NEXT ENGINEERS

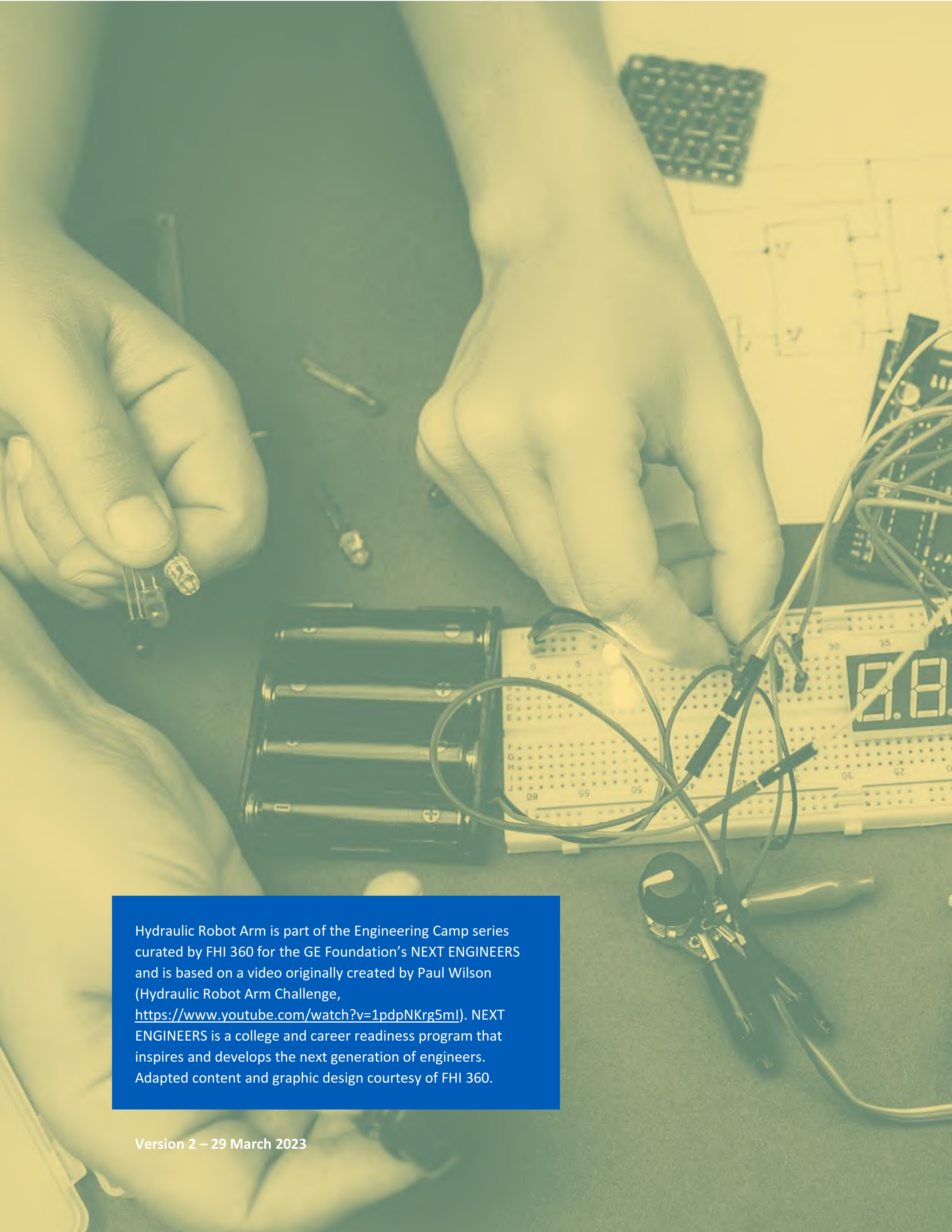
ENGINEERING CAMP

Difficulty Level 3

Hydraulic Robot Arm

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 2 – 29 March 2023

Hydraulic Robot Arm

DESIGN CHALLENGE

Time	Cost	Group size (teams)	Activity type
4.5 hours	Medium	3 - 4 students	Design Challenge
Engineering Areas			
• Mechanical Engineering • Hydraulic Engineering	• Engineering Design Process		

Challenge description

Water is a nearly incompressible fluid. This means that it is very effective at transferring force and power (much like a steel rod would be). Hydraulic systems take advantage of this fact and the nature of fluid pressure 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.

The 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 90°.

Success Criteria

- The robot arm must be able to pick up and release marshmallows.
- The robot arm must stand on its own (i.e., it cannot be held).
- The robot arm must be able to swivel through about 90°.
- 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, spring, elastic, 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 more about engineering
- Learn about the Engineering Design Process
- Participate in a team-based design experience
- Learn about the importance of testing and iterating
- Learn about hydraulic pressure and hydraulic systems
- Learn about how to use hydraulic pressure to do useful work
- 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:

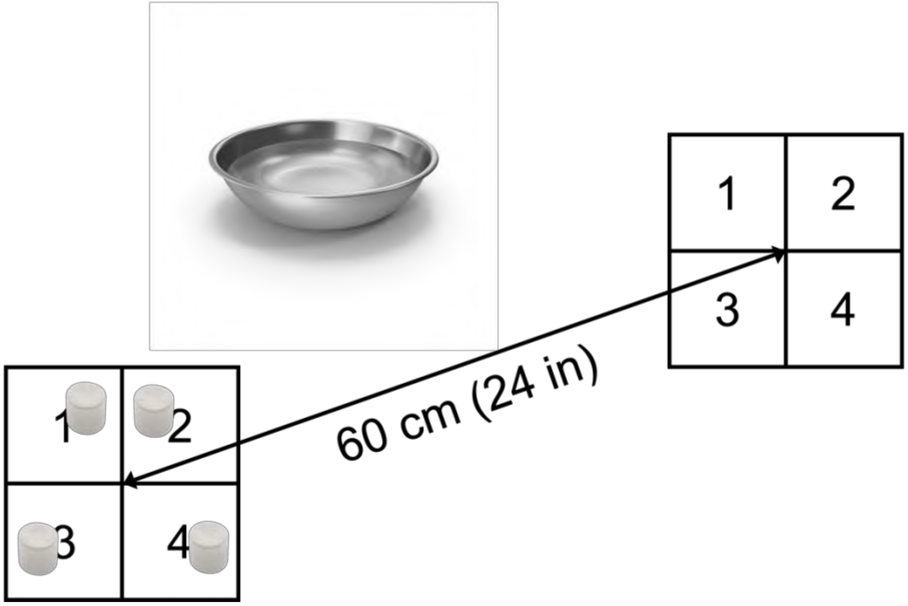
- About 80 small cable ties
- About 400 popsicle sticks or tongue depressors
- About 40 craft cubes, 25 mm^3 (1 in^3), with holes
- About 25 wooden dowels or skewers (that fit through the craft cube holes)
- Corrugated cardboard (a few small to medium packing boxes should do)
- A box of toothpicks
- 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 container 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 electrical tape
- Two practice marshmallows

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

KEY WORDS

- Articulated joint
- Compression
- Constraints
- Criteria
- Design
- Engineering Design Process (EDP)
- Engineering Habits of Mind (EHM)
- Engineers
- Hydraulic pressure
- Incompressible
- Iteration
- Pascal's Law
- Pivot
- Pressure
- Prototype

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.

Time required

This design challenge will require approximately **4.5 hours** to complete. You may decide how to structure and organize this time.

Activity	Duration
1. Introduction	**15 min**
2. Identify the problem and gather information	**30 min**
3. Generate possible solutions	**45 min**
4. Create, test and redesign	**2.25 hours**
5. Present the solution and reflect	**45 min**

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).

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.

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.

Activity 1: Introduction

15 MIN

1. 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.
2. 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?

A backhoe working on beach erosion 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

3. Show the group pictures of following types of hydraulic machines (you can use the suggested images or find your own). Help students to identify the various pistons that are used to make the machines move and work. State that these pistons operate using hydraulics. Ask if anyone knows what a hydraulic system is and how it works.
   a. *Earth working and earth moving equipment*
   b. *Cranes*
   c. *Hydraulic press*
   d. *Lifts*
   e. *Aircraft landing gear*
   f. *Vehicle brakes*
   g. *Bicycle brakes*
4. Play the video called *How Do Hydraulic Machines Work?* (3:39) to give the group a simple overview.
5. 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.
6. Explain that their success criteria are that:
   a. The robot arm must be able to pick up and release marshmallows.
   b. The robot arm must be able to swivel through about 90°.

DID YOU KNOW?

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

CREATING TEAMS

- As far as possible, keep teams to no more than four students. Three students per team is ideal.
- Make sure there is a good mix of students in each team.
- Assign roles or allow teams to determine and designate their own roles. Some roles you can suggest teams consider are Project Lead, Research Lead, Design Lead, Resource Manager, and Finance Manager.

   c. The robot arm must be able to lift marshmallows using at least one articulated joint.

7. Explain that the constraints they need to work under are that:
   a. All actions of the robot arm must be powered only by hydraulic pressure.
   b. 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.
   c. They may not touch the marshmallows in any way.
   d. They may only use the materials provided.
   e. They must complete the challenge in the given time.
8. Explain if, in the final activity, teams will need to compete against each other to see who can pick up, dunk, and move their marshmallows the quickest.
9. Finally, divide students into their challenge teams. They will work in these teams in the next activity.

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.

Activity 2: Identify the problem and gather information

30 MIN

1. Have students split into their teams and give each team the following materials:
    a. Two of the eight syringes
    b. 2 m (6.5 ft) flexible tubing
2. Have teams connect their two syringes (one with the plunger drawn out and the other with it pushed in) with the piece of flexible tubing. Ask teams what they think will happen if the person with the drawn-out syringe pushes their plunger in. Why is this? What will happen if they draw their plunger out again? Why? Have two students hold a syringe each and stand as far apart as possible.
3. Now ask the person with the drawn-out plunger to try and force the other plunger out but this time the person holding the other syringe 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 plunger to keep their plunger from being pushed out?
4. Next, have teams disconnect one of the syringes and fill the syringe still connected to the tubing with water by drawing the water through the tubing and then reconnect the second syringe with its plunger pushed. To completely fill the tubing, teams will have to disconnect the syringe, remove the air, reconnect it and continue drawing water into the tubing and syringe. They should repeat this until the tubing and syringe are completely full.
5. Now ask teams to predict what will happen if the person with the drawn-out syringe now tries to push their plunger in. Why does this happen? Once again, two students should hold one syringe each and stand as far apart as possible.
6. Ask teams to predict what will happen if this action is repeated while the other person resists their plunger being pushed out. What is the difference? Why is there a difference?
7. Explain that while air (a gas) can be easily and 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 by the drawn-out plunger being pushed in went mostly into compressing the air. Very little of this force was transferred to the plunger of the other syringe to push it out.
8. However, with water, very little of the force was 'wasted' on compressing the water, and almost all of it was transferred directly to the plunger of the second syringe.
9. 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).
10. Explain that we call the force that is transferred through a fluid like water **hydraulic pressure**. Sometimes the pressure comes from an external force pushing on the fluid. Sometimes it comes from the height of the fluid above a certain point.
11. Explain that it is this hydraulic pressure that teams will need harness to operate their hydraulic arm.

TOP TIP

You can do the experiment with shorter lengths of tubing, but allowing students to see and experience hydraulic force over a distance of 2 m is powerful.

TOP TIP

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.

Activity 3: Generate possible solutions

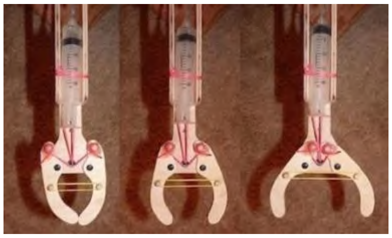
45 MIN

1. Explain that during this part of the challenge, teams will have the opportunity to:
   a. 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.
   b. 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).
   c. Use the Internet to search for design ideas that they might like to explore further or build on. If teams need some help finding design ideas, you can point them at the following videos which showcase some interesting ideas:
      - *DIY Hydraulic Powered Robotic Arm from Cardboard* (7:18)
      - *How to Make Hydraulic Powered Robotic Arm from Cardboard* (6:56)
      - *Three-Axis Hydraulic Robotic Arm* (6:06)
      - *Hydraulic Robotic Arm* (9:05)
2. Invite teams to investigate the materials in the central store and to use the Internet to search for design ideas that might be helpful. As teams do this, have them consider the following questions:
   a. What kind of gripping mechanism will they need to pick up a marshmallow? How large are the marshmallows? How much force do they need to be able to apply to hold a marshmallow?
   b. Will they build a gripper that looks and works like a claw or like a vice?
   c. 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?
   d. 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?
   e. What mechanism can they use to swivel their robot arm through 90^{o}? How can they keep their robot arm upright and stable?
   f. What kind of base does their robot arm need to remain steady?

	
A claw type gripper	**A vice type gripper**

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.



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/

3. 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 final annotated sketch (or set of sketches) that describes and explains 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.
4. Once each team has a sketch or set of sketches of their design, have them compile a list of materials they require from the central store. Only when they have completed their sketches and list should you allow them to take materials from the store and start building.

ANNOTATED SKETCH

A line drawing of a design or idea that includes labels and explanatory text to describe and explain primarily how the design will work and what the design will be made of.

Activity 4: Create, test, and redesign

2.25 HOURS

1. Have teams build, test, and optimize their designs. Make sure teams have their marshmallows to test and practice with.
2. Circulate between teams helping and advising as required. As needed, you can challenge teams to think differently about their designs. For example, ask them if they have tried:
   a. 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.
   b. Changing the position of their syringes to change the initial or final position of an articulated joint.
   c. Connecting the syringe and the plunger to the arms of the robot by pivots to allow the joints to twist.
   d. Trying another kind of gripper design.
3. Be aware of the following dynamics in some teams or individuals and intervene as required.
   a. **Aiming too high** – some teams or individuals may wish to aim for perfection. Remind teams of the constraints of time and materials within which they are working and that, often, engineering is about finding the solution that best balances the criteria and constraints rather than the very best solution. This is sometimes termed 'satisficing' – the solution that meets the specifications and goals in an acceptably efficient and functional manner.
   b. **Not aiming high enough** – some teams or individuals may become demotivated or inclined to accept their very first design even if it does not adequately meet the criteria. Explain that the engineering design process is all about incremental improvement. Work with these teams to help them see how they can improve their designs and encourage them to keep pressing into the design process.

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

Activity 5: Present the solution and reflect

45 MIN

1. Give each team three attempts to complete the challenge of moving and dipping their four marshmallows. Should teams wish, they can adjust their designs between tests.
2. After the tests, bring the whole group together to discuss the following questions.
    a. How well was your robot arm able to meet all the criteria while working within the constraints?
    b. What features of your robot arm do you think are the most unique and you are most proud of?
    c. How similar was your original design to the actual robot arm your team eventually built and tested?
    d. 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?
    e. Which robot arm that another team developed was the most effective or interesting to you? Why?
    f. If you could have used one additional material, what would you choose and why?
    g. 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?
    h. What did you learn about engineering?
    i. 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!

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.

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

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 the pressure a liquid applies within a container and 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.
- **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.
- **Pivot:** A point or shaft around which a mechanism can turn.
- **Pressure:** This is the perpendicular force applied per unit area.

- **Constraints**: Limitations of materials, time, budget, size of team, etc.
- **Criteria**: Conditions that the design must satisfy to be considered successful.
- **Design**: a plan or drawing made before something is built to show and explain what it will look like, and how it will work.
- **Engineering Design Process (EDP)**: The iterative process of researching, designing, prototyping, and testing engineers use to solve problems and design solutions.
- **Engineering Habits of Mind (EHM)**: Six unique ways that engineers think.
- **Engineers**: Inventors and problem-solvers of the world. Twenty-five major specialties are recognized in engineering (have a look at the infographic at https://tryengineering.org/wp-content/uploads/18-EA-381-InfographicEngineering_R2-6.pdf).
- **Iteration**: The process of gradual improvement through repeated design, testing, and redesign.
- **Prototype**: A working model of the solution to be tested.

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.

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

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).

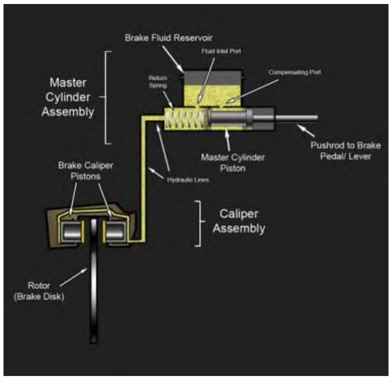
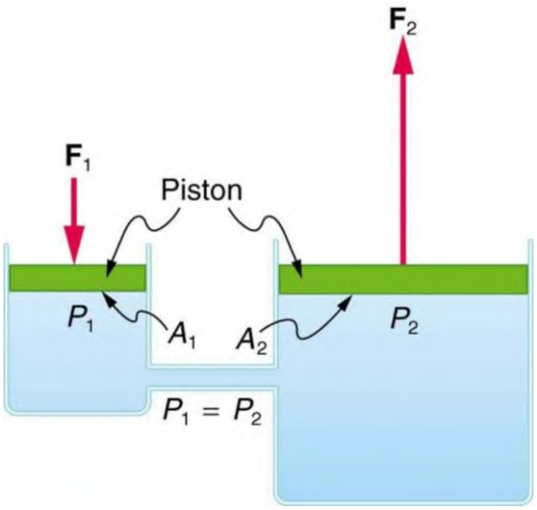


Image of a the basic working principle of hydraulic brakes by KDS444 is released under a CC-BY-SA 3.0 license https://commons.wikimedia.org/wiki/File:Hydraulic_disc_brake_diagram.gif



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

$$A_2 = 10 \times A_1$$

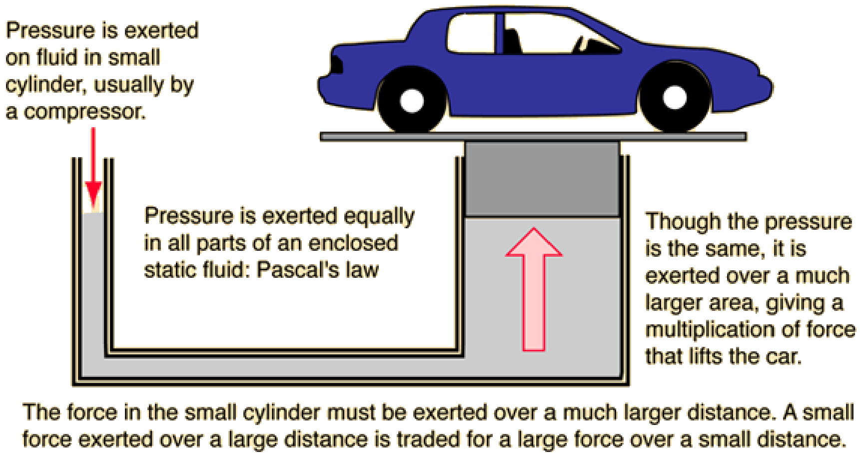
then

$$F_2 = 10 \times F_1$$

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 farther 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.