Unit 10

Answers: Nature and Propagation of Light

Quick checks

1 b Both theories explain reflection and straight-line travel. But to bend light towards the normal, Newton's corpuscles had to speed up in water, while Huygens' waves had to slow down. Foucault measured it in 1850: light is slower in water, as the wave theory says.

2 c They left the star as spheres, but by the time they reach Earth the spheres are so enormous that the small piece entering a telescope is practically flat: plane wavefronts, parallel rays. That is why starlight focuses to a point in the telescope's focal plane.

3 b The new wavefront is the forward envelope of the wavelets. The surface joining their centers is the old wavefront; the envelope on the near side would be a backward wave, which doesn't exist.

4 c $v = c/\mu = 3.0 \times 10^8 / 1.33 = 2.26 \times 10^8$ m/s. A speed higher than in air, 4.0×10^8 m/s, is what Newton's corpuscles would have needed.

5 c Corpuscles traveling in straight lines and bouncing off surfaces explain reflection, refraction (with the wrong speeds) and straight-line travel; bending round edges into the shadow, diffraction, needs waves.

6 b Huygens' principle describes the spreading of a wave: wavefronts and wavelets.

7 d To bend light towards the normal, Newton's corpuscles had to be pulled into the denser medium and speed up there: so the theory predicts light is faster in every denser medium, water and glass alike. Experiment shows the opposite.

8 c The bright and dark bands come from waves from the two slits adding up and canceling: interference.

9 c Wavelets spread in all directions, so they ought to carry light into the shadow and blur every edge. It took Fresnel's interference of the wavelets to show that they cancel in the shadow except very near its edge.

10 b The wavelets from the points of the wavefront at the obstacle's edge spread out sideways, into the region behind the obstacle.

11 b Newton's theory needed light to be faster in water; Foucault (1850) found it slower, as the wave theory says. The other three are explained by both theories.

12 a That is the principle's first part. The second option is Newton's theory, the third its wrong prediction, and the fourth the photon picture.

13 b Wavefronts and their wavelets explain how waves spread round edges and add up or cancel. (They also give straight-line travel, reflection and refraction; polarization needs the further idea of transverse waves.)

14 b Newton: corpuscles. Huygens: waves in a medium.

11. a. A **wavefront** is an imaginary surface joining all the points of a wave that vibrate in the same phase at a given instant (for example, all the points at a crest).
b.

- **Spherical:** from a point source, such as a small bulb or a single LED; the fronts are spheres centered on the source, diverging (spreading out) or, after a convex lens, converging to its focus.
- **Plane:** far from a source, such as sunlight reaching Earth or a laser beam; the fronts are flat, parallel planes.
- **Cylindrical:** from a line source, such as a lit narrow slit or a long tube light; the fronts are cylinders with the source along their axis.

c. Light travels along rays, and the rays are always **perpendicular to the wavefront**. Spherical fronts mean rays spreading out from (or converging to) a point; plane fronts mean parallel rays; cylindrical fronts mean rays spreading out at right angles from a line.

12.

a. **Huygens' principle:** every point on a wavefront acts as a source of secondary wavelets, which spread out in all directions with the speed of the wave in the medium; the new position of the wavefront at any later time is the forward envelope (the surface touching) of these wavelets.

b. For a plane wavefront, wavelets of radius $c\Delta t$ from every point all touch a plane $c\Delta t$ ahead, parallel to the old one; so the front stays plane and moves straight forward, along rays perpendicular to it, step after step. When the light passes an obstacle or an opening much wider than its wavelength, the wavelets from the edge do spread into the shadow, but there the wavelets from different parts of the front arrive in all phases and cancel, except within a few wavelengths of the edge. Light's wavelength is under a micrometer, so this band is far too thin to see, and light appears to travel in straight lines and cast sharp shadows.

c.

	Wave theory (Huygens)	Particle theory (Newton)
Nature of light	a wave, a disturbance spreading out	a stream of tiny particles (corpuscles)
How it travels	as wavefronts, each point sending out wavelets	particles flying in straight lines
Straight-line travel	from the envelope of wavelets (needs interference to be complete)	natural: particles go straight
Refraction	the front slows in the denser medium and swings round	particles pulled into the denser medium, speeding up
Speed in water	less than in air (correct)	more than in air (wrong)
Interference, diffraction	explained	not explained

13.

a. Take the wavefront AB at $t = 0$, from a source S. Mark many points on it. Around each, draw a sphere of radius $c\Delta t$, where c is the speed of the wave. The surface touching all these spheres on the side away from the source, A′B′, is the new wavefront at time Δt (as in Figure 10.3). The envelope on the near side, A″B″, would be a backward wave and is discarded.

b. It treats light as a wave, and gives the wavefront's position at any time from its position now. From it follow straight-line travel (a plane front stays plane), the laws of reflection ($i = r$) and refraction ($\sin i / \sin r = c/v$, with light slower in denser media, as measured), and, once wavelets from different places are allowed to interfere, diffraction and interference too. So it describes both the nature of light (a wave) and how it propagates (as wavefronts moving at right angles to themselves, along rays).

c. Any two of:

- it gives no reason why there is no backward wave;
- it needs a medium, the ether, which doesn't exist;
- as Huygens left it, it can't explain polarization (he took light's waves as longitudinal);
- no wave theory explains the photoelectric effect or atomic line spectra, which need photons.

14.

a. The **phase** of a vibrating particle (or of the field at a point) is its state of vibration at an instant, where it is and which way it is moving, expressed as an angle: in $y = a\sin(\omega t - kx)$, the phase is $\omega t - kx$. One complete vibration is a phase change of 2π.

b. All points on a wavefront are **in the same phase**: that is how a wavefront is defined. They were all set vibrating by the source at the same instant and the wave has taken the same time to reach each of them, so they all reach a crest (or any other stage) together.

c. Points a path x apart along a wave differ in phase by $\phi = \dfrac{2\pi}{\lambda}x$; this is why the wave moves forward: each point repeats the motion of the one behind it, a little later. When two light waves meet, their phase difference decides the result: in phase ($\phi = 0, 2\pi, 4\pi \ldots$) they add up, bright; out of phase ($\phi = \pi, 3\pi \ldots$) they cancel, dark. A phase difference that stays fixed gives a steady pattern of bright and dark bands (interference, Unit 11); a randomly changing one averages out, and no pattern is seen.

15. a. **Huygens' principle.**

b. Each point of the present wavefront is taken as a source of secondary wavelets. Around each point a sphere of radius $v\Delta t$ is drawn, where v is the speed of the wave in the medium and Δt the time interval. The forward envelope of these spheres, the surface touching all of them on the side away from the source, is the wavefront at time Δt later. (If the medium changes, the wavelets in each part are drawn with that part's speed, which is how refraction comes out.)

c. In a homogeneous medium the wave travels at the same speed in every direction, so the points in the same phase are all at the same distance from the source: a **spherical** wavefront, centered on the source (diverging).

16. a. The secondary wavelets are drawn as complete spheres, so they reach backwards, towards the source, as well as forwards. Their envelope on the near side, A″B″ in Figure 10.3, would be a **backward wavefront**, a wave traveling back towards the source.

b. Because the secondary wavelets do not radiate equally in all directions: their amplitude is greatest straight ahead and falls to **zero** straight back. So the backward wave carries no energy, and there is nothing to observe. (Light shone through a window doesn't send a second beam back towards the lamp from inside the room.)

c. The **obliquity (inclination) factor** of Fresnel and Kirchhoff: the amplitude of a wavelet in a direction at angle θ to the forward direction is proportional to $\frac{1}{2}(1 + \cos\theta)$, which is 1 for $\theta = 0$ and 0 for $\theta = 180°$. Huygens himself simply assumed that only the forward envelope counts.

17.

a. In air, each layer reached by a sound wave is pushed into vibration and pushes on the next, so every point on a wavefront of sound acts as a source of sound wavelets traveling at the speed of sound there. Their forward envelope gives the next wavefront: spheres from a small source, plane fronts far away. Since sound's wavelength (centimeters to meters) is comparable to doorways and walls, its wavelets spread well into the "shadow", so sound bends round corners. Where the air's temperature changes (warmer air above at night), the wavelets grow faster in the warmer part, and the fronts tilt: sound is refracted, bending back down towards the ground, and distant sounds carry far.

b. Let AB be a plane wavefront in air (speed c) meeting the boundary XY with glass (speed v) at an angle of incidence i, A first. While B travels $BB' = ct$ to the boundary, the wavelet from A grows only $AA' = vt$ into the glass. The tangent from B′ to this wavelet, A′B′, touches the wavelets from all the points in between, so it is the refracted wavefront; the rays are perpendicular to it. In triangle ABB′, $\sin i = BB'/AB' = ct/AB'$; in triangle AA′B′, $\sin r = AA'/AB' = vt/AB'$. Dividing, $\dfrac{\sin i}{\sin r} = \dfrac{c}{v} = \mu$, a constant for the two media: Snell's law. Since $v < c$, $r < i$: the light bends towards the normal. The fronts and the boundary are all perpendicular to the paper, so the incident ray, the normal and the refracted ray are in one plane.

c. Treat every point of the present wavefront as a source of secondary wavelets. After a time Δt, each wavelet is a sphere of radius (speed $\times\ \Delta t$) about its point. The surface that touches all these spheres in the forward direction is the new position of the wavefront.

d. A wavefront is a surface of one phase, and the wave travels at right angles to it. If two wavefronts of the same wave crossed, the point where they meet would have two different phases at the same instant, and the wave would be traveling in two different directions there at once, both of which are impossible. So wavefronts of a wave never cross. (Two different waves can pass through each other, but where they overlap they add up into a single disturbance, by the principle of superposition.)