29 Light Waves

The first photo opener is Bob Greenler blowing a large soap bubble. A good read is Bob's *Chasing the Rainbow: Recurrences in the Life of a Scientist*, Cambridge University Press, 2000. Photo 2 shows Richard Feynman with Helen Yan and Marshall Ellenstein, a gem. Photo 3 is Jennie McKelvie, teaching physics at Massey University, Palmerston North, in New Zealand. Photo 4 is Janie Head, who has been eliciting a love of conceptual physics to her students in Texas for many years. All these photos are of physics educators who enjoy the challenge of getting students to appreciate that physics is an enjoyable part of their world.

The profile for this chapter features one of these outstanding teachers, Marshall Ellenstein.

In your treatment of light waves, emphasize that light does not travel in little sine-wave lines as some diagrams of light suggest. More than one student has asked me if light wiggles as it travels. The wavy lines represent a graph of the changes in the intensity of the E&M fields of which light is composed.

The text mentions how diffraction blurs images in microscopes. Diffraction also tricked Galileo into mismeasuring distances to the stars. This occurred some 200 years before wave optics was understood. Read more on this in Christopher Graney's article "Objects in Telescopes Are Farther Than They Appear" in the Sept. 2009 issue of The Physics Teacher.

If you put some care into the two demonstrations of interference with music suggested here, you'll impress your students with the beauty of physics that should be among the high points of your course.

Practicing Physics Book:
- Diffraction and Interference
- Polarization

Laboratory Manual:
- The Fringe of Optics *Two Slit Interference Equation Simulation* (Tech Lab)
- Light Rules *Turn an mm into a μ to find λ* (Demonstration)
- Diffraction in Action *Diffraction of Light* (Activity)
- Laser Tree *The Geometry of Diffraction Maxima* (Activity)
- Pole-Arier *The Polarization of Mechanical Waves* (Demonstration)
- Blackout *The Polarization of Light Waves* (Demonstration)

Next-Time Questions:
- Three Polaroids
- Soap Bubble
- Polaroid Glasses

Hewitt-Drew-It! Screencasts: •*Diffraction* •*Interference of Light* •*Interference Colors* •*Polarization of Light*

SUGGESTED LECTURE PRESENTATION

Huygens’ Principle

A model for understanding the propagation of light is presented in Huygens’ principle. Careful investigation of Figure 29.5 illustrates *why* the angle of reflection equals the angle of incidence. The figure also shows another view of refraction. Going further, one can see why light travels in straight lines when passing through a transparent medium. Recall the “photon” cascading in a straight-line fashion back in Figure 26.8. Why the cascade is along a straight-line path is unclear, especially if considered from a *ray* point of view. But for many photons, wavefronts cancel one another in random directions and reinforce along the path that makes up the straight line of the ray. The overlapping wavelets of Huygens is a useful model.

Diffraction

Discuss examples of diffraction as in Figures 29.7 – 29.11.

> DEMONSTRATION: After discussing diffraction, pass some index cards with razor slits in them throughout the class. Show a vertical show-case lamp or fluorescent lamp separated into three segments by colored plastic; red, clear, and blue. Have your students view the diffraction of these three segments through the slit, or through a slit provided by their own fingers. Note the different fringe spacings of different colors.

Diffraction is accounted for in the small holes in the door of a microwave oven. The holes allow you to see the food cooking inside, and they’re too small for the 12-cm wavelength microwaves to penetrate.

Interference

Sketch the overlapping of water waves on the board, like that shown in Figure 29.12 on the board. Point out that interference is a property of light waves, sound waves, and ALL kinds of waves.

Prepare your class for your laser demonstration by holding a piece of glass with an irregular surface (shower door glass, sugar bowl cover, crystal glassware) against a laser and show the interference pattern on a screen. Be sure to hold the glass steady so the pattern is fixed. Then make a sketch similar to Figure 29.15 on the board to explain the fringes (a dark area is the result of waves meeting out of phase; a bright area where waves meet in phase).

> DEMONSTRATION: This is a great one! With the lights out, shine laser light through the same irregular piece of glass while making slight movements of the glass and display beautiful interference patterns on the wall. I do this in rhythm with music (Bach’s Suite Three in D). Your students will not forget this demonstration!

The Practice Page that treats Figure 29.18 should be helpful at this point. Pass around diffraction gratings if available. (Arbor Scientific 33-0980, or the *Elements, Mixtures and Molecules* spectrum viewer Web: www.hermograph.com/spectrumviewers.)

Interference Colors by Reflection from Thin Films

Bubble time! Your class will be delighted if you show a display of giant bubbles (made with a wide hoop in a wide tray of bubble solution—a mixture of equal amounts of Joy or Dawn dishwashing liquid, glycerin, and water). Point out that the film of the soap bubble is the thinnest thing seen by the unaided eye—5000 times thinner than a human hair or cigarette paper. The smallness of light waves is sensed here also. Emphasize the need for two reflecting surfaces for interference colors.

Go through the text explanation of interference colors seen from splotches of gasoline on a wet street (Figure 29.26). Shown is a single wave of blue light that reflects from the upper surface and travels to the eye. The eye would see blue light if this wave were alone reflecting from a single surface. This would be the case with no gasoline film on a water surface. Ask how many students have ever seen gasoline films illuminated with blue light. None. But sunlight, yes. Reflection of blue from the second surface of water produces cancellation of the blue light. (This wave is drawn in black, only to distinguish the two waves, the other of which is blue in color.) And when sunlight is incident blue light is canceled. The complementary color of blue, yellow, is what is seen.

> CHECK QUESTION: Why are interference colors not seen from gasoline spilled on a dry surface? [Only one plane reflecting surface is present.]

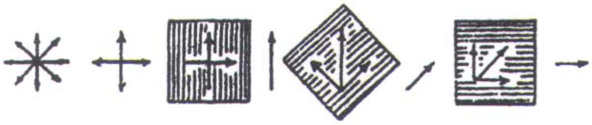
The example of the bluish tint of coated lenses nicely illustrates interference. The predominant yellow of most light is cancelled.

> DEMONSTRATION: Do the experiment "Light Rules" with your class! You'll measure the wavelength of laser light using a ruler with raised grooves as a diffraction grating. Doing so in your class makes a wonderful demonstration. It is the only one I've done at CCSF that elicited a class ovation! I've also done it several times for general talks at physics meetings. Very impressive!

Polarization
Distinguish between polarized and non-polarized light.

> DEMONSTRATION: Tie a rubber tube to a distant firm support and pass it through a grating (as from a refrigerator or oven shelf, as Janie Head shows in the chapter opening photo). Have a student hold the grating while you shake the free end and produce transverse waves. Show that when the grating "axis" and the plane of "polarization" are aligned, the wave passes. And when they are at right angles, the wave is blocked.

Crossed Polaroids with another sandwiched between, as shown by my daughter-in-law in Figure 29.34, is an intriguing demonstration. Second only to the sailboat sailing into the wind, it is my favorite illustration of vectors. The explanation for the passage of light through the system of three Polaroids is not given in the chapter, but is indicated in Figure D.6, Appendix D (repeated here more quantitatively).



[For an ideal polarizer, 50% of nonpolarized incident light is transmitted. That is why a Polaroid passes so little light compared to a sheet of window pane. The transmitted light is polarized. So in the above diagram, only the electric vector aligned with the polarization axis is transmitted; this is 50% of the incident light transmitted by the first sheet. The magnitude of this vector through the second sheet is 50% cos ø, where ø is the angle between the polarization axes of both sheets, and (50% cos ø) cos ß of the original vector gets through the third sheet, where ß is the angle between the polarization axes of the second and third sheet. The intensity of light is proportional to the square of the emerging vector (not treated in the textbook). In any event, the polarizers are less than ideal, so less than this actually gets through the three-sheet system.]

After explaining how the light that reflects from nonmetallic surfaces is polarized in a plane parallel to the surface (by drawing an analogy of skipping flat rocks off a water surface only when the plane of the rock is parallel to the water surface), draw a couple of pair of sunglasses on the board with the polarization axes as shown in the Check Yourself question in the text and ask which are the best for reducing road glare. If you want to discuss the viewing of three-dimensional slides and movies, you'll have a transition to such by the third choice of sunglasses with Polaroids at right angles to each other.

3-Dimensional Viewing
Not everybody can flex their eyes to see the depth of Figures 29.36, 29.37, and 29.39, although with practice most students can do it. Stereograms are easy to construct. Figure 29.39 was easily done on a typewriter with simple line displacement, or such can be drawn by hand. The snowflake stereogram of Figure 29.37 was made by John Dennis, editor of the magazine, *Stereo World*. Make your own by placing

cutouts of snowflakes on a photocopier for one view, then horizontally displace some a bit for a second view. By good old trial and error, students can easily construct their own stereograms.

Stereo buff Marshall Ellenstein contributed the computer generated stereogram shown in Figure 29.41—which reads, “$E = mc^2$.”

> DEMONSTRATION: The vivid colors that emerge from cellophane between crossed Polaroids makes a spectacular demonstration. Have students make up some 2 by 2 inch slides of cut and crinkled cellophane mounted on Polaroid material (which can be obtained inexpensively from Arbor Scientific.). If you have a slide projector, insert a slide of crinkled cellophane and rotate a sheet of Polaroid in front of the projecting lens so that a changing montage of colors is displayed on the screen. Also include a showing of color slides of the interference colors seen in the everyday environment, as well as of microscopic crystals. This is more effective with two projectors with hand dissolving from image to image on the screen. Do this in rhythm to some music and you’ll have an unforgettable lecture demonstration! [My students report that this is the best part of my course—to which I have mixed feelings. I would prefer that some of my *explanations* were the highlight of my course.]

Holograms

To understand the hologram, view the spectral lines of a gas discharge tube through a diffraction grating and emphasize that there are really no physical lines where they appear to be—that the lines are virtual images of the glowing tube (just as they would be images of slits if a slit were being used). With a fairly good idea of how these images are produced by the diffraction grating, show the class a really sophisticated diffraction grating—not of vertical parallel lines in one dimension, but of microscopic swirls of lines in two dimensions—a hologram, illuminated with a laser.

Interestingly enough, holography does not require a laser. As the text states, Dennis Gabor created the first hologram using light from a sodium vapor lamp. Holography requires monochromatic light from a point source. Gabor simply passed sodium light through a pinhole, which reduced intensity and required long exposures and sensitive film. The advantage of the laser for holograms is that a laser emits all its light in a point-source form. Lasers make holography much easier to do.

Although some layered holograms can be viewed with ordinary white light, like those on credit cards, they are nevertheless made with the coherent light of the laser.

Answers and Solutions for Chapter 29

Reading Check Questions

1. Every point on a wavefront behaves as a source of new wavelets which combine to form new wavefronts.
2. Plane waves through a small opening will fan out on the other side.
3. Diffraction is more pronounced through small openings.
4. Diffraction is more pronounced for longer wavelengths.
5. Longer wavelength waves diffract more than shorter waves, so the longer waves of AM diffract more.
6. Interference is a property of all types of waves.
7. Thomas Young demonstrated the wave nature of light.
8. Light bands are regions of constructive interference; dark bands of destructive interference.
9. An optically flat surface is one where interference fringes are uniform in shape.
10. Interference of light is the cause of Newton's rings.
11. Iridescence is produced by light interference.
12. These are interference colors, a result of different thicknesses of gasoline on a water surface. On a dry street there is no underlying reflective surface as water provides.
13. These colors are interference colors, resulting from double reflection from two surfaces.
14. The colors that make up interference colors are the result of cancellation of primary colors each of which is a single frequency.
15. Polarization distinguishes between longitudinal and transverse waves.
16. The directions match for both light and the vibrating electron producing it.
17. When aligned, what gets through one gets through the other. When at right angles, what gets through the first is absorbed by the second.
18. An ideal Polaroid will transmit 50% of incident ordinary light.
19. The reflected light is polarized in the direction of the plane surface of reflection.
20. Parallax is evident when you view something with both eyes, but is not evident when viewed with one eye.
21. Yes, the phenomenon of parallax does underlie depth perception.
22. No, each image must have been created when viewed somewhat apart from each other.
23. Polarization filters at right angles to each other project a pair of images that merge on a screen. These images can reach separate eyes when the screen is viewed through polarization filters at the same right angles to each other.
24. A hologram shows three-dimensional images, whereas a photograph does not.

Think and Do

25. Diffraction is nicely evident.
26. The rays to each viewer are slightly displaced, and therefore different, producing different interference colors.
27. This activity reveals polarization in the sky.
28. This activity is even more dramatic if the colors are projected on a screen.

Think and Explain

29. Earth intercepts such a tiny fraction of the expanding spherical wave from the Sun that it can be approximated as a plane wave (just as a small portion of the spherical surface of the Earth can be approximated as flat). The spherical waves from a nearby lamp have noticeable curvature (see Figures 29.3 and 29.4).

30. Diffraction around ordinary-sized objects is most pronounced for waves with a wavelength as long or longer than the objects. The wavelength of sound waves is relatively long, and for light, extremely short. Hence the diffraction of sound is more evident in our everyday environment.
31. The wavelengths of AM radio waves are hundreds of meters, much larger than the size of buildings, so they are easily diffracted around buildings. FM wavelengths are a few meters, borderline for diffraction around buildings. Light, with wavelengths a tiny fraction of a centimeter, show no appreciable diffraction around buildings.

32. Both interference fringes of light and the varying intensities of sound are the result of the superposition of waves that interfere constructively and destructively.

33. By a half wavelength, or an odd number of half-wavelengths.

34. The fringes will be spaced farther apart if the pattern is made of longer-wavelength yellow light. The shorter wavelength green light will produce closer fringes.

35. Blue light will produce narrower-spaced fringes.

36. Constructive interference.

37. Destructive interference.

38. You'll photograph what you see through the lens—a spectrum of colors on either side of the streetlights. We'll see in the following chapter that the colors diffracted correlate with the illuminating gas in the streetlights.

39. Fringes become closer together as the slits are moved farther apart. (Note this in the photos of Figure 29.14.)

40. Young's interference experiment produces a clearer fringe pattern with slits than with pinholes because the pattern is of parallel straight-line-shaped fringes rather than the fringes of overlapping circles. Circles overlap in relatively smaller segments than the broader overlap of parallel straight lines. Also, the slits allow more light to get through; the pattern with pinholes is dimmer.

41. Refraction: rainbow. Selective reflection: flower petals. Thin-film interference: soap bubbles.

42. Diffraction is the principle by which peacocks and hummingbirds display their colors. The ridges in the surface layers of the feathers act as diffraction gratings.

43. Interference colors result from double reflections from the upper and lower surfaces of the thin transparent coating on the butterfly wings. Some other butterfly wings produce colors by diffraction, where ridges in the surface act as diffraction gratings.

44. The optical paths of light from upper and lower reflecting surfaces change with different viewing positions. Thus, a change in color can be seen by tilting the shell at different angles.

45. Interference of light from the upper and lower surfaces of the soap or detergent film is occurring.

46. A necessary condition for interference is that the out-of-phase parts of the wave coincide. If the film is thick, the part of the wave that reflects from one surface will be displaced from the part that reflects from the other surface. No interaction, no cancellation, no interference colors. For thin films, the two parts of the wave coincide as they recombine.

47. Light from a pair of stars will not produce an interference pattern because the waves of light from the two separate sources are incoherent; when combined they smudge. Interference occurs when light from a single source divides and recombines.

48. Each colored ring represents a particular thickness of oil film, just as the lines on a surveyor's contour map represent equal elevations.

49. Blue, the complementary color. The blue is white minus the yellow light that is seen above. (Note this exercise goes back to information in Chapter 27.)

50. Ultraviolet, due to its shorter wavelengths.

51. Polarization is a property of transverse waves. Unlike light, sound is a longitudinal wave and can't be polarized. Whether a wave can be polarized or not, in fact, is one of the tests to distinguish transverse waves from longitudinal waves.

52. To say that a Polaroid is ideal is to say that it will transmit 100% of the components of light that are parallel to its polarization axis, and absorb 100% of all components perpendicular to its polarization axis. Nonpolarized light has as many components along the polarization axis as it has perpendicular to that axis. That's 50% along the axis, and 50% perpendicular to the axis. A perfect Polaroid transmits the 50% that is parallel to its polarization axis.

53. If the sheet is aligned with the polarization of the light, all the light gets through. If it is aligned perpendicular to the polarization of the light, none gets through. At any other angle, some of the light gets through because the polarized light can be “resolved” (like a vector) into components parallel and perpendicular to the alignment of the sheet.

54. With polarization axes aligned, a pair of Polaroids will transmit all components of light along the axes. That’s 50%, as explained in the preceding answer. Half of the light gets through the first Polaroid, and all of that gets through the second. With axes at right angles, no light will be transmitted.

55. You can determine the polarization axis for a single sheet of Polaroid by viewing the glare from a flat surface, as in Figure 29.34. The glare is most intense when the polarization axis is parallel to the flat surface.

56. Glare is composed largely of polarized light in the plane of the reflecting surface. Most glaring surfaces are horizontal (roadways, water, etc.), so sunglasses with vertical polarization axes filter the glare of horizontally polarized light. Conventional nonpolarizing sunglasses simply cut down on overall light transmission either by reflecting or absorbing incident light.

57. The axis of the filter should be vertical, not allowing the passage of the glare, which is parallel to the plane of the floor—horizontal.

58. Since most glare is due to reflection from horizontal surfaces, the polarization axes of common Polaroid sunglasses are vertical.

59. You can determine that the sky is partially polarized by rotating a single sheet of Polaroid in front of your eye while viewing the sky. You’ll notice the sky darken when the axis of the Polaroid is perpendicular to the polarization axis of the skylight.

60. Making holograms requires coherent light, exactly what a laser provides. Hence practical holography followed the advent of the laser. (Interestingly enough, the first holograms were made before the advent of the laser, and were crude by today’s standards. They were made with monochromatic light from a sodium vapor lamp, through a tiny pinhole to provide a close approximation of coherent light, and required very long exposures.)

61. Interference is central to holography.

Think and Discuss

62. Larger wavelengths diffract more (since the ratio of wavelength to slit size is greater), so red diffracts the most and blue the least.

63. Longer wavelength red light.

64. Wider fringes in air, for in water the wavelengths would be compressed (go back to Figure 28.24), with closer-together fringes.

65. The spot will be bright due to constructive interference.

66. Longer wavelength red light produces wider fringes.

67. The problem is serious, for depending on the orientation of the polarization axes of the display and the glasses, no display may be seen.

68. Call the three Polaroids 1, 2, and 3. The first one acts as a polarizer of the unpolarized light, ideally letting half of it through with a specific polarization direction that is perpendicular to the axis of Number 3. So when only 1 and 3 are present, no light gets through. But Number 2, when placed between 1 and 3, is illuminated by light aligned at 45° to its axis, so it lets half of the light through. The light striking Number 3 is now aligned at 45° to the axis of Number 3. So Number 3 transmits half of the light that strikes it. (The amount that gets through is one-eighth of the original intensity.)