

Competencies Data integration · Scientific communication · Scientific reasoning · Tree thinking

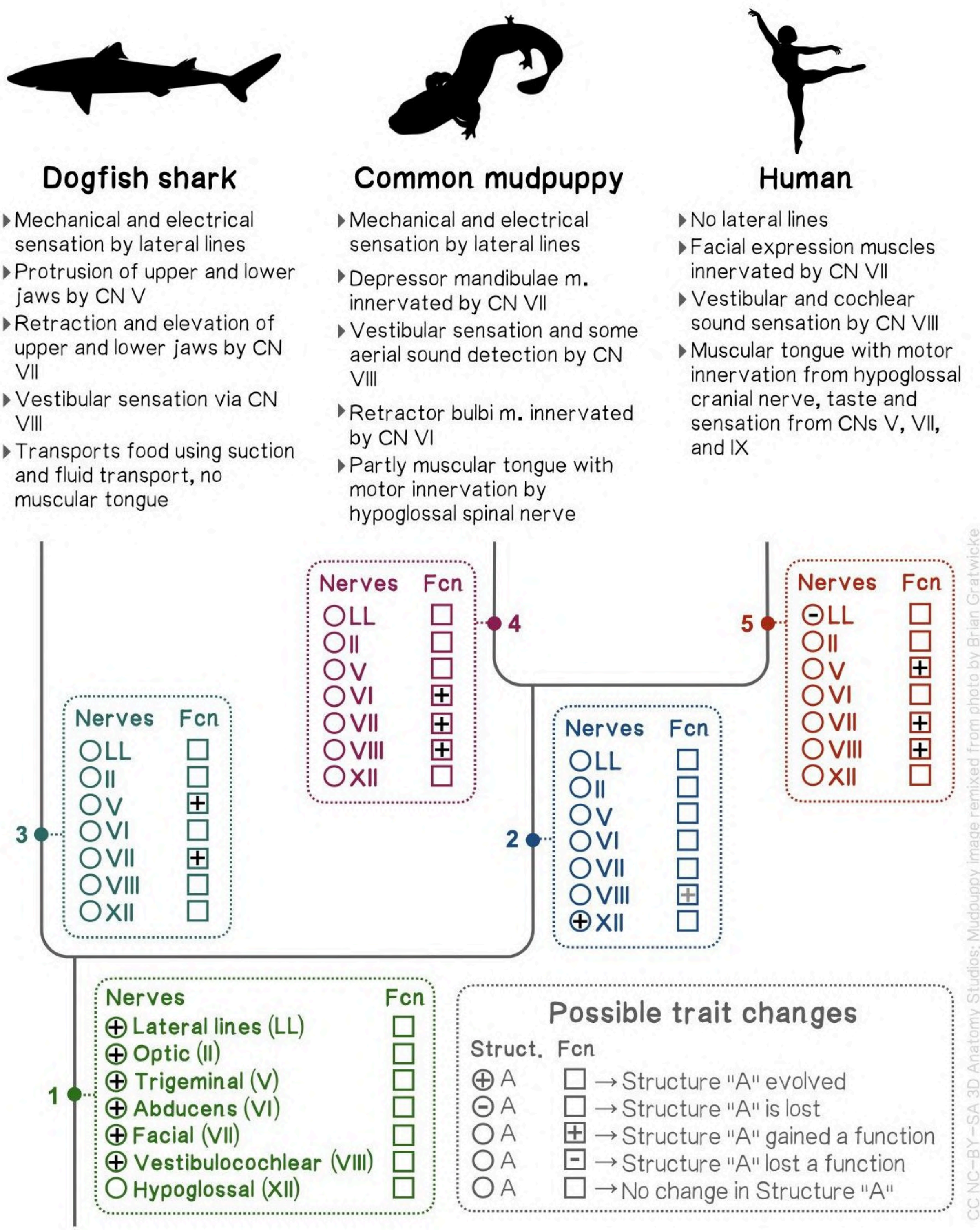
Answer key

Section 1. How are the shark cranial nerves different or similar to one another?

Create a Venn diagram of the shark cranial nerves following the instructions in the guide
The image below shows one possible Venn diagram.



Section 2. What cranial nerves and functions are ancestral versus derived in vertebrates?



If you were to construct a narrative about your completed evolutionary tree on the previous page, what would be the main points around which you would construct that narrative? List at least three brief takeaways as bullet points below.

- Each taxon/lineage has specializations depending on their particular ecological or behavioral needs
- No one taxon/lineage is necessarily more complex or specialized as a whole than another, each just has a different suite of traits
- If an ancestral trait is already well suited to a new context, it is conserved and there is little evolutionary change (e.g., the optic n.)
- If a cranial nerve is specific to a particular context, it will likely be lost or modified when that context changes through evolution (e.g., the lateral line)
- The transition from an aquatic to a terrestrial ecology was a major driver of evolutionary changes in the cranial nerves of vertebrates and responsible for most of the changes in the tree.

Updates

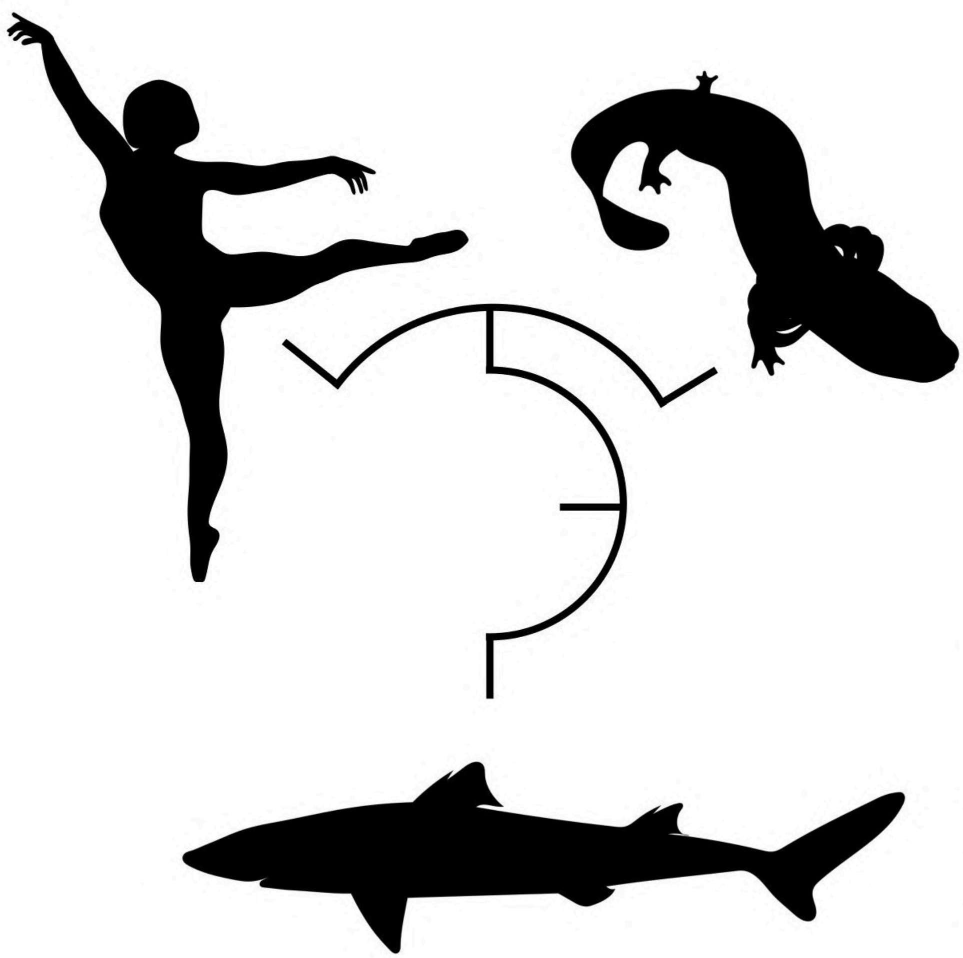
Version 1.1

- Moved completed graphic and open-ended self-assessment from the Student to Educator Guide.

STUDENT GUIDE

Mapping the functional evolution of cranial nerves

Text and images by Aaron M Olsen, PhD



Description

In this module, you will compare and classify the shark cranial nerves and explain the functional evolution of some of the cranial nerves in vertebrates more broadly.

Introduction

At first, the vertebrate cranial nerves may seem like an arbitrary list of names and numbers, with seemingly no pattern uniting them. Seeing them only in this way will make it difficult for you to remember and understand them at a deeper level. While there is a certain arbitrariness to the way in which they were numbered and grouped, there are patterns in the functions of the cranial nerves and in the evolutionary conservation and modification of cranial nerves in different lineages of vertebrates.

In this module, you'll learn to recognize and explain these patterns. You'll also understand the broader functional and evolutionary context of the cranial nerves, and with this added context it will be easier for you to remember them.

Materials needed

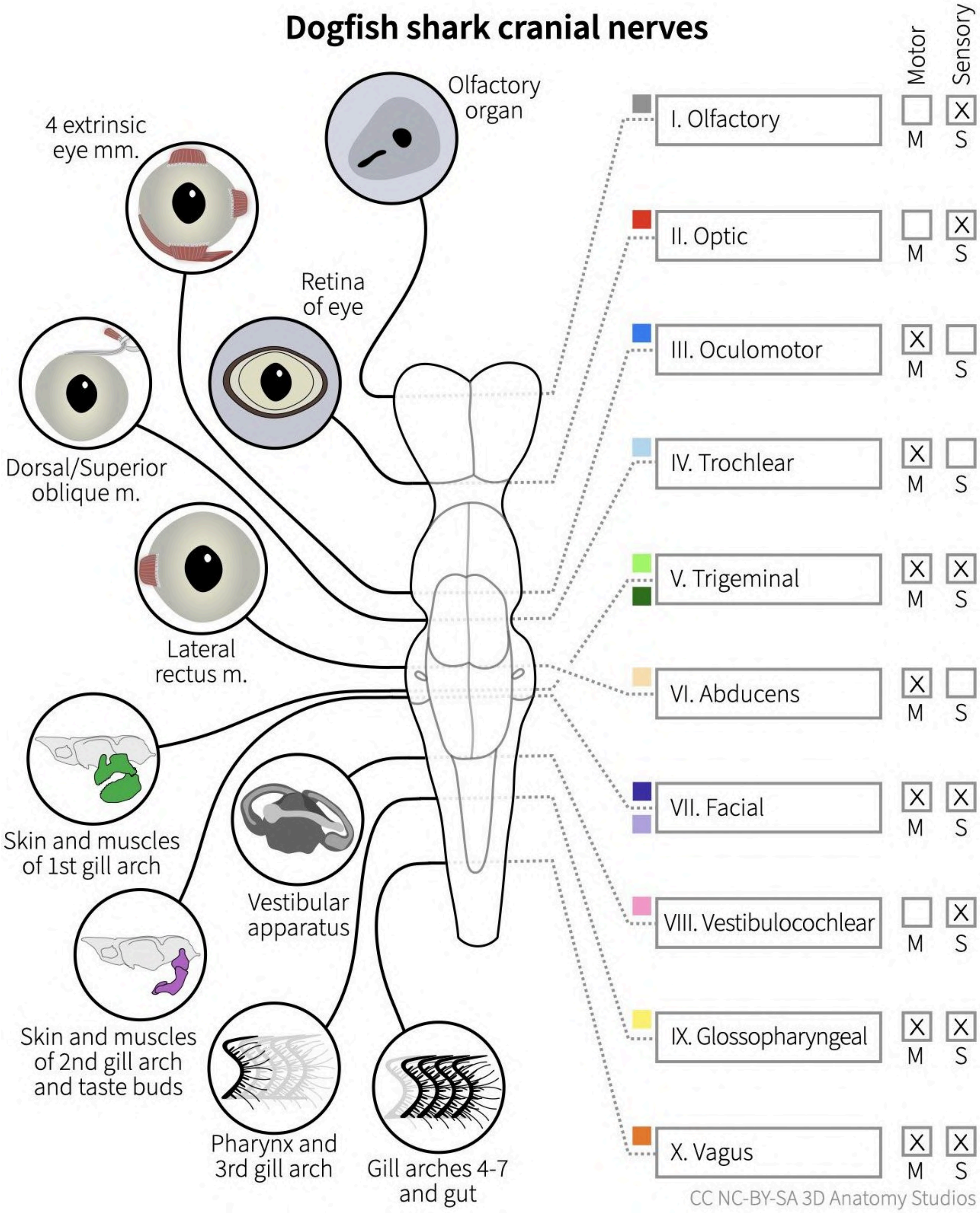
For this module, you'll need:

- The **Student Notebook** for this module (SA04).

You don't need any components from your shark kit. If you have the chondrocranium and brain with all of the cranial nerves (pipe cleaners) attached, they can be a handy reference.

Materials needed (continued)

For this module you can use the completed diagram from your **SA03 Student Notebook** or you can refer to the completed diagram below.



Section 1. How are the shark cranial nerves different or similar to one another?

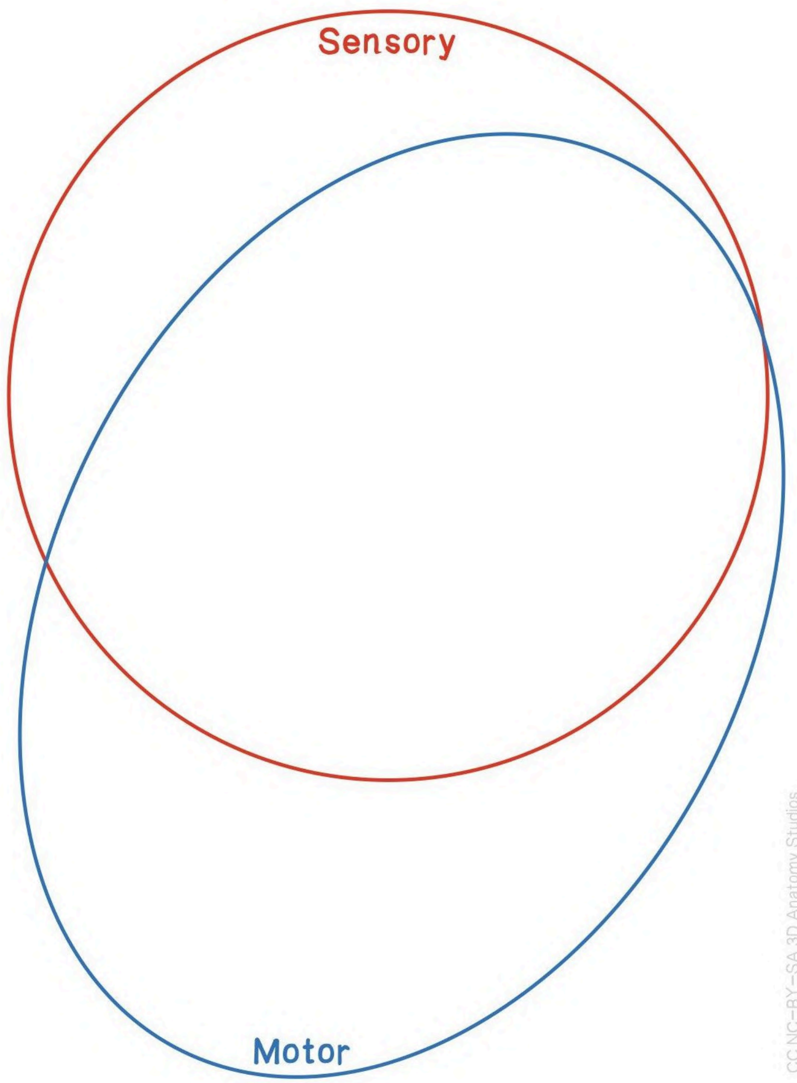
The 10 cranial nerves of the shark have similarities and differences with one another. On page 1 of your **Notebook**, create a Venn diagram of the shark cranial nerves forming groups of two or more cranial nerves based on any characteristics you'd like. You can use the diagram on the previous page as a reference. To give you as much space as possible, just use the roman numerals for each cranial nerve (e.g., “I”, “II”, “III”), rather than the full name.

Before you draw any ovals, you might want to make a list of potential groups and the nerves in those groups first; you should be able to come up with at least six groups. That will help you plan the positions and sizes of your ovals. As you plan the groupings, you may find that your ovals need to be repositioned or resized; you may also want to create a few drafts on scratch paper before drawing the final version on page 1.

If you need some help getting started, check out the hint on the following page.

HINT: Start with sensory vs. motor

One classification that applies to all cranial nerves is whether they have a sensory component, motor component, or both. If you were to draw two large, overlapping ovals, one for sensory and one for motor (see image below), which cranial nerves would you put in each oval and in the overlapping space?



When you've completed your Venn diagram, what grouping did you use? Which groupings are structural? Which groupings are functional? Thinking of the cranial nerves within these conceptual groups is one technique that will help you learn and remember them.

Section 2. What cranial nerves and functions are ancestral versus derived in vertebrates?

The cranial nerves of vertebrates are, in general, highly conserved through evolution. For example, most of the cranial nerves are present in some form in all vertebrates, including in sharks and humans. However, just as with any anatomical system, throughout vertebrate evolution there have been losses and gains of cranial nerves and cranial nerve functions depending on the selective pressures and evolutionary histories of particular lineages.

On page 2 of your **Notebook** you'll find an evolutionary tree with three **extant** (living) **taxa**: dogfish shark, common mudpuppy (an amphibian), and human. Below the names of each **taxon** (the singular form of taxa), you'll find information for each taxon related to some of the cranial nerves and their functions. And in the tree, you'll find "trait change summary boxes," numbered 1-5, at each branching point within the tree, with a subset of cranial nerves. These boxes summarize changes in these nerves at different points of time in the evolutionary history of these three taxa.

In this module, you'll use the information supplied for each extant taxon (in the top half of the page) to infer the trait changes in the tree (in the bottom half of the page). This tree does not contain *all* of the cranial nerves nor does it contain *all* of their functions- if it did, the figure would not fit on a single page. These are just a subset of the cranial nerves and their functions for you to learn *some* of the major evolutionary changes in vertebrate cranial nerves.

Understanding tree relationships

To get you oriented toward tree thinking, first observe the branching pattern of the tree. Based on the branching, are mudpuppies more closely related to sharks or to humans? Once you think you know the answer, check the solution on the following page.

ASSESS: Our cousin, the mudpuppy

If you answered “humans,” you are correct! In this tree, mudpuppies and humans are **sister groups** that have a **most recent common ancestor** (MRCA) at the dot labeled “2”; think of them like two siblings, closely related. The MRCA of mudpuppies and humans at “2” does not include sharks. Sharks are then related to mudpuppies and humans as a group and all three taxa share a MRCA at the dot labeled “1”; if mudpuppies and humans are like siblings, sharks are like a cousin to both. Thus, you and a mudpuppy are more closely related to each other than either of you is to a shark.

Lateral line nerves

Now that you understand the evolutionary relationships depicted in the tree, it’s time to start filling in the sequence of trait changes, starting with the first nerve in the list: the **lateral line nerves** (abbreviated “LL”). These are a set of cranial nerves that connect to the brain at several points and carry mechanical and, sometimes, electrical information detected by sensory organs on the skin underwater. Use the information provided at the top of the tree on page 2 of your **Notebook** to guess the changes (if any) in the summary boxes at points 1-5 on the tree.

Refer to the “Possible trait changes” box on page 2 of your **Notebook** for examples of all the possible trait changes that can occur at each point. If the nerve evolves at a particular point in the tree, add a “+” to the circle; if the nerve is lost, add a “-” to the circle. If the nerve gains a function, add a “+” to the box; if the nerve loses a function add a “-” to the box. And if there is no change, leave the circle and box empty.

If you’re unsure how to proceed, check out the hints on the following page!

HINT: Two gains or a gain and a loss?

Note that both dogfish sharks and common mudpuppies can sense mechanical and electrical stimuli via their lateral lines (Bullock, Bodznick & Northcuttet 1983). This raises two possible scenarios: either lateral lines evolved independently in each lineage (at points 3 and 4 in the tree) or evolved once in the ancestor of both sharks and mudpuppies (point 1) and were lost after the split between mudpuppies and humans in the lineage that includes humans (point 5). Which of these two scenarios do you think is most likely?

HINT: More about lateral lines

As you fill in the trait changes for this nerve, you're facing one of the major challenges of inferring changes within a tree given only information (and *limited* information!) from living taxa, the taxa "at the tips" of the tree. Depending on how easy it is to evolve versus lose a trait, either of the scenarios mentioned in the hint above are likely. Here's some additional information:

- Lateral lines are found throughout fishes and some aquatic vertebrates
- Fossils that are descendants of the most recent common ancestor of sharks and mudpuppies, at point 1 in the tree, show evidence of lateral lines (they leave indications in bone)

ASSESS: Lateral lines mapped

Because of the widespread distribution of lateral lines among aquatic vertebrates and their ancestors, lateral lines likely evolved once at point 1 and were later lost. The lateral line is only useful for gathering sensory information underwater. This explains why mudpuppies *retain* their lateral line from their ancestors, while more terrestrial vertebrates lost their lateral line.

Optic nerve (CN II)

Next, complete the trait changes for the second nerve in the list: the **optic nerve (CN II)**. Though it is not included in the bulleted lists above the tree, note that all of the taxa on the list have an optic n. that sends visual perception information to the brain. Check your work against the solution on the following page.

ASSESS: Optic nerve mapped

There is no loss of the optic n. (CN II) nor changes to its function indicated for any of the taxa in the information at the top of the tree. So the most likely scenario is that the optic nerve evolved once at the base of the tree (at point 1) without any losses or changes in its function at any other point in the tree. The optic n. actually evolved even earlier than at point 1, but since your tree doesn't go further back in time, this is the best place to put it for this activity.

Trigeminal nerve (CN V)

Next, complete the trait changes for the third nerve in the list: the **trigeminal nerve (CN V)**. Note that all of the taxa have a trigeminal n. that provides motor and sensory innervation to structures derived from the **first gill arch**. Check your work against the solution on the following page.

ASSESS: Trigeminal nerve mapped

There is no loss of the trigeminal n. (CN V) indicated for any of the taxa at the top of the tree. So it's most likely that this nerve evolved once at the base of the tree (point 1) or earlier. However, there are changes to its function. Unlike mudpuppies and humans, sharks are able to protrude their upper and lower jaws, in part, due to the **orbitalis muscle**, innervated by the trigeminal n. And in humans, the trigeminal n. provides general sensation for the muscular tongue (in amphibians, tongue general sensation appears to come from spinal nerves, not cranial nerves; Anderson & Nishikawa, 1997). Since these are different functions, it's most likely that the trigeminal n. gained these functions independently at points 3 and 5 in the tree.

Abducens nerve (CN VI)

Complete the trait changes for the next nerve in the list: the **abducens nerve (CN VI)**. Note that all of the taxa have an abducens n. that innervates the **lateral rectus** extrinsic eye muscle. Check your work against the solution on the following page.

ASSESS: Abducens nerve mapped

There's no loss of the abducens n. (CN VI) indicated. So it's most likely that this nerve evolved once at point 1 or earlier. However, there are changes to its function: in common mudpuppies, and some other amphibians, the **retractor bulbi** pulls the eyeball backward in the orbit. When animals swallow in air (versus water), they can't rely on water to help push back the food. And in amphibians, no bony structures separate the eyeball and mouth, only soft tissue. It's thought that the eyeball is pulled by the retractor bulbi to physically push the food down the throat. This also explains why a frog's eyeballs move when it swallows (Levine, Monroy & Brainerd 2004).

The retractor bulbi muscle is innervated by the abducens nerve and the most likely scenario is that this nerve gained this function once at point 4 in the tree.

Facial nerve (CN VII)

Complete the trait changes for the next nerve in the list: the **facial nerve (CN VII)**. Note that all of the taxa have a facial n. that provides motor and sensory innervation to structures derived from the **second gill arch**. Check your work against the following page.

ASSESS: Facial nerve mapped

There's no loss of the facial n. (CN VII) indicated, so the most likely scenario is that this nerve evolved once at the base of the tree (point 1) or earlier.

However, functions of the facial n. specific to each taxon are listed. In sharks, the facial n. innervates the **levator hyomandibulae** muscle, which helps retract and elevate the upper and lower jaws. In mudpuppies and other amphibians, the facial n. innervates the **depressor mandibulae** muscle, which depresses the **mandible**. And in humans and other mammals, the facial n. innervates the **muscles of facial expression**. Given the differences among these functions, each function mostly likely evolved independently at points 3, 4, and 5 in the tree.

Vestibulocochlear nerve (CN VIII)

Complete the trait changes for the second to last nerve in the list: the **vestibulocochlear nerve (CN VIII)**. Check your work against the solution on the following page.

ASSESS: Vestibulocochlear mapped

In all of the taxa, the vestibulocochlear n. (CN VIII) carries sensory information from the **vestibular system** to the brain. The vestibular system helps all vertebrates sense orientation and acceleration. So the most likely scenario is that this nerve evolved once at the base of the tree (point 1).

However, there are functions of this nerve indicated for mudpuppies and humans that are not indicated for sharks. In sharks and some other aquatic vertebrates, the vestibular system can also function in hearing by perceiving sound vibrations that are transmitted from the water into the body. However, for vertebrates that live in air (above water), a different type of hearing system is required because sound vibrations (i.e., waves) do not easily pass from the air into the body.

Amphibians (which are generally only partially aquatic) and mammals (which are generally terrestrial) have evolved different solutions to this. Amphibians, which includes mudpuppies, have a limited ability to detect sounds in air and these signals are carried by the vestibulocochlear nerve (Christensen et al., 2015). Humans and other mammals have evolved a specialized hearing system, the **cochlea**, which is also innervated by the vestibulocochlear nerve.

Since these functions are different, the most likely scenario is that this nerve gained functions at points 4 and 5 in the tree. However, since these functions involve the same nerve and auditory sensation, it's also likely that the vestibulocochlear n. of the most recent common ancestor of mudpuppies and humans (at point 2 in the tree) also had some kind of new function. So you could also add a gain in function for VIII at point 2 (indicated as "optional" by gray font).

Hypoglossal nerve (CN XII)

Complete the trait changes for the last nerve in the list: the **hypoglossal nerve (CN XII)**. Check your work against the solution on the following page.

ASSESS: Hypoglossal mapped

As was mentioned previously with the retractor bulbi muscle and abducens nerve, once vertebrates started feeding in air (as opposed to water), they had to find additional ways to move food into and through their mouth that didn't rely on being underwater all the time. One way is to use a muscular tongue to capture and transport food. Both the mudpuppy and human have a tongue that is at least partially muscular (the human tongue is entirely muscular while the amphibian tongue has a skeleton, derived from the posterior gill arches).

Despite the very different structure and function of these tongues, the tongue muscles of the mudpuppy and human are both innervated by the hypoglossal nerve (Anderson & Nishikawa, 1997). This nerve is considered a *spinal* nerve in amphibians because it emerges from the **central nervous system** (CNS) within the *spine* and a *cranial* nerve in humans because it emerges from the CNS within the skull. However, both nerves are thought to be **homologous**; that is, the hypoglossal nerve that is present in humans and in mudpuppies is the same nerve that is present in their most recent common ancestor, at point 2 in the tree.

Since this nerve is absent in sharks, it's most likely that the hypoglossal nerve evolved at point 2 in the tree.

Your story of cranial nerve evolution in vertebrates

You've now created a picture of *some* of the evolutionary changes in vertebrate cranial nerves (see the full, completed tree on the following page). Even though your tree only has three vertebrate taxa, only seven cranial nerves, and just a handful of the cranial nerve functions, it still captures many of the major evolutionary changes. If you were to explain the main takeaways of this evolutionary tree to someone, what would you say? What would you conclude are some of the principal narratives in cranial nerve evolution, based on the tree you just filled in?

Jot down at least three brief bullet points that you would use to construct your narrative on page 3 of your **Notebook**. If you get stuck, check out the hint on the next page.

HINT: Questions to spur ideas

If you're having trouble thinking of takeaways, answer one or more of the following questions:

- What are the different patterns of trait changes that you see at points 1-5 in the tree (including gains and losses of a structure and gains and losses of function)?
- Do two or more of the changes in cranial nerve functions have anything in common?
- Do evolutionary gains and losses of cranial nerves (e.g., the hypoglossal nerve, lateral line nerves) have anything in common?

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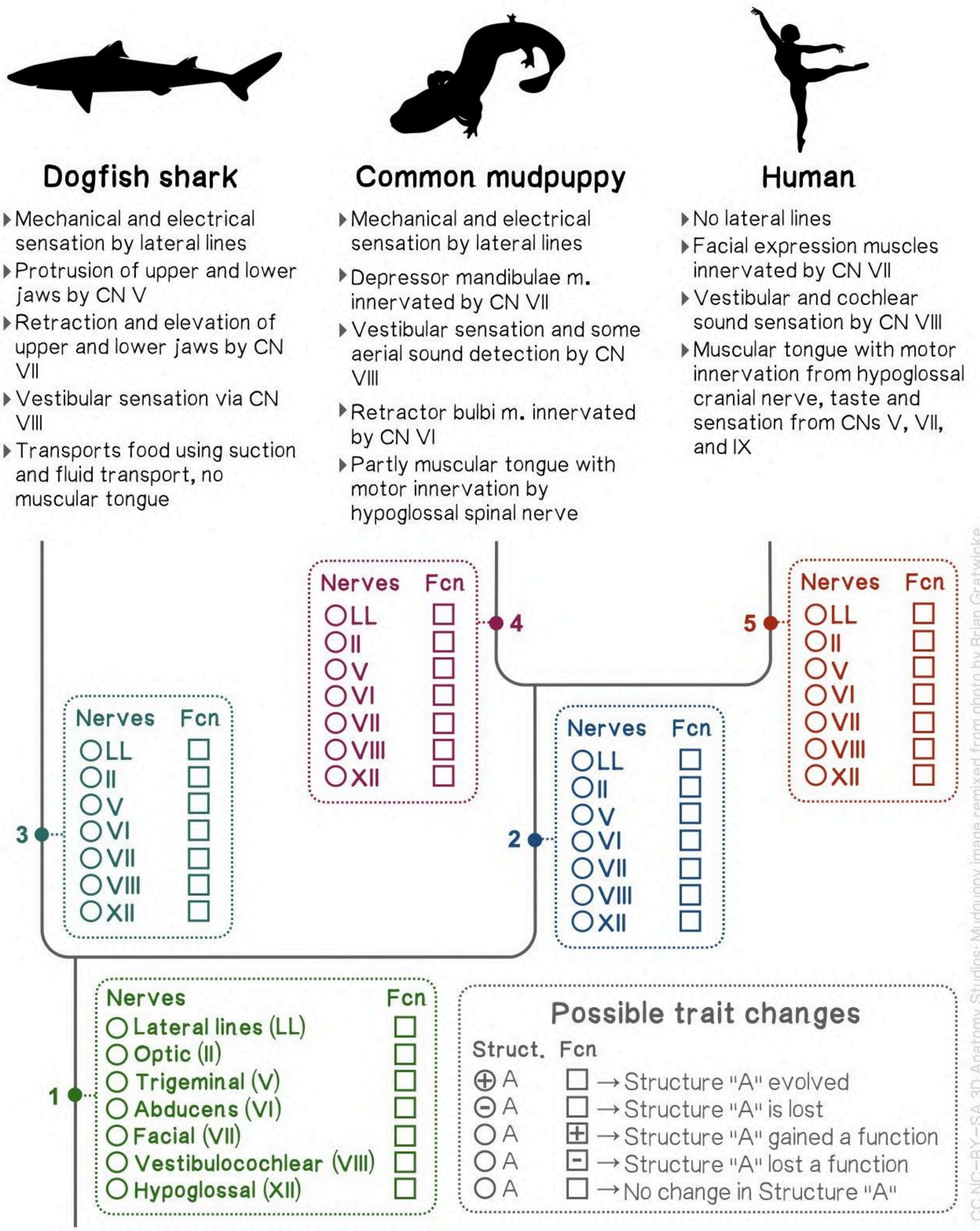
- Levine, Robert P., Jenna A. Monroy, and Elizabeth L. Brainerd. "Contribution of eye retraction to swallowing performance in the northern leopard frog, *Rana pipiens*." *Journal of Experimental Biology* 207.8 (2004): 1361-1368. DOI: 10.1242/jeb.00885.
- Anderson, Curtis W., and Kiisa C. Nishikawa. "The functional anatomy and evolution of hypoglossal afferents in the leopard frog, *Rana pipiens*." *Brain research* 771.2 (1997): 285-291. DOI: 10.1016/S0006-8993(97)00803-2.
- Christensen, Christian Bech, et al. "Better than fish on land? Hearing across metamorphosis in salamanders." *Proceedings of the Royal Society B: Biological Sciences* 282.1802 (2015): 20141943. DOI: 10.1098/rspb.2014.1943.

STUDENT NOTEBOOK

Section 1. How are the shark cranial nerves different or similar to one another?

Create a Venn diagram of the shark cranial nerves

Section 2. What cranial nerves and functions are ancestral versus derived in vertebrates?



Your story of cranial nerve evolution in vertebrates

If you were to construct a narrative about your completed evolutionary tree on the previous page, what would be the main points around which you would construct that narrative? List at least three brief takeaways as bullet points below.

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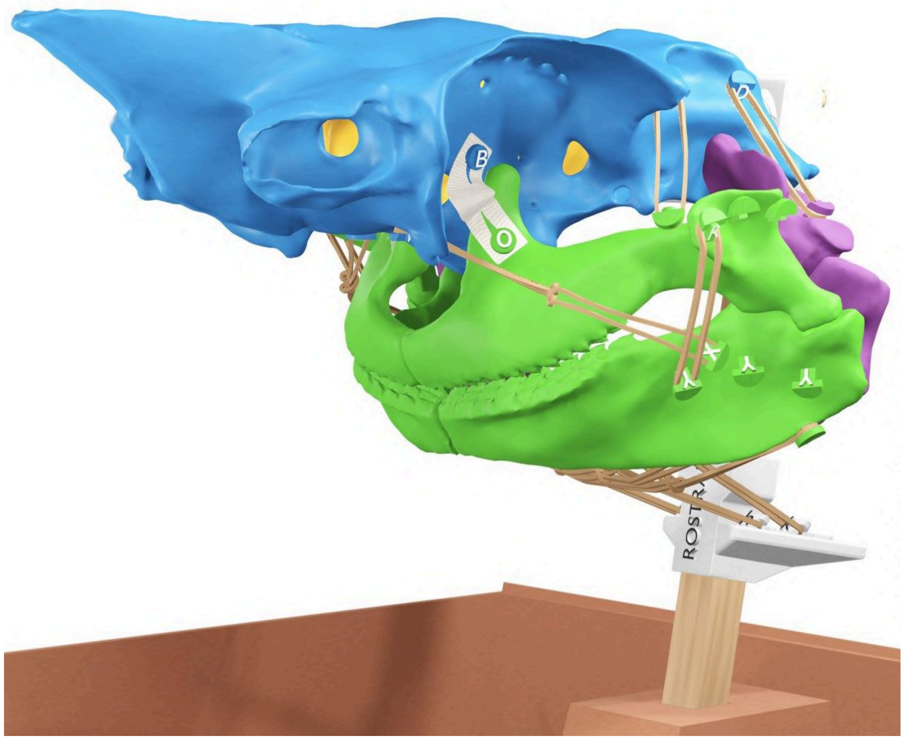
EDUCATOR GUIDE

Simulating the motions of your shark's jaws

Text and images by Aaron M Olsen, PhD



Time to complete: 60-80 min
Age level: Grades 11-12 or College
Bloom's levels: 1, 2, 3, 4 & 5
Description: In this module, your students will identify the jaw muscles of the spiny dogfish shark (*Squalus acanthias*), infer their actions by simulating motions, and explain how sharks can manipulate food without a tongue.
Materials needed:

- SA05 Student Guide & Notebook v1.0
- Dogfish Shark Skull Kit v1.0
- **OPTIONAL** Dressing forceps

Systems:

- Muscular
- Skeletal

Core concepts:

- Structure & Function

Competencies:

- Observation
- Scientific reasoning

Module ID: SA05
Module version: 1.1
Module sequence (suggested):
SA02 → SA03 → SA01 → **SA05** → SA04

How to use and edit this module

This is an open-source active learning module created by 3D Anatomy Studios and licensed under CC NC-BY-SA for use with the Dogfish Shark Skull Kit.

Module Structure

This module has an **Educator Guide**, a **Student Guide**, and a **Student Notebook** and is divided into one or more sections, each with a number, a motivating question as its heading, and a learning objective.

Educator Guide

The **Educator Guide** is intended for educators and contains a pedagogical schema for the module to help implement the module in a course (e.g., learning objectives, target Bloom's level and competencies, core concepts), an answer key for certain prompts/questions in the the **Student Notebook**, and module updates.

Student Guide

The **Student Guide** is intended for students to read as they complete the module's activities and can be read on a device or printed out.

Student Notebook

The **Student Notebook** contains worksheets or diagrams on which students can write or draw as a part of the module's activities. The **Student Notebook** can be printed out or filled in using a digital tablet.

Sharing and Editing

The CC NC-BY-SA license allows you to share and edit this module as long as you (1) do not sell the module or module derivatives ("NC"), (2) attribute the author(s) of all the content, including preserving text and graphic attributions ("BY"), and (3) share the module under the same license ("SA"). You can edit this module by copying the current Google Doc of this module (accessible at 3danatomystudios.com/guides/SA00) and editing that copy.

Purchasing Kits

To purchase kits, please visit 3danatomystudios.com/shop/dogfish-skull-kit.

Pedagogical schema

Section 1. What are the shark jaw muscles?

Learning objective	**Identify (Bloom's Level 1 - Remember)** the shark jaw muscles, **interpret (Bloom's Level 2 - Understand)** their orientations, and **demonstrate (Bloom's Level 3 - Apply)** their origins and insertions by **building (Bloom's Level 3 - Apply)** a 3D model.
Activity	Attach rubber bands to muscle attachment sites on a 3D model of a shark skull and fill in the blanks of a table.
Self-assessment	Compare the constructed 3D model and filled table responses with answers in the student guide.
Systems	**Muscular** **Skeletal**
Core concepts	**Structure & function**
Competencies	

Section 2. How can your shark's jaws move and which muscles drive those motions?

Learning objective	**Demonstrate (Bloom's Level 3 - Apply)** the motions of the jaws by **simulating (Bloom's level 5 - Evaluate)** the motions with a 3D model and **infer (Bloom's level 4 - Analyze)** the actions of the jaw muscles by **experimenting (Bloom's level 4 - Analyze)** with and **interpreting (Bloom's level 5 - Evaluate)** how rubber band muscles on the model change length during the motions.
Activity	Simulate muscle actions using a 3D model with rubber bands and fill in the blanks of a table.
Self-assessment	Compare the filled table responses with possible responses in the student guide.
Systems	**Muscular** **Skeletal**
Core concepts	**Structure & function**
Competencies	**Scientific reasoning**

Section 3. How do sharks use body muscles to open their mouth?

Learning objective	**Explain (Bloom's Level 4/5 - Analyze/Evaluate)** how sharks use their epaxial and hypaxial muscles to open their mouth by **experimenting (Bloom's level 4 - Analyze)** with a 3D model.
Activity	Simulate cranial and jaw motions using a 3D model and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Muscular** **Skeletal**
Core concepts	**Structure & function**
Competencies	**Scientific reasoning**

Section 4. How do sharks manipulate their food without a tongue?

Learning objective	**Explain (Bloom's Level 4/5 - Analyze/Evaluate)** how sharks are able to manipulate their food without a tongue by observing an articulated and mobile model of a shark skull.
Activity	Observe model of shark cranial skeleton and write short answers
Self-assessment	Compare written responses with possible responses in the student guide
Systems	**Muscular** **Skeletal**
Core concepts	**Structure & function**
Competencies	**Observation** **Scientific reasoning**

Answer key

Section 1. What are the shark jaw muscles?

	Attachments		Potential actions (concentric only)							
Muscle name	**Which elements does this muscle connect?** (Use abbreviations below table)		Lower jaw		Upper+Lower				Hyoid arch	
			Elevation	Depression	Elevation	Depression	Protrusion	Retrusion	Elevation	Depression
Levator palatoquadrati	CC	PQ								
Levator hyoideus	CC	HM								
Preorbitalis	CC	MC								
Quadratomandibularis	PQ	MC								
Coracomandibularis	PG	MC								
Coracohyoideus + Coracoarcualis	PG	BH								
Interhyoideus	LCH	RCH								
Intermandibularis	LMC	RMC								

Section 2. How can your shark's jaws move and which muscles drive those motions?

	Attachments		Potential actions (concentric only)							
			Lower jaw		Upper+Lower				Hyoid arch	
Muscle name	Which elements does this muscle connect? (Use abbreviations below table)		Elevation	Depression	Elevation	Depression	Protrusion	Retrusion	Elevation	Depression
Levator palatoquadrati	CC	PQ			X			X		
Levator hyoideus	CC	HM						X		
Preorbitalis	CC	MC	X		X		X			
Quadratomandibularis	PQ	MC	X							
Coracomandibularis	PG	MC		X		X		X		
Coracohyoideus + Coracoarcualis	PG	BH		(X)		X		X		X
Interhyoideus	LCH	RCH					X		X	
Intermandibularis	LMC	RMC					X		(X)	

Lower jaw elevation and depression

The adductor mandibulae complex (preorbitalis and quadratomandibularis) can elevate the lower jaw (these rubber bands shorten during elevation) whereas the coraco muscles can depress the lower jaw (these rubber bands shorten during depression). Because the hyoid and lower jaw are variably coupled, the coracohyoideus may also be able to depress the lower jaw to some degree; since this is variable and not well understood, this "X" has parentheses.

Upper+Lower jaw elevation and depression

Levator palatoquadrati and preorbitalis can elevate the upper+lower jaw whereas the coraco muscles can depress the upper+lower jaw.

Upper+Lower jaw protrusion and retrusion

Preorbitalis can protrude the upper+lower jaw but so can the ventral sheet muscles (interhyoideus and intermandibularis). As the jaws protrude, they also compress mediolaterally. This is a common feature of linkage mechanisms: the connections among links cause certain motions to be correlated with other motions. As a consequence, the ventral sheet muscles could also help protrude the jaws by compressing the jaws mediolaterally. You can also observe this correlated motion of the jaw linkage in the rotation of the hyomandibula during protrusion-retrusion. As the jaws protrude, the hyomandibula rotates ventrally, stretching the levator hyoideus. Thus, by contracting, the levator hyoideus can help to retrude the protruded jaws, along with the levator palatoquadrati and the coraco muscles.

Hyoid arch elevation and depression

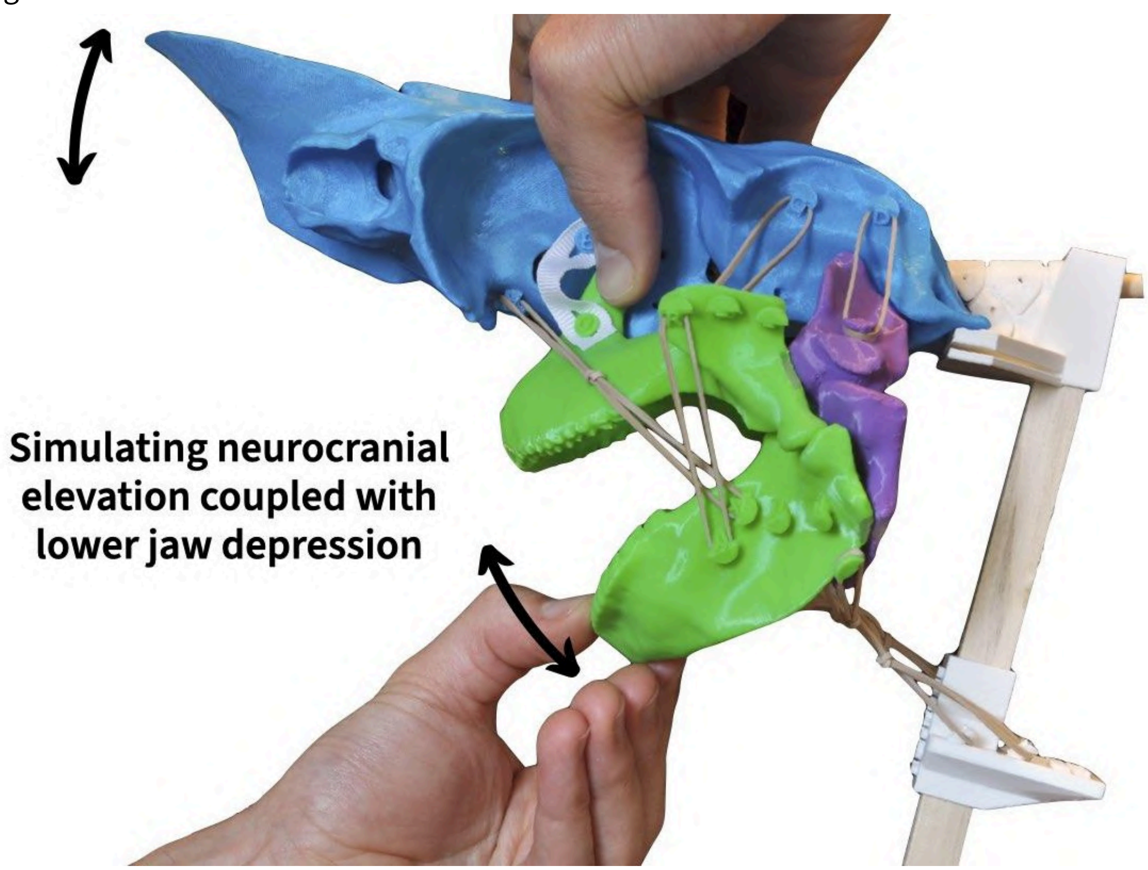
The coracohyoideus and coracoarcualis can depress the hyoid arch by pulling it back toward the pectoral girdle; in other species of sharks, the coracohyoideus can even store energy as a part of a spring-loaded system to rapidly depress the hyoid (Ramsay & Wilga 2017). As the hyoid arch is depressed two things can happen. At moderate levels of depression, the ceratohyals rotate such that the attachments of the interhyoideus are pulled further apart. This means that by shortening, the interhyoideus can elevate the hyoid arch. If the hyoid arch is depressed further, it pushes up against and stretches the intermandibularis. Thus, at greater levels of depression, the intermandibularis can also elevate the hyoid arch. Since the intermandibularis may not always be able to elevate the hyoid arch, parentheses are added around the "X" in the table.

Section 3. How do sharks use body muscles to open their mouth?

Using your shark skull to perform simulations, can you explain how fish can use their body muscles to open their mouth and generate suction? Your explanation should include which muscles are involved and their role. Feel free to write in bullet points.

- If the epaxials and levator palatoquadrati shorten at the same time, the epaxials will elevate the chondrocranium and upper jaw together.
- If the coraco muscles and hypaxials shorten at the same time, the lower jaw and hyoid will be depressed.
- Thus, if the epaxials, levator palatoquadrati, coraco muscles, and hypaxials all shorten at the same time, the mouth will open and the throat will be expanded.
- Expansion of the throat (i.e., expansion of a volume) will generate suction.

To simulate this in your shark, your students could do something similar to the following image.



Section 4. How do sharks manipulate their food without a tongue?

How can sharks manipulate their food without a tongue? Feel free to write in bullet points.

- Sharks don't just bite up and down, they're capable of moving their jaws in many different ways.
- The jaws and skull of sharks are capable of at least five different actions (including neurocranial elevation) and even more when asymmetrical motions are included.
- Sharks compensate for their lack of a kinetic tongue by having a kinetic cranial skeleton.
- Sharks have at least 9 muscles on each side of the skull for moving the chondrocranium and jaws. This is similar to the number of muscles that humans have for moving their jaws and tongue.
- Sharks have a similar number of muscles associated with jaw motions as we do, they just attach to rigid skeletal elements rather than to a muscular tongue.

Updates

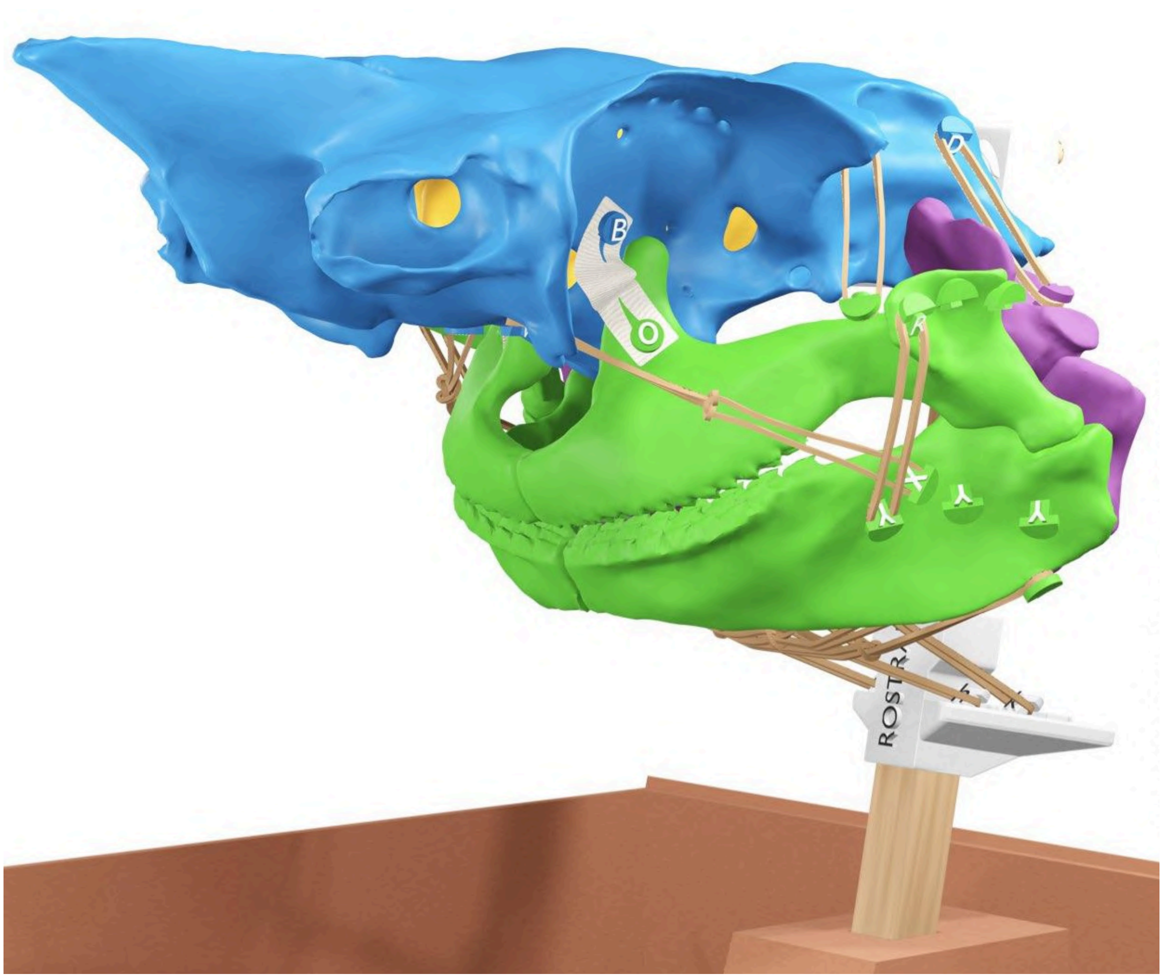
Version 1.1

- Moved most of the self-assessment from the Student to Educator Guide.

STUDENT GUIDE

Simulating the motions of your shark's jaws

Text and images by Aaron M Olsen, PhD



Description

In this module, you will identify and attach jaw muscles to the skeleton of your spiny dogfish shark (*Squalus acanthias*) and figure out the actions of each muscle by using your model to simulate the motions of the jaws.

Introduction

After learning the skeletal elements of the shark skull, you may be thinking: relative to sharks, humans have a much simpler cranial skeleton! Excluding the tiny middle ear bones, we only have two moving cranial bones: our mandible and hyoid. In this sense, the human cranial skeleton is **less kinetic** (i.e., capable of moving in fewer ways) than the shark cranial skeleton. With so few moving bones, how do we bite, chew, suck, process, and swallow food?

Our trick to achieving all of these complex motions is having a highly kinetic **tongue**. Just three or so muscles are associated with moving the mandible but more than seven muscles make up and attach to the human tongue. This gives the tongue a high degree of mobility that, in coordination with the mandible and hyoid, helps us perform complex manipulations.

Although sharks process their food differently from us, they still need to manipulate their food in complex ways to eat (e.g., moving food around inside their mouth, reducing its size, moving it toward the stomach to swallow). Yet, if you were to look inside a shark's mouth you wouldn't see a tongue. The floor of their mouth and pharynx can move up and down but it's nothing like a tongue. How do sharks achieve these manipulations without a tongue?

Sharks, such as this white shark (*Carcharodon carcharias*), don't have a tongue. Modified from a photograph by Bernard Dupont licensed under CC BY-SA 2.0.

Whereas humans have a highly kinetic *tongue*, sharks have a highly kinetic *cranial skeleton*. Sharks have nine separate jaw cartilages that make up the first and second arches of their jaws and that connect together to form a **linkage mechanism** (an engineering term for rigid elements connected by mobile joints). Sharks move their jaw cartilages to manipulate and transport food and water through their mouth rather than using a tongue (Dean, Wilga & Summers 2005). How do sharks use their jaw muscles to drive this complex cranial linkage mechanism? In this module, you will figure this out for yourself, by attaching muscles to your shark skeleton, simulating jaw motions, and discovering which muscles drive which motions.

Materials needed

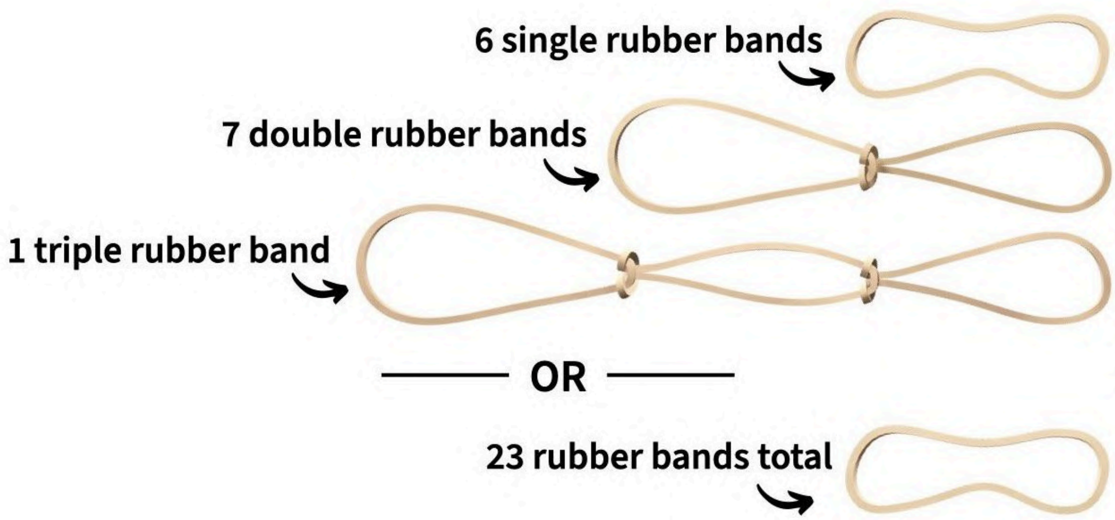
For this module, you'll need:

- The **Student Notebook** for this module (SA05).
- To first complete the module **Building the skeleton of your shark skull** (SA01). In that module, you'll mount your chondrocranium and brain to the stand and attach all of the jaw cartilages. After completing that module, your shark skull will look like the image below and you'll be ready to start this module.

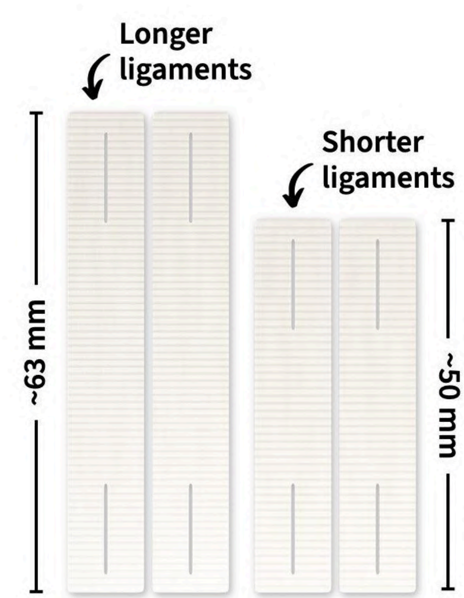
If your skull has the branchial arches attached, it's fine to leave them in place; you may need to remove and reattach them as you complete this module to attach some muscles.

Materials needed (continued)

- The **rubber bands** from your kit box (there should be more in your kit than you need for this module). Your rubber bands may be all single rubber bands or some may be knotted together (if your kit has been used before). Either is OK- if you need double or triple rubber bands, you'll make them as a part of this module.



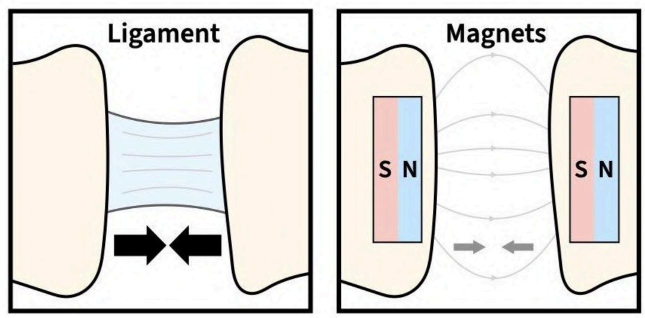
- The **ribbons** from your kit box with slits at each end. For this module, you'll only use the two shorter ribbons (~50 mm in length; see image below).



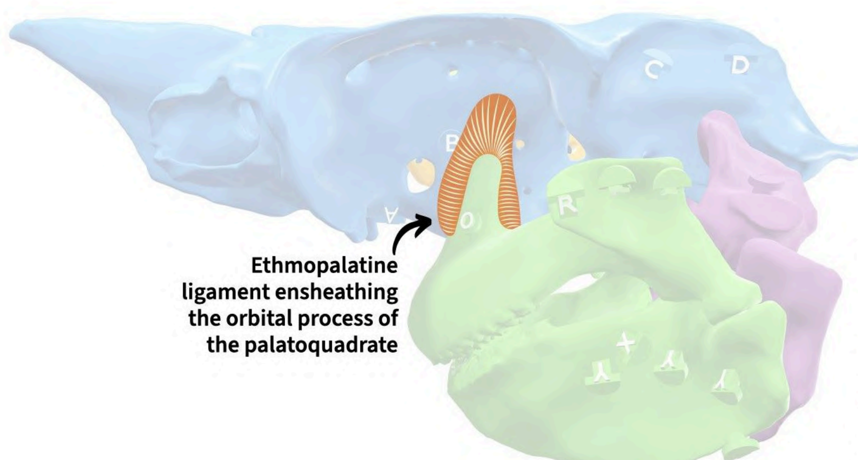
- **OPTIONAL** "Dressing forceps" (not "rat tooth" or "tissue" forceps) can be helpful for attaching the ligaments and muscles, though they are not necessary.

Adding ligaments to stabilize your shark's jaws

Recall that from the **Building the skeleton of your shark skull** module, each pair of attracting magnets in your jaw cartilages represents one or more ligaments. Ligaments function in holding together but also limiting the motion of skeletal elements. However, these magnetic connections are *much* weaker than real ligaments and they can only act over a short distance.



A key ligament limiting the motion of your shark's jaws is the **ethmopalatine ligament**.

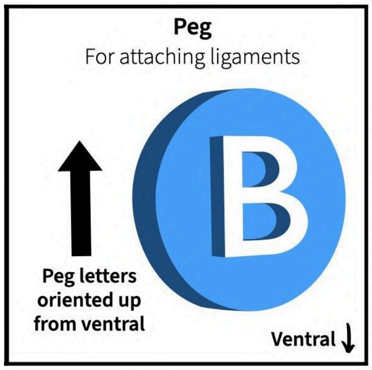


This ligament prevents the **palatoquadrate** from moving too far from the **chondrocranium**. To make your simulations more realistic and to help keep your jaw cartilages from coming apart, you can add a more realistic ethmopalatine ligament (i.e., a ribbon) to your shark. It's easier to add this ligament *before* adding any muscles, so if you add it, it's best to do that now.

Before you add any ligaments, read through the **Build note** on the next page. If you're having trouble attaching the ligaments, you can just complete this module without attaching them.

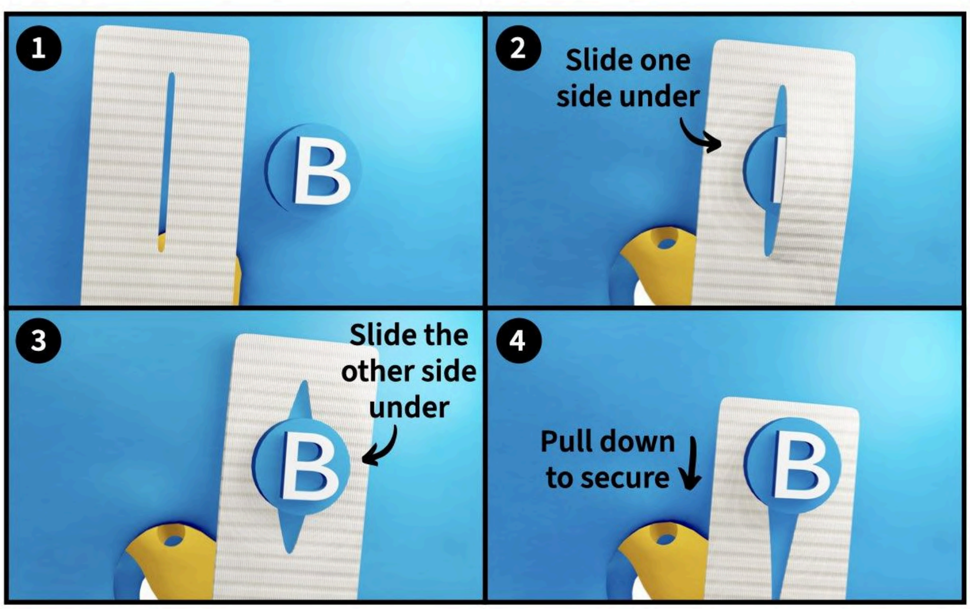
BUILD NOTE: Attaching ligaments

The 3D printed pieces in your kit have small hooks and pegs with raised letters on them: the hooks are for attaching muscles and the pegs are for attaching ligaments (ribbons). Each peg has a unique letter on it oriented approximately with the bottom pointing **ventrally**.



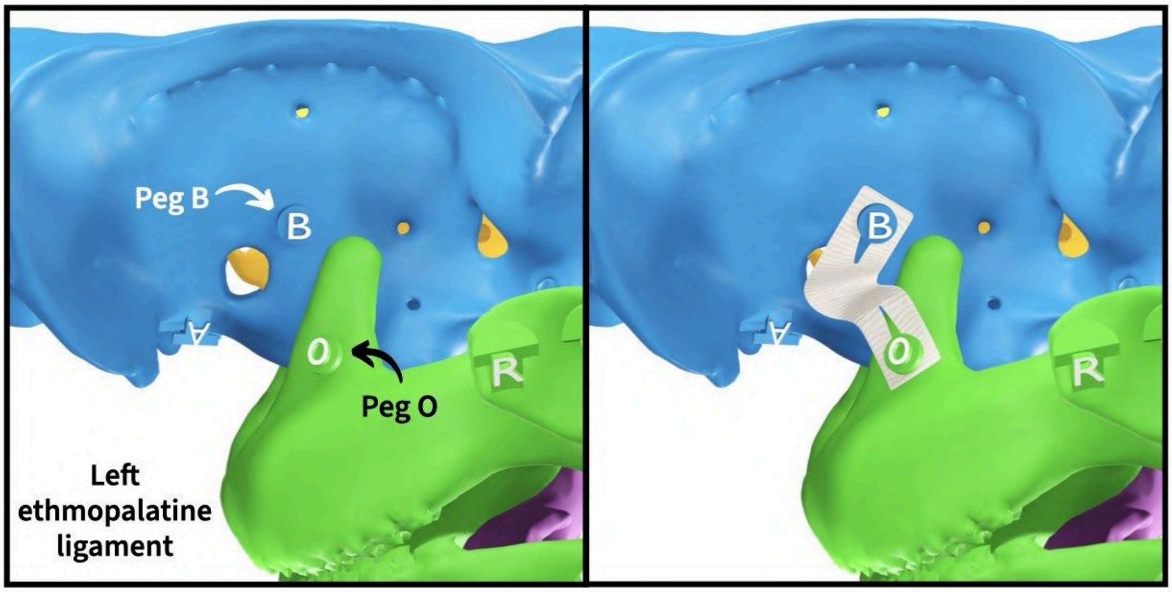
Each ligament has a slit cut in either end, like a buttonhole. To attach a ligament, attach each end to a peg, like to buttoning a button (a pair of dressing forceps can be helpful):

1. Position one end of the ligament next to one of the pegs.
2. Slide one edge of the slit under one side of the peg.
3. Pull the other edge of the slit across and under the peg.
4. Carefully pull the ligament down to secure it in place.

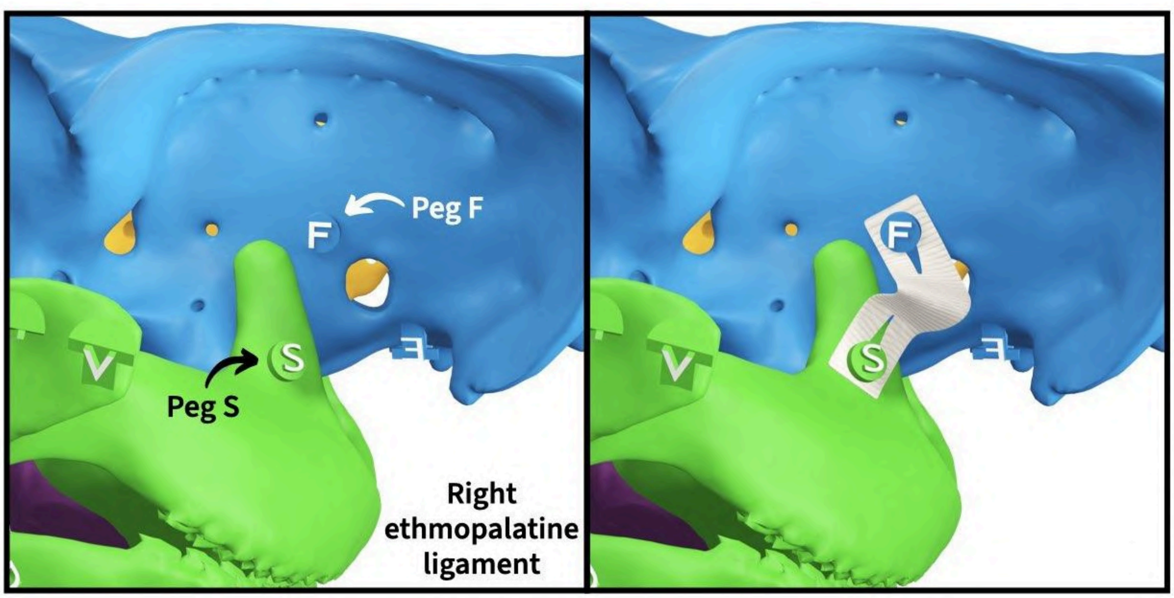


To detach the ligament, just follow the same steps in reverse.

Using the **Build note** on the previous page, attach one of the two *shorter* ribbons in your kit to the "O" peg of the left palatoquadrate and the "B" peg on the wall of the left orbit of the chondrocranium. It may be easier to remove the palatoquadrate to attach the ligament to the "O" peg; you should be able to carefully remove the left palatoquadrate while keeping all the other jaw cartilages connected.



Repeat this on the right side, attaching the second shorter ribbon to the "S" peg of the right palatoquadrate and the "F" peg on the wall of the right orbit of the chondrocranium.

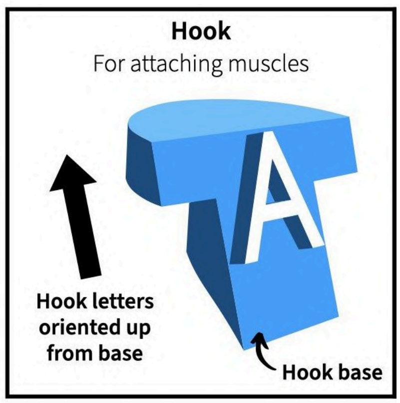


Section 1. What are the shark jaw muscles?

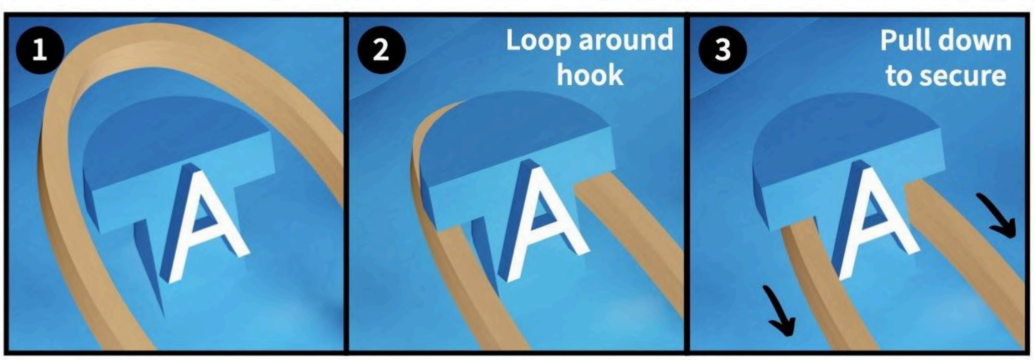
Muscles are the motors of animals. Every intrinsically driven movement of an animal (driven by the animal itself, not externally) is driven by a muscle. So to fully understand how an animal can (and cannot) move, you need to understand the attachments and orientations of the muscles that drive those movements. In this section, you'll attach eight muscles that drive most of the motion of your shark's jaws. For how to attach muscles, see the **Build note** below.

BUILD NOTE: Attaching muscles

The hooks on the 3D printed pieces in your kit are for attaching muscles (rubber bands). Each hook generally has a unique letter and every hook letter is oriented with the bottom toward the base of the hook, as shown in the image below.



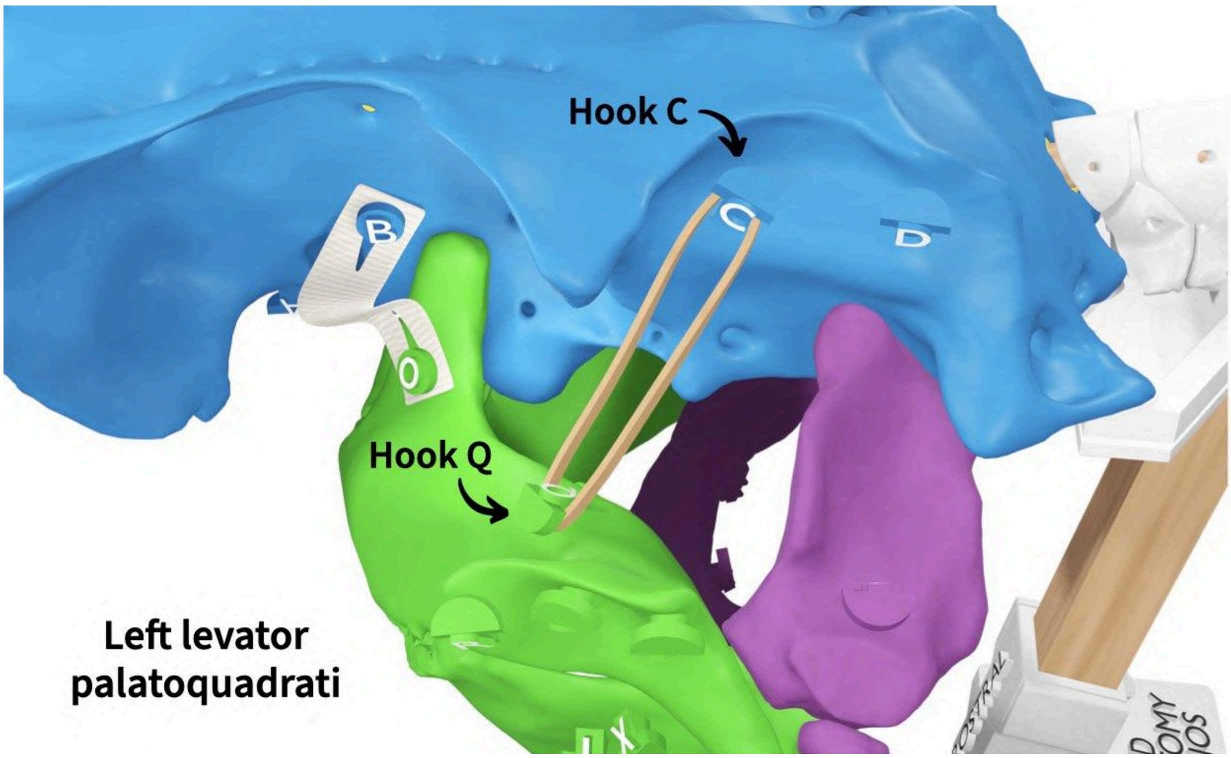
Attach each muscle by looping the rubber band around the hook and secure it by pulling it down around the base of the hook (a pair of dressing forceps can be helpful for this).



Once attached at both ends, the rubber band should be tight enough to stay in place.

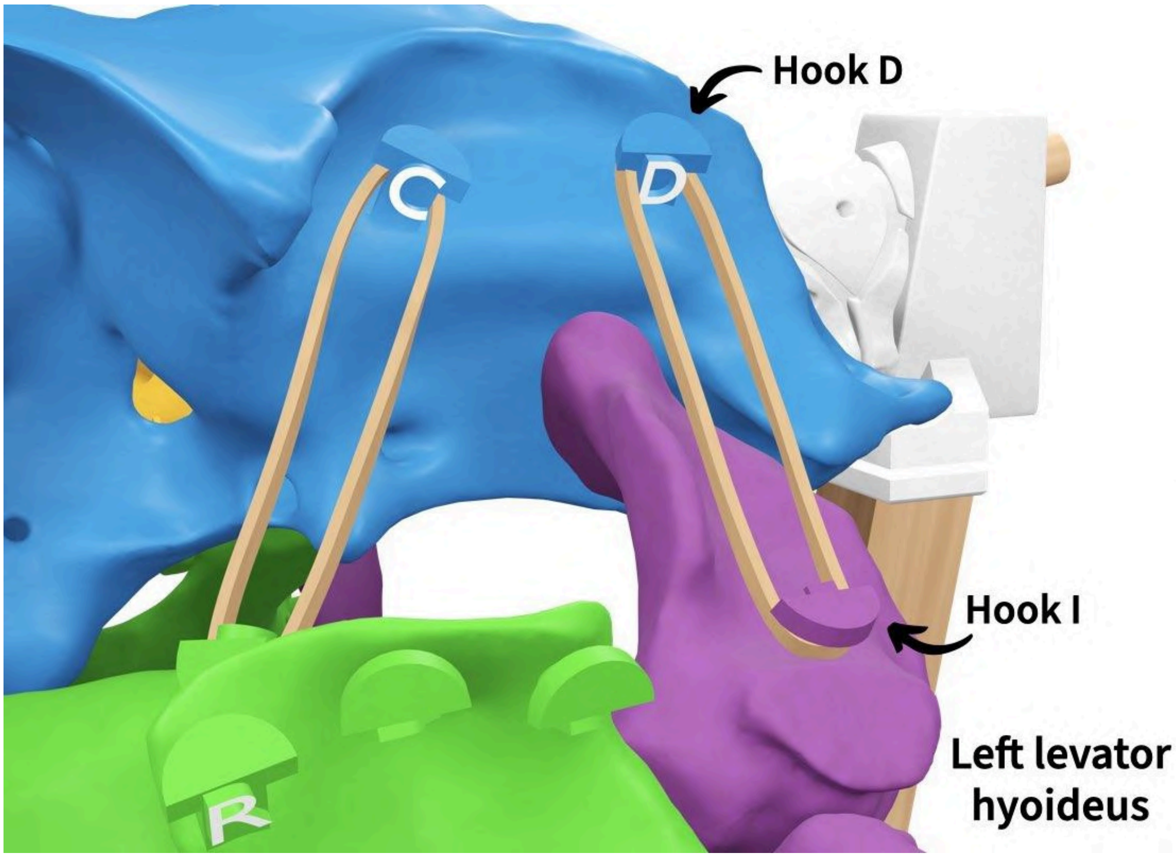
The levators

The first two muscles you'll add are both "levators," so named because their actions include **elevation**. The first is **levator palatoquadrati**, which originates on the chondrocranium and inserts on the palatoquadrate. Add the left levator palatoquadrati to your shark skull by attaching one end of a single rubber band to hook "C" on the left side of the chondrocranium and attaching the other end to hook "Q" on the left palatoquadrate.



Repeat this on the right side of your shark's skull by attaching a single rubber band to hook "G" on the chondrocranium and hook "U" on the right palatoquadrate. On page 1 of your **Notebook**, fill in the "Attachments" column for levator palatoquadrati with the two elements this muscle attaches to.

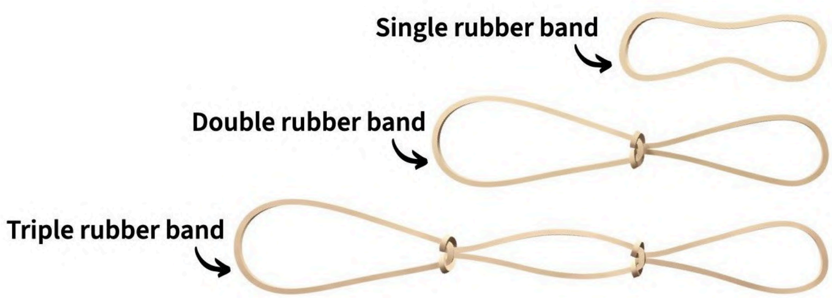
The second levator is the **levator hyoideus**, which originates on the chondrocranium and inserts on the hyomandibula. Add the left levator hyoideus by attaching a single rubber band to hook "D" on the left side of the chondrocranium and hook "I" on the left hyomandibula.



Repeat this on the right side by attaching a single rubber band to hook "H" on the chondrocranium and hook "J" on the right hyomandibula. On page 1 of your **Notebook**, fill in the "Attachments" column for levator hyoideus.

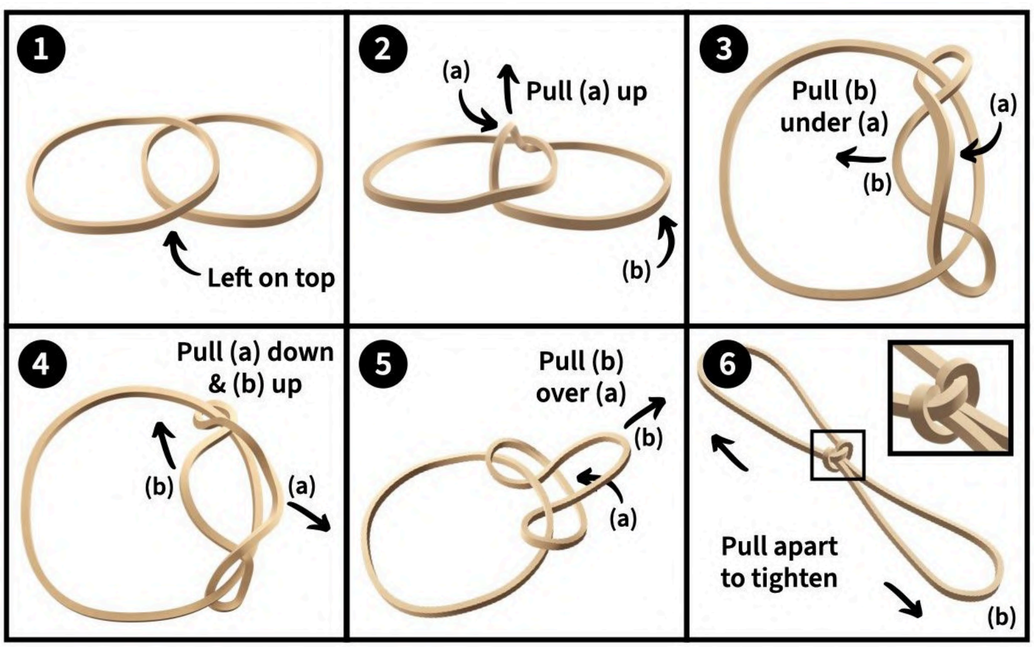
BUILD NOTE: Making a longer muscle

Your kit includes rubber bands of just one length but your shark's muscles are different lengths. To make longer muscles, you'll loop together two and three rubber bands.



If your kit already has rubber bands looped together, sort them into separate piles. If not, follow the instructions and image to form square knots between the rubber bands.

1. Place two rubber bands on your work surface so they are slightly overlapping.
2. Pull the left-most part of the right rubber band (a) up.
3. Insert the right-most part of the right rubber band (b) through the gap.
4. Pull loop (a) down to the right and loop (b) up.
5. Continue pulling loop (b) up and over (a) toward the right.
6. Pull apart to tighten the knot but *don't pull it too tight* or the length will be off.

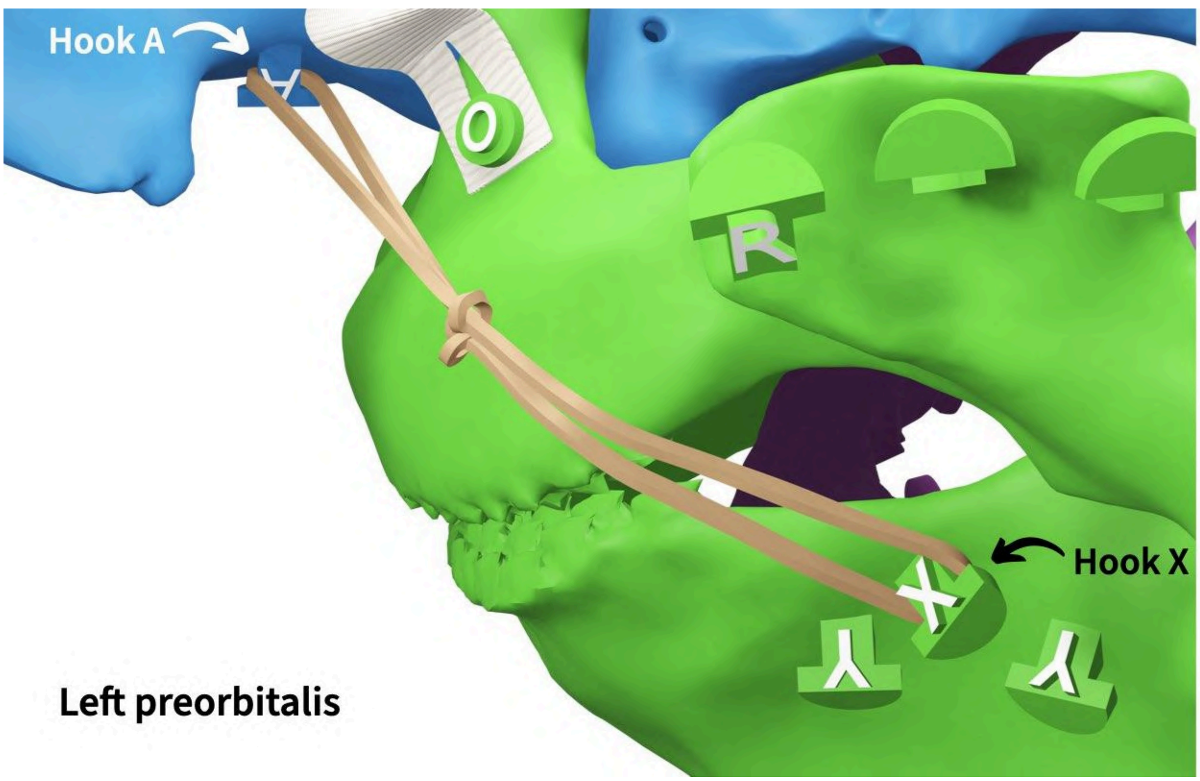


To create a triple rubber band, just repeat these steps with a second rubber band.

The adductor mandibulae complex

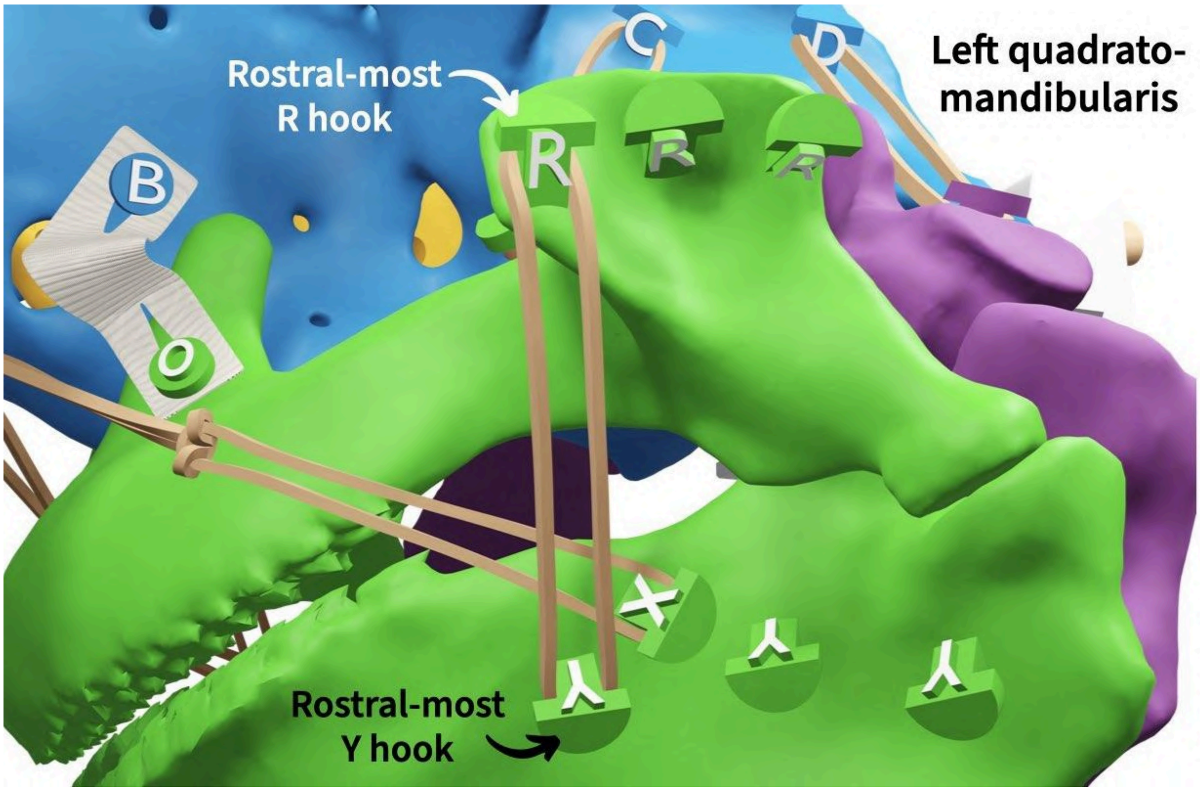
The next two muscles you'll add are part of what's called the **adductor mandibulae complex**. To **adduct** means to bring together, whereas **abduct** means to pull apart. The first is **preorbitalis**, which originates on the chondrocranium and inserts on the **mandible**. The preorbitalis is longer than the previous two muscles so you'll need to use a double rubber band; if your kit doesn't already have these made, use the build note on the previous page to make them.

Add the left preorbitalis to your shark skull by attaching a *double* rubber band to hook "A" on the left side of the chondrocranium and to hook "X" on the left mandible.



Repeat this on the right side by attaching a *double* rubber band to hook "E" on the chondrocranium and hook "d" on the right mandible. On page 1 of your **Notebook**, fill in the "Attachments" column for preorbitalis.

The second muscle of the adductor mandibulae complex is the **quadratomandibularis**, which originates on the palatoquadrate and inserts on the mandible. Add the left quadratomandibularis by attaching a *single* rubber band to the rostral-most "R" hook on the palatoquadrate and the rostral-most "Y" hook on the left mandible. The other hooks are alternate attachment sites for this muscle (thus the repeat letters) that you'll use in another module.



Notice how you added the quadratomandibularis muscle "on top of" the preorbitalis muscle? This matches the layering in an actual shark skull: the quadratomandibularis is **superficial to** the preorbitalis, meaning closer to the external surface of the body. An equivalent way to say this is that preorbitalis is **deep to** the quadratomandibularis.

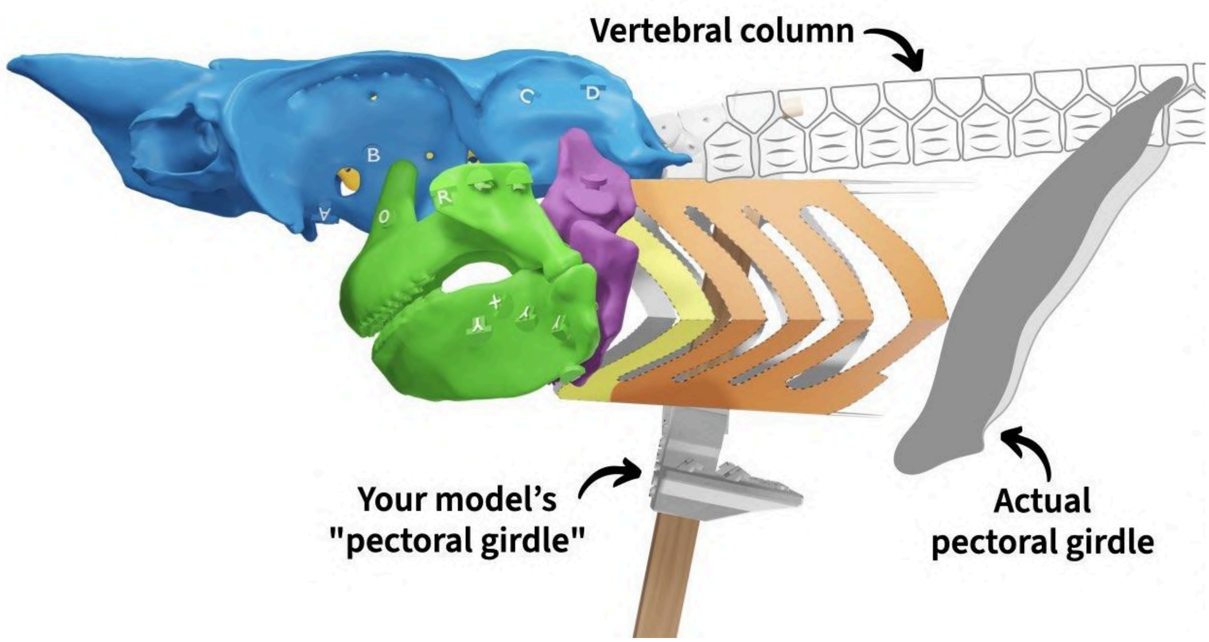
Repeat this on the right side by attaching a single rubber band to the rostral-most "V" hook on the right palatoquadrate and the rostral-most "e" hook on the right mandible. On page 1 of your **Notebook**, fill in the "Attachments" column for quadratomandibularis.

The "coraco" muscles

The next muscles you'll add could be collectively called the "coraco" muscles: all these muscles attach directly (or indirectly) to the **coracoid**, the main element that makes up the **pectoral girdle** (or **shoulder girdle**). The first is the **coracomandibularis**, which originates on the pectoral girdle (specifically, the coracoid part) and inserts on the mandible.

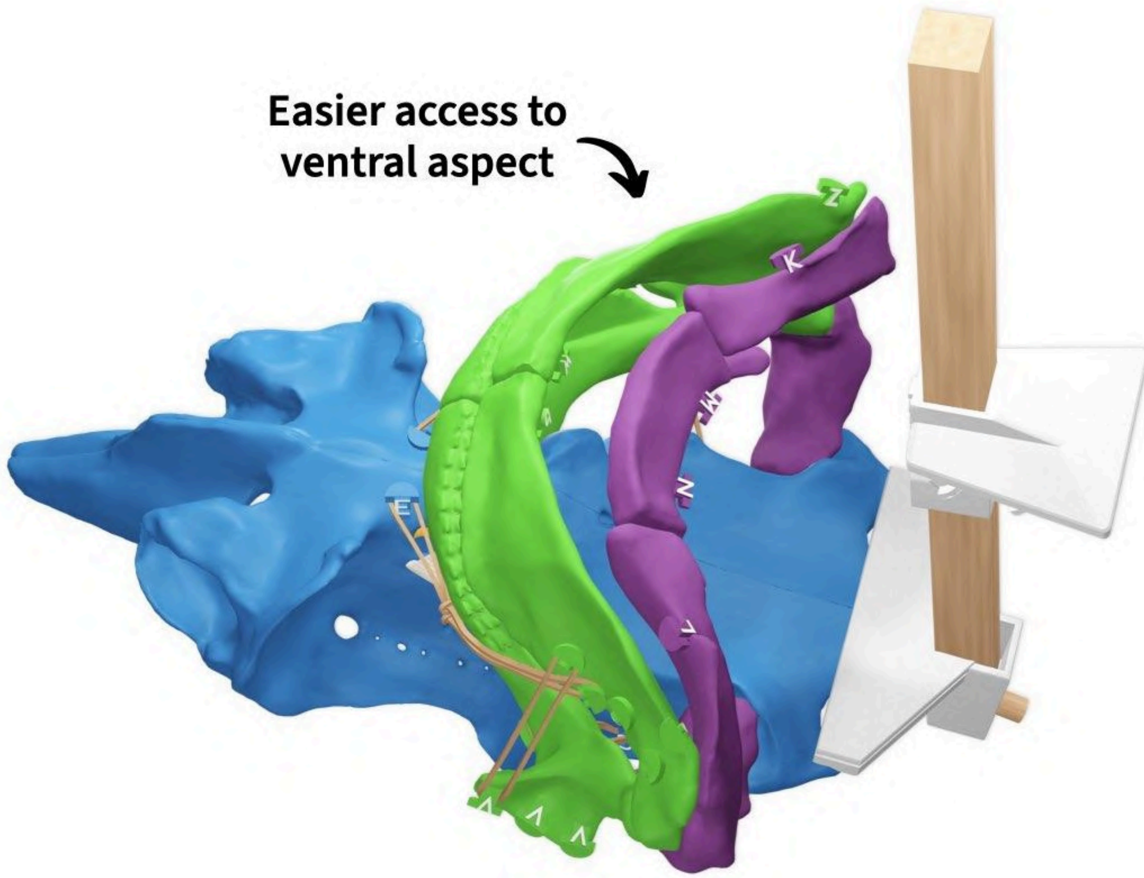
BUILD NOTE: A shoulder stand-in

The middle 3D printed piece of the stand rod in your kit serves as an approximate stand-in for the pectoral girdle. Although the stand rod is located more rostrally than in an actual spiny dogfish shark, the **dorsoventral** position (i.e., its height) is approximately the same.

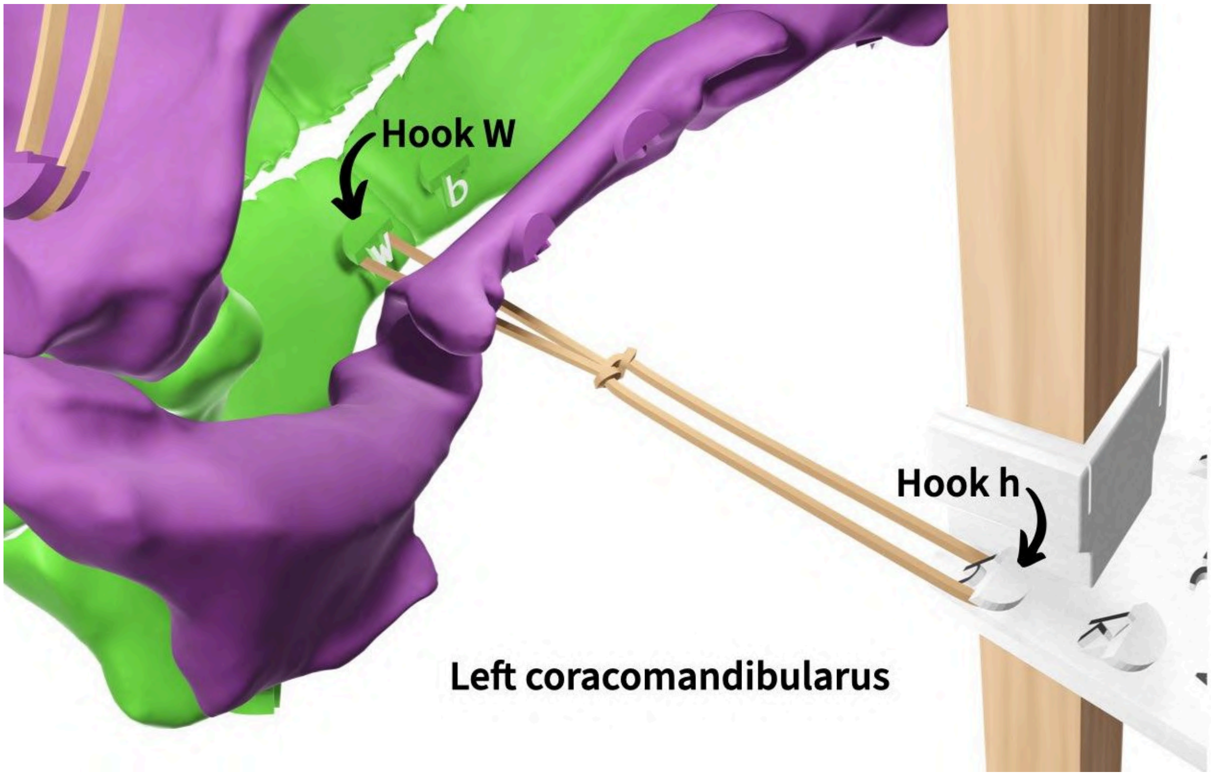


BUILD NOTE: Flipping your shark

Since the coraco muscles are on the ventral aspect of your shark skull, you might find it easier to flip your shark upside down. To do this, remove the stand rod plus shark skull from the stand base, flip it over, and set the skull upside down onto your work surface.



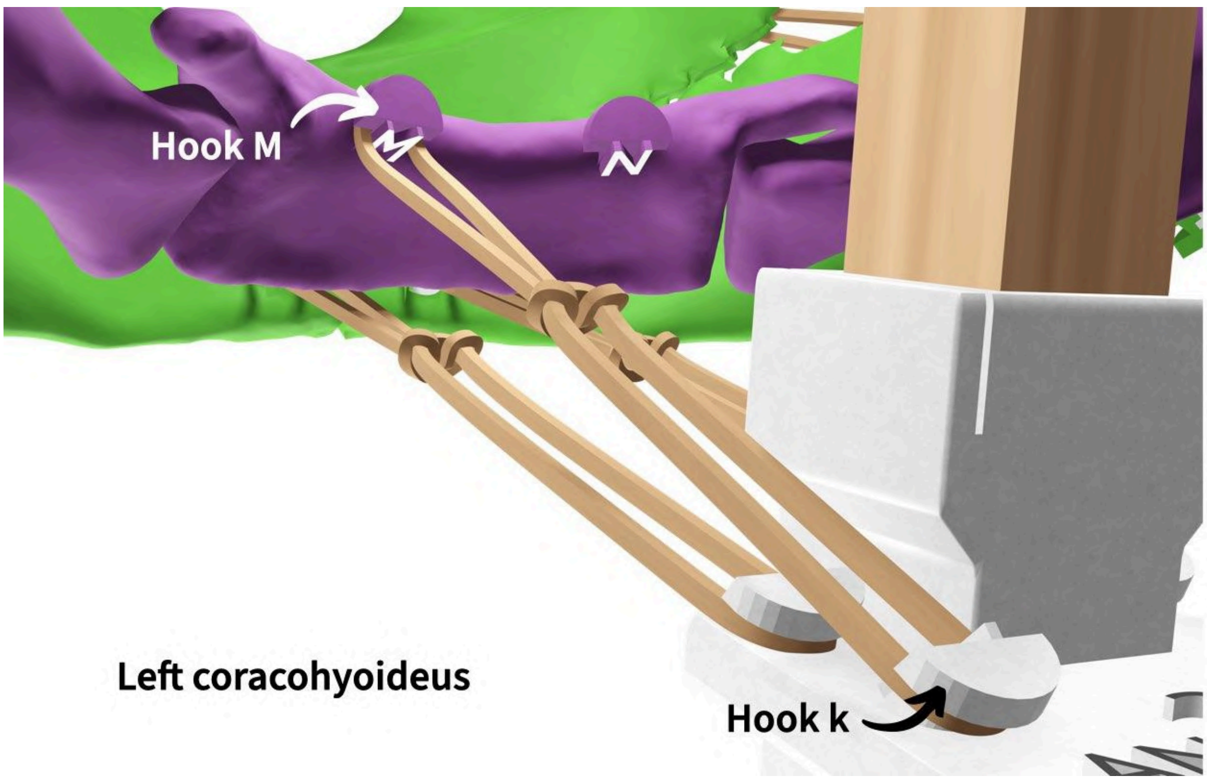
Add the left coracomandibularis to your shark skull by attaching a *double* rubber band to hook "W" on the left mandible and hook "h" on the middle piece of the stand rod.



Repeat this on the right side by attaching a *double* rubber band to hook "b" on the right mandible and hook "m" on the stand rod. On page 1 of your **Notebook**, fill in the "Attachments" column for coracomandibularis.

The other two coraco muscles are the **coracohyoideus** and **coracoarcualis**. These two muscles form something like a "muscle chain": the coracoarcualis originates on the pectoral girdle and inserts on the coracohyoideus *muscle*, and the coracohyoideus originates on the coracoarcualis *muscle* and inserts on the **basihyal cartilage** of the **hyoid arch**. (The coracomandibularis actually attaches to the coracoarcualis too, in addition to the pectoral girdle - it's just been simplified for your shark skull model.)

Because these muscles connect to each other, you'll add them together as a double rubber band. Add the left "coracohyoideus + coracoarcualis" to your shark skull by attaching a *double* rubber band to hook "M" on the basihyal and hook "k" on the stand rod. The double rubber band may not be very tight once it's attached; that's OK - if you secure the band by pulling them around the hooks, it should stay attached.

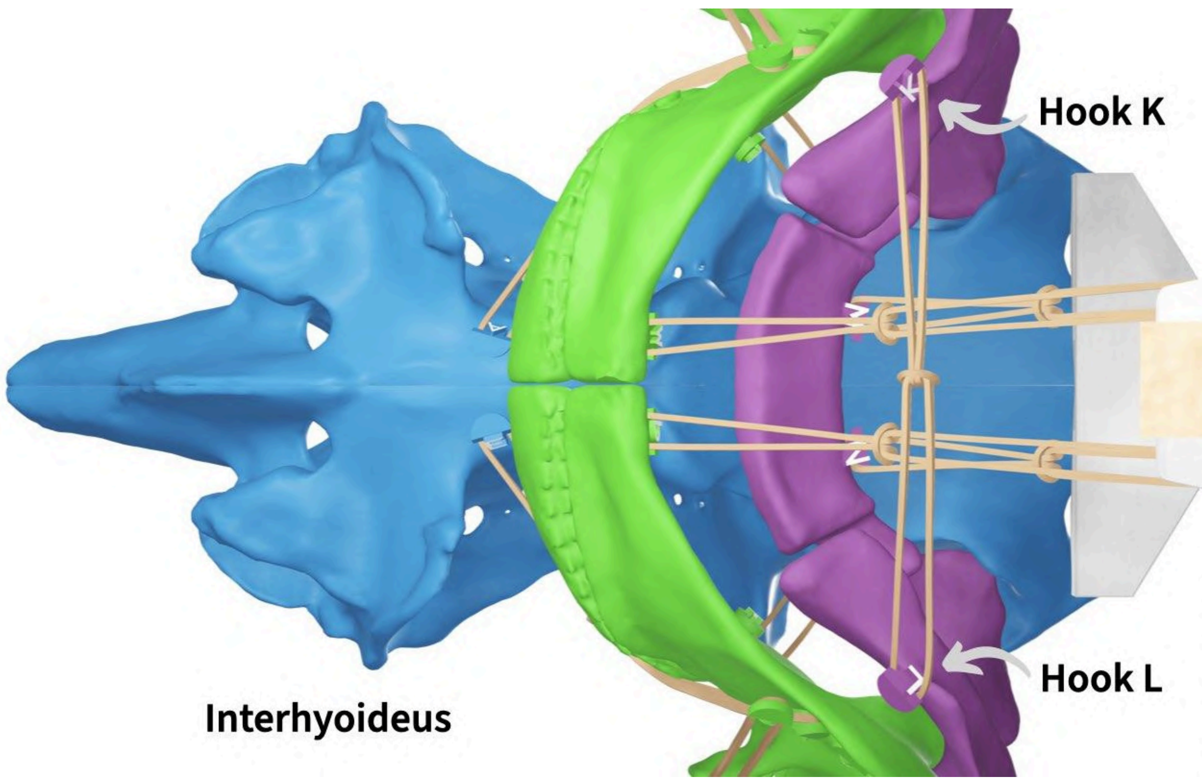


Repeat this on the right side by attaching a *double* rubber band to hook "N" on the basihyal and hook "n" on the stand rod. On page 1 of your **Notebook**, fill in the "Attachments" column for the combined "coracohyoideus + coracoarcualis."

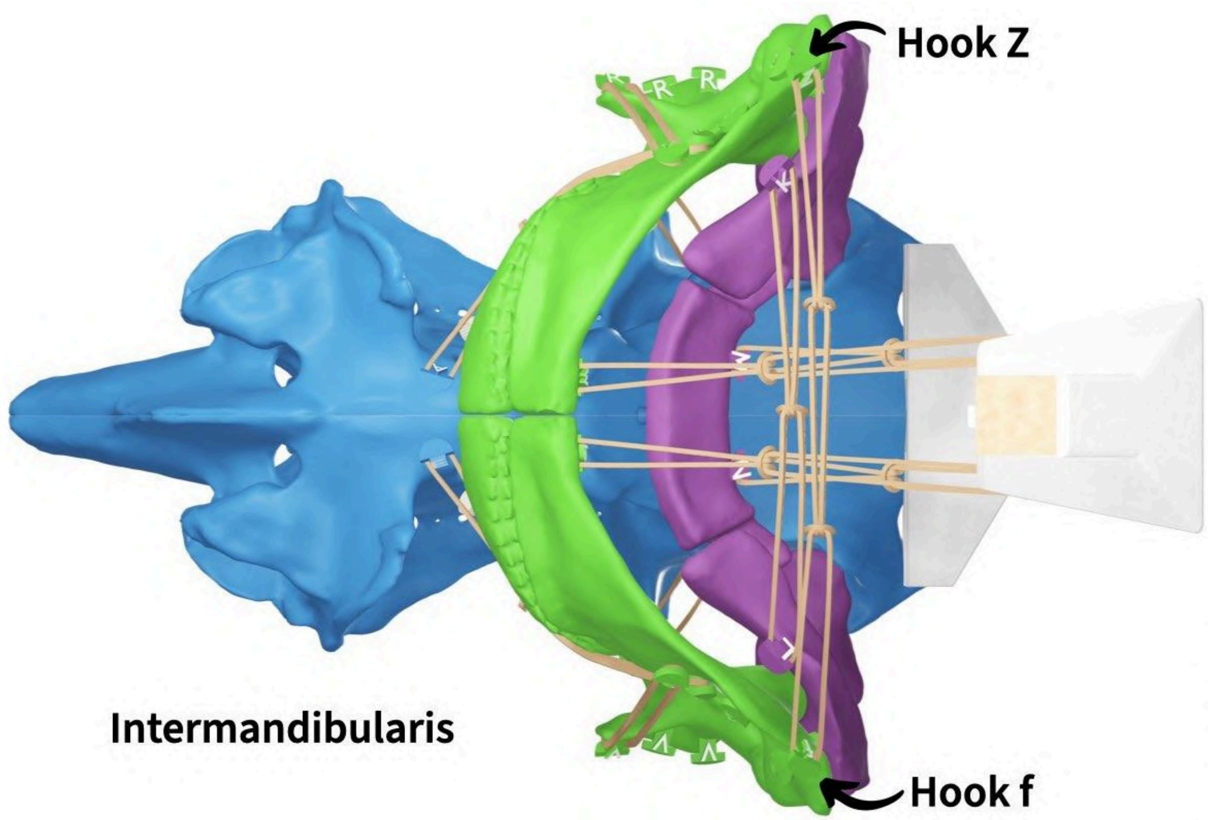
The ventral sheet muscles

The last two muscles you'll add could be called the "ventral sheet muscles." These muscles are broad, thin sheets of muscles that cover most of the ventral surface of the shark's skull and are superficial to the coraco muscles. So keep in mind that the rubber bands just represent the approximate orientation of these muscles, not their shape. For these muscles, it will probably be easiest to remove and flip your shark skull again so you can more easily access the ventral aspect of the skull.

The deepest of these two is the **interhyoideus**. The interhyoideus runs between ("inter") the two left and right **ceratohyals** of the hyoid arch. Add the interhyoideus to your shark skull (superficial to the coraco muscles) by attaching a *double* rubber band to hook "L" on the left ceratohyal and hook "K" on the right ceratohyal.



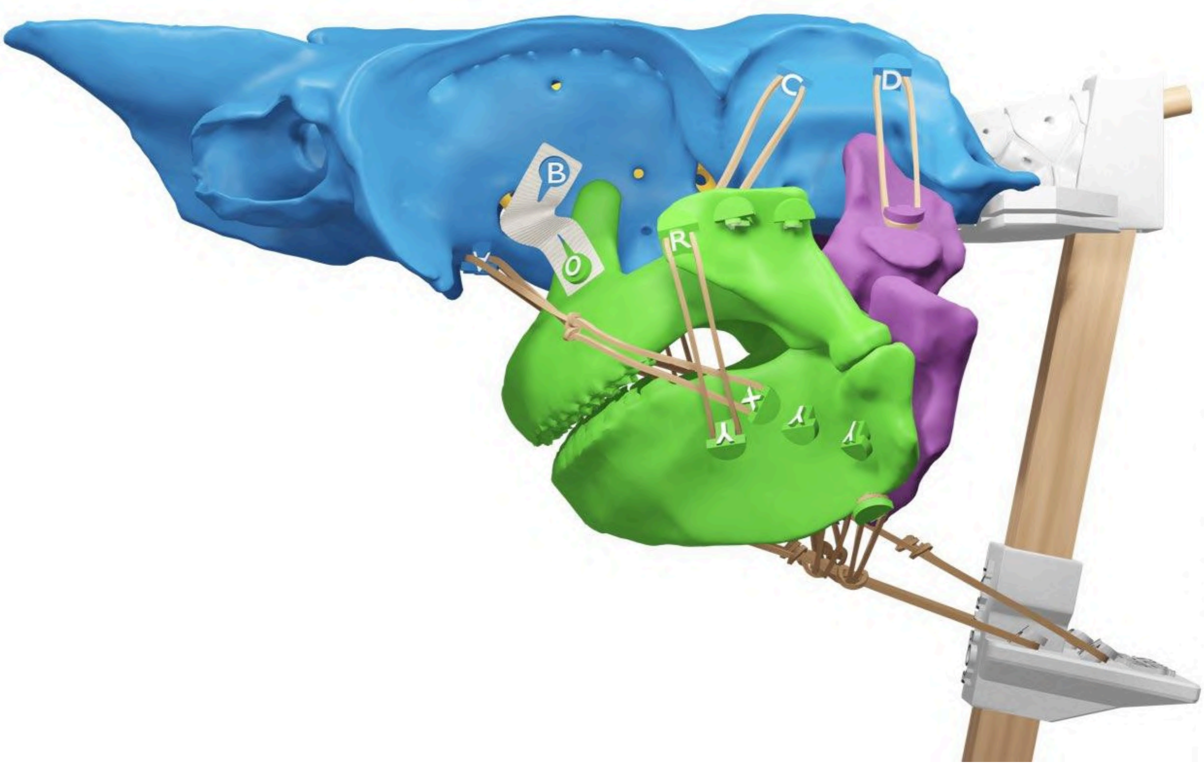
Superficial to the interhyoideus is the **intermandibularis**. Analogous to the interhyoideus, the intermandibularis runs between the left and right mandibles. Add the intermandibularis by attaching a *triple* rubber band to hook "f" on the left mandible and hook "Z" on the right mandible.



On page 1 of your **Notebook**, fill in the "Attachments" columns for interhyoideus and intermandibularis. Once you've finished, check that you have all of your muscles attached correctly by comparing your shark with the image on the following page.

ASSESS: Muscles added

With all the jaw muscles added, your shark should look like the image below.

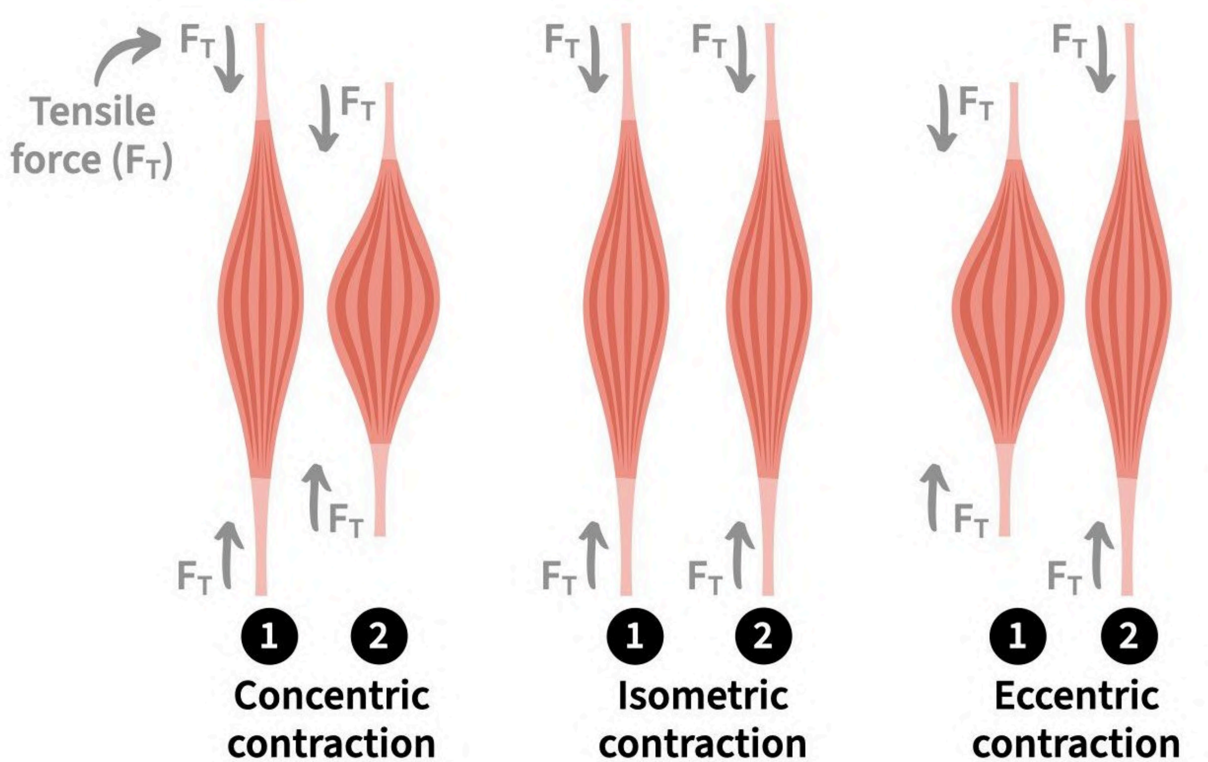


Section 2. How can your shark's jaws move and which muscles drive those motions?

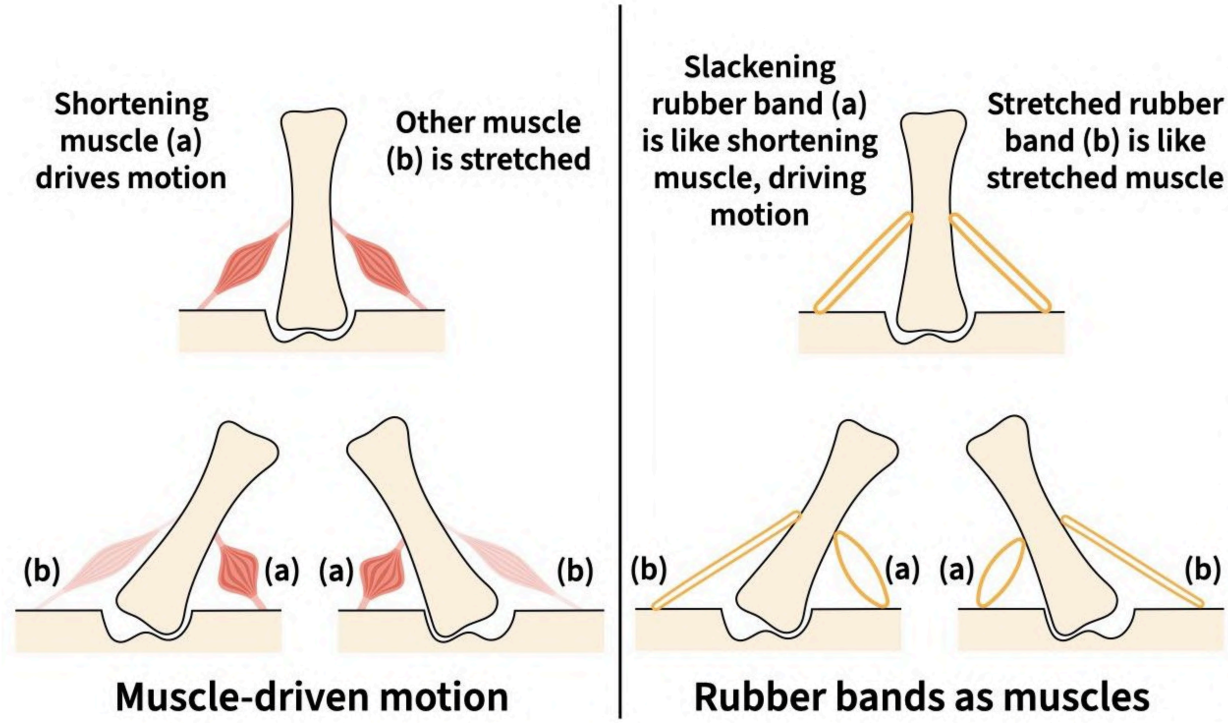
Now that you've added all of the jaw muscles to your shark, you're ready to simulate some motion and figure out which muscles drive which motions! Before you do that, however, it's important to talk about how to infer muscle actions from simulated motion and the limitations of those inferences.

How to infer muscle action from simulated motion

At the cellular level, muscles can only produce **force in tension** (also called a **tensile force**). This means, basically, that muscle cells can only pull, not push. It is possible for whole muscles composed of cells in multiple orientations to effectively push (one example is your tongue), but that's not relevant for this module. Muscles can produce tension while they are shortening (**concentric contraction**), staying the same length (**isometric contraction**), or lengthening (**eccentric contraction**; Dickinson et al. 2000). For this module, we'll just consider muscle actions from concentric contractions.



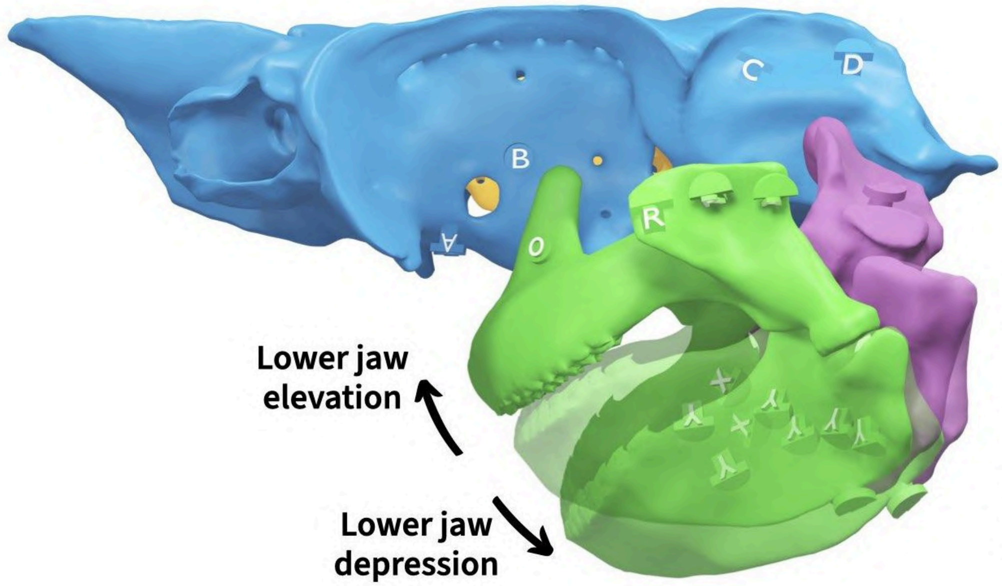
To infer the actions of muscles with your shark skull, you'll simulate a particular motion (i.e., action) of the jaws and observe which rubber bands shorten or slacken during that motion; the rubber bands that shorten correspond to muscles that could drive that motion.



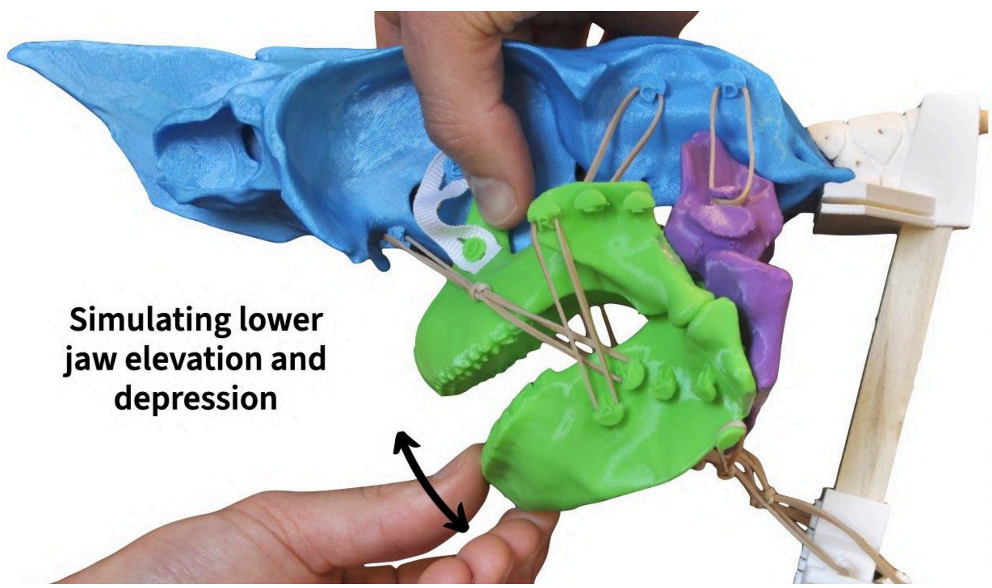
Be aware, however, that just because a muscle *could* drive a motion doesn't mean that it *does*. To actually prove a muscle's action, you need to show that it is **active** during that action in a live animal. This is done by recording electrical signals from the muscle, a technique called **electromyography (EMG)**. EMG experiments have actually been performed for the spiny dogfish shark by Wilga and Motta 1998 and, despite your more basic approach, the results of your simulations will be very similar to their results.

Lower jaw elevation and depression

The first action you'll simulate is elevation-depression of the lower jaw (mandible).



Since all the jaw cartilages are connected, if you try to just move the lower jaw, it will move other elements too. To simulate motion of only the lower jaw, use your right hand to secure the palatoquadrates and use your left hand to elevate and depress the lower jaw.

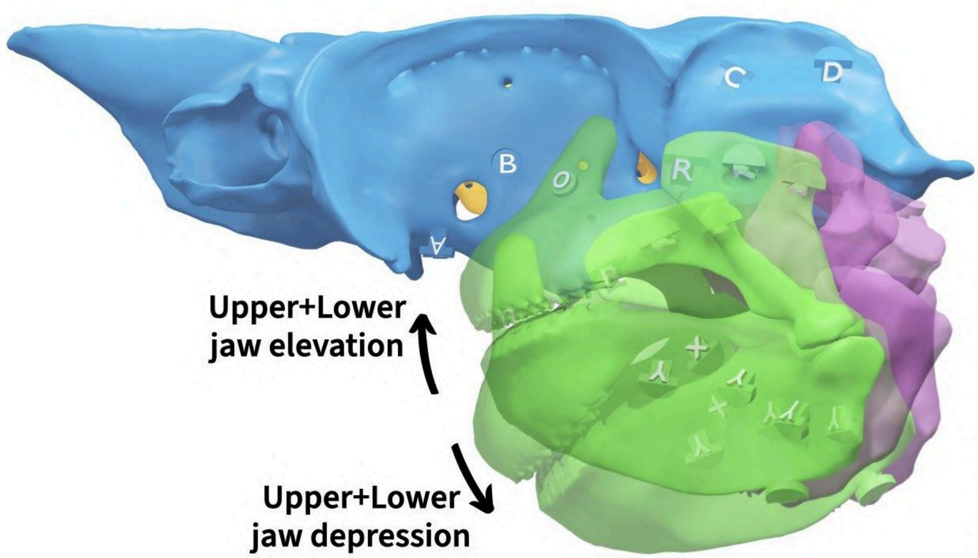


Which muscles shorten or slacken during each action? On page 1 of your **Notebook**, indicate the muscles that could potentially drive these motions by filling in the corresponding column(s) with an "X.

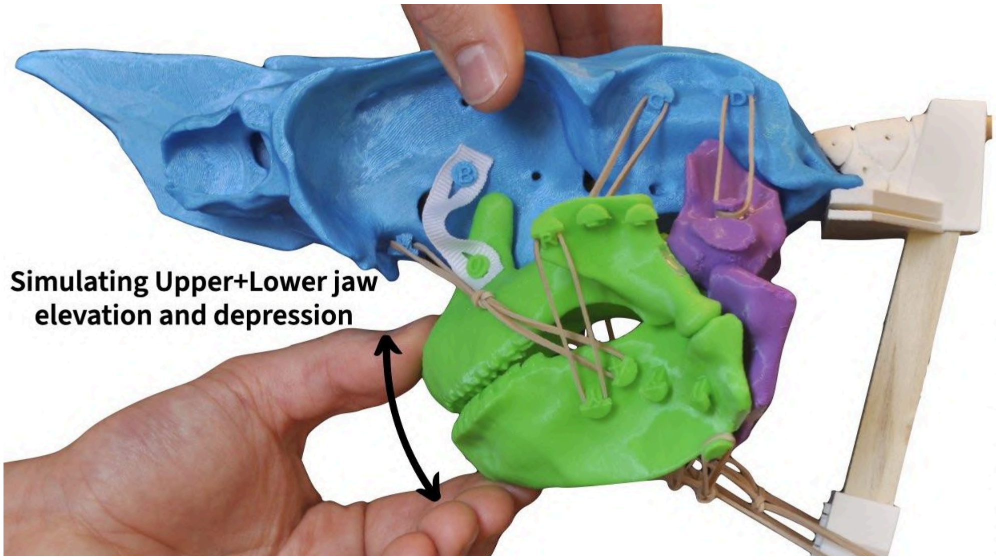
You may have noticed how the hyoid arch moves along with the lower jaw. This is partially due to how your model is put together but also due to ligaments connecting the mandible and the ceratohyal at the caudal end of these elements (the magnets in your kit reproduce this to some extent). These connections can produce *variable* coupling between the hyoid and **mandibular arch** (the upper+lower jaw), potentially allowing the coracohyoideus to indirectly depress the lower jaw. However, this coupling is not absolute nor is it fully understood in spiny dogfish sharks.

Upper+Lower jaw elevation and depression

You just simulated elevation and depression of the *lower* jaw but sharks can also elevate and depress their upper and lower jaw together; you could call this "jaw elevation and depression" (without the "lower"). This motion is primarily along the dorsoventral axis.



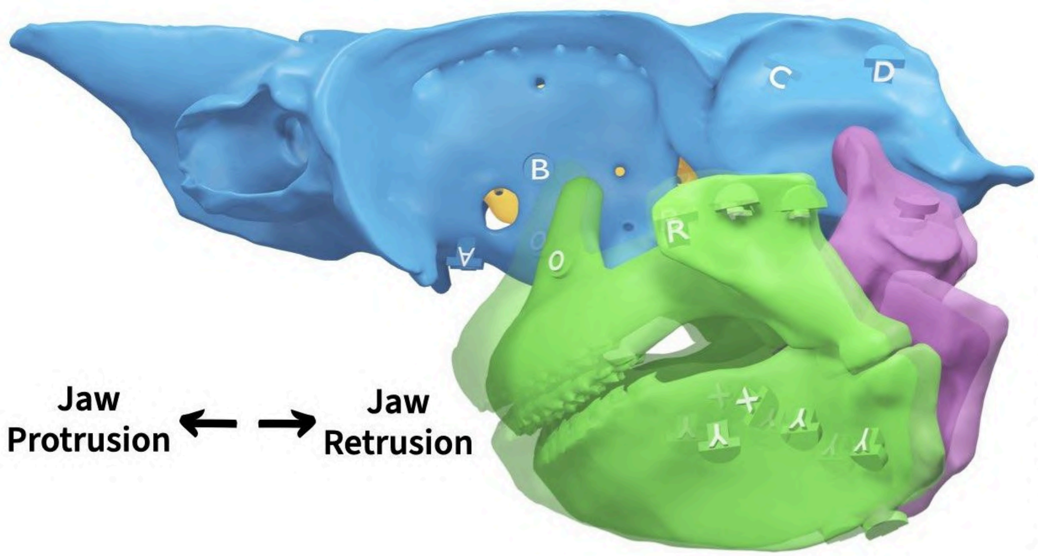
Simulate elevation and depression of the upper+lower jaw by holding the chondrocranium in place with one hand and, with your other hand, gripping the upper and lower jaw together at the **symphysis** (where the left and right side connect at the midline).



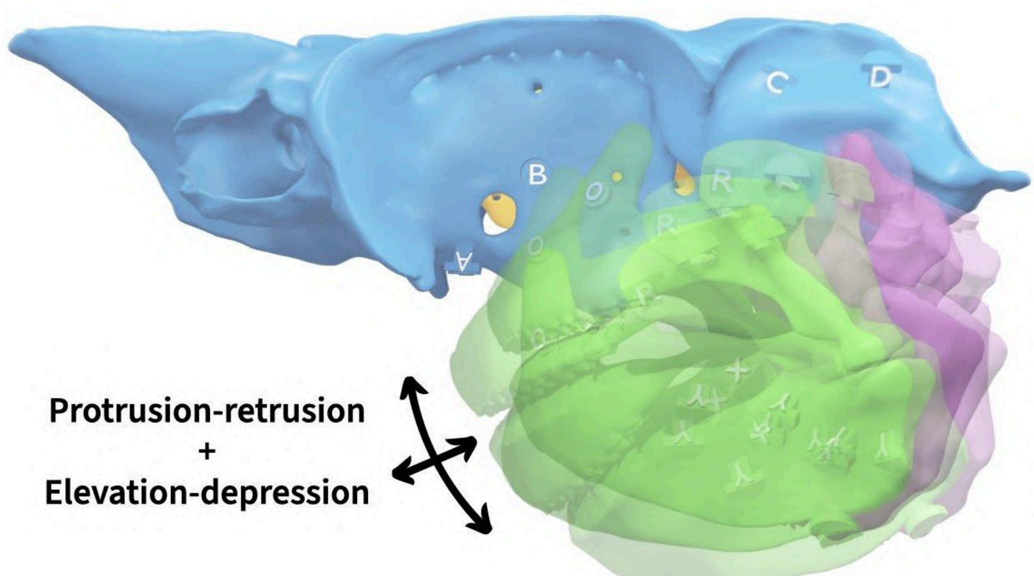
Which muscles shorten or slacken during each of these actions? Fill in the table on page 1 of your **Notebook** with your results.

Upper+Lower jaw protrusion and retrusion

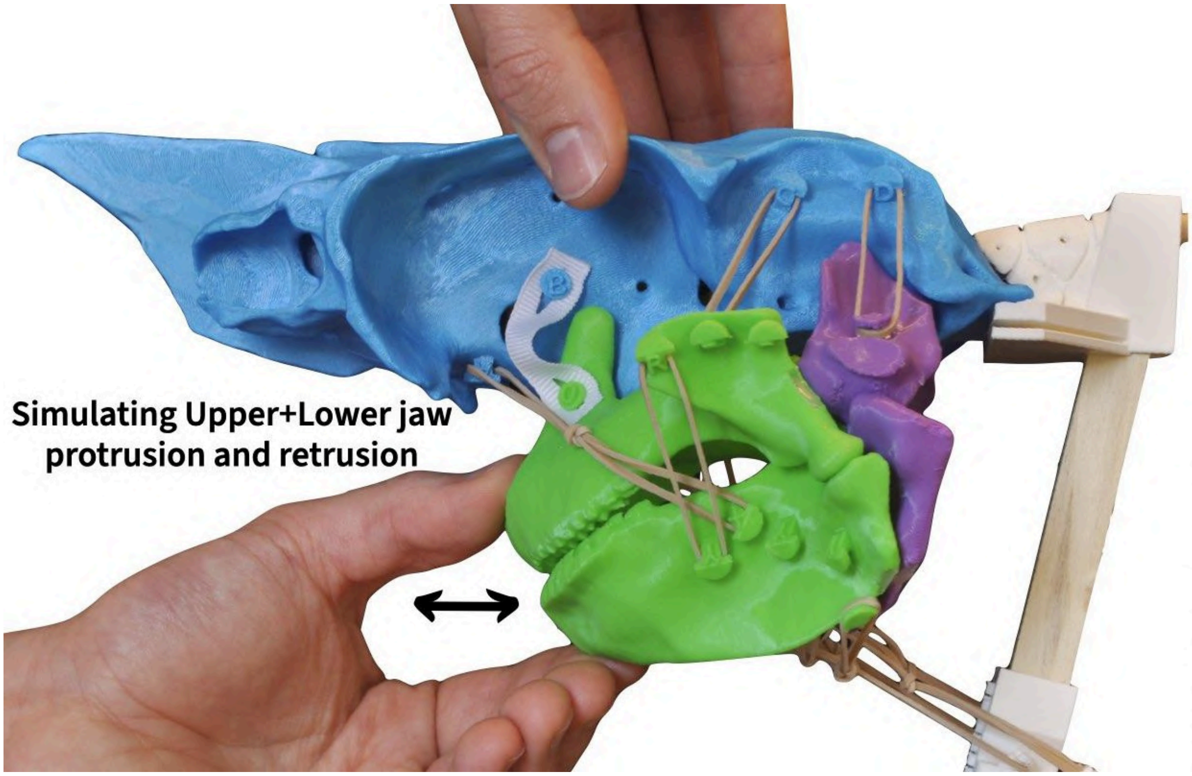
What is traditionally called **jaw protrusion** in sharks is actually a *combination* of two different motions: up-and-down motion and forward-and-back motion. When you simulated upper+lower jaw depression-elevation previously, you simulated the up and down motions (primarily along a dorsoventral axis). The second motion, forward-and-back, occurs primarily along the **rostrocaudal axis**. In this module, we'll call this rostrocaudal motion **protrusion** and **retrusion** (to match the terms used in other animals, such as mammals).



When combined, these two axes allow the jaws to move up, down, forward, and backward.



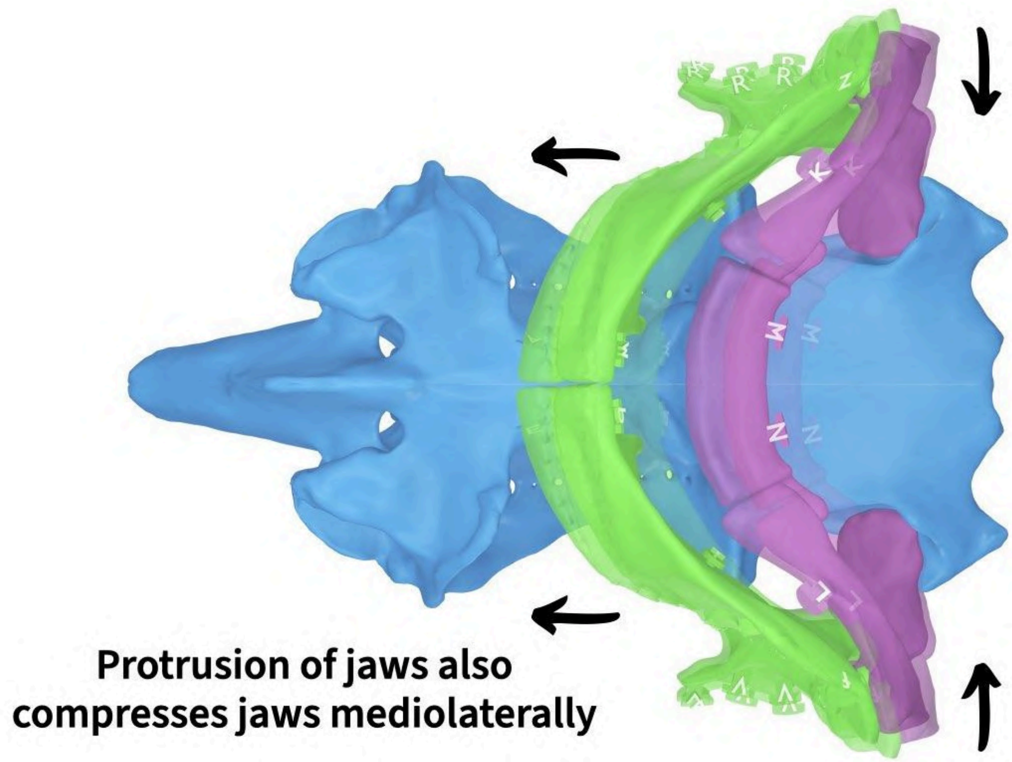
For the purposes of determining muscle actions, however, it's simpler to break this complex motion down into two axes. Simulate protrusion and retrusion of the upper+lower jaw similar to how you simulated elevation-depression, but this time pull the jaws rostrally *by just a couple millimeters*. Note that the jaws move *much* less rostrocaudally than they do dorsoventrally.



Which muscles shorten or slacken during each of these actions? Because the motions are relatively small, the length changes are subtle. Fill in the table on page 1 of your **Notebook** with your results. This one is a bit more challenging so use the following two hints to help you.

HINT: Try a ventral view

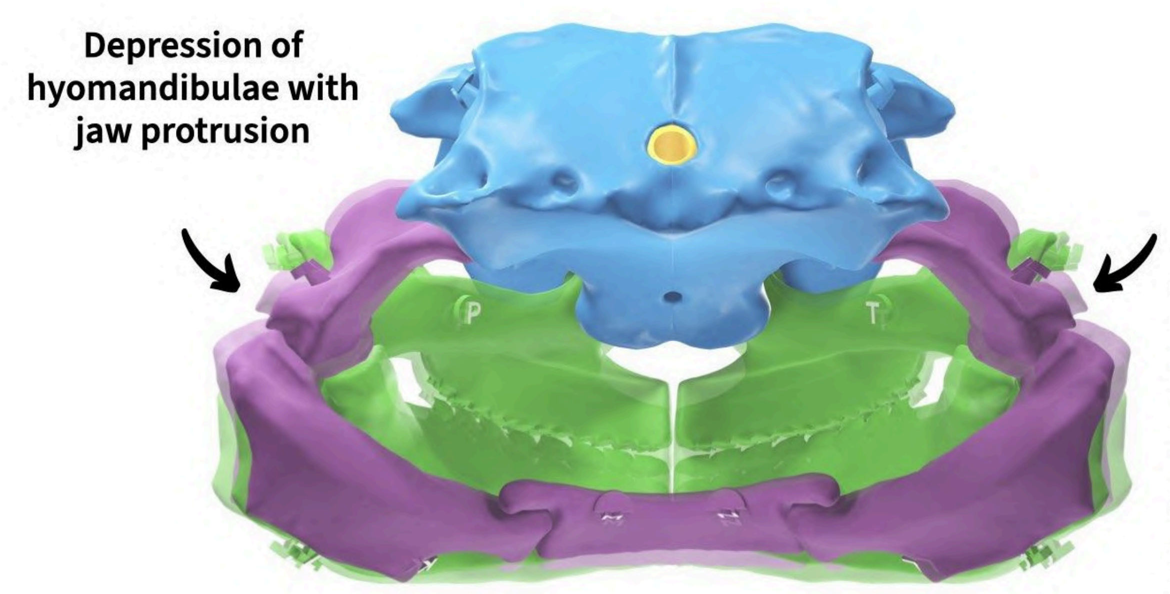
If you view the ventral aspect of your skull as you simulate protrusion, you can observe that as the jaws protrude rostrally, they also narrow (are compressed) **mediolaterally** (along the left-right axis).



What muscle(s) could drive this mediolateral expansion or compression?

HINT: Try a caudal view

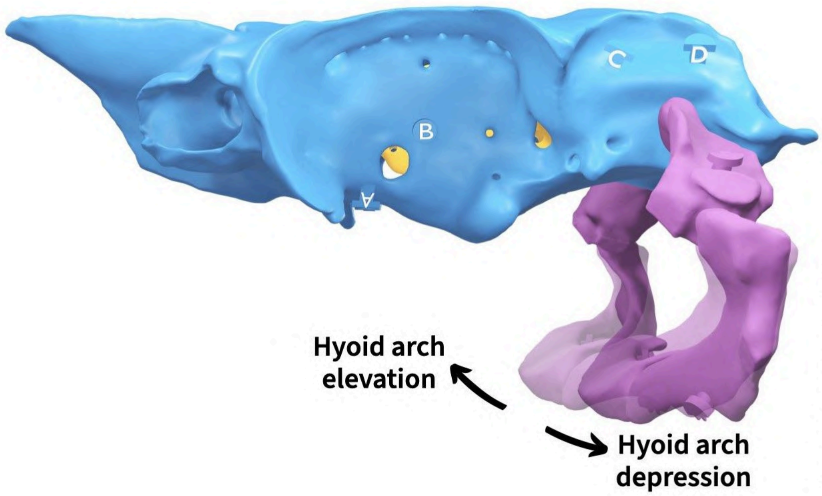
If you view your skull caudally as you simulate protrusion, you can observe that as the jaws protrude rostrally, the hyomandibulae adduct (rotate inward).



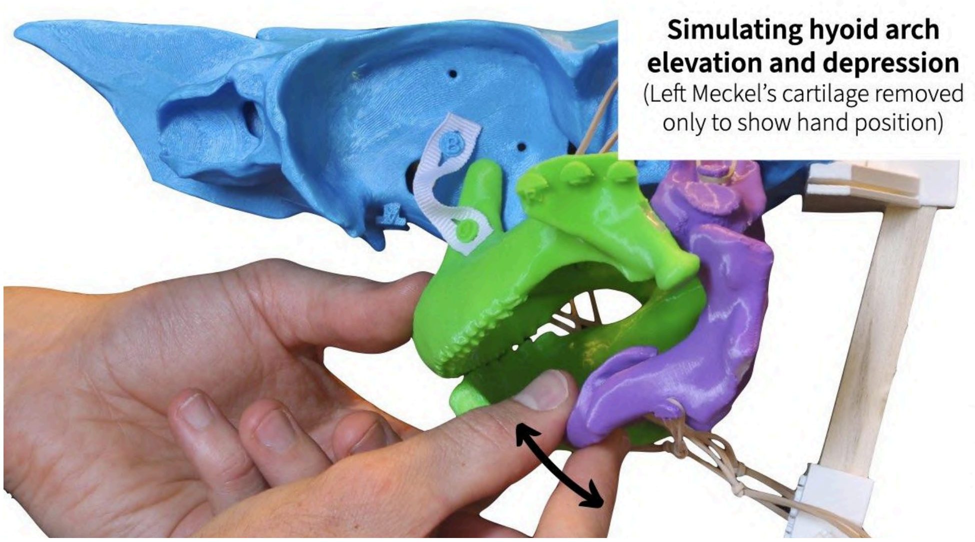
What muscle(s) could drive this depression or elevation of the hyomandibulae?

Hyoid arch elevation and depression

Elevation and depression of the hyoid arch is how fish compress and expand, respectively, their throat to create suction for drawing prey into their mouth and for moving water over their gills. As mentioned when you simulated lower jaw elevation-depression, the hyoid arch has some coupling with the mandibular arch (the "hyoid arch" here refers primarily to the ceratohyals and basihyal, since the hyomandibulae move in a different way). However, this coupling is not absolute: the hyoid arch can also move independently of the mandibular arch.



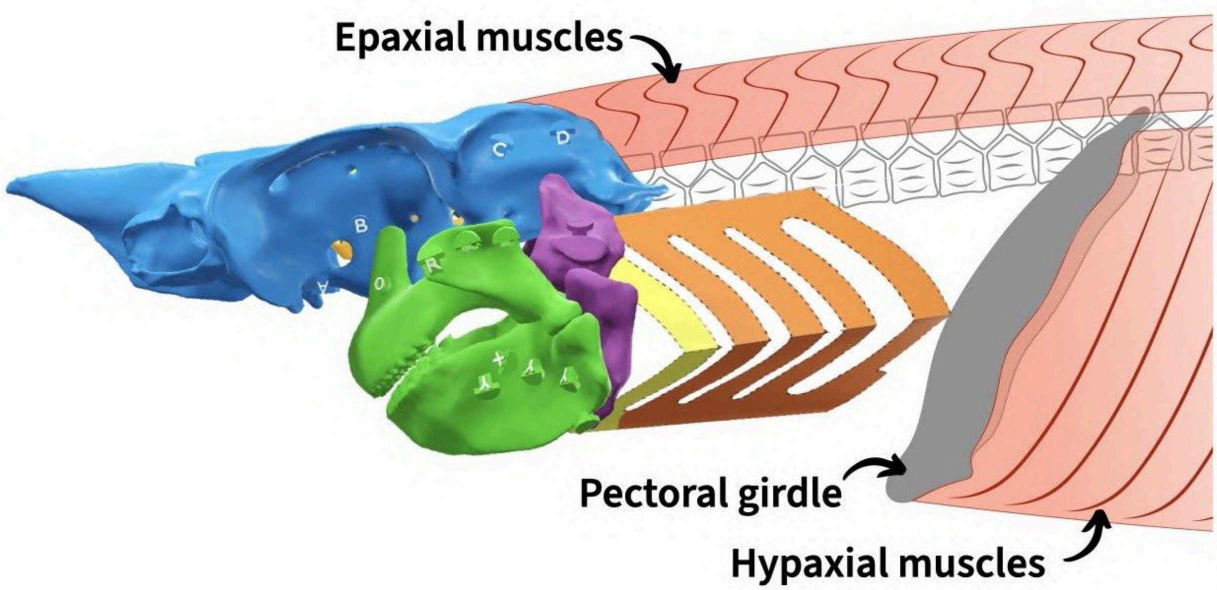
To simulate hyoid elevation-depression, hold the lower jaw in place with one hand and use your other hand to push and pull the basihyal dorsally and rostrally.



Which muscles shorten or slacken during each of these actions? Fill in the table on page 1 of your **Notebook** with your results.

Section 3. How do sharks use body muscles to open their mouth?

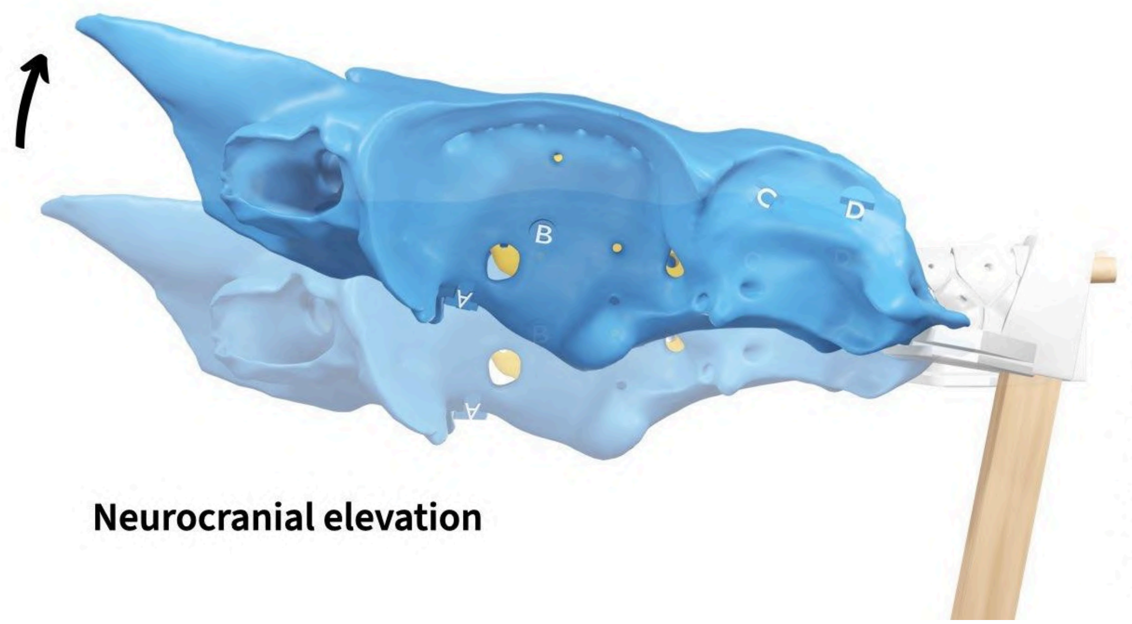
You've added all of the major jaw muscles to your shark skull, however, there are two additional muscles (groups of muscles really) that have an essential role in jaw opening: the **epaxial** and **hypaxial** muscles. The epaxials (also called **epaxialis**) are essentially the "back muscles," whereas the hypaxials (also called **hypaxialis**) are essentially the "belly muscles." At their rostral-most points, the epaxials insert on the caudal surface of the chondrocranium, whereas the hypaxials insert on the pectoral girdle.



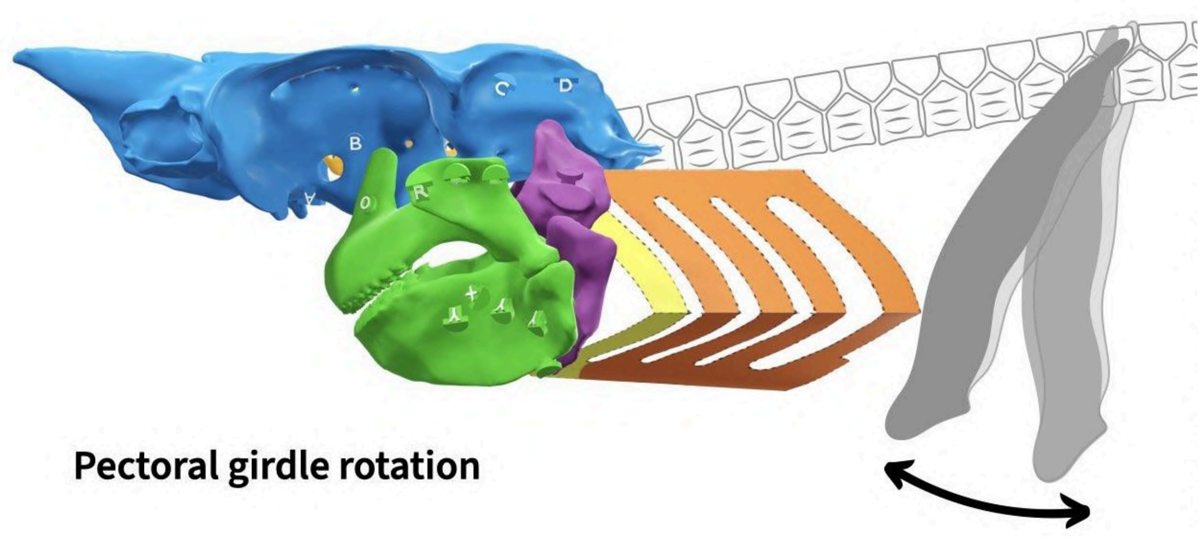
Why are these *body* muscles essential to opening the mouth? The answer is related to **power** (energy per unit time). Fish need a lot of power to open their mouth quickly against the resistance of water and generate a strong suction force that will capture prey. And the power a muscle can generate is directly related to its volume: the larger the muscle volume, the greater the power. By using the largest muscles in their body to open their mouth, fish are able to generate much more power than they would if they were to rely solely on their cranial muscles (Camp et al. 2017).

Using your shark skull to perform simulations, can you explain *how* fish can use their body muscles to open their mouth *and* generate suction? Write your explanation on page 2 of your **Notebook**; feel free to use bullet points.

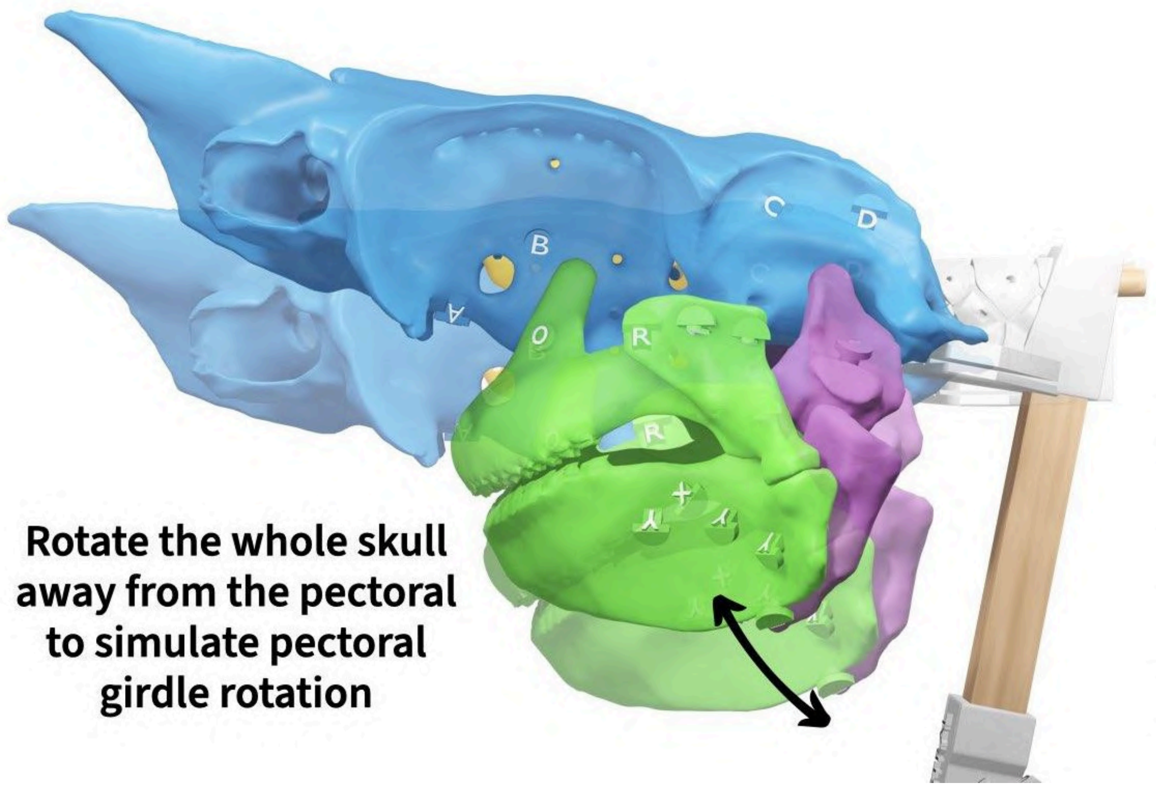
Your explanation should include which muscles are involved and their role. To help you figure this out, your stand mount rotates up to simulate neurocranial elevation.



Also, recall that the middle piece of your stand rod represents the pectoral girdle. In your model, the pectoral girdle is fixed to the stand but in an actual fish it can rotate rostrally and caudally.



Even though your shark's pectoral girdle is fixed, you can simulate motion of all the other elements relative to the pectoral girdle, which is similar.



If you need some help, check out the hint below. Then check your work on the next page.

HINT: It takes coordination

The epaxials and hypaxials don't act alone. Their actions are coordinated with those of the jaw muscles.

Section 4. How do sharks manipulate their food without a tongue?

Based on what you now know about the motions and muscles of your shark's jaws, can you explain how sharks are able to manipulate their food without a tongue? In other words, if someone were to say, "sharks can't manipulate food and water in complex ways because they don't have a tongue," how would you counter this argument? Write your explanation on page 2 of your **Notebook**; feel free to use bullet points.

In this module, you've learned how to use physical models to perform simulations and predict biomechanical function. While simulations are just one tool in your toolbox, they are invaluable for testing our understanding of systems and generating hypotheses. You've learned how muscles can drive complex motions of biomechanical systems through concentric contraction, acting through linkage mechanisms, and coordination. And you've learned that just because sharks are humans' distant relatives or just because they're fish, doesn't mean that their feeding system is any less complicated. The jaws of sharks are a mix of specialized (e.g., jaw suspension) and conserved (e.g., using body muscles for added power) features, like for any vertebrate feeding system.

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STUDENT NOTEBOOK

Sections 1-2. What are the shark jaw muscles and what are their actions?

	Attachments		Potential actions (concentric only)							
Muscle name	**Which elements does this muscle connect?** (Use abbreviations below table)		Lower jaw		Upper+Lower				Hyoid arch	
			Elevation	Depression	Elevation	Depression	Protrusion	Retrusion	Elevation	Depression
Levator palatoquadrati										
Levator hyoideus										
Preorbitalis										
Quadratomandibularis										
Coracomandibularis										
Coracohyoideus + Coracoarcualis										
Interhyoideus										
Intermandibularis										

The table above lists all eight muscles that you'll attach to your shark. In the "Attachments" columns, you'll list the two skeletal elements that each muscle connects (using the abbreviations listed below, the order doesn't matter). In the "Actions" columns, you'll add an "X" for the action(s) corresponding to each muscle.

Helpful abbreviations

Basihyal: BH

Ceratohyal: CH

Chondrocranium: CC

Hyomandibula: HM

Mandibular cartilage: MC

Palatoquadrate: PQ

Pectoral girdle: PG

If you need to specify left vs. right, add an "L" or "R" in front of the abbreviation, respectively. For example, use "LMC" for left mandibular cartilage.

Section 3. How do sharks use body muscles to open their mouth?

Using your shark skull to perform simulations, can you explain how fish can use their body muscles to open their mouth and generate suction? Your explanation should include which muscles are involved and their role. Feel free to write in bullet points.

Section 4. How do sharks manipulate their food without a tongue?

How can sharks manipulate their food without a tongue? Feel free to write in bullet points.

TITLE PAGES

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.

Observing your shark's braincase and brain

Text and images by Aaron M Olsen, PhD

Description

In this module, you will become more familiar with the structure of the braincase and brain of the spiny dogfish shark (*Squalus acanthias*) through observation and gain a better understanding of why they have the shape that they do.

Wiring your shark's brain

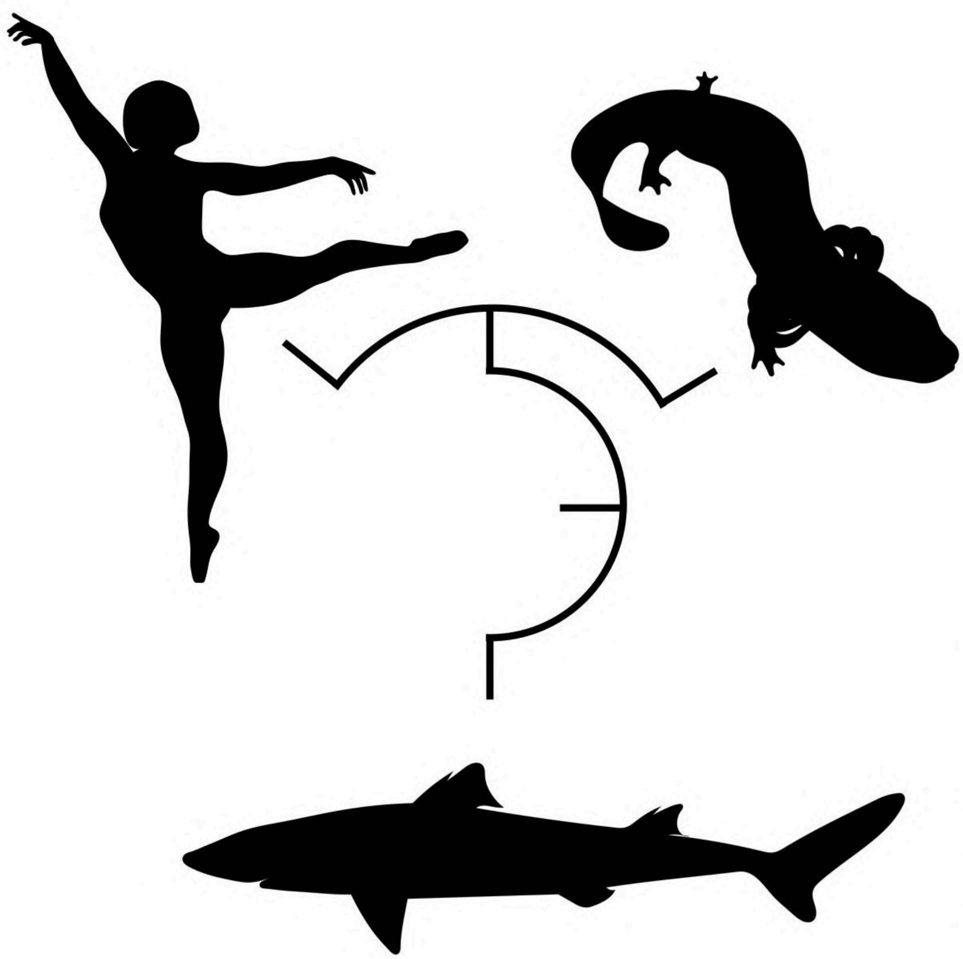
Text and images by Aaron M Olsen, PhD

Description

In this module, you will learn the shark cranial nerves by connecting nerves to a brain model of the spiny dogfish shark (*Squalus acanthias*), tracing their paths out of the braincase, and completing a schematic diagram.

Mapping the functional evolution of cranial nerves

Text and images by Aaron M Olsen, PhD

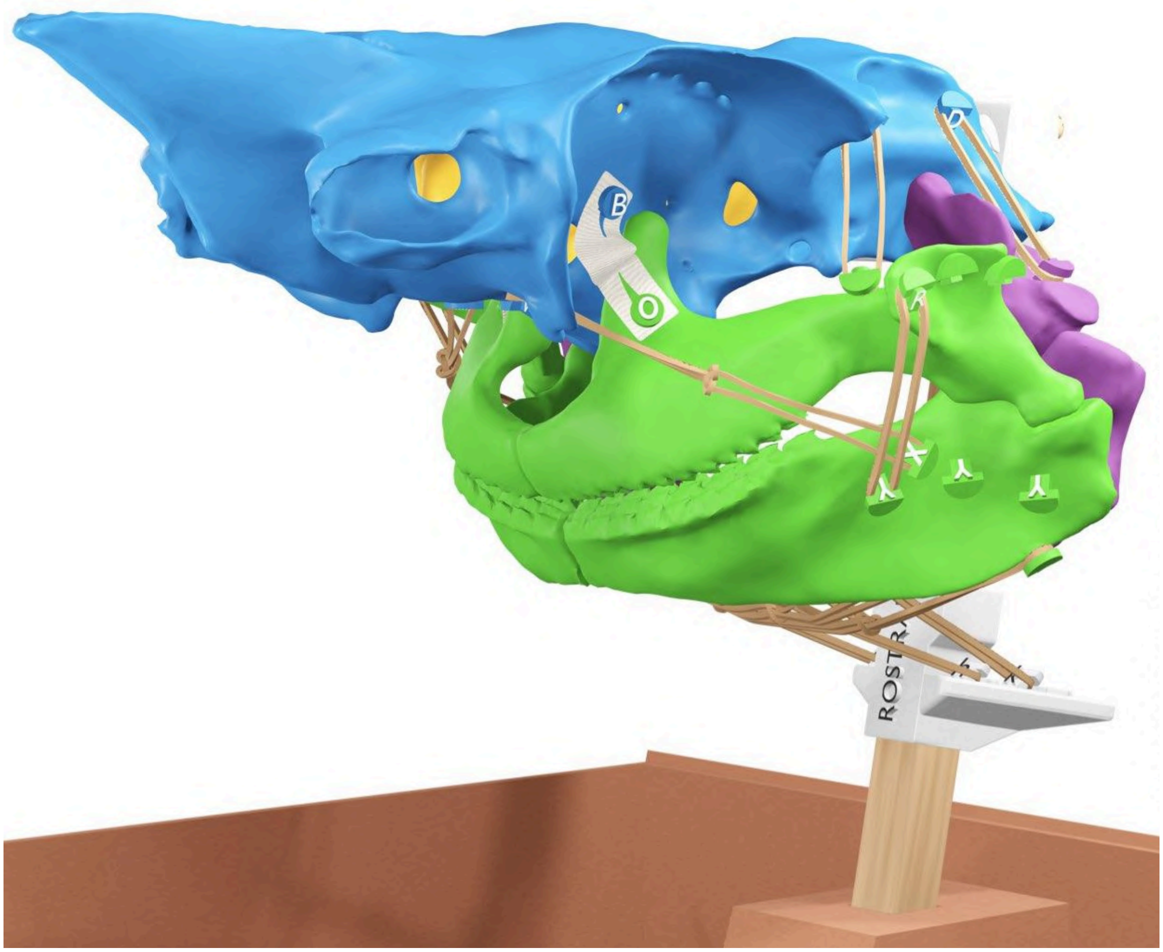


Description

In this module, you will compare and classify the shark cranial nerves and explain the functional evolution of some of the cranial nerves in vertebrates more broadly.

Simulating the motions of your shark's jaws

Text and images by Aaron M Olsen, PhD



Description

In this module, you will identify and attach jaw muscles to the skeleton of your spiny dogfish shark (*Squalus acanthias*) and figure out the actions of each muscle by using your model to simulate the motions of the jaws.