**Robot Arm Challenge**

**Description**

In this activity students are introduced to fluid power, articulated robot arms and end effectors. Students will work with a partner to design and construct an arm that allows them to move a number of small objects from one location to another.

This activity helps students by:

* Introducing them to fluid power (hydraulics and pneumatics)
* Introducing them to the concept of moment (torque)
* Developing design and manufacturing skills
* Demanding teamwork and cooperation to accomplish a task

### Lesson Outcomes

Students will be able to:

* Describe the operation of a fluid power system, including:
  + How pressure and piston area affect force
  + The relationship between piston area, stroke length and force
  + Why pistons are good at pushing but poor at pulling
* Identify live loads and dead loads and their impact on arm performance
* Apply techniques to reduce the impact of dead load on arm performance
* Describe the role of force and distance in calculating moment (torque)
* Use the tools and equipment provided to create a hydraulic robot arm
* Use the robot arm they create to accomplish a predefined task

### Assumptions

Students will have basic understanding or background knowledge in the following areas:

* Use of simple hand tools:
  + Wire strippers
  + Hot glue
  + Soldering irons
  + Sharp knives
* Sketching and drawing



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### Foundational Learning

* Fluid power transmission
  + Pressure / force / area relationship
  + Pushing vs. pulling (you can’t “pull”)
* How pushing force and distance affect moment (torque)
  + Effect of pushing at an angle when calculating moment

### Key Terminology

**Area**: a measurement of surface.

**Cylinder**: the outer container of a fluid power actuator.

**Degrees of freedom**: the number of axes upon which a device may move or rotate. For example the human arm has seven degrees of freedom: three at the shoulder joint, one at the elbow, and three at the wrist.

**End effector**: the tool at the end of a robot arm that accomplishes the desired task. Often used to grasp objects, it may be any type of tool, including a spray gun or welder.

**Moment**: a twist, or *torque*, created by a force acting at a distance from a pivot point.

**Piston**: the sliding component inside a cylinder.

**Pressure**: a force distributed evenly over a surface. Force: a push or pull upon one object exerted by a second object.

### Estimated Time

Total time 8–12 hours:

* 2–3 hours of lesson time
* 5–7 hours of build and testing time
* 1–2 hours of activity/competition time

### Recommended Number of Students

Two students per arm to a maximum of 20 students, based on *BC Technology Educators' Best Practice Guide*

If time and resources permit, having each student build their own robot arm allows them to take the arm home at the end of the activity.

### Facilities

A multipurpose tech studies shop or lab with access to:

* Drawing or sketching resources
* Drills (ideally drill presses)
* Fine-toothed saws or sturdy knives for cutting wooden sticks
* Ideally one or more band saws for cutting plywood pieces
* Hot glue area
* Water and “wet work space” with towels or paper towel for drying parts

### Tools

* Drill press (or suitable hand drill arrangement)
* Whitney punch (if available)
* Wire strippers
* Screwdrivers
* Scissors
* Hot glue guns

### Materials

* Syringes: available from medical supply stores or online. The “Luer-Lok” tip on the right in Figure 1 holds tubing much better. 10 cc syringes are about the right size for this project.
* Tubing: ¼" clear vinyl tubing from Home Depot works well. Test the tubing with a syringe first to ensure a good fit.
* Wood strips
* Plywood for robot base platform
* Assorted blocks of wood
* Dowels
* Screws, nuts, bolts
* Stiff wire or thin rod (1⁄16" and ⅛" welding rods work nicely)
* Cardboard and thumbtacks for “Cardboard Aided Design”
* ¼"–1" game elements for the robot challenge of moving small objects. You can use a range of sizes, giving more points for the little ones. Nuts and bolts work well. Other possibilities include:
  + Marbles and ball bearings
  + Empty aluminum cans
  + M&M candies (The team can share as many M&Ms as they can place into a cup in 60 seconds.)
* You may want to use a plastic cup, about 10 cm high, as the “goal” where the robot will place the game pieces.



### Resources

**Figure 1—**Syringes

This is a common STEM activity performed in slightly different ways in many different schools around the world. There are many excellent resources available by searching for “syringe robot arm,” “hydraulic robot arm” and similar combinations. Some current resources (as of 2016) include:

Tufts University “Teach Engineering” Educational Outreach is an excellent, alternative activity guide including a short video: https://[www.teachengineering.org/activities/view/wpi\_hydraulic\_arm\_challenge](http://www.teachengineering.org/activities/view/wpi_hydraulic_arm_challenge)

The “Syringe Hydraulic Arm” at Ideas-Inspire.com is another excellent write-up with photos, videos and instructions for building arms:

<http://ideas-inspire.com/syringe-hydraulic-arm/>

A well-documented build of an articulated 3 DOF syringe arm with gripper, including plans, is available at:

<http://jefenry.com/main/MechanicalArm.php>

This site presents instructions for assembling a commercially prepared kit. The fine detail of these instructions may serve as a guide in the design of your students’ arms: <http://www.copernicustoys.com/doc/COP-Arm-Instructions1.2.pdf>

The Instructables site has a nice arm built from cardboard and duct tape: <http://www.instructables.com/id/Hydraulic-robot-made-of-cardboard-and-scotch-duct-/>

Commercially produced educational robot arm kits are available for purchase. However, they can be manufactured in-house for a fraction of the cost:

<http://www.pitsco.com/T-bot_II_Hydraulic_Arm>

There are also 3D printable robot arms on Thingiverse: http://www.thingiverse.com/thing:1328020 and http://www.thingiverse.com/thing:39803

### Demonstration

If a sample syringe arm is available, use it to demonstrate the challenge. Otherwise you may wish to use one of the many videos available on-line. Links are provided above.

### Procedure

Following is an outline of the procedures for this lesson. Detailed procedure guidelines are provided below in the *Detailed Procedure Guidelines* section on page 9. Items marked with

an asterisk have supporting materials included in the *Lesson Support Materials* section of this activity guide.

|  |  |  |
| --- | --- | --- |
| Day 1: | Lesson: | Introduce Activity.\*  Discuss types of robot arms.\* Discuss types of end effectors. |
|  | Activities: | Put students into teams.  Begin drawing / modelling exercise to determine arm type and dimensions.\* |
| Day 2: | Lesson: | Fluid power\* |
|  | Activities: | Fill and bleed syringes.  Compare the force on different size syringes.  Compare the difference between pushing on a syringe and pulling on it. Where do the bubbles come from when pulling?  Finish design of robot arm if time allows. |
| Day 3: | Lesson: | Moments and counterbalances\* |
|  | Activities: | Finish design of robot arm. Begin construction of robot arm. |
| Day 4: | Lesson: | Review fluid power and moment concepts |
|  | Activities: | Continue arm construction. |
| Day 5: | Lesson: | Quiz on fluid power and moment concepts\* |
|  | Activity: | Continue arm construction. |
| Day 6: | Lesson: | Cable and tubing management |
|  | Activity: | Continue arm construction and test. |
| Day 7: | Lesson: | Review challenge |
|  | Activity: | Arm practice and refinement |
| Day 8: | Activity: | Robot Arm Challenge Day! |

#### Lesson Support Materials

The following lesson support materials are provided in this activity:

* Robot Arm Challenge page 7
* Fluid Power Worksheet page 18
* Moments and Counterbalances Worksheet page 25
* Robot Arm Quiz page 28

# The Robot Arm Challenge

Name: Date: Block:

Robot arms are used everywhere! From an excavator to a chocolate factory to the Canadarm2 on the International Space Station, the robot arm is one of the most practical applications for robotics. Many robot arms operate using motors for control, but some of the most powerful ones use hydraulics. In this challenge you will work with a partner to design and build a hydraulic robot arm and have it complete a task as efficiently as possible.

##### The Challenge:

The game object for your challenge will be:

The game objects will be placed on a 20 cm × 20 cm playing field.

The only thing that may enter the space above the playing field or touch the game objects shall be your robot arm.

The base of your robot arm must be at least 5 cm from the playing field at all times.

Your arm will have to pick up the game objects and place them in a container approximately 10 cm tall.

Your task will be to get as many game objects into the container as possible in : seconds.

##### Your Supplies:

You will be given a collection of building materials by your teacher. Your robot must be built from the materials supplied.

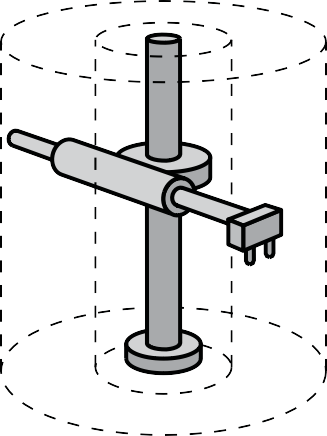
You will be given : plastic syringes and tubing to join them. These will form your hydraulic actuators.

##### Your Process:

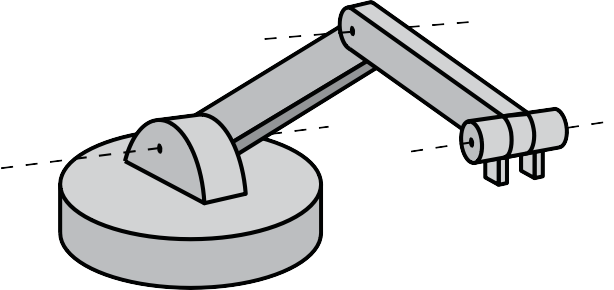
You will need to start by designing your robot arm. The six common types of robot arm are shown below.

For this challenge the articulated robot arm is the most common solution. Your teacher will guide you through an exercise in designing your arm.

Once you have a design that works, sketch it at ½ scale using the back of this handout.



Rectangular coordinate robot Cylindrical coordinate robot



## Spherical coordinate robot

Articulated arm robot

## Gantry robot SCARA robot

**Figure 2—**Six most common types of robot arm

### Detailed Procedure Guidelines

**Day 1 Lesson: Arm Geometry: exercise and tips on designing an articulated arm** Robot arms are often described in terms of “degrees of freedom” (DOF). A degree of freedom is provided by a joint that can either translate (slide) or rotate.

In the CNC world these are sometimes described as “axes” (plural of axis, not the tools for lumberjacks). A standard three-axis CNC router or 3D printer is a “3 DOF Cartesian” system.

You can see a 5 DOF CNC machine in action here: https://[www.youtube.com/watch?v=KDPA06D1r\_8.](http://www.youtube.com/watch?v=KDPA06D1r_8)

Most of the six common robot arm designs have at least one DOF from a translational element. Unless you have provided the students with a way to build a linear slide, they will have a problem. They might be able to solve it—it’s up to them to figure it out.

Most of the arms built to solve this challenge are the articulated type. Using eight syringes allows for three DOF plus one end effector (“gripper”).

Typically they are referred to as the:

* base (rotation)
* shoulder joint (rotation)
* elbow joint (rotation)

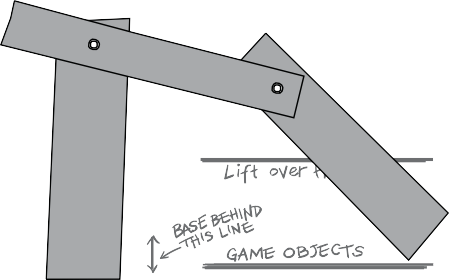
To save on syringes you may want to allow students to turn the base by hand.

Designing an articulated robot arm is fairly easy; it’s connecting the hydraulics that is the challenge. 3D parametric modelling programs such as AutoDesk Inventor make this easier.

To help in the design, have your students use CAD: Cardboard Aided Design (credit to Randy Schultz at BCIT for the term). Students can mark out the baseline, playing field and “lifting line” at 1:1 scale on a piece of cardboard.

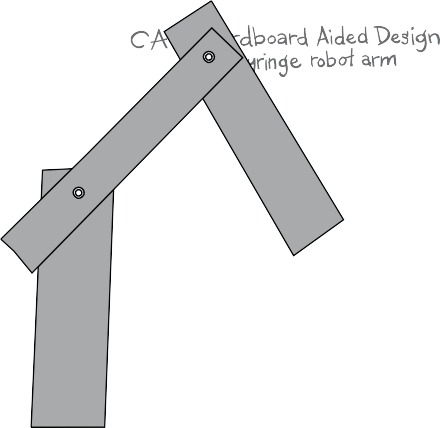
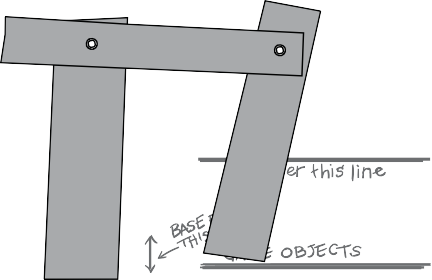
They can cut a representation of their base, upper arm and lower arm from cardboard. They can use thumbtacks, pushpins or even brads to serve as joints.

The process is detailed in Figures 3–14 on the following pages.



**Figure 3—**The starting point **Figure 4—**Pin the parts

Pin down base and arm joints. Arm should reach farthest point on playing field.

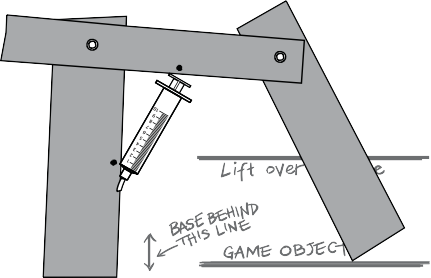
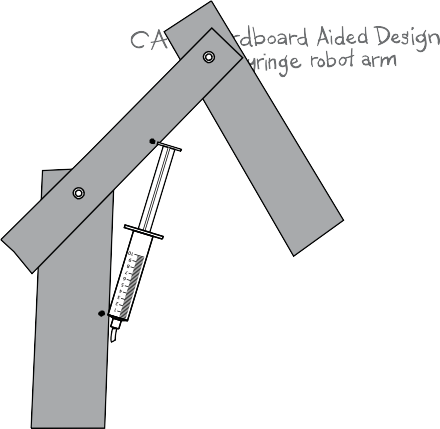


**Figure 5—**Test nearest reach point

Arm should also reach nearest point on playing field.

**Figure 6—**Height clearance

Arm should clear the lifting line.



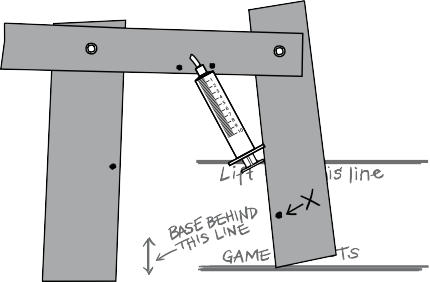
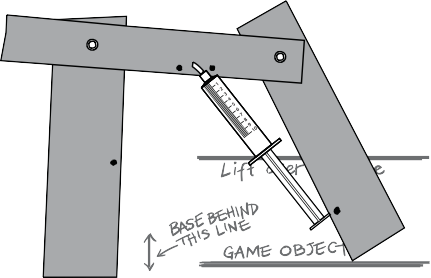
**Figure 7—**Test-fit shoulder syringe

Test-fit shoulder joint syringe at full extension.

Mark mounting points for the syringe.

**Figure 8—**Test-fit retracted syringe

Test-fit shoulder joint syringe at full retraction. It MUST fit the same mounting points as at full extension.



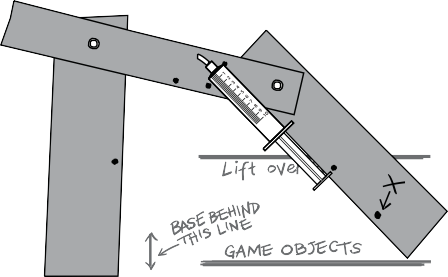
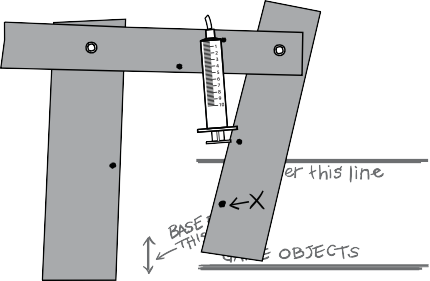
**Figure 9—**Test-fit elbow syringe

Test-fit elbow joint syringe at full extension. Mark mounting points. Note that this syringe may not intersect

with the shoulder syringe. It may be easier to use two syringes in this exercise.

**Figure 10—**Test-fit retracted elbow

Test-fit elbow joint syringe at full retraction. Note that it cannot retract the arm to the near side of the playing field. This mounting point will not work.

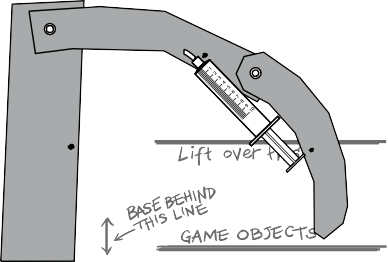
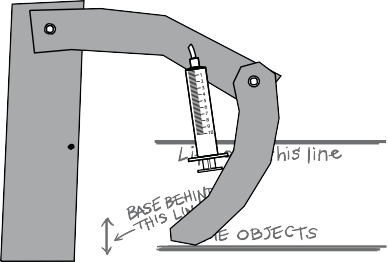


**Figure 11—**Adjust syringes to fit

Try a new mounting point for the elbow joint syringe. Mark the new mounting points.

**Figure 12—**Pay attention to torque

The new syringe location might work, but note that it is almost perfectly in line with the lower arm. This means that it will not be delivering a lot of torque to the elbow joint. It might work, but there might be a better design.



**Figure 13—**Try curved arms

Students might want to try using bent or curved arms in order to improve mounting points and torque transfer. They may find some inspiration in the backhoe or excavator, although they are

designed for double-acting cylinders.

**Figure 14—**Curved arms may offer better performance A process of iteration should lead students to develop a workable design. Once they have finalized their design, have

them sketch a ½ scale model on the back of their handout.

The teacher may wish to have the students demonstrate their design using their cardboard model..

### End Effectors or “Grippers”

The design of the end effector will be based on the chosen game object and should be designed at the same time as the arm; a similar CAD process may be used. Elastics or springs can be very useful. As you use a syringe to push the effector open, the elastics will hold it tight when

the syringe is retracted.

See the Day 2 notes on pulling on a hydraulic cylinder. You could pull, of course, just not very well.

Links to some examples can be found in the “Resources” section of this activity.

#### Day 2 Lesson: Fluid Power

These notes are intended to support the fluid power worksheet. It is helpful to have a few syringes and tubing filled in advance of the lesson to serve as demonstrations. A small amount of food colouring in the water will make it easier to see the fluid. Placing the syringes on an overhead projector will allow all students to see the syringes move as the instructor pushes and pulls the pistons. Having buckets filled with water (perhaps a couple of buckets with different colours of water) will help students fill and bleed their systems.

Fluid power systems include both pneumatic and hydraulic systems. In both, power is transmitted from one location to another by moving a pressurized fluid. Gases, like air, are considered fluids because they flow. Liquids, like water, are also fluids.

##### Hydraulic systems

In hydraulic systems the fluid is a liquid. We use water for our hydraulic arm (that’s where the hydro comes from).

Industrial equipment uses oil, which helps prevent corrosion in the system.

Hydraulic fluids are incompressible. They don’t change their volume when you push on them. When using a hydraulic fluid, it is important to get all of the air out of the system. Even tiny air bubbles will compress under pressure. This makes the system “spongy” or “springy.” Removing the bubbles from the system is called *bleeding* the system. Have you ever heard of someone bleeding their brakes?

##### Pneumatic systems

In pneumatic systems the fluid is usually air (that’s where the “pneum” comes from … like pneumonia).

Gases are compressible. Compressed gas acts like a spring: it stores a lot of energy! This can be useful when used in a paintball gun but dangerous when used with “home-made” storage tanks like the Schedule 40 ABS pipe in potato cannons. When a pneumatic vessel fails, it tends to explode violently.

##### Steam power

**Question for students**: Would steam power be considered hydraulic or pneumatic?

Answer: It uses water to make steam, but steam is a gas so it is pneumatic. In reality, however, steam often gets its own category because of the high temperatures involved and the fact that the steam often condenses into liquid.

**Steam power** is a very important part of industrial operations in BC. Its uses include:

* heating buildings
* running industrial plants such a pulp mills and refineries
* creating electricity through turbines driven by steam generated by burning natural gas or even garbage!

People who run and operate steam power plants are called power engineers or steam engineers. There are many good jobs for people who can work safely with steam. You can learn to be a power engineer at BCIT or other schools.

##### Hydraulics vs. Pneumatics: Quick Reference

|  |  |  |
| --- | --- | --- |
|  | **Hydraulic** | **Pneumatic** |
| Type of Fluid | Water, oil or other liquid | Air or other gas |
| Compressible? | No. Does not change volume when under pressure. | Yes. It compresses when under pressure. |
| Movement | Very precise. Good for moving actuators a specific distance. | Very flexible. Good for gripping objects of unknown size. |
| Explosion Hazard | Very low. If a cylinder ruptures, a small leak will instantly relieve all of the pressure in the line. (Just don’t get hit by the stream … it will be a very high- pressure jet!) | Very high. If a cylinder ruptures, the stored energy in the compressed  gas will be released as an explosion. Higher pressures bring higher danger! |
| Spill Hazard | Leaks can create a big mess, particularly when using oil. | No clean up required. |
| Speed | Liquids are more viscous than air. They move more slowly. | Pneumatic actuators can move very quickly, as air flows easily. |
| Force | Can be used safely at high pressure, so can transmit high forces safely. | High pressures create an explosion hazard. The working pressure is lower than for hydraulic systems. |
| General Uses | Larger, heavier, slower moving equipment that transmits a lot of force. | Smaller, quicker moving machines that may pick up objects of unusual sizes or shapes |

**Pressure, Area and Force: How to Move a Piston with Fluid Power**

Our syringes work like a hydraulic or pneumatic cylinder. The cylinder is the “outside” part that stays still and contains the fluid. The piston is the “inside” part that moves. The fluid in the system is under pressure—the same pressure at every point in the system.

Pressure is measured in terms of force divided by area. In the metric system we use the *pascal*, or one newton of force per square metre. Since the pascal is a very small amount of pressure, we tend to use the kilopascal (kPa). One kPa is 1000 newtons of force per square metre. This is roughly the force exerted by 100 kg of mass at the surface of the Earth. Standard air pressure is about 100 kPa. Standard air pressure is 101.3 kPa at sea level.

In the imperial system we use pounds per square inch (psi). Standard air pressure is about 15 psi.

Imagine a 1" square on the palm of your hand. The air pressure pushing on that square is 15 pounds.

* How much air pressure is pushing on your whole palm?
* Why doesn’t your hand move under the pressure?
* Why don’t you feel it?
* What would happen if the air pressure wasn’t there?

Within a closed hydraulic system it is assumed that the pressure is the same everywhere in the system.

Force can be calculated by multiplying the pressure by the area: F = P × A

##### Worked Example of Pressure Calculation

If you have 15 psi acting on 3 square inches, you have: F = 15 psi × 3 square inches = 45 pounds of force

If you have 100 kPa acting on a 10-cm diameter circle:

1. Convert 1 cm to 0.01 m.
2. Calculate the radius of the circle: 0.1 m diameter / 2 = 0.05 m radius
3. Calculate the area of the circle: 3.14 x (0.05 m radius)2 = 0.008 m2
4. Convert the pressure to pascals: 100 kPa = 100,000 Pa
5. Now calculate the force: 100,000 Pa x 0.008 m2 = 800 N

To estimate the equivalent “weight,” divide the newton value by 10:

800 N / 10 = approximately 80 kg of force will be acting on the circle.

The metric example may seem more complex, but the metric system is used by scientists and engineers. Metric calculations become much easier with practice.

##### Pushing a Piston: Mechanical Advantage

Typically a piston will have two forces acting on it:

1. The load: applied by something or someone “outside” the hydraulic system.
2. The pressurized fluid: acting on the piston by the fluid “inside” the system.

When the two forces are equal the piston won’t move. When the two forces are unequal, the piston will move.

The piston will move “out” if the pressurized fluid presses with more force than the load. It will move “in” if the load presses with more force than the fluid.

When you have two pistons with different areas, the force acting on each piston will be different (Figure 15). The larger piston, with more surface area, will push with a higher force but it will move a shorter distance than the small piston.

The smaller piston, with less surface area, will push with a lower force. It will move a greater distance than the large piston. This is similar to the principles of gearing, or leverage:

Smaller force × longer distance = bigger force × shorter distance

Piston

Piston

Two single acting cylinders joined by a hose. Which will push with the most force?

Which will travel the longer distance?

**Figure 15—**Two single-acting cylinders of different diameters joined by a base

Consider a car’s braking system (or hydraulic disc brakes on a mountain bike). The brake pad needs to move a very small distance but push very hard. The brake pedal can move a long distance but needs to be easy to push. The pedal gets a small cylinder and the brake gets a large cylinder.

Since larger cylinders will exert more force at the same fluid pressure, you need to design your arm to work with the cylinders that you have. If the hose keeps popping off the cylinder, then perhaps your fluid pressure is too high.

Do you need a bigger cylinder? Do you need to reduce the load on the cylinder? See the notes under Day 3: Moments and Counterbalances, below.

##### Pushing vs. Pulling a Piston

**Question for students**: When you pull on one piston, what pushes on the other piston?

**Answer**: The other piston is “pushed” by ambient air pressure, which is usually much lower than the pressure inside the system.

You can’t pull on a hydraulic system. Well, you CAN … but not with as much force as you can push. What happens if you pull harder? Bubbles form inside the system. Demonstrate by placing syringes on an overhead projector and pulling. Where do the bubbles come from? Dissolved gases in the water.

Consider a bottle of soda pop. Do you see bubbles in it when it is closed? What pressure is it at when it is closed? What happens when you open it? What pressure is it at after opening? There is a LOT of carbon dioxide gas dissolved in soda.

Students may have heard of scuba divers being affected by “the bends.” This happens when oxygen and carbon dioxide build up in their blood at high pressure when they are under water. If they come up to the surface too fast, their blood bubbles, just like the soda pop when it is opened. The bubbles block the flow of blood and can kill.

If you pull hard enough you will get water vapour. As water pressure is reduced, the boiling temperature drops. This is used in vacuum dehydration of foods. But industrial hydraulic cylinders can push AND pull. How do they do it?

Our syringes are a single-acting piston: fluid contacts only one end of the piston. The pistons are designed to push in one direction only.

Most industrial cylinders are *double-acting*: fluid contacts both ends of the cylinder (Figure 16). The piston can be pushed in both directions. Do you think it will push harder in one direction than the other? Take a look at the area of the piston on each side. The shaft on one side slightly reduces the area. There isn’t as much area, so there isn’t as much force!

Pis

ton

Fluid hoses

Seals

Piston rings

**Figure 16—**Double-acting cylinder

# Fluid Power Worksheet

Name: Date: Block:

These are some of the words and ideas that engineers use when working with fluid power. They are also used by mechanics and equipment operators when controlling and repairing heavy equipment. Can you think of any other careers where people need to know about fluid power?

#### Terms:

Hydraulics use a such as or

to make things move.

Pneumatics use a such as to make things move.

A liquid is an fluid. That means that it doesn’t “shrink” when you push on it.

A gas is a fluid. That means that it acts kind of like a spring when you push on it.

Pressure is a measure of divided by .

Air pressure acts on us all the time. One “atmosphere” of air pressure is the pressure we feel on Earth at sea level. In metric measure, one atmosphere is measured as

kPa. In imperial measure it is measured as psi.

Our robot will use syringes to make things move. In the photo below, label the part of the syringe that is the “piston.” Label the part that is the “cylinder.” Label the piston rings that keep the fluid

in the syringe.



The fluid can push on the piston to make it move. How hard the piston pushes is called the

It is calculated by multiplying the of the fluid by the of the piston.

When filling a hydraulic system with fluid, it is important to get all the out of the system. This is called the system.

##### Calculations

When engineers, mechanics and equipment operators use fluid power, they need to know how much force their system can apply. These are some of the calculations that they use. Fill in the spaces.

|  |  |  |
| --- | --- | --- |
|  | **10 cc syringe** | **5 cc syringe** |
| Diameter of piston | 14.5 mm | 12 mm |
| Diameter of piston in metres (divide mm by 1000) |  |  |
| Radius of piston (divide diameter by 2) |  |  |
| Area of piston (3.14 × radius squared) |  |  |
| Force on piston at 100,000 Pa  (multiply area by 100,000) |  |  |

Which piston exerts the larger force at 100 kPa?

Why does the larger piston exert the larger force?



**10 cc syringe**

**5 cc syringe**

In the photo above, a 10 cc syringe is connected to a 5 cc syringe so that the fluid can flow from one to the other. If you push on the piston in the 10 cc syringe, the 5 cc syringe’s piston will

move outward. It will move with force than is pushing on the 10 cc syringe piston, but will move a distance.

If you push on the piston in the 5 cc syringe, the 10 cc syringe’s piston will move outwards. It will move with force than is pushing on the 5 cc syringe piston but will move a distance.

Fluid power works best when pushing. When you “pull” on one syringe you are relying on ambient pressure to push the other piston inward. If you pull too hard, then will form in the hydraulic fluid.

**Day 3 Lesson: Moments and Counterbalances**

These notes are to complement the “Moments and Counterbalances Worksheet.” Having a long (1–2 m) lever arm with holes drilled at regular intervals and a selection of weights to hang from the arm will help illustrate the concepts described here.

A moment, also known as torque, is a twisting force that is the result of a force pushing at a distance from a pivot point. A 100 g mass at the end of a 10-cm long pivot will create a moment of 10 cm × 100 g = 1000 g × cm (Figure 17).

10 cm

|  |  |
| --- | --- |
|  |  |
|  |  |

100 g

**Figure 17—**A moment

Technically, the metric unit for torque is the newton metre. Since in Earth’s gravitational field 100 g of mass creates 1 N of force, and 10 cm = 0.1 m, our calculation would be better stated as:

1 N × 0.1 m = 0.1 Nm

The imperial unit for moment is the foot-pound, although you’ll also find inch-pounds used on smaller torque wrenches. One newton meter is 0.738 foot-pounds or 8.85 inch-pounds.

Regardless of whether you are using metric, imperial, inch-pounds, g x cm, Nm or foot-pounds, the basic concept is the same: a moment, or torque, is simply force x distance.

Since the force of gravity is always pulling down, moments change as a robot arm lifts an object (Figure 18).

When a 10-cm arm is rotated to 45 degrees, the load is now only 7 cm from the pivot point. The moment about this pivot point is now 100 g × 7 cm = 70 g × cm, or more accurately,

1 N × 0.07 m = 0.07 Nm.

100 g

7 cm

**Figure 18—**Load is closer to pivot point

##### What would the moment be when the arm is perfectly vertical?

You may wish to have a student demonstrate by holding a weight in one hand with their arm extended horizontally. Have them slowly rotate their arm to vertical while keeping their arm straight. Ask, “When did the load feel heaviest?”

To counteract a clockwise moment, we need to apply a counter-clockwise moment. In Figure 19, the syringe is applying an upward force at a distance of 5 cm from the pivot, so it must counteract a clockwise moment of 100 g × 10 cm = 1000 g × cm.

The syringe must create a counter-clockwise moment of 1000 g × cm.

10 cm

5 cm

100 g

**Figure 19—**Piston counteracts moment

Since the piston is 5 cm from the pivot, we can calculate the upward force: 1000 g × cm / 5 cm = 200 g.

Had we calculated it all in newton metres, we would have arrived at 2 N of upward force. This makes sense: the load is twice as far from the pivot as the syringe, so the syringe must exert twice as much force.

Sometimes a hydraulic actuator (syringe) can’t provide enough force to lift the arm. Adding a counterbalance can help. In Figure 20, the 100 g counterbalance at a distance of 5 cm from the pivot provides 100 g × 5 cm = 500 g × cm of counter-clockwise moment. This means that the syringe only needs to create a 500 g × cm counter-clockwise moment. The syringe only needs to push with a force of 100 g (1 N).

10 cm

5 cm

5 cm

100 g

100 g

**Figure 20—**Counterbalance supporting load

Sometimes adding a counterbalance can make the arm too heavy or too slow. Springs or elastic bands can be used to provide a counteracting force (Figure 21).

10 cm

5 cm

5 cm

100 g

**Figure 21—**Elastics or springs replacing counterweight

It can be more difficult to calculate the effect of a spring or elastic band. The amount of tension changes as the band is stretched or relaxed. One alternative is to use a constant force spring, which is a coil of thin metal strip that can be used at the pivot point to counteract the load.

There are two main types of load that a robot arm experiences:

* 1. The *live load*: the weight of whatever is being lifted
  2. The *dead load*: the weight of the arm, grippers and actuators

Normally counterbalances are used to counteract the dead load of the arm. The live load is left for the actuators (pistons or motors) to manage.

An additional live load to consider is the momentum of the arm. A heavy arm does not want to start (or stop) moving quickly. Fast-moving arms have to be either very light or very powerful.

When a heavy live load must be held in position for an extended time, it may be helpful to also apply a brake or locking mechanism to the pivot point. This reduces the strain on the motors or cylinders holding the arm in place.

Your arm design will likely be a bit more complicated to calculate. The syringes will probably be at an angle to the arm. This can be calculated by hand or modelled by computer.

The syringe in Figure 22, for example, has to push harder than a vertical syringe because it is

at an angle. So long as you understand the basic principles of moment, however, you should be able to make your arm work.

10 cm

5 cm

5 cm

100 g

**Figure 22—**More complex piston arrangement

# Moments and Counterbalances Worksheet

Name: Date: Block:

Your robot arm will rotate about joints, or pivot points. The amount of force acting on the arm and the distance of that force from the pivot point will be important in making sure that your arm can lift its load. Learning about moments and counterbalances will help you design and build a better robot arm.

A is a twisting force, also known as . It is

the result of a pushing at a distance from a point.

In metric measure the standard unit for a moment is the

or Nm. In imperial measure people use the

or ft. lb.

The equation to calculate a moment is × . In this diagram the live load is 100 g and acts at a distance of 10 cm from the pivot.

10 cm

5 cm

100 g

100 g of mass in Earth’s gravitation gives a force of N. A distance of 10 cm expressed in metres is m.

The moment is:

N × m = Nm.

The syringe must counteract the moment of the live load. The syringe is at a distance of

m, so we can calculate the force on the syringe as Nm /

= N.

This force is roughly the same as that exerted by a mass of g. This makes sense because the syringe pushes as hard, but at

the distance as the load.

The moment can change as the arm rotates. In this diagram the arm is still 10 cm long, but now the load is closer to the pivot point. The moment is now:

N × m = Nm.

100 g

7 cm

To help balance an arm and make it easier to lift, we sometimes add a weight on the opposite

|  |  |  |
| --- | --- | --- |
| side of the pivot point from the main load. We call this a |  | . |
| In this arm it creates a counter-clockwise moment of  Nm. | N × | m = |

10 cm

5 cm

5 cm

100 g

100 g

This means the syringe only has to create a moment of Nm to balance the arm.

One problem with counterbalances (also called counterweights) is that they make an arm

.

Robot arm designers can help support the load by adding or

to help pull the arm up.

There are two main types of load on the arm. The load is the

weight of the object the arm is lifting, while the load is the weight of the arm itself. The weight of the object might change, but the weight of the arm usually

remains constant. For this reason robot designers will usually use the counterbalance to support the moment caused by the dead load, and let the piston or motor support the weight of the live load.

# Robot Arm Quiz

Name: Date: Block:

Score: /16

1. Matching—Place the letter that best represents the term in the column indicated. (0.5 mark each–6 marks)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Place Letter Here** | **Term** |  |  |  |
|  | Hydraulic power | A  Force / Area | B  About 100 kPa in metric, about 15 psi in imperial | C  A metric unit of force, about equal to a mass of 100 g |
|  | Pneumatic power |
|  | Pressure |
|  | Air pressure at sea level | D    10 cm  100 g | E  Fluid power using a liquid such as oil or water as the fluid | F  The metric unit of torque, the newton metre |
|  | Bleeding |
|  | Moment |
|  | Newton | G  A weight or spring added to the back of your robot arm to assist with lifting the load | H  Fluid power using a gas such as air as the fluid | I  The imperial unit of torque, the foot pound |
|  | Nm |
|  | Ft. lb. |
|  | Live load | J  The weight of the structure; in this case, the weight of the arm | K  Removing air bubbles from a hydraulic system | L  The weight of the object you are moving |
|  | Dead load |
|  | Counterbalance |

1. Our syringes work best when pushing. Why? (1 mark)
2. What do we call a cylinder that can both PUSH and PULL? (1 mark)
3. In this photo there are two syringes of different diameters. (3 marks)



**15 mm diameter**

**10 mm diameter**

* 1. If the syringe on the right (10 mm) is pushed with a force of 8 N, how much force will the larger syringe exert?
  2. Which piston will move the greatest distance?

1. In this diagram an arm has a counterweight that exerts 5 N at a distance of 0.15 m from the pivot point and a syringe that exerts 6 N at a distance of 0.1 m. (5 marks)

.3 m

.15 m

.1 m

6N

5N

F

* 1. How much torque does the counterweight create?
  2. With the counterweight and syringe working together, how much force can be exerted to lift the load labelled “F”?

**Extension Activities**

This challenge can be extended by placing robots on opposite sides of the playing field. The robots can either cooperate to gather game objects as quickly as possible, OR compete to gather more game objects than the other arm.

You can also change the goals and have the robots place game objects ON the field, potentially for playing a game of Tic-Tac-Toe.

Advanced students may wish to design components in CAD and create them using a 3D printer, laser cutter or CNC machine.

Students who finish early may wish to experiment with a motor-controlled robot arm kit such as this one, if available:

<http://www.pitsco.com/Robotic_Arm_Edge_Kit>

### Assessment

##### Student name:

“Cardboard Aided Design” Score: /5

Team demonstrates shoulder and elbow joint movement. Team demonstrates suitable range of motion for end effector. Team demonstrates suitable locations for piston mount points.

Mount points do not exceed syringe extension/retraction limits. Mount points allow for syringe to rotate arm.

Scale Model Drawing Score: /5

Scale model matches “CAD” model.

Drawing completed with care and attention to detail.

Student uses straightedge, pencil and eraser.

Drawing shows key measurements.

Pivot points

Syringe mount points

Robot Arm Quiz Score: /16

Robot Arm Construction Score: /10

Parts fit snugly

Appropriate use of fasteners and adhesives Tubing secured and tidy

Overall appearance of final product

Robot Arm Performance Score: /10

Arm can pick up playing piece.

Arm has sufficient range of movement to pick up pieces anywhere on playing field. Arm can successfully deposit playing pieces in receptacle or goal location.

Arm has reasonable degree of control.

Arm demonstrates reliability and robustness.

Robot Arm Competition Score: /10

Criteria based upon the challenge as set by the teacher

Total score: /56

**Electronics and Robotics Robot Arm Challenge**

##### Robot Arm Design (1 square = 1 cm Name: Partner’s Name: Block:

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Robot base must be behind this line Playing field—robot must be able to reach each end and lift above the grey line.