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Building a Heart: The Function and Mechanics

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Introduction

The heart is an inconceivably beautiful organ combining form and function. In high school physics classes it is rare to get an opportunity to spend time on an extended project. It is my intention to begin the year with my second year AP Physics B students with the challenge of designing and constructing an artificial heart. The initial process will rely on their previous year's knowledge of Mechanics. This will serve two purposes. The project will reinforce their prior knowledge while developing or reinforcing the students' hands-on construction knowledge. We will begin by determining the necessary parameters of the heart, through research and guided reading. My students will then incorporate their acquired knowledge of the heart as a system with their knowledge of Mechanics to produce a simplified heart pump. Their prototype will simulate the left heart that pumps oxygenated blood to the body. As my students work on their artificial hearts, I intend to provide them with opportunities to explore the background fluid dynamical properties of blood flow through the circulatory system of the body. This will enable my students to transition from the study of Mechanics to that of fluid dynamics.

Heart Function

The heart is a remarkable organ that pumps from 5 to 30 liters of blood per minute. It is roughly the size of a fist and pumps two-thirds of its contents, approximately 70mL of blood, upon each contraction, which occur 60 to 80 times per minute. The heart must continue this pace without fail for millions of contractions a year for potentially a hundred years or more. On average the heart pumps 4800 liters of blood throughout the body each day. How does it do it?

My unit will focus on the mechanics of heart function. First, we will explore the parameters that the heart must meet. This includes the differential heart pressure, called the pulse pressure, which in healthy adults is around 40 mm Hg (this is the differential between 120 mm Hg systolic pressure over 80 mm Hg diastolic pressure). This pressure drives the blood through the vessels of the cardiovascular system. This pressure is necessary to create a flow, which is generated against the resistance to flow provided by the blood vessel network.

Therefore, the unit will also address the resistance of the arteries, capillaries and veins, particularly the arterioles where muscular activity controls the diameter of opening. Vessel diameter is the chief factor in vessel resistance to flow, which the resistance R varies as radius, r, to the fourth power, r^4 ! In completing this unit, students will experiment with the fact that the cross sectional surface area of fluid in the capillaries is large and, as a result, the blood velocity in the capillaries is slow, allowing sufficient residence time in the capillaries for diffusion. All of this will be devoted to getting the students to have a sufficient appreciation of the parameters of the heart to create and to design a single pump heart that will behave in a similar way to a real heart with a simulated circulation system.

Purpose of the Heart

The purpose of the heart is to circulate nutrients, oxygen, and other chemicals to all cells in the body and to carry waste away from the cells. Our blood is a remarkable fluid that makes all of this possible. It is the job of the heart to act as a pump to move the blood throughout the body. The heart pumps at a rate that ensures that a blood flow sufficient to satisfy the requirements of the cells is achieved. The circulatory system carries the blood from the heart to the cells and back.

The circulatory system is made up of vessels of varying size. Vessels carrying blood away from the heart are called arteries. The smallest vessels, where most transport of nutrients occurs, are called capillaries. Vessels that carry blood back from the capillaries to the heart are called veins. The circulatory system provides mechanisms for regional control of blood flow, so that blood goes where it is needed at any given moment in time. This control is provided primarily by changes in diameter of small arteries known as arterioles. Because the whole network of blood vessels displays resistance to flow, the blood must leave the heart at a high pressure and return at very low pressure.

Circulatory System Analogous to Electrical Circuit

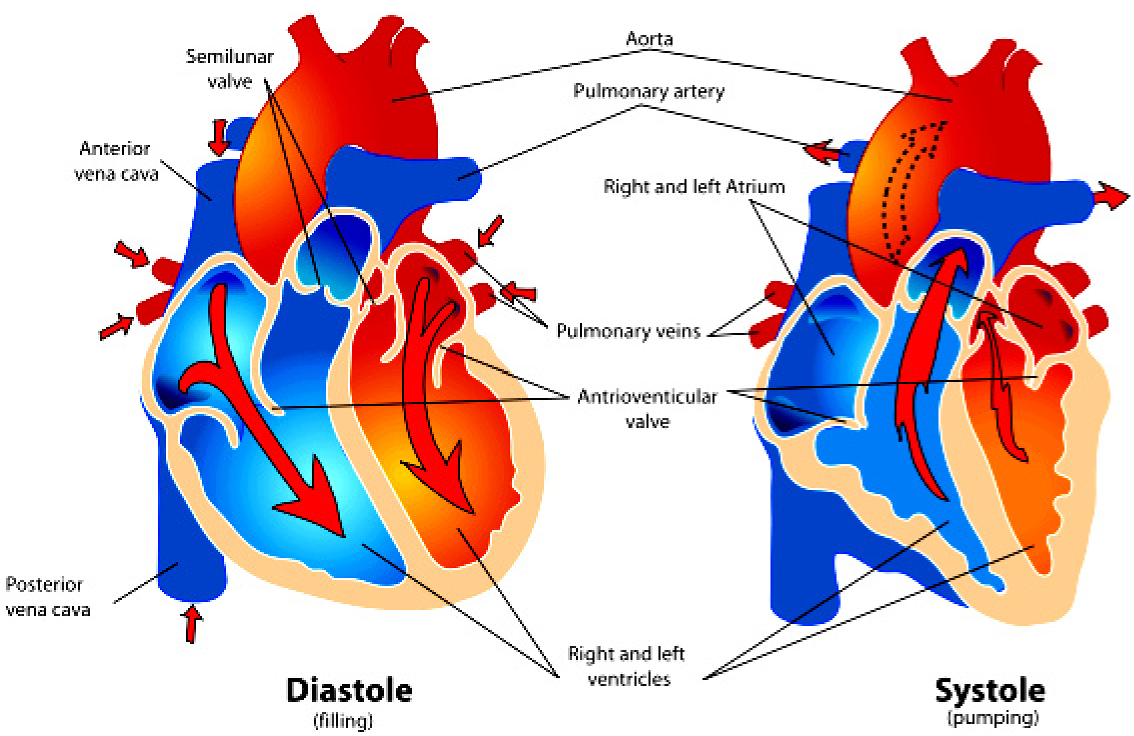
A strong correlation can be made between the flow of fluid through a cylindrical tube and the flow current through a simple electrical resistor. Fluid flowrate is related to pressure drop by the following equation: $\Delta P = QR$,where ΔP is the pressure drop from tube inlet to outlet, Q is the volumetric flowrate of fluid, and R is resistance. This is an equivalent equation to Ohm's Law: $\Delta V = IR$, where ΔV is electric potential difference or voltage, I is electrical current and R is electrical resistance. So $\Delta P = (P_o - P_i) = RQ$ where $R = 8\mu L / \Pi r^4$, where M is viscosity, L is length and r is the radius of the vessel. Therefore, pressure-flow behavior in the circulatory system can be equated to voltage-current behavior in a simple resistive electrical circuit. In addition, the resistance to flow in a simple cylindrical vessel can be estimated from the geometry of the vessel—its radius r and length L—and the viscosity of the fluid flowing through it.

Heart Anatomy

The heart is composed of four chambers. There is a right side and a left side, with two chambers each. The two chambers on each side are an atrium and a ventricle. The left side of the heart is larger and pumps oxygenated blood to the entire body. The right side of the heart pumps deoxygenated blood to the lungs, where it is oxygenated.

Oxygenation in the lungs is accomplished by flowing blood through an immense array of capillaries (the smallest vessels that are so small that they may only allow red blood cells to travel through single file!) in close proximity to lung air, which is possible because of the tremendous surface area of the lung. Although the lung's volume is only about a liter, the surface area is approximately the size of a tennis court as a result of the fractal bifurcation (branching into two) of the lung into 2^{23} nearly spherical alveoli (the smallest unit of the lung)! Diffusion is the passive process of transport from high concentration to low concentration. The blood flowing into the lungs is deoxygenated; it has relatively high concentrations of carbon dioxide and low concentrations of oxygen. The blood utilizes a compound in red blood cells called hemoglobin as the component that greatly increases the solubility of oxygen, greatly increasing the efficiency of the heart and circulatory system. Upon reaching the lung, blood exchanges carbon dioxide and oxygen, there by becoming "oxygenated". The blood is pumped to the lungs at low pressure, since there is low resistance and the lungs are close to the heart

The heart is a double pump with two separate parts. The circulatory system is a closed loop, which can be described by starting at any point, so let's start when the blood comes back from the cells. The deoxygenated blood returns to the heart by the two largest veins called the superior and inferior vena cava. The vena cavae carry the blood into the right atrium at low pressure passively, meaning that there is no valve between the vena cavae and the atrium. When the heart begins to contract, contraction starts in the right atrium, causing blood to flow from the right atrium into the right ventricle, through the tricuspid valve, which prevents back flow. As the heart contraction moves from atrium to ventricle, the pressure in the right ventricle increases until the blood is ejected into pulmonary artery through the pulmonary valve. This blood, ejected from the right ventricle, divides into two paths continuing to one of the two lungs, where it is oxygenated (as described in the paragraph above). The blood returns to the heart in the pulmonary veins which both go into the left atrium. When the left atrium contracts, blood is forced through the bicuspid valve into the left ventricle. Ventricle contraction causes an increase in the blood pressure, because blood is an incompressible liquid, and the volume is decreasing. When the pressure inside the ventricle exceeds the normal blood pressure in the aorta (the artery leaving the left ventricle), the aortic valve opens, ejecting the majority of the blood in the ventricle into the aorta! This blood travels through the arteries, arterioles, capillaries, venules and veins until it reaches the vena cava and begins the circulation again (See Diagram 1 below).



(Diagram 1 - thanks to wpclipart.com- public domain)

The blood flow path to the lung is called the pulmonary circulation and the path to the body is called the systemic circulation. The heart contracts approximately once per second, and each side of the heart beats simultaneously with each contraction. The pathway for electrical excitation is a bit complicated, but it results in the contraction of both atria first then the ventricles in a wonderfully synchronized and efficient pumping motion. The excitation of the heart cells causes a spreading wave of contraction from heart cell to heart cell. Each cell has a delay mechanism of approximately a half-second, before re-excitation is possible, so that the contraction is perfectly synchronized and does not circle back upon itself. The beating heart operates with an amazingly choreographed motion that optimizes the heart's pumping function.

Heart Valves

The valves of the heart are necessary to prevent back flow when the heart contracts. The valves allow blood to flow in only one direction. The valves are open when the pressure behind the valve is higher than the pressure up-stream from the valve. This elevation in pressure occurs when the heart contracts. First the atrium begins to contract, in effect, priming the ventricular pump for maximum stroke volume. The valves are a beautiful design of tissue that is separated into two or three triangular flaps that open when the pressure difference behind them is greater than the pressure in front. The open valve allows fluid to flow, but when the pressure in front of the valve exceeds the pressure behind it, the valve shuts. There are also a myriad of tendon fibers that attach some of the valves to the heart wall.

The natural design of human heart valves is ingenious and difficult to successfully replicate. Biomedical engineers have found ways to use valves from other animals—usually pigs and cows—to replace valves in humans: the animal valves are treated with chemicals to make them inert after implantation. In addition, engineers have made totally synthetic valves from polymers and metals and ceramics, which can function almost as well as natural valves.

The Aorta

The total flow rate from the heart (also called cardiac output) is the stroke volume (or volume of blood ejected on each contraction or beat) times the number of beats per minute. When the left ventricle contracts, blood flows into the aorta. The heart beat results in high pressure in the aorta. The aorta is flexible so that it can expand when the blood is ejecting from the heart. This also results in a "secondary pump" when the aorta rebounds elastically back to its original shape, which helps to maintain a more constant blood pressure between beats.

Biocompatible Materials

An advanced consideration and a primary reason for the limited success so far with artificial heart replacement has to do with biocompatibility. The artificial hearts that we will design are made out of non-living materials. The body's immune system is designed to detect foreign bodies and to attack them in an effort to isolate them and eradicate them if possible. Therefore, it is necessary to fool the body's immune system into not recognizing the implanted material as foreign or to at least limit the body's immune reaction. This is the nature of a biocompatible material. In the projects that students will conduct as I teach this unit, the students will have to consider what their artificial heart prototype could eventually be made of to make it biocompatible. Some metals and some polymers have proven to be a good starting point.

Many students may know or find out that the problem, or danger, with many implanted devices, is clotting. To further explain the body's immune system response, it is important to understand how the body attempts to isolate an implanted material. A simplified explanation is that the body's immune system, upon recognizing a material as foreign, will attempt to isolate the material. It does this by surrounding it, or coating it. This coating is the result of a complex set of reactions within the body, and it is related to the body's attempt to heal a wound. The immune system forms fibrous "clots" that in the case of the wound seal the "hole" while in the case of the foreign material attempt to encapsulate it.

Clotting on a biomaterial is dangerous because of the risk that a piece of a clot will break free and travel through the circulatory system. If this happened, the embolized clot can block smaller blood vessels down-stream. This is potentially deadly. If it occurs in the brain, the embolism can cause a stroke and in the lung an embolism can prevent a region of blood flow from collecting oxygen. Clotting is particularly problematic with implanted devices because the foreign material causes a large scale clotting that then poses a very high risk of the clots breaking free. My students will have to consider the biocompatibility of the materials from which they would construct their optimized prototype. Another issue that must be researched and addressed is the concern of having a foreign material contract to simulate a beating heart and whether this poses more danger of throwing clots.

The Physics of the Heart

There are a wide range of physics concepts involved in constructing an artificial heart. Here I will consider the Mechanics of constructing a heart and the biomedical considerations. The designs of the students will inevitably dictate the teacher of creative design to expound on additional physics concepts.

Mechanical Principals of an Artificial Pump

The first challenge for the students is to design a "beating" or reciprocating heart pump. How can this be done? Most pumps are propellers powered by a motor. However, these propellers do not simulate an actual heart, they are not the simplest solution, and they are known to cause problems with clotting. So I would like my students to explore the most direct methods that will simulate a "contracting" heart. To do this, we must first consider the Mechanics involved in this type of motion and the physics that can help to guide this exploration.

Simple Machines

My students will have to utilize simple machines to design and create solutions for a moving artificial heart. Simple machines are broken down into two families, levers and inclined planes. Levers include simple levers, wheel and axle, and pulleys. Inclined planes include the simple inclined plane, the screw, and the double inclined plane the wedge. It is not necessary for my students to know which type of simple machine they are using or which class of simple machine they are creating; however, a basic knowledge of simple machines will provide my students with more tools to address how to create different types of motions, such as up and down, circular, and at an angle. With an understanding of simple machines, they can begin to combine them into a complex machine. Students will determine the mechanical advantage of utilizing various simple machines and how to combine them for the desired effect.

Mechanical Advantage

Mechanical advantage (MA) is the proportional increase or decrease in the output force related to the input force. An MA of 1 means that a simple machine provides no increase in the output force. An example of this is a seesaw (which is a lever) where the pivot is in the middle. The input and output forces are the same so $MA=F_{output}/F_{input}$ = 1. A lever involves the use of a pivot and the MA can be calculated by the relationship of the length of the lever on the side of the input force relative to the size of the remaining lever on the output force. So if the pivot is two-thirds down the lever away from the input force, then the proportion would be *2/1 = MA of 2*. This means that the output force would be twice as great as the input force. This concept will be useful to the students in the design of their complex machine that make up their artificial hearts. Now we know that, in physics, you cannot get something for nothing (because of conservation of energy) so what is the consequence of having a mechanical advantage? The output force in our last example doubled. This is achieved by the input distance increasing by the same proportion. So the input distance is double the output distance (I must move the lever twice as far when the MA is 2 to produce double the force which acts over half the distance!). This is a crucial concept in design utilizing machines.

I have used the example of the lever, but the same concept of mechanical advantage applies to all simple machines, whether it is an inclined plane or a wheel and axle. Usually we think in terms of MA's over one so that we are increasing the output force, however, there are situations in which the MA will be less than one, where the intention is to decrease the input distance instead. Disregarding friction (which may not be possible in real world designs), the input force times input distance = output force times output distance. Manipulating this simple equation will be essential in our design of a heart.

Motors

Motors convert electrical energy into the rotational motion of a shaft or axle. They do this by utilizing the physical principal that moving electricity produces a magnetic field and vice versa. Consequently, by supplying current (moving electricity) in a magnetic field a force will be generated. A motor is an application of this principal. A magnet coiled with wire that is able to pivot around its center while receiving current experiences a force that causes the assembly to rotate. This is the basis of the motor.

It is likely that motors will be a central element of the students' artificial hearts. Some of the key concepts necessary to utilize motors are revolutions per minute (RPM) and torque. The RPM of a motor rates the speed that the motor will spin. The torque provided by the motor is an indication of how much force the shaft of the motor can supply. These parameters are often inversely proportional so the students will have to understand what kind of motor they will need. Most likely, the students will need low speed, high torque motors, but most motors are high speed, low torque. Therefore, the students will need to understand how to use gears to convert speed and torque. Gears utilize the concept of MA to convert the motion of the motor into the desired output. Usually motors are geared down. This means that a high number of rotations (RPM's) of the motor at low torque are converted into a low number of rotations (RPM's) at proportionally higher torque. There are a variety of different types of gears that may be required if the students are not able to have access to the type of motor that they require and must make adjustments.

Advanced Biomedical Considerations

Students will need to solve a variety of problems to create a mechanical model simulating the heart. First, they will need to design a pump. Eventually, the students will be able to consider how to solve other issues such as: how to get a valve to work; how to limit flow disturbances that lead to clotting; how to maintain a constant pressure once the pumping is achieved; how to use compliant tubing to mitigate fluctuations in pressure; how to balance output and return in a closed circuit; how to control the flow to different areas of the body; and how the pump will be powered.

These are some of the concerns that students may address once they have created a functional pump. Each individual group will build a prototype of a beating heart and will determine which additional aspects to explore. Each area is rich enough to justify the groups to differentiate into sub groups that will explore various aspects or systems of the project. This will be determined by the time required to create the heart pump.

Each team will design a functional pump. The cardiovascular system (that is, the flow circuit that the pump must serve) will be presented to the students as a series of vessels decreasing in size dramatically, but paradoxically increasing in volume from arteries to arterioles to capillaries because of branching. The artery can be simulated as a single large vessel that connects to the capillary bed for the purposes of testing our pump. The capillary bed can be reduced to a large container of fluid, which simulates the large cross sectional area of fluid in the capillaries. The veins leading back to the heart can be simplified to a single large vein, one of the vena cava, which exits the "capillary bed" container and returns to the artificial heart pump. This representative "circulatory system" can be utilized to test the artificial heart pumps. If this "cardiovascular system" were expanded, it would entail a forking system of vessels that decrease in diameter and likely would have hose clamps on the "arterioles" that would enable for the control of resistance and pressure and a variable output to different parts of the system. In our circulatory system the vessels will be clear and the "blood" fluid (water) will have some particulate (likely glitter) floating in it so that the rate of flow can be seen and measured.

As a preliminary exploration, a pumpless "circulatory system" can be built that relies on gravity for the pressure. This beginning "heart" will consist of a container with a hole in it raised a certain height to create a desired pressure and flow rate (the pressure drop generated by a column of water of height h is equal to: $\Delta P = dgh$, where d is the density of water and g is the acceleration due to gravity. This reservoir will be attached to the "circulatory system" of clear vessels and allowed to drain into another container that rests on the ground. The primary task for creating the artificial heart will be to address and solve how to get the "blood" back up into the top container. Initially the size of the pumps designed by the students will not be a consideration. Eventually, as the work proceeds, the students will be asked how they would optimize their design so that the pump could be able to be inserted in the chest of a recipient.

In my two second year physics classes (AP Physics B), for which this unit is intended, we will utilize this unit to lead into the correlative concepts of fluid flow rates, Bernoulli's equation, hydrostatic pressure, surface tension, cohesion and capillary action as they relate to laminar flow and resistance in vessels. We will consider the pressure exerted on parts of the mechanical pump system by the incompressible liquid once we have explored hydraulic pumps and the relationship of pressure to area. I also envision this unit as a capstone project for first year physics students once they have completed their study of Mechanics.

Student Demographics

My high school has approximately 1350 students with 400 of them being designated as gifted. The school is roughly 55% Caucasian and 36% African American and 9% other. There is a range of socioeconomic backgrounds as well, with approximately 35% of the students receiving free or reduced lunch. However, all students are required to take physics and all juniors are encouraged to consider taking a second year of physics. My Physics AP B is a second year algebra based physics course. There are 50 students taking the class. In addition, in our school 20 students are taking calculus based AP Physics C and 20 are taking advanced AP C Mechanics and Electricity and Magnetism. My AP Physics B classes are fairly representative of the school population.

Rationale

The goal of this unit is to provide the necessary understanding of the heart and its parameters for the students to design and build an artificial heart. To simplify the process I will have my students concentrate on the left side of the heart, which is the larger pump that supplies blood to the entire body. I believe that my students will be able to grasp the role of the heart as a hydraulic pump and create mechanical solutions to simulate the beating of the heart. It is my hope that my students will be able to find mechanical solutions that partially mimic the functional properties of the left side of the heart.

This creative design process of engineering and system design will result in my students designing and creating their own solutions to the heart as a pump. I intend to utilize this creative process which consists of several steps: defining the problem; establishing individual roles within the group; determining the parameters of the required design; brainstorming about a variety of possible approaches; experimenting and testing the design in phases by breaking the problem into definable and solvable sub-systems; regularly looping back to earlier steps to check the design parameters and to evaluate the progress; setting timelines for the different stages of the process; creating at least one prototype, and evaluating the success of the project. In my experience as a teacher of creative design, it is essential to provide enough knowledge or access to knowledge to define the project successfully. I have also found that students need to be encouraged to seek creative solutions by being presented with some stimulating examples of related but not reproducible options that allow them to get started. The team needs to coalesce into a functional unit that is excited by the task sufficiently to address and overcome inevitable frustration generated by attempting to solve a formidable task. One of the most challenging aspects of the creative design process for a teacher is that it is the teacher's responsibility to provide a central project task and engaging options and materials that will instill a passion for the project and the incentive and capability of successfully completing the project. I am convinced that creating an artificial heart with circulatory system is a sufficiently compelling system to captivate my second year students who have studied mechanics and will be introduced by this process to fluid dynamics.

As indicated by the National Research Council (NRC) in its recent report, "K–12 science and engineering education should focus on a limited number of disciplinary core ideas and crosscutting concepts, be designed so that students continually build on and revise their knowledge and abilities over multiple years, and support the integration of such knowledge and abilities with the practices needed to engage in scientific inquiry and engineering design." [1] This is exactly what this curriculum unit proposes to accomplish.

I have found that most students have little pragmatic experience with confronting a challenging problem that involves breaking the system down into parts in order to solve the overall project. It is incumbent upon me to imagine and explore a plethora of options and to provide a multitude of possible materials to pursue those options. There are a variety of types of artificial heart pumps, few of which function like the human heart. It is my goal to get my students to pursue both traditional mechanical pumps, such as propellers, as well as designs that are more associated with the contracting that the heart actually does by introducing springs, memory foam and other materials that will stimulate the students' creativity.

It is my intention to imbed these concepts in the experimental, hands-on activities and construction that the students experience as they pursue the goal of producing a working prototype of their pump and "circulation" system. It is my hope to harness this opportunity to create a fundamentally experiential and experimental unit utilizing concepts of engineering systems and design to create a prototype. The physics that we will explore is partly determined by the project but also partially determined by the direction that the students take in their design. Consequently, this unit is as much about the process of determining the scope of the project as it is about the biology, physiology and physics content. I will present the relevant physics as an integral part of the student's exploration into their design and the students' individual paths for creating successful pumps. I will provide the students with introductory experiences that will guide them towards comprehension of the task, enthusiasm for the design and creativity in the outcome. From my experience, these must all be intertwined. The materials provided will further inform the relevant physics concepts that are required.

The students will also be researching artificial heart and valve designs. The possibilities are very diverse and exciting. In addition, the need for artificial hearts is real, since heart disease remains the number one killer of adults in the US. [2] When I first visited colleges, and was considering biomedical engineering, in the '80's, I remember how impressive and awe inspiring it was that successful artificial hearts were being developed. It appealed to me then and I believe will spark the interest and passion of my students because it captivates the imagination. As Mark Saltzman indicates in his book, "To many people, design of a synthetic replacement for the human heart is the most heroic goal in biomedical engineering." [3]

Creative Design Strategies

Designing an artificial heart by utilizing a creative process is intended to create an educational and physical environment that will put the students in the zone of proximal learning. This concept in conjunction with constructivist learning will engage students in an extremely challenging and difficult task. The intention is to captivate the students' interest enough to overcome their initial incredulity that the task is attainable. The students' discomfort at the momentous task is intentional and is a highly unusual experience for students. Typically tasks and problem solving is limited to manageable and comfortable steps that lead to a predetermined or predictable outcome. This is a different approach! In fact, the intention is to create a context in which the students are pushed beyond what they believe they can achieve. The problem posed is meant to be beyond their immediate grasp and experiential knowledge. This state of temporary discomfort is known as the zone of proximal learning and I believe creates the real life environment and skills to pursue truly authentic problem solving in which the solutions are neither obvious, proscribed nor guaranteed. However, the intention is to captivate the students' imagination and creativity.

In addition, the process provides some engineering strategies to approach the problem. In particular, the students are placed in a cooperative team setting that makes team work crucial both for the purpose of collaboration and drawing on the each team members' individual strengths as well as to maintain the enthusiasm of the group. The team members must trust the process in order to begin to pursue the task and to move toward the possibility of a successful outcome and the production of a prototype!

Few of my students will have embarked on a task with a group that is self-defined and largely self-motivated. It is intentional to envision and construct a task that is a bit overwhelming at first, because it is my belief, informed by having participated in the process of creative design as a stone fabricator, a sculptor, a physicist and as a teacher, that the greater the challenge the greater the sense of accomplishment. So the goal with this task of designing an artificial heart is to put the students in a zone that will stretch them, engage their confidence in themselves and their peers on their team, and provide them with a rich experience that will transform their sense of what is attainable. I believe that this is true education and learning.

Most of my students do not have a sense of working with materials in a process of physical and mental problem solving, so they must be provided with some practical skills of construction. It is also essential to provide them with a wealth of materials that will stimulate their creativity. The students' must also be provided with a method to approach the task. The task may be daunting but the teacher of creative design provides practical guidelines and an approach to problem solving based on defining the problem, establishing the required parameters, breaking the problem down into manageable parts or systems, brainstorming creative solutions, evaluating possible alternative solutions or approaches using concrete methods, productive teamwork that helps determine optimum participation from each team member, provides continual encouragement, values the process as much as the outcome, and encourages iterations that allow for the continual refinement and reevaluation of ideas and approaches. This process is meant to engage and empower the individual learner and the group. The student's engagement with meaningful problem solving is enhanced, their capacity for confronting and overcoming challenge and frustration is greatly increased and the difficulty of the problem is re-envisioned as an invitation to explore the creative process of generating possibility.

As an educator, it is my conviction that the process of creation is a profound experience. Coupled with the experience of substantive problem solving I believe this makes creative design a profound, memorable and potentially formative learning experience for students that is well worth the extended time and effort required. If this is accomplished, the rewards for all who participate are great.

The Process of Developing A Creative Design Project

In order for this process to be successful, the first step is that the proposed problem must be well conceived and compelling. I believe that designing and creating an artificial heart is captivating because we all take our beating heart for granted, but upon reflection, it is truly an awesome organ and my second year physics students can grasp the problem and apply a wealth of knowledge about mechanics to problems about fluid dynamics with which they are much more unfamiliar. I am confident, however, that my students have enough conceptual knowledge of physical systems to make the task of building a prototype of their own design extremely challenging but discernable. The background information that I provide will enable my students to define the problem and apply their conceptual and mathematical knowledge of Newtonian Mechanics to create exciting mechanical solutions. I am confident that creating a tangible prototype will be tremendously rewarding.

The second step for me, as the teacher, after having envisioned the problem, is to investigate a multiplicity of possible solutions to the problem! I have achieved an initial prototype of a simulated beating heart with the help of Stephen Griffith, who co-invented the first prototype, Rajendra Jaini (the co-creator of the idea of "Sexy Science") and constant enthusiast and technical supporter, Tom Barkus, who was invaluable in formulating the original conceptions of an artificial heart as a hydraulic press, Wolfgang and Gertrud Mergner, whose medical expertise of the heart was both an inspiration and an invaluable resource, and Mark Saltzman whose tutelage has instilled in me a passion for and knowledge of biochemical processes and physiology. We have collectively succeeded in creating the prototype which is pictured below.

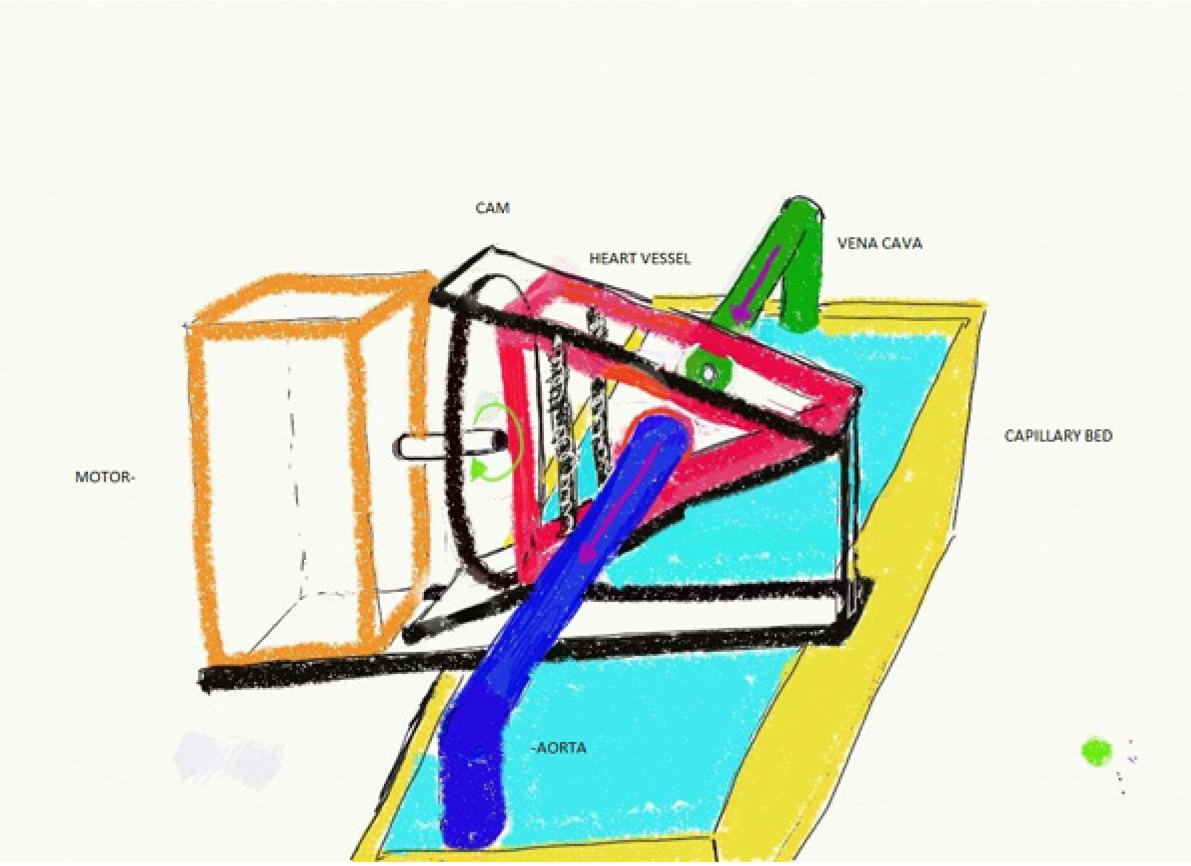


Diagram 2

The third step towards realizing the building of an artificial heart as a successful curriculum unit is to find and accumulate materials that will allow the students to find creative and innovative solutions to the problem. I continue to explore materials that will stimulate the students' imaginations and activate their comprehension of mechanics and simple machines. Within my ability I will allow the students the opportunity to seek out materials and request the fabrication of manageable parts based on their design parameters and technical drawings. The goal is to enable the students to envision solutions and interact with mechanical parts in a physical way to seek out solutions both conceptually and physically. In the meeting of these two separate processes, I believe the deepest learning and success will occur. I will do my best to facilitate the fluidity of design and construction.

The next step is to create the scaffolding that will enable the students to define the problem, break the problem into sub-systems, explore the materials for potential and optimal solutions to the subsets and support the students in successfully looping back on these steps while encouraging them to remain engaged and enthusiastic.

In order to begin building the artificial heart, the students most likely will need to see potential places to start. This is a delicate balancing act as a teacher of creative design. A balance must be struck between engaging the students' creativity and providing too much information or examples that will steer the students in a particular direction.

The last step is to continue to create a satisfying, stimulating and supportive classroom laboratory environment that will allow for controlled risk-taking and experimentation. The students must remain invested, curious, motivated and content with their progress toward the goal of creating a prototype. All groups must be supported at whatever stage they are at and all students must be encouraged to engage in the process and to realize that effort is its own reward and a successful design can only be achieved by trial and error and failures are an essential part of the road to success. I am confident that the students will embrace the project and inevitably will surprise me with their own innovations!

Promising Prototype Designs

I have developed promising ideas for prototypes. The first, and simplest, is to place a pump (already built) in-line with a "heart" or bladder. This is the most prevalent design currently for artificial hearts but it is not simplified enough. The students and myself are not able to build a functional pump from scratch, so it is my inclination that this option is not direct enough and does not draw on my students' mechanical knowledge, although there are plenty of auxiliary issues to get this design to work and to optimize it. It is my hope that my students can conceive of their design based on simple machines and Newtonian physics. The second design requires a motor and a cam. The cam, as in the diagram of the first prototype (Diagram 2), operates much like a heart that is contracting and relaxing. The cam is attached to a motor and provides two "beats" per cycle. Two hinged boards are compressed by springs onto a cam shaft and a bladder representing the heart sits closest to the hinge. The cam is oval and when it is in its vertical position the heart is most full. As the cam rotates the heart quickly "contracts" or beats causing an ejection of fluid from the heart (which is attached to a "capillary bed" as indicated in the diagram. As the cam rotates another 90° the cam is again vertical and the heart is "relaxed". Check valves are attached that only allow the fluid to flow in one direction, as indicated by the purple arrows on the diagram of the prototype. The third prototype involves the cam directly compressing the bladder. Although this provides a compressing force that provides a flow, it is much more gradual, involving the majority of the stroke of the cam, and consequently does not as closely simulate the heart beat as the diagrammed prototype, unless a pressure valve were designed to open only when the pressure reached a certain point. This would in effect provide a beat like an actual heart. The last design for a prototype involved a cam mounted on top of the hinged-levered boards. The cam and motor would have to be mounted to the bottom board, while in contact with the top board. However, this design has the same problem as the third design, in that the long stroke of the cam is the contraction and the short stroke is the relaxation, which is the reverse of the heart.

Although we did not produce a prototype for piston-activated contraction, we did spend a considerable time thinking about how they might be utilized. In our brain storming designs we imagined, like a two cylinder engine, that one piston could force downward while the second "linked" piston would travel upward. We tried to envision how this could act like the heart but were unable to effectively solve the problem. However, it seems worth exploring the possibility that at least to some extent, the double piston could potentially act as two separate pumps that in some ways could simulate the two sides of the heart.

So far we have only developed a prototype with one chamber. It is yet to be determined if there are ways to design a heart that might simulate the action of the atrium as well. By producing so many promising ideas and a functioning prototype that requires only a motor, (currently a geared down electrical motor, which certainly could be optimized to be battery powered and much smaller, maybe even allowing for the motor to be turned around and interior to the hinge allowing for a much smaller "heart") I am confident that my students can produce their own designs and prototype that only require simple machines and a motor!

History of Artificial Heart Design and Development

The remarkable effort to produce a fully functioning artificial heart entirely contained within the body has only achieved limited success. There are such devices that exist but they are not permanent and are utilized as a means to prolong patients' lives, hopefully, until they can get a human heart transplant. Most of the problems with the artificial heart are related to the issues that we discussed regarding biocompatibility, but there are other issues. One unsolved problem is the source of power, which results in cumbersome rechargeable batteries. Although a promising option exists, (provided by RF (radio frequency) power sources, like the battery source that powered our Vagus Nerve Stimulation Apparatus and Associated Methods invention), which are external to the device and the body and therefore, easily replaceable. Another issue is the difficulty of making the artificial heart entirely contained within the body, and complications involving infection inevitably arise from long term breaches in the skin. There are still many issues to be resolved for the artificial heart to be able to satisfy the tremendous need that exists. This is an additional reason for my students to get exposure to the problem and the process of biomedical engineering design.

Classroom Activities

Classroom Activity- Exploring the Parameters of the Heart as a Pump

My students will explore the heart as a pump. They will consider the parameters that the heart must maintain in terms of rate of blood flow, pressure, and control of backflow. This will begin to get my students thinking about what a pump does and how it can be simulated. This will lead us into exploring simple machines. The students will explore simple machines and their mechanical advantage. Once the students have some experience with individual simple machines, we will explore how simple machines can be combined into complex machines that magnify or enhance their properties. The students will experiment with motors and pumps to understand how they work. Once the students have some hands-on experience with machines, it is time for them to direct their energy to designing their own artificial heart.

Classroom Activity- Designing an Artificial Heart

The students will utilize their understanding of the heart as a pump and the background information about the parameters of the heart to begin designing their own heart. I will provide the students with a plethora of building materials to spark their imagination. My students will have to figure out how to recognize the simple machines and mechanical advantages contained within the materials. They will work in groups of five and collectively decide how to break the heart into component systems that can be independently solved. The groups will be provided with inventors notebooks where they will document all of their ideas collectively. The creative design process will be a combination of exploring materials and ideas that will allow the students to begin transforming materials in their minds to potential parts of an artificial heart.

Once each group has had an opportunity to explore (and play) with the variety of materials, they will begin to sketch potential ideas for beginning to build their artificial heart. I don't expect a consistent transition point for every group, as they will move from exploring to planning at different times. Some groups may generate their best ideas during the process of interacting with the building materials. Other groups may approach the task primarily from a conceptual point of view. Everyone is different, and those unique styles will be supported in this process.

Classroom Activity- Building an Artificial Heart

My students will be off and running by this point. I expect the classroom to be an eclectic mix of creative exploration into ideas and materials. This is the confluence of creativity and design and background knowledge put into a context of group endeavor towards an attainable but elusive goal! In my experience, this level of challenge, discomfort and excitement leads to remarkable outcomes.

The students will be encouraged to work equitably among their group to draw on the group members strengths. Additionally, my students will be required to document their progress and setbacks as well as their ideas, intentions, and insights. This will occur in their investigators notebooks where the process will be recorded. We will also take photos and videos that can be included in the final presentations of the students' prototypes. The goal is for each team to create a working prototype of a beating heart within the four weeks allocated for the project. I will strongly encourage my students to break the problem into independent systems that can be worked on individually and potentially by part of the group. Going through multiple iterations is also critical. We are not after the prototype only, although it is part of the motivation. Instead we must embrace the process and allow for the revelations that occur from fully engaging our mind and creativity in the process of pragmatic design. I look forward to the "ah-ha" moments that inevitably will occur and I will strive to reinforce my students determination to produce a successful prototype of an artificial heart. Now enjoy building!!!

Resources

Kapit, Wynn, and Macey, Robert and Esmail Meisami *The Physiology Coloring Book*. Addison Wesley Longman, Inc, New York. 2000.

An excellent introductory, hands-on coloring book of physiological systems.

Montaigne, Fen. Medicine by design [electronic resource] : the practice and promise of biomedical engineering / Fen Montaigne. Baltimore : Johns Hopkins University Press, 2006. Online book.

A good resource of biomedical engineering principals.

Quinn, Helen and Heidi Schweingruber. *Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas*. Committee on Conceptual Framework for the New K-12 Science Education Standards. National Research Council. 2011.

An engaging report about the future of k-12 Science Standards.

Roger, Veronique L., et al. *Heart Disease and Stroke Statistics—2011 Update : A Report From the American Heart AssociationCirculation* 2011, 123:e18-e209. American Heart Association, 2010.

A source of data regarding the prevalence of mortality resulting from heart failure.

Saltzman, W. Mark. *Biomedical Engineering: Bridging Medicine and Technology*. Cambridge University Press, New York. 2009.

An invaluable source of background information pertaining to the physiology and biomedical engineering.

My unit for an artificial limb. www.lrdc.pitt.edu/schunn/RET/.../Limb%20Teacher%20Guide%20(Draft).doc

My own curriculum developed for creating an artificial limb.

My patent on the Vagus Nerve Stimulation Apparatus and Associated Methods

http://www.wipo.int/patentscope/search/en/WO2007106692

My own patent that address RF (radio frequency) remotely powered devices

Appendix: Experts

For this unit, I am seeking out specialists in a variety of areas as well as the typical academic resources. Primarily I have engaged experts in their fields. Wolfgang Mergner is a heart specialist in pathology and has been enormously helpful in my appreciation of the heart and his passion for this organ. I have also had ongoing conversations with an anesthesiologist who specialized in heart research, my mother-in-law, Gertrud Mergner. And on a pragmatic side I will continue to consult with an electrician, Tom Barkus, who specializes in heat and refrigeration systems and who is a master in design and construction. Stephen Griffith, a teacher and engineer, has helped design the artificial heart prototype.

Appendix- Standards

National Research Council (NRC) Report, July 2011

Framework for K-12 Science Education outlines a broad set of expectations for students in science and engineering in grades K-12. These expectations will inform the development of new standards for K-12 science education and, subsequently, revisions to curriculum, instruction, assessment, and professional development for educators. This book identifies three dimensions that convey the disciplinary core ideas and practices around which science and engineering education in these grades should be built. These three dimensions are: cross-cutting concepts that unify the study of science and engineering through their common application across these fields; scientific and engineering practices; and core ideas in four disciplinary areas: physical sciences, life sciences, earth and space sciences, and engineering, technology, and the applications of science. The overarching goal is for all high school graduates to have sufficient knowledge of science and engineering to engage in public discussions on science-related issues; be careful consumers of scientific and technological information; and have the skills to enter the careers of their choice.

Notes

1. *1 Framework for K-12 Science Education*
2. 2 Heart Disease and Stroke Statistics—2011 Update : A Report From the American Heart Association
3. *3 Biomedical Engineering: Bridging Medicine and Technology*