

# Educational Innovations<sup>INC</sup><sup>®</sup>

## SC-300

### Pressure Pullers

#### Introduction

Pressure Pullers provide a memorable demonstration of the power of atmospheric pressure, and the effect of balanced and unbalanced forces in a system. More significantly, perhaps, Pressure Pullers can provide the basis for a true-to-life critical thinking exercise. In order to complete a design challenge, students must decide what data they require to solve the problem, and then how to best determine that information.

#### Correlation with Next Generation Science Standards

##### Third Grade

**3-PS2-1. Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.** [Clarification Statement: Examples could include: an unbalanced force on one side of a ball can make it start moving; and, balanced forces pushing on a box from both sides will not produce any motion at all.] [Assessment Boundary: Assessment is limited to one variable at a time: number, size, or direction of forces. Assessment does not include quantitative force size, only qualitative and relative. Assessment is limited to gravity being addressed as a force that pulls objects down.]

##### Middle School

**MS-PS2-2. Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.** [Clarification Statement: Emphasis is on balanced (Newton's First Law) and unbalanced forces in a system, qualitative comparisons of forces, mass and changes in motion (Newton's Second Law), frame of reference, and specification of units.] [Assessment Boundary: Assessment is limited to forces and changes in motion in one-dimension in an inertial reference frame, and to change in one variable at a time. Assessment does not include the use of trigonometry.]

**MS-ESS2-5. Collect data to provide evidence for how the motions and complex interactions of air masses results in changes in weather conditions.** [Clarification Statement: Emphasis is on how air masses flow from regions of high pressure to low pressure, causing weather (defined by temperature, pressure, humidity, precipitation, and wind) at a fixed location to change over time, and how sudden changes in weather can result when different air masses collide.]

**MS-ETS1-2.** Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

##### High School

**HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.** [Clarification Statement: Examples of data could include tables or graphs of position or velocity as a function of time for objects subject to a net unbalanced force, such as a falling object, an object rolling down a ramp, or a moving object being pulled by a constant force.] [Assessment Boundary: Assessment is limited to one-dimensional motion and to macroscopic objects moving at non-relativistic speeds.]



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**HS-PS2-2. Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.** [Clarification Statement: Emphasis is on the quantitative conservation of momentum in interactions and the qualitative meaning of this principle.] [Assessment Boundary: Assessment is limited to systems of two macroscopic bodies moving in one dimension.]

**HS-ETS1-2.** Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

**HS-ETS1-3.** Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.

### Background Information

The phenomenon we call “suction” has something in common with that other familiar phenomenon “centrifugal force”; neither one actually exists. The sticking power of a suction cup is actually the result of unbalanced forces.

Suction cups are not uncommon in nature; for example, octopi and other cephalopods use the cups on their tentacles to grasp prey. Hippocrates, the 3<sup>rd</sup> century BC physician, is reputed to have invented “cupping”, a procedure by which devices originally made from gourds were used to suck “bad blood” out of ailing individuals. Cupping with glass contraptions was a mainstay of medicine well into the 1800s. The first United States patent for a non-medicinal suction device was issued to T.C. Roche in 1866 for his *Photographic Developer Dipping Stick*. This was followed in 1868 by Orwell Needham’s *Atmospheric Knob*, a device to open drawers. We have all observed suction cups employed to attach items to windows, or applied to car top carriers to keep them in place. Suction cups are extremely important in modern robotic manufacturing; suction cups lift and move panels and other components from one section of an assembly line to another. Video clips of automated assembly lines are readily available online.

The source of a suction cup’s sticking power is atmospheric pressure, the force per unit area exerted on a surface by the weight of air above that surface. One standard atmosphere (atm) equals  $1.01325 \times 10^5$  pascals or 14.69595 pounds per square inch. The units one chooses depends on the application; for the purposes of this discussion pressure will be given in the SI unit pascals (Pa).

$$1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg/ms}^2 \quad 1 \text{ Newton (N)} = 1 \text{ kg m/ s}^2$$

The actual atmospheric pressure we experience depends on a number of factors including altitude and temperature.

When we push on a suction cup, flattening it against a smooth surface, the air molecules under the cup are forced out. This results in a vacuum under the cup, i.e. nearly zero air pressure under the cup. The difference in air pressure, lower under the cup, higher outside the cup, causes the cup to be pushed securely against the surface. It will stay there unless air molecules seep under the rim of the cup, releasing the vacuum. The loud “pop” you hear when you pull a suction cup off of a surface is the sound of the air molecules rushing in to fill the vacuum. Vacuum lines remove some, but not necessarily all, of the air out from underneath the cups on manufacturing assembly lines; as long as the pressure contained under the cup is less than that outside, the cup will grip the surface. Suction cups will lift an object as long as the force applied by the weight of that object does not exceed the force supplied by the pressure differential holding the cup against the object.

The ability of the cup's rim to form an airtight seal against a surface determines how long it will maintain its grip. Natural rubber was used in early devices. Today vinyl (PVC) and neoprene rubber are typically employed for everyday applications. Nitrile, silicone, fluoroelastomers, polyurethane, and natural rubber are commonly used in industrial settings. The choice of material depends on the surface characteristics of items to be picked up, temperature, resistance to specific chemicals, anti-static properties, and/or the potentially delicate nature of the materials to be gripped.

The force holding a suction cup against a surface can be represented by the following formula

$$F = (\Delta P \times A)$$

where F is the force holding the cup against the surface,  $\Delta P$  is the difference in the pressures inside and outside the cup, and A is the effective suction area, i.e. the area covered by the suction cup. If a vacuum, zero air pressure, exists under the suction cup then  $\Delta P$  is the same as the atmospheric pressure. If the effective suction area remains constant, then force is directly proportional to the difference in pressure

Engineers designing automated equipment for assembly lines use a slightly different formula

$$F = (\Delta P \times A) / (c \times S)$$

where F is the weight of the item to be lifted,  $\Delta P$  is the difference in pressure between inside and outside the cup, A is the effective suction area, c is the number of suction cups employed, and S is a safety factor, usually 2, to make sure that the system supplies more than enough lifting power.

The friction between the cup and the surface is an important consideration if one is using suction cups to lift or hold an object in a direction perpendicular to the force holding the cups against the surface. In this instance

$$F = (\Delta P \times A \times \mu)$$

where  $\mu$  is the *coefficient of friction*, a dimensionless value. Too little friction and the suction cup with its load may slide and shift. Low coefficient of friction values indicate surfaces with little friction; larger values indicate more friction. Coefficient of friction values for some typical surfaces are:

Surface	Coefficient of Friction ( $\mu$ )
Oily	0.1
Dry glass, stone or plastic	0.2-0.4
Wood and metal	0.5
Dry sandpaper	1.1

The Pressure Pullers rely on a different strategy to reduce the air pressure between two pullers, or underneath a single puller touching a smooth surface. When the two handles of the puller(s) are brought together, the volume of gas trapped by the puller(s) increases. No gas has been expelled so a vacuum has not been produced. To calculate the force pushing two pullers together, or pushing a single puller against a surface, one still has to calculate  $\Delta P$ , the difference between the pressure of the gas trapped between two pullers or under a single puller and the ambient air pressure outside. This can be accomplished by employing the Ideal Gas Law, which defines the relationships between the pressure of a gas and its volume, temperature, and quantity.

$$PV=nRT \quad \text{or} \quad P= nRT/ V \quad \text{or} \quad (\text{if } n \text{ and } T \text{ are constant}) \quad P \propto 1/V$$

where (in SI units):

P is pressure in pascals (Pa)

V is volume in cubic meters ( $m^3$ )

n is the number of moles of the gas (mol)

R is the ideal gas constant = 8.314 joules/kelvins x moles (J/Kmol)

T is the temperature in kelvins (K)

If temperature and quantity of gas remain constant then any change in pressure is solely due to change in volume.

Using Pressure Pullers to demonstrate the force exerted by atmospheric pressure mimics the classic Magdeburg Hemispheres demonstration. The experiment was first performed in 1657 at Magdeburg, Germany by engineer and diplomat Otto von Guericke. The space enclosed by two 1.2 ft in diameter bronze hemispheres was evacuated. Two teams of eight horses failed to pull the halves apart. Smaller versions of the Magdeburg Hemispheres remain a mainstay in the physics classroom.

**Materials:**

One or more sets of *Pressure Pullers SC-300*

Wooden rulers or wooden paint stirring sticks

Sheets of paper ~ 8.5 x 11 inches

Small suction cup or plunger (“plumber’s helper”)

For middle school or high school, collect materials and supplies that the students might use to calculate the force pushing the pressure pullers together by determining the change in volume and thus  $\Delta P$ . Some items may be found in your school’s fabrications lab or woodshop, or do-it-yourself minded parents may be able to lend them. The list might include, but is not limited to:

Fine sand

Salt

Spatulas or other straight edged items

Graduated cylinders

Containers large enough to submerge a Pressure Puller within

Assorted cups and containers for pouring and containing water, salt, sand etc.

Balance

Rulers (both metric and customary)

Contour or profile gauges (used in wood and metal working to determine cross section profiles)

Graph paper (available for free online in metric and customary grids)

Scissors

Micrometers

Fishing line, string, and/or fine wire

Pencils

Calculators

Assorted weights

Spring scales

Atlas or internet access (high school)

## Lesson

### Introduction: (all grade levels)

The source of a suction cup's sticking power is atmospheric pressure, the force per unit area exerted on a surface by the weight of air above that surface. The effect of that air pressure can be simply demonstrated using a piece of regular paper and a wooden ruler or paint stick. Lay the ruler on a table so that one third of the ruler projects past the edge of the table. Place the piece of paper over the ruler. The paper should be centered lengthwise on the ruler and not extend past the table's edge. Strike the unsupported end of the ruler sharply with your fist. The downward force exerted by air pressure, approximately 14 pounds per square inch, exceeds the upward force exerted by the ruler so the paper does not fly off of the table as one might expect.

Push the small suction cup or plunger against a smooth surface. Why does it stick to the surface? When we push on a suction cup, flattening it against a smooth surface, the air molecules under the cup are forced out. This results in a vacuum under the cup, i.e. nearly zero air pressure under the cup. The difference in air pressure, lower under the cup, higher outside the cup, causes the cup to be pushed securely against the surface. It will stay there unless air molecules seep under the rim of the cup, releasing the vacuum. The loud "pop" you hear when you pull a suction cup off of a surface is the sound of the air molecules rushing in to fill the vacuum. Vacuum lines suck some of the air out from underneath the cups on manufacturing assembly lines; as long as the pressure inside the cup is less than that outside the cup will grip the surface. (You may want to show a video clip of an automated assembly line at this point.) Suction cups will lift an object as long as the force applied by weight of that object does not exceed the force supplied by the pressure differential holding the cup against the object.

**Following the instructions and safety guidelines that come with the Pressure Pullers**, invite pairs of students to attempt to separate the joined devices. Why do the two pullers stick together? Explain that the pressure of the air trapped between the joined pullers is less than that of the air pressure outside so they are forced together. How large is the force pushing them? Introduce the formula

$$F = (\Delta P \times A)$$

where  $\Delta P$  is the difference in pressure between inside and outside the pullers. As a class, calculate force for several values of  $\Delta P$ . For simplicity's sake you may want to use customary rather than SI units. The following illustration uses the atmospheric pressure at sea level; you should substitute the actual atmospheric pressure for your location. Even very small towns and their vital statistics are often found on *Wikipedia*. Help your students determine the atmospheric pressure using the chart on the formula sheet.

Area (in <sup>2</sup> )*	Outside Pressure (psi)	Inside Pressure (psi)	$\Delta P$ (psi)	Force (pounds)
16.8	14.7	0	14.7	247
16.8	14.7	5	9.7	163
16.8	14.7	10	4.7	79
16.8	14.7	14.7	0	0

\* based on a Pressure Puller with a diameter of 4.625 inches. Your device may be slightly different.

It is unlikely that you have access to equipment that would allow you to safely measure the value of the force pushing the cups together. You might, however, ask the class for ideas on how one might measure that force.

**Middle School Exploration:** This exploration assumes that the students have not been introduced to the Ideal Gas Law. Explain that the pressure exerted by a given quantity of gas is inversely proportional to its volume as long as temperature stays the same.

$$P \propto 1/V \text{ or } P_{\text{initial}} \times V_{\text{initial}} = P_{\text{final}} \times V_{\text{final}} \text{ or } P_{\text{initial}} \times (V_{\text{initial}} / V_{\text{final}}) = P_{\text{final}}$$

As a class, calculate some hypothetical values for  $\Delta P$  as volume increases. If the original pressure is 20 psi and the initial volume is 10 cubic inches then

Volume (in <sup>3</sup> )	Pressure (psi)	$\Delta P$ (psi)
10	20	0
20	10	10
40	5	15
50	4	16
100	2	18
200	1	19

Challenge teams of students to calculate the force holding the pressure pullers together given the information on the formula sheet and the supplies provided. After the allotted time period, as a class compare teams' strategies and results. Did teams correctly conclude that they had to determine the ratio of initial to final volumes of the trapped air, not the actual volumes in cubic inches? Did the students realize that the units employed to measure volume were unimportant as long as they were consistent? (If not, revisit the equation  $P_{\text{initial}} \times (V_{\text{initial}} / V_{\text{final}}) = P_{\text{final}}$ . Insert hypothetical values including the units to show how the units of volume always cancel out.) Possible solutions could include comparing the weights or volumes of sand, salt, or water contained in the open and closed cups. Students might prepare representations of the cross-sections of the cups on paper, determined by direct measurement or use of a contour gauge; then compare these by weight or area. Each method has strengths and weaknesses. In the opinion of the class, which produced the most accurate values for the initial versus final volume ratio and why?

### High School Exploration:

Continue the introductory discussion by explaining that the force formula introduced already is only valid in the situation when all forces acting upon a suction cup act parallel to one another. In the case of a suction cup holding a sign onto a window, or a robotic arm lifting a panel from a horizontal to a vertical position, friction between the cup and the surface must be considered. Insufficient friction between cup and surface allows the cup to shift and slide. The applicable force equation now becomes

$$F = (\Delta P \times A \times \mu)$$

where  $\mu$  is the *coefficient of friction*, a dimensionless value.

Briefly review the Ideal Gas Law if your students are already familiar with it. If not, then briefly introduce it in the form

$$PV=nRT$$

Explain the variables using SI units, P is pressure in pascals, V is volume in cubic meters, n is the number of moles of the gas, R is the ideal gas constant (8.314 joules/kelvins x moles) and T is the temperature in kelvins. As a class, mathematically manipulate the equation to this form

$$P = nRT / V$$

and discuss the effect on pressure due to changes in the other variables. For example, “What happens to pressure if volume and the amount of gas remain the same, but temperature increases?” When your students seem comfortable with the concepts presented, pose the following scenario:

*You are part of a six-man crew rebuilding a storm-damaged school in Fairplay, Colorado\*. The large windows of the school were broken by hail and flying debris. You will have to remove any broken glass left in the window frames, and replace it with plain panes of window glass. The windows measure eight feet by six feet, and the glass is one-quarter inch thick. Your team needs to come up with a way to safely handle this glass. The new glass was delivered to the site in a crate, which now lies flat on the ground. Besides basic hand tools, ropes, and ladders, your crew has access to several sets of Pressure Pullers found in the science classroom.*

\*The location and details of the scenario are up to you, for example, if many of your students participate in church-sponsored mission trips to a particular location you might choose that, or you may want to select a location in your own state or region. Be sure to choose a location whose altitude is easy to obtain online or is given on available printed maps. Even very small towns and their vital statistics are often found on *Wikipedia*. Avoid choosing a locale close to sea level since failure of the students to consider altitude would then be of little consequence.

Supply teams of students with the formula sheet and access to the supplies. The formula sheet assumes that the students are comfortable with basic algebra and can derive the relationship  $P_{\text{initial}} \times (V_{\text{initial}} / V_{\text{final}}) = P_{\text{final}}$  on their own. After the allotted time, invite the teams to present their solutions to the problem. Which teams succeeded in considering all relevant information such as site elevation, coefficient of friction, and safety concerns? Did teams correctly conclude that they had to determine the ratio of initial to final volumes of the trapped air, not the actual volumes in cubic meters? Did the students realize that the units employed to measure volume were unimportant as long as they were consistent? Possible solutions could include comparing the weights or volumes of sand, salt, or water contained in the open and closed cups. Students might prepare representations of the cross-sections of the cups on paper, determined by direct measurement or use of a contour gauge; then compare these by weight or area. Each method has strengths and weaknesses. In the opinion of the class, which produced the most accurate values for the initial versus final volume ratio and why?