Make Yourself Invisible!

- Ever since the # dawn of man, people have wanted to make themselves invisible. # Maybe you want to hide from teachers at school # [pause]. # Maybe you want to hunt down Adrien Brody # [pause]. # Maybe you want to ask, "What has it got in its pocketssss" # Regardless, invisibility is one of those things like flying cars and ponies that science may never bring us.
- Or will it! We're starting to see hints that, thanks to science, we may someday be able to look like # the invisible man. Finally we may have the solution to # TITLE SLIDE how to make yourself invisible.
- So let's talk about invisibility. First of all #, let's talk about what I mean by invisibility. I'm mainly interested in how to make something invisible to us humans. How could we make it so that you can't see me even if I'm standing right in front of you?
- Okay, so we have to talk about what seeing is. We see objects thanks either to # light that they emit or to light that they reflect from something like the sun. You know, that thing you saw briefly when you scurried over here to the Hilton.
    - You don't normally have to worry about hiding the light you emit, # since most of us aren't lightbulbs. That just leaves the light that bounces off of us. (Though that does become a problem with hiding spaceships in space; # which you can hear more about by being next door in 203 at 2:30 this afternoon for my space talk. Okay, plug over).#
    - Well, then, why don't we just absorb that light? Then you can't see me! True, but # I can see where you are. You'll be a completely black shadow, which won't work so well in the day.
    - That leaves # bending the light around us, like how water moves around a rock. Think about it: you shine a flashlight at me. The light gets bent around me so none of it reflects back to you. Tah dah! We're the invisible man! # No, see, those are typical hand gestures indicating that a LARPer is invisible...never mind.
- # Anyway, as you've probably guessed, bending light like that # is easier said than done. Let's talk about how you bend light. Anyone? Anyone?
- Glass!
    - Glass bends light! # Let's talk about why that is. Light travels at different speeds when it's in a material. The speed of light that we're used to, # 300,000 km/s, is only in vacuum. If light goes through a material, like water or glass, it goes slower. # We measure that using something called the index of refraction. One simplified way of looking at the index of refraction # is that it's the ratio of the speed of light in a vacuum to the speed of light in the material. So vacuum has an index of refraction of # 1. Water has an index of refraction of # 1.33, so light travels 1.33 times slower in water than in vacuum. Air is like # 1.000277. Diamond is # 2.417.
    - When light goes from one material to another, with a different index of refraction, it # bends. If light goes slower in the new medium, it bends towards what we call the # normal to the surface, the line that's at right angles to the surface. If it goes

faster, it bends away.
    - Let's say I was going to shine light from air into water. # Air has an index of refraction, or n, of about 1. Water has an n of 1.33. Light's going to go slower in the water, so it # bends towards the surface normal from where it should be going.
    - This is how glasses work. # The material in glasses bends light to compensate for nearsightedness or farsightedness. Notice how these glasses make the side of my head look a lot closer in, because of how it's bending light.
    - So there's our answer! We just use some material that will let us bend light all the way around us! Only one problem: light wants to go in a straight line. In fact there's no way to make a piece of glass or other material that will bend light in every direction around someone.
- # Fiber optics!
    - Fiber optics works because of total internal reflection. # If light is moving from a medium with a larger index of refraction to one with a smaller index of refraction, and if it hits the surface at a shallow enough angle, you get # total internal reflection. "Total" because all of the light is reflected and "internal" because it stays in the same material it started out in.
    - # So take a long, thin, narrow length of glass. Wrap it in cladding -- something with a smaller index of refraction. Light that goes in the end of the tube will bounce around until it comes out the other end. And since the glass is thin, it's flexible!
    - Problems: # optical fibers only take light that comes in in a very narrow cone, and you want it that way since otherwise you'll make a distorted picture on the other end of the fiber. You'd have to wrap yourself with thousands of fibers, all very carefully aligned, for this to work, and also drive yourself around in a forklift.
- # Projection technology!
    - Film what's behind you; project it onto your front.
    - # As you can see, this is invisibility in the same way that me jumping up is flying, though.
- There's one technology no one seems to be pursuing seriously: # black holes.
    - Light is bent by things with a lot of gravity. Stars and nebulae bend light a little. Black holes bend a lot!
    - Unfortunately black holes act as a kind of weird lenses, so I may need several of them orbiting stably around me. I can see no way in which this can go wrong. #
- So what are we left with? # Metamaterials! Metamaterials may give us invisibility. How? you ask. # No, not magic! # Better. Metamaterials work by tailoring the content of the material to control our old friend, # the index of refraction.
    - Light interacts with most materials based on their chemical compound, and the materials are pretty much the same throughout, as in glass, or diamond, or air. # Metamaterials are different. Imagine that most materials are kind of like a flat sheet and the photons of light are like a marble that you roll across the sheet. The marble goes straight. Nothing much happens to it. Now, a metamaterial is like a sheet that has all of these bumps and ridges in it, so now the marble curves around and goes in directions you might not expect. Those bumps and ridges are designed by scientists to get the effect that you want.

- At this point you're probably wondering # how exactly metamaterials work. Here's the thing: When you talk about working with light, one of the important things to know is the light's wavelength. Light comes in # waves, and the distance between # two peaks in the wave is the wavelength. # Visible light has wavelengths from about 300 nm to 800 nm. Now, if you've got a # pattern on a material that's a lot smaller than the light's wavelength,then the light sort of glosses over the pattern and treats it as a single material. # It's like this trampoline material. It's actually full of holes, but you don't feel it when you jump on it because the holes are so small.
- # But the properties of a patterned material depends on that pattern, and we can change the pattern as we go through the material. In this case, look how the spacing changes as you go deeper in this waffle pattern. By doing this, scientists controlling microscopic properties of the material and in return get macroscopic effects.
- What can you do with this? Well, one thing you can do is tailor what the index of refraction is. In fact, you can even get a negative index of refraction.
  - A negative index of refraction? # How is that even possible? # I originally said that *n* is speed of light in a vacuum divided by light speed in the material. How do you get a negative number out of that? What does that even mean?
  - I lied. A teeny bit. In general that's the definition for *n*. # Here's the real definition.
  - Remember that light is actually electromagnetic radiation. It's waves of electrical and magnetic fields that propagate through space. Well, # epsilon here is the material's permittivity, or how susceptible its electrons are to being dragged around by light's electric field. It's relative to the vacuum permittivity. # mu is the materials permeability, or how easy it is to magnetize the material. Taken together, they describe how easy or hard it is to send both electrical and magnetic waves through the material.
  - What we're doing with these patterns is tuning epsilon and mu. We have two knobs that we can tweak to make the index of refraction do all kinds of things. In fact, like I said, you can make it negative.
  - In terms of the sign of epsilon and mu, we've got # four choices. Normally permittivity and permeability are positive in # transparent materials, like glass. # Metals have a negative permittivity to visible light, which makes them absorb light really well and also makes the index of refraction be imaginary -- it contains the square root of negative one. You can sometimes get a negative permeability, but it's # rare, and it doesn't happen at wavelengths of visible light. And we have # never found any material that has both a negative permittivity and permeability, a so-called double negative material. # But metamaterials can be double negative!
  - Now, when both the permeability and permittivity are negative, you get a negative index of refraction! # Light bends the wrong way! The Doppler shift works opposite from how it normally does! # Cats and dogs, living together!
- # So what? What's the big deal if you can tailor the index of refraction?

        - The index of refraction controls how light bends. If you keep changing it, you can make light *curve*. That means you can make an invisibility cloak! And in fact, we've made the first steps towards it.
        - October 2006: # David Smith's group at Duke University were able to hide a small metal cylinder from microwaves. # The "cloak", made of cylindrical rings, bent microwaves around the cylinder, greatly reducing how much of a shadow it cast and how much reflected microwaves it scattered.
        - That's got limitations, obviously. First of all, it's not visible lights, it's microwaves. So it's great if you want to keep something from cooking in your microwave oven. Second, it only works in two dimensions. Third, it only works for certain narrow wavelengths of microwaves. It's like making an invisibility cloak that only works for green light.
        - 2007: Igor Smolyaninov at the University of Maryland makes an # invisibility cloak that works with visible light -- sort of. They injected polarised cyan light into a gold surface using a tiny optical fibre with a fine tip. The light waves become converted into surface plasmons - waves rippling through the electrons of the gold surface, effectively in two dimensions -- that passed around the cloaked area
        - 2009: Physicists at the University of California, Berkeley, and Cornell University independently made an actual invisibility cloak! # It was a bump in a metallic mirror hidden by adding a tailored metamaterial on top. They hid a teeny tiny bump (4 microns wide and 400 nm tall) from light that bounced off of the bump in one direction only. Oh, and only near infrared light. Seems underwhelming, but it's a start!
        - And then in 2010 a group of scientists at Germany's Karlsruhe Institute of Technology made a 3D version of that carpet cloak! They built up a structure # that looks kind of like a woodpile. The cloak structure was then placed on top of a reflective gold surface containing a bump. They bounced light off of the gold mirror and measured how much was reflected back. They were able to cloak the bump from wavelengths between 1.4 and 2.7 μm – the near-infrared. Importantly, this effect held for viewing angles up to 60 degrees (with zero degrees representing viewing in just two dimensions). The bump, however, was very small – just 30 μm (10–6 m) × 10 μm × 1 μm.
    - But wait! There's more!
        - In 2008 David Smith (remember him?) and others showed you could theoretically make this work for sound waves! Imagine subs that can't be seen by other subs' sonar, # or by bats. Researchers have made acoustic metamaterials called sonic crystals, though it's still way early in this research.
        - # You can possibly cloak against water waves, in the case of tsunamis (c.f. http://www.newscientist.com/article/dn14829), or earthquake waves around buildings.
- # SUMMARY SLIDE So invisibility cloaks aren't right around the corner, but this is an extremely new field of optical materials where advances are being made very rapidly. We may not get to true invisibility, but imagine if we could reduce the damage to cities

due to earthquakes or, say, oil rigs due to tsunamis. This research may not give us Harry Potter invisibility cloaks, but it may give us results that are of more practical use.