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Work and Energy

The physical description of energy

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Energy: the capacity to do work

- This notion makes sense even in a colloquial context:
  - hard to get work done when you're wiped out (low on energy)
  - work makes you tired: you've used up energy
- But we can make this definition of energy much more precise by specifying exactly what we mean by *work*

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Work: more than just unpleasant tasks

- In physics, the definition of work is the application of a *force through a distance*

$$W = F \cdot d$$

- W is the *work* done
- F is the *force* applied
- d is the *distance* through which the force acts
- Only the force that acts in the direction of motion counts towards work

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Okay, what is Force, then

- Force is a pushing/pulling agent
- Examples:
  - gravity exerts a downward force on you
  - the floor exerts an upward force on a ball during its bounce
  - a car seat exerts a forward force on your body when you accelerate forward from a stop
  - the seat you're sitting in now is exerting an upward force on you (can you feel it?)
  - you exert a sideways force on a couch that you slide across the floor
  - a string exerts a centrally-directed (centripetal) force on a rock at the end of a string that you're twirling over your head
  - the expanding gas in your car's cylinder exerts a force against the piston

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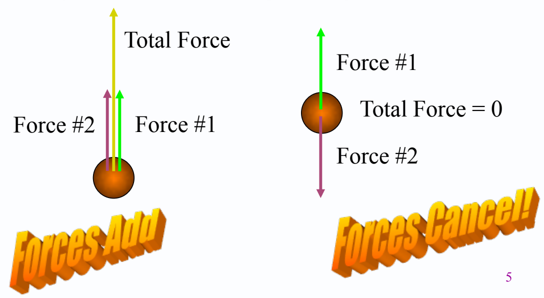
Forces have Direction

- In all the previous examples, force had a direction associated with it
- If multiple forces act on an object, they could potentially add or cancel, depending on direction



When net force is not zero

- When an object experiences a non-zero net force, it *must* accelerate
- Newton's second law:

  $F = m \cdot a$ Force = mass times acceleration
- The same force makes a small object accelerate more than it would a more massive object
  - hit a golf ball and a bowling ball with a golf club and see what happens

Yeah, but what is acceleration, exactly

- This is getting to be like the "hole in the bucket" song, but we're almost there…
- Acceleration is *any* change in *velocity* (speed *and/or* direction of motion)
- Measured as rate of change of velocity
  - velocity is expressed in meters per second (m/s)
  - acceleration is meters per second <u>*per second*</u>
  - expressed as m/s^2 (meters per second-squared)

Putting it back together: Units of Energy

- Force is a mass times an acceleration
  - mass has units of kilograms
  - acceleration is m/s^2
  - force is then $kg \cdot m/s^2$, which we call Newtons (N)
- Work is a force times a distance
  - units are then $(kg \cdot m/s^2) \cdot m = kg \cdot m^2/s^2 = N \cdot m$ = Joules (J)
  - One Joule is one Newton of force acting through one meter
  - Imperial units of force and distance are pounds and feet, so unit of energy is foot-pound, which equals 1.36 J
- Energy has the same units as work: Joules

A Zoo of Units

- Our *main unit* of energy will be the metric unit of the Joule, but many others exist:
- The calorie is 4.184 Joules
  - raise 1 gram (c.c.) of water one degree Celsius
- The Calorie (kilocalorie) is 4,184 J
  - raise 1 kg (1 liter) of water one degree Celsius
- The Btu (British thermal unit) is 1,055 J (roughly 1 kJ)
  - raise 1 pound of water one degree Fahrenheit
- The kilowatt-hour (kWh) is 3,600,000 J
  - one Watt (W) is one Joule per second
  - a kWh is 1,000 W for one hour (3,600 seconds)

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A note on arithmetic of units

- You should carry units in your calculations and multiply and divide them as if they were numbers
- Example: the force of air drag is given by:

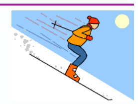
$F_{drag} = \frac{1}{2} c_D \rho A v^2$

- c_D is a dimensionless drag coefficient
- ρ is the density of air, 1.3 kg/m^3
- A is the cross-sectional area of the body in m^2
- v is the velocity in m/s

units: $(\text{kg/m}^3)\cdot(\text{m}^2)\cdot(\text{m/s})^2 = (\text{kg}\cdot\text{m}^2/\text{m}^3)\cdot(\text{m}^2/\text{s}^2) = \frac{\text{kg}\cdot\text{m}^2\cdot\text{m}^2}{\text{m}^3\cdot\text{s}^2}$

$= \frac{\text{kg}\cdot\text{m}^4}{\text{m}^3\cdot\text{s}^2} = \text{kg}\cdot\text{m/s}^2 = \text{Newtons}$

Kinetic Energy



- Kinetic Energy: the energy of motion
- Moving things carry energy in the amount:

$K.E. = \frac{1}{2} m v^2$

- Note the v^2 dependence—this is why:
  - a car at 60 mph is 4 times more dangerous than a car at 30 mph
  - hurricane-force winds at 100 mph are much more destructive (4 times) than 50 mph gale-force winds
  - a bullet shot from a gun is at least 100 times as destructive as a *thrown* bullet, even if you can throw it a tenth as fast as you could shoot it

Numerical examples of kinetic energy

- A baseball (mass is 0.145 kg = 145 g) moving at 30 m/s (67 mph) has kinetic energy:

$\text{K.E.} = \frac{1}{2}\times(0.145 \text{ kg})\times(30 \text{ m/s})^2$

$= 65.25 \text{ kg}\cdot\text{m}^2/\text{s}^2 \approx 65 \text{ J}$

- A quarter (mass = 0.00567 kg = 5.67 g) flipped about four feet into the air has a speed on reaching your hand of about 5 m/s. The kinetic energy is:

$\text{K.E.} = \frac{1}{2}\times(0.00567 \text{ kg})\times(5 \text{ m/s})^2$

$= 0.07 \text{ kg}\cdot\text{m}^2/\text{s}^2 = 0.07 \text{ J}$

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More numerical examples

- A 1500 kg car moves down the freeway at 30 m/s (67 mph)

  K.E. = ½×(1500 kg)×(30 m/s)^2

  = 675,000 kg·m^2/s^2 = 675 kJ
- A 2 kg (~4.4 lb) fish jumps out of the water with a speed of 1 m/s (2.2 mph)

  K.E. = ½×(2 kg)×(1 m/s)^2

  = 1 kg·m^2/s^2 = 1 J

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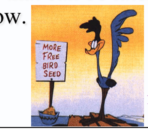
Gravitational Potential Energy

- It takes *work* to lift a mass against the pull (force) of gravity
- The force of gravity is $m \cdot g$, where m is the mass, and g is the gravitational acceleration

  $F = mg$ (note similarity to $F = ma$)
  - g = 9.8 m/s^2 on the surface of the earth
  - $g \approx$ 10 m/s^2 works well enough for this class
- Lifting a height h against the gravitational force requires an energy input (work) of:

  $\Delta E = W = F \cdot h = mgh$
- Rolling a boulder up a hill and perching it on the edge of a cliff gives it gravitational *potential* energy that can be later released when the roadrunner is down below.



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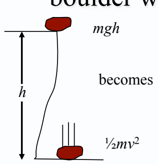
First Example of Energy Exchange

- When the boulder falls off the cliff, it picks up speed, and therefore gains kinetic energy
- Where does this energy come from??

  ⇒ from the *gravitational potential energy*
- The higher the cliff, the more kinetic energy the boulder will have when it reaches the ground



Energy is conserved, so
$\frac{1}{2}mv^2 = mgh$

Can even figure out v, since $v^2 = 2gh$

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Examples of Gravitational Potential Energy

- How much gravitational potential energy does a 70 kg high-diver have on the 10 meter platform?

  mgh = (70 kg)×(10 m/s^2)×(10 m)

  = 7,000 kg·m^2/s^2 = 7 kJ
- How massive would a book have to be to have a potential energy of 40 J sitting on a shelf two meters off the floor?

  $mgh = m$×(10 m/s^2)×(2 m) = 40 J

  so m must be 2 kg

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The Energy of Heat

- Hot things have more energy than their cold counterparts
- Heat is really just kinetic energy on microscopic scales: the vibration or otherwise fast motion of individual atoms/molecules
  - Even though it's kinetic energy, it's hard to derive the same useful work out of it because the motions are *random*
- Heat is frequently quantified by calories (or Btu)
  - One calorie (4.184 J) raises one gram of H_2O 1ºC
  - One Calorie (4184 J) raises one kilogram of H_2O 1ºC
  - One Btu (1055 J) raises one pound of H_2O 1ºF

Energy of Heat, continued

- Food Calories are with the "big" C, or kilocalories (kcal)
- Since water has a density of one gram per cubic centimeter, 1 cal heats 1 c.c. of water 1ºC, and likewise, 1 kcal (Calorie) heats one liter (1 kg) of water 1ºC
  - these are useful numbers to hang onto
- Example: to heat a 2-liter bottle of Coke from the 5ºC refrigerator temperature to 20ºC room temperature requires 30 Calories, or 122.5 kJ

Heat Capacity

- Different materials have different *capacities* for heat
  - Add the same energy to different materials, and you'll get different temperature rises
  - Quantified as heat capacity
  - Water is exceptional, with 4,184 J/kg/ºC
  - Most materials are about 1,000 J/kg/ºC (including wood, air, metals)
- Example: to add 10ºC to a room 3 meters on a side (cubic), how much energy do we need?

  air density is 1.3 kg/m^3, and we have 27 m^3, so 35 kg of air; and we need 1000 J per kg per ºC, so we end up needing 350,000 J (= 83.6 Cal)

2×Q

Power

- Power is simply energy exchanged per unit time, or how fast you get work done (Watts = Joules/sec)
- One horsepower = 745 W
- Perform 100 J of work in 1 s, and call it 100 W
- Run upstairs, raising your 70 kg (700 N) mass 3 m (2,100 J) in 3 seconds → 700 W output!
- Shuttle puts out a few GW (gigawatts, or 10^9 W) of power!

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Power Examples

- How much power does it take to lift 10 kg up 2 meters in 2 seconds?

  $mgh = (10\text{ kg})\times(10\text{ m/s}^2)\times(2\text{ m}) = 200\text{J}$

  200 J in 2 seconds → 100 Watts
- If you want to heat the 3 m cubic room by 10ºC with a 1000 W space heater, how long will it take?

  We know from before that the room needs to have 360,000 J added to it, so at 1000 W = 1000 J/s this will take 360 seconds, or six minutes.

  But: the walls need to be warmed up too, so it will actually take longer (and depends on quality of insulation, etc.)

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Getting to know the Watt

- How much energy does a 100 W light bulb use?
  - what does 100 W mean?
    - it's a *rate* of energy expenditure
  - does 100 W per second, per minute, etc. make sense?
    - this would be an *acceleration* of energy use
  - answer depends on time the light bulb is *on*
    - 100 W bulb uses 100 J/s or 6,000 J per minute; 360,000 J/hr
- Think of power as something measured by a speedometer
  - a rate of usage
- And energy as the odometer measurement
  - the amount used

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Examples of Power, in Watts

heating → lots of power 23

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The kilowatt-hour

- We will often see the kilowatt-hour (kWh) as a unit of…
- …Energy
- 1 kWh is a power times a time → energy
  - 1000 W (kW) for one hour
    - 1 hr = 3600 sec → 1 kWh = 3,600,000 J = 3.6 MJ
  - 1 W for 1000 hours
  - 100 W for 10 hours
  - 2000 W for 30 minutes
  - 3.6 MW for one second
- so a 100 W bulb left on for a day is 2.4 kWh

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Clip from today's paper

The New York Times

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AFRICA **AMERICAS** ASIA PACIFIC EUROPE MIDDLE EAST

In Sign of Warming, 1,600 Years of Ice in Andes Melted in 25 Years

Throughout the Andes, glaciers are now melting so rapidly that scientists have grown deeply concerned about water supplies for the people living there. Glacial meltwater is essential for helping Andean communities get through the dry season.

(transient) it's what we do

In the short run, the melting is producing an increase of water supplies and feeding population growth in major cities of the Andes, the experts said. But as the glaciers continue shrinking, trouble almost certainly looms.

Douglas R. Hardy, a University of Massachusetts researcher who works in the region, said, "How much time do we have before 50 percent of Lima's or La Paz's water resources are gone?"

just like our jar doubling time questions

Assignments

- Read Chapter 1 and Appendix in textbook
- Homework #1 due April 12 in class:
  - Chapter 1: Q&P 1, 2, 8; M.C. 2, 3, 4, 5, 7, 8, 11, 14
  - plus supplemental required problems, posted online