This is how batteries are engineered.

This is why we have a revolution in batteries.

So this is a couple of years old.

There so many great review articles on battery technologies.

This is the cathode.

By the way, what is a battery?

Well, a lithium battery is basically two sponges.

And one of them is usually carbon.

And when you're running your battery, lithium ions are going in.

And the carbon is so strong and able to hold those lithium in and not break down.

So we often use carbon on the anode side.

And then when we charge it up, we push them back over to where?

Where they came from.

That's the cathode, which is a lithium compound.

But it has to be a material that can hold lithium in it, hopefully at very high concentration, but also be OK to lose it and not completely collapse.

And so you've got lithium ion phosphate, those are these ones.

You've got manganates.

You've got cobalts, cobalt oxide materials.

There are so many battery materials.

They all work the same way.

If it's a lithium battery, the lithium is going to leave some crystal that has lithium in it.

But the crystal has to stay.

So it's like a sponge that loses something from it but stays intact.

And that's something goes over to the anode.

It gets soaked up there.

And you can recharge, discharge, recharge, as you're just pushing these lithiums back and forth.

Oh, but you're pushing them back and forth.

You are diffusing them.

That's what you're doing.

You are diffusing them through whatever structure you're putting them into.

So if it's the cathode, and you're trying to get the lithium to come back in or to go back out, then you can imagine that the barriers and the dimensionality itself are crucial.

What is an activation energy for a lithium atom in a given material?

And does it take a 1 D path?

It turns out these can be extremely efficient.

Look at those.

They're practically holes, they're lines in the lithium ion phosphate.

It's a really nice cathode material, because you've got these channels.

These high conduction channels, these highways.

But then you say, well, but maybe I need 3D voids.

Maybe it shouldn't have channels.

It should have voids, so it can choose more paths.

Maybe we have planes.

Maybe it's a layered structure where they have these 2D planes they can travel through.

What's the best?

Well, it's not trivial, because it's one of these, as usual, constrained optimization problems, where, when you make the pathway faster, you might need to have more voids where you'll lose material.

Or maybe you make the material unstable.

So you want it to have a really high density.

The lithium diffusion and a battery material is related to the charge time.

So here's another paper from a few years ago.

If you plot materials-- now, here's the specific power.

And so that's how much power, watts per weight.

Here's the watt hours.

So that's the energy per weight.

And this is the charge rate.

This is the charge rate.

And notice, so you want it to be very, very fast-charging.

And these are good materials.

There's the lead-acid battery that's still in your car.

These are nickel metal hydrides and so forth, other technologies.

Here are the lithium ion batteries.

This is what's in your cell phone.

Notice something, as I get up to faster charge rates, more open voids in material, I lose energy density.

I go this way.

I don't want to go that way.

I want to go this way.

Constrained optimization, these are the things.

What goes into solving these problems is calculating diffusion barriers and energy densities and all the other things that matter.

But if you want to target fast charging, you've got to know the diffusion barriers.

One of the number one challenges in battery design is to keep that high while continuing to push up that way.

Polymers, you could imagine that a polymer is slower.

It makes sense, right?

Because it's harder-- as we talked about when we talked about polymers, it's harder to make crystalline polymers, to keep a polymer from having some amorphous region.

After all, you've got these 100,000-unit long strands of spaghetti.

So it kind of makes sense that the diffusion is going to be lower in a polymer than in one of these crystals, like an olivine, lithium ion phosphate.

So that makes sense.

But polymers would be great, because they're lighter.

And they can be flexible.

And so we like polymer batteries a lot.

We want them for many applications.

So these are the kinds of tradeoffs that you think about.

And D is right there in the center, because none of us want a battery that takes two days to charge.