NEXT ENGINEERS

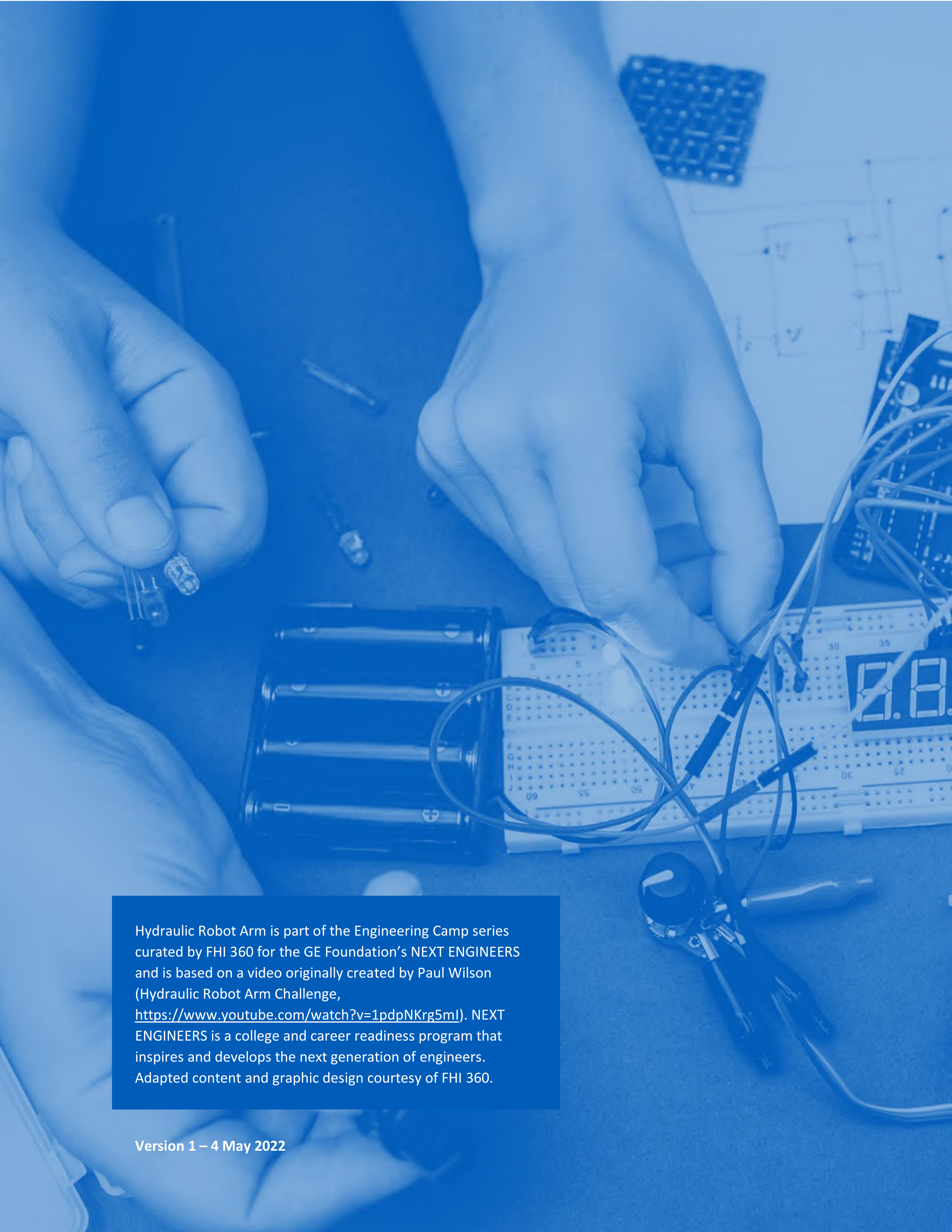
ENGINEERING CAMP

# Hydraulic Robot Arm

Topics:

Mechanical Engineering
Hydraulic Engineering

GE Foundation



Hydraulic Robot Arm is part of the Engineering Camp series curated by FHI 360 for the GE Foundation's NEXT ENGINEERS and is based on a video originally created by Paul Wilson (Hydraulic Robot Arm Challenge, https://www.youtube.com/watch?v=1pdpNKrg5mI). NEXT ENGINEERS is a college and career readiness program that inspires and develops the next generation of engineers. Adapted content and graphic design courtesy of FHI 360.

**Version 1 – 4 May 2022**

# Hydraulic Robot Arm

DESIGN CHALLENGE

| Time | Cost | Group size (teams) | Activity type |
|---|---|---|---|
| 4.25 hours | Medium | 3 - 4 students | Design Challenge |

**Engineering Areas**

- Mechanical Engineering
- Hydraulic Engineering
- Engineering Design Process

## Challenge Description

Water is a nearly incompressible liquid. This means that it is very effective at transferring force and power. Hydraulic systems take advantage of this fact and are used in many different industries to convert small forces applied over small areas into large forces applied over large areas. This is called Pascal's Principle or Pascal's Law. Hydraulic systems like this are used extensively in earth moving equipment, cranes, and industrial robots. In this challenge, students will design and build their own hydraulic powered robot arms to move marshmallows from one location to another.

## About the Engineering Design Challenge

In this design challenge, students design and build their own hydraulic powered robot arm to dunk four marshmallows into water while moving them from one location to another. The robot arm needs to be able to pick up and release the marshmallows, move up and down through at least one articulated joint, and swivel through about 45°.

### Success Criteria

- The robot arm must be able to pick up and release marshmallows.
- The robot arm must be able to swivel through about 45°.
- The robot arm must be able to lift marshmallows using at least one articulated joint.

### Constraints

- All actions of the robot arm must be powered only by hydraulic pressure.
- The force needed to grip the marshmallows and hold them securely may only come from hydraulic power. No locking or other mechanism can be used.
- Students may not touch the marshmallows in any way.
- Students may only use the materials provided.
- Students must complete the challenge in the given time.

STUDENT DISCOVERIES

Students will:

- Learn the about the Engineering Design Process
- Participate in a team-based learning experience
- Learn about hydraulics and hydraulic systems
- Have fun experiencing engineering

## Materials

Students will need blank paper and pens/pencils to draw their designs.

The following materials will be required for a **group of 50 students** for this challenge and should form a central store of materials:

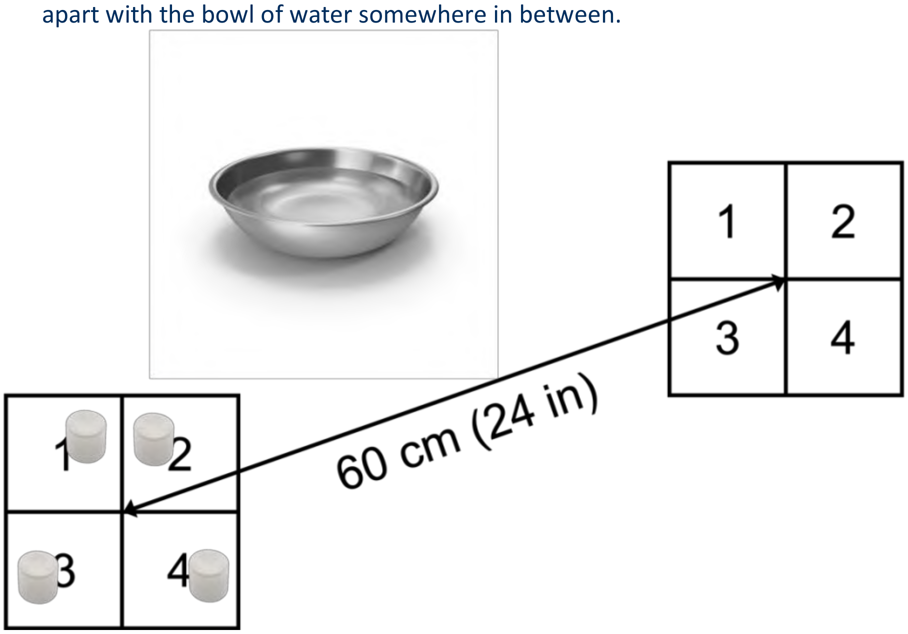
- 80 small cable ties
- 400 popsicle sticks or tongue depressors
- 40 craft cubes, 25 $mm^3$ (1 $in^3$), with holes
- 25 wooden dowels or skewers (that fit through the craft cube holes)
- A box of toothpicks
- A bag of elastic/rubber bands
- 2 – 3 glue guns and about 10 glue sticks for the group to share (if it is not possible for each team to have its own)
- 2 – 3 craft, utility, or box cutter knives (if it is not possible for each team to have its own)
- A bowl of water with which teams can fill their syringes

The following materials are required **per team** for this activity:

- Eight 10 ml or 20 ml syringes
- 2 m (6.5 ft) flexible tubing that fits tightly onto the end of the syringes
- A sharp nail with which to make holes in the popsicle sticks and syringe plungers
- A roll of tape

The following additional materials will be required for **testing** the robot arms:

- 4 marshmallows per team
- A bowl of water
- 2 pieces of paper with a numbered grid on each, placed about 60 cm (24 in) apart with the bowl of water somewhere in between.




*Suggested challenge setup*

### FACILITATOR NOTE

Each team will be using three or four separate hydraulic systems to power their robot arms. To help them distinguish the control mechanisms, you can provide water for these systems in four different colors. Simply add a few drop of food coloring to the water.

### KEY WORDS

- Articulated joint
- Compression
- Hydraulic pressure
- Incompressible
- Pascal's Law
- Pressure
- Pivot

## Facilitation Principles

These documents contain helpful advice for anyone facilitating a Next Engineers engineering activity or challenge.

- **Working with Youth: Facilitation Tips** (https://www.nextengineers.org/resource/working-youth-facilitation-tips) is a handy summary of the key facilitation principles that facilitators need to keep in mind when facilitating any activity with students.
- **Ten Guidelines for Building New Engineers** (https://www.nextengineers.org/resource/ten-guidelines-building-new-engineers) gives ten practical guidelines on how to facilitate all Next Engineers engineering activities and challenges to build new engineers.

## Facilitator Preparation

1. Read through this facilitation guide.
2. Collect the materials.
3. Practice doing the activity yourself to identify where students may struggle. In particular, experiment with both a claw and vice type of gripper as well as mechanisms to enable the robot arm to swivel. The most challenging part of this is usually creating a joint that is stable and strong but also able to turn.
4. Think how you could share your story and career journey in a relevant and personal way during the challenge. Find the following resources for how to tell your story on the Next Engineers website:
    a. **I'm an Engineer! Storytelling Worksheet** (https://www.nextengineers.org/resource/im-engineer-storytelling-worksheet)
    b. **I Work with Great Engineers! Storytelling Worksheet** (https://www.nextengineers.org/resource/i-work-great-engineers-storytelling-worksheet)
5. Practice asking and answering questions students may ask. See **Frequently Asked Student Questions** (https://www.nextengineers.org/resource/frequently-asked-student-questions).
6. Print out copies of the Student Worksheet for each group.

## Introduction

**15 MIN**

Welcome students to the activity and, if necessary, briefly introduce yourself, noting what kind of engineer or engineering student you are. Say a little about why you decided to pursue engineering and why you enjoy it.

Ask the group if anyone has ever seen large earthmoving machinery (like a backhoe or digger), a crane, or a large industrial robot in operation. What was the machinery being used for?

**TOP TIP**

Instead of having each team complete the final challenge of moving and dipping the four marshmallows one after the other, you can set up the final challenge as a race, with the first team to move and dip all their marshmallows declared the winner. This will require more grids, marshmallows, and bowls of water.

**TOP TIP**

Remember that you can adjust the criteria and the constraints to suit the capability of the group. If you think moving and dipping marshmallows will be too difficult for the group, you can have them move or dip the marshmallows only.

You can make the challenge more difficult by requiring teams to move larger or heavier items.

*A backhoe working on beach erosion*
*Image by Paul Brennan is released under a CC0 license*
*https://www.publicdomainpictures.net/en/view-image.php?image=294695&picture=backhoe-working-on-beach-erosion*

Show the group a few pictures of different types of machinery that operate using hydraulics. Lead students to identify the various pistons that are used to make the machines move and work and ask if anyone knows how they operate.

Explain that these pistons operate using hydraulics. The group will explore what hydraulics are in the next section of the challenge.

Tell students that in this challenge they will work as teams of engineers to design and build their own hydraulic powered robot arm to pick up, dunk, and move four marshmallows from one location to another about 60 cm (24 in) away.

Explain that their success criteria are that:

- The robot arm must be able to pick up and release marshmallows.
- The robot arm must be able to swivel through about 45°.
- The robot arm must be able to lift marshmallow using at least one articulated joint.

Explain that the constraints they need to work under are that:

- All actions of the robot arm must be powered only by hydraulic pressure.
- The force needed to grip the marshmallows and hold them securely may only come from hydraulic power. No locking or other mechanism can be used.
- They may not touch the marshmallows in any way.
- They may only use the materials provided.
- They must complete the challenge in the given time.

Explain if, in the final challenge, teams will need to compete against each other to see who can pick up, dunk, and move their marshmallows the quickest.

## Identify the Problem and Gather Information

**30 MIN**

For this challenge, students need to work with the concepts of hydraulic pressure and pivots. While there are elements of mechanical advantage involved, these will not play a significant role in the design or operation of the robot arms.

Start this section of the challenge by allowing students to explore the basics of Pascal's Law – that a force applied in one part of a closed system is transmitted without loss to all other parts of the system.

Connect two syringes (one drawn out, the other not) with a piece of flexible tubing. Hand a syringe to each of two students. Ask students what they think will happen if the student with the drawn-out syringe pushes their syringe in. Why is this? What will happen if they draw their syringe out again? Why?

Now ask the student with the drawn-out syringe to try and force the other syringe out, but this time the other student needs to try and prevent this from happening. What happens to the air in the drawn-out syringe? Why is this? What happens to the other syringe? How easy is it for the student with the pushed-in syringe to keep their syringe from being pushed out?

Disconnect one of the syringes and fill the syringe still connected to the tubing with water by drawing the water through the tubing. Connect the second pushed-in syringe again.

Hand the syringes to two different students and ask the group to predict what will happen if the student with the drawn-out syringe now tries to push their syringe in while the other student resists their syringe being pushed out. What is the difference? Why is there a difference?

Explain that while air (a gas) can be greatly compressed (forced into a smaller volume), water (like most other liquids) cannot. Water is largely incompressible. When the syringes were filled with air, the force exerted on the drawn-out syringe went mostly into compressing the air. Very little force was transferred to the plunger of the other syringe to push it out.

However, with water, very little of the force was 'wasted' on compressing the water, and almost all was transferred directly to the plunger of the second syringe.

Explain that this system of two syringes is a simple kind of hydraulic system – the transfer of force from one syringe to the other through water (or some other incompressible liquid).

Explain that we call the force that is transferred through a fluid like water hydrostatic pressure. Sometimes the pressure comes from an external force pushing on the fluid (like in the case of a syringe plunger being pushed in). Sometimes it comes from the height of the fluid above a certain point.

**TOP TIP**

If the group is very big, you can split students into their teams and hand each team their syringes and flexible tubing.

**TIPS FOR MAKING CONNECTIONS**

- **Give constructive feedback** to help students grow and improve.
- **Ask open-ended questions** to better understand what and how students are thinking.
- **Be respectful** by listening actively and responding openly and authentically. Give students your undivided attention and the respect you want them to give you.
- **Be honest** about what you know. Say if you don't know something. Encourage students to keep trying by sharing some of your own failures and the lessons you learned.

Students will need to find a way to harness this hydrostatic pressure and the way it can be used to move a syringe plunger in and out to drive their robot arm.

If necessary, remind teams that their robot arm will need to be able to move in the following ways:

- The robot arm must be able to pick up and release marshmallows.
- Swivel through 45°.
- The robot arm must be able to lift marshmallows using at least one articulated joint.

If you have not yet done so, break the group up into teams and give each team their building materials. Explain that during this part of the challenge, teams will have the opportunity to:

- Investigate the materials available to them in the central store to determine their properties and to start thinking about how they could be used in the challenge.
- Think about some possible solutions (e.g., how a syringe plunger moving in and out through hydrostatic pressure can be used to move their robot arm).
- Use the Internet to search for design ideas that they might like to explore further or build on.

Invite teams to investigate their materials and to use the Internet to search for design ideas that might be helpful. As teams do this, have them consider the following questions:

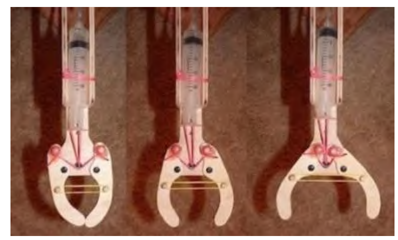
- What kind of gripping device will they need to pick up a marshmallow? How large are the marshmallows they will have to grab? How much force do they need to be able to apply to hold a marshmallow?
- Will they build a gripper that looks and works like a claw or like a vice?

| | |
|---|---|
|  |  |
| **A claw type gripper** | **A vice type gripper** |

- What mechanism can they use to lift their marshmallow up once they have grabbed it? How high do they need to lift it? Do they need to be able to move the marshmallow in and out as well as up and down?
- How far is 60 cm (24 in)? How big or long does their robot arm need to be to be able to move a marshmallow over this distance?
- What mechanism can they use to swivel their robot arm through 45°? How can they keep their robot arm upright and stable?
- What kind of base does their robot arm need to have to remain steady?

**DID YOU KNOW?**

The pistons operating backhoes typically exert a force of over 300 000 N, enough to lift a 30 ton truck.



An example of a hydraulic powered claw type gripper by Hudson Valley Post is used under fair use https://hudsonvalleypost.com/events-poughkeepsie/poughkeepsie-hydraulic-robot-claw-maker-lab/09-october-2017-mid-hudson-childrens-museum/

## Design Phase

**30 MIN**

It is now time for teams to start generating possible design solutions for their robot arms. Teams need to consider the following factors in their design.

- What kind of grip will they use?
- How will they allow their robot arm to swivel?
- How will they keep their robot arm stable?
- How many articulated joints will their robot arm have?
- How will the joint(s) of their robot arm be made to move? Where will the syringe(s) be placed?

Encourage team members to make their own design sketches first and then to share their ideas with the rest of their team. Teams should use the process of sharing design ideas as a brainstorming exercise to arrive at the best ideas possible. Teams need to produce a combined set of final sketches that describe and explain how their robot arm will work and what materials they are going to need from the store. Remind teams that they will be able to change part or all of their design as they start testing and redesigning.

Once each team has a sketch or set of sketches of the idea they want to prototype, have them compile a list of materials from the store that they require. Only when they have completed their sketches and list should you allow them to take materials from the store and start building.

## Create, Test, and Redesign

**2.25 HOURS**

This is the part of the challenge when teams get to build, test, evaluate, and redesign their designs. Encourage teams to test early and often, and to test different aspects of their design individually. Before teams do any testing, ask them to think about what aspects of their design they are testing, how they will record and evaluate the results of the test, and how they will use these results to inform further iterations.

During this part of the challenge, it is important that you circulate constantly around the teams and ask them to describe and explain what they are doing, what tests they have done, what they have learned from these tests, and how this has informed or changed their designs.

As needed, you can challenge teams to think differently about their designs. For example, ask them if they have tried:

- Creating a second articulated joint on their robot arm that allows a second degree of motion, i.e., up and down as well as in and out.
- Changing the position of their syringes to change the initial or final position of an articulated joint.
- Connecting the syringe and the plunger to the arms of the robot by pivots to allow the joints to twist.
- Trying another kind of gripper design.

### TIPS FOR WORKING WITH STUDENTS

- **Be prepared** by practicing the activity beforehand. Being prepared is the best start to leading confidently and having fun.
- **Facilitate like an engineer** by reflecting during and after each session. What worked? What could be improved? How could you do things differently next time?
- **Teamwork is critical** in engineering so encourage it among students. Make sure no one dominates and that everyone gets to play.
- **Give one instruction at a time** to keep a large group on task and doing what you need them to do.
- **Give regular time updates** to keep students on track.

Image of a basic hydraulic powered articulated joint by Exploratorium is used under fair use [https://www.exploratorium.edu/snacks/hydraulic-arm](https://www.exploratorium.edu/snacks/hydraulic-arm)

## Present the Solution and Reflect

**45 MIN**

It is now time for teams to put their robot arms through an official test. Each team will get at most three attempts to complete the challenge. Should teams wish, they can adjust their designs between tests.

After the tests, bring the whole group together to discuss the following questions.

1. How well was your robot arm able to meet all the criteria while working within the constraints?
2. What features of your robot arm do you think are the most unique and you are most proud of?
3. How similar was your original design to the actual robot arm your team eventually built and tested?
4. If you found you needed to make changes during the construction phase, what were the most significant changes you made and why did you decide to make these changes?
5. Which robot arm that another team developed was the most effective or interesting to you? Why?
6. If you could have used one additional material, what would you choose and why?
7. Do you think that this challenge was more rewarding to do as a team, or would you have preferred to work alone on it? Why?
8. What did you learn about engineering?
9. How do you think the challenge relates to a career in engineering?

**TOP TIP**

If you decide to set up the final challenge as a race, give teams two attempts to perfect their robot arms before commencing the race. The first team to move and dip all their marshmallows wins!

Image of a cardboard hydraulic robot arm by Technovision is used under fair use https://www.instructables.com/CARDBOARD-Robotic-Hydraulic-Arm/

## Extension

This activity can be extended in the following ways:

- Increase the distance over which the marshmallows need to be moved.
- Replace the marshmallows with items that are larger and/or heavier and/or different shapes, sizes, and masses
- Introduce other intermediate steps in addition to dunking the marshmallows in water, e.g., posting them through a hole or stacking them.

## Key Words

- **Articulated joint:** A flexible or moveable joint allowing a range of motion in one or more directions.
- **Compression:** To compress a substance means to use a force to press it into a smaller volume. This has the effect of forcing the atoms in the substance to get closer than they would normally be. Gasses are easy to compress. Liquids and solids are far harder.
- **Hydraulic pressure:** Hydraulic pressure is measured as a force per unit of area, for example, bar ($kg/cm^2$) or PSI (Pounds per square inch). The hydraulic pressure at any point within a fluid is the same in all directions if the fluid is static.

## Key Words, continued

- **Incompressible:** A fluid or solid is said to be incompressible if it cannot be forced into a smaller volume by an external force. While any substance can technically be compressed if the force applied is great enough for most practical purposes, the fluids used in hydraulic systems are taken as being incompressible.
- **Pascal's Law:** Also called Pascal's Principle. States that a pressure change in fluid at rest in one part of a closed system is transmitted without loss to every portion of the fluid and the walls of the container without loss. A pressure exerted on one piston produces an equal pressure on another piston in the same system.
- **Pressure:** This is the perpendicular force applied per unit area.
- **Pivot:** A point or shaft around which a mechanism can turn.

## Challenge Background

Hydraulic systems are everywhere. They are used in the braking systems of cars, trucks, trains, and planes. They are used in many building and earth moving machines like cranes, front loaders, bulldozers, and diggers. They are used in forklifts, jacks, and other lifting devices. Power steering relies on hydraulics, as do shock absorbers. Most of the mechanisms used to control the flight of airplanes also use hydraulic systems.

No matter how complicated they may be or what they are used for, all hydraulic systems work on the same basic principle – Pascal's Principle (or Pascal's Law). This states that any change in the pressure of a liquid in a closed container is transmitted without loss to every other portion of the fluid in that container and to the walls of the container. There is virtually no loss in the transmission process because liquids, like water, are practically incompressible.

But why does this lossless transmission of changes in pressure matter? To understand why, we need to remember that pressure is defined as force per unit area.

$$P = \frac{F}{A}$$

Now, consider a closed system with two round movable pistons, one with a small surface area ($A_1$) and one with a large surface area ($A_2$) (see the image below).

Image of a hydraulic crane is released under a CC0 license https://pxhere.com/en/photo/1328373

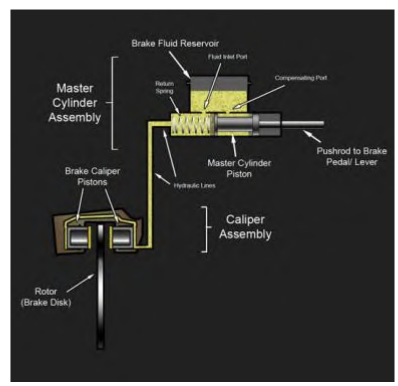
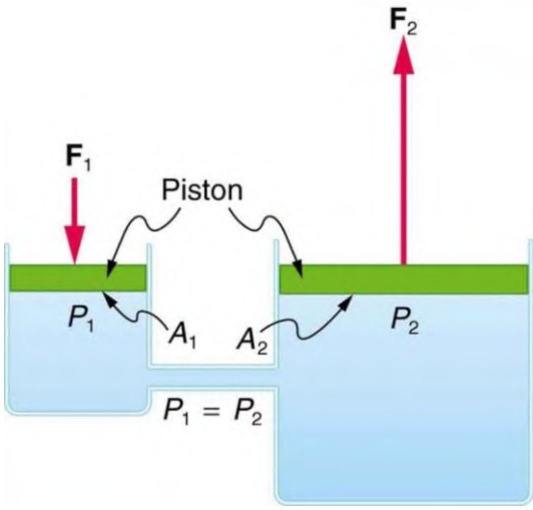



Image of a the basic working principle of hydraulic brakes by KDS444 is released under a CC-BY-SA 3.0 license https://commons.wikimedia.org/wiki/File:Hydraulic_disc_brake_diagram.gif




*A typical hydraulic system by Lumen Learning is licensed under a CC-BY license*
*https://courses.lumenlearning.com/physics/chapter/11-5-pascals-principle/*

If a force, $F_1$, is applied to the smaller piston, this will result in an increase in the pressure $P_1$. But Pascal's Principle says that this change in pressure is transmitted throughout the system without loss. Therefore, as $P_1$ increases so does $P_2$. $P_1 = P_2$.

But we know that

$$P = \frac{F}{A}$$

Therefore, this means that

$$\frac{F_1}{A_1} = P_1 = P_2 = \frac{F_2}{A_2}$$
$$\therefore \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

This means, for example, that, if

$$A_2 = 10 \times A_1$$

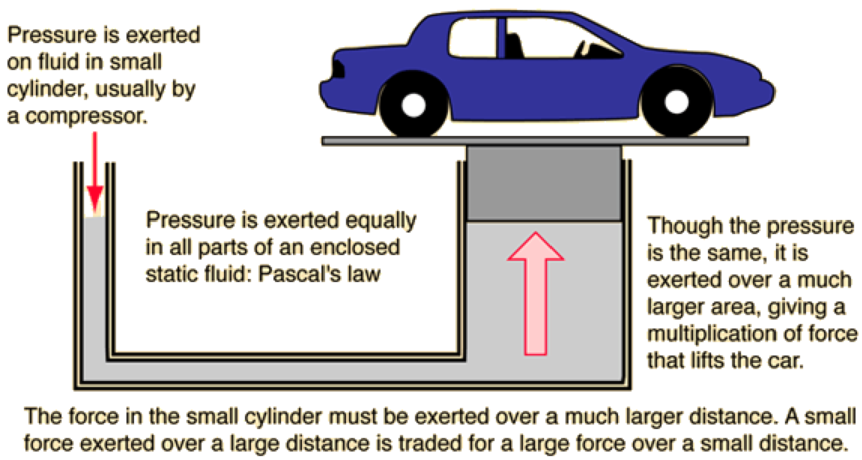
then

$$F_2 = 10 \times F_1$$

So, a small force applied to the smaller piston is converted to a larger force applied to the bigger piston. Seems like magic! But nothing is ever free.

Because the volume of the fluid in the larger piston is much bigger than the volume of the fluid in the smaller piston, the smaller piston will move much further than the larger piston.

This is how a simple hydraulic lift works.




*Automobile hydraulic lift by Hyperphysics is used under fair use http://hyperphysics.phy-astr.gsu.edu/hbase/pasc.html*

In the case of this activity, however, the surface areas of the pistons (the syringe plungers) are the same. Therefore, there is no force multiplication and hence no mechanical advantage.

But you could extend the learning in this activity by introducing syringes with plungers of different cross-sectional areas so that students can explore and discover the force multiplier effect usually in operation in real-world hydraulic systems.

## Additional Resources

- *CARDBOARD Robotic Hydraulic Arm*
  https://www.instructables.com/CARDBOARD-Robotic-Hydraulic-Arm/
- *DIY Hydraulic Powered Robotic Arm from Cardboard* (7:18)
  https://www.youtube.com/watch?v=Tb5H8GIazJ0
- *Hydraulic Arm*
  https://www.exploratorium.edu/snacks/hydraulic-arm
- *Pascal's Principle*
  https://courses.lumenlearning.com/physics/chapter/11-5-pascals-principle/
- *How a hydraulic jack works (3D Animation | Pascal Principle)* (3:19)
  https://www.youtube.com/watch?v=42dtoqUKY8I
- *Hydraulic Jack how it works* (3:10)
  https://www.youtube.com/watch?v=Ykgi09b8BiI
- *Pascal's Principle, Hydraulic Lift System, Pascal's Law of Pressure, Fluid Mechanics Problems* (21:04)
  https://www.youtube.com/watch?v=MZ6GCH2nLy0

## References

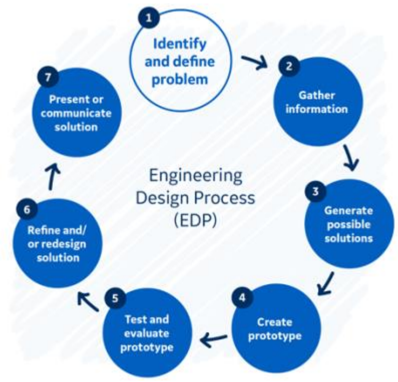
This activity is based on **Hydraulic Robot Arm Challenge** originally created by **Paul Wilson** and available at https://www.youtube.com/watch?v=1pdpNKrg5mI.

# The Engineering Design Process

**STUDENT HANDOUT**

The engineering design process (EDP[1]) is the key process engineers follow when they solve problems and design solutions.

## 1. Identify and define the problem




Engineers start by asking lots of questions. What problem must be solved? Who has the problem? What do we want to accomplish? What are the project requirements? What are the limitations? What is the goal? Through this process, engineers start to identify the **criteria** (the conditions the solution must satisfy to be considered successful) and the **constraints** (the limitations they need to design within).

## 2. Gather information

Engineers dig deep into the problem by collecting **information and data** about the problem and any existing solutions that might be adaptable. They talk to people from many different backgrounds and specialties to assist with this research.

## 3. Generate possible solutions

Now the fun really starts! Engineers start to **brainstorm** ideas and develop as many solutions as possible, sometimes even crazy ones. This is the time for wild ideas and deferred judgment. It is important to build on the ideas of others while staying focused on the core problem and keeping the criteria and constraints in mind. For example, if there is a budget, can the potential solution be developed within that budget?

## 4. Create a prototype

Engineers choose one or more of the most promising solutions to **prototype**. A prototype is a working model to be tested.

## 5. Test and evaluate the prototype

Most prototypes **fail**, but that is good. It tells engineers which ideas they should focus on. Engineers also need to decide if the design really does solve the original problem.

## 6. Refine and/or redesign the solution

After learning through testing, engineers **redesign and retest** until they have the best solution possible – one that balances the criteria and constraints.

## 7. Present or communicate the solution

Finally, engineers reach a point where they are satisfied with their solution. It does not need to be perfect, but it should '**satisfice**' - meet the criteria within the constraints. Engineers now communicate their solution to others.

[1] Adapted from https://www.teachengineering.org/design/designprocess