Lect. 12 Summary, Clas. Phys. - Michelson-Morley Exp.

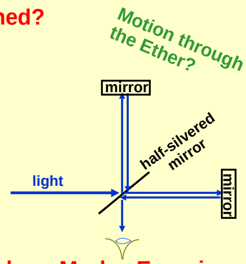
Summary of Classical Physics
Start the Revolutions of Modern Physics

Classical Physics in 1880's

Is Conceptual Physics finished?

Only details left?

What does a scientist do?
Seek to:
Ask the right question.
Find the crucial experiment that provides a definitive test of the theory

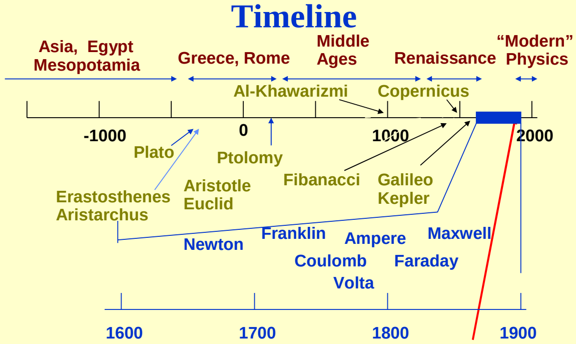


Michelson-Morley Experiment

Announcements

- Today: Summary of Classical Physics
- The beginning of a new scientific revolution
  - Does the earth move? The Michelson-Morley Experiment
  - Lightman Ch 3, March Ch 8
- Next Time: Einstein and the Birth of Relativity
  - Lightman Ch 3, March Ch 9
- Give out Homework 6 – due Wed., Oct. 22
- Homework 5 due Wednesday, Oct. 15

Timeline



- "Classical Physics" was complete around 1880
- See Timeline description of lives of various scientists on WWW pages.

Summary of Classical Physics – I

- Physics as it stood near the end of the 19th Century
- Fundamental quantities (Primitives):
  - Time flows the same everywhere for all observers
  - Space is described by 3 dimensions (Euclidean Geometry)
  - Mass is never created nor destroyed (conserved)
  - Charge (plus and minus) total is conserved – defined by force
- Units for primitives (standards)
  - Time - second – defined by standard clock in Paris – other clocks are brought to Paris; if they agree with the standard, they become secondary standards; it is assumed that each measures "time" valid for everyone
  - Space - meter – defined by standard meter in Paris
  - Mass - kilogram – defined by standard kilogram in Paris
  - Charge - Coulomb – defined by standard kilogram in Paris

Summary of Classical Physics – Ia

- Physics as it stood near the end of the 19th Century
- Derived quantities:
  - Velocity – directly defined by space and time
  - Acceleration – directly defined by space and time
  - Force originates in interactions between particles of matter
  - Energy changes form but is conserved
  - Momentum is conserved
  - ……

Summary of Classical Physics – II

- Physics near the end of 19th Century (Continued)
- Fundamental Objects:
  - Particles have mass and move according to Newton's laws
    - baseballs, rockets, …..
  - Waves are moving patterns in a medium
    - Sound, Light, …..
- Waves exhibit interference
- Particles do not exhibit interference

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Summary of Classical Physics - III

- Physics near the end of 19th Century (Continued)
- Laws that describe particles and waves were formulated by
  - Newton – three laws + law of gravity describe motion of particles
  - Maxwell – four laws describe all electromagnetic effects including light
  - First and second laws of thermodynamics describe heat and irreversible behavior
- Fundamental physics appeared finished – The laws appear to be so comprehensive that all that remained was more precise measurements and new discoveries of force laws
- The laws are deterministic - If one could measure the positions of all objects at one time the future would be completely determined

Summary of Classical Physics - IV

- Physics near the end of 19th Century (Continued)
- Question 1: How does one know these laws and concepts are "true" ?
- What does "true" mean in science?
  The law applies to nature.
- How does one "know"
  By careful, reproducible experiments
- The laws give a framework - a paradigm - that allows questions to be asked and answered by experiment
  -- Is the set of laws internally consistent?
  -- Does the law apply within the accuracy of the experiment?

Summary of Classical Physics – V

- Physics near the end of 19th Century (Continued)
- Question 2: To what extent have the laws of classical physics passed the tests?
- By the 1880's they appeared to pass every test attempted, but there are limitations:
  - Many things were not (yet?) explained ……
  - Accuracy of measurements could only test each of the conservation laws (mass, energy, momentum) to some level
  - New experiments were becoming possible

What does a scientist do?

- Ask clear well-defined questions that:
  Address the fundamental issues - the foundations
  Can be tested by decisive experiments
- Already deep issues can be seen.
  Recall:
  Galileo's principle of relativity (also called superposition) – all velocities are relative – no experiment can detect absolute motion – no experiment can determine whether or not the earth is moving at a constant velocity
- Can this be tested using sensitive experiments and what has been learned about light?
- By careful formulation of questions and consideration of to small details, complete revolutions in science emerged - with all their consequences for humanity

Toward the question: Can we detect absolute motion

- According to Galileo, Newton all motion is relative
  - Also our common sense – examples ……
- But waves present another possibility
  All waves known by physicists in 1800's traveled through some medium at a fixed speed in that medium
  - Sound waves in air (around 340 m/s)
  - Waves on a string (depends on string)
    Waves on water
- An experiment can detect motion <u>relative</u> to this medium

What is light?

- Proposed to be an wave in the "ether"
- Ether: Substance that permeates all space

  Matter (planets, ….) can move through the either with no resistance

  Yet the ether must be very tight tom transmit light at extremely high speeds
- If it exists, this is the universal medium that can define "absolute rest" – motion can be measured relative to the ether

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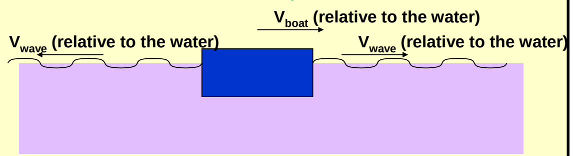
Example – boat in water

- According to Galileo, Newton all motion is relative
  - Also our common sense – examples ……



- Measured from the boat:
  - front wave moves at $V_{wave} - V_{boat}$
  - back wave moves at $V_{wave} + V_{boat}$
  - Difference = $(V_{wave} + V_{boat}) - (V_{wave} - V_{boat}) = 2V_{boat}$
- An experiment can detect motion relative to the medium

Fundamental Question

- Can we detect the earth moving through the ether?

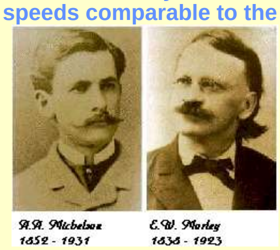
Earth

V_{earth} (relative the the ether)

- Can this be the definition of absolute motion; absolute rest?

Beginning of the New Revolutions

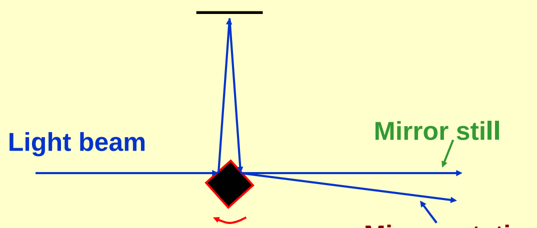
- The Michelson-Morley experiment (1887)
- At the time, Classical Physics had not really been tested at speeds comparable to the speed of light



- How to find the key experiment? This is the creative challenge of experimental physics!

Measurement of Speed of light

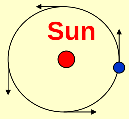
- Michelson (1870's) established his scientific reputation first by greatly improving on the previous measurement of the speed of light by Foucault



Important but not the key experiment!

Michelson-Morley Experiment

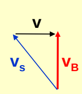
- If light is a wave in some medium (ether) then if the earth moves in the ether it should be detectable
- If Newton's laws are correct the earth "moves" around the sun:



- In 1887 Michelson & Morley do experiment to try to measure the velocity of the earth with respect to (wrt) the "ether"
- Testing key ideas: Does the ether exist, as appears to be required by electromagnetic waves? Can we measure the "absolute motion of the earth"?

Key Part of Classical Physics Tested by Michelson-Morley Experiment

- Addition of velocities - Applied to light
- Superposition principle of Galileo - Also contained in Newton's law of inertia
- Leads to the formulas for addition of velocities: Example swimmer in river moving at speed v



With respect to

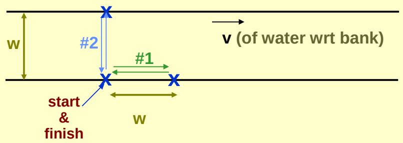
$\vec{v}_B$ (smimmer wrt bank) = $\vec{v}$ (river wrt bank) + $\vec{v}_s$ (swimmer wrt river)

Important point: s = speed of swimmer = magitude of v_s (swimmer wrt river) depends only on the swimmer.
s does not change if swimmer is going up, down or across the stream

Lect. 12 Summary, Clas. Phys. - Michelson-Morley Exp.

M-M Experiment & Swimmers

- **Principle behind experiment easier to understand from swimmers in a stream analogy.**
  - Two swimmers of equal ability have a race in a river. They swim at the same speed s.
  - Each swims the same distance (wrt river bank), but swimmer #1 swims across the river and back, while swimmer B swims downstream and then upstream.
  - Who wins?



Swim Upstream & Downstream

- **Calculate the time it takes swimmer #1 with speed s (wrt water) to go a distance w downstream and w upstream if the speed of the water is v (wrt bank).**
  - Downstream:
    - What is swimmer's speed (wrt bank)? $v_D = s + v$
    - How long does it take to go distance w? $t_D = w/v_D = w/(s+v)$
  - Upstream:
    - What is swimmer's speed (wrt bank)? $v_U = s - v$
    - How long does it take to go distance w? $t_U = w/v_U = w/(s-v)$
  - Total Time:
    - Add the times t_D and t_U: $T_1 = w/(s+v) + w/(s-v)$
    - After some algebra, we can rewrite in a more compact form:

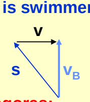
$$T_1 = \gamma^2 (2w/s)$$

where

$$\gamma = 1 / \mathrm{sqrt}(1 - (v/s)^2)$$

Swim Across Stream & Back

- **Calculate the time it takes swimmer #2 with speed s (wrt water) to go a distance w across stream and w back if the speed of the water is v (wrt bank).**
  - Note: this is more difficult because the swimmer must aim somewhat upstream of his final destination so that the current will carry him to the point directly across from the starting point.
  - What is swimmer's speed (wrt bank)?



$\vec{v}_B$ (smimmer wrt bank) = $\vec{v}$ (river wrt bank) + $\vec{v}_s$ (swimmer wrt river)

Magnitude = s

  - Pythagoras:
    - $v_B^2 = s^2 - v^2 \Rightarrow v_B = s\ \mathrm{sqrt}(1 - (v/s)^2)$
  - How long does it take the swimmer to cross the stream?
    - $T = w/v_B = \gamma\ w/s$
  - Total Time:

$$T_2 = 2T = \gamma\ (2w/s)$$

So who wins??

- **Total time for swimming up and downstream:**

$$T_1 = \gamma^2 (2w/s)$$

- **Total time for swimming across stream and back:**

$$T_2 = \gamma\ (2w/s)$$

- **Which time is smaller?**

Take ratio: $T_1 / T_2 = \gamma$

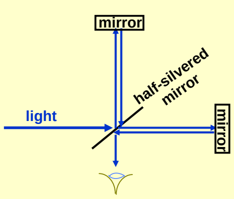
For race to be possible, $s > v$

$\Rightarrow \gamma = 1 / \mathrm{sqrt}(1 - (v/s)^2) > 1$

- **Therefore, swimmer going across stream and back wins!**

Michelson-Morley Experiment

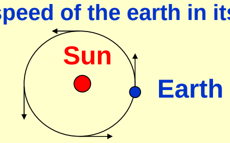
- **What does this swimming race have to do with Michelson-Morley?**
  - Replace swimmers with light beams (speed s = c)
  - Replace river with the ether
  - Try to measure the velocity of the ether (wrt Earth) by setting up a race for light and see who wins and by how much!



If ether "wind" moves to the right in this diagram, we expect light beam going up and down to beat the one going right and left.

Michelson-Morley Experiment

- **How big is the effect?**
- **Consider the speed of the earth in its orbit?**



- **With respect to (wrt) the sun, the speed is about** $v = 2\pi\ 1.5 \times 10^8$ km / yr = 3×10^4 m/s = 30 km/s
- **Small compared to** $c = 3 \times 10^6$ km/s !
- **From the "swimmer problem" the time difference is** $T_1 - T_2 = 2w/c\ (\gamma^2 - \gamma)$
- **Putting in numbers for w = 11 m,** $T_1 - T_2 = 3.7 \times 10^{-16}$ sec

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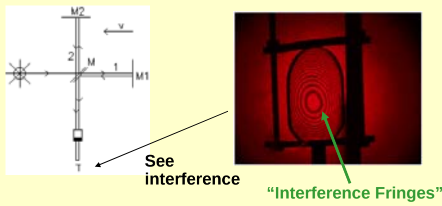
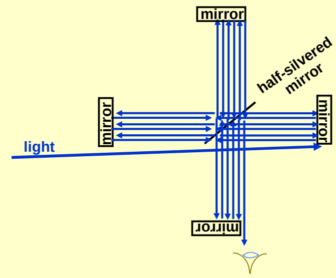
Defining the experiment

- How is it possible to measure such a small time difference?
  - Must use interference which is sensitive to a fraction of a wavelength λ!
  - (Same method used now for very precise measurements of distances using lasers, global positioning system, …)



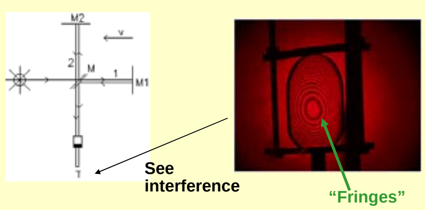
Michelson-Morley Experiment

- Larger lenths (larger w) w means longer time difference
- This can be accomplished by arranging the light to bounce back and forth many times



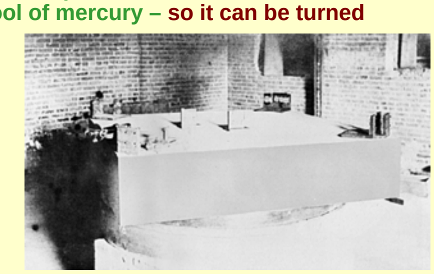
Results??

- For light, wavelength - $5X10^{-7}$ m
  - $\Rightarrow \Delta T = 1/f = \lambda/c = 2 \times 10^{-15}$ sec
  - Can measure time differences smaller than 10^{-15} sec
  - With multiple passes of the light the experiment is more sensitive to the "swimmer effect"
  - Final accuracy 1 km/s - much smaller the 30 km/s speed of earth relative to the sun



Michelson-Morley experiment

- Case School of Applied Science (Now Case Western Reserve) in Cleveland (1887)
- Optical experiment on sandstone slab that floats on a pool of mercury – so it can be turned



Results

- M-M experiment: Rotate apparatus to search for direction which maximizes the time difference (largest fringe shift)
- Result: THEY SAW NO DIFFERENCE!
- What does this mean??
  - They set an upper limit of around 1 km/sec for the velocity of the ether (the medium for light waves) with respect to the Earth.
  - Michelson called this a NEGATIVE result, not a NULL result.
  - Can you think of a reason why he used these words?

Conclusions of Experiment

- Either
  The earth does NOT move through space -- which would be a fundamental failure of classical mechanics
- Or
  The speed at which light travels does not obey the laws of classical physics (addition of velocities)
- Either way - a fundamental failure of classical physics

Lect. 12 Summary, Clas. Phys. - Michelson-Morley Exp.

Summary

- Newton, Maxwell and others formulated the laws for what we now call "Classical Physics"
- Described nature in terms of a small number of laws and a few fundamental quantities
- Appeared to pass all the scientific tests, but in science one keeps on testing!

- Michelson, Morley experiment
  - Used interference of light to make a very sensitive experiment
- Result: Light appears to have the same speed in all directions, independent of the motion of the earth - a fundamental failure of classical physics

- What does this mean? -- Next Time