Search for the aether

- HW3 today, Thursday Feb 8th at 5pm.
- Quiz next Thursday, Feb 15th on relativity:

  Short answers. 20 mins. Closed book.

  Materials from Rohrlich pgs.34-88, Cushing Chpts. 13,16-17, Sklar pgs. 25-40 & class notes.

Does the Earth Move?

The Problem:

- Maxwell's equations describing electrodynamics violate Galilean invariance. They contain an absolute (not relative) speed.
  - Consider the wave equation, which describes the motion of radio and light waves (E is the electric field):

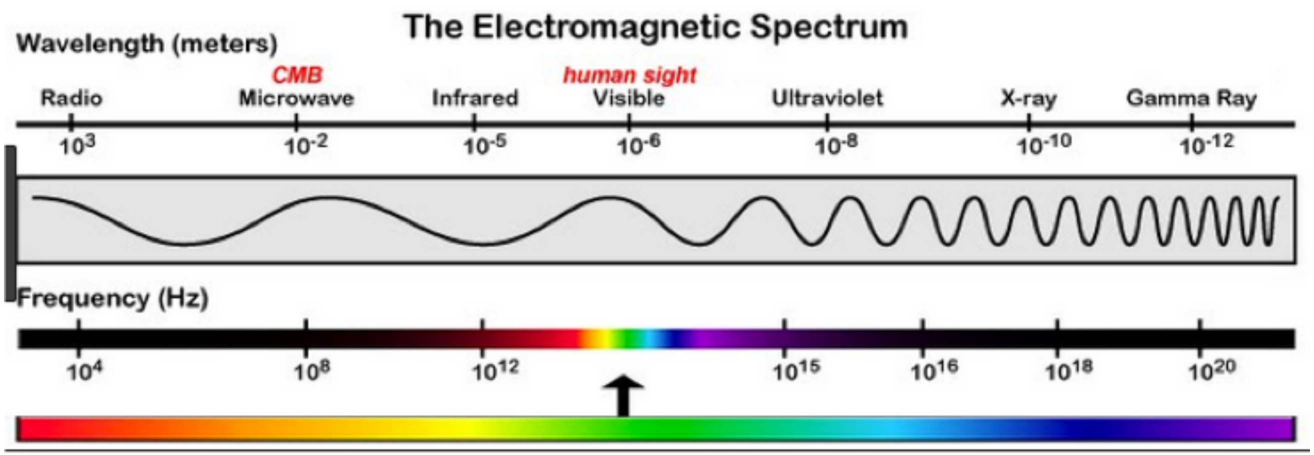
$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}$$

  - That c is the speed at which the waves move, and its presence in the equation is a *not good for Galilean relativity*, even though the equation is pretty.
- Galilean relativity says that if one person observes an object to have a certain velocity another person (who is moving) will observe a different velocity.
- Maxwell's equations don't seem to accommodate this behavior for light, because the equation doesn't say to use a different c for different observers.
- **How does one try to solve the problem?**
  - If one is a late 19th century physicist, the natural guess is that c is the speed relative to the aether, NOT to any arbitrary observer.

Electromagnetism and the Aether

Electric and magnetic fields were discovered in the 19th century to have two properties which gave credence to their reality.

- Faraday discovered that if the magnetic field **B** varies with time, this gives rise to an electric field **E**. Relation of **E** and **B** is not just a re-description of forces between charges.
- James Maxwell discovered (1864) that changes in **E** give rise to **B** as well. That implies that **E** and **B** can exist in the *absence of any electrical charges* (i.e., no sources).
- Maxwell **unified** the description of electricity and magnetism and claimed that light is a wave composed of oscillating **E** and **B** fields. He predicted the existence of other "electromagnetic waves," which were observed by Hertz.
- Three previously distinct phenomena have been subsumed by a single theory.



Two problems for Maxwell's E&M theory

1. When an EM wave propagates through the vacuum, what is the medium? What is oscillating?
2. The equations that describe electrodynamics violate Galilean invariance. This violation should show up in the wave motion.
   Is the speed of light uniform only constant with respect to the medium?

The medium was dubbed the luminiferous aether, the stuff of which E-M fields are the disturbances.

Classical Physics

We have now completed an introduction to the classical synthesis of physics. The common view was that in all important questions, physics was complete. Lord Kelvin, in 1900, made a famous speech declaring that physics was basically done, except for two little "dark clouds on the horizon":

1. Black-body radiation
2. The Michelson-Morley experiment.

Before we encounter stormy weather, let's try to sum up classical physics and its relation to traditional philosophical questions.

Physics (as of 1900)

- Nature consists of particles and fields, embedded in time and space.
- Elementary ingredients of the classical description:
  - Position and time are both undefined quantities. One cannot explain them to someone who does not already have a mental construct. Try to imagine a universe with two time dimensions.
  - Mass is another undefined quantity. Its *mathematical behavior* is defined by Newton's second law together with specific force laws, and some rule for measuring accelerations.
  - We still need some implicit understandings to connect all these constructs to actual experiences.
- The influence of the particles and fields on each other is described by definite deterministic equations.
- Not all the particles and fields are known.
  - There are other empirical forces, but only G and E&M look fundamental.
  - None of the detailed properties of chemistry, materials, etc., are accounted for. They might require some new fields on a small scale.
- There are some unifying conservation laws related to symmetry:
  - Momentum, angular momentum, energy, mass, electrical charge, atoms.
- Symmetries
  - Time translation, space translation, rotation, mirror-image (parity),
  - Time reversal (but, oddly, only on a *microscopic* level)
  - Galilean relativity (but not for electromagnetism!)

Why look for the aether?

- By analogy with the behavior of other waves (*e.g.*, sound and water waves) it was natural to expect light waves ("light" means any electromagnetic wave) to be carried by a medium. The aether might transmit other long distance effects, such as gravity, as well.

- It offered the possibility of a resolution of the Newton-Leibniz (*i.e.*, the substantivalist-relationist) debate. If the aether exists, then it becomes a candidate for Newton's absolute space. (Sklar, *Space, Time, & Spacetime*, p. 196)

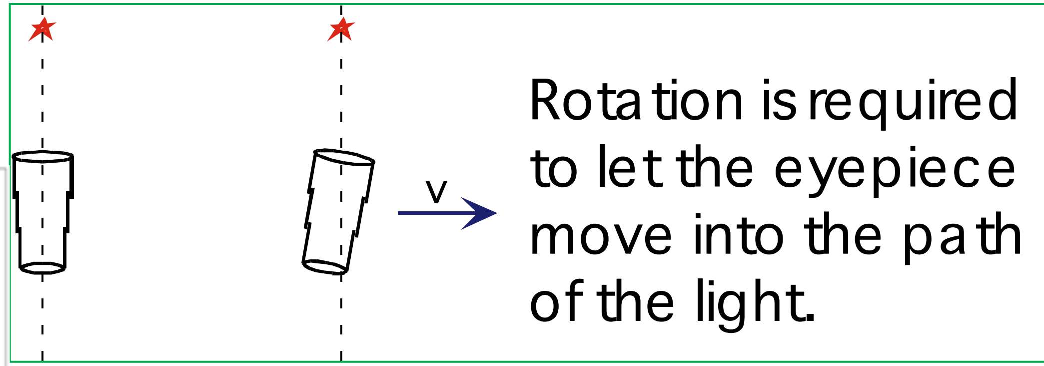
- If the aether takes over the role of absolute space, there is now just one reference frame in which you can use the simple laws of physics (Maxwell's equations.) Galilean relativity would be out the window.

  <u>A careful experiment could either verify or falsify Maxwell's equations in the observer's frame, and thus say in a meaningful way if that frame is moving.</u>

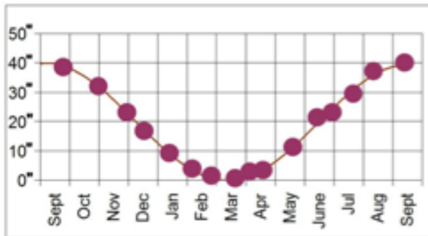
How to look for the aether

- If you are moving through a medium, the observed speed of the wave will vary with direction.
- The apparent direction of a source will vary with the observer's velocity (aberration, see Rohrlich, p. 53).
- These effects are not large. The largest speed you have easy access to is the speed of the Earth in its orbit, about 30 km/s, which is about 10^{-4} c. (except for an unknown average velocity of the solar system)

Searches for the aether: Aberration



Aberration had been seen in 1674, (Hooke), described in 1728 by Bradley



- If the telescope (mounted on the earth) moves through the aether, you have to tilt the scope a little so that the rear end is in the right place when the light gets to it. As the Earth goes around the sun, the apparent direction of a star changes by ±0.3 minutes of arc. This is only 10 times smaller than Tycho could see by eye, and is easily measured with a telescope.
- Conclusion: The Earth changes its motion through the aether periodically, just as it's supposed to if it orbits a Sun which is not accelerating.
  - (Proof of Copernicus' theory?) (Proof of aether idea?)
- But since we don't independently know which is the "true" position of the stars, we don't know when our telescope is pointed straight at the stars and when it's tilted.
- We've *measured* the Earth's velocity changes, i.e. acceleration, but not its velocity relative to the aether.

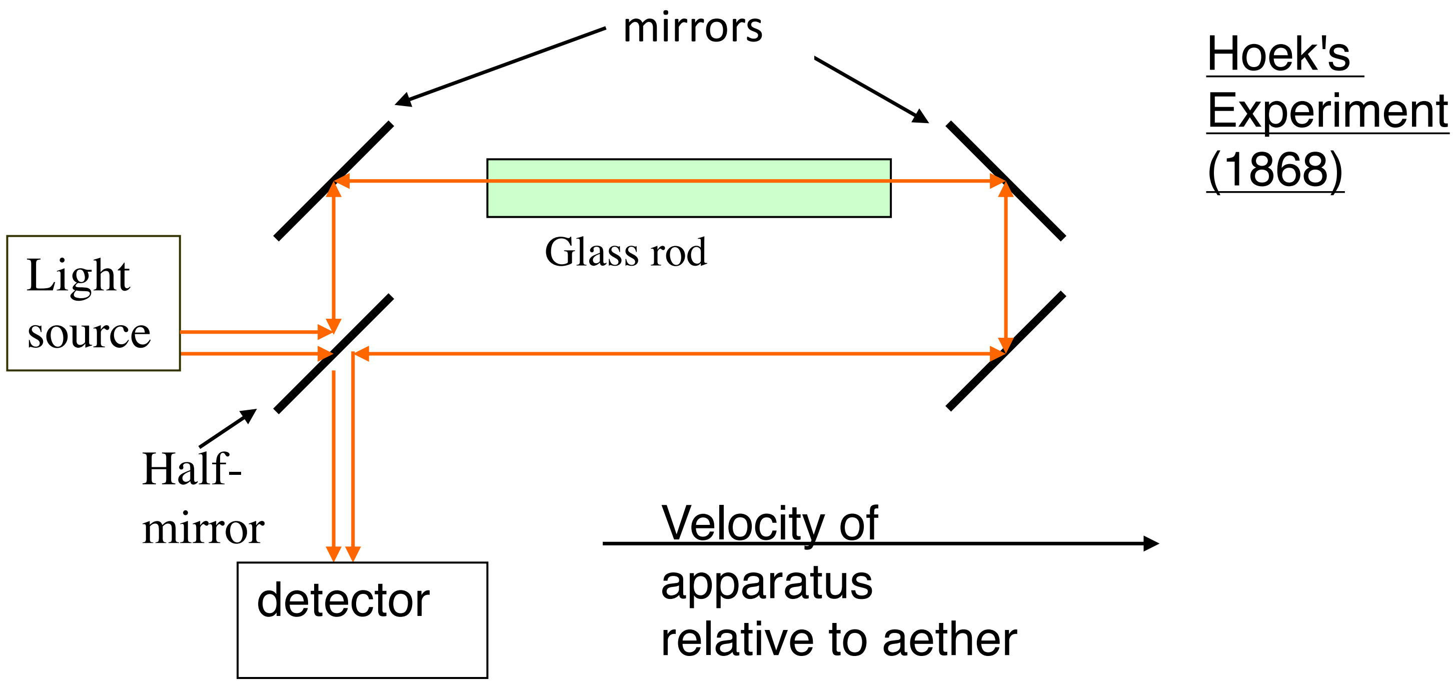
More key searches for the aether

- Aether drag. It was known that light moves more slowly through materials which have an index of refraction. So, filling a telescope with water (Fresnel) should have a calculable effect on aberration. (You would have to tilt the telescope a little more, to allow for the longer time-of-flight.)
  - It didn't.
- Conclusion: The aether is partially dragged along with the moving material:

$$v_{aether} = v_{matter}\left(1 - \frac{c'^2}{c^2}\right)$$

where c' is speed of light in the matter.

More key searches for the aether



At the detector, there are interference stripes between light that went around clockwise and counterclockwise. The position of the stripes is a very sensitive function of the time difference between those two trips, which go in opposite directions through the moving rod.
The observation is that the fringes DO NOT SHIFT regardless of the Earth's motion. That again requires that the aether be partially dragged along with the glass, by the same amount that Fresnel claimed.

More key searches for the aether

- Fizeau's experiment was like Hoek's, except that the rod was replaced with a tube containing water. When the water was *flowing*, the fringes *did* shift, in the amount predicted by the partial-aether-drag picture
- But we still haven't managed to measure the Earth's speed- we just measured the change in velocity of the water (relative to apparatus) when it is flowing, but that's nothing new!

The searches don’t work

Something is frustrating: we have all sorts of experiments that fit a theory that says that Maxwell's equations only work in a special frame- but somehow we can't quite measure our motion with respect to that frame, and can’t even tell if we’re at rest in that frame.

- Even worse, there was a major paradox:
  - Because the index of refraction of the water (or glass) *varies with color*, the speed of light in these materials varies with the color, so the inferred speed of the aether depended on the color of the light.
  - How could this be? Are there a whole collection of different aethers, for all the possible frequencies of light?

Lorentz fixes a lot

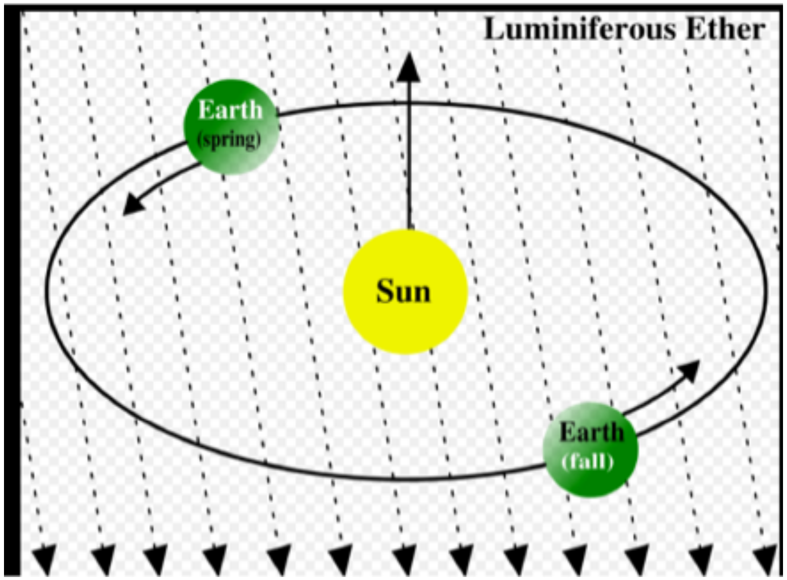
- H. A. Lorentz (1853-1928) resolved all but one of the problems above.
  - if the aether were entirely stationary, the propagation of light would still be affected by the motion of the electrons with which it interacts in the material it's travelling through.
  - He derived from Maxwell's equations how big that effect would be. It gave exactly the Fresnel effect, and thus explained ALL of the experiments above.
    - The medium in which light propagates is actually (aether + electrons, etc.) so "partial ether drag" becomes just "fixed aether + moving electrons."
    - All those experimental results follow naturally from Maxwell's electromagnetism, plus the quantitative theory of how light interacts with the electrons in materials.
  - We don't need separate aethers for each color, just need the simple fact that the electrons scatter an amount of light that depends on color.

But are we moving?

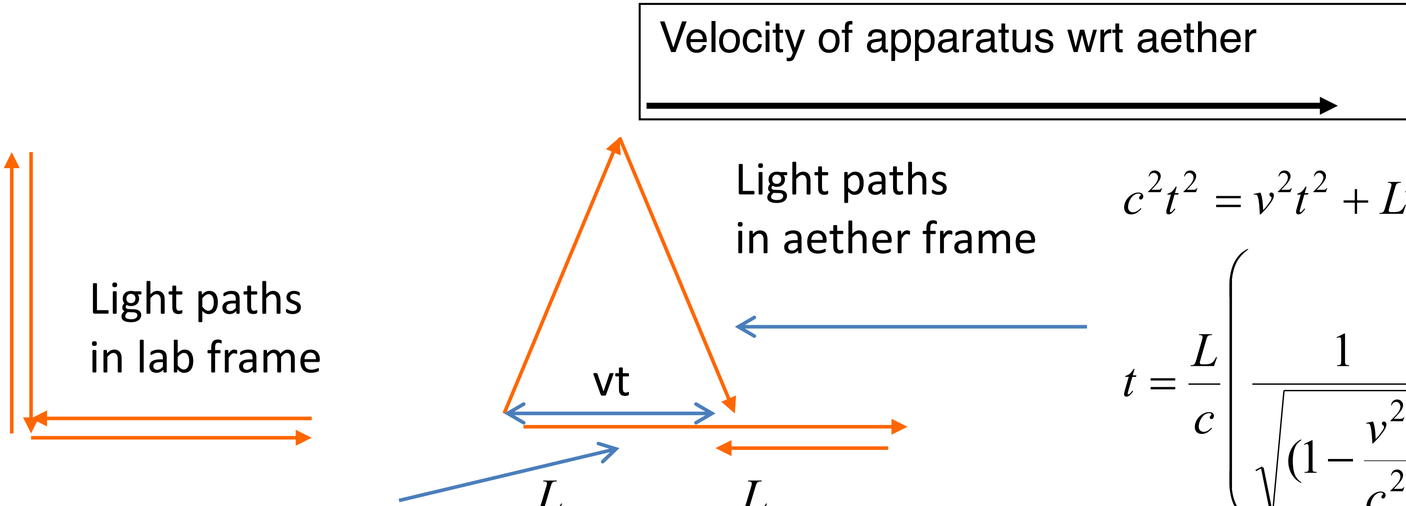
- <u>So none of these experiments have done anything to measure our absolute motion through the aether,</u>
  - although aberration at least seems to have shown *changes* in that motion.

- Why is it so hard to think of an experiment to measure that absolute motion?
  - Is there a serious experiment to measure the absolute motion of the Earth?
  - We need light just propagating in a vacuum, not any of these messy complications due to interactions with moving media. And we need a round-trip, so that we can compare timing of two signals at the same place.

Wikipedia: Michelson-Morley



Michelson-Morley (1887)



$$c^2t^2 = v^2t^2 + L^2$$

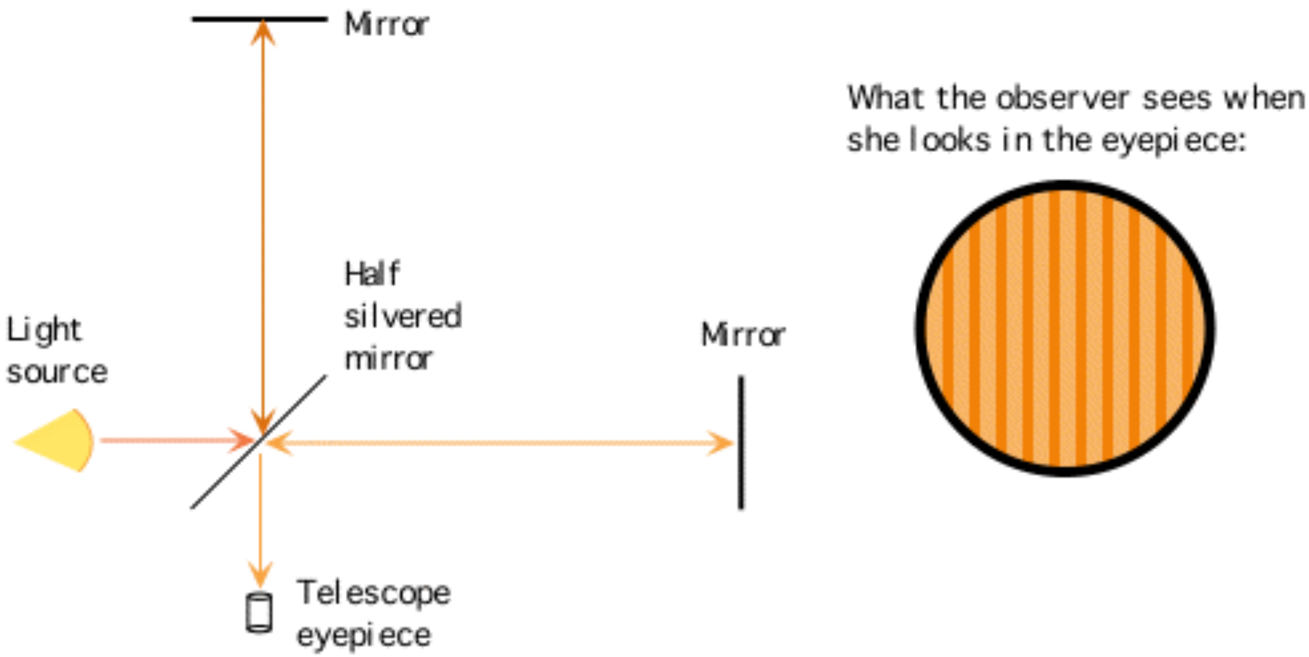
$$t = \frac{L}{c}\left(\frac{1}{\sqrt{(1-\frac{v^2}{c^2})}}\right)$$

$$t = \frac{L}{2(c+v)} + \frac{L}{2(c-v)} =$$

$$\frac{L}{c}\left(\frac{1}{1-\frac{v^2}{c^2}}\right)$$

So the time taken on the two round-trip paths is different, depending on which way lines up with the motion through the aether. The fractional change in the time is about v^2/c^2, or about 10^{-8} for the earth's orbital speed. But that's comparable to one wavelength of light, if the path L is a few tens of meters.

M-M results



- If the apparatus is moving through the aether, the interference pattern will shift left or right. This is a very sensitive method, since the wavelength of light is $5*10^{-7}$ m. The experiment was supposed to be sensitive enough to detect even the rotation of the Earth (300 m/s) as well as the orbital motion. <u>It didn't.</u>
- Possible explanations:
  - <u>Complete aether drag</u>: local aether is always at rest with respect to local matter
    - <u>incompatible with aberration</u>.
  - Speed of light is determined by the source.
    - Ruled out by using the Sun as the interferometer's light source.
  - The apparatus shrinks in one direction as it moves through the aether.

Lorentz-Fitzgerald Contraction (1892)

- In order for the third explanation to work, the contraction must exactly cancel the expected effect, "a conspiracy." The size of the effect is tiny:
-
$$L \rightarrow L \times \sqrt{1-\left(\frac{v}{c}\right)^2}$$
  - For v = 30 km/s the factor is ~0.999999995 (*i.e.*, $1 - 5*10^{-9}$).
  - Did this make sense? Maybe, because materials are held together by chemical (electrical) forces, so the same thing that affects light might affect materials as well. However, there was no quantitative theory that predicted the contraction.
- To maintain a consistent picture, clocks which are moving through the aether must also run slowly by the same factor (time dilation). Lorentz also found that it seemed necessary for masses to change as they moved through the aether.
- These two effects are part of what is called the Lorentz transformation, a set of rules for how things change in moving reference frames.

- **Warning:** The interpretation of these effects will soon change.

Aether effects

- The aether started out as an almost meaningless hypothesis, "the stuff in which light is a wave" or "the stuff which is always at rest in the frame in which Maxwell's equations work". Now to explain experiments, we find that the ether has all sorts of effects on things moving through it
  - Shrinks rods
  - Slows clocks
  - Changes masses.
- That sounds like a great confirmation of the aether's reality, until you notice that the net effect of all these changes together is that:

The motion through the aether is undetectable!

- Maxwell's equations seem to work in ANY inertial frame!
- Lorentz griped that nature was conspiring against us.

“Almost” Relativity

- In 1904, Poincaré suggested that it might be impossible to measure one’s speed through the aether. He proposed that "A complete conspiracy is itself a law of nature." He asked, “What must be true if one’s speed through the aether is to be unobservable?” He was able to show that the mass of an object (the “m” in “momentum = mv”) would increase as an object’s speed increased. Also, the speed of light would be the maximum possible speed.
- However, there was still an underlying assumption, left over from the first impression made by Maxwell's equations, and perhaps from our Aristotelian instinct, that one reference frame was "right", however hidden it might be.

Will the aether frame reveal itself?

- "The principle of physical relativity is an experimental fact ... and as such it is susceptible to constant revision." "The principle of relativity thus does not appear to have the rigorous validity which one was tempted to attribute to it."
  Poincaré,quoted by Holton, p. 205.

- The situation was unsatisfying from a philosophical point of view to Lorentz and Poincaré and others:
  - "...surely this course of inventing special hypotheses for each new experimental result is somewhat artificial. It would be more satisfactory if it were possible to show by means of certain fundamental assumptions ..."
    H.A. Lorentz, quoted by Holton, *Thematic Origins of Scientific Thought*, p.229.

- Maybe the principle of relativity should be taken as a postulate, not just a contingent fact.

Einstein's approach

- Initially motivated by Mach's conception of a completely relationist universe. For Mach, even acceleration was relative. For Poincaré the aether had become as undetectable as Newton's absolute space. This was unsatisfying to Einstein.

- Why does one use one equation to describe a conductor moving past a magnet and another to describe a magnet moving past a conductor?
  - "It is known that Maxwell's electrodynamics – as usually understood at the present time – when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena." Einstein, *On the Electrodynamics of Moving Bodies*, *Annalen der Physik*, **17** (1905).

- "The phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. The same laws ... will be valid for all frames of reference." Einstein
- That postulate (relativity) sounds familiar, but how can we combine it with Maxwell's equations?

Einstein’s Two Postulates

1. “If, relative to K, K’ is a uniformly moving coordinate system devoid of rotation, then natural phenomena run their course with respect to K’ according to the same general laws as with respect to K. This statement is called the *principle of relativity* (in the restricted sense).” Einstein, *Relativity*, p. 16.

This principle applies to **all** phenomena (including electrical and optical), not merely mechanical.

So, what to do about Maxwell’s equations? We accept them:

2. “... experience in this domain leads conclusively to a theory of electromagnetic phenomena, of which the law of constancy of the velocity of light *in vacuo* is a necessary consequence.” p. 23.

- <u>The insistence that these two "apparently incompatible" principles are consistent is the new idea.</u>

- Let's see more carefully why these two ideas seem inconsistent- the worst thing you can do is to simply accept them without drawing the necessary consequences.