SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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SCOPE, SEQUENCE, and COORDINATION

Student Materials

Learning Sequence Item:

925

Gas Pressure, Volume, and Temperature

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Contents

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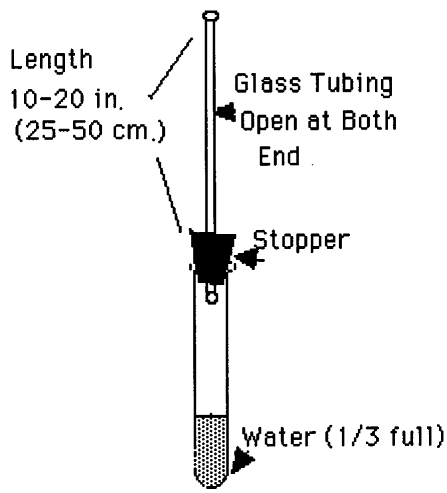
Student Sheet

Science as Inquiry

The Mysterious Effects of Hands

How do temperature changes affect a confined volume of liquid water and air?

Assemble a device like the one shown below. Predict what will happen when you grasp the bottom end of the test tube, turn it upside down, and hold it for a minute or two. Try it. What happens?



Suppose that you were to cool your hands with ice or warm your hands by rubbing them rapidly together and then to repeat the experiment. What would you predict? Test your prediction of what you would observe in a repetition of the experiment. Explain in terms of particles what happens.

1. What theory or model did you base your prediction on?

2. How did it relate to your prediction? Were they different in any way?

3. Explain what came from your hand to produce what you observed?

4. Which substance had the greater effect in producing what you observed—the air or the water inside the test tube? Use a model to explain why.

5. Design an experiment that will test your hypothesis about which substance is the major source of the observed changes—the air or the water.

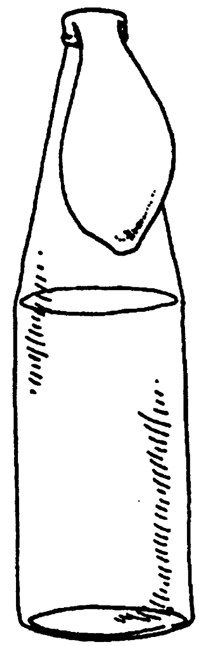
Student Sheet

Science as Inquiry

Balloon and Bottle

Place a glass soda bottle or flask in the freezer for about 15 minutes. Remove it and immediately place a flattened balloon (so there is initially no air inside) over the mouth of the bottle. Observe what happens to the balloon.

Now place the balloon on the bottle back in the freezer, wait 15 minutes and look at it again. Take it out of the freezer and watch what happens.



1. Describe your observations.

2. Why would we want a balloon large enough not to begin to inflate?

3. Explain your observations in terms of heat and a particle model for gases.

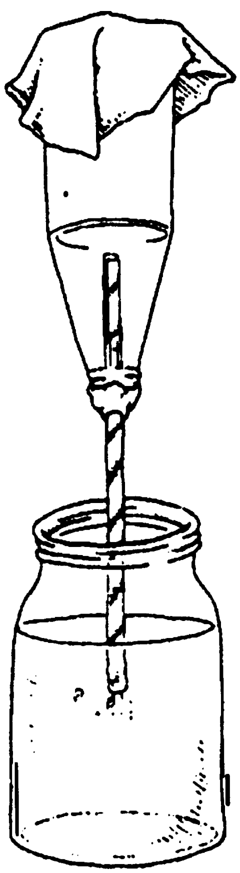
4. When you returned the balloon on the bottle to the freezer, explain your observations in terms of a particle model.

Student Sheet

Science as Inquiry

Fountain Machine

Create an apparatus like the one below. Secure a straw with clay in a bottle and turn it upside down into a large jar of water. Food coloring can make things more interesting, so add some to the water. Now for an experiment. First place a hot, wet rag on the bottle and observe what happens. Then quickly place a very cold, wet rag on the bottle and observe what happens.



1. Describe the effect of the hot, wet rag. Do the volume and pressure of the confined gas change between the start and the end of this experiment? What aspect of the gas has changed? How can you explain these results in terms of a particle model of gases?

2. Describe the effect of the cold, wet rag. How have the volume and pressure changed in this situation? How can you explain these results in terms of a particle model of gases?

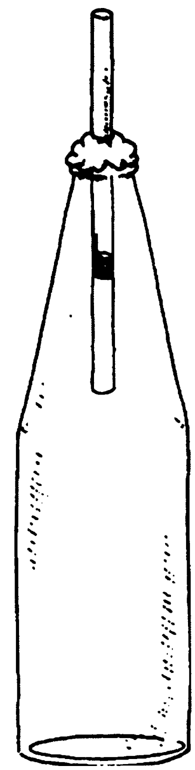
3. Explain how your hand can produce what you observed.

Student Sheet

Science as Inquiry

A Reacting Bottle

Using a straw, glass soda bottle, and clay, construct the device that follows. To trap a small column of colored water in the straw, dip one end of the straw into colored water to a depth of about 2 cm, and then cover one end of the straw with your finger. Continue holding your finger over the end of the straw and place the other end in the bottle, sealing the straw in place with the clay. Cover the bottom of the bottle with your hands and observe what happens.



1. Describe what happens to the column of water in the straw when you place your hands on the bottom of the bottle.

2. What happens to the pressure during this experiment? How does the pressure of the confined gas at the beginning of the experiment compare with that at the end? How do you know? How is the volume occupied by the confined gas different?

3. Explain your observations in terms of a particle model for gases.

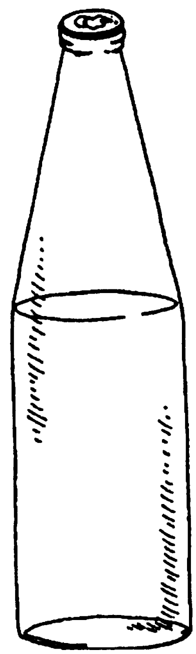
4. Explain how something from your hand can cause what you observe in terms of heat and a particle model for gases.

Student Sheet

Science as Inquiry

Coin Tricks

Cool a soda bottle for at least 15 minutes by placing it in a freezer. After it has cooled, remove it and place a wet dime on the mouth of the bottle. (Drip some more water along the edge of the dime to seal it.) Stand back and watch.



1. Describe what you observe.

2. Explain what you observed in terms of heat and a particle model of gases.

3. Try other coins. What happens?

4. If you ride in an airplane, the small package containing pretzels and peanuts appears swollen, and sometimes ink will come out of roller ball pens (but not always). How can you explain these observations?

5. What causes your ears to “pop” when you go up a mountain road or ride in an elevator?

*6. When you remove the bottle from the freezer and place a dime on the mouth, hold your hands around the bottle. What do you observe?

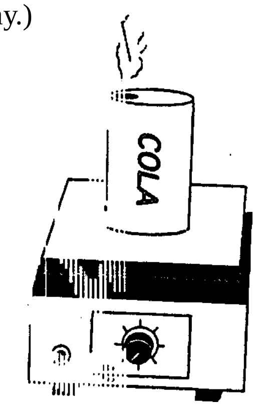
*optional

Student Sheet

Science as Inquiry

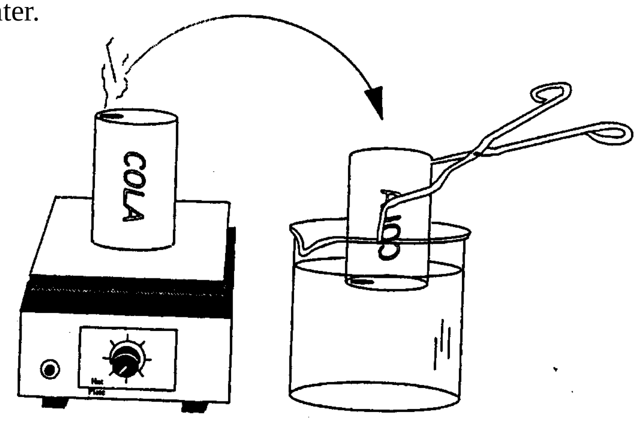
The Hot Can Trick

Pour water into an empty aluminum soft drink can to a depth of about 1 cm. Then place this can with the water on a hot plate until the water begins to boil and you can see steam coming out the opening. (Caution: do not let all the water boil away.)



As soon as the water begins to boil and you can see steam coming out, use tongs to remove the can from the hot plate and place the can in an upright position on the table top. What do you observe?

Repeat the process. This time after heating the can containing water, use tongs to invert the can and submerge it into the bucket of cold water.



1. Describe what happens in each case.

2. Explain the phenomenon in the latter case in terms of changes in pressure, gas volume, or number of particles of gas present.

3. Using a particle model for gases, explain how this phenomenon occurs.

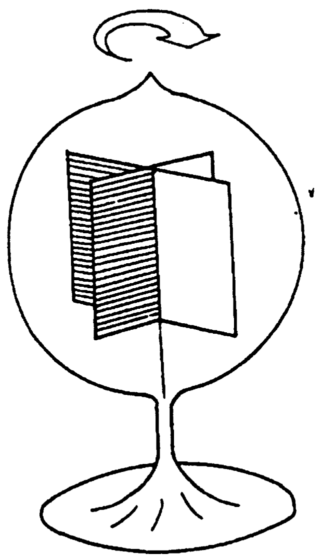
4. Why doesn't the water in the bucket just enter the can instead of what you observe? Explain this in terms of Newton's laws of motion.

Student Sheet

Science as Inquiry

Radiometer

Place the radiometer in a bright light and observe what happens. Try different light sources of different intensities. Cover the radiometer with a black cloth and look under the cover. What are the vanes doing?



1. Describe the motion of the radiometer vanes under the various conditions.

2. In terms of a particulate model of gases, explain what you have observed.

3. Light actually does exert a pressure. It is called radiation pressure. As a result, which way should the vanes turn from the pressure of light? How do you know that this pressure is much lower than the pressure produced by heated gas particles?

4. Using a particulate model for gases, explain why the radiometer would not work if the vanes were removed from the enclosure and the experiment repeated using air in the room.

*5. Set up an arrangement where sunlight is passed through a prism. Place a radiometer in that region just outside of the red end of the spectrum, where no visible light strikes the radiometer vanes. What do you observe? Explain this observation.

*optional

Science as Inquiry

Descartes' Rules of Inquiry

I. That in order to seek truth, it is necessary once in the course of our life to doubt, as far as possible, of all things.

As we were at one time children, and as we formed various judgments regarding the objects presented to our senses, when as yet we had not the entire use of our reason, numerous prejudices stand in the way of our arriving at the knowledge of truth; and of these it seems impossible for us to rid ourselves, unless we undertake, once in our lifetime, to doubt of all those thing in which we may discover even the smallest suspicion of uncertainty.

II. That we ought also to consider as false all that is doubtful.

Moreover, it will be useful likewise to esteem as false the things of which we shall be able to doubt, that we may with greater clearness discover what possesses most certainty and is the easiest to know.

III. That we ought not meanwhile to make use of doubt in the conduct of life.

In the meantime, it is to be observed that we are to avail ourselves of this general doubt only while engaged in the contemplation of truth. For, as far as concerns the conduct of life, we are very frequently obliged to follow opinions merely probable, or even sometimes, though of two courses of action we may not perceive more probably in the one than in the other, to choose one or other, seeing the opportunity of acting would not unfrequently pass away before we could free ourselves from our doubts.

VII. That we cannot doubt of our existence, while we doubt, and that this is the first knowledge we acquire when we philosophise in order.

While we thus reject all of which we can entertain the smalles doubt, and even imagine that it is false, we easily indeed suppose that there is neither God, nor sky, nor bodies, and that we ourselves even have neither hands nor feet, nor finally, a body; but we cannot in the same way suppose that we are not while we doubt of the truth of these things; for there is a repugnance in conceiving that what thinks does not exist at the very time when it thinks. Accordingly, the knowledge, *I think, therefore I am*, is the first and most certain that occurs to one who philosophises orderly.

Excerpts from Descartes, R., *A Discourse on Method*, pp. 165, 167, 181, 182. London, 1949. From Guerlac, H. (Ed.), *Selected Readings in the History of Science, Vol. II.* Ithaca: Henry Guerlac, 1953.

And this is the best mode of discovering the nature of the mind, and its distinctness from the body: for examining what we are, while supposing, as we now do, that there is nothing really existing apart from our though, we clearly perceive that neither extension, nor figure, nor local motion, nor anything similar that can be attributed to body, pertains to our nature, and nothing save though alone; and, consequently, that the notion we have of our minds precedes that of any corporeal thing, and is more certain, seeing we still doubt whether there is any body in existence, while we already perceive that we think.

XLIII. That we shall never err if we give our assent only to what we clearly and distinctly perceive.

But it is certain we will never admit falsity for truth, so long as we judge only of that which we clearly and distinctly perceive; because, as God is no deceiver, the faculty of knowledge which he has given us cannot be fallacious, nor, for the same reason, the faculty of will, when we do not extend it beyond the objects we clearly know. And even although this truth could not be established by reasoning, the minds of all have been so impressed by nature as spontaneously to assent to whatever is clearly perceived, and to experience an impossibility to doubt of its truth.

XLV. What constitutes clear and distinct perception.

There are indeed a great many persons who, through their whole lifetime, never perceive anything in a way necessary for judging of it properly; for the knowledge upon which we can establish a certain and indubitable judgment must be not only clear, but also distinct. I call that clear which is present and manifest to the mind giving attention to it, just as we are said clearly to see objects when, being present to the eye looking on, they stimulate it with such sufficient force, and it is disposed to regard them; but the distinct is that which is so precise and different from all other objects as to comprehend in itself only what is clear.

Science as Inquiry

Antoine Arnauld on Method in Scientific Investigation

Of the Two Kinds of Method—Analysis and Synthesis.
Example of Analysis.

Method may be called, in general, the art of disposing well a series of many thoughts, either for the discovering truth when we are ignorant of it, or for proving it to others when it is already known.

Thus there are two kinds of method, one for discovering truth, which is called analysis, or the method of resolution, and which may also be termed the method of invention; and the other for explaining it to others when we have found it, which is called synthesis, or the method of composition, and which may be also called the method of doctrine. We do not commonly treat of the entire body of a science by analysis, but employ it only to resolve some question.

All questions are either of words or things.

By questions of words we here mean, not those in which we inquire into words, but those in which, through the words, we inquire into things, as those in which we engage to find the sense of an enigma, or to explain, from obscure or ambiguous words, what is the true meaning of an author.

Questions of things may be reduced to four principal kinds.

(1). The first is, when we seek causes through effects. We know, for example, the different effects of the loadstone -- we inquire into the cause of these; we know the different effects which are commonly attributed to the abhorrence of a vacuum -- we inquire whether that is the true cause, and we have found that it is not; we know the ebb and flow of the sea -- we ask what can be the cause of a motion so great and so regular.

(2). The second is, when we seek effects through causes. It was always, for example, known that wind and water possessed great power over the movements of bodies; but the ancients, not having sufficiently examined what effects might flow from these causes, did not apply them as they have since been applied, by means of mills, to a great number of purposes very useful to society, which wonderfully lessen the labour of men, the appropriate result of true

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Excerpt from Antoine Arnauld, *The Port-Royal Logic*, translated by Thomas S. Baynes, pp. 308–3l5. London, 1854. From Guerlac, H. (Ed.), *Selected Readings in the History of Science, Vol. II*. Ithaca: Henry Guerlac, 1953.

physics: so that we may say that the first kind of questions in which we seek causes through effects constitutes the speculative part of physics; and the second kind, in which we seek effects by causes, the practical.

(3). The third kind of questions is, when through the parts we seek the whole: as when, having one number and another which is to be subtracted from it, we seek what remains; or when, having a number, we seek what such a part of it will be.

(4). The fourth is, when, having the whole and some part, we seek another part; as when, having one number and another which is to be subtracted from it, we seek what remains; or when, having a number, we seek what such a part of it will be.

But it must be remarked that, in order to extend further the two last kinds of questions, and in order that we may comprehend what cannot be properly brought under the two first, it is necessary to take the work part in its most general signification for all that a thing comprises -- its modes, its extremities, its accidents, its properties, and, in general, all its attributes, so that, for example, we shall seek the whole by its parts when we seek to find the area of a triangle from its height and base, and we shall, on the contrary, seek a part by the whole, and another part when we seek to find the side of a rectangle from knowing its area and one of its sides.

Science and Technology

Gas Laws and Scuba Diving

What happens if scuba divers hold their breath while making emergency ascents to the surface from depths of 30 meters or more?

Why shouldn't divers fly or take hot showers soon after deep dives?

Is contaminated compressed air more dangerous to the diver at the surface or at a depth of 30 meters?

Pressure

We live in a sea of air. Since air molecules constantly bombard us, we always experience a pressure of about 760 mm of mercury (or one atmosphere) at the Earth's surface. This is equivalent to 14.7 lb on each square inch of surface. If we zoom to the top of a tall building in an elevator we are no longer as deep in the sea of air as at ground level and, therefore, the pressure around us becomes lower. Ears are usually the first to respond to this change. Wiggling your jaw or swallowing sometimes corrects any discomfort or strange sensations in the ear by opening the tubes connecting the inner ear and throat, allowing the inside pressure to equalize with the outside. A reverse pressure effect is obvious during a rapid airplane descent or during a drive from a mountain pass to the valley floor below.

Divers are surrounded by water molecules in constant motion that exert pressure on their bodies. When you dive to the bottom of the deep end of a swimming pool, you feel a great deal of pressure exerted by the water. Because water is much more dense than air, pressure changes are much greater for a given change in depth in water than for the same depth change in air. For example, water exerts over 100 lb of force on the surface of a onegallon metal can pushed just one foot below the water surface. If the metal can contains air, it would not have to be pushed very far below the water surface before the can would start to collapse due to water pressure. Can divers be crushed by the pressure of water in the same manner as the can if they go too deep? After all, for every 10 meters (about 33 ft) in depth, divers experience an additional pressure of one atmosphere.

Pressure-Volume Effects

The changes in pressure experienced by divers are most noticeable on body cavities that contain air, such as the lungs, the middle ear, and the sinus cavities. Boyle's law describes how these gas volumes respond to changes in pressure. For a constant

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amount of gas at a constant temperature, Boyle's law states: The volume of a gas sample varies inversely with its pressure.

If divers descend without scuba gear, the amount of gas contained in their body cavities is constant and the volume of these cavities decreases as the surrounding water pressure becomes greater. However, this crushing effect or squeeze is not experienced by divers using scuba gear because the regulator on their air tanks delivers air at the same pressure as the surroundings.

This means that the air in divers' lungs is at a pressure equivalent to four atmospheres at a depth of 30 meters. If divers must make emergency ascents from this depth they must remember to breathe out regularly as they return to the surface. If they don't, the pressure of the air in their lungs will cause their lungs to expand. The extreme distortion of the lungs can cause some of the alveoli (the small sacks in the lungs) to rupture. If this happens, air can enter the bloodstream and cause a blockage that may lead to a variety of problems including loss of consciousness, brain damage, and heart attacks.

The rate of lung expansion increases dramatically as the divers ascend. According to Boyle's law the volume of a flexible gas container will approximately double when the surrounding pressure decreases to onehalf its original value. If the divers ascend while holding their breath from a depth of 30 meters (where the pressure is about four atmospheres), their lungs would have to double in volume when they are at 10 meters (where the pressure is about two atmospheres) to equalize the pressure of the water. Of course, this does not happen because the lungs are contained by the rib cage and the muscle system, and the divers are forced to breathe out.

Pressure-Solubility Effects

Not only does the pressure affect the volume of trapped gases, it also influences the solubility of gases in liquids. Divers must be aware of the principles described by Henry's law, which states: The amount of gas that will dissolve in a liquid at a given temperature varies directly with the pressure above the liquid.

Henry's law is useful, therefore, in explaining why during a dive any gases entering the lungs are absorbed to a greater extent in the diver's blood. Although this increased solubility of gases in the blood may create no problems during the dive, the diver's body experiences an effect similar to opening a can of soda when the diver ascends rapidly to the surface. This effect can be accentuated if the diver takes a high-altitude plane flight soon after a dive. In particular, nitrogen gas bubbles that form in the blood and other body fiuids can produce a multitude of problems.

These problems depend on the location of the gas bubbles, the size and number formed, and the way they are transported by the diver's circulatory system. The bubbles can cause localized pain, itching of the skin, breathing difficulty, and can lead to paralysis, unconsciousw ness, and death.

To minimize gas bubble formation (decompression sickness or "the bends"), divers carefully follow tables prepared by the U.S. Navy that describe the time limits for dives at various depths greater than 10 meters. The essence of the process described by the tables involves ascending to a certain point and then remaining at that depth for a time period to allow some of the dissolved nitrogen to escape.

Depending on the initial depth, there may be several of these "hold points" during the ascent. If divers experience decompression sickness, the only mode of treatment is to put them in a decompression chamber, increase the pressure surrounding their bodies, and slowly decompress them back to one atmosphere of pressure.

The increased solubility of nitrogen gas at higher pressures may also have a narcotic effect. Nitrogen narcosis or "rapture of the deep" generally does not occur until divers reach depths of about 30 meters. The symptoms are similar in nature to intoxication by alcohol. The divers have a feeling of happiness, overconfidence, tingling or numbness in their arms or legs, and memory impairment. This narcotic effect of nitrogen is just one of the many reasons divers should never work alone underwater.

Another application of Henry's law involves contaminants such as carbon monoxide (CO) that might be present in the compressed air used by divers. Of course, every attempt is made to ensure the purity of the air in scuba tanks, but if a contaminant is present to the extent of just 1%, its presence is more serious during a dive. For example, at a depth of 40 meters, the pressure is equivalent to about five atmospheres.

Because the regulator divers air at the same pressure as the surroundings, each breath contains five times more contaminant molecules than each breath from that same tank at the surface. This is equivalent to breathing air containing 5% of that contaminant at the surface.

As the pressure increases during a dive, the solubility of oxygen in the blood also increases proportionately. This means that the effects of poisoning by a trace of carbon monoxide cf)ntaminant may go unnoticed during a dive since sufficient oxygen is available for normal cellular respiration. However, as divers surface, the solubility of oxygen decreases in their bloodstreams.

Because the carbon monoxide-hemoglobin combination is so stable, there may not be a corresponding decrease of carbon monoxide in the blood. If the divers do not have enough hemoglobin available to bond with oxygen cell respiration, they may lapse into unconsciousness.

Temperature-Solubility Effects

Gas solubility is also affected by changes in temperature. Have you ever noticed that as a cold glass of water warms to room temperature, air bubbles form, clinging to the inside of the glass surface? These bubbles are composed of air that was dissolved in the cooler water. Can you use this information to explain why it is dangerous for a diver to take a hot shower after a deep dive?

A scuba diver with a good basic understanding of gas behavior will better appreciate what is happening during a dive. If you are a scuba diver, this understanding could save your life!

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History and Nature
of Science

Galileo (1564-1642) on the Effect of a Vacuum

SALV [*Salviati (1582-1614), a very wealthy and intelligent man from Florence, Italy, Signore Filippo Salviati, whom Galileo knew and respected (and had been Galileo's student) and wanted to honor by having him serve as one of the persons discussing these scientific matters. Salviati represents Galileo in these Dialogues*]. . . .

I must not now digress [*change my focus*] upon this particular topic

since you are waiting to hear what I think

about the breaking strength of other materials

which, unlike ropes and most woods,

do not show a filamentous [*threads bunched together*] structure.

The coherence [*sticking together*] of these bodies is, in my estimation,

produced by other causes

which may be grouped under two heads.

One is that much-talked-of repugnance [*extreme dislike*]

which nature exhibits towards a vacuum;

but this horror of a vacuum not being sufficient,

it is necessary to introduce another cause

Galileo, *Two New Sciences* (1638), translated by Henry Crew, pp. 11–13, 16–17. Evanston: Northwestern University, 1939. From Guerlac, H. (Ed.) *Selected Readings in the History of Science, Vol. 2.* Ithaca: Henry Guerlac, 1953.

in the form of a gluey or viscous [*like thick oil*] substance

which binds firmly together the component parts of the body.

First I shall speak of the vacuum,

demonstrating by definite experiment

the quality and quantity of its force (virtu).

If you take two highly polished and smooth plates of marble, metal, or glass

and place them face to face,

one will slide over the other with the greatest ease,

showing conclusively that

there is nothing of a viscous nature between them.

But when you attempt to separate them

and keep them at a constant distance apart,

you find the plates exhibit such a repugnance to separation

that the upper one will carry the lower one with it

and keep it lifted indefinitely,

even when the latter [*the lower plate*] is big and heavy.

This experiment shows

the aversion [*dislike, or turning away from because of dislike*] of nature

for empty space,

even during the brief moment

required for the outside air to rush in

and fill up the region between the two plates.

It is also observed

that if two plates are not thoroughly polished,

their contact is imperfect

so that when you attempt to separate them slowly

the only resistance offered

is that of weight;

if, however, the pull be sudden

then the lower plate rises,

but quickly falls back,

having followed the upper plate

only for that very short interval of time

required for the expansion

of the small amount of air

remaining between the plates,

in consequence of their not fitting,

and for the entrance of the surrounding air.

This resistance which is exhibited [*observed*] between the two plates

is doubtless

likewise present between the parts of a solid,

and enters, at least in part

as a concomitant [*goes along with*] cause of their coherence [*sticking together*].

SAGR. [Signore Giovanni Francesco Sagredo (1571-1620), a former pupil of Galileo's, and his closest friend, a competent scientist himself, and whom Galileo wished to honor by using Sagredo's name in these dialogues]

Allow me to interrupt you for a moment, please;

for I want to speak of something which just occurs to me,

namely, when I see how the lower plate follows the upper one

and how rapidly it is lifted,

I feel sure that,

contrary to the opinion of many philosophers [*we would today call these people scientists*],

including perhaps even Aristotle [*a very famous Greek philosopher*] himself,

motion in a vacuum is not instantaneous.

If this were so

the two plates mentioned above

would separate without any resistance whatever,

seeing that the same instant of time

would suffice [*would be needed*] for their separation

and for the surrounding medium [*the air particles*] to rush in

and fill the vacuum between them.

The fact that the lower plate follows the upper one

allows us to infer [*draw a conclusion*],

not only

that motion in a vacuum is not instantaneous,

but also

that, between the two plates,

a vacuum really exists,

at least for a very short time,

sufficient [*enough time*] to allow the surrounding medium

to rush in

and fill the vacuum;

for if there were no vacuum

there would be no need

of any motion in the medium.

One must admit then

that a vacuum is sometimes produced by violent [*great force*] motion (violenza)

or contrary [*against or violating*] to the laws of nature,

(although in my opinion

nothing occurs contrary to nature

except the impossible,

and that never occurs).

But here another difficulty arises.

While experiment convinces me

of the correctness of this conclusion,

my mind is not entirely satisfied

as to the cause

to which this effect

is to be attributed.

For the separation [*moving them apart*] of the plates

precedes [*comes before*] the formation of the vacuum

which is produced as a consequence [*a result*]

of this separation;

and since it appears to me

that, in the order of nature,

the cause [*what makes it happen*]

must precede [*come before*] the effect,

even though it appears to follow in point of time [*come afterward*],

and since every positive effect [*something that happens*]
must have a positive cause [*something makes it happen*],

I do not see how the adhesion [*sticking together*] of two plates

and their resistance to separation--actual facts--[*observed facts*]

can refer to a vacuum as cause [*facts being the cause*]

when this vacuum is yet to follow [*vacuum occurs after what happens, rather than before*].

According to the infallible [*always right*] maxim [*statement of truth*] of the Philosopher [*Aristotle*],

the non-existent [*no vacuum present the before observations*]
can produce no effect [*something can't be caused by nothing*].

SIMP. [Simplicius, who was not a singular real person; instead, Simplicius represented all of those people who accepted Aristotle's "maxims" as ultimate truth and could not seem to question anything. He might have represented the authorities of that time, since Galileo was brought before the inquisition, tried and convicted. He had to recant what he believed was true (otherwise he would have been tortured and burned at the stake.]

Seeing that you accept this axiom of Aristotle, I hardly think you will reject

another excellent and reliable maxim of his,

namely,

Nature undertakes only that

which happens without resistance;

and in this saying [*this maxim*],

it appears to me,

you will find the solution of your difficulty [*a better explanation*].

Since nature abhors [*intensely dislikes*] a vacuum,

she [*nature*] prevents that

from which a vacuum would follow [*which would produce a vacuum*]

as a necessary consequence [*because of this maxim*].

Thus it happens

that nature prevents the separation of the two plates.

SAGR. Thanks to this discussion,

I have learned the cause of a certain effect

which I have long wondered at

and despaired of understanding [*could never figure out*].

I once saw a cistern [*a storage space below ground for rainwater*]

which had been provided with a pump [*a water pump*]

under the mistaken impression

that the water might thus be drawn [*brought up out of the cistern*] with less effort [*than by lowering a bucket into the cistern*] in greater quantity

than by means of the ordinary bucket.

The stock [*main part*] of the pump

carried its sucker [*pump parts that lifted water*] and valve [*kept water once pumped from falling back down*] in the upper part

so that the water was lifted by attraction

and not by push [*pipe went down into the cistern, but pump was above ground*]

as is the case [*when pushing is done by a pump*] with pumps

in which the sucker is placed lower down [*into the cistern*].

This pump [*the pump above ground*] worked perfectly

so long as the water in the cistern

stood above a certain level [*cistern was not too deep*];

but below this level [*water too far below pump*]

the pump failed to work.

When I first noticed this phenomenon [*something that happens in nature*]

I thought the machine was out of order;

but the workman whom I called in to repair it

told me the defect was not in the pump

but in the water

which had fallen too low

to be raised through such a height;

and he added that it was not possible,

either by a pump or by any other machine working on the principle of attraction [*pump to far above water level, lifting by "vacuum."*],

to lift water a hair's breadth [the width of a hair] above eighteen cubits [*about 30 feet; the cubit was an ancient length measure, roughly the distance from your middle finger to your elbow, which is about 18-22 inches, or a little less than two feet*];

whether the pump be large or small

this is the extreme limit [*cannt be more*] of the lift [*of the pump*].

Up to this time

I had been so thoughtless [*had not thought carefully enough*] that,

although I knew a rope or rod [*long circular piece*] of wood, or of iron,

if sufficiently long,

would break by its own weight

when held by the upper end,

it never occurred to me

that the same thing would happen,

only much more easily,

to a column [*the water in the pipe from the bottom of the cistern to the pump above ground*] of water.

And really

is not that thing which is attracted in the pump

a column of water

attached at the upper end

and stretched more and more

until finally a point is reached

where it breaks, like a rope,

on account of its excessive weight?

SALV. That is precisely the way it works;

this fixed elevation of eighteen cubits [*about 30 feet*]

is true for any quantity of water whatever,

be the pump [*the pump pipe itself*] large or small

or even as fine as a straw.

We may therefore say that,

on weighing the water

contained in a tube eighteen cubits long [*30 feet high*],

no matter what the diameter [*width of the pipe*],

we shall obtain

the value of the resistance [*the 'breaking strength in pounds*]

of the vacuum in a cylinder of any solid material

having a bore [*having a hole in it of the same width*] of this same diameter.

History and Nature
of Science

Galileo (1564-1642) on the Effect of a Vacuum

SALV. . . .
I must not now digress upon this particular topic since you are waiting to hear what I think about the breaking strength of other materials which, unlike ropes and most woods, do not show a filamentous structure. The coherence of these bodies is, in my estimation, produced by other causes which may be grouped under two heads. One is that much-talked-of repugnance which nature exhibits towards a vacuum; but this horror of a vacuum not being sufficient, it is necessary to introduce another cause in the form of a gluey or viscous substance which binds firmly together the component part of the body.

First I shall speak of the vacuum, demonstrating by definite experiment the quality and quantity of its force [virtu]. If you take two highly polished and smooth plates of marble, metal, or glass and place them face to face, one will slide over the other with the greatest ease, showing conclusively that there is nothing of a viscous nature between them. But when you attempt to separate them and keep them at a constant distance apart, you find the plates exhibit such a repugnance to separation that the upper one will carry the lower one with it and keep it lifted indefinitely, even when the latter is big and heavy.

This experiment shows the aversion of nature for empty space, even during the brief moment required for the outside air to rush in and fill up the region between the two plates. It is also observed that if two plates are not thoroughly polished, their contact is imperfect so that when you attempt to separate them slowly the only resistance offered is that of weight; if, however, the pull be sudden then the lower plate rises, but quickly falls back, having followed the upper plate only for that very short interval of time required for the expansion of the small amount of air remaining between the plates, in consequence of their not fitting, and for the entrance of the surrounding air. This resistance which is exhibited between the two plates is doubtless likewise present between the parts of a solid, and enters, at least in part as a concomitant cause of their coherence.

SAGR.
Allow me to interrupt you for a moment, please; for I want to speak of something which just occurs to me, namely, when I see how the lower plate follow the upper one and how rapidly it is lifted, I feel sure that, contrary to the opinion of many philosophers, including perhaps even Aristotle himself, motion in a vacuum is not instantaneous. If this were

---

Galileo, *Two New Sciences* (1638), translated by Henry Crew, pp. 11–13, 16–17. Evanston: Northwestern University, 1939. From Guerlac, H. (Ed.) *Selected Readings in the History of Science, Vol. 2.* Ithaca: Henry Guerlac, 1953.

so the two plates mentioned above would separate without any resistance whatever, seeing that the same instant of time would suffice for their separation and for the surrounding medium to rush in and fill the vacuum between them. The fact that the lower plate follows the upper one allows us to infer, not only that motion in a vacuum is not instantaneous, but also that, between the two plates, a vacuum really exists, at least for a very short time, sufficient to allow the surrounding medium to rush in and fill the vacuum; for if there were no vacuum there would be no need of any motion in the medium. One must admit then that a vacuum is sometimes produced by violent motion [violenza] or contrary to the laws of nature, (although in my opinion nothing occurs contrary to nature except the impossible, and that never occurs).

But here another difficulty arises. While experiment convinces me of the correctness of this conclusion, my mind is not entirely satisfied as to the cause to which this effect is to be attributed. For the separation of the plates precedes the formation of the vacuum which is produced as a consequence of this separation; and since it appears to me that, in the order of nature, the cause must precede the effect, even though it appears to follow in point of time, and since every positive effect must have a positive cause, I do not see how the adhesion of two plates and their resistance to separation--actual facts--can refer to a vacuum as cause when this vacuum is yet to follow. According to the infallible maxim of the Philosopher, the non-existent can produce no effect.

SIMP.
Seeing that you accept this axiom of Aristotle, I hardly think you will reject another excellent and reliable maxim of his, namely, Nature undertakes only that which happens without resistance; and in this saying, it appears to me, you will find the solution of your difficulty. Since nature abhors a vacuum, she prevents that from which a vacuum would follow as a necessary consequence. Thus it happens that nature prevents the separation of the two plates.

SAGR.
Thanks to this discussion, I have learned the cause of a certain effect which I have long wondered at and despaired of understanding. I once saw a cistern which had been provided with a pump under the mistaken impression that the water might thus be drawn with less effort in greater quantity than by means of the ordinary bucket. The stock of the pump carried its sucker and valve in the upper part so that the water was lifted by attraction and not by push as is the case with pumps in which the sucker is placed lower down. This pump worked perfectly so long as the water in the cistern stood above a certain level; but below this level the pump failed to work. When I first noticed this phenomenon I though the machine was out of order; but the workman whom I called in to repair it told me the defect was not in the pump but in the water which had fallen too low to be raised through such a height; and he added that it was not possible, either by a pump or by any other machine working on the principle of attraction, to ife water a hair's breadth above eighteen cubits; whether the pump be large or small this is the extreme limit of the lift. Up to this time I had been so thoughtless that, although I knew a rope or rod of wood, or of iron, is sufficiently long, would break by its own weight when held by the upper end,

it never occurred to me that the same thing would happen, only much more easily, to a column of water. And really is not that thing which is attracted in the pump a column of water attached at the upper end and stretched more and more until finally a point is reached where it breaks, like a rope, on account of its excessive weight?

SALV.
That is precisely the way it works; this fixed elevation of eighteen cubits is true for any quantity of water whatever, be the pump large or small or even as fine as a straw. We may therefore say that, on weighing the water contained in a tube eighteen cubits long, no matter what the diameter, we shall obtain the value of the resistance of the vacuum in a cylinder of any solid material having a bore of this same diameter.

History and Nature
of Science

Torricelli on the Weight of the Atmosphere

Letter of Torricelli to Michelangelo Ricci
Florence, June 11, 1644

My most illustrious Sir and most cherished Master:

Several weeks ago

I sent some demonstrations of mine on the area of the cycloid

to Signor Antonion Nardi,

entreating [*almost begging*] him to send them directly to you

or to Signor Magiotti after he had seen them.

I have already intimated [*suggested*] to you

that a certain physical experiment

was being performed on the vacuum;

not simply to produce a vacuum,

but to make an instrument

which would show the changes in the air,

which [*the air*] is at times heavier and thicker

and at times [*the air is*] lighter and more rarefied.

Many have said that a vacuum cannot be produced,

Reprinted from Spiero, I.H.B. and Spiero, A.C.H., *The Physical Treatises of Pascal*, pp. 163-166. New York, 1937. From Guerlac, H. (Ed.), *Selected Readings in the History of Science, Vol. II.* Ithaca: Henry Guerlac, 1953.

others [*have said*] that it can be produced,

but with repugnance [*intense dislike*] on the part of Nature

and with difficulty;

so far, I know of no one

who has said

that it can be produced without effort

and without resistance on the part of Nature.

I reasoned in this way:

if I were to find a plainly apparent [*what appears to be*] cause for the resistance

which is felt when one needs to produce a vacuum,

it seems to me

that it would be vain [*pointlessly or hopelessly impossible*]

to try to attribute that action,

which patently [*definitely*] derives from some other cause,

to the vacuum;

indeed,

I find that by making certain very easy calculations,

the cause I have proposed (which is the weight of the air)

should in itself

have a greater effect

than it does in the attempt to produce a vacuum.

I say this because some Philosopher,

seeing that he could not avoid the admission

that the weight of the air

causes the resistance which is felt

in producing a vacuum,

did not say that he admitted the effect of the weight of the air,

but persisted in asserting

hat Nature also contributes

at least to the abhorrence of a vacuum [*based upon Aristotle's authority, not fact or observation*].

We live submerged at the bottom of an ocean of the element air,

which by unquestioned experiments

is known to have weight,

and so much, indeed,

that near the surface of the earth

where it is more dense,

it weighs [volume for volume]

about the four-hundredth part of the weight of water [*2.5 oz. per cubic foot, compared with 62.5 pounds per cubic foot for water*].

Those who have written about twilight, moreover,

have observed that the vaporous and visible air [*an estimate of the visible depth of the atmosphere as observed on the horizon at sunrise or sunset*]

rises above us about fifty or fifty-four miles;

I do not, however, believe its height is as great as this,

since if it were,

I could show

that the vacuum would have to offer

much greater resistance than it does--

even though there is in their favor

the argument that the weight referred to by Galileo

applies to the air in very low places [*near sea level*]

whereas that on the tops of high mountains

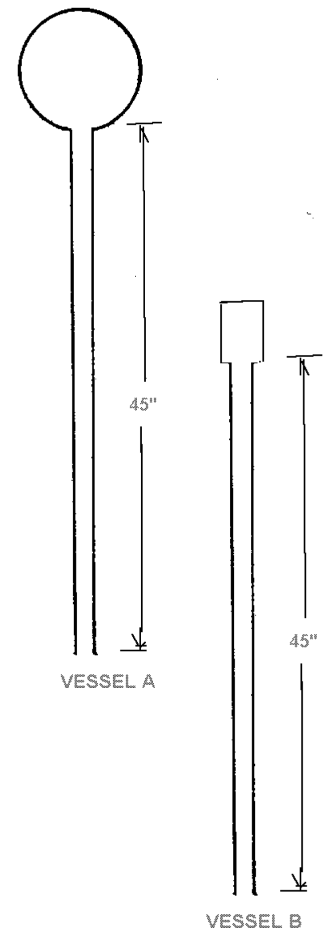
begins to be distinctly rare

and of much less weight

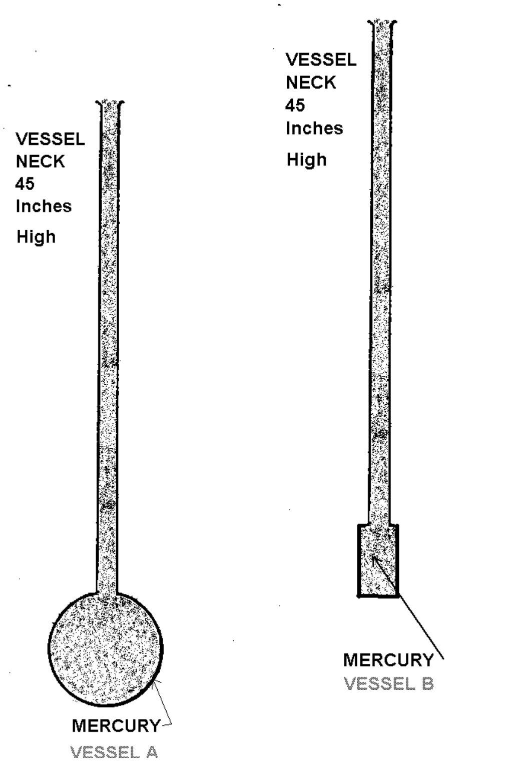
than the four-hundredth part of the weight of water.

We have made many glass vessels

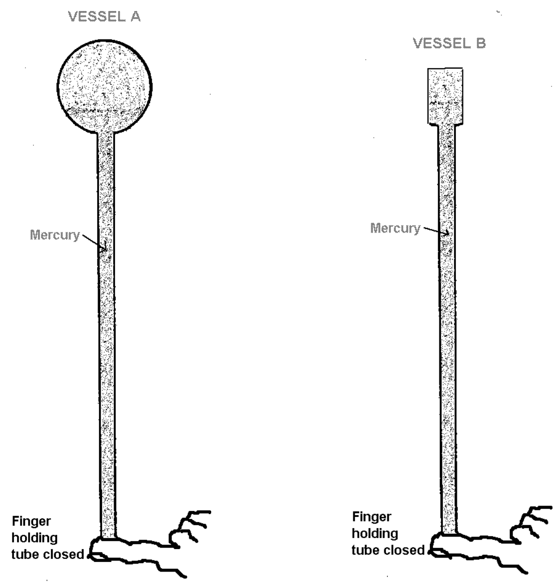
like the following marked A and B with necks two cubits [*about 45 inches*].



We filled
these with quicksilver [*liquid mercury*],

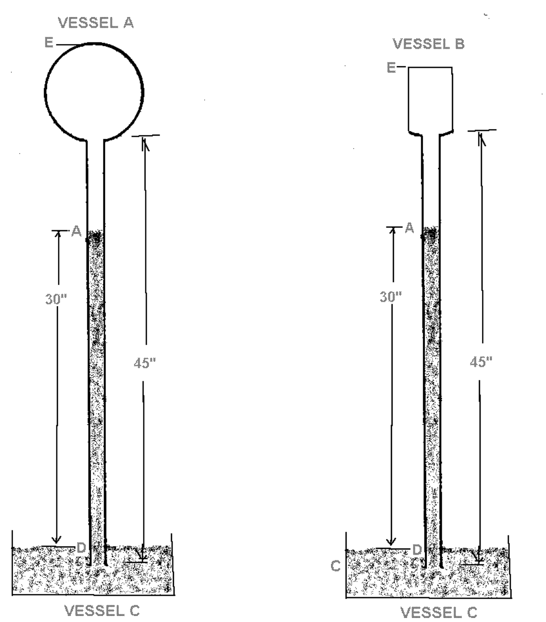


and then, the mouths being stopped with a finger



and being inverted in a basin

where there was quicksilver C,



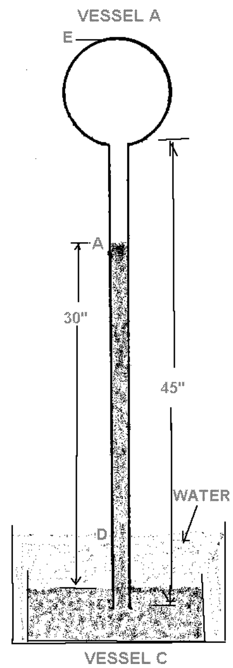
they seemed to become empty

and nothing happened in the vessel that was emptied;

the neck AD, therefore,

remained always filled

to the height of a cubit and a quarter and an inch besides [*a total of about 30 inches*].



To show that the vessel was perfectly empty,

the underlying basin was filled with water up to D,

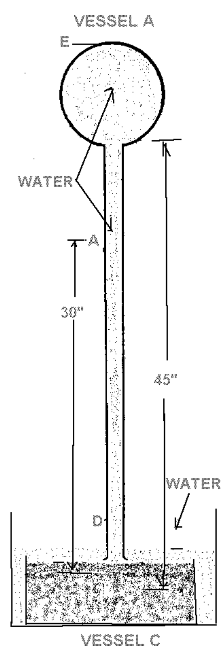
and as the vessel was slowly raised,

when its mouth reached the water,

one could see the quicksilver fall from the neck,

whereupon with a violent impetus

the vessel was filled with water completely to the mark E.



This experiment was performed
when the vessel AE was empty
and the quicksilver,
although very heavy,
was held up in the neck AD.
The force which holds up that quicksilver
against its nature to fall down again,
has been believed hitherto to be inside of the vessel AE,
and to be due either to vacuum
or to that material [*mercury*] highly rarefied;
but I maintain that
it is external
and that the force comes from without.
On the surface of the liquid
which is in the basin,
there gravitates a mass of air fifty miles high;
is it therefore to be wondered at
if in the glass CE,
where the mercury is not attracted
nor indeed repelled,
since there is nothing there,
it enters and rises to such an extent
as to come to equilibrium

with the weight of this outside air

which presses upon it?

Water also,

in a similar but much longer vessel,

will rise up to almost eighteen cubits [*almost 33 feet*],

that is,

as much further than the quicksilver rises

as quicksilver [*mercury*] is heavier than water,

in order to come to equilibrium with the same force,

which presses alike the one and the other [*a given volume of mercury is 13.6 times heavier than an equal volume of water, and water rises 13.6 times further than mercury in an evacuated tube*].

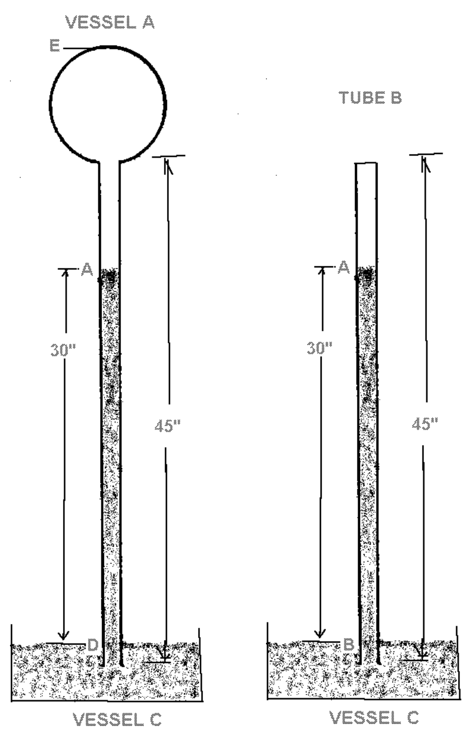
The above conclusion was confirmed

by an experiment made at the same time

with a vessel A and a tube B,

in which the quicksilver always came to rest

at the same level, AB.



This is an almost certain indication
that the force was not within;
because if that were so,
the vessel AE
would have had greater force,
since within it
there was more rarefied material
to attract the quicksilver,
and a material much more powerful
than that in the very small space B,
on account of its greater rarefaction.
I have since tried to consider
from this point of view
all the kinds of repulsions
which are felt in the various effects
attributed to vacuum,
and thus far
I have not encountered anything
which does not go [to confirm my opinion].
I know that you will think up many objections,
but I also hope that,
as you think about them,

you will overcome them.

I must add that my principal intention--

which was to determine

with the instrument EC

when the air was thicker and heavier

and when it was more rarefied and light

--has not been fulfilled;

for the level AB changes from another cause

(which I never would have believed),

namely,

on account of heat and cold;

and changes very appreciably,

exactly as if the vase AE were full of air.

History and Nature
of Science

Torricelli on the Weight of the Atmosphere

Letter of Torricelli to Michelangelo Ricci
Florence, June 11, 1644

My most illustrious Sir and most cherished Master:

Several weeks ago I sent some demonstrations of mine on the area of the cycloid to Signor Antonion Nardi, entreating him to send them directly to you or to Signor Magiotti after he had seen them. I have already intimated to you that a certain physical experiment was being performed on the vacuum; not simply to produce a vacuum, but to make an instrument which would show the changes in the air, which is at time heavier and thicker and at time lighter and more rarefied. Many have said that a vacuum cannot be produced, others that it can be produced, but with repugnance on the part of Nature and with difficulty; so far, I know of no one who has said that it can be produced without effort and without resistance on the part of Nature. I reasoned in this way: if I were to find a plainly apparent cause for the resistance which is felt when one needs to produce a vacuum, it seems to me that it would be vain to try to attribute that action, which patently derives from some other cause, to the vacuum; indeed, I find that by making certain very easy calculations, the cause I have proposed (which is the weight of the air) should in itself have a greater effect that it does in the attempt to produce a vacuum. I say this because some Philosopher, seeing that he could not avoid the admission that the weight of the air causes the resistance which is felt in producing a vacuum, did not say that he admitted the effect of the weight of the air, but persisted in asserting that Nature also contributes at least to the abhorrence of a vacuum. We live submerged at the bottom of an ocean of the element air, which by unquestioned experiments is known to have weight, and so much, indeed, that near the surface of the earth where it is more dense, it weights [volume for volume] about the four-hundredth part of the weight of water. Those who have written about twilight, moreover, have observed that the vaporous and visible air rises above us about fifty or fifty-four miles; I do not, however, believe its height is as great as this, since if it were, I could show that the vacuum would have to offer much greater resistance than it does--even though there is in their favor the argument that the weight referred to by Galileo applies to the air in very low places where men and animals live, whereas that on the tops of high mountains begins to be distinctly rare and of much less weight than the four-hundredth part of the weight of water.

Reprinted from Spiero, I.H.B. and Spiero, A.C.H., *The Physical Treatises of Pascal*, pp. 163-166. New York, 1937. From Guerlac, H. (Ed.), *Selected Readings in the History of Science, Vol. II.* Ithaca: Henry Guerlac, 1953.

We have made many glass vessels like the following marked A and B with necks two cubits **[figure 1]**. We filled these with quicksilver **[figure 2]**, and the, the mouths being stopped with a finger **[figure 3]** and being inverted in a basin where there was quicksilver C **[figure 4]**, they seemed to become empty and nothing happened in the vessel that was emptied; the neck AD, therefore, remained always filled to the height of a cubit and a quarter and an inch besides **[figure 5}**. To show that the vessel was perfectly empty, the underlying basin was filled with water up to D, and as the vessel was slowly raised, when its mouth reached the water, one could see the quicksilver fall from the neck, whereupon with a violent impetus the vessel was filled with water completely to the mark E **[figure 6]**. This experiment was performed when the vessel AE was empty and the quicksilver, although very heavy, was held up in the neck AD. The force which holds up that quicksilver against its nature to fall down again, has been believed hitherto to be inside of the vessel AE, and to be due either to vacuum or to that material [mercury] highly rarefied; but I maintain that it is external and that the force comes from without. On the surface of the liquid which is in the basin, there gravitates a mass of air fifty miles high; is it therefore to be wondered at if in the glass CE, where the mercury is not attracted nor indeed repelled, since there is nothing there, it enters and rises to such an extent as to come to equilibrium with the weight of this outside air which presses upon it? Water also, in a similar but much longer vessel, will rise up to almost eighteen cubits, that is, as much further than the quicksilver rises as quicksilver is heavier than water, in order to come to equilibrium with the same force, which presses alike the one and the other. The above conclusion was confirmed by an experiment made at the same time

Figure 1

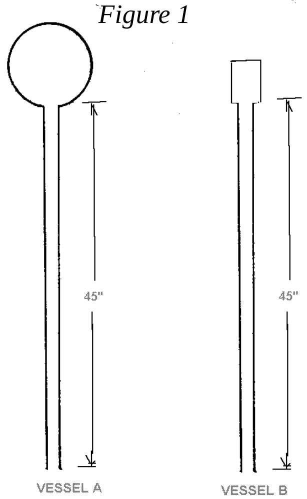


Figure 2

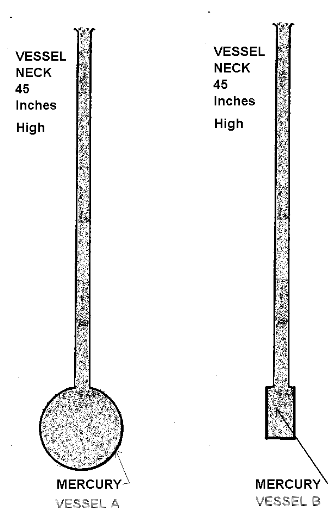


Figure 3

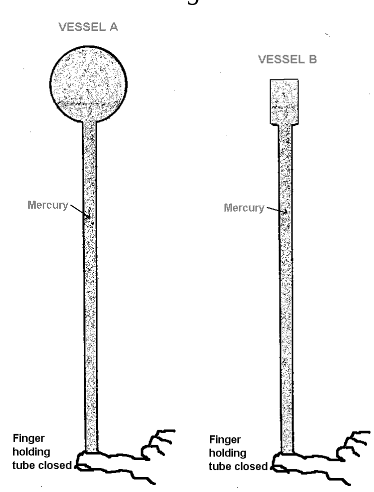


Figure 4

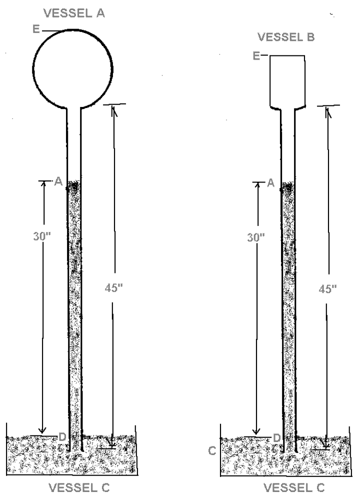


Figure 5

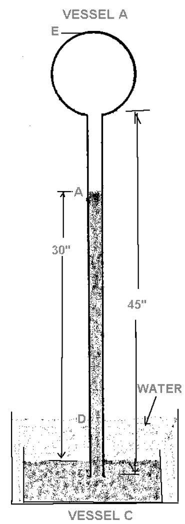
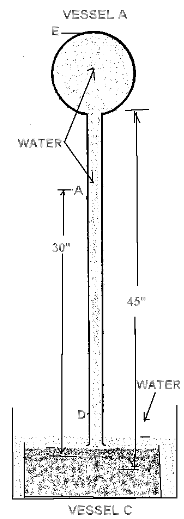


Figure 6



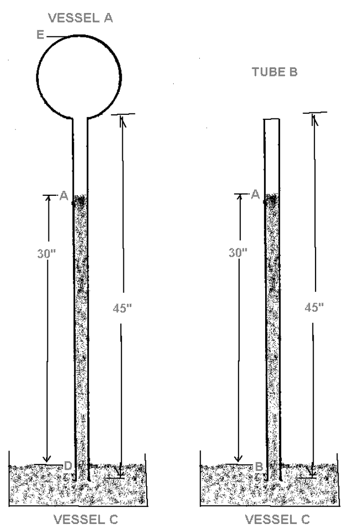


Figure 7

with a vessel A and a tube B, in which the quicksilver always came to rest at the same level, AB **[Figure 7]**. This is an almost certain indication that the force was not within; because if that were so, the vessel AE would have had greater force, since within it there was more rarefied material to attract the quicksilver, and a material much more powerful than that in the very small space B, on account of its greater rarefaction. I have since tried to consider from this point of view all the kinds of repulsions which are felt in the various effects attributed to vacuum, and thus far I have not encountered anything which does not go [to confirm my opinion]. I know that you will think up many objections, but I also hope that, as you think about them, you will overcome them. I must add that my principal intention--which was to determine with the instrument EC when the air was thicker and heavier and when it was more rarefied and light--has not been fulfilled; for the level AB changes from another cause (which I never would have believed), namely, on account of heat and cold; and changes very appreciably, exactly as if the vase AE were full of air.

History and Nature of Science

Some Experiments of the Academia del Cimento

It is most useful, and indeed a necessary thing in the making of Natural Experiments, to be truly informed of all the Alterations the Air is incident to; for since it receives into it self, and as it were, embraces all things, leaning on them with its whole weight from a vast height, they must needs all bend under this Pressure; and as this violence which they suffer, is more or less, so are they more imprisoned or enlarged. Thus the Mercurial Standard either rises or falls, at the different height of the Atmosphere, or as some think, correspondent to the various Temperaments which the Air receives from the Sun, or from the Shade, from the Heat, or from the Cold, when open and free, or when shaded and apprest with Clouds when it either rarifies or condenses it self, and so gravitates more or less upon the Stagnant Mercury, by which, with different Pressures, it forces it higher or lower into the immersed Cane. It is therefore requisite (as well for that Experiment which we shall amply treat of in the first place, as for others, which in the sequel of this Discourse we shall handle) to be provided with such Instruments that we may be able to assure our selves, what is the true Measure, not onely of the greatest changes of the Air; but if it be possible, the niceties of the smallest variation. We will therefore in the first place, describe those which have been serviceable to us, though they may have been already dispersed hence to several parts of Europe, so that they will want the pleasing dress of Novelty to recommend them: nevertheless, they will not be unacceptable to those that desire a more nice and particular Information (if not of their use, which is easily comprehended, yet) of the way and Artifice of making them.

Excerpt from Magalotti, Lorenzo, *Saggi di Naturali Esperienza,* passim, translated by Richard Waller, London, 1684. From Guerlac, H. (Ed.), *Selected Readings from the History of Science, Vol. II.* Ithaca: Henry Guerlac, 1953.