Name______________________________

Group Member Names:____

Part 2: Engineering Design Using Biomimicry

PURPOSE

- To describe the steps of the engineering design process
- To utilize the engineering design process to create a new technology that addresses a specific problem
- To define thrust and identify specific evolutionary adaptations that maximize thrust
- To define drag and identify specific evolutionary adaptations that minimize drag
- To describe 3 specific modes of fish swimming and apply this knowledge to inform your design of the body and propulsive elements of a biomimetic underwater vehicle
- To identify the main appendages (fins) of fish and apply this knowledge to inform your design of a propulsive fin and stabilizing fins for a biomimetic underwater vehicle

INTRODUCTION:

In this lab you will design, construct, and test a small biomimetic underwater vehicle. The underwater vehicle is needed to collect water samples along the Florida coastline with the goal of monitoring populations of harmful algal species. You will apply knowledge of both biology and engineering by utilizing biomimicry in the design of your vehicle.

Harmful Algal Blooms

The National Oceanic and Atmospheric Administration (NOAA) is a United States government agency that conducts scientific studies of the climate and weather, as well as the oceans and the coast. NOAA maintains a "NOAA Watch" webpage (www.noaawatch.gov) that reports on its monitoring of a variety of hazards. One of these hazards is Harmful Algal Blooms (HABs); a rapid increase in the population of one or more species of algae. Some algal species produce toxins which can kill fish, and other marine vertebrates. These same toxins may even cause illness, or death, in humans who eat contaminated shellfish from an area that is experiencing a harmful algal bloom. Thus, it is important to monitor the population levels of these harmful algal species so that toxic blooms can be predicted and, when necessary, shellfish harvesting can be shutdown, thereby preventing human illness.

Recently, a research project has been funded with the goal of engineering an underwater vehicle that can repeatedly collect water samples from specific global positioning system (GPS) coordinates. This would be a useful technology because the collection of samples must occur on a regular basis and without this vehicle water sample collections require multiple people and a boat. The robot will simplify the collection process. In order to be effective, the robot will need to operate in the open ocean and travel long distances from site to site, while maintaining a reasonable swimming velocity and remaining stable.

Engineering Design Process

The engineering design process is the method that is utilized by engineers to develop a new technology, or refine an existing technology. Technology is NOT limited to electronic devices, but rather can be something as simple as a paper clip, or as complex as the Hubble Space Telescope. A **technology** is a

Rebecca Westphal, North Shore Community College
Melanie Trecek-King, Massasoit Community College

Museum of Science
Engineering is Elementary

structure, material, or process that has been designed by human beings to solve a specific problem. The engineering design process can be summarized in 5 steps (Table 1).

Table 1: Steps of the engineering design process.

ASK	Engineers *identify a problem*. They then *ask questions* to determine the specific limitations that may restrict the supplies and/or budget available to them. Engineers will also want to know how their design will be evaluated.
IMAGINE	Engineers *brainstorm* to develop possible designs that would create a technology that meets the specific requirements. *Multiple designs* are developed, to be narrowed down later.
PLAN	A single *design is chosen* and a *more specific and detailed plan is formulated*. This often involves sketching plans, listing materials and determining cost.
CREATE	Once a plan is developed, a *prototype is developed and tested*.
IMPROVE	The first prototype is rarely the final design; engineers often *make improvements* after the prototype test.

The engineering design process is similar in many ways to the process of the scientific method. Scientific studies utilize the scientific method to generate and test hypotheses, with the ultimate goal of developing scientific theories. The steps of the scientific method are outlined below:

Table 2: Steps of the scientific method

OBSERVATIONS	Scientists make observations of the world around them. These observations *generate questions*.
HYPOTHESIS	Scientists will choose a question and generate a hypothesis. A hypothesis is a *possible explanation* for an observation. More than one hypothesis may be generated for each question.
EXPERIMENT	An *experiment is designed* to test the proposed hypothesis. The experiment is executed and data is collected.
CONCLUSIONS	After analyzing the data collected, the scientist will choose to *accept or reject the proposed hypothesis*.

Design Using Biomimicry:
This laboratory will allow you to test your knowledge of the field of biomimicry by giving you the chance to apply your understanding of biomimetic design to a specific problem. You will be designing an underwater vehicle to navigate coastal waters, traveling long distances from sample site, to sample site. The vehicle will need to travel fast, maintaining a heading. It will also need to remain stable. In this section, we will consider how evolution has dealt with the challenge of underwater locomotion, by exploring the adaptations seen in fish that allow them to thrive in their environment. In lab you will have the opportunity to use your biological knowledge to inspire the design of an underwater vehicle.

The aquatic environment differs in a number of important ways from the terrestrial environment. These differences have lead to the evolution of specific structural adaptations in aquatic species. A huge number of taxa are specialized for the aquatic environment, from microscopic protists, to the great whales. For our purposes we will confine our discussion to the largest group of vertebrates: fish. Fish can be broadly categorized into two groups: The jawless fishes and the Jawed fishes. Jawless fishes, as the name suggests, do not have jaws and represent a primitive group of fish. The jawed fishes include both bony fishes (e.g. tuna, goldfish, catfish) and the cartilaginous fishes (sharks, rays, and skates).

Modes of Swimming:
Fish, like their terrestrial vertebrate counterparts, have muscular (contractile skeletal muscle) and nervous systems (brain, spinal cord and nerves). These organ systems generate thrust, and coordinate movement, respectively. We will focus on the generation of thrust.

The thrust produced by muscles is transferred to the environment by the whole body, or by appendages (fins) as they push against the water. Water is a dense and "incompressible" fluid. These properties cause the water to "push back", moving the fish through the water. **Thrust** then, is the force with which the water pushes on the body of the fish *in reaction* to the fish moving the water.

As a fish is generating thrust so that it can move through the water, the fish is also subjected to drag. **Drag** can counteract thrust and resist movement. **Evolution has favored body forms that maximize thrust and reduce drag**, leading to efficient locomotion. A **streamlined** body shape will minimize drag. An optimally streamlined body is like a torpedo and will coast for a long time after active thrust generation ceases.

There are specific mechanisms, or **modes of swimming,** that are employed to generate thrust. Many fish generate a wave of muscular contractions that propagate down the body of the fish, traveling from anterior to posterior ending at the caudal (tail) fin. This type of swimming is called "body & caudal fin swimming" (BCF). The most extreme version of this can be seen in eel swimming, where the entire body undulates. Figure 2 displays the body shape of representative fish that exhibit different modes of swimming. The fish is shaded so that the area of the body that is generating thrust is highlighted. As you can see, **anguilliform** swimmers, such as eels, generate thrust with the entire body. **Carangiform** swimmers (e.g. many species of shark) bend only the more posterior portions of their body, and **thunniform** swimmers (e.g. tuna) simply oscillate their caudal fin (tail), with very little movement of the body.

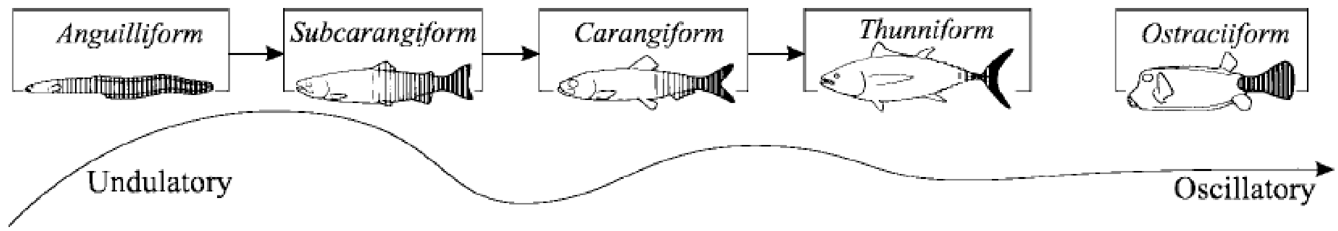

Figure 1: Swimming Modes (Adapted From: Sfakiotakis, Lane & Davies, 1999)

These different modes of swimming can be correlated with the organisms ecology. For example, anguilliform swimmers exhibit greater acceleration and maneuverability and are also capable of both forwards and backwards swimming. Anguilliform swimmers, like eels, live in environments where the water is unpredictable, rapidly shifting from calm to turbulent.

Carangiform swimmers cannot accelerate as rapidly as anguilliform swimmers, and also have reduced maneuverability. Instead, carangiform swimmers are "cruisers" that can often maintain higher cruising speeds and may be found in open water. Finally, thunniform swimmers excel at high-speed cruising in calm water. They are the least capable of executing fine maneuvers, and instead excel at high-speed steady swimming.

Fins:
In addition to the caudal fin (tail), fish have dorsal, anal and pectoral fins (See Figure 2). In some species of fish, these other fins are used for propulsion (an alternative to BCF propulsion). We will not focus on this type of propulsion. More importantly for this activity, these fins may also function to maintain stability.

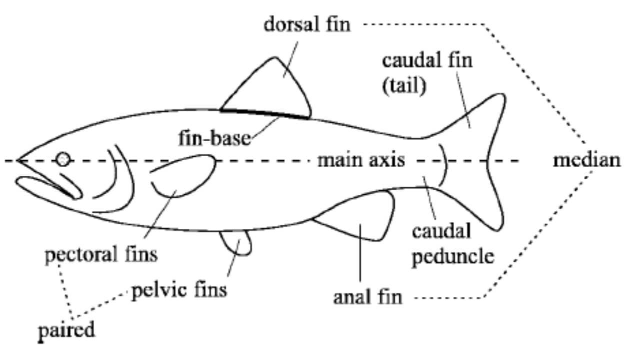

Figure 2: Fish fins (From: Sfakiotakis, Lane & Davies, 1999)

A study of the shape of caudal fins in many different species of fish revealed that the **aspect ratio** is directly correlated with the cruising speed of the fish. The aspect ratio is determined from two measurements: The height of the caudal fin and the surface area of the caudal fin (See equation 1). Some examples of caudal fin shapes and their aspect ratios are show below (Figure 3). As you can see from the examples, if the caudal fin is tall, but the surface area is low (e.g. tuna) then the aspect ratio is large and it can be predicted that the cruising speed of the fish will be relatively fast.

(eqn 1) $$\boldsymbol{Aspect\ Ratio} = \frac{\boldsymbol{height}\ (\boldsymbol{cm}) \times \boldsymbol{height} (\boldsymbol{cm})}{\boldsymbol{surface\ area}\ (\boldsymbol{cm^2})}$$

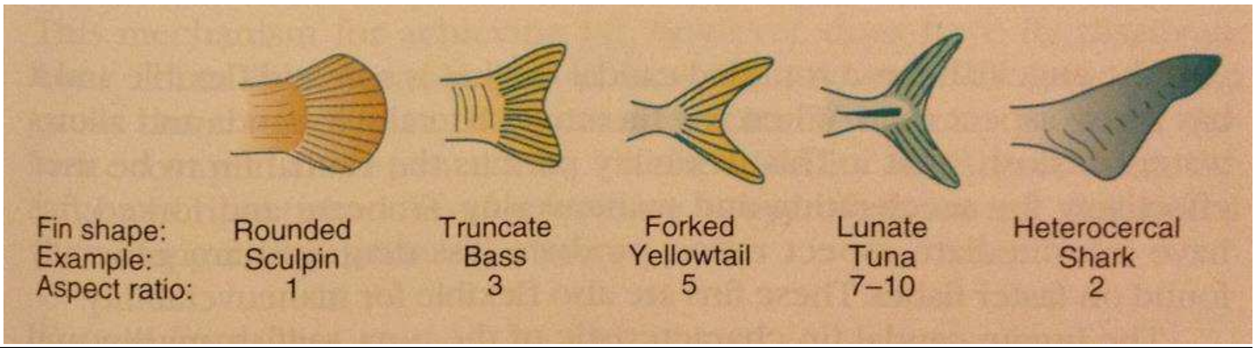

Figure 3: Examples of caudal fin shapes with aspect ratios indicated below (From: Sumich, 1999).

PRE-LAB QUESTIONS:

1. Provide 3 specific examples of technologies developed by engineers that may be useful to scientists.

2. Compare and contrast the steps of the engineering design process with the steps of the scientific method. Include at least 2 things that are the same and at least 2 things that are different.

3. Provide an example of a specific environmental pressure that influenced the evolution of fish shape.

4. What technology will you be designing in this lab? How will biomimicry assist you in your design?

5. Fins are evolutionary adaptations. Provide three specific examples of a feature of a fish fin that can be linked to the function of that fin.

MATERIALS:

Fish "body" frame (1 per group):

- Empty, clean soda bottle (not water bottle) with ring cut off

Propulsive system and controller

- Waterproof micro servomechanical device with attachment
- Programmed Controller

Materials to modify shape of bottle and to construct and attach fins:

- Popsicle sticks
- Coffee Stirrers
- Straws
- Panty hose
- Elastic bands
- Foam
- Scissors
- Duct tape
- Cardboard
- Pipe cleaner
- Balloons
- Hot glue /glue gun
- Various other craft supplies suitable for "building" fins, etc.

PROCEDURE: You will work in small groups (4-5 students/group). Each group will receive an empty, clean soda bottle and have access to additional supplies.

Step 1-- ASK: Using a soda bottle as the starting point, your goal is to design a biologically-inspired underwater vehicle that can swim *fast*, in a *straight* line. A servomechanical device (motor) will be coupled by a custom built bracket to the mouthpiece of your plastic bottle. This servo will generate the force used to beat a caudal fin laterally (side to side). You will need to design your own caudal fin to attach to the servo. Additionally, you can design other fins (pectoral, dorsal etc.) and modify the overall shape of the bottle. Remember that the success of your design will be assessed by quantifying the speed of your "fish" in a race to the finish line. The most efficient (fast and straight) design will win! The materials available for your design are listed in the above section.

Design considerations that you should address include:

1.) **Propulsion:** The bottle needs to move forward through the water. You must *design a caudal (tail) fin* that will be attached to a preassembled (reusable) servomechanism that beats the tail. The more thrust generated by the tail, the faster your vehicle will move.

*Remember that the servo motor will be attached to the mouthpiece of your bottle, which is the posterior (back) end of your fish.

2.) **Stability:** The bottle should be stable in the roll, yaw and pitch planes (Figure 4). You should *design and place fins* on your model to ensure stability. If your bottle is not stable, then it will not travel in a straight line; this will be detrimental to the overall speed of the vehicle.

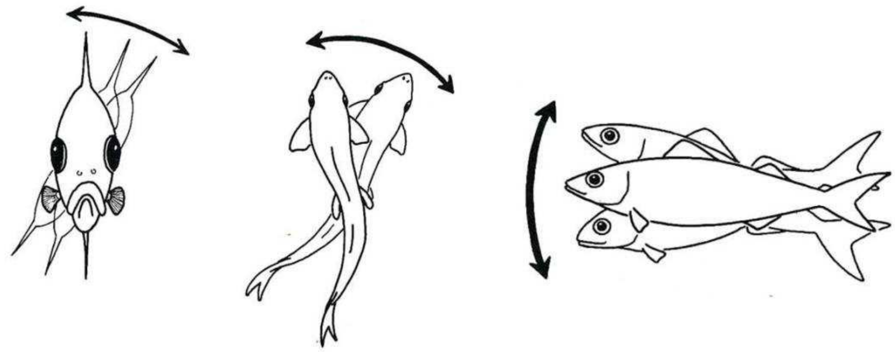

Figure 4: Roll, yaw, and pitch of fish bodies (from: http://www.biology-resources.com/drawing-fish-pitch-roll-yaw.html)

3.) **Buoyancy:** A sealed empty bottle will float. This is not optimal for your design. You should flood your bottle so that the inside of your "fish" is the same density as the water in which it will be operating.

4.) **Streamlining:** Since the propulsive mechanism is attached to the mouthpiece of the bottle, the relatively flat bottom of the bottle is the anterior (front) end of the "fish". This flat base is not hydrodynamically efficient. You should develop a *design for a more streamlined anterior end* that minimizes drag.

Consider your challenge; including the type of environment the vehicle operate in and what the vehicle needs to do. How will you use biomimicry to address this design challenge?

Step 2- IMAGINE: You should spend 5-10 minutes brainstorming design ideas with your group. Be sure to think about what materials are available, as well as the design considerations outlined in the ASK step.

Detail two of your group's initial design ideas. You should include a sketch, a list of materials and the rationale for your design.

***STOP HERE**: Check with your instructor before continuing to Step 3. *(Instructor's Initials: ______)*

Step 3- PLAN**:** As a group you should agree on a single prototype design and document that plan with a detailed sketch of the design, and a list of the materials you will use and how those materials will be attached to the body of the design (water bottle).

Sketch, materials list and related prototype design plans:

***STOP HERE**: Check with your instructor before continuing to Step 4. *(Instructor's Initials: ______)*

Step 4- CREATE: You should now build your biomimetic vehicle. If time permits, you should assess your design in the test tank and make appropriate changes. You can detail any of these changes below. Once you have settled on your final design, you will need to determine the **velocity** of your biomimetic vehicle. Velocity is determined by measuring how far (distance) your vehicle traveled and dividing that distance by the amount of time it took. Calculate the velocity for your vehicle below:

$$\boldsymbol{Velocity} = \frac{\boldsymbol{Distance\ Traveled}\ (\boldsymbol{meters})}{\boldsymbol{Time}\ (\boldsymbol{seconds})}$$

***Distance Traveled**: ___________meters* ***Time:** ___________seconds*

***Velocity**:___________meters/second*

Next, you will calculate the **aspect ratio** of your caudal fin. Use a ruler to measure the **height** of your caudal fin in centimeters, *cm* (See Figure 5). You will now need to measure surface area. **Surface area** is an estimate of how much contact your fin has with the water. Surface area will be recorded in square centimeters (cm^2). Trace your caudal fin on a sheet of graph paper. Since each box is a known to be 1 cm^2, you can now simply count the number of boxes to determine surface area on cm^2.

You can now use these measurements (height and surface area) to determine the aspect ratio of your caudal fin.

Recall the equation for aspect ratio:

$$\boldsymbol{Aspect\ Ratio} = \frac{\boldsymbol{height}\ (\boldsymbol{cm}) \times \boldsymbol{height}(\boldsymbol{cm})}{\boldsymbol{surface\ area}\ (\boldsymbol{cm^2})}$$

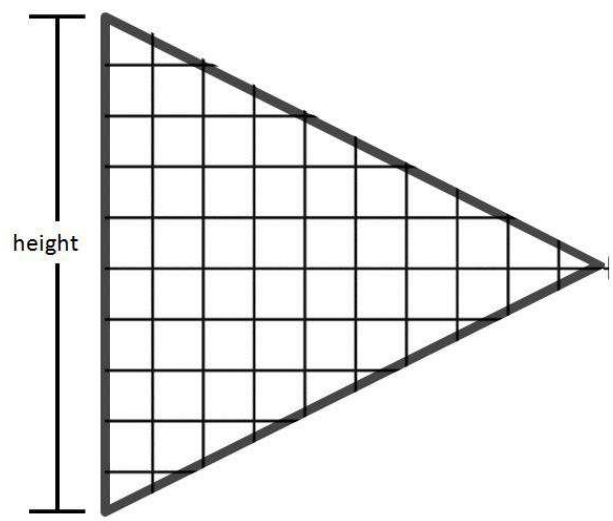

Figure 5: Estimating height and surface area of a caudal fin.

A. ***Height of your caudal fin**: ___________cm*

B. ***Height x Height**: ___________cm^2*

C. ***Surface area of caudal fin* (count squares)**: ___________*cm^2*

D. ***Aspect Ratio** (B/C): ___________*

Record the velocity and aspect ratio for each groups design in the table below. Also provide a description of each design. :

Group	***Velocity(m/s)***	***Aspect Ratio:***	***Description of Design:***
1			
2			
3			
4			
5			

***Step 5- IMPROVE*:** Your group should consider the performance of your design compared to the other groups and explore possible improvements to your design.

Which group's model had the fastest design? Why do you think their design was so effective?

Which group's model had the slowest design? Why do you think their design was ineffective?

POST LAB:

1. Identify a specific adaptation seen in fish that achieves each of the goals identified below:

   A. Forward Propulsion

   B. Maximum Stability

   C. Minimum Drag

2. All aquatic animals do not swim in the same way. Identify, and describe, two different mechanisms (modes) of locomotion seen in fish.

3. What are two recommendations you would give to NOAA for engineering a water collection robot to make sure it is fast and stable?

4. What step of the engineering design process did you find the most helpful as you and your group were engineering your robot? Explain.