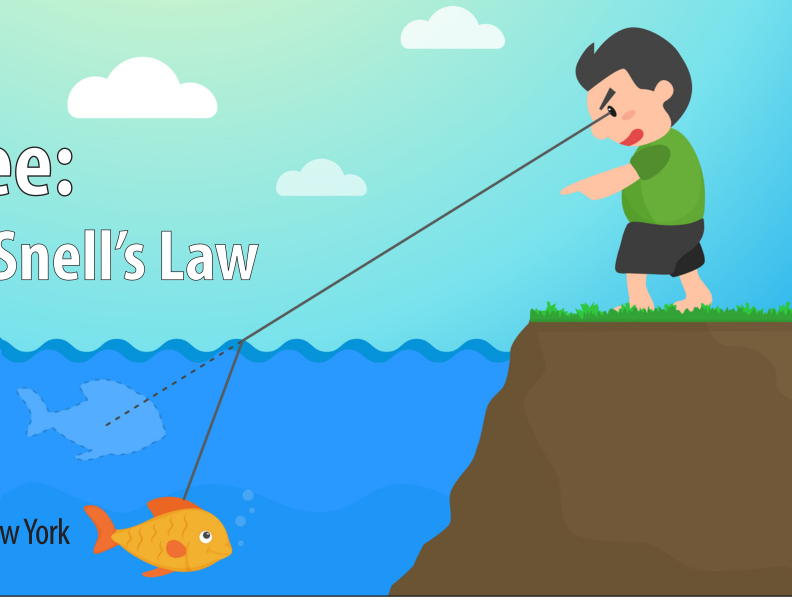
NATIONAL CENTER FOR CASE STUDY TEACHING IN SCIENCE

Fooled by What We See:
Looking into the Water and Snell's Law



by
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It is 1pm. Anthony and his younger brother Andrew are in a swimming pool, paddling around in an inflatable boat. Anthony is an undergraduate studying physics at his local community college. His brother Andrew is taking physical science in high school. Anthony challenges his brother intellectually as he helps him to understand the variation in the appearance of objects above and below the surface of the water.

Anthony: Hey Andrew, can you pass me the paddle so I can row?

Andrew: Sure. Here you go.

Andrew holds out the oar to Anthony from the side of the pool. The blade enters the water and when he looks at it, Andrew becomes puzzled.

Andrew: Anthony, I think I broke the paddle.

Anthony: You couldn't possibly have broken it by handing it to me. What are you talking about?

Andrew: I don't know…. I'm looking at the paddle, and it's bent.

Anthony: It wasn't bent when you picked it up. Wait a minute; where do you see the bend?

Andrew: Right where it enters the water.

Anthony: Move it up and down in the pool. Does the bend always stay at the surface of the water no matter how deep the oar is? It sounds like Snell is playing tricks on you with his law of refraction.

Andrew: Hey, yeah, it does.

Anthony: Ha. That's just Snell's law in action.

Andrew: What? Who is Snell, some kind of politician?

Anthony: No. Snell was a physicist who first explained why light bends when it travels from air into a transparent substance, such as water, which has different optical properties.

Andrew: Really? I don't understand. Why would light want to bend when it enters water?

Anthony: It bends because light travels slower in water than it does in air. People think that the speed of light is an absolute, but it's not. When we talk about light speed, that's really referring to light traveling in the vacuum of space. When it travels through a substance it slows down depending on the optical properties of the substance. Therefore light travels slightly slower in air than in space, more slowly in water than in air, and even more slowly through the glass of a camera lens than in water and air. If light crosses a boundary at any angle other than 90°, part of the light wave is in one medium traveling at one speed

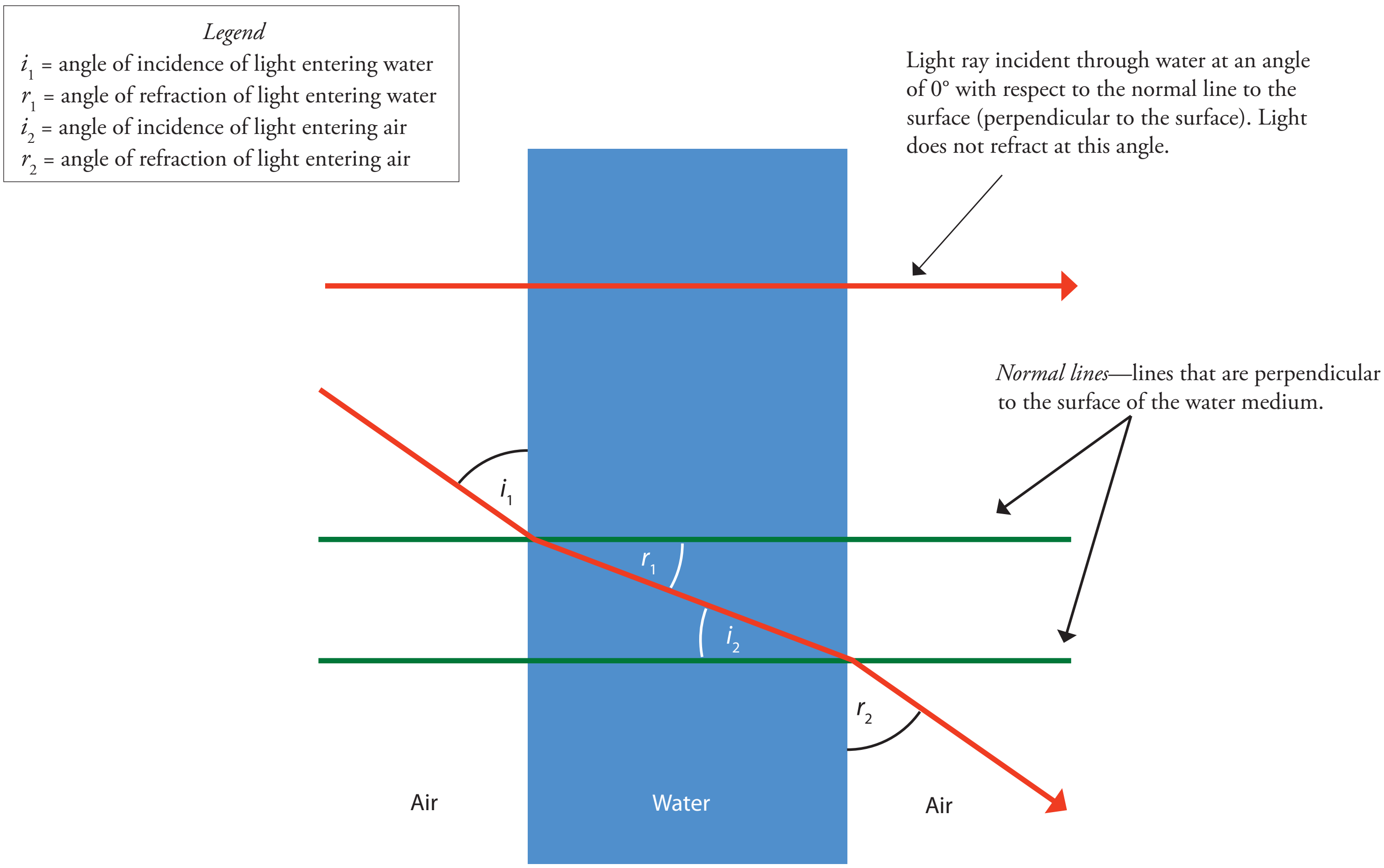

Figure 1. Light entering a medium where it bends towards the normal as it enters and away from the normal as it leaves the medium.

while part of it is in another medium traveling at another. The result is that the light bends towards the theoretical perpendicular line called the normal (Figure 1).

Andrew: Oh yeah, they talked about a normal line in my physical sciences class, except they said it is perpendicular to a surface that an object rests on.

Anthony: Yup, it's the same idea.

Andrew: Okay, but wait a minute. Why does the light bend in the first place again? Also, why would it bend away from the surface line or towards the normal?

Anthony: All right, think of it this way. Suppose you have a toy train rolling across the floor at an angle toward the edge of a rug. Since it's hitting the rug at an angle the left leading wheel hits the rug first. What do you think would happen?

Andrew: It would twist around. There would be more friction on the rug than on the floor, so the left wheel on the rug would spin slower than the right wheel on the floor until both wheels are finally on the rug.

Anthony: Exactly! And while the right wheel spins faster it will travel farther, causing the train to turn to the left, or toward the normal line.

Andrew: Oh wow! That makes perfect sense. So, it has to turn toward the perpendicular, or the normal, and away from the boundary.

Anthony: You got it.

Andrew: So does the light bend the same amount for any substance?

Anthony: Well, no. Think about it. If the car went over a thicker rug with more friction, the left wheel would slow down even more and cause the car to turn even more. There is a measurement for transparent and translucent materials called the index of refraction. It is a number greater than one. The higher the index of refraction for a material, the more light slows down when it enters the material, and therefore, the more the light bends towards the normal when it enters the second material.

Andrew: So, the index of refraction is like a measure of how rough the rug is?

Anthony: Exactly. The denser the material is, the higher its index of refraction.

Andrew: Okay, that makes sense. But why does that make the paddle look bent in the water?

Anthony: Remember, the only reason you can see anything is because light bounces off of it and travels to your eye. So light bouncing off the handle end of the paddle is only traveling through air and so is not refracted. Light bouncing off the blade of the paddle is traveling through water and then air to get to your eye so it is refracted when it crosses the surface (Figure 2). Because of that refraction the image of the blade appears to be in a different place than it actually is and we perceive a bend in the paddle where it enters the water.

Andrew: Okay, I'll go along with that, but so what?

Anthony: So now it's the reverse. Light is moving from a denser medium (water) to a less dense medium (air). It's like that train sliding onto the rug but in reverse. Here the leading wheel hits the air first and speeds up causing the light to bend away from the normal.

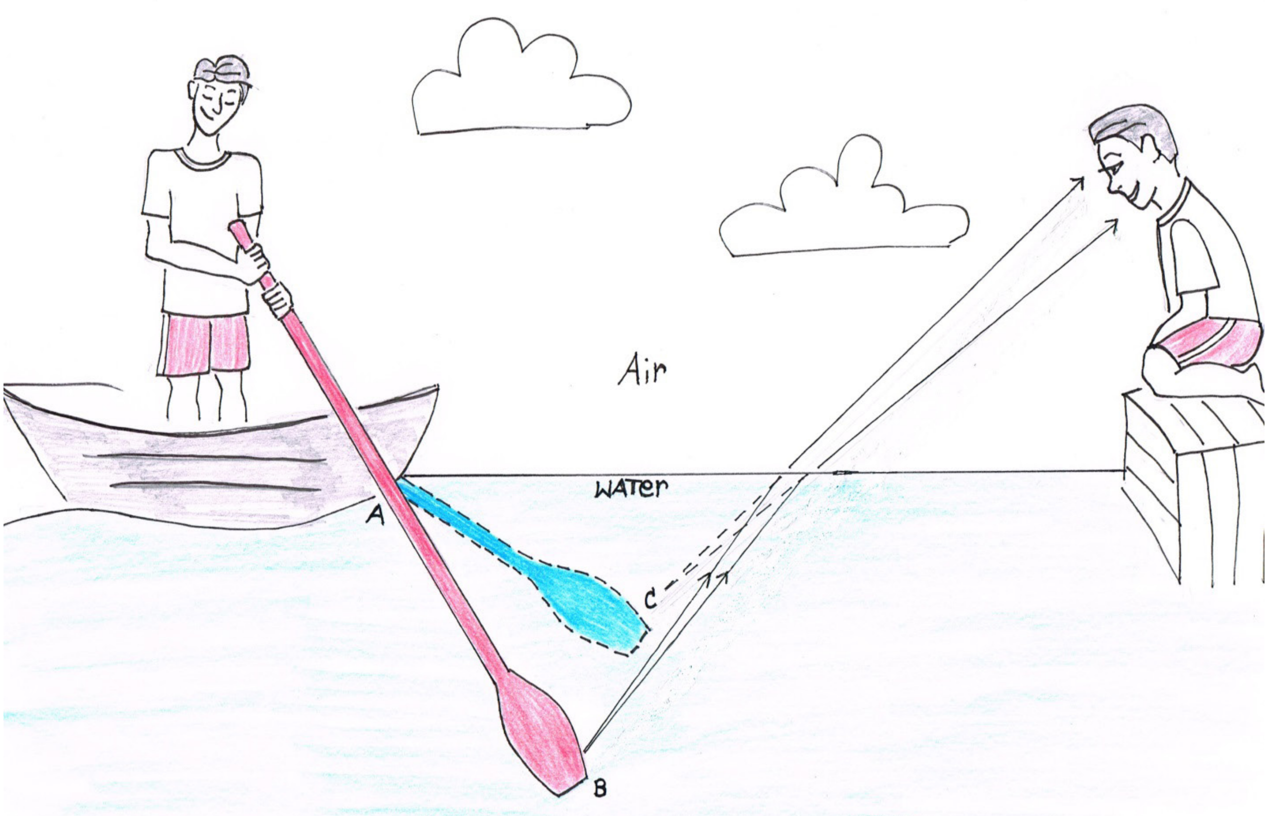

Figure 2. A paddle partially immersed in water (shown between points A and B) appears bent because of the refraction of light (shown between points A and C).

Andrew: That makes sense.

Anthony: If you get that then you understand it. The light reflecting off the handle of the paddle travels to your eye directly, while the light reflecting off the blade is refracted by the boundary between the air and the water creating the illusion of a bend in the paddle.

Andrew: I get it! Refraction fools us by making different parts of the paddle look like they're in different places.

Anthony: Correct little brother. Let me show you something else.

Andrew: What are you going to show me, another law?

Anthony: Nope. Same law to explain something that nearly got you in trouble when you were little.

Anthony takes his brother to the deep end of the pool and drops a small toy fish into the water.

Andrew: Hey! Isn't that the fish I used to play with?

Anthony: Good memory. Do you remember thinking that you could reach in and grab it? You couldn't swim back then and you almost fell in after it.

Andrew: Yeah. You told me that I was wrong and the fish was too deep at the bottom of the pool. It still doesn't look too deep.

Anthony: It's the same principle. When the light rays reflecting off the fish leave the water they bend away from the normal (Figure 3). Our eyes can only see in straight lines so we perceive the apparent image of the fish along the angle of refraction making it look like it's above its actual point at the bottom of the pool.

Andrew: So if I stick the paddle in the water again I could theoretically measure the angle of the apparent, but not real, bend. I would then see an apparent image of the fish at that same angle from the surface rather than straight down at the bottom.

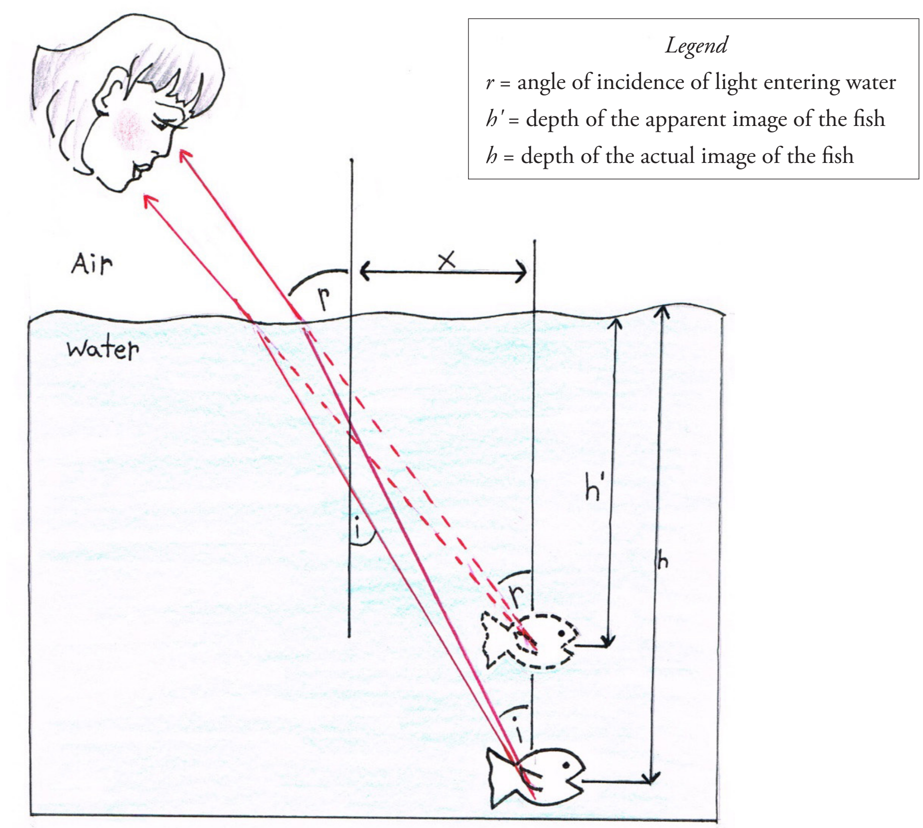

Figure 3. A submerged fish appears closer to the surface than it actually is.

Anthony: Now you understand.

Andrew: Yes, I do. I wish Mr. Snell was around when I had to explain to Dad why I threw my favorite toy fish in the pool because I thought it could swim.

Anthony: Yeah, well, I don't think Mr. Snell could have gotten you out of that one.

Anthony and Andrew jump into the water and swim to the deep end. From the bottom of the pool Andrew notices something odd and asks Anthony about it when they surface.

Andrew: Hey Anthony, when I looked straight up from the bottom I could see what's above us, but when I looked at an angle all I could see was the reflection from the sides and the bottom of the pool.

Anthony: Yes. That's right.

Andrew: That makes no sense. I shouldn't be seeing the bottom and sides of the pool when I'm looking up away from the bottom. Wait, don't tell me Snell's law again!

Anthony: I'm afraid so. It's what we were just talking about except now you're viewing your surroundings from inside the substance with the higher index of refraction rather than the lower index of refraction—you're in the water. When light goes from a material of a higher index of refraction such as water to a material of a lower one such as air, one can calculate from Snell's law an angle called the critical angle. If you try to look up out of the water at an angle greater than this angle as measured from the normal line, the light path that your eyes will follow will reflect off the water back into the pool. For light going from water to air, this angle is equal to 49°

Andrew: So you're saying if I tilt my head by more than 49°, I'm going to see reflections of the sides or bottom of the pool?

Anthony: That's right. But if you look straight up or don't tilt your head more than 49°, you won't see any reflections (Figure 4).

Andrew: Wow. I guess I won't be seeing much from the bottom of the pool.

Anthony: That's ok Andrew. The view of the world is better in air than in water.

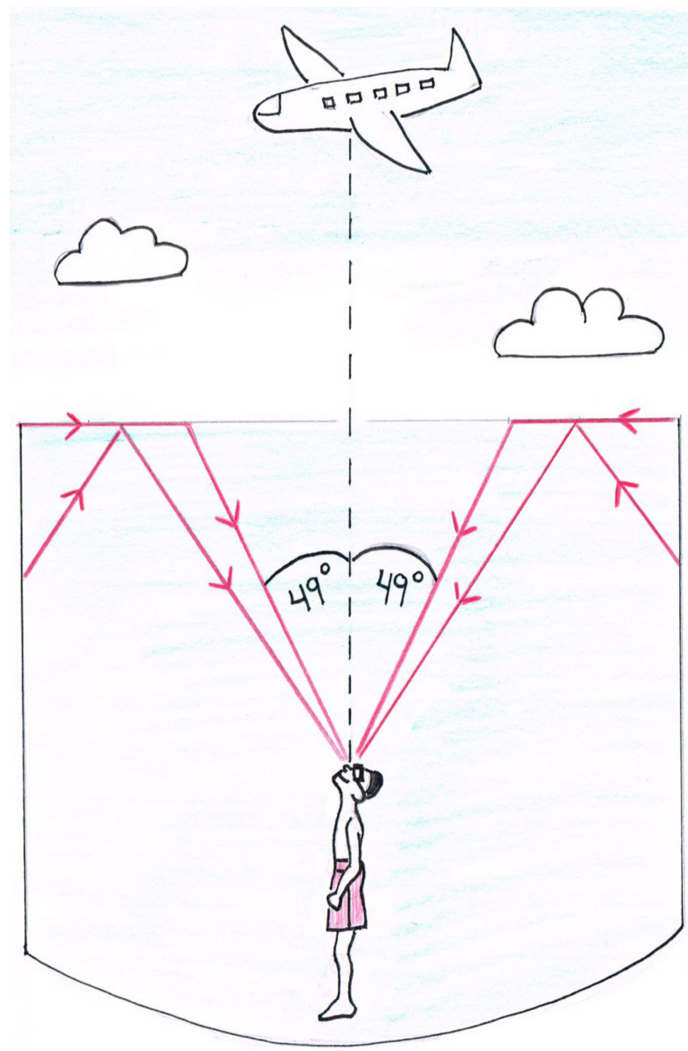

Figure 4. A person looking outside of a pool of water will see reflections of the side and bottom of the pool if their head is tilted at an angle greater than the critical angle of 49°.

Questions

1. What does Snell's law describe in the physical world?
2. What does the index of refraction describe with a transparent/translucent material?
3. What is a normal line?
4. How do the indices of refraction of two materials determine how light travels between the two materials?
5. How does Snell's law explain how we see apparent images of objects that are in a different location than the actual object?
6. What is the critical angle? How is it affected by the way light travels from one material to another?