

TODAY:

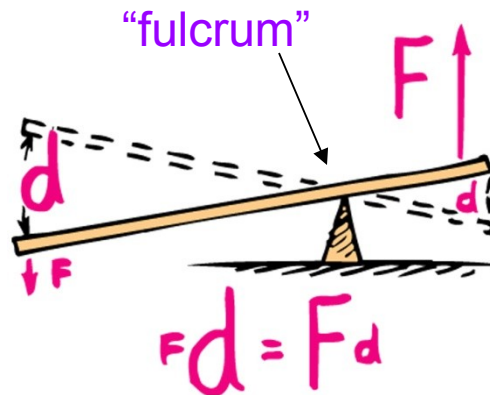
Finish Chapter 7 on Energy

Start Chapter 8 on Rotation

Machines

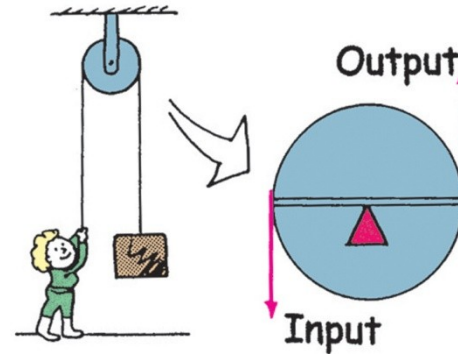
- Something that multiplies forces, and/or changes their direction.
- Main principle: energy is conserved,
 $\text{Work input} = \text{work output}$
(if we can neglect friction)

Eg. Lever : put load close to fulcrum. Then small input force (down on the left) yields a large output force on the load (up on the right). Input force moves over large distance, load is lifted up short distance ($W = Fd$ same for output and input)



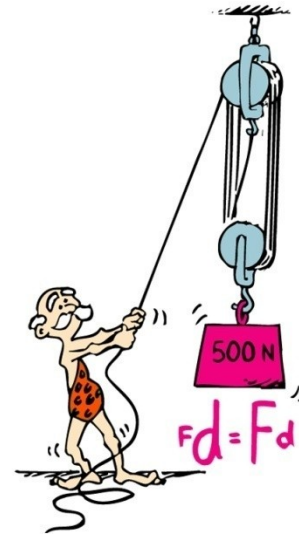
- Eg. Pulley –same principle as lever

Here, it just reverses direction of input force (no multiplication)



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

- Here (“block and tackle” pulley system), man pulls with a force of 50 N, but can lift 500 N weight up: he moves the rope 10x the distance that the weight moves vertically up.



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

NB: Always, energy is conserved – machines just trade force for distance, but so that the product Fd is the same input as output.

Efficiency

In reality, **Work output < Work input**, because some energy is dissipated as heat – i.e. thermal energy, which is random molecular kinetic energy, not useful.

Define

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

Eg. Pulley system – much of the input energy goes into thermal energy from friction, with ropes and pulleys turning and rubbing about the axles.

Say you put in 100 J of work but the output is only 40 J. Then efficiency = 40%.

Comparing kinetic energy and momentum

- Both are a measure of motion, and both are bigger when things go faster, and when things are heavier.
- Differences:
 - momentum is a vector, with direction, whereas KE is a scalar, always greater or equal to 0.
 - Also, momentum is always conserved in a collision, whereas KE is not
 - Momentum scales with speed as v , however KE scales as v^2
 - The change in momentum is determined by impulse imparted on the object, whereas change in KE is determined by the work done on it.

· **Example:** You're standing on a log while a friend tries to knock you off by throwing balls to you. Should you try to catch the ball, or let it bounce off you, in order to try not to fall off the log?

(analyze in terms of change in momentum)

If you catch the ball, ball changes its mom. from mv to 0 .

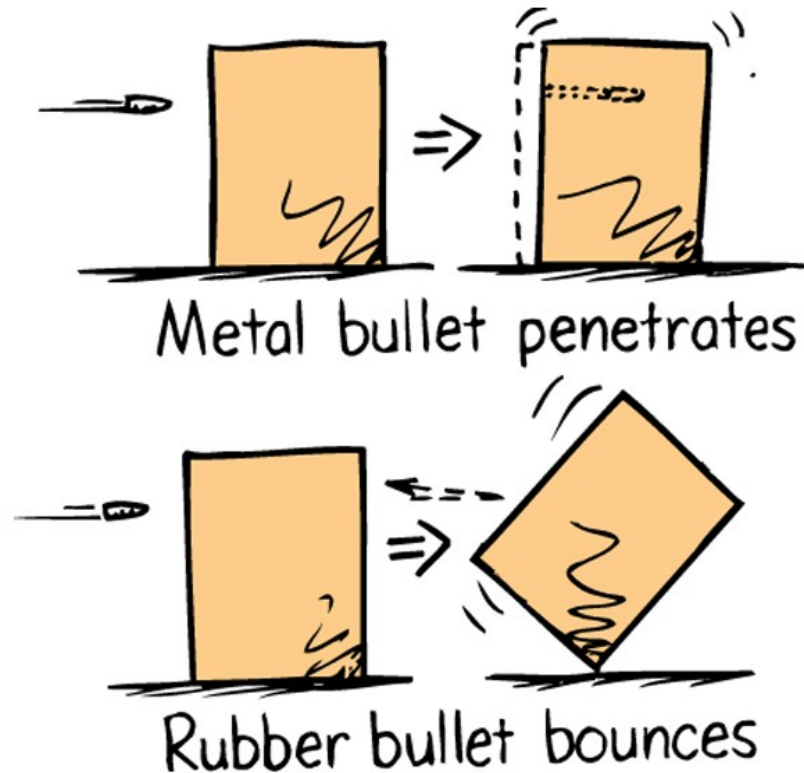
Whereas, if you let it bounce off you, ball reverses direction of momentum, so change in momentum is twice as large.

So it's better to try to catch it, as there is less change.

- That example has similar physics to one in your book – metal vs rubber bullet on a wooden block (or a person λ). The rubber bullet tends to bounce off, whereas the metal bullet penetrates.

For rubber bullet, the change in mom. and the impulse, is greater: if it bounces back elastically, the change is twice that of the metal bullet.

Because it does not penetrate, it does little damage – very little (none if elastic) change in its KE. Whereas the metal bullet comes to rest and all its KE becomes heat – so damage...



Sources of energy

- Except for nuclear, and geothermal power, source of our energy is ultimately the **sun**: eg. Gas, wood, coal, petroleum combustion – all these come from plants, which used sun's radiant energy in photosynthesis.

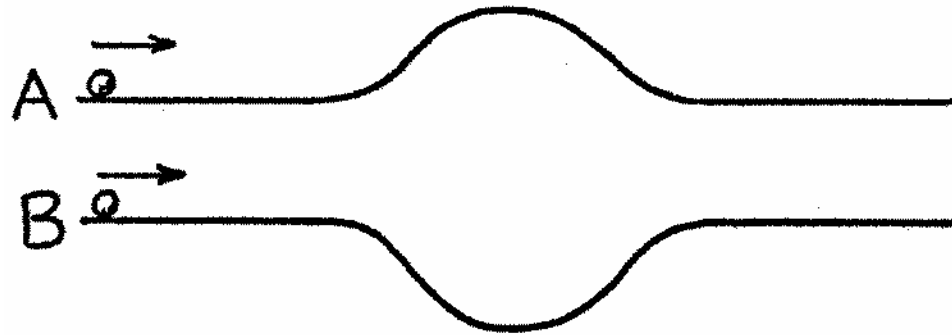
Also, sun is responsible for energy in photovoltaic cells in solar-powered panels, or calculators, and in generating electricity (see earlier, hydropower)

Wind power, in a sense comes from sun too, since wind is due to unequal warming of Earth's surface. Harder for us to control.

- **Nuclear power** - uranium, plutonium, very powerful. Fears of radiation leakage have limited its growth.

Note that the earth's core is so hot because of naturally occurring nuclear radioactive decay.

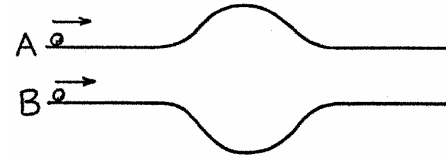
- **Geothermal energy** – from underground reservoirs of hot water, so often in volcanic lands.



Two smooth tracks of equal length have “bumps”—A up, and B down, both of the same curvature. If two balls start simultaneously with the same initial speed, the ball to complete the journey first is along

1. Track A.
2. Track B.
3. Both at same time

Answer: Track B



Two smooth tracks of equal length have “bumps”—A up, and B down, both of the same curvature. If two balls start simultaneously with the same initial speed, the ball to complete the journey first is along

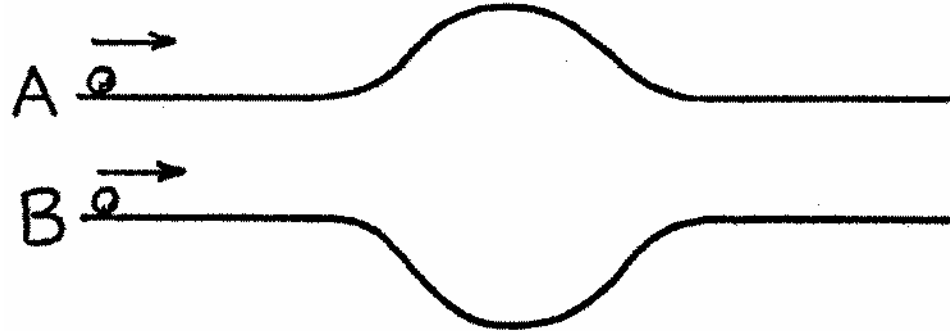
1. Track A. 2. Track B. 3. Track C.

Although both balls have the same speed on the level parts of the tracks, the speeds along the curved parts differ. The speed of the ball everywhere along curve B is greater or same than the initial speed, whereas everywhere along curve A it is less. So the ball on Track B finishes first.

Does the gain in speed at B’s bottom equal the loss at A’s top?

No! Speed isn’t conserved: *energy* is. The loss in *kinetic energy* at the top of A will be equal to the gain in *kinetic energy* at the bottom of B—if there is enough energy to begin with.

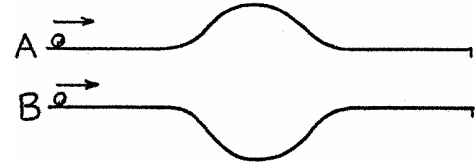
Extra Question



Two smooth tracks of equal length have “bumps”—A up, and B down, both of the same curvature. If the initial speed = 2 m/s, and the speed of the ball at the bottom of the curve on Track B is 3 m/s, then the speed of the ball at the top of the curve on Track A is

1. 1 m/s.
2. > 1 m/s.
3. < 1 m/s.

Answer: < 1m/s



Two smooth tracks of equal length have “bumps”—A up, and B down, both of the same curvature. If the initial speed = 2 m/s, and the speed of the ball at the bottom of the curve on Track B is 3 m/s, then the speed of the ball at the top of the curve on Track A is

1. 1 m/s. 2. > 1 m/s. **✓ 3. < 1m/s.**

The change in the speed in either track comes from change in the kinetic energy that happens because potential energy changes (change in height) while total energy remains constant.

For track B, at the bottom, gain in KE = $mgh = \frac{1}{2} m(32 - 22) = \frac{1}{2} m(5)$.

This means for track A, loss in KE = $\frac{1}{2} m(5)$ at the top – but this is *greater* than the initial KE $\frac{1}{2} m (2)^2 = \frac{1}{2} m(4)$. So the ball actually never makes it to the top of A’s curve!

Chapter 8: Rotational Motion

If you ride near the outside of a merry-go-round, do you go faster or slower than if you ride near the middle?

It depends on whether “faster” means

- a faster **linear speed (= speed)**, ie more *distance* covered per second,

or

- a faster **rotational speed (=angular speed, ω)**, i.e. more *rotations or revolutions* per second.

· The *linear* speed of a rotating object is greater on the outside, further from the axis (center), but the *rotational* speed is the same for any point on the object – all parts make the same # of rotations in the same time interval.

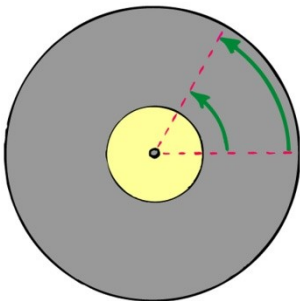
More on rotational vs tangential speed

For motion in a circle, linear speed is often called **tangential speed**

- The faster the ω , the faster the v in the same way (e.g. merry-go-round), i.e. $v \sim \omega$.

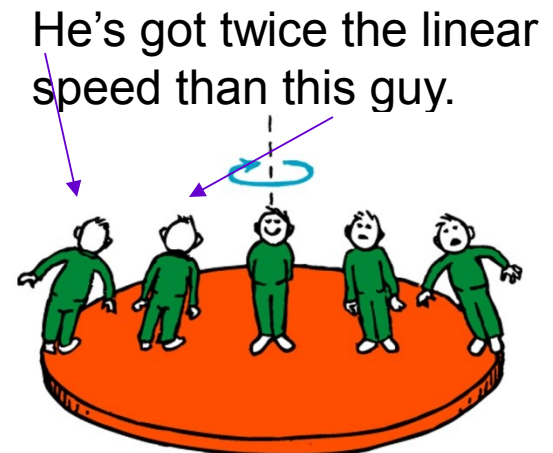
directly proportional to

- ω doesn't depend on where you are on the merry-go-round, but v does: i.e. $v \sim r$



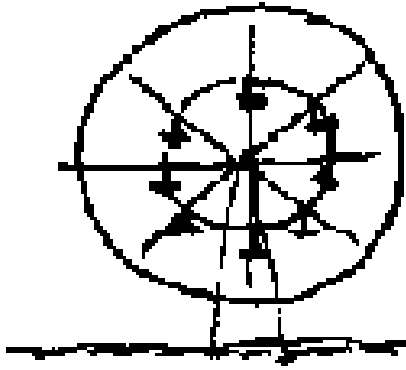
Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley

Same RPM (ω) for all these people, but different tangential speeds.



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley

Clicker Question



A carnival has a Ferris wheel where the seats are located halfway between the center and outside rim. Compared with a Ferris wheel with seats on the outside rim, your angular speed while riding on this Ferris wheel would be

- A) more and your tangential speed less.
- B) the same and your tangential speed less.
- C) less and your tangential speed more.
- D) None of the above

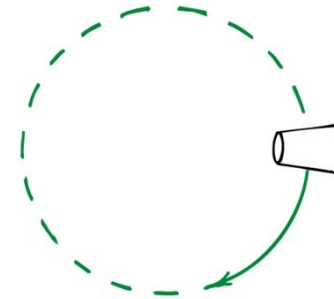
Answer: B

Same # cycles per second i.e. same angular speed, but less distance covered each second, so less tangential speed

Example and Demo: Railroad train wheels

Model: two tapered cups stuck together and rolling along meter sticks

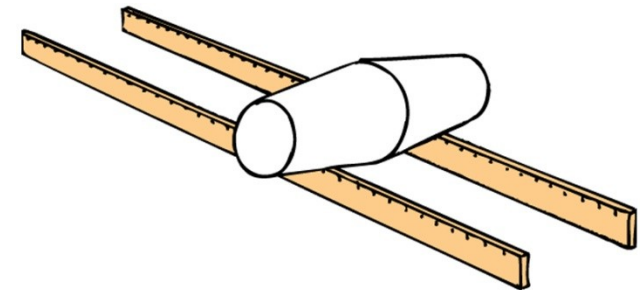
First note that if you roll a tapered cup along a table, it follows a circle because the wide part moves faster than the narrow part. (Larger v so more distance covered by the wide end).



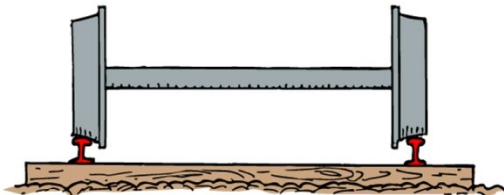
Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Now, if you tape two together, at their wide ends, and let them roll along two meter sticks (“tracks”), they will stay stably on the tracks.

Why? When they roll off center, they self-correct: say they roll to the left, then the wider part of the left cup and the narrower part of the right cup are on the tracks, causing rolling back to the right, since the left cup has larger tangential speed.



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.



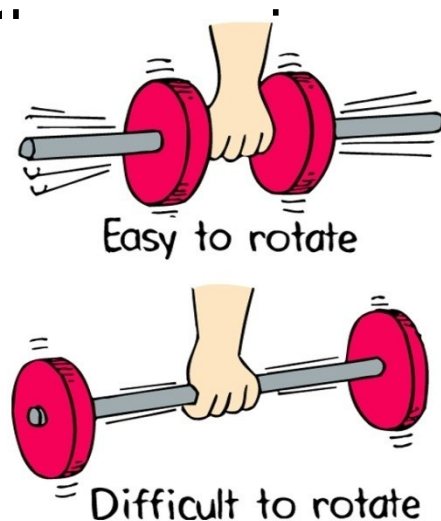
Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Railroad wheels act on this same principle!

Rotational Inertia

- An object rotating about an axis tends to remain rotating about the same axis, unless an external influence (*torque*, see soon) is acting. (c.f. 1st law)
- The property to resist changes in rotational state of motion is called **rotational inertia**, or **moment of inertia, I** .
- Depends on **mass**, as well as the **distribution of the mass relative to axis of rotation** – largest if “further away from the axis”

Eg. DEMO: Spinning a pencil with globs of play-doh on it – if the globs are near the ends of the pencil, it is harder to spin, than if the globs are nearer the middle.



Eg. Tight-rope walker carries a pole to increase his rotational inertia - if he starts to wobble, the pole starts to rotate but its inertia resists this, so the tight-rope walker has time to adjust balance and not rotate and fall.



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Better balance (more rotational inertia) if pole is longer and has weights at the ends.

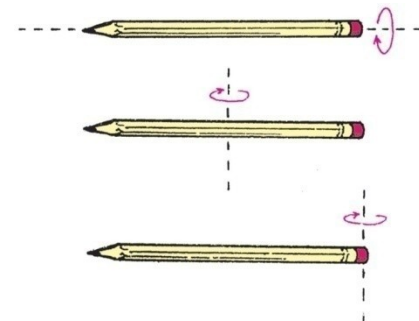
· Rotational inertia depends on the axis around which it rotates:

Eg With a pencil:

Easiest to spin here (smallest I)

Harder here

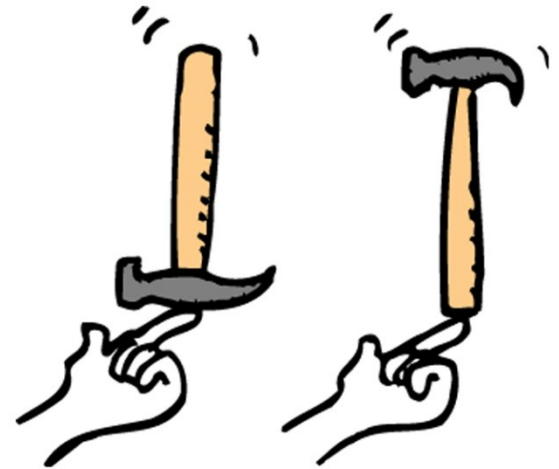
Even harder here



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Question

Consider balancing a hammer upright on the tip of your finger. Would it be easier to balance in the left-hand picture or the right-hand picture, and why?



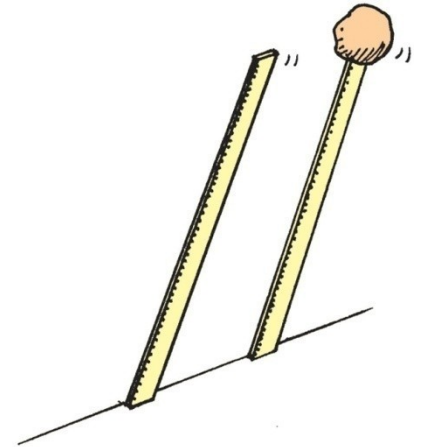
Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Easier on the right, because it has more rotational inertia (heavy part further away from your finger), so is more resistant to a rotational change.

Clicker Question

Consider the meter sticks shown, one with a glob of clay at the top end. If released from upright position, which reaches the ground first?

- A) The one without the clay
- B) The one with the clay
- C) They both reach the ground together



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Answer: A

The one without the clay! Try it! Because the stick-with-clay has more rotational inertia, so resists rotation to ground more.

(Also, experiences more torque...see later)

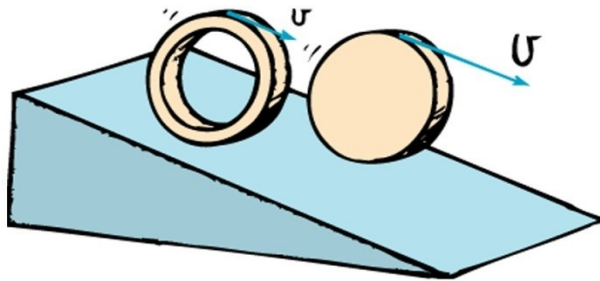
More about rotational inertia: rolling objects down a hill...

- Which rolls to the bottom of an incline first, a solid ball, a solid cylinder or a ring?

First ask: which has smallest rotational inertia? – since this will resist rolling the least, so will reach the bottom first.

The shape which has most of its mass closest to the center has least rotational inertia, i.e. first is ball, second is cylinder, and last is the ring.

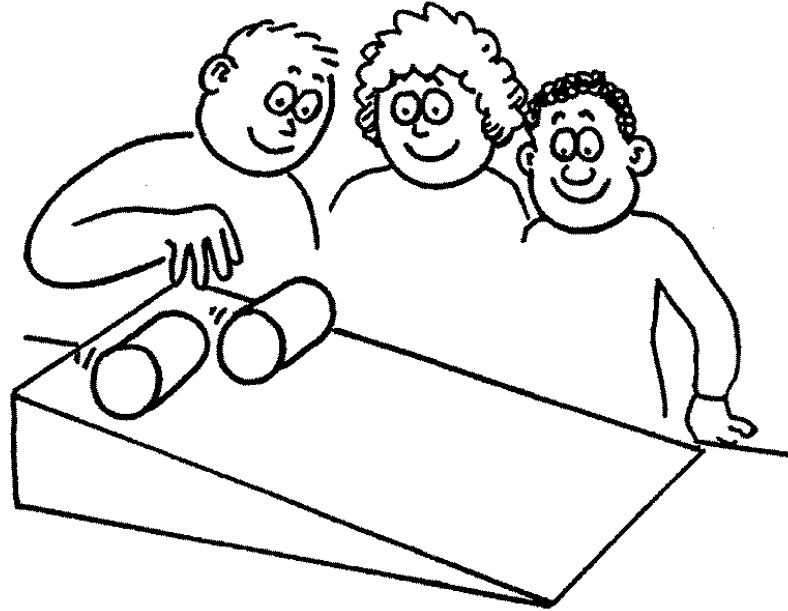
(In fact this is independent of size and mass, it just depends on their shape!)



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

- Fig 8.14 in your text illustrates some rotational inertia values of various objects – you don't need to learn these, but do try to understand why the bigger ones are bigger from considering mass distribution.

Clicker Question

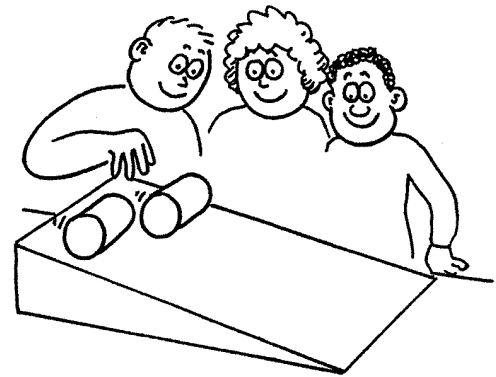


Which will roll down a hill faster, a can of regular fruit juice or a can of frozen fruit juice?

1. Regular fruit juice
2. Frozen fruit juice
3. Depends on the relative sizes and weights of the cans

Hint: Note that the regular juice is a liquid and so is not forced to roll with the can i.e. much of it slides. The frozen juice must roll with the can. So which has less rotational inertia?

Answer: 1. Regular fruit juice



Which will roll down a hill faster, a can of regular fruit juice or a can of frozen fruit juice?

- ✓ 1. Regular fruit juice
- 2. Frozen fruit juice
- 3. Depends on the relative sizes and weights of the cans

The regular fruit juice has an appreciably greater acceleration down an incline than the can of frozen juice: Because the regular juice is a liquid and is not made to roll with the can, as the solid juice does. Most of the liquid effectively slides down the incline inside the rolling can.

The can of liquid therefore has very little rotational inertia compared to its mass.

The solid juice, on the other hand, is made to rotate, giving the can more rotational inertia.

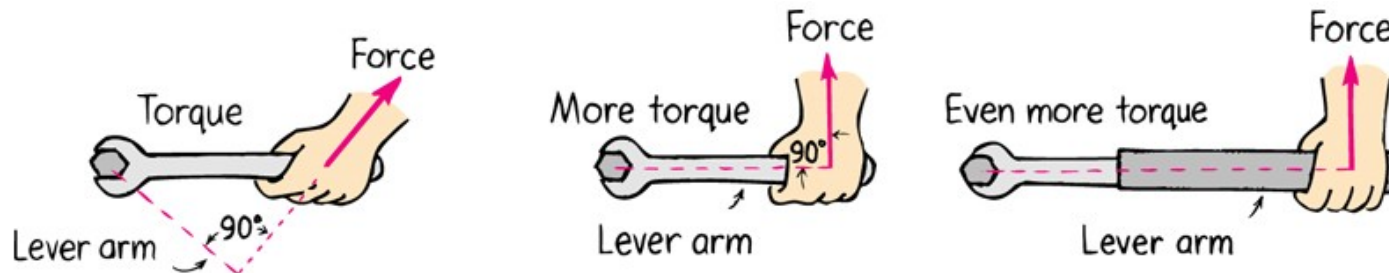
Torque

- Rotational analog of force – i.e. causes changes in rotations of objects.

$$\text{Torque} = \text{lever arm} \times \text{force}$$

lever arm = the perpendicular distance from the axis of rotation to the line along which the force acts.

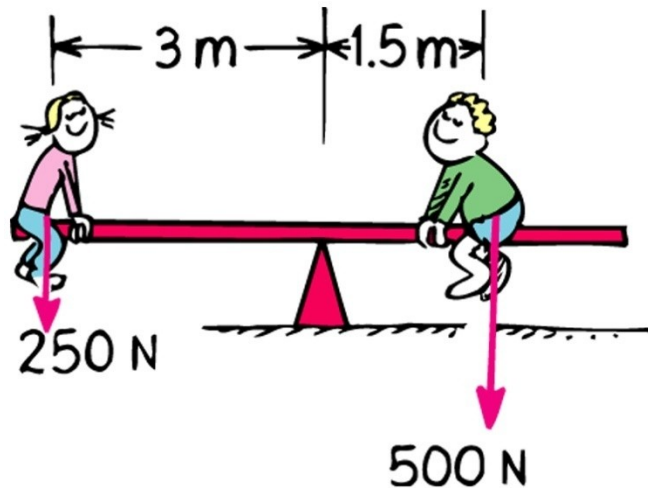
Eg. Turning a bolt



- Eg. See-saws.

The dependence of the torque on the lever arm is why kids can balance see-saws even when they have different weights – The heavier one sits closer to the center :

Larger F x Smaller lever-arm = Smaller F x Larger lever-arm.

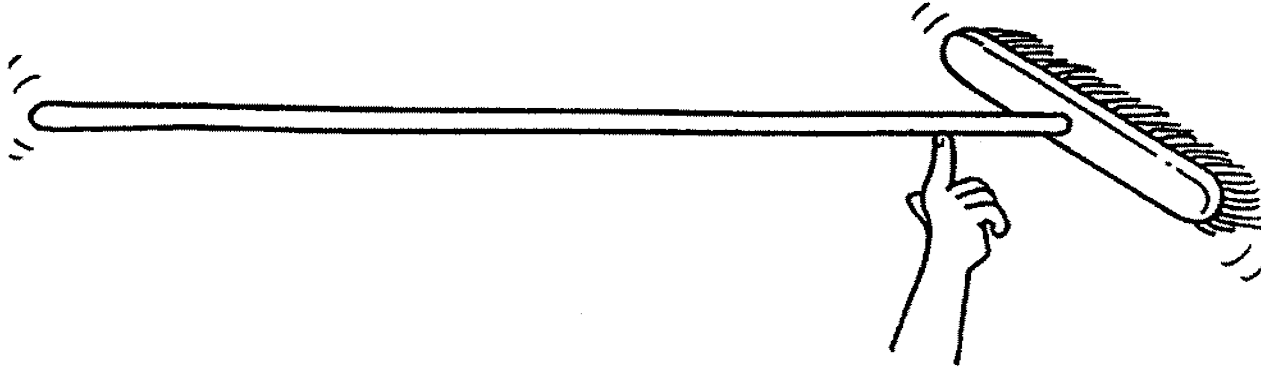


Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

- **Mechanical equilibrium:**

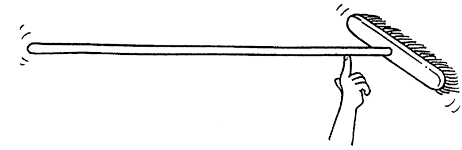
not only $\Sigma F = 0$ (chap 2) but also $\Sigma \text{torques} = \text{net torque} = 0$

Clicker Question



The broom balances at its center of gravity. If you saw the broom into two parts through the center of gravity and then weigh each part on a scale, which part will weigh more?

1. Short broom part
2. Long broom part

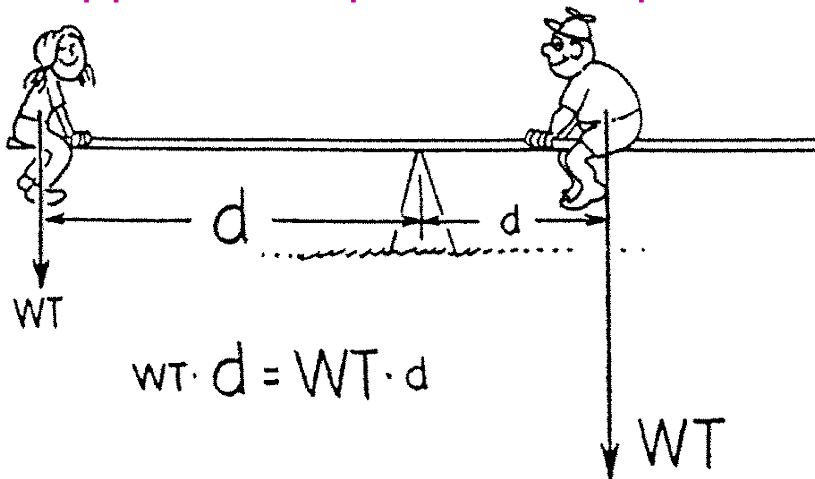


The broom balances at its center of gravity. If you saw the broom into two parts through the center of gravity and then weigh each part on a scale, which part will weigh more?

- ✓ 1. Short broom part
2. Long broom part

Answer: 1. short broom part.

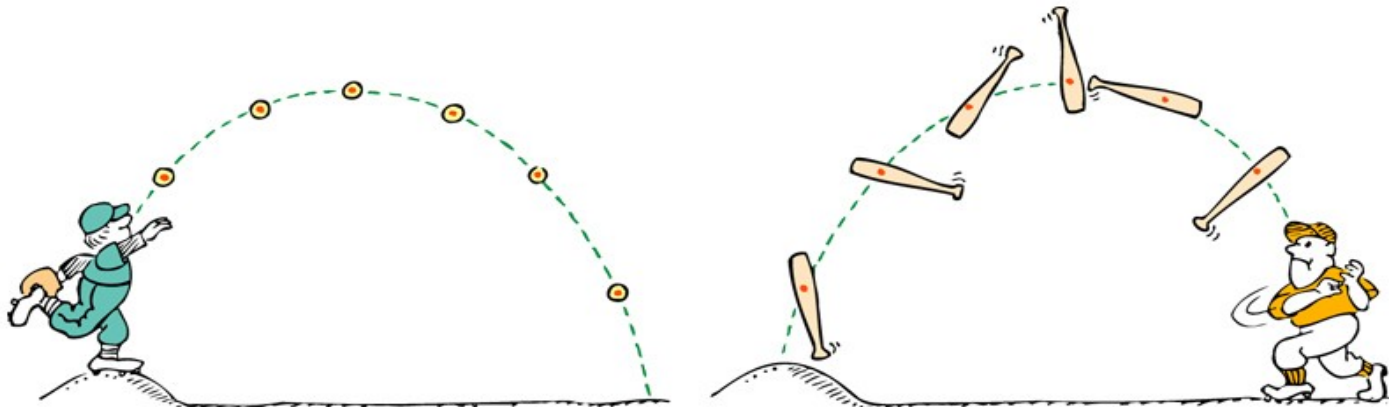
The short broom part balances the long handle just as kids of unequal weights can balance on a seesaw when the heavier kid sits closer to the fulcrum. Both the balanced broom and seesaw are evidence of equal and opposite torques—not equal weights.



Center of mass/Center of gravity

- Center of mass (CM) = average position of all the mass that makes up the object.
- Center of gravity (CG) = average position of weight distribution
 - So $CM = CG$ for objects on earth. We'll use CM and CG interchangeably.
- Often, motion of a body is complex, but CM motion is very simple:

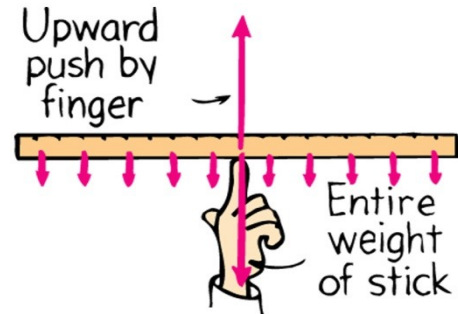
Eg. Any shaped object thrown in the air may spin in a complicated way as it falls, but the CM always follows a parabola (as if it were a point object, or ball)



Locating the CM

- When object is symmetric, it's simple eg. For a meter stick, CM is at the center. It acts as if all the mass is concentrated there.

All the small arrows indicate gravity along the stick – can combine to single large arrow acting downward through CM.

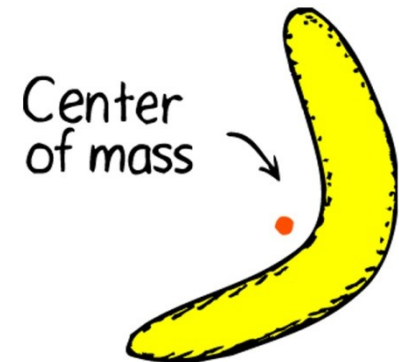


Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

- If freely suspend an object from any point, the CM lies somewhere along the line vertically down from it. So, to determine exactly where, suspend it freely from some other point on the object, let it adjust, draw again the vertical line: the intersection of the two lines gives CM.

- Sometimes, the CM is outside of the object.

Eg. A hollow ring, CM in the center, Or banana:

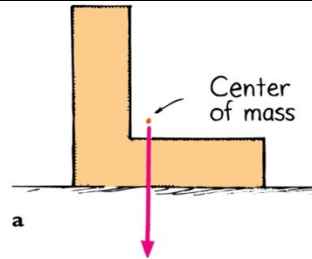


Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

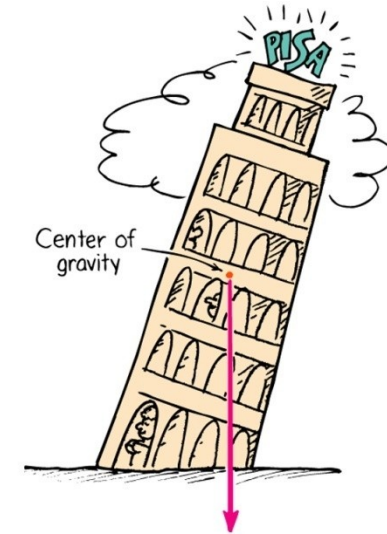
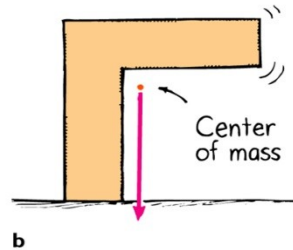
Stability

Stable equilibrium – if vertical line down from CM falls inside the base of object.

stable



unstable



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

So often design objects with a wide base and lower CM.

Clicker Question

Why should you not leave the top drawers of a heavy cabinet open while the others are closed ?

- A) The center of mass becomes too high to be stable, so it would tip
- B) The center of mass would extend in front of the cabinet, beyond the support base, so it would tip
- C) The torque exerted by the gravitational force on the drawers decreases
- D) It looks messy

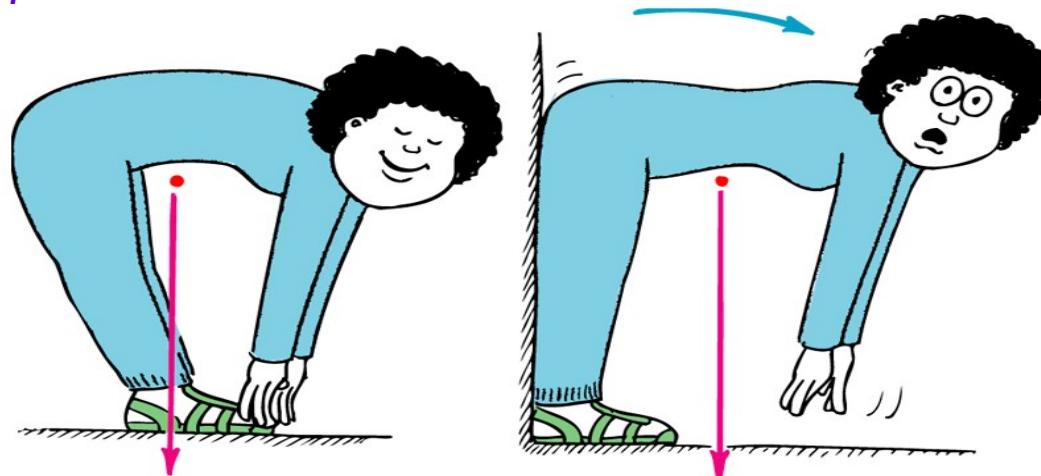
Answer B:

Objects are stable if a vertical line dropped from their COM goes through the base of the object. Leaving the top drawers open makes it look like the Γ shape on previous slide.

Example

- Why is not possible for a flexible person to bend down and touch her toes keeping legs straight, while standing with her back against a wall? (*Try this!!*)

Hint: Deduce first the CM of the person, approximating her as an L-shape (see last slides)



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

If she leans back, the CM is above the base (her feet) - stable

If she can't lean back, CM is no longer above her feet - unstable

The torque from gravity acting on the upper half of the body is larger in the RH case because the lever arm is longer.

Related problem: Try getting up from a chair without putting your feet under your chair.

Centripetal Force

- Is *any* force that is **directed toward a fixed center**.
- Often leads to motion in a circle – then, force is inwards, towards center of circle

Examples

Moon orbiting earth

Electrons orbiting nucleus in atom

Whirling object at end of a string

Car rounding a bend

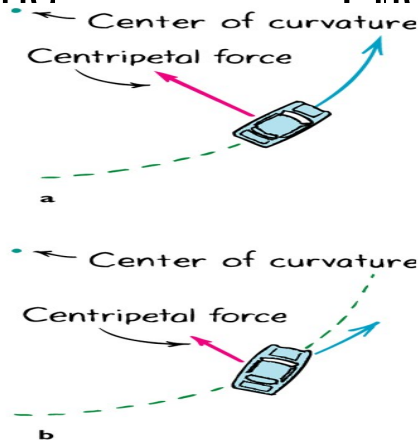
Centripetal force

Gravitational force

Electrical force

Tension in the string

Friction between tires and road



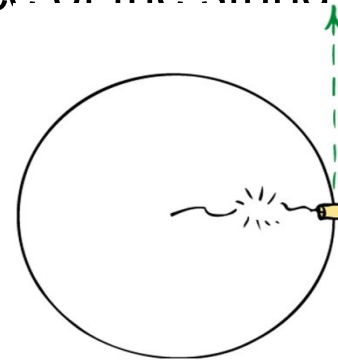
Centrifugal force

- When *you* are the object moving in a circle, you feel an **outward force** – called centrifugal force. It is a type of “inertial” force , as it is a result of rotation.

- First, consider again whirling can on end of string:

Common misconception: to say centrifugal force pulls outward on the can – wrong!

If the string breaks, the can goes off in a straight line because no force acts on it. It is the inward-directed centripetal force of the string that keeps it in a circle before string breaks.



Copyright © 2008 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley

Then why, if we were the can whirling around in a circle, would we feel we are being pushed out, rather than the inward directed centripetal force?

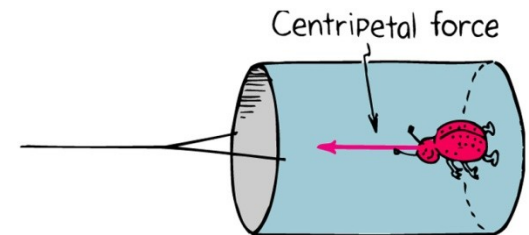
Centrifugal force continued..

...why, if we were the can, would we feel we are being pushed out rather than the inward directed centripetal force?

It's to do with the **frame of reference**: a rotating frame is a “non-inertial” frame, unlike inertial (non-accelerating) frames. **Only in inertial frames do Newton's laws strictly hold.**

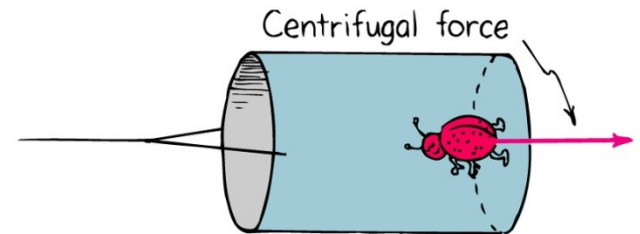
Consider a ladybug inside the can from the point of view of someone outside watching it (i.e. in an inertial frame).

Then the only force acting on it is the walls of the can on her feet, giving the inward directed centripetal force.



Now consider from the ladybug's rotating frame.

In her own frame, she is at rest. So there must be a force to cancel the wall inwardly pushing - this is the centrifugal force directed outward.



Angular momentum

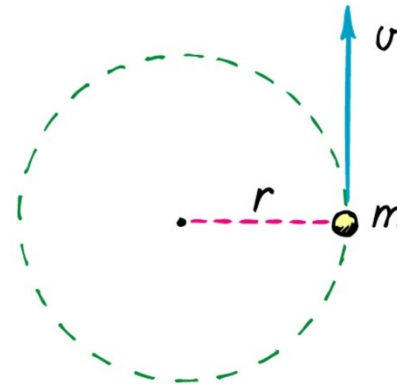
(c.f. momentum = linear momentum of Ch.6)

$$\text{Angular Momentum} = \text{rotational inertia} \times \text{rotational velocity} \\ = I \omega$$

For an object rotating around
a circular path at const speed :

$$\text{ang mom.} = m v r$$

Eg. a whirling tin can



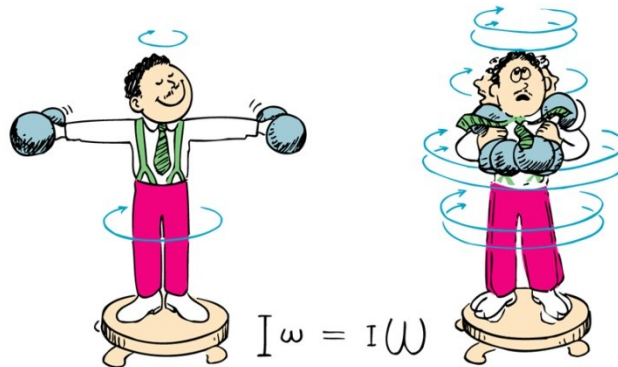
Copyright © 2008 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

Angular momentum is a vector quantity, but in this course, we won't deal with the (many interesting) consequences of its vector nature (eg gyroscopes).
Come ask me later if you'd like to learn more about this!

Conservation of Angular Momentum

An object or system of objects will maintain its angular momentum unless acted upon by an unbalanced external torque.

- So, if there is no net torque, ang mom is conserved.
- **DEMO:** Sit on a rotating stool, holding weights away from you. Then pull the weights in – you go much faster! Your I decreases when you pull in the masses, and your ω compensates, to keep $I\omega$ constant.



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

This principle is often used by a figure skater, drawing arms and legs in to spin faster.

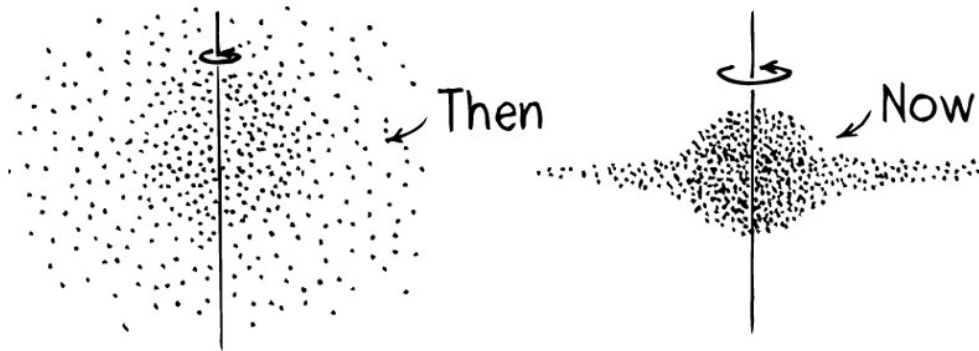
Another example: a falling cat.

Cat begins to fall upside-down but rights itself by twisting yet conserving zero angular momentum: twist parts of its body in such a way that it rotates through 180 degrees but keeping zero angular momentum!



- Another place where ang mom conservation plays big role, is in understanding motion of planets, and galaxy shapes.

e.g. we believe originally our galaxy was a huge spherical cloud of gas, rotating very slowly. Gravitational attraction between particles pulled the cloud together, so giving it a smaller radius. By ang mom cons, this means faster rotation; some stars being spun out...



Copyright © 2006 Paul G. Hewitt, printed courtesy of Pearson Education Inc., publishing as Addison Wesley.

- Read in your book about how the moon is gradually getting further away from us because earth's ang mom is decreasing from ocean-water friction, and so the moon's must increase to compensate.

If all of Earth's inhabitants moved to the equator, what would happen to the length of a day?

- A) The day would be longer
- ~~B) The day would be shorter~~
- C) The length of the day would remain the same
- D) There would be no day, only night

Answer:A

If mass moves to the equator, it is further from the axis of rotation, so the rotational inertia of the earth increases. Because the angular momentum of the earth is conserved, this means its rotational speed decreases, i.e. the length of the day would be longer.