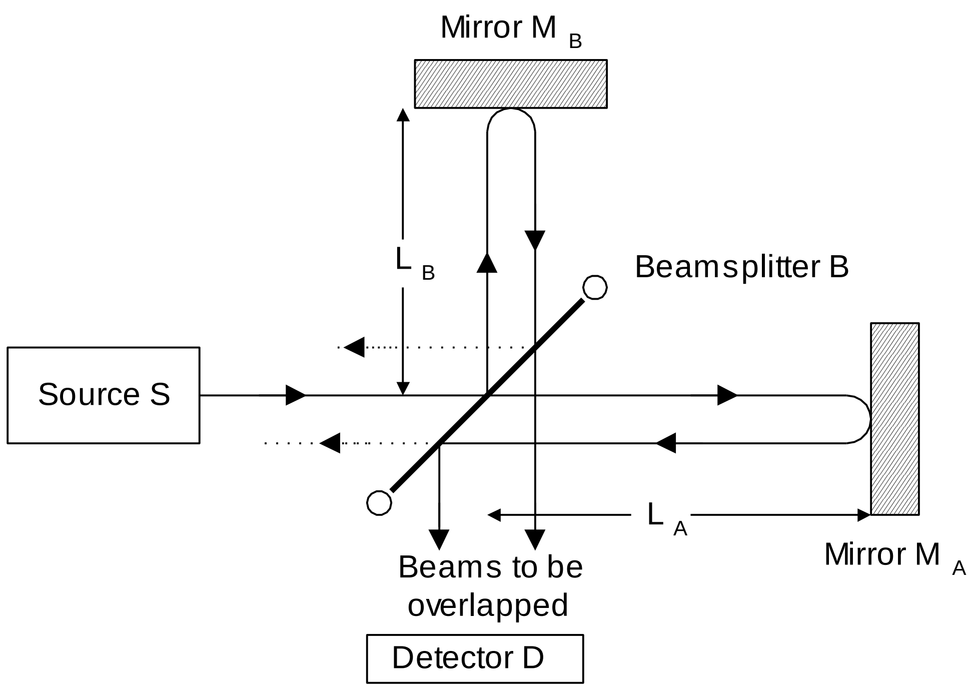
TeachSpin's Modern Interferometry
A Conceptual Introduction to the Experiment

This document cannot begin to cover the whole field of optical interferometry, but it does describe what you can do in a first, hands-on, encounter with the construction, alignment, and use of an interferometer. It's meant to empower you, teaching you that an interferometer is something you can understand from first principles, and that you can build from scratch on an empty table.

Of all the experiments that demonstrate the interference of light, the Michelson interferometer is the most famous, due to its historical connection with 'ether-drift' experiments and the historical foundations of relativity. This kind of interferometer is also one of the easiest to set up and align, and it's also suited to a variety of amazingly sensitive measurements.

Lots of people have seen a stylized diagram of a Michelson interferometer. The crucial optical component is the beamsplitter B (a.k.a. a 'half-silvered mirror', nowadays a dielectric layer deposited on a glass substrate, giving 50% transmission and 50% reflection). Light from a source S reaches this beamsplitter, and forms two beams which go to plane mirrors M_A and M_B; those beams come back to the beamsplitter and head (in part) toward a detector D. (We've offset the reflected beams in the diagram to make the paths easier to follow.)



If we use L_A and L_B to denote the one-way lengths of the two arms, and use λ for the wavelength of the light, then the equations for the intensity of light at detector D is:

$$I(at\ D) = \frac{I_{max}}{2}\ (1 + cos\ 2\pi\ \frac{L_A - L_B}{\lambda/2})$$

That is to say, if arms lengths L_A and L_B are equal (or, if they differ by an integer multiple of λ/2), then the cosine factor is 1, and the intensity of the light at the detector reaches a maximum, I_{max}. That's because under these conditions, the *round-trip* distances $2L_A$ and $2L_B$ will differ by an integer number of wavelengths, and the two beams rejoining at the beamsplitter will meet in the in-phase condition. But if the two arm lengths *mis*-match, by as little as a quarter-wavelength, then the intensity at the detector point drops all the way to zero.

For an interferometer illuminated by red light, λ ≈ 600 nm, so a trifling motion of either mirror by a quarter-wavelength ($\lambda/4 \approx 150$ nm = 0.150 μm = 0.00015 mm = 1.5×10^{-7} m) turns an easily observed light intensity from a maximum value down to zero. This illustrates 'interferometric sensitivity', and it illustrates how sensitive to displacements (whether deliberate or inadvertent) an interferometer can be. And if a 150-nm displacement gives a 'full-scale' change in intensity, much *smaller* displacements will still give detectable signals.

But what does it take to translate this paper diagram into working table-top reality? Here are some issues you'll encounter.

A. *The light source needs to be 'coherent'*; really, that means 'coherent enough'. The bigger the difference between the arm lengths L_A and L_B, the more stringent this requirement is. Conversely, if L_A and L_B are matched to better than 1 μm, even *white* light can be used in the interferometer. Everyone's favorite first light source is a red helium-neon laser, operating at λ = 633 nm = 0.633 μm, and it has sufficient temporal coherence (i.e. its optical frequency, near 473,000 GHz, is well-defined to better than 1 GHz) that arm length differences of an inch or two (2 - 5 cm) can be tolerated.

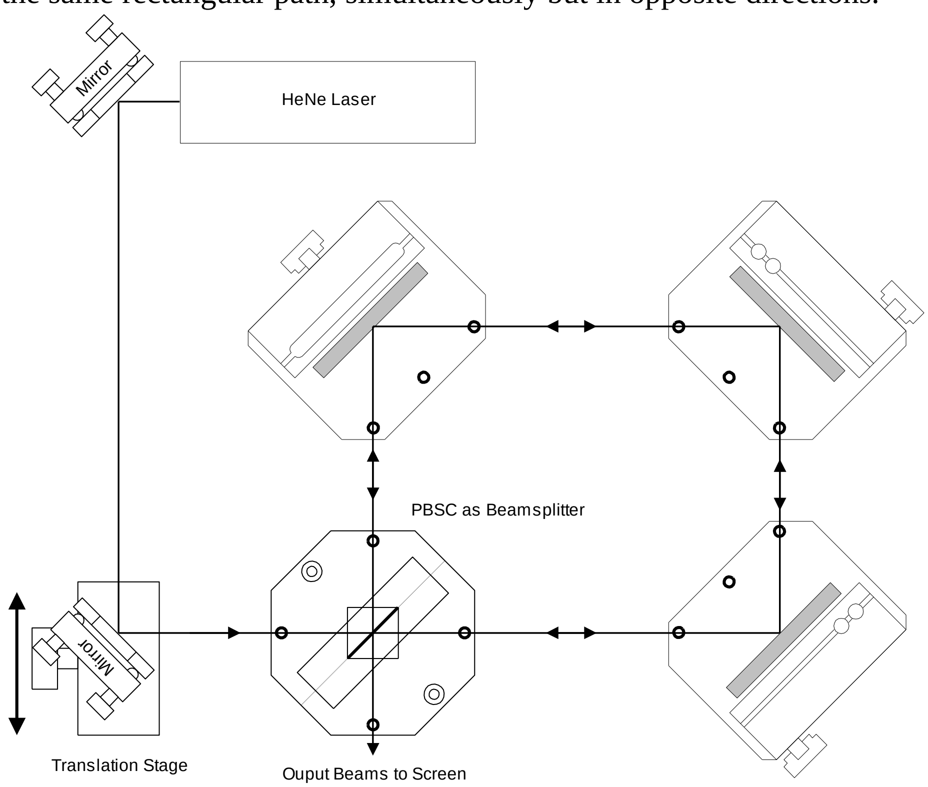
B. *The interferometer needs to be aligned*, so that the light beams really do take on the paths suggested by the figure. In particular, for interference to be visible, the beams returning from mirrors M_A and M_B need to encounter the beamsplitter so that they head toward the detector both parallel in direction and overlapping in space. The art of building an interferometer is to include just enough mechanical adjustments to make this alignment possible, but to ensure that everything else stays fixed and rigid.

C. *The interferometer needs to be mechanically stable*. If you build it with arms L_A and L_B a foot long, then $L_A \approx L_B = 0.30$ m. A change of $\lambda/4 \approx 0.15$ μm in dimension L_A or L_B, whether fast or slow, will change an interference maximum to a minimum -- and that distance represents just *half of a part-per-million* change in the arm lengths! There are lots of influences, including small temperature changes, mechanical stresses, air-pressure fluctuations, and room vibrations, that can cause such tiny changes.

D. *The 'detector' can be as simple as eyeball sighting of light on a screen, but it's much better to have an electronic photodetector.* The photodetector gives the capability of fast response (0.1 ms is easily achieved), and a quantitative and linear response to the intensity at detector D. It also allows the interference signals to be displayed on an oscilloscope or captured by a computer.

Let's consider using Michelson interferometer to measure an optical wavelength λ directly, using ordinary tools. Suppose we have a way to move mirror M_A, by carefully controlled amounts -- we want to move it parallel to itself, by tiny yet measurable amounts. The TeachSpin interferometer achieves this using 'flexure translation stage', driven by a differential micrometer. As mirror M_A is slowly moved through a distance of λ/2, the round-trip path of the light in arm #A increases by a total distance λ. In the process, the intensity of the light at detector D goes through one full cycle – perhaps from I_{max} down to 0 and back up to I_{max} again. If you achieve a motion that allows you to count 100 such cycles of intensity variation, or 100 'fringes', then you have moved the mirror by an amount that is equal to 50 λ. Since you are using a micrometer, you can also measure that distance in ordinary length units. Just let 50 λ = distance on micrometer and solve for the wavelength in ordinary units.

But there are other ways to configure an interferometer. In the Sagnac topology, shown below, a beamsplitter divides an entering laser beam into two emerging beams which go around the same rectangular path, simultaneously but in opposite directions.

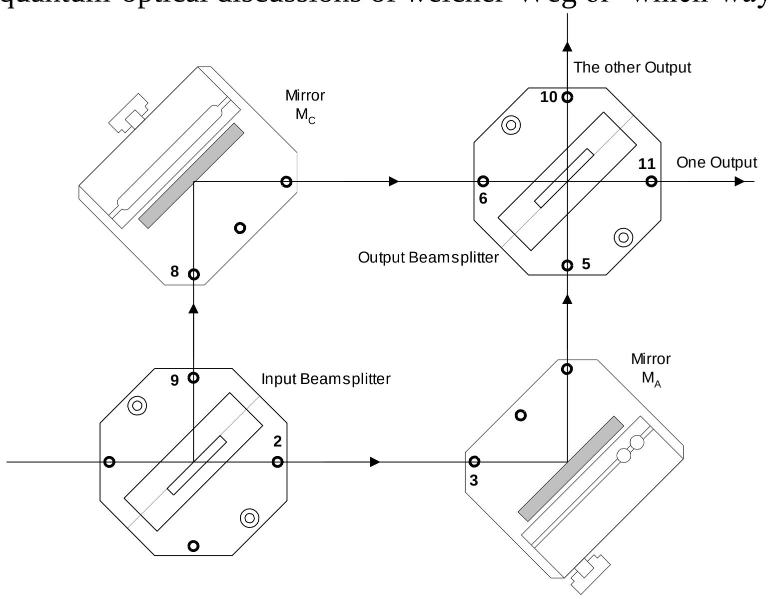


The two beams recombine back at the beamsplitter. The interferometer responds to the total phase difference developed as the beams traverse their equal and opposite paths. Since both beams are reflected by the same set of surfaces and components, most of the vibrational noise becomes a common-mode effect, to which the interferometer is thus *in*sensitive. As a result, phase shifts equivalent to $\lambda/1000$, or even less, create obvious changes in the interference signals. This corresponds to being sensitive to differences in the time-of-flight of the two beams around the system at the level of 10^{-18} s.(!)

Depending on the experimental set-up, the counter-propagating beams within the interferometer can either overlap or be separated in space. One application of adjacent but non-overlapping beams is to let one of the beams pass through a gas cell. Now a variation of gas pressure in the cell causes phase changes in the interferometer, and hence in its output signal. Using a differential pressure transducer allows quantitative and *very* sensitive measurement of the index of refraction of gases.

Part of the romance of interferometry lies in the use of these techniques to establish facts about the nature of space and time. It was the *failure* of the Michelson-Morley experiment to display the expected fringe shifts which contributed to the realization that 'absolute translation in space' is experimentally undetectable. But that's all the more reason for students to encounter the Sagnac interferometer, which *does* permit the optical detection of 'absolute rotation in space'. That's why optical gyroscopes, based on the Sagnac effect in light beams counter-propagating in optical fibers, now find a place in inertial navigation units – but Michelson interferometers do not!

Modern Interferometry can also be used to create a Mach-Zehnder layout, which often figures in glamorous quantum-optical discussions of welcher-Weg or 'which-way' experiments.



And so we can see that Modern Interferometry does more than teach tabletop optical-layout and alignment skills. With it, students begin to understand important interferometric concepts currently used in neutron and even neutral-atom interferometry.