Chapter 17: Wave Optics

Section 17.1: What Is Light?

Wave Model

- Light exhibits many wave behaviors
- These can be observed easily and measured directly
- Light is definitely a wave!

Photon Model

- Light exhibits behaviors consistent with particles
- These particle properties are inconsistent with waves
- Particle behavior can also be observed and measured
- Light is definitely a particle!

The Ray Model

- Let's not argue particle or wave
- Let's just observe and measure how light behaves, develop some rules, and use them to invent all sorts of really useful optical instruments because honestly, your eyes don't care whether light is a particle or a wave when you just need a pair of glasses to be able to read the fine print

The Propagation of Light Waves

- Straight-line propagation is ray behavior
- Does light actually do this? Yes
- How do we know? Shadows

Is This Consistent With Wave Behavior?

- You can observe this behavior easily with matter waves (specifically, water waves)
- Straight line propagation is normal (pun intended)
- Also, diffraction—what's up with that? Spoiler alert: It explains why you can hear around corners, but you can't see around corners

Light is an Electromagnetic Wave

- Yes, we may have mentioned this once or twice already
- Transverse wave, no need for a material medium
- Speed of light $c=3\times10^8$ m/s through vacuum
- Any medium that isn't vacuum slows light down

The Index of Refraction

- If everything other than vacuum is slower, then we want a way to quantify this
- Index of refraction n = ratio of speeds vacuum/medium
- n =1 for vacuum
- n > 1 for everything else, and the bigger n is; the slower the medium is

Section 17.2: The Interference of Light

Start With Diffraction

- No, we have not yet analyzed this—but neither had Thomas Young in 1801 when he developed his double-slit experiment
- Anyway, start with a single very (very) narrow slit: light through the slit behaves like a point source
- Now add a second slit—why? Well, because Young did not have a laser
- When a wavefront hits the slits, it creates two point sources that are perfectly in phase (the in-phase is the important part)

Young's Double-Slit Experiment

- If you don't have a laser, you can use sunlight and a slit plate
- Take a glass slide, black it out, then use a razor blade to score two slits
- Make your slits about 0.1mm wide, and put them no more than 0.5mm apart
- While you're at it, make another slide with a single slit, you're going to need it

What Actually Happens

- Sunlight through the first single slit creates a point source
- That light hits the second slit plate, and now you have two coherent point sources
- The light hits a screen—and if it's 1801, holy wow are you surprised by the results

The Interference Pattern

- Central maximum—this is critical!
- Evenly-spaced pattern of bright and dark fringes

Analyzing Double-Slit Interference

- You remember that discussion of path-length difference from the last chapter?
- Nothing has changed. Literally, nothing.
- The next step? Pay attention to the screen

Find the Bright Fringes

- Central bright maximum: m=0
- Sinθ = m(λ/d)
- y_m = (mλL)/d (uses the small-angle approximation!)
- Measure from center of central maximum
- Fringes are evenly spaced: Δy does not depend on m

Find the Dark Fringes

- Waves must be ½ λ out of phase
- y_m = (m+½)(λL)/d

Intensity as a Function of Distance

- You already know from experience that the farther the source, the dimmer the light appears
- Farther screen, less bright overall pattern
- Increase lateral distance (y) from central maximum also decreases intensity

Section 17.3: The Diffraction Grating

The Next Logical Step

- If two slits gives you an interesting result, why not 4? 8? 16?
- Fast-forward to the 21st century where it's possible (and relatively easy) to create a grating with N slits even spaced a distance d apart

Slit Width and Slit Spacing

- Note that the slit width w doesn't actually show up in the equations! But it's important to note that w should be similar in size to the wavelength of the source you are hoping to diffract
- Typically gratings are expressed as n = lines/mm; n = 1000 lines/mm is a commonly-available grating
- Slit spacing d = mm/line, so d = 1/n, which is not the same as N!

Here's Where We Lose the Small Angle Approximation

- The math has not changed, but the angles have: gratings can result in large-scale patterns with large angles
- Maxima still located using sinθ = m(λ/d)
- y_m = Ltanθ_m (loses the small-angle approximation!)

Fringe Width and Intensity

- The higher N, the narrower the fringe
- The narrower the fringe, the greater its intensity
- Intensity is proportional to N^2

Spectroscopy

- We are so far ahead of ourselves, but different colors (different frequencies) will diffract differently
- Longer wavelength (lower frequency) light is diffracted more (red diffracts more than blue)
- You can separate light into its constituent colors, which is insanely useful (ask an astronomer or a molecular chemist)

Section 17.4: Thin-Film Interference

Soap Bubbles, Oil Slicks, Peacock Feathers

- Anything iridescent is an example of thin-film interference
- Notice that the color you perceive changes with the angle of view

Interference of Reflected Light Waves

- Remember the idea of phase change of a reflected wave from the last chapter?
- We need that right now
- The rules are the same, only we are connecting the wave speed to the index of refraction now

Reflection Off a Slower Medium

- Incident medium (n_1) faster than reflective medium (n2)
- $n_2 > n_1$
- Reflected wave will not change phase

Reflection Off a Faster Medium

- Incident medium (n_1) is slower than reflective medium (n_2)
- $n_1 > n_2$
- Reflected wave will undergo a λ/2 phase change

Change in Medium Means Change in Speed

- Don't forget: The change in medium changes the wavelength along with the speed!
- This is because the frequency doesn't change: v = λf means that if v decreases, λ does too
- $v_2 = c/n_2$ means $\lambda_2 = \lambda_{vac}/n_2$

Here's How That Geometry Works Out: Destructive

- Ray 1 reflected off first boundary: λ/2 phase change

- Ray 2 reflects off second boundary: No phase change
- Path length difference $\Delta r = 2t$, where t is the film thickness
- Destructive interference means Rays 1 and 2 have to be out of phase when they hit your eye
- Ray 1 has phase changed, but Ray 2 has not: Ray 1 has a half-wavelength head start on Ray 2
- $\Delta r = \lambda_1$ (or $m\lambda$) because Ray 1 is already ahead
- $\Delta r = 2t = m\lambda_1$, so $t = ½(m\lambda_1)$

Constructive Geometry

- Ray 1 reflected off first boundary: $\lambda/2$ phase change
- Ray 2 reflects off second boundary: No phase change
- Path length difference $\Delta r = 2t$, where t is the film thickness
- Constructive interference means Rays 1 and 2 have to be in phase when they hit your eye
- Ray 1 has phase changed, but Ray 2 has not: Ray 1 has a half-wavelength head start on Ray 2
- $\Delta r = ½\lambda_1$ (or $(m+½)\lambda$) because Ray 1 is already ahead
- $\Delta r = 2t = (m+½)\lambda_1$, so $t = (m+½)(½\lambda_1)$

But What If $n_2 > n_1$??? What Then?

- The film (n_1) will always be slower than the air ($n_1 > n_0$)
- But the substrate might be slower or faster than the film
- If $n_1 > n_2$: Only 1 phase change, previous example applies
- If $n_1 < n_2$: Phase change at both boundaries!

Subtractive Color

- Color means wavelength
- If a film is exactly the right thickness, it can cancel a single color
- Only one color interferes destructively, but the remaining colors do not
- When you remove red from white light, you're left with cyan
- Remove only green light, you're left with magenta
- Remove only blue light, and you're left with yellow

Structural Color From Thin Films

- This is how the soap bubble and the oil slick get their colors
- As the thickness of the film or your angle of view changes, the destructive color changes
- You perceive that shifting color iridescence

Section 17.5: Single-Slit Diffraction

Back to the Beginning

- You would think we would have started here
- Observing this is laughably easy, but explaining it...not so much
- It's not obvious at all why you would get a fringe pattern with only one slit

The Diffraction Pattern

- Looks familiar: central max, alternating bright/dark fringes
- Central maximum is twice as wide
- Brightness drops off dramatically for subsequent fringes

Huygens' Principle

- Each point on a wave front is the source of a spherical wavelet that spreads out at the wave speed
- At a later time, the shape of the wave front is the curve that is tangent to all the wavelets
- This is pretty sophisticated thinking for 1678, so naturally it was ignored
- Not to mention, Newton was an advocate of the 'corpuscular' (particle) model

Analyzing Single-Slit Diffraction

- Notice that we are locating the dark minima!
- Use Huygens to set up a series of wavelets right at the slit
- Pair each wavelet with the one half the slit width away: Δr_{12}, Δr_{34}, Δr_{56}
- Each Δr is exactly the same, and for minima, $\Delta r = ½\lambda$
- Also, we are back to being able to use the small angle approx!
- $\theta = p(\lambda/a)$

How Wide Is That Central Maximum?

- Find the first dark minimum (y_1)
- Maximum is $w = 2y_1$ wide
- Assume distance from slit to screen is L
- Use the small-angle approximation ($\tan\theta \approx \sin\theta$