Physics 9 — Friday, October 12, 2018

- Turn in HW4. Pick up HW5 handout.
- For last Monday, you read Giancoli ch10 (fluids)
- For last Wednesday, you read PTFP ch2 (atoms & heat)
- For Monday, read PTFP ch9 (invisible light)
- For Wed, read Giancoli ch13 (temperature & kinetic theory)
- If you'd like to do some extra-credit reading on Architectural Acoustics, you can read one or more chapters of a nicely illustrated (more drawings, less text) textbook I have (by Egan). For each chapter you read, you can collect extra credit by writing a few paragraphs (1–2 pages) to summarize what you learned from the chapter. Email me if you're interested.
- I found a way to run both Odeon and CATT-Acoustic on MacOS without a virtual machine! Stay tuned.

"Blackboard optics" quick redo with better lasers

- Measure f for converging lens
- Ray tracing with laser: $d_o = 2f\,,\quad d_o = 3f\,,\quad d_o = \frac{3}{2}f$

The usual mirror/lens equation still works!

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \qquad\qquad \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

Solve for d_i and h_i:

$$d_i = \frac{d_o f}{d_o - f} \qquad\qquad h_i = \frac{h_o f}{f - d_o}$$

But now $d_i > 0$ ("real image") means the **far side** of the lens!

- A follow-up to Chloe's question from Wednesday.
- Then a fun little segue from optics into fluids.

The key concept for fluids is *pressure*.

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

$$1 \text{ pascal} = 1 \ \frac{\text{newton}}{\text{meter}^2}$$

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It's an everyday occurrence to confine a fluid (e.g. the air in your car or bicycle tires) and to use the fluid's pressure to hold something up. Can you think of an example on campus of using the pressure of a confined fluid to hold up a (temporary/seasonal) structure?

What are the forces on a small square of fabric at the top of the dome? What balances the force of gravity to hold the fabric up?

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Penn Current says canvas weighs 32000 kg and is 8700 m^2: $\frac{mg}{\mathrm{area}} = 36\ \mathrm{N/m}^2$. But surface is not all horizontal: pressure points outward, while gravity points downward. So divide by $\mathrm{average}(\cos\theta) \approx \frac{1}{2}$, to get $\boxed{72\ \mathrm{N/m}^2}$. Still an underestimate, because tie-downs exert an additional downward force on fabric.

To compare, how many $\mathrm{N/m}^2$ is atmospheric pressure at sea level?

I estimated 0.07% of an atmosphere (about 70 $\mathrm{N/m^2}$) gauge pressure inside this dome. The Wikipedia "Air-Supported structure" article estimates 250 $\mathrm{N/m^2}$ (0.25% atm) as a commonly used value, with a typical range of 75–750 $\mathrm{N/m^2}$.

So it looks as if I underestimated by about a factor of 3. Bill Berner went over there with his altimeter wristwatch, and measured 0.002 atm higher pressure (about 200 $\mathrm{N/m^2}$) inside than outside.

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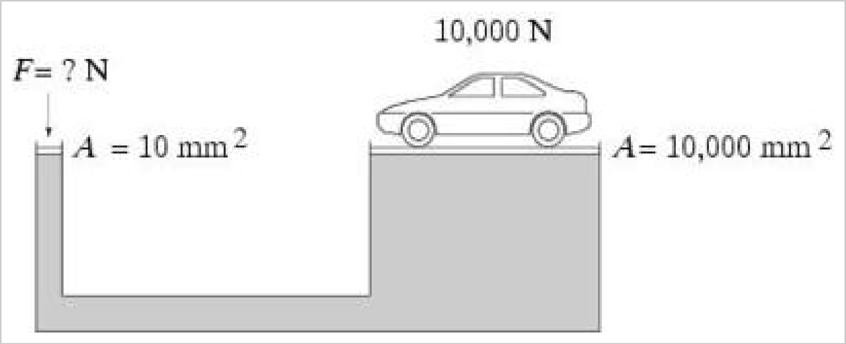
(0.002 atm pressure difference corresponds to about 15–20 meters of elevation change. Atmospheric pressure drops about 1% for a rise in altitude of about 85 meters. Atmospheric pressure at sea level = 1 atm = 101325 $\mathrm{N/m^2}$.)

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

Pascal's principle: external force applied to confined fluid increases pressure at every point within the fluid by the same amount.

What useful device can you build using Pascal's principle? How about a hydraulic jack?

A container is filled with oil and fitted on both ends with pistons. The area of the left piston is 10 mm^2. The area of the right piston is 10000 mm^2. What force must be exerted on the left piston to keep the 10000 N car on the right at the same height?

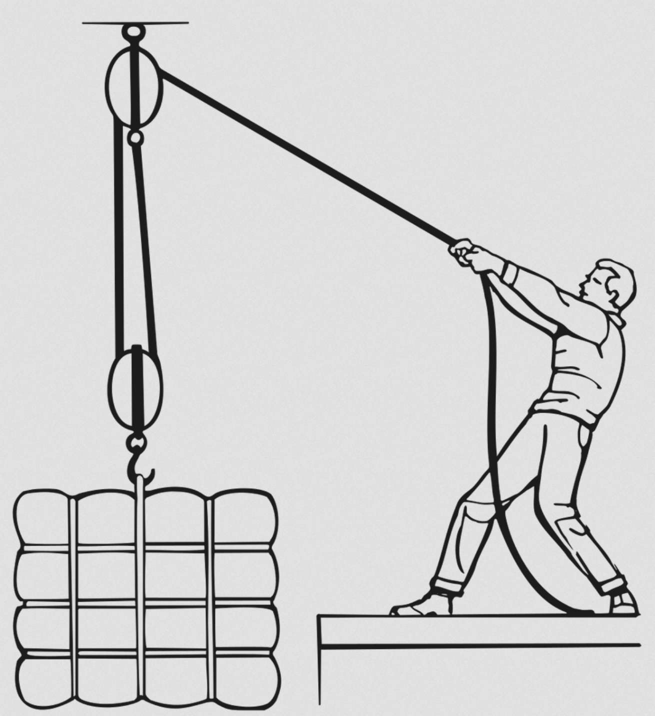


(A) 10 N

(B) 100 N

(C) 1000 N

(D) 10000 N



Another key idea is that fluid pressure varies with depth. Assuming (a) constant density ρ, and (b) earth's gravity g, then

$$\Delta P = -\rho g \Delta y$$

(Pressure increases as you go **down**.)

The stuff on the bottom has to hold the weight of everything above it.

Similarly, water at bottom of swimming pool must support the weight of all the water above it. (Plus the weight of all the air above the surface!)

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At the top of a swimming pool, ambient pressure is 1 atm. How deep do you need to dive beneath the water surface to double that pressure (i.e. to increase pressure by an additional 1 atm)?

(a) 1.03 meter (b) 10.3 meters (c) 103 m (d) 1030 m

Fluid pressure varies with depth. Assuming (a) constant density ρ, and (b) earth's gravity g, then

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(Pressure increases as you go **down**.)

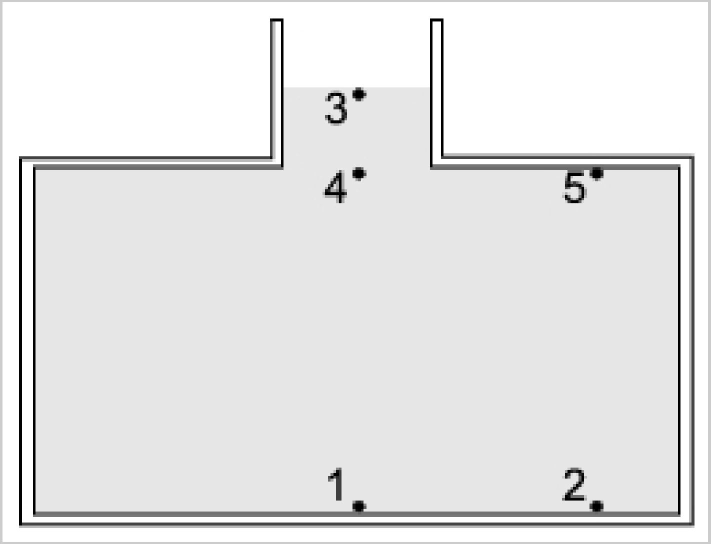
This is why special effort (e.g. pumps, or a rooftop water tower) is required to maintain good water pressure on the top floors of tall buildings.

The water towers you see on flat terrain are typically about 40 m tall. So "gauge pressure" of the water at ground level would be

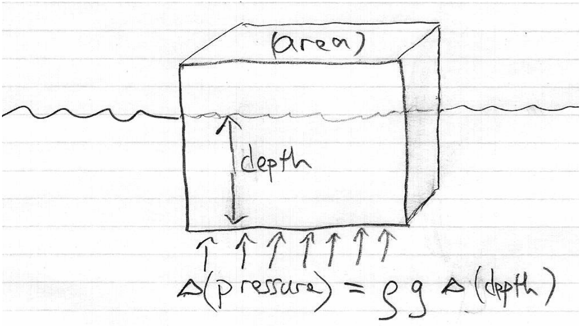
$$\rho g h = 1000\ \frac{\mathrm{kg}}{\mathrm{m}^3} \times 9.8\ \frac{\mathrm{m}}{\mathrm{s}^2} \times 40\ \mathrm{m} = 3.9 \times 10^5\ \mathrm{Pa} \approx 4\ \mathrm{atm}$$

And absolute pressure (i.e. including the atmospheric pressure) would be $\approx 5\ \mathrm{atm}$.

For this container filled with a stationary (non-moving) fluid, how do the pressures compare at points 1, 2, 3, 4, and 5? (No clicking — just explain your answer to your neighbor.)



Buoyancy — object partially submerged in water



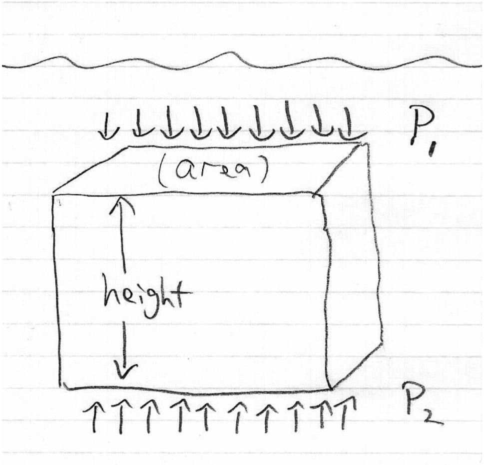
Top surface feels downward atmospheric pressure. Bottom surface feels upward pressure of water $= P_{\text{atm}} + \rho g h$. Cube with cross-section A, partially immersed to depth h: upward buoyant force is

$$F = A\,(P_{\text{bottom}} - P_{\text{top}}) = A\ \rho_{\text{water}}\ g h = \rho_{\text{water}}\ g\ V_{\text{immersed}}$$

which is exactly the weight of the displaced water.

Buoyancy — object fully submerged in water

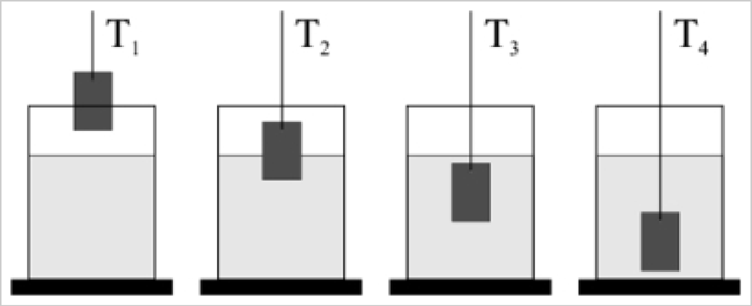
Top surface feels downward push of pressure P_1. Bottom surface feels upward push of pressure $P_2 = P_1 + \rho g h$. Upward buoyant force is



$$F = A\,(P_2 - P_1) = A\,\rho_{\text{water}}\,gh = \rho_{\text{water}}\,g\,V$$

which again is exactly the weight of the displaced water.

A Lucite block sinks when it is dropped into a bucket of water. Suppose that the same block is supported by a string and slowly lowered (at constant speed) into a bucket of water. How do the tensions in the string compare at the four positions shown?



(A) $T_1 > T_2 > T_3 > T_4$

(B) $T_1 < T_2 < T_3 < T_4$

(C) $T_1 > T_2 > T_3 = T_4$

(D) $T_1 = T_2 = T_3 = T_4$

A boat carrying a large boulder is floating on a small lake. The boulder is thrown overboard and sinks. As a result, the water level (with respect to the bottom of the lake)

(A) rises

(B) drops

(C) remains the same

Do you want a hint? (Hint on next page.)

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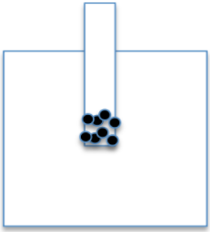
Hint: What volume of water is displaced by floating the boulder inside the boat? What volume of water is displaced by sinking the boulder into the lake?

A glass tube of square cross-section 1 cm $\times$ 1 cm floats vertically in water. What mass of lead pellets would you need to add to the tube in order to make it sink by 2 cm? (Assume that the top is initially more than 2 cm above the surface.)



How does pressure P vary with depth h beneath water surface?

What is the difference in pressure forces exerted on the bottom of the tube by the water vs. on the top of the tube by the atmosphere, as a function of immersed depth h?

What is the condition for static equilibrium?

depth h below water surface

$$P(h) = P_{atm} + \rho g h$$

A = tube's cross-sectional area

force on top $= P_{atm} \cdot A$ (downward)
force on bottom $= (P_{atm} + \rho g h) \cdot A$ (upward)

gravitational force on lead pellets $= Mg$ (downward)

$$(P_{atm} + \rho g h)A - P_{atm} \cdot A - Mg = 0 \Rightarrow \rho g h A = Mg$$

$$(\rho_{water})(Ah) = M_{lead}$$

volume of displaced water

mass of displaced water

$$(\rho_{water})(A \cdot \Delta h) = \Delta M_{lead} = \left(1 \tfrac{g}{cm^3}\right)(1 cm^2 \cdot 2 cm)$$

$$= \boxed{2 \text{ grams}}$$

When a sphere of volume 1 m^3 floats in water, 75% of its volume is submerged beneath the surface. What is the mass of the sphere?

Notice that pressure and stress are both force-per-unit-area.

Suppose lumber has density ρ (measured in kg/m^3) and will crush if the force-per-unit-area exceeds the compressive strength S (measured in N/m^2). [About $3 \times 10^6\,\mathrm{N}/\mathrm{m}^2$ for eastern white pine, compressed perpendicular to grain; density (dry) is about $400\,\mathrm{kg}/\mathrm{m}^3$.]

If you build a rectangular pile of lumber, of height h and cross-section A, how much weight (measured in newtons) does the bottom of the pile need to support?

How much pressure, or stress, measured in N/m^2, does the bottom surface need to support?

How big is h when the pressure (or stress) on the bottom reaches the maximum allowed value, S ?

You have a cubic box, 1 meter on a side. Its mass is 1500 kg.

When it is on the ground, how much force must you exert to lift it (at constant velocity, i.e. negligible acceleration)? (Let's use $g = 10\ \mathrm{m/s^2}$ for convenience.)

If you put this box in water, will it float?

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If you put this box in water, will it float?

If the box is sitting on the bottom of a swimming pool, what is the buoyant force acting on the box? In which direction?

If you want to lift the box while it is fully immersed in water, how large a force must you exert?

Once you start lifting, how high can you go before the box requires a larger force to continue lifting?

Equation of continuity

Expresses the fact that mass is not accumulating anywhere, for a steady flow of fluid. Time rate of mass flowing past a given surface of area A is constant:

$$\frac{\Delta m}{\Delta t} = \text{constant}$$

$$\frac{\Delta m}{\Delta t} = \rho \, A \, \frac{\Delta x}{\Delta t} = \rho \, A \, v = \text{constant}$$

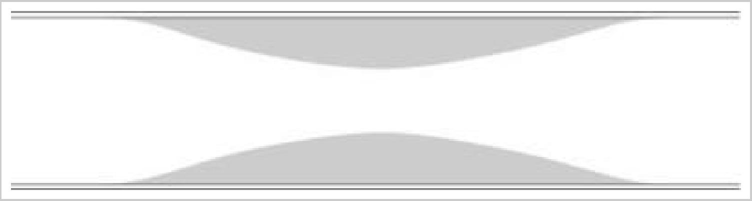
And if density ρ is constant (i.e. incompressible), then

$$A \, v = \text{constant} \quad \Rightarrow \quad A_1 v_1 = A_2 v_2$$

For example, the water running out of your faucet is accelerating (gravity), so the area must decrease as the speed increases.

Another example: river flows at higher speed where it is narrower.

Water flows through an old plumbing pipe that is partially blocked by mineral deposits along the wall of the pipe. Through which part of the pipe is the fluid speed largest?

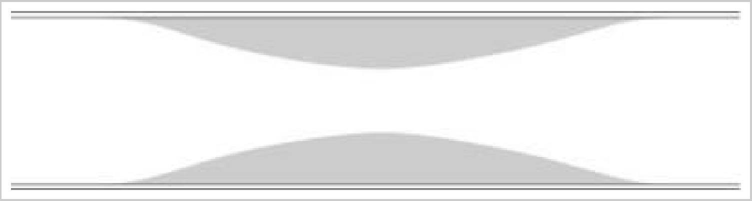


(A) Fastest in the narrow part.

(B) Fastest in the wide part.

(C) The speed is the same in both parts.

Water flows through an old plumbing pipe that is partially blocked by mineral deposits along the wall of the pipe. Through which part of the pipe is the flux (volume of water per unit time) largest?



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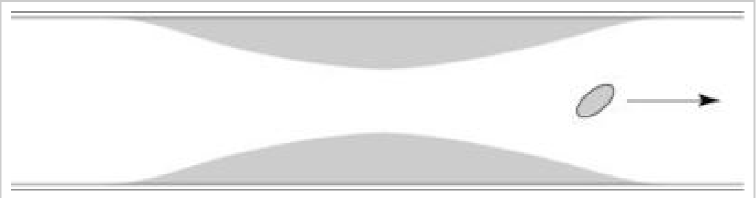
A water-borne insect drifts along with the flow of water through a pipe that is partially blocked by deposits. As the insect drifts from the narrow region to the wider region, it experiences



(A) a forward acceleration (it speeds up)

(B) a backward acceleration (it slows down)

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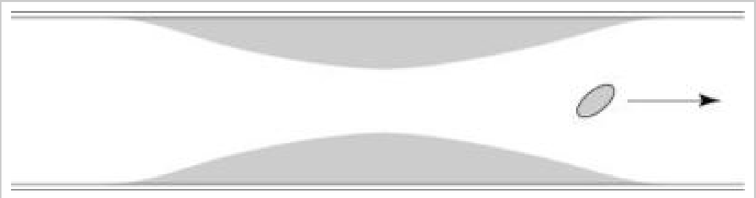

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If you said that the speed changes, now ask yourself: Is there a net force (per unit area) that causes this change in speed?

This one is trickier

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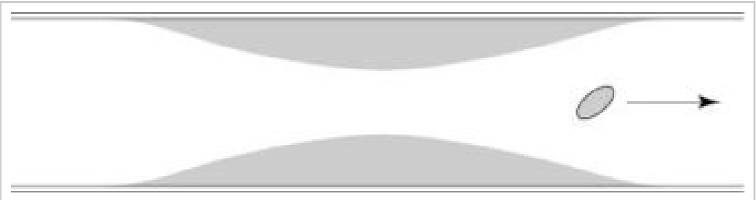

(A) an increase in water pressure ($P_{\text{wide}} > P_{\text{narrow}}$)

(B) no change in water pressure ($P_{\text{wide}} = P_{\text{narrow}}$)

(C) a decrease in water pressure ($P_{\text{wide}} < P_{\text{narrow}}$)

Hint: is the speed the same or different? Is there a net force (per unit area) that causes this change in speed?

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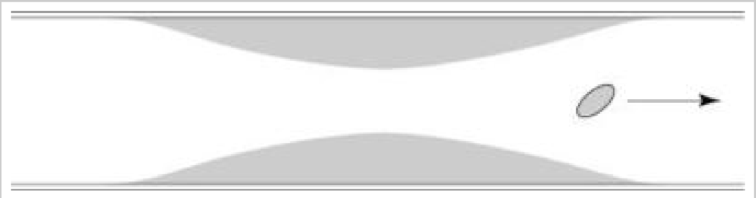

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Hint: is the speed the same or different? Is there a net force (per unit area) that causes this change in speed?

Stop to ponder the net force acting on the insect when insect is just upstream of vs. just downstream of the narrow region.

Buoyancy demo: bottle of blue water; diet coke; coke; pepsi.

How can we make the water a bit more dense? Hint: swim at ocean vs. lake/pool.

Demo: Application of

$$(\text{pressure}) \;=\; P_{\text{atmospheric}} \;+\; (\rho g)\,(\text{depth})$$

why does water "seek its level" ?

We've been looking for a while now at the equation

$$\Delta P = -\rho g \Delta y$$

which says that the pressure in a stationary incompressible fluid increases in proportion to depth.

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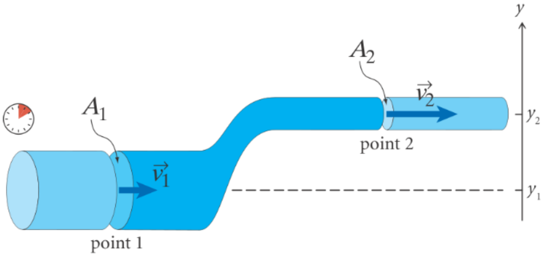
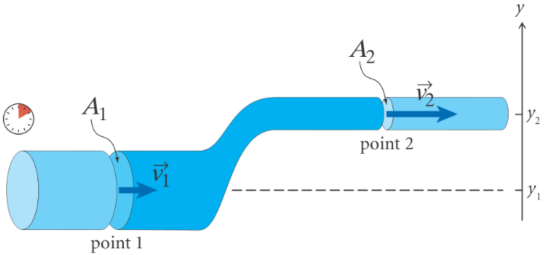
We just saw in the insect-in-pipe example that pressure seems to increase when flow speed is slower, and pressure seems to decrease when flow speed is faster.

We can use "Bernoulli's equation" to make sense of both of these facts, by considering **conservation of mechanical energy** for an incompressible fluid.



Consider the mechanical energy of a little chunk of fluid flowing through a pipe, from point 1 to point 2.

If $v_2 > v_1$, what form of mechanical energy has increased?



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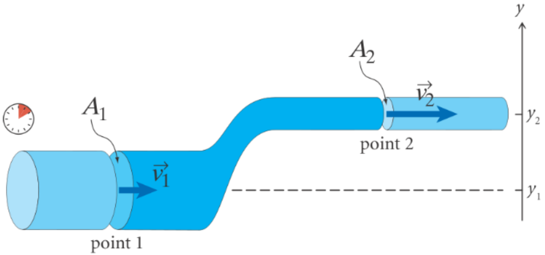

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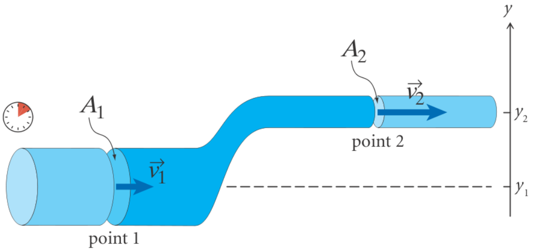
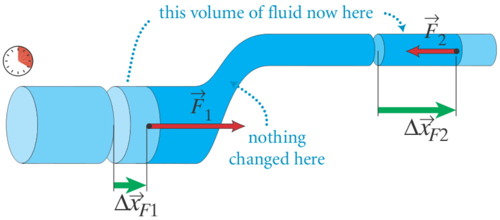
If $y_2 > y_1$, what form of mechanical energy has increased?

Suppose the combined kinetic + potential energy of this chunk of fluid has increased from point 1 to point 2. So some external agent has done work to provide this energy.

Work is force times displacement. What force (per unit area) could perform this work on that chunk of fluid?





$$(P_1A_1)(v_1\Delta t) - (P_2A_2)(v_2\Delta t) = \frac{1}{2}m(v_2^2 - v_1^2) + mg(y_2 - y_1)$$

$$(P_1 - P_2)(\text{Volume}) = (P_1 - P_2)\frac{m}{\rho} = \frac{1}{2}m(v_2^2 - v_1^2) + mg(y_2 - y_1)$$

Pressure in a fluid depends both on depth and on speed. To analyze this, we consider mechanical energy of the fluid.

Notice PV has units of energy, and of course work has units of energy. (Work $=$ force $\times$ displacement.)

$$(\text{pressure})(\text{volume}) = \left(\frac{\text{force}}{\text{area}}\right)(\text{area} \times \text{length}) = (\text{force})(\text{length})$$

If a difference in pressure causes a volume of fluid to be displaced, that pressure difference is doing work on the fluid, thus changing the fluid's energy.

In the absence of friction (a.k.a. "viscosity,"), we expect mechanical energy to add up. So we set the work done (due to the pressure difference) equal to the change in mechanical energy: $(\text{work}) = \Delta\,(\text{energy})$.

$$(P_1 - P_2)V = \frac{1}{2}m(v_2^2 - v_1^2) + mg(y_2 - y_1)$$

$$(P_1 - P_2)V = \frac{1}{2}m(v_2^2 - v_1^2) + mg(y_2 - y_1)$$

rearranging terms, we get

$$P_1 V + \frac{1}{2}mv_1^2 + mgy_1 = P_2 V + \frac{1}{2}mv_2^2 + mgy_2$$

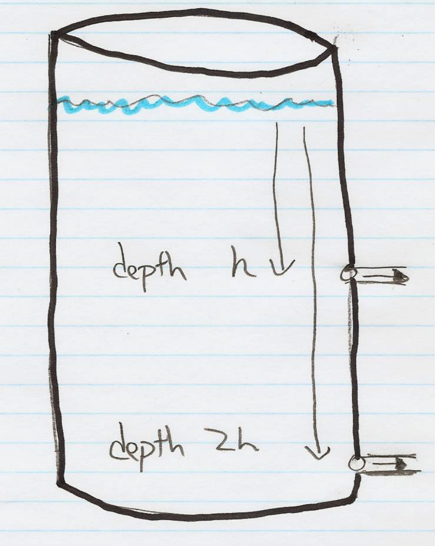
If we divide all terms by volume, we get *Bernoulli's equation:*

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2$$

or in this more compact form:

$$\boxed{P + \frac{1}{2}\rho v^2 + \rho g y = \mathrm{constant}}$$

Strictly speaking, Bernoulli's equation only works if the fluid is incompressible, if the flow is steady and non-turbulent, and if there is no dissipation of energy by friction. But it's handy for estimation even in cases where it is not strictly valid.



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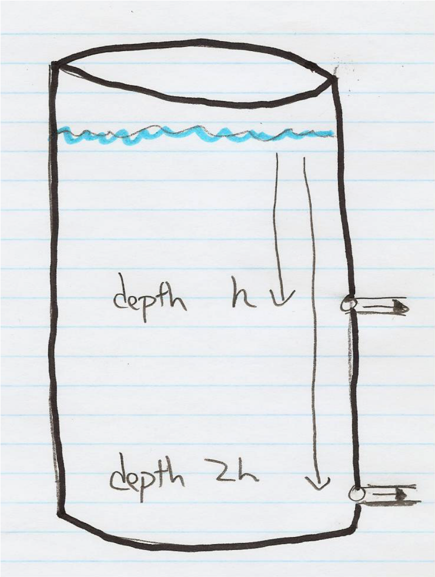


A large, water-filled cylinder has two horizontal spigots. Spigot 1 is at depth h, and spigot 2 is at depth $2h$. If I neglect the small downward motion of the top surface of the water, what I can I say about the horizontal velocity v_x of the water emerging from each spigot?

(A) $v_{2x} = \frac{1}{2} v_{1x}$

(B) $v_{2x} = \sqrt{2} v_{1x}$

(C) $v_{2x} = v_{1x}$

(D) $v_{2x} = 2 v_{1x}$

The measured pressure inside the Penn Park seasonal air structure was 1.002 atm. That's $\Delta P = 200\ \mathrm{N/m^2}$ from inside to outside.

One normally uses revolving doors to enter/exit the dome. Suppose one threw open the emergency exit and then released a bag of confetti so that you could watch the air flow out. Can you use Bernoulli's equation to estimate the horizontal speed of the escaping air?

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2$$

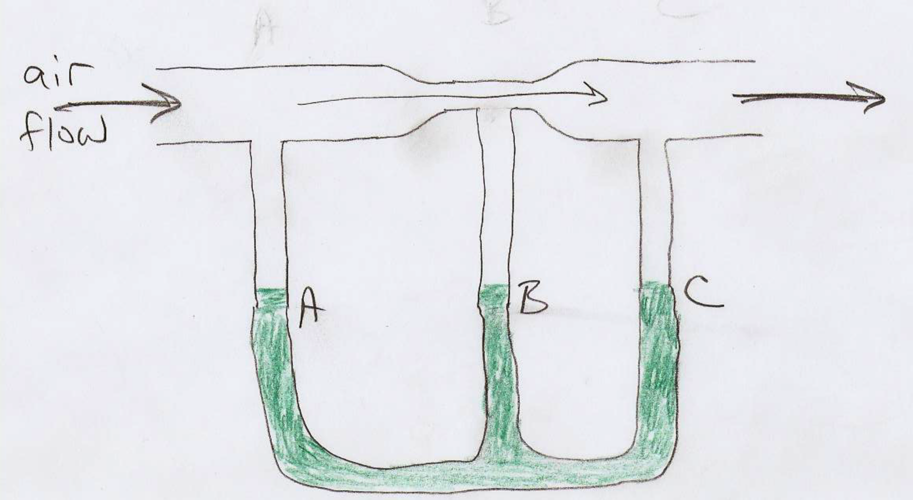
$$\rho_{\mathrm{air}} \approx \frac{0.028\ \mathrm{kg/mol}}{0.0224\ \mathrm{m^3/mol}} \approx 1.3\ \mathrm{kg/m^3}$$

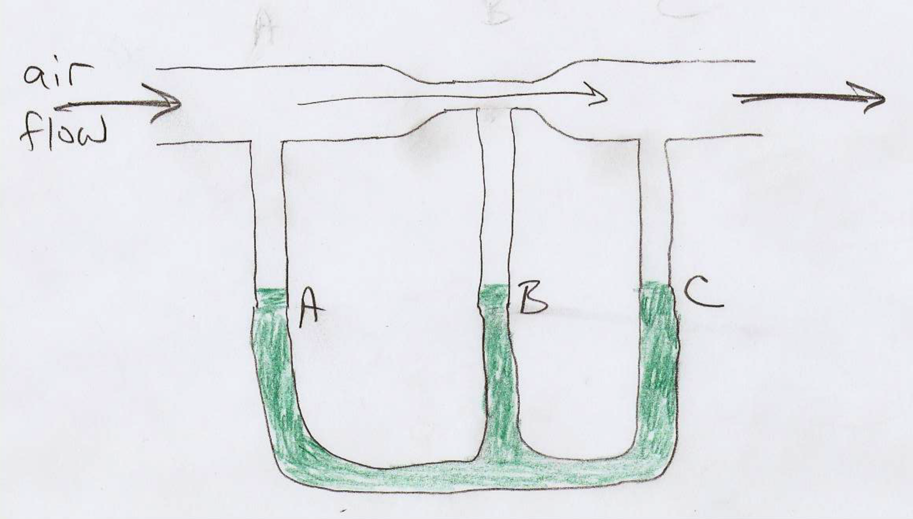
I get $v = \sqrt{2\Delta P/\rho} \approx 18\ \mathrm{m/s} \approx$ 65 kph (40 mph)

Seems plausible, but maybe too fast?

(Using Bernoulli's equation here is OK for a rough estimate, but in real life, there will be some dissipation of mechanical energy into heat, reducing the speed. Also, Bernoulli's equation assumes perfectly smooth flow, with no turbulence, which isn't fully realistic here. And air is not incompressible. But I'll bet this estimate is still not wildly off. To test it, we'd need to get permission to open one of the non-revolving doors for a moment, while one person films and another person drops confetti . . . .)

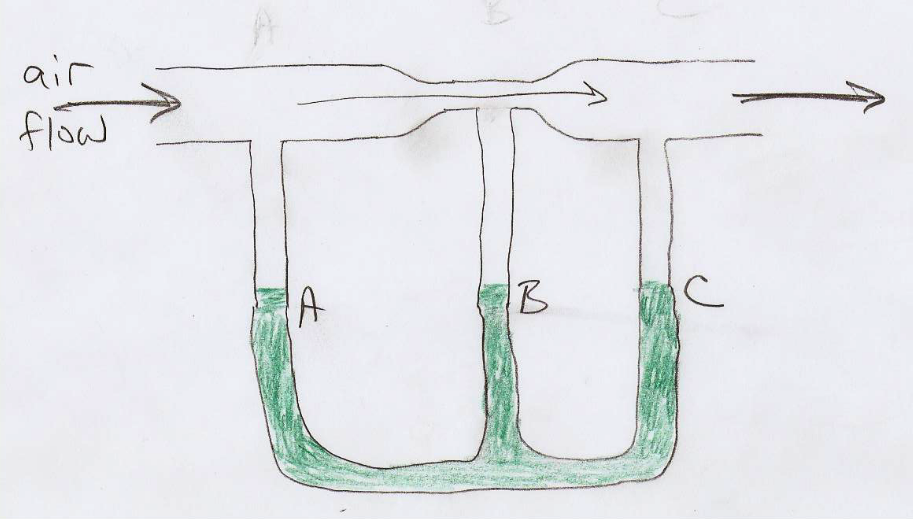
This experiment combines the "equation of continuity" with Bernoulli's equation. When I open the valve, compressed air will flow from left to right through the horizontal tube. The tube is wide on the left and right, but narrow in the middle. Where is the speed largest? Where is the pressure lowest? How will height of the green liquid respond to changes in pressure in the horizontal tube?





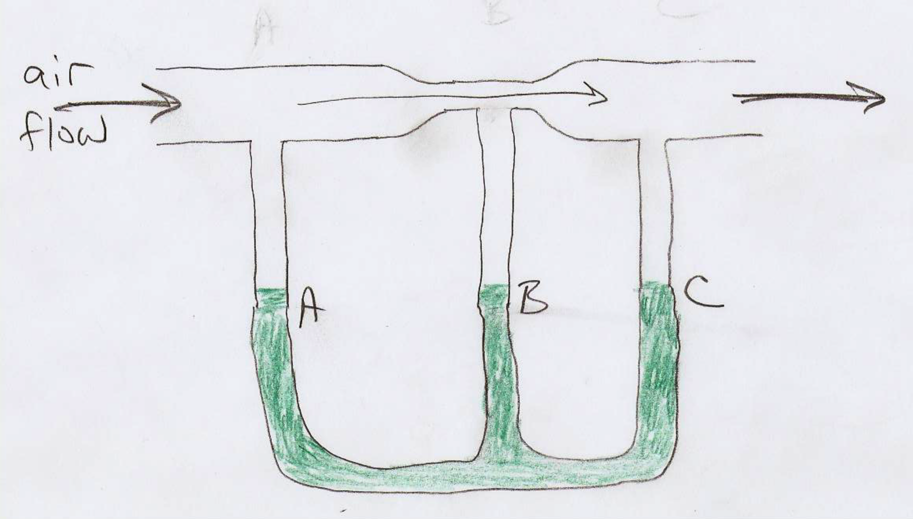
Once I turn on the air flow, the horizontal speed of the flowing air will be

(A) fasteset above tube B
(B) slowest above tube B
(C) the same above all tubes



Once I turn on the air flow, the air pressure above the green liquid will be

(A) lowest in tube B
(B) highest in tube B
(C) the same in all tubes



Once I turn on the air flow, the height of the green liquid will be

(A) lowest in tube B

(B) highest in tube B

(C) the same in all tubes

What gauge pressure in the water mains is necessary if a firehose is to spray water to a height of 10 meters? (Use $g = 10\ \mathrm{m/s^2}$ and ignore all friction or other dissipative effects.)

(a) $10^3\ \mathrm{N/m^2}$ (b) $10^4\ \mathrm{N/m^2}$ (c) $10^5\ \mathrm{N/m^2}$ (d) $10^6\ \mathrm{N/m^2}$

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How many atmospheres is this?

If the "gauge pressure" is 1 atm, what is the absolute pressure?

What is the speed at which water flows from a faucet if the pressure head is 20 meters? (In other words the height of the nearby water tower is 20 meters above the height of the faucet.) Neglect all friction or other dissipative effects. Use $g = 10\ \mathrm{m/s^2}$.

(a) 5 m/s (b) 10 m/s (c) 14 m/s (d) 20 m/s

What is the volume rate of flow of water from a 2 cm-diameter faucet if the pressure head is 20 meters? (In other words the height of the nearby water tower is 20 meters above the height of the faucet.) Neglect all friction or other dissipative effects. Use $g = 10\ \mathrm{m/s^2}$. Use $\pi \approx 3$.

(a) 6 $\mathrm{cm^3/s}$ (b) 0.6 Ł$/\mathrm{s}$ (c) 6 Ł$/\mathrm{s}$ (d) 6 $\mathrm{m^3/s}$

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This seems unrealistically fast, even though a 20 meter (2 atm) pressure head is not unrealistic. What are we neglecting?!

If the wind blows horizontally at speed $v = 10 \text{ m/s}$ over a house (that's about 22 mph), what is the net force on a flat roof of area $A = 100 \text{ m}^2$ (that's about 1100 sqft)? For the density of air, use $\rho = 1.3 \text{ kg/m}^3$.

recap

pressure: $P = F/A$. $1 \text{ Pa} = 1 \text{ N/m}^2$. $1 \text{ atm} = 101323 \text{ Pa} = 760 \text{ mm-Hg}$.

Pascal's principle: if an external pressure is applied to a confined fluid, the pressure at every point within the fluid increases by that amount.

Archimedes' principle: the buoyant force on an object immersed (or partially immersed) in a fluid equals the weight of the fluid displaced by that object.

Equation of continuity: $\rho_1 A_1 v_1 = \rho_2 A_2 v_2$

Bernoulli's equation (neglects viscosity, assumes constant density):

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2$$

Physics 9 — Friday, October 12, 2018

- Turn in HW4. Pick up HW5 handout.
- For last Monday, you read Giancoli ch10 (fluids)
- For last Wednesday, you read PTFP ch2 (atoms & heat)
- For Monday, read PTFP ch9 (invisible light)
- For Wed, read Giancoli ch13 (temperature & kinetic theory)
- If you'd like to do some extra-credit reading on Architectural Acoustics, you can read one or more chapters of a nicely illustrated (more drawings, less text) textbook I have (by Egan). For each chapter you read, you can collect extra credit by writing a few paragraphs (1–2 pages) to summarize what you learned from the chapter. Email me if you're interested.
- I found a way to run both Odeon and CATT-Acoustic on MacOS without a virtual machine! Stay tuned.