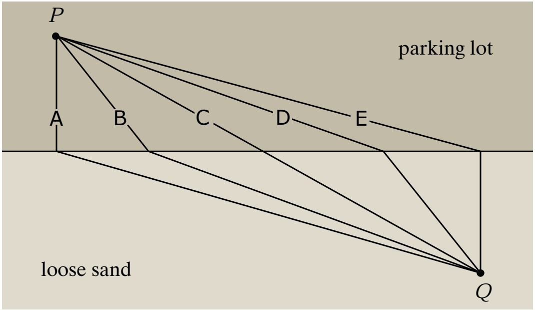
Refraction

A group of sprinters gather at point P on a parking lot bordering a beach. They must run across the parking lot to a point Q on the beach as quickly as possible. Which path from P to Q takes the least time? You should consider the relative speeds of the sprinters on the hard surface of the parking lot and on loose sand.

A.–E. as in the diagram

F. All paths take the same amount of time.



ANS: Path **D** is the correct path.

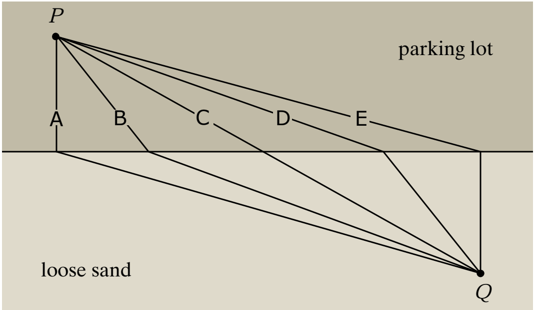
The runners move faster on pavement than they do on sand. Therefore, you might think that the fastest path is the one that spends the most time on the pavement and the least time on the beach (path e). However, it is also clear that path e is the longest path, and there should be some time penalty due to this extra distance. The fastest path is one that is somewhere between shortest path (path c) and the one that spends the most time on the pavement (path e). This fastest path is path d.

The specific shape of the path (how close it is to c or e) depends on the relative speeds. If the speeds on pavement and sand were nearly the same, then the best path will be closer to c. If the speed on pavement were much faster than on sand, then the best path will be closer to e.

Suppose the sprinters wish to get from point Q on the beach to point P on the parking lot as quickly as possible. Which path takes the least time?

A.–E. as in the diagram

F. All paths take the same amount of time.



ANS: Path **D** is the correct path.

The reasons for this are the same as above. The only difference is the direction of motion, not how much relative time the runners should spend on each surface.

Note: Both of the preceding questions establish what is known as Snell's law for refraction of light as it is transmitted from one medium to another. The speed of light in a medium is related to its index of refraction, n, which is the ratio of the speed of light in vacuum to the speed of light in the medium. In other words, light travels slower through glass than through a medium, so its index of refraction is greater than 1.

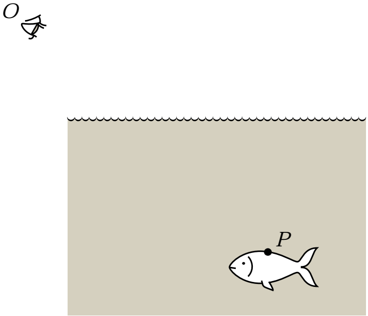
Baby oil happens to have almost exactly the same index of refraction as glass. If you immerse a glass beaker entirely in baby oil, what will it look like?

A. It will be reduced in size
B. It will be increased in size
C. Its appearance will be unchanged
D. It will become essentially invisible

ANS: D—It will become essentially invisible.

Part of the reason you see "transparent" objects is because as light passes through them, the light is refracted. Images you observe through the materials are distorted by the effect. When you put the glass beaker in oil of essentially the same index of refraction, there will be no bending from the oil to glass and glass to oil interfaces. Therefore, the image of something observed through the oil and glass will not be distorted, and you won't really see the glass beaker at all.

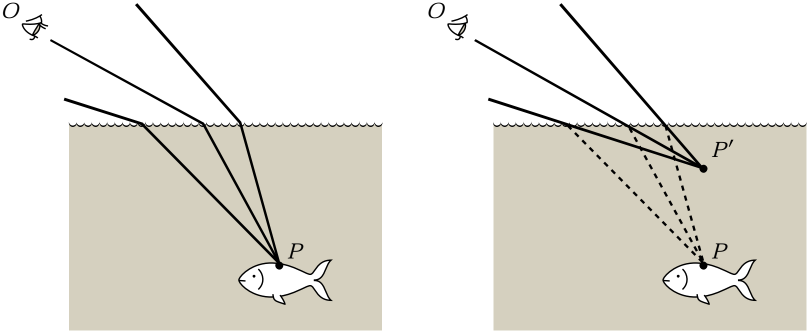
A fish swims below the surface of the water at P. An observer at O sees the fish at



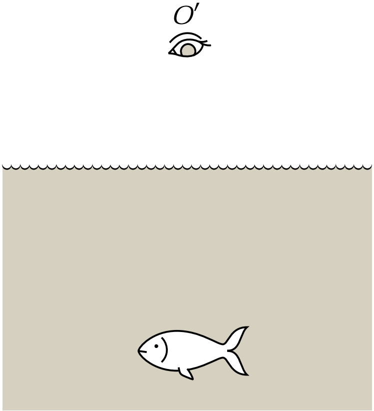
A. a greater depth than it really is.
B. the same depth.
C. a smaller depth than it really is.

ANS: **C**—The fish will appear to be at a smaller depth than it really is.

Snell's Law tells us that rays from the fish bend away from the vertical direction (because the ray goes from a region of high *n* to a region of low *n*). The rays that someone above the water sees are shown in the diagram below. The image of the fish is located at the point where all rays outside the water converge. This is at a shallower depth.



A fish swims below the surface of the water. Suppose an observer is looking at the fish from point O' straight above the fish. The observer sees the fish at



A. a greater depth than it really is.

B. the same depth.

C. a smaller depth than it really is.

ANS: C—The fish will appear to be at a smaller depth than it really is.

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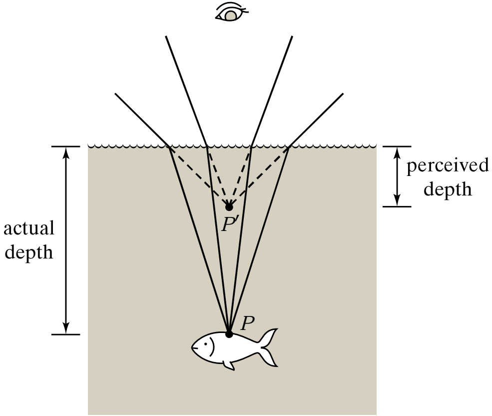
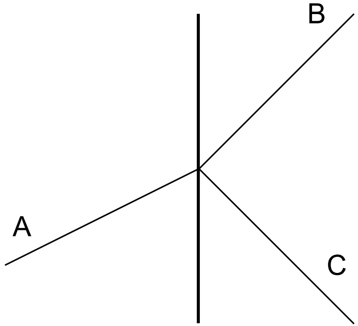


The figure below illustrates three light rays that exist together at the interface between two media. Which of them could be incident rays?



A.–C. As shown

D. A or B

E. B or C

F. C or A

G. Any of them could be incident rays

ANS: Ray **B** is the only possible incident ray.

Let's discuss each ray in turn.

Ray A cannot be an incident ray. If it were, there would be two transmitted rays, B and C, as the light passes through the interface.

Ray B can be an incident ray. If it were, ray C would clearly be a reflected ray, while ray A would be a transmitted ray. Ray A is on the opposite side of the normal from the incident ray, as we would expect.

Ray C cannot be an incident ray. If it wre, ray B would clearly be a reflected ray, while ray A would be a transmitted ray. However, ray A would be on the same side of the normal as the incident ray. Incident ray C would be "bent back" into transmitted ray A, which implies a negative transmission angle. This would require a negative index of refraction, which makes no sense.

Warmup Question

The speed of waves on the ocean increases as the water gets deeper (up to some limit when the water gets too deep). Imagine a beach where the depth is fairly constant out to some distance from shore, where it suddenly drops off to twice the depth. To be specific, consider a nice beach on the Gulf of Mexico running directly east-west with waves arriving from the southwest. How would you expect those waves to change as they cross over from the faster to the slower region?

ANS: The waves would bend toward the north. This is analogous to light moving from a vacuum (high speed) to glass (lower speed). The lower speed of light in the glass corresponds to an index of refraction that is greater than 1, meaning that a light ray will bend toward the normal to the surface.

The same thing happens here. The normal to the "surface" (the line between shallow and deep water) runs south-to-north, so the waves will turn more toward the north, but still moving somewhat to the east. In other words, the waves will be moving more to the north-northeast, rather than northeast as they originally had.

Warmup Question

If you developed a material in which light traveled at the top speed of your car, what would its index of refraction be? Estimate a numerical value knowing that the speed of light in a vacuum is 300 000 km/s.

ANS: Let's assume, for simplicity, that the top speed of your car is 0.06 km/s (about 134 miles per hour!) Then the index of refraction would be $(3 \times 10^5\,\mathrm{km/s})/(6 \times 10^{-2}\,\mathrm{km/s}) = 5 \times 10^6$.