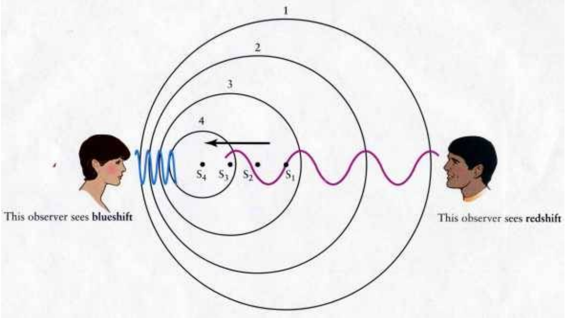
Doppler Effect and the Expansion of the Universe



1. θ=0° : $\nu = \nu' \sqrt{\frac{1+\beta}{1-\beta}}$
2. θ=180° : $\nu = \nu' \sqrt{\frac{1-\beta}{1+\beta}}$
3. θ=90° : $\boxed{\nu = \nu' \sqrt{1-\beta^2}}$

Transverse doppler effect

For light and other electromagnetic waves, the relationship must be modified to be consistent with the Lorentz transformation and the expression becomes.

Doppler effect for light

$$\nu_{observed} = \left[\frac{\sqrt{1-\frac{v^2}{c^2}}}{1-\frac{v}{c}}\right]\nu_{source}$$

which can be rearranged to the form

$$\nu_{observed} = \nu_{source}\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$$

or in common relativity notation:

$$\nu_{observed} = \nu_{source}\sqrt{\frac{1+\beta}{1-\beta}}$$

Here v is the relative velocity of source and observer and v is considered positive when the source is approaching.

1. A galaxy in the constellation Ursa Major is receding from the earth at 15,000 km/s. If one of the characteristic wavelengths of the light the galaxy emits is 550 nm, what is the corresponding wavelength measured by astronomers on the earth?

Concept of Ether: Michelson-Morley experiment

Ether: According to Maxwell, light waves are transverse electromagnetic wave. A material medium is necessary for the propagation of transverse waves. For light, it was assumed ‘limuniferous ether’.

Tranverse waves require shearing and these forces can occur in solid only. It means that ether must be rigid solid filling the whole space. As the velocity of wave propagation depends on the elasticity of the medium, ether must be highly elastic. Thus, the whole free space must be filled up with this medium called ether which is difficult to conceive.

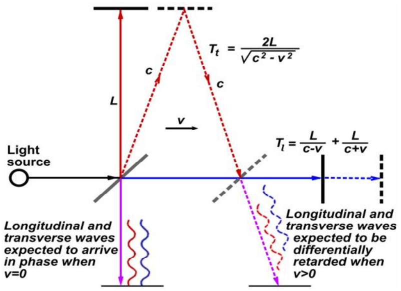
If light is propagated through the ether medium, then in optical experiments, one would expect change in velocity (drift) depends upon the direction of light propagation with respect to motion of the apparatus.

Michelson’s most significant achievement, carried out in 1887 in collaboration with Edward Morley, was an experiment to measure the motion of the earth through the ‘ether’, a hypothetical medium pervading the whole universe in which light waves were supposed to occur. The notion of the ether was a hangover from the days before light waves recognized as electromagnetic, but nobody at the time seemed willing to discard the idea that light propagates relative to some sort of universal frame of reference.

Michelson-Morley experiment

To look for the earth’s motion through the ether, Michelson and Morley used a pair of light beams formed by half-silvered mirror as shown in figure.

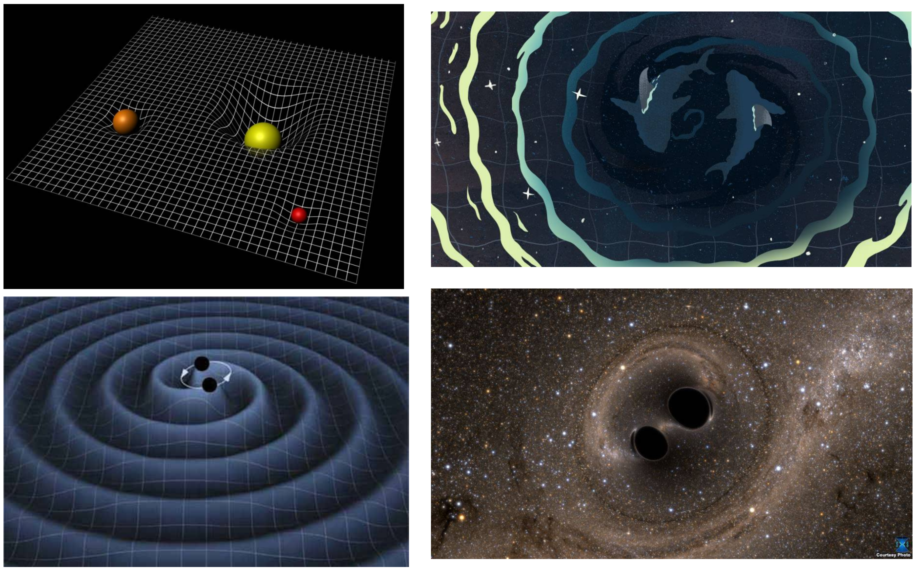
One light is directed to a mirror along a path perpendicular to the ether current, and the other goes to a mirror along a path parallel to the ether current. Both beams end up at the same viewing screen. The clear glass plates ensure that both beam pass through the same thickness of air and glass. If the transit times of the two beams are the same, they will arrive at the screen in phase and will interfere constructively. Ether current due to the earth’s motion parallel to one of the beams, however, would cause the beams to have different transit times and the result would be destructive interference at the screen. This is the essence of the experiment.



Although the experiment was sensitive enough to detect the expected ether drift, to everyone’s surprise none was found. The negative result had two consequences.

- First, it showed that the ether does not exist and so there is no such thing as “absolute motion” relative to ether: all motion is relative to a specified frame of reference, not to a universal one.
- Second, the result showed that the speed of light is the same for all observers, which is not true for waves like sound and water waves that need a material medium in which to occur.

Space-Time in Relativity and the Gravitational wave



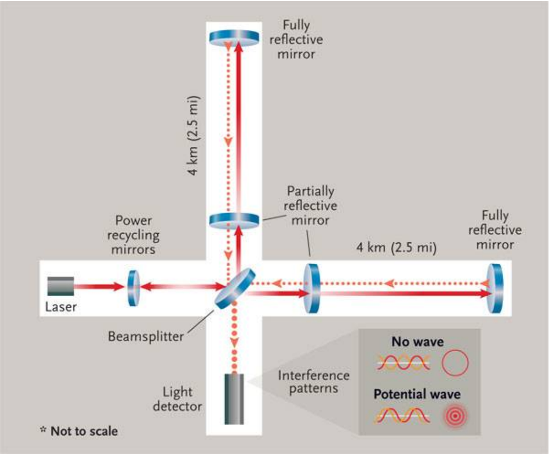
Gravitational Wave Detection by LIGO (Laser Interferometer Gravitational-Wave Observatory)

Recently, physicists announced the first-ever direct detection of gravitational waves, ripples in the fabric of space-time predicted by Einstein's general theory of relativity. Two massive accelerating objects — in this case, a pair of stellar-mass black holes in a death-spiral — passed through space-time like paddles sweeping through water, creating vibrations that could (barely) be felt on Earth. The results are published in *Physical Review Letters*.

https://www.ligo.caltech.edu/

LIGO scientists have announced the direct detection of gravitational waves, a discovery that won't just open a new window on the cosmos — it'll smash the door wide open.

LIGO's Interferometer



* Not to scale

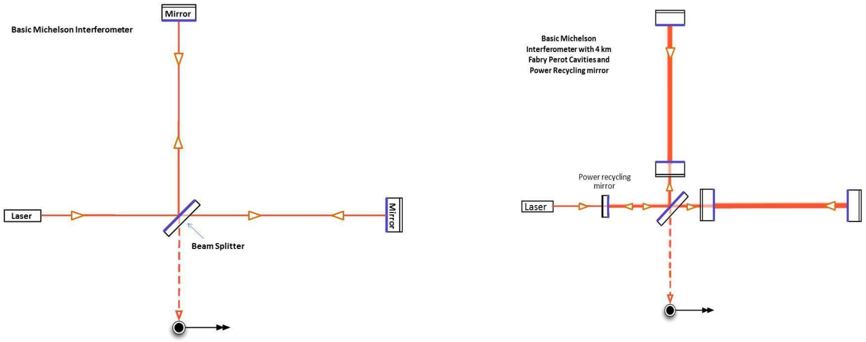
- LIGO consists of two L-shaped facilities, one near Hanford, Washington, and the other near Livingston, Louisiana. At 5:51 a.m. (EDT) on September 14, 2015, both labs caught the gravitational-wave signature of two colliding black holes, shortly after both facilities were turned on following five years of intensive upgrades.
- In this schematic of LIGO, a beamsplitter sends light along two paths perpendicular to each other. Each beam bounces between two mirrors, one of which allows a fraction of the light through. When the two transmitted beams meet and interfere, they'll cancel each other out — if the length of the path they've each traveled has remained constant. But if a gravitational wave passes through, it'll warp space-time and change that distance, creating an interference pattern.

Michelson and LIGO’s Interferometers

Although they are much more sophisticated, at their cores, LIGO's interferometers are fundamentally Michelson Interferometers, a device invented in the 1880's. We can say this because both Michelson and LIGO interferometers share these characteristics:

- They are both are L-shaped (not all interferometers are this shape)
- They both have mirrors at the ends of the arms to reflect light in order to combine light beams and create an interference pattern
- They both measure patterns and intensity of a resulting light beam after two beams have been superimposed or forced to 'interfere'

But this is where the similarities end. The size and added complexity of LIGO's interferometers are far beyond anything Michelson could have envisioned or that his original interferometer could have achieved.



Basic Michelson Interferometer with Fabry Perot cavities and Power Recycling mirror. Mirrors placed near thebeam splitter cause multiple reflections and keep the laser contained within the arms. This increases the distance traveled by the beams, greatly improving LIGO's sensitivity to changes in arm length like those caused by gravitational waves. LIGO's interferometers use multiple power recycling mirrors, but for simplicity only one is shown in the diagram.