Lecture 6

Conservation Laws: The Most Powerful Laws of Physics

Momentum $p = m_1 v_1 + m_2 v_2 + ...$

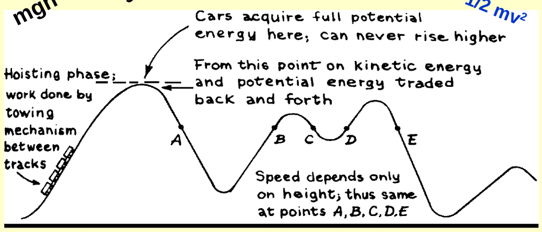
Energy $E = PE + KE + ...$

Potential Energy

mgh

Kinetic Energy

$1/2\ mv^2$



Other forms of energy

Announcements

- Mon., Sept. 22: Second Law of Thermodynamics
  Give out Homework 4
- Wed., Sept. 24: Waves
  Homework 3 due
- Mon., Sept 29: Review before Exam I
  Homework 4 due
- Wed., Oct. 1: Exam I
  Covers material through the Review
  Chapters 1 – 5, 7 of March; Ch. 11-2 of Lightman

Introduction

- Last Time:
  Newton's 3 Laws & Gravitational Forces
  - Newton's 3 laws tell us how to predict the motion of any body if we know the forces that act on it
  - The examples we used were the simplest cases:
    Constant acceleration (which means constant force)
    Uniform circular motion
    Examples of the effects of gravitational forces
  - Very complicated to apply in most cases!
- Today: Conservation Laws
  - The most useful conclusions without solving equations!
  - Conservation of momentum: Follows from Newton's third law. (Chapt. 2 in March)
  - Conservation of energy: The most important and useful law. (Chapt. 5 in March)
  - MORE important than Newton's Equations! - still valid in modern physics even though Newton's laws are not !

Conservation Laws Why they are so powerful

- Newton's Laws show how to describe the motion of every object
  - Determined by the FORCES acting on each object at a each time t.
  - Newton's 2nd Law gives the ACCELERATION at time t.
  - Acceleration determines how the velocity and position of the object will change at time t.
  - VERY complicated to apply to most problems !
- What can be known without finding all the details?
- Can any predictions of future behavior be made?
  - Yes.. conservation laws allow us to make important conclusions without knowing any details!

Conservation Laws Examples outside physics (May be not be exact like physical laws)

- Example in Lightman - Child's blocks
  - Even if blocks disappear, there may be ways to detect them and show the number does not change
- Money in your pockets
  - Conserved if you do not add or subtract
  - Change in total can be related directly to income minus outgo
- Other
  - ....

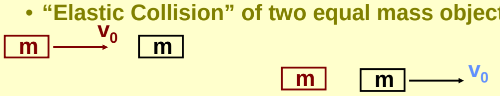
Momentum and Kinetic Energy Two Different Measures of Motion

- Momentum (vector)
  - Momentum for one particle $\vec{p} = m\,\vec{v}$
  - Momentum for many particles $\vec{p} = \sum_i m_i \vec{v}_i$
- Energy (scalar - no direction)
- Kinetic Energy for a particle $KE = \frac{1}{2} m\,|v|^2$
- Kinetic Energy for many particles $KE = \sum_i \frac{1}{2} m_i |v_i|^2$

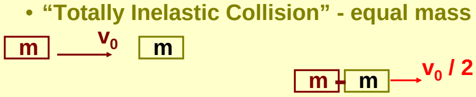
Lecture 6

Conservation of Momentum

- As discussed previously, Newton's 3rd Law (in conjunction with the 2nd Law) implies that the total momentum of two interacting objects is conserved (*ie* does not change in time).
- Air Track Demos:
  - "Elastic Collision" of two equal mass objects:



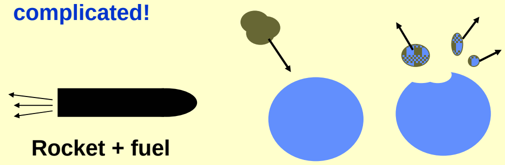
  - "Totally Inelastic Collision" - equal mass objects:



Momentum is conserved in both these cases, but the final motions are quite different. How do we understand the origin of this difference?

Conservation of Momentum

- Momentum is conserved in both cases, even though in the both cases complicated things are going on the causes the cars to bounce or to stick together.
- For an isolated system (no external forecs) momentum is conserved no matter how complicated!



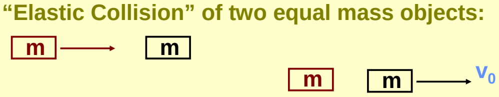
Momentum is conserved in all these cases.

Conservation of Momentum

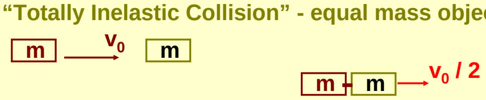
- Exercise - List examples
- For an isolated system (no external forces) momentum is conserved no matter how complicated!
- Put list on board

What about Energy?

- "Elastic Collision" of two equal mass objects:



- Kinetic Energy:
  Before: $(1/2)mv_0^2$ same as After: $(1/2)mv_0^2$
- "Totally Inelastic Collision" - equal mass objects:



- Kinetic Energy:
  Before: $(1/2)mv_0^2$
  After: $(1/2)(2m)(v_0/2)^2 = (1/4)mv_0^2$
  Kinetic Energy NOT the same after collision!

Conservation of Energy
First Law of Thermodynamics

- Total energy is conserved - this is even more basic than Newton's laws
- Holistic Law
- Energy comes in many forms. One form can be converted into another, but the total never changes!
- Kinetic energy: energy of motion
  Potential energy: Stored energy
  (due to gravity, compressed springs, batteries, chemical reactions, ...)
  Heat: Hotter objects contain more energy
  Other: Nuclear, ...
- (Later we will see that Einstein showed a different interpretation of this idea, but nevertheless the conservation law still applies!)

Conservation of Energy

- Exercise - List examples
- For an isolated system (no exchange with the rest of the world) energy is conserved no matter how complicated!
- Types of energy
- Put list on board

Lecture 6

Conservation of energy (continued)

- The conservation of energy is one of the most important laws in physics - One of the most important for society as well!
- Energy is the engine of modern society
- Conversion of energy from one form to another is the "infrastructure" of nations
  - Oil to kinetic energy
  - Gravity to lights in your home
  - Sun's energy to food
- All uses of energy have some loss - to friction - that wind up as heat
- Reducing losses (for example by thermal insulation, efficient motors, . . .) is a key goal for the future

Gravitational Potential Energy

- How do we describe freely falling bodies in terms of energy?
  - Initially, if released from rest, there is NO kinetic energy.
  - When the body falls, the kinetic energy increases.
  - Where does this energy come from? What has changed? Only the position of the body with respect to the surface of the Earth!
- Define the gravitational potential energy of mass m near the surface of the Earth as:

  Potential Energy = mgh

  where h = height of mass above some reference point (*e.g.* floor)

- As the mass falls, its potential energy is converted to kinetic energy. This energy can be recovered!
- Works for complex problems - like roller coasters

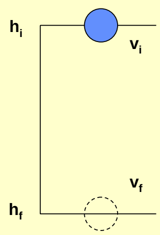
Gravitational Potential Energy & Kinetic Energy

- Derivation of formulas for conservation of energy
  - Assume the energy is all gravitational or kinetic energy.
- We know

  $v_f - v_i = g(t_f - t_i)$ and $h_i - h_f = ½ (v_f + v_i)(t_f - t_i)$
- Thus $h_i - h_f = ½ (v_f + v_i)(v_f - v_i)/g = (v_f^2 - v_i^2)/2g$

  And $mg(h_i - h_f) = ½ m (v_f^2 - v_i^2)$
- Then $E = mgh_i + ½ m v_i^2$

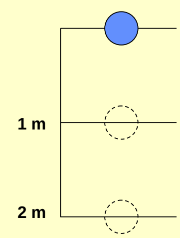
  $= mgh_f + ½ m v_f^2$



- PE + KE is conserved

Gravitational Potential Energy

- Example of conservation of energy
  - Assume the energy is all gravitational or kinetic energy.
  - That is we assume there is no input from an engine, no loss to heat or other conversion of energy to other forms
- Use conservation of $E = mgh + ½ m v^2$
- If v= 0 at $h = h_{top}$, what is v at $h = h_{top}$ - 1 m?
- What is v at $h = h_{top}$ - 2 m?



Other types of Potential Energy

- A compressed (or extended) spring
  For a high quality spring essentially all the energy required to deform it can be recovered - i.e., it is useful potential energy
- Twisted rubber band
- Bending of the bow which transfers energy to the arrow

Work

- Work is the transfer of energy by force acting on an object that is displaced
- Work is a form of energy: conservation of energy means that the energy of a system increases by the amount of work done on it
- Example: it takes work to raise a body and increase its potential energy
  - Work is needed to raise a roller coaster to the top
- Formula: $W = F \times \cos(\theta)$
  - W = 0 for force perpendicular to displacement (such as the effect of a centripetal force on a body moving in a circle)
  - W = Fx for force parallel to displacement

Lecture 6

Work

- Formula: $W = F \times \cos(\theta)$
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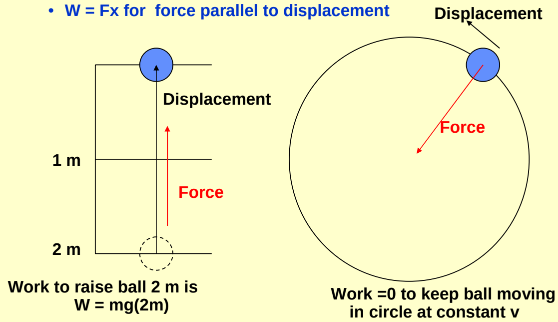
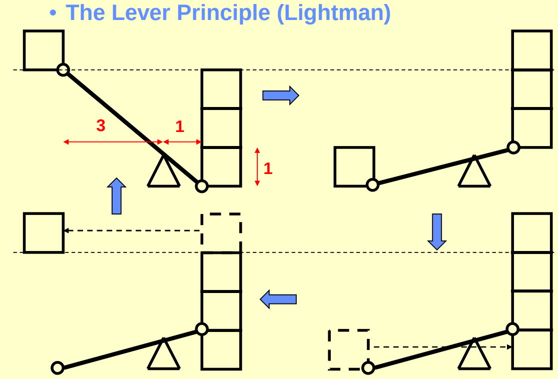


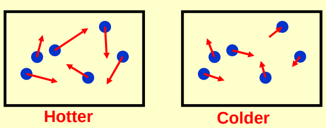
Solving problems using Cons. of Energy

- The Lever Principle (Lightman)



Heat

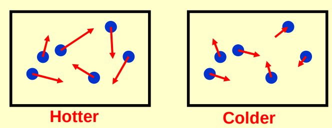
- Heat is a form of energy – internal energy of a material made up of atoms in motion (Atoms? More about them later)



- Heat is due to motions of atoms in random directions - cannot be completely channeled into useful work
- Why? This brings in new concepts and the second law of thermodynamics – Next time.
- Friction causes conversion of mechanical energy to heat.

First law of thermodynamics

- Conservation of Energy is The First Law
- Heat was very important in generalizing the conservation law to ALL forms of energy

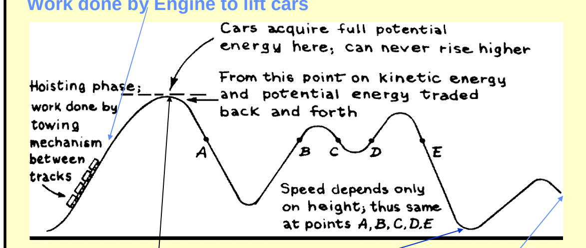


- Heat is not obviously visible like mechanical motion of a large object
- Julius Meyer is credited with formulating the law as conservation of all forms of energy

Conservation of Energy: Roller Coaster

Energy at top = mgh + (1/2) mv^2 + Heat energy

Work done by Engine to lift cars



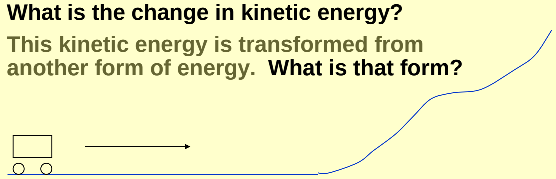
Potential energy largest = mgh

Kinetic energy largest = 1/2 mv^2

Brakes convert remaining Kinetic energy to heat

Exercise: Cons. of Energy

- An automobile of mass 2000 kg goes from rest to 30 m/s on a level road.
- What is the change in kinetic energy?
- This kinetic energy is transformed from another form of energy. What is that form?

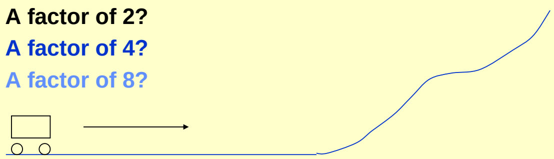


- The car moving at 30 m/s now starts up a hill. If no energy is supplied by the engine, what is the maximum height to which the car can coast.

Lecture 6

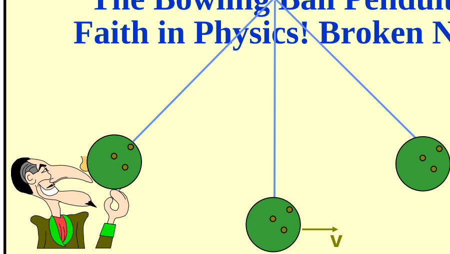
Exercise II: Cons. of Energy

- If the speed of the car is doubled to 60 m/s, is the maximum height it can reach increased by:
- A factor of 2?
- A factor of 4?
- A factor of 8?



- If the car does not reach the maximum height, where does the energy go?
- If the car exceeds the maximum height, what will you say? Physics is wrong?

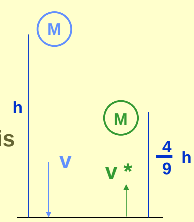
The Bowling Ball Pendulum: Faith in Physics! Broken Nose?



- Demo: Hold bowling ball to nose and release
- What *should* happen?
  - Conservation of energy predicts no broken nose!
  - Ball should swing out, having maximum velocity at the low point of its swing.
  - Ball should have zero velocity when it returns to height of nose!
  - Secrets: don't move head and don't push!!!

Exercise: Gravitational Energy

- A ball dropped on a hard floor bounces back to 4/9 of its original height.
- What fraction of its kinetic energy is lost during the bounce?
- Into what other forms is the energy transformed?
- What is the ratio of the speed just after the bounce to the speed just before?



Power

- Power = energy per unit time
- Unit: Watt = 1 Joule per second
- Light bulb - typical 100 watts = 100 joules/sec
  Heaters, etc, quoted in kilowatts
- Often Energy is quoted in kilowatt hours = 10^3 joules/sec x 3600 sec = 3.6 x 10^6 joules
- (Costs about $0.10 – cost of 10 light bulbs for 1 hour)

Exercise related to Power

- A 100 watt light bulb is on 24 hours a day
- How much energy is used in a month?
- E = 100 W x 24 hr/day x 30 days =
  = 0.1 KW x 720 hr = 72 KW-hours

  At $0.10/ 72 KW-hours, this costs $7.20.
- (Also E =
  100 J/s x 60 s/min x 60 min/hr 24 hr/day x 30 days
  = 100 x 60 x 60 x 24 x 30 J
  = 2.592 x 10^8 J (not a practical scale!))

Summary

- Conservation Laws are the most powerful laws of physics
  - Important conclusions with no details
  - We considered them in the context of Newton's laws
  - Really more general. These will still apply in the new revolutions of physics
- Conservation of Momentum (Vector)
  - For an isolated system (no external forces) the momentum is conserved , i.e., the magnitude and direction never changes!
- Conservation of Energy
  - Energy comes in many forms. One form can be converted into another, but the total never changes!
  - Can apply to an isolated system
  - If system is not isolated, the change of energy exactly equals the energy added from the rest of the world (e.g. work)
  - No free lunch!

Lecture 6

Next Time

- The second Law of Thermodynamics
  - Entropy
  - The "arrow of time"
- Read
  - Lightman, Ch. 2