# 4–26 Wave Nature of Light

**Diffraction:** When light hits the edge of a barrier, as shown in the left diagram in Fig 26.1, it will bend around it. If the barrier is small compared to the wavelength of light the light will pass the barrier uninterrupted. Like water flowing around a buoy. But, if the barrier is large compared to the wavelength of light the waves will bend around the edge of the barrier in a circular fashion. Imagine water waves hitting the end of a jetty, or going through a hole in a jetty.

**Slit Width:** The smaller the opening the more pronounced the circular effect, as shown in the right diagram in Fig 26.1.

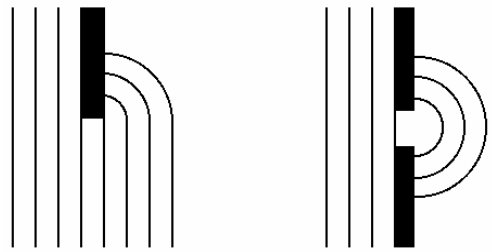

Fig 26.1

**Huygen's Principle:** Every point on a wave front can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The wave front is formed by the constructive interference of the circular wavelets, as shown in Fig 26.2.

So, if the barrier has a hole in it, the particles of the wave create new circular wave fronts when they exit on the other side. This is why you get the circular patterns shown on the previous page.

The particles of light that create this diffraction pattern are the photons. Each photon generates circular wave fronts that constructively interfere to generate linear wave fronts.

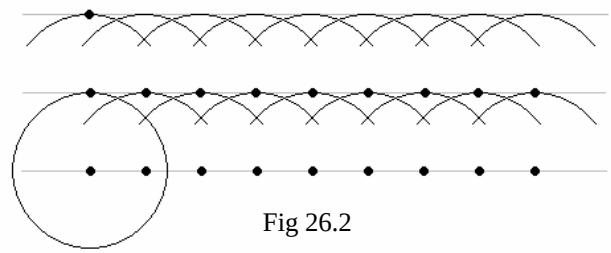

Fig 26.2

**Young's Double Slit Experiment:** Young shined a monochromatic light source on two very narrow slits. He used a monochromatic light source, since white light consisting of all the colors would result in a rainbow refraction. Light has the same characteristic pattern as water waves and is ***<u>evidence that light behaves as a wave</u>***. Light from two slits interferes with each other. As a result you get dark and light bands if the pattern is shown on a screen.

**Interference Fringes:** The bands of light and dark that appear at regular intervals, as shown in Fig 26.3. They follow a

m geometric relationship described by the following equations. $\boxed{d \sin\theta = m\lambda}$ $\boxed{x_m \approx \frac{m\lambda L}{d}}$

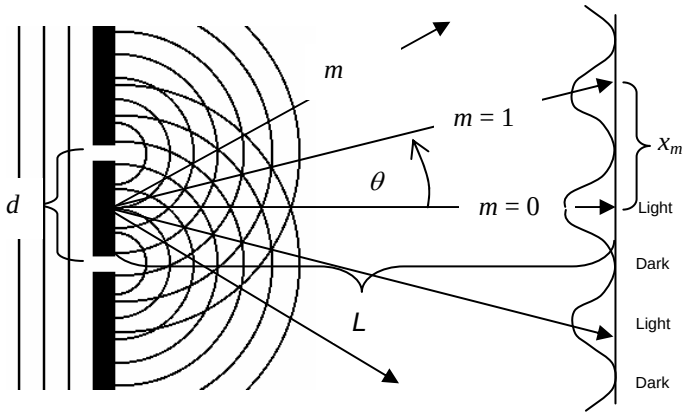


Fig 26.3

$d$ is the distance between the slits.

$m$ is the fringe number. $m = 0$ is the central maximum. It is also the ***<u>path difference in wavelengths</u>***.

Whole numbers are used for the bright ***Constructive Interference Fringes***. $m$ = 0.0, 1.0, 2.0, 3.0, etc.

Half numbers are used for the dark ***destructive interference fringes***. $m$ = 0.5, 1.5, 2.5, 3.5, etc.

$\theta$ is the angle from the midline (from the middle fringe).

$L$ is the distance from slits to the screen.

$x_m$ is the distance from the midline (center fringe) to the fringe being measured.

The second formula $\boxed{x_m \approx \frac{m\lambda L}{d}}$ is only approximately equal. If $\sin\theta = \frac{x_m}{L}$, then $d\sin\theta = m\lambda$ would become $d\frac{x_m}{L} = m\lambda$. This would simplify to $\boxed{x_m = \frac{m\lambda L}{d}}$. But $\sin\theta = \frac{x_m}{L}$ is not true. $x_m$ is the opposite and $L$ is the adjacent.

So $\tan\theta = \frac{x_m}{L}$ is the true equality. But, as long as the angle is small $\sin\theta \approx \tan\theta$, and then we can use $\boxed{x_m \approx \frac{m\lambda L}{d}}$.

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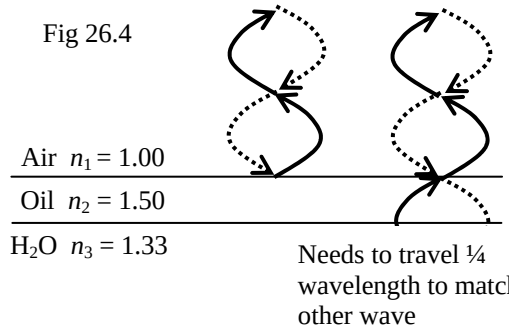
**Thin Films:** Most people are familiar with the rainbow effect seen when a thin oil/soap film is floating on top of water. The phenomenon can also be seen in the thin film coatings that give modern sunglasses their protective properties. The ***thickness*** of a thin film and the ***density*** of the film and the mediums around it, combine to create the thin film optical effect.

**Important background information to keep in mind.**

- Denser mediums have higher indices of refraction.
- A reflected ray will change phase by 180° when going from a medium with a low $n$ to a medium with a high $n$.
- A reflected ray going from a medium with a higher $n$ to a medium with a lower $n$ is a soft boundary reflection.

## Case 1: The middle medium has the greatest density.

Fig 26.4




***Example: Oil Suspended On Water:*** Light moving from air to oil and then to water. It goes from low density (low $n$) to a high density (high $n$), and back to a lower density (lower $n$). Two beams of light shown as dashed lines strike the thin film, in Fig 26.4. One reflects off the air-oil boundary. The high to low index of refraction change is like hitting a hard boundary. This causes a 180° shift in the outbound reflected light wave, as seen on the left in Fig 26.4. This is similar to the wave reflection in a guitar string that is tied down, creating a hard boundary. The right light wave makes it through the first surface and reflects off the second surface. The change from oil to water is from more to less dense and the index of refraction gets smaller. This is like hitting a soft boundary, such as air reflecting in an open tube. If the thin film has an exact thickness the two outbound light waves will be in phase. Waves in phase constructively interfere creating a larger wave. In the case of light it creates a brighter light. If the wavelength is an observable color our eye would see a brightening of that color. In the diagram above this occurs when the film is ¼ of a wavelength.

**Problem:** The oil film is 1x10$^{-7}$ m (100 nm) thick, $n_1$ = 1.00, $n_2$ = 1.50, $n_3$ = 1.33. What wavelengths will results in maximum intensity? $\boxed{thickness_{film} = \frac{1}{4}\lambda_{film}}$ $\lambda_{film} = 4\left(thickness_{film}\right) = 4\left(1\times10^{-7}\right) = 4\times10^{-7}\,m = \boxed{400nm}$

**Caution**: You have now found the wavelength in the film (the oil). Your eye will see the color in the air, so this wavelength needs to be converted from oil to air. There is a formula that converts wavelengths based on the index of refraction $\boxed{n_1\lambda_1 = n_2\lambda_2}$. Rewritten to match this situation: $\boxed{n_{air}\lambda_{air} = n_{film}\lambda_{film}}$ $\lambda_{air} = \frac{n_{film}\lambda_{film}}{n_{air}} = \frac{(1.5)(400nm)}{(1.0)} = \boxed{600nm}$.

***Is there any destructive interference?*** Yes, if the thickness of the film is changed to ½ of a wavelength

**Conclusion:** When $n_1 < n_2 > n_3$

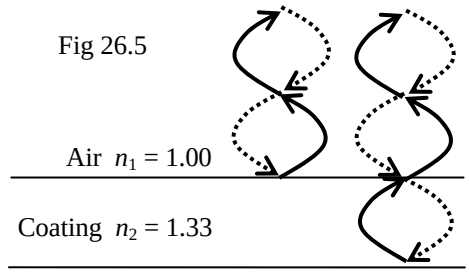
Constructive Interference: $\lambda_{film} = 4\left(thickness_{film}\right)$

Destructive Interference: $\lambda_{film} = 2\left(thickness_{film}\right)$

Followed by $\boxed{n_{air}\lambda_{air} = n_{film}\lambda_{film}}$ $\lambda_{air} = \frac{n_{film}\lambda_{film}}{n_{air}}$

## Case 2: Mediums With Progressively Higher Densities

Fig 26.5




At both boundaries the change is to a higher density (higher n), so there are two 180° reflections. Here the film needs to be the thickness of ½ wavelength to get maximum intensity. $\boxed{thickness_{film} = \frac{1}{2}\lambda_{film}}$ It is the reverse of the above scenario. Even multiples of ¼ wavelength create constructive interference, while odd multiples of ¼ wavelength create destructive interference.

**Problem:** The sunglass coating 2x10$^{-7}$ m thick, $n_1$ = 1.00, $n_2$ = 1.33, and $n_3$ = 1.50. What wavelength will result in maximum intensity?

$\lambda_{film} = 2\left(thickness_{film}\right) = 2\left(2\times10^{-7}\right) = 4\times10^{-7}\,m = 400nm$

$\boxed{n_{air}\lambda_{air} = n_{film}\lambda_{film}}$ $\lambda_{air} = \frac{n_{film}\lambda_{film}}{n_{air}} = \frac{(1.33)(400nm)}{(1.0)} = \boxed{532nm}$

**Conclusion:** When $n_1 < n_2 < n_3$

Constructive Interference: $\lambda_{film} = 2\left(thickness_{film}\right)$

Destructive Interference: $\lambda_{film} = 4\left(thickness_{film}\right)$

Followed by $\boxed{n_{air}\lambda_{air} = n_{film}\lambda_{film}}$ $\lambda_{air} = \frac{n_{film}\lambda_{film}}{n_{air}}$

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