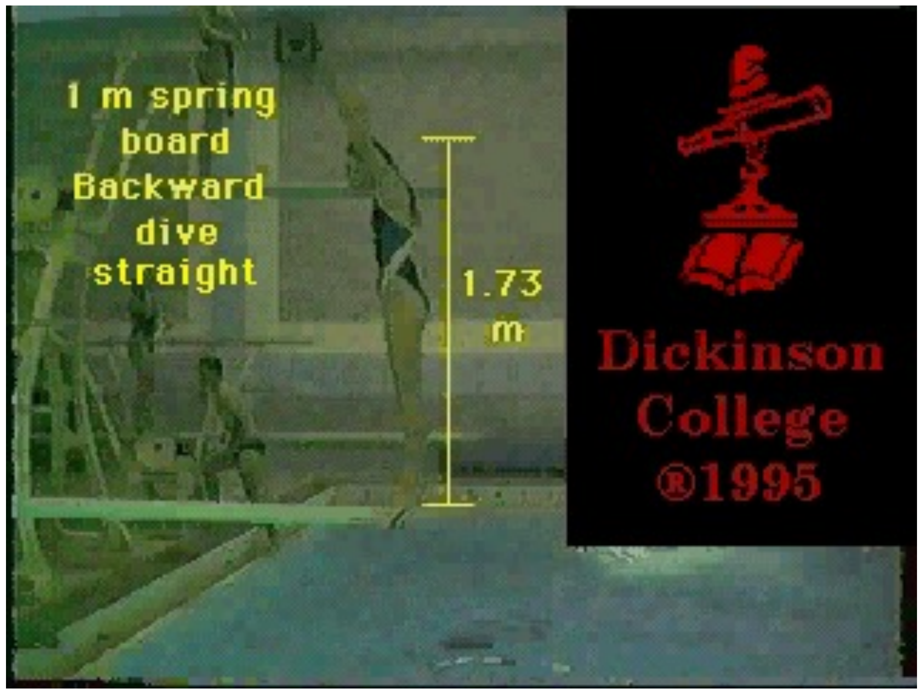
Physics 141.
Lecture 13.

There are multiple-particle systems in your future.



Physics 141.
Lecture 13

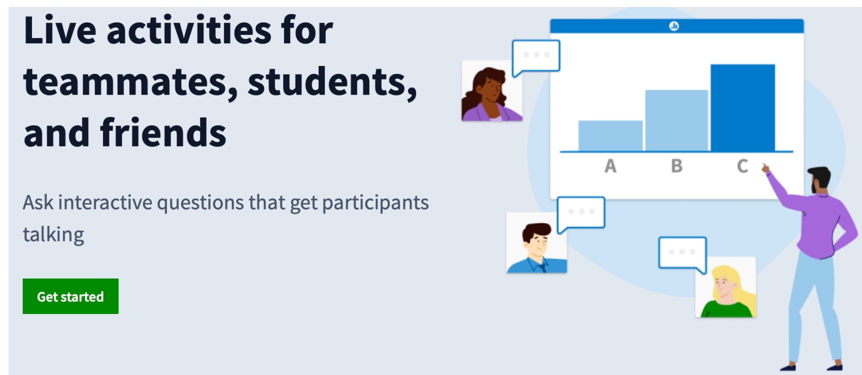
- Course Information:
  - Homework set # 6
  - Laboratory experiment # 3
- Complete our discussion of Chapter 8:
  - A quick review of topics discussed on last time:
    - Emission and absorption spectra.
    - Vibrational energy levels.
    - Rotational energy levels.
  - Incoherent and coherent emission of light – the laser.
- Start our discussion of Chapter 9:
  - Center of mass.
  - Motion of complex objects.

Physics 141.
Course information.

- Homework:
  - Homework set 6 will be WebWork only and will be due Friday 10/25 at 12 pm.
- Laboratory:
  - Laboratory report # 3 will count twice as much as reports # 2, which counted twice as much as report # 1. Make sure you put into practice what you learned from reports # 1 and # 2.
  - Laboratory report # 3 is due on Wednesday 10/23 at noon.
- No office hours today.

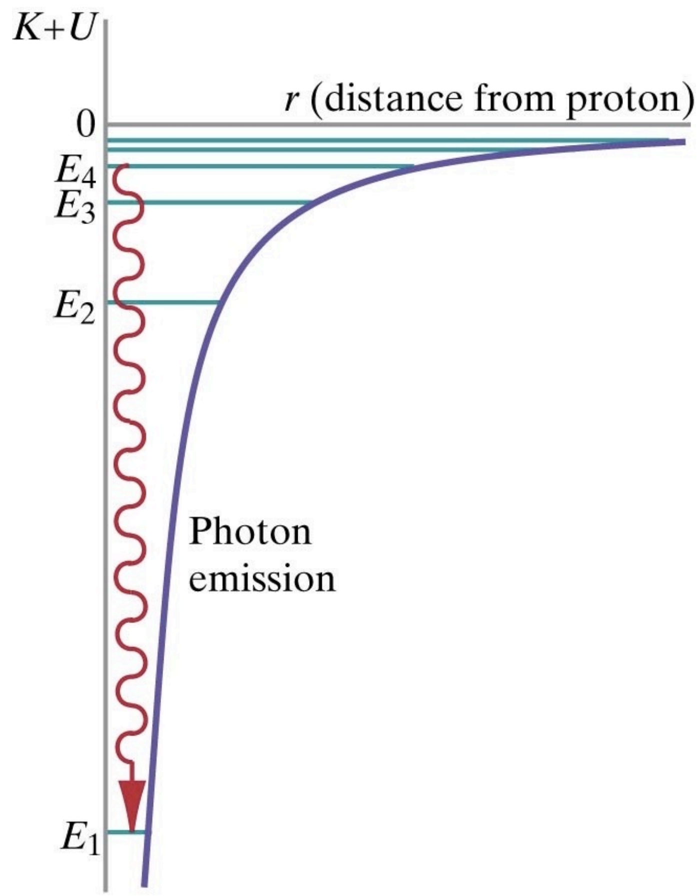
Quiz lecture 013.
PollEv.com/frankwolfs050

- The quiz today will have three questions. All answers are correct!
- I will collect your answers electronically using the Poll Everywhere system.
- The answers for each question will be entered in sequence (first 30 s for question 1, followed by 30 s for question 2, etc.).



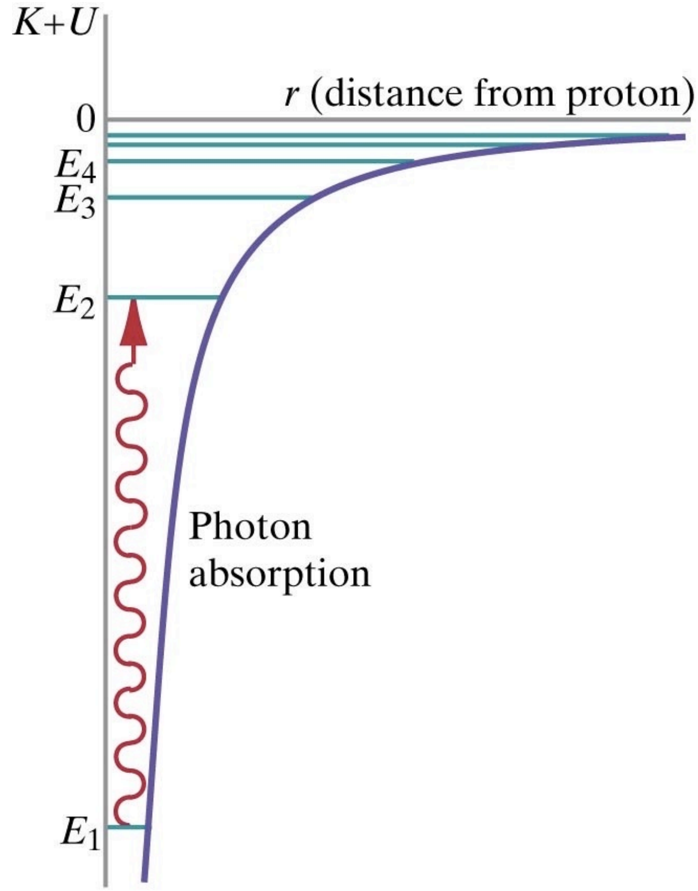
Quantization of energy.
A quick review: emission patterns.

- Light is emitted when an excited atom makes a transition to a lower energy level.
- Since the light emitted during these transitions have discrete wavelengths, the energy levels of atoms must be quantized.
- The energy levels serve as a signature (finger print) for the atom, and the **emission pattern** can be used to identify the atom.



Quantization of energy. A quick review: absorption patterns.

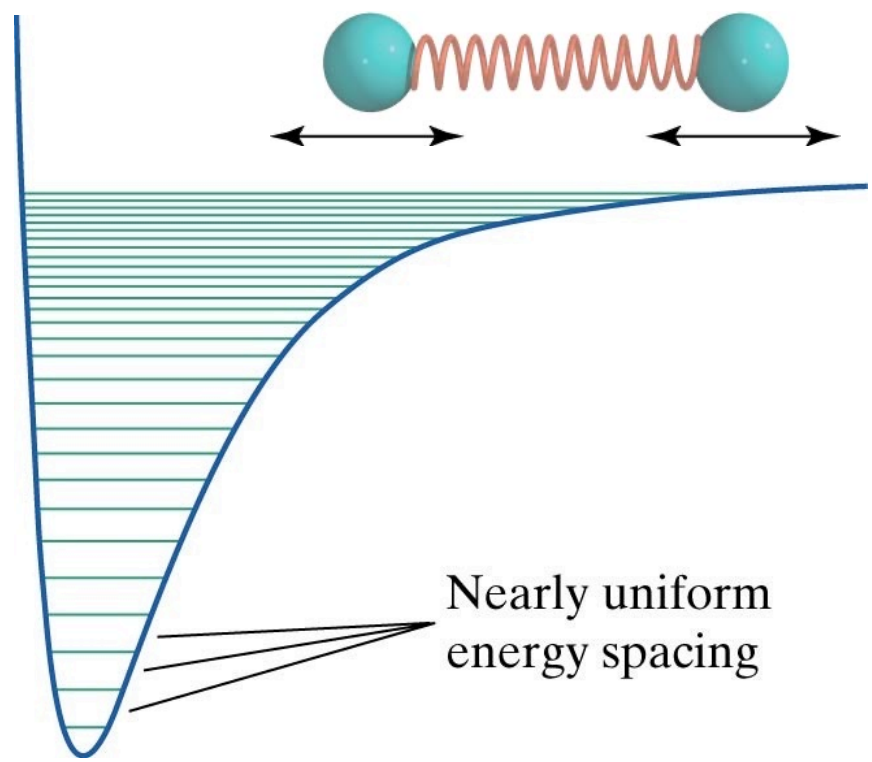
- When an atom is in its ground state, it can only absorb photons of specific frequencies.
- Only photons with an energy that exactly match possible transitions between energy levels in the atom are absorbed by the atom.
- The **absorption spectrum** can also be used as a signature of the atoms.



Quantization of energy.
A quick review: molecular vibrational energy.

- When we measure the vibrational energy levels for a two-atomic molecule we find that at low energies the vibrational model works fine (nearly uniform energy spacing).

- At higher energies, the potential well starts to deviate from a harmonic oscillator well, and the vibrational energy levels are no longer uniformly spaced.

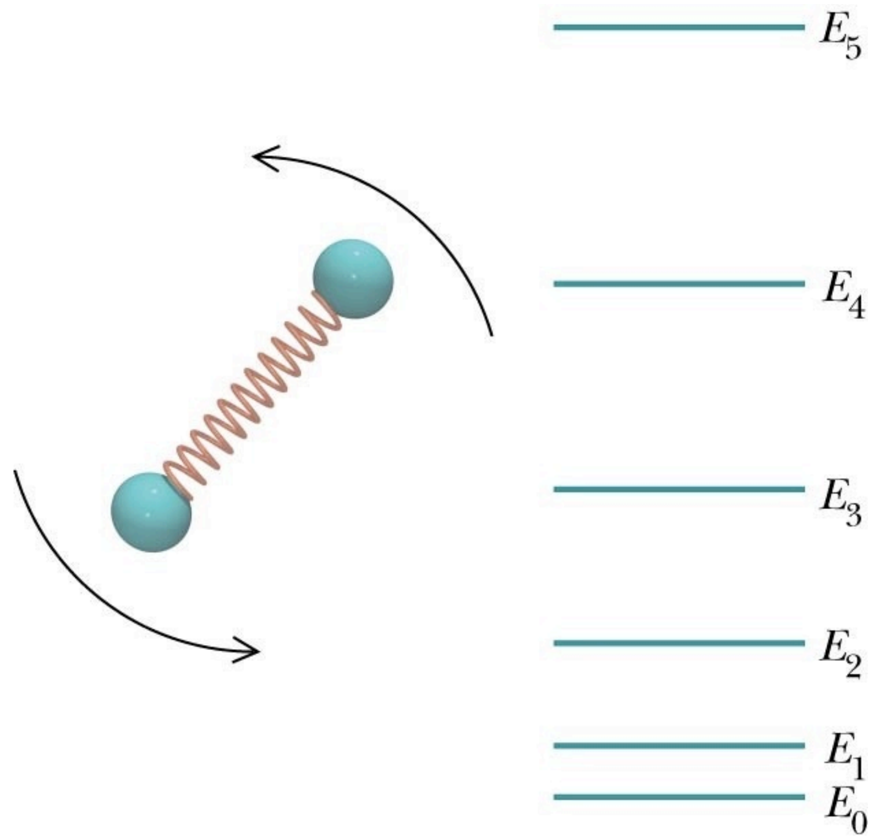


Quantization of energy.
A quick review: molecular rotational energy.

- Molecules can also carry rotational energy.
- The rotational energy of a molecule is also quantized, but the spacing between levels increases with increasing excitation energy.
- The rotational energy is found to be equal to

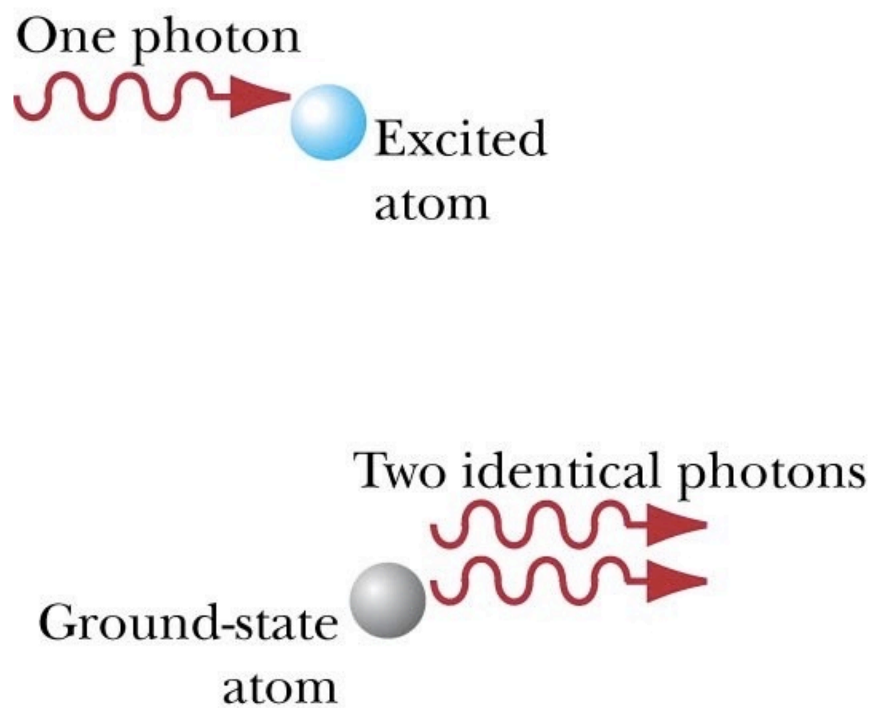
$$E_l = \frac{1}{2I} l(l+1)\hbar^2$$

where l is an integer (0, 1, …) and I is the moment of inertia (depends on mass and shape).



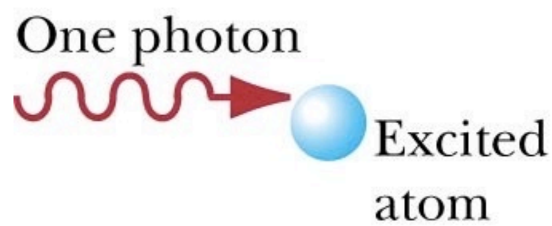
Completing Chapter 8. Applications: the laser.

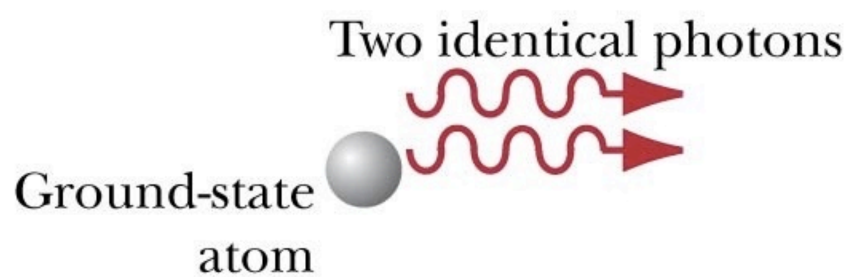
- An important application of energy quantization in atoms is the laser.
- Since light emitted when an atom transitions between states has a well-defined energy, the light emitted is well defined (the uncertainty in the wavelength is dominated by the thermal motion of the atoms).
- The mono-energetic nature of laser light is important for many optical applications.



Completing Chapter 8. Applications: the laser.

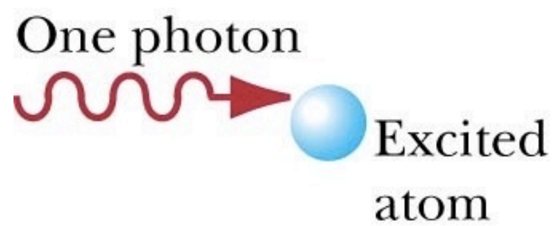
- The atoms used in lasers have long lived excited states.
- Although eventually the atom will make a transition to the ground state, and emit the light a photon with energy *E*, this transition can be "stimulated" when a photon with exactly the same energy *E* interacts with the excited atom.
- This type of emission is called **stimulated emission**, and the second photon is in phase with the first photon (coherent photons).

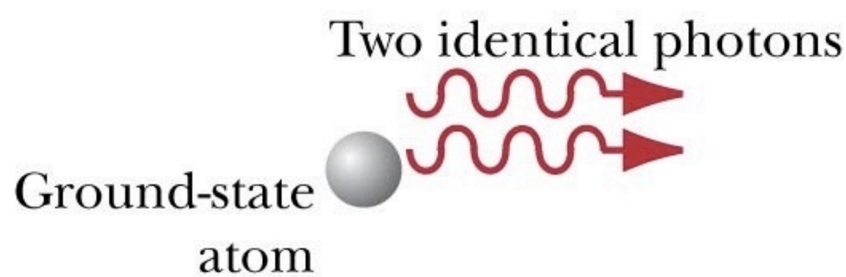




Completing Chapter 8. Applications: the laser.

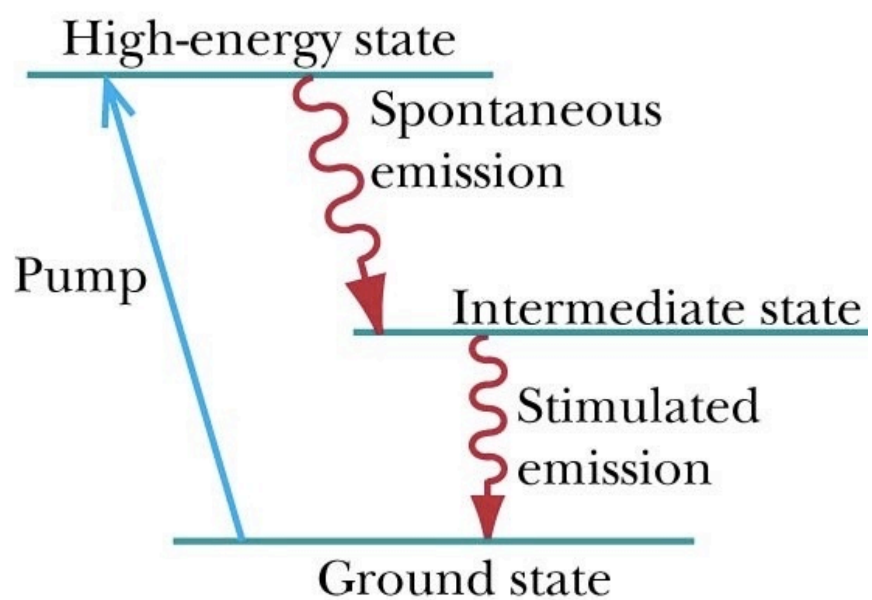
- If most of the atoms in the system are in their ground state, it is very likely that the emitted photons will be reabsorbed.
- In order for the photons to escape, a mechanism needs to be developed which:
  - Makes it unlikely to find atoms in their ground state.
  - Ensures that most atoms are in the long-lived excited state.
- The mechanism that is used to reduce the number of atoms in their ground state is called **pumping**.



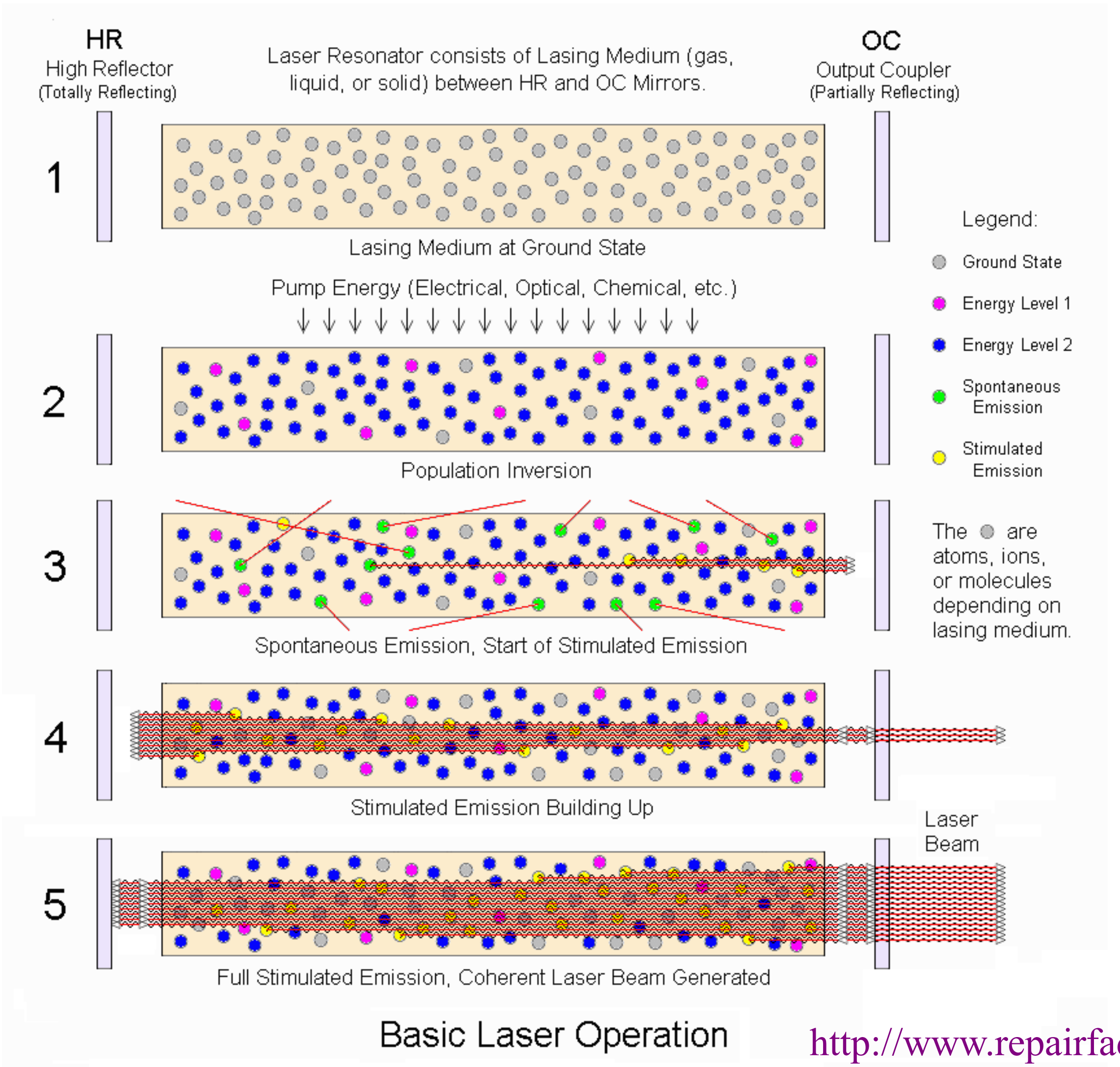


Completing Chapter 8. Applications: the laser.

- The pumping mechanism works in the following way:
  - The atoms are excited to a high-energy state (this can be done in various way, such as an electric discharge).
  - The atoms in the high-energy excited state decay quickly to a long-lived intermediate state (this process is called **spontaneous emission**).
  - At any given time, most atoms will be in the long-lived intermediate state.
- As soon as the atoms are stimulated to decay to the ground state, the pumping mechanism will remove them from that state.



Lasers.
Principle of operation.



http://www.repairfaq.org/sam/laserfaq.htm#faqwil

3 Minute 56 Second Intermission.

- Since paying attention for 1 hour and 15 minutes is hard when the topic is physics, let's take a 3 minute 56 second intermission.
- You can:
  - Stretch out.
  - Talk to your neighbors.
  - Ask me a quick question.
  - Enjoy the fantastic music.
  - Go asleep, as long as you wake up in 3 minutes and 56 seconds.

The center of mass.

- Up to now we have ignored the shape of the objects we are studying.
- Objects that are not point-like appear to carry out more complicated motions than point-like objects (e.g. the object may be rotating during its motion).
- We will find that we can use whatever we have learned about motion of point-like objects if we consider the motion of the center-of-mass of the extended object.

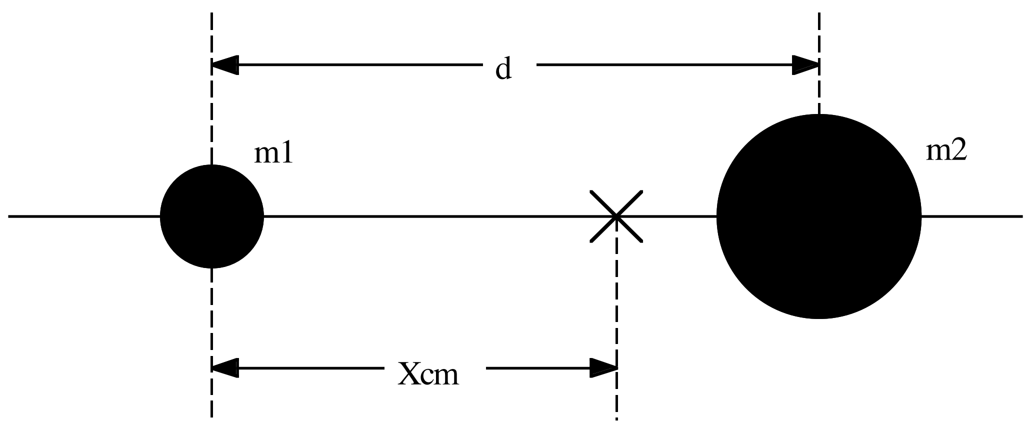
(a)

(b)

But what is the center of mass and where is it located?

- We will start with considering one-dimensional objects. For an object consisting out of two point masses, the center of mass is defined as

$$x_{cm} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2} = \frac{1}{M} \sum_i m_i x_i$$

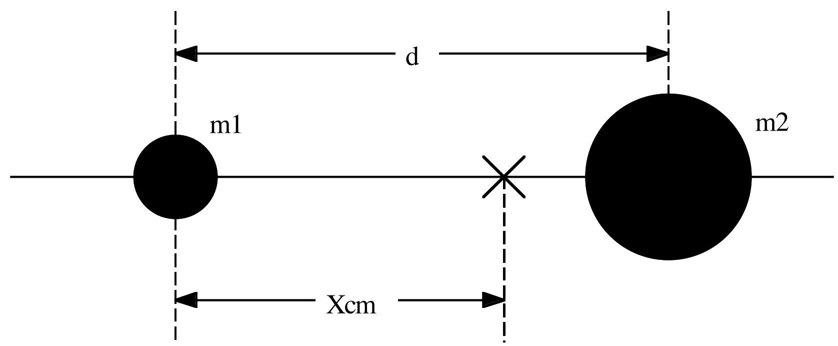


But what is the center of mass and where is it located?

- Let's look at this particular system.
- Since we are free to choose our coordinate system in a way convenient to us, we choose it such that the origin coincides with the location of mass m_1.
- The center of mass is located at

$$x_{cm} = \frac{m_2 d}{m_1 + m_2}$$

Note: the center of mass does not need to be located at a position where there is mass!

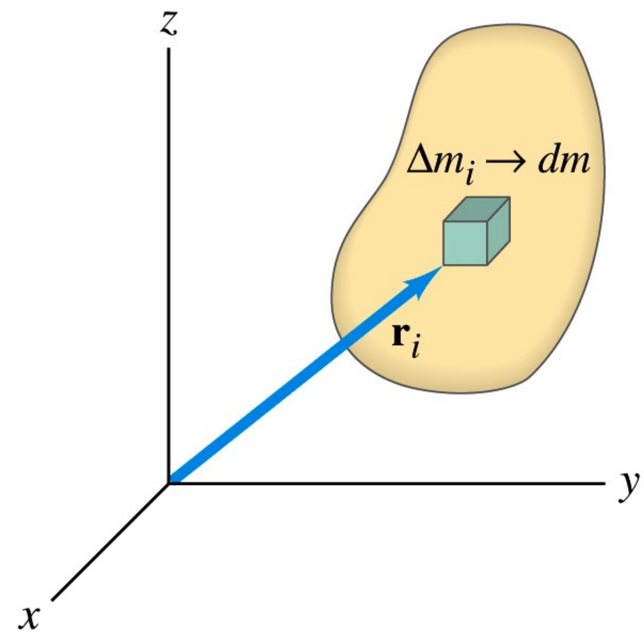


But what is the center of mass and where is it located?

- In two or three dimensions the calculation of the center of mass is very similar, except that we need to use vectors.

- If we are not dealing with discreet point masses we need to replace the sum with an integral.

$$\vec{r}_{cm} = \frac{1}{M}\int_V \vec{r}\,dm$$



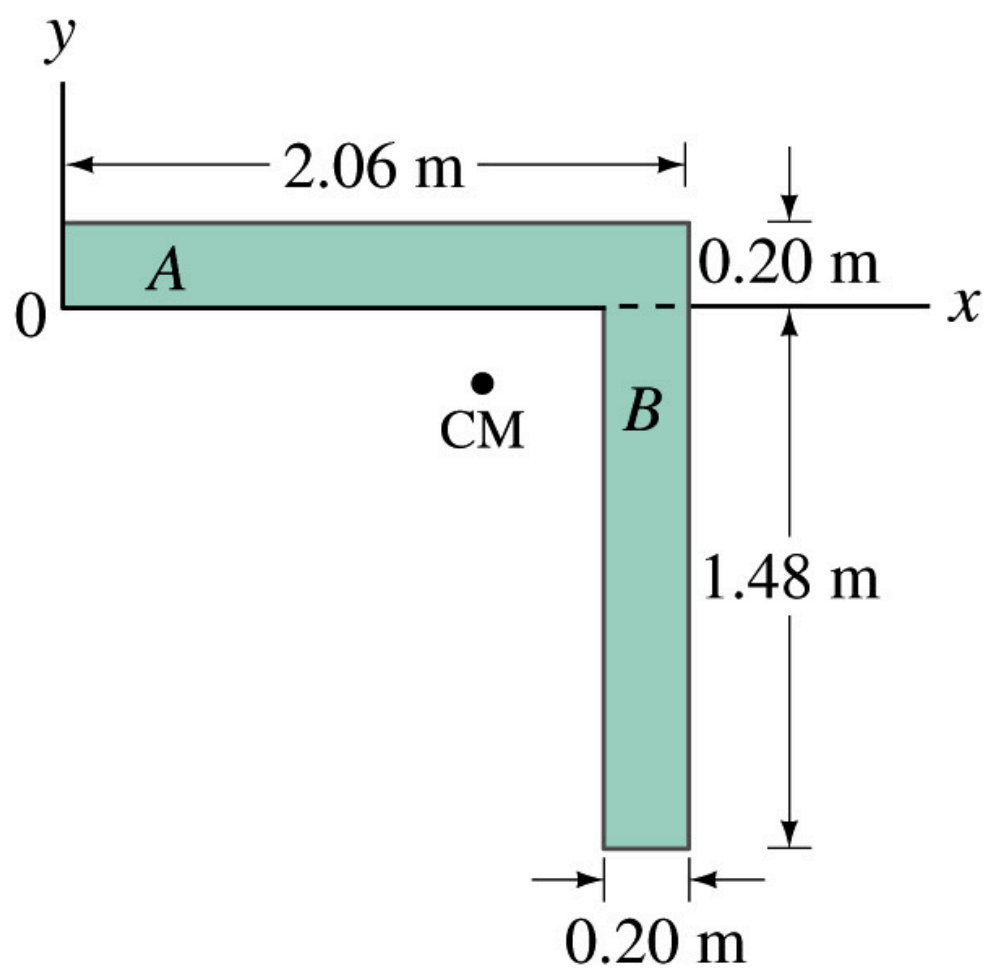
But what is the center of mass and where is it located?

- We can also calculate the position of the center of mass of a two or three-dimensional object by calculating its components separately:

$$x_{cm} = \frac{1}{M}\sum_i m_i x_i$$

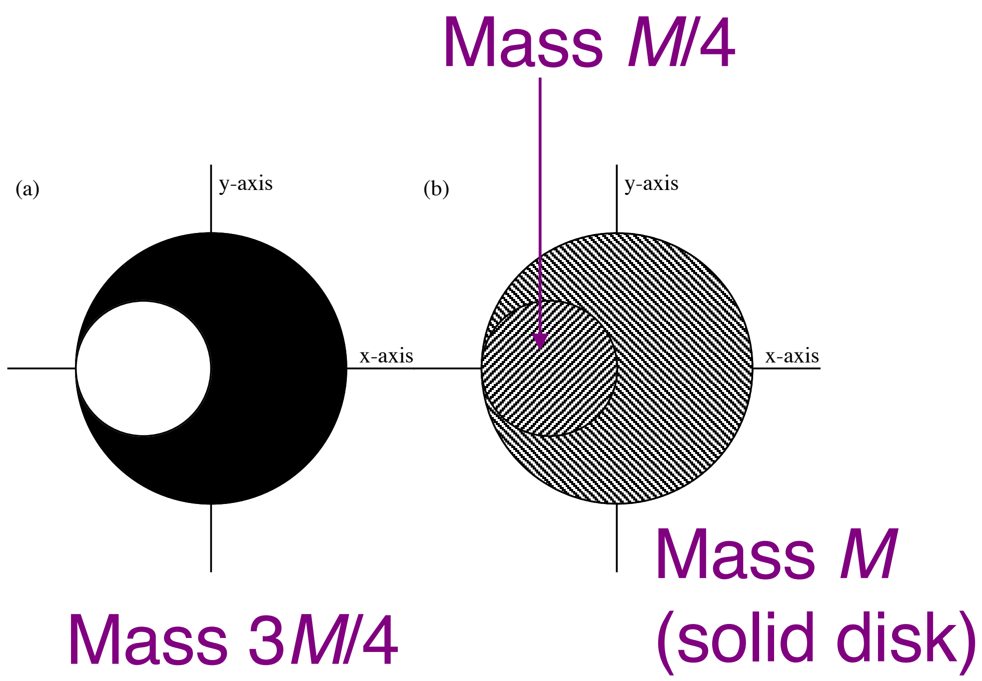
$$y_{cm} = \frac{1}{M}\sum_i m_i y_i$$

$$z_{cm} = \frac{1}{M}\sum_i m_i z_i$$



Calculating the position of the center of mass. An example.

- Consider a circular metal plate of radius $2R$ from which a disk if radius R has been removed. Let us call it object X. Locate the center of mass of object X.
- Since this object is complicated we can simplify our life by using the principle of superposition:
  - If we add a disk of radius R, located at $(-R/2, 0)$ we obtain a solid disk of radius R.
  - The center of mass of this disk is located at (0, 0).



Calculating the position of the center of mass. An example.

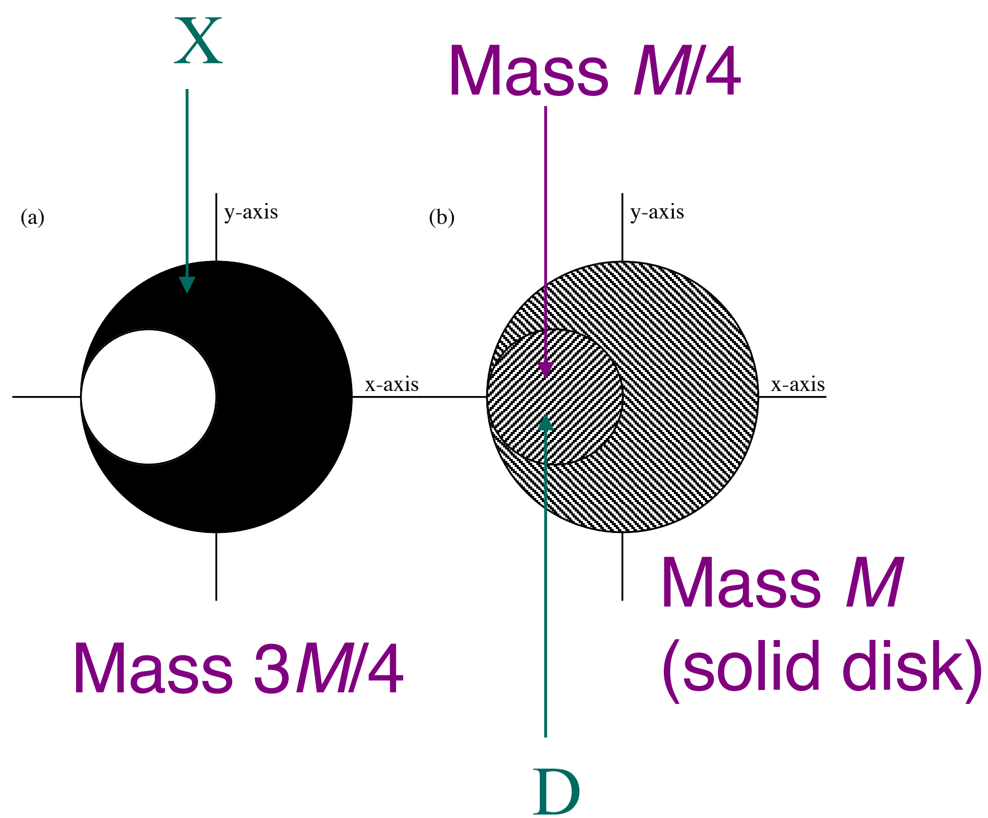
- The center of mass of the solid disk can be expressed in terms of the disk X and the disk D we used to fill the hole in disk X:

$$x_{cm,C} = \frac{x_{cm,X}m_X + x_{cm,D}m_D}{m_X + m_D} = 0$$

- This equation can be rewritten as

$$x_{cm,X} = -\frac{x_{cm,D}m_D}{m_X} = \frac{Rm_D}{m_X}$$

- Where we have used the fact that the center of mass of disk D is located at (-*R*, 0).
- Thus, $x_{cm,X} = R/3$.



Motion of the center of mass. Non-relativistic limit.

- To examine the motion of the center of mass we start with its position and then determine its velocity and acceleration:

$$M\vec{r}_{cm} = \sum_i m_i \vec{r}_i$$

$$M\vec{v}_{cm} = \sum_i m_i \vec{v}_i$$

$$M\vec{a}_{cm} = \sum_i m_i \vec{a}_i$$

Motion of the center of mass. Non-relativistic limit.

- The expression for Ma_{cm} can be rewritten in terms of the forces on the individual components:

$$M\vec{a}_{cm} = \frac{d}{dt}(M\vec{v}_{cm}) = \frac{d\vec{P}_{cm}}{dt} = \sum_i m_i\vec{a}_i = \sum_i \vec{F}_i = \vec{F}_{net,ext}$$

- We conclude that the motion of the center of mass is only determined by the external forces. Forces exerted by one part of the system on other parts of the system are called internal forces. According to Newton's third law, the sum of all internal forces cancel out (for each interaction there are two forces acting on two parts: they are equal in magnitude but pointing in an opposite direction and cancel if we take the vector sum of all internal forces).

Motion of the center of mass. Linear momentum.

- Now consider the special case where there are no external forces acting on the system:

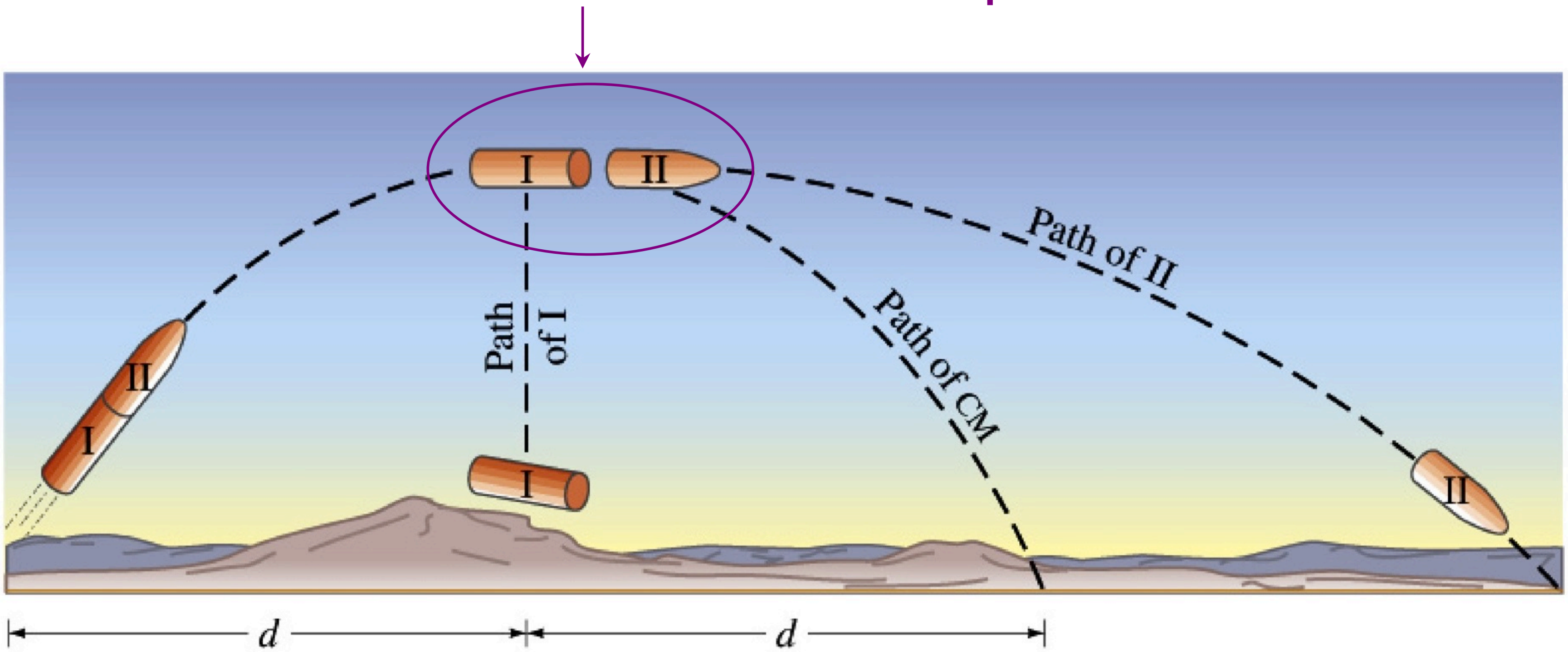
$$\frac{d\vec{P}_{cm}}{dt} = 0$$

- This equations tells us that the total linear momentum of the system is constant.
- In the case of an extended object, we find the total linear momentum by adding the linear momenta of all of its components:

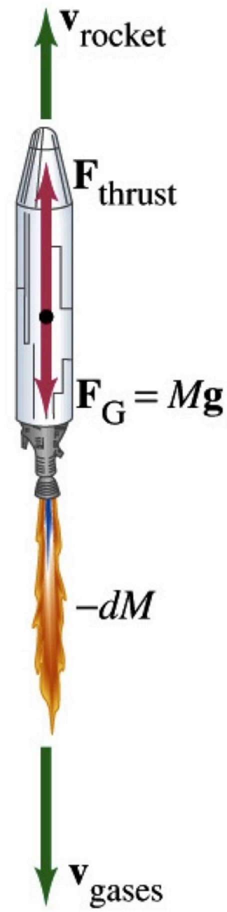
$$\vec{P}_{tot} = M\vec{v}_{cm} = \sum_i m_i\vec{v}_i = \sum_i \vec{p}_i$$

Conservation of linear momentum. Applications.

Internal forces are responsible for the breakup.



Conservation of linear momentum. Applications.



Next: more about multi-particle systems.