[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: So I will just go through the old-fashioned paper syllabus.

So the course is going to be taught on Canvas. So the Canvas site has been published. We will-- for homeworks, and things like that, they'll be handed out and turned in on paper, but you can download them from Canvas as well.

The classes are going to be here Mondays, Wednesdays and Thursdays. So our usual class schedule is 1:00 PM.

I've mentioned the textbook. There are some other textbooks that you might find handy, and I've listed those in the course handout. Those are completely optional. You don't have to buy them. The libraries also have copies.

The way homeworks will work in this class is that will typically be issued on a Monday and due the following Monday. And, for the most part, you are allowed to collaborate and talk about the homework problems. So feel free to get together and discuss the problems. It's intended that you do so.

The only constraint we have is that you must hand in your own solution. Right? So you can trade ideas. But, in the end, the thing you write up, it can't be a copy of your neighbor's. It has to be your solution, but you can base it on ideas you've exchanged with others.

For those who don't know anybody, or who don't have access to study partners and may have questions, first of all, there will be office hours. [? Monse's ?] office hours will be Thursdays, 4:00 to 5:00 PM, and Fridays, 4:00 to 5:00 PM, in 10-178, in Building 10. But there are also a number of students in the Lees Laboratory, 10-050, who have had this class before and will be happy to answer any questions. And a few of those students are listed in the course description.

We've also decided not to have exams this term, or in-class exams. Rather, we're going to have assessments, which are, essentially, take-home mini quizzes. They will generally be-- they'll be generally issued weekly. And this says they're going to be issued starting on March 1. I should check if that-- yeah. Starting on March 1, they'll be issued weekly. They'll be issued on a Wednesday. They will be due the next day, Thursday. And those will be submitted through Canvas, through Gradescope.

As for homeworks, we can take late homeworks, if you arrange it ahead of time and there's some compelling reason why they're late. Assessments are a different story.

Also, the collaboration policy for assessments is different. You cannot collaborate or discuss the problems at all for assessments. And we can't prove or not prove that you're doing so, but this is an exam, effectively. So don't discuss it with your neighbors, and don't discuss anything until the solutions are out because there may be people who have made some special arrangement because they're traveling, or for whatever reason, to hand it in late.

So we're going to have homeworks and assessments. And the goal of the assessments, really, is, instead of a very few high-stakes opportunities to show your abilities, the assessments are distributed in low stakes and focused and gives you a better opportunity to show what you really know. So please complete them entirely on your own. No consultation. The only thing you're allowed to do is ask the course staff clarifying questions, just the way you might in an exam.

And, as for the assessments, you can use any of the course materials-- read the book, whatever you want. Do not go outside and try to use the world wide web. And for that matter, the use of bibles is also prohibited. I know that there's collections of old 6.334 materials floating around. You're not supposed to be consulting those. This is just supposed to be a measure of what you've learned.

So the grading will be based on three components. Homeworks are going to be 40%. These assessments will be 50%. And there's also a final project, which is 10%. And the final project sounds like it's only 10%, but it's the last thing we look at when we're going to assign a grade to everybody. And it really is your opportunity to put together knowledge that you've learned throughout the class into a real-- it's on paper. It's not a physical converter you will construct, but it's a paper design-- but it's really your opportunity to show us how you've synthesized all this knowledge, to be able to really design power electronics.

And I should say, just as an aside, in this class, we only have a paper design, but this complements nicely the undergraduate power electronics class, which has a lot of really nice lab activities and design activities there. So even if you're a graduate student, it can be a pretty good thing to take, in terms of rounding out your lab skill set in this area.

If you have any necessary technical accommodations-- don't have access to iPads, or whatever else you need for Gradescope-- please let us know. We'll try to assist with that.

So, with that, are there any questions about anything associated with the course mechanics?

OK. So let me give you a sense of what this course is going to be about.

And this is one of my favorite photos. It is actually one that Nikola Tesla mocked up. He wasn't really sitting next to his Tesla coil when he did this, or he might have gotten killed. He kind of double exposed this.

But, more to the point, the quote from him is, "If we could produce electrical effects of the required quality, this whole planet, and the conditions of existence on it, could be transformed." And I think the more than 100 years since he said that, or well more than 100 years since he said that, have borne that out.

But it's also true that, even today, there's really revolutions happening in the way we use energy. Everything's being electrified-- from vehicles, to transportation, to power generation-- from renewable resources. And handling all that requires some means of processing, controlling, and converting energy. And that's really what we're about, processing, controlling, and converting electrical energy.

If you look at what the IEEE, which is the governing body of electrical engineering, says about power electronics, it says, "This technology encompasses the use of electronic components, the application of circuit theory and design techniques, and the development of analytical tools towards efficient electronic conversion control and conditioning of electric power."

And that's what we're really about here. So we're going to do circuit theory. We're going to learn design techniques. We're going to learn about all the components you need to do this. We're going to learn about controls. How do you put it all together, to make energy conversion systems?

So, as I mentioned, the primary function of power electronics is to take electrical energy in one form and convert it into some other form you need. It's really a core technology in the electrical infrastructure.

It used to be that the AC grid was generators, and you'd connect it up to things like-- directly to things like motors, or lighting, or whatever. But that's pretty much changed, at this point. Lighting is LED lighting. You need power supplies to go between the grid and the lighting. Same thing. Heavily loads computers, motors, everything else you need.

Energy tends to flow through one, or even several, layers of power conversion circuitry, from the principal source to the final usage.

And so the power electronics-- first of all, the efficiency of that is very important. But also, how you do it impacts the quality of the final system. So the power electronics can really be a major factor impacting what you can and can't do and how well it works.

So if you showed up 100 years ago, this is what power electronics would have looked like-- some vacuum tubes, and some transformers, and that kind of thing. Interestingly-- of course, it's nothing like that today. But, with the techniques you're going to learn in this course, you could actually go back and analyze this thing and figure out what it did. Right? So this is some foundational ideas that we're going to come back to, which can be 100 years old. But there's also elements that are extremely new.

And today-- this was fancy 100 years ago. Today, power electronics is everywhere, from-- I say, from milliwatts to gigawatts. And it does, actually, use switched-mode power conversion down to those power levels. This is actually a multi-watt power supply. And this is, literally, at the gigawatt scale.

So if you go out to the Sandy Pond terminal, there is a power converter that takes 2 gigawatts, coming down from Canada Hydro, and converts it to AC, to power homes and everything else around here. Right?

And the techniques that we're going to learn in this class really span the entire range. So some of the details change, and we'll learn about that. But there's underlying principles that cut across all kinds of electrical energy conversion systems.

What kind of applications?

Well, portable electronics. This is slightly older, an iPhone 5. And you think, OK. iPhone's got radio transmitters, and displays, and other stuff in it. But it turns out that a large fraction of the volume in board area is actually associated with energy conversion in the thing. Because no matter what you're doing, you're processing energy to process information. So something like 40% of the motherboard, in this example, is associated with power conversion.

Likewise, at some point, you're going to charge your phone, or your iPad, or your computer, into the wall. That's mostly power electronics, too. All kinds of computers. If you're in a data center, there's several layers of power conversion between the AC grid and the final set of processors.

This is more of what it looks like inside your home computer. We will actually learn exactly about those kind of converters and about all the components that are in them.

If you're going to communicate, the transmitters-- we tend to think of this as analog circuits to make RF transmitters. But, in fact, power electronics are heavily embedded in any real communication systems to increase the efficiency of transmission.

All kinds of commercial applications, whether you're doing LED lighting or-- this is actually from some water purity device, but, of course, it requires a power supply. So almost any use of energy these days requires a power supply.

Even in your home. I mentioned that it used to be that you'd connect motors up to the grid, and they'd run, and maybe you'd turn them on and off, something like that. But no longer. Right? If you want high performance, you need to be able to modulate that energy.

So two examples here. This is for an air conditioning unit, and it uses an inverter, a DC to AC converter, inside it to drive the motor much more quietly and much more modulated, for higher overall system efficiency. Even your dishwasher, these days, has power converters in it because it's more efficient-- in this case, quieter-- to do it that way.

Ideas that you might not think of as power converters-- medical applications. This is, actually, a magnetic stimulator. It generates 5,000 amps pulse trains in a transducer coil to throw out magnetic fields that can trigger nerves.

This is an interesting one. It's actually homework 0. So the thing you're analyzing in the first homework, just to break the rust off, is actually this box, right here.

Scientific applications. And you may not be processing energy, but even if you just need to generate electric-- high electrical fields, for whatever reason, or magnetic fields-- as in the magnetic stimulator-- you need energy conversion circuits to do it.

Then there's the more-- maybe, the applications you might think of, transportation. Let's say, the electric vehicle, or a hybrid vehicle. You need power electronics to drive the energy conversion.

And this is not a small thing. First of all, you need the power electronics to drive these things. Secondly-- in fact, in one example, they redesigned the power converter for a Prius, the powertrain for the Prius. The fuel economy went up by 5%, just by redesigning the power electronics to be better. So it has a huge impact on the overall application.

And, of course, that's electric vehicles. But traction, trains, that's higher power, but the same issue. Actually, even, future trains. It's a little hard to see behind this railing. That's a maglev-- magnetically levitated-- train. Along the wayside, over in the back corner, you see this big building here. Inside that big building is these racks of power electronics.

Now, you better have pretty reliable power electronics, if your vehicle is flying along at 400 kilometers an hour, floating on that far off the ground. Right? So not only do you need efficiency, but you need reliability and precision.

Even stranger things-- this is an example of a drone, just powered by high voltage. You just apply high voltage. It breaks down the air, accelerates ions, and you can use that for propulsion. That's the first demonstration of it.

But it actually-- it's very similar, in some regards, to what people use for space propulsion. You've heard of ion engines, the twin ion engine, TIE, fighter? Or what, more practically, they use to reposition satellites. Those require power electronics to generate high voltages and accelerate ions.

Power transmission and generation. So you're getting your energy from somewhere, and, increasingly, we're getting it from renewable resources. Well, generally, the way things are trending, you take some mechanical, or solar, or other source of energy, and you transition it, not only through a generator, but through power electronics, to get there.

And that's true for terrestrial things, things like-- this is a house rooftop PV system. This is a microinverter.

Automotive systems. Or even much smaller things, like power harvesting, energy harvesting, techniques. You need power electronics in it.

Also, all kinds of industrial applications, whether you're doing plasma processing, for semiconductor processing, or you want to refine metals, like a DC arc furnace, you need power electronics there too.

So that's just a long way of saying, power electronics are in almost everything you care about these days, and it's only getting more so because we have to be better about how we use energy.

So what's inside a power converter? And we're going to talk about this in much greater detail. But if you want to think about it, what we have is, typically, some kind of energy storage elements. These could be inductors, or capacitors, or sometimes other things.

And what we're going to do is we're going to use semiconductor switches, and we're going to draw energy from some source. We're going to manipulate it somehow.

So we store it in these energy storage elements, and then we're going to put it to the output. And we're going to repeat that. So draw, transform, put it to the output.

Because we do this on a cyclic basis, we generate sort of ripple and, potentially, noise, that could interfere with things like television or electronics. So you generally need filters to do that, too.

We also, of course, need to control that flow of energy. We can't be stupid about it. We have to-- especially for something high performance, like a microprocessor, which might be changing its operation very, very fast, we need to control that flow. So there's control circuitry. And we're going to be learning about all of the aspects of designing all of these kinds of elements.

So we're leveraging everything from circuit design, semiconductor devices, passive components and materials. Increasingly, packaging, and cooling, and controls also matter. And things have been getting better, and better, and better, both because the ways we can manufacture things get better and because the devices which we have access to, in order to implement these things, get better.

And so, we're going to look at some of the different ways you can do that. I'll just give you one example.

This is what you would find something like in a data center. So they come in. They rectify the voltage. They get it 400 volts, for reasons we'll go into. This converter, here, was designed to take that 400 volt and bring it down to 12 volts. That tiny little thing, a little bit bigger than a penny, there, actually, can handle a kilowatt. Then you need more converters, to take it down from there to the 1 volt that the processor uses.

So a long way of saying all kinds of things are limited by energy and how we can control it, across all these applications. And what we're usually trying to do is figure out how to make them smaller and lighter. If it's taking up 40% of your iPhone, you want to make that thing smaller, so it doesn't take that up. And you can replace that volume either with nothing or with things that are more interesting to you.

We need higher efficiency, both for the converters and the systems. How we process energy can matter to the-- not only the ultimate efficiency of the converter, but the efficiency of the system. How it uses energy can be determined by the power electronics.

We want higher performance. That could mean higher bandwidth or other aspects. And then, there's all kinds of means that we can use-- better electrical processing-- to enable new applications.

So these are the kind of things that we're going to learn about this term. I'll pause there. I've been going on a while. Are there any questions about any of this, before we get going? And this is just to orient you as to what we're going to focus the term on.

I can put the slides on Canvas. Sure. Any other questions?

OK.

I will just give you a slight notion. OK? Just-- this is a favorite thing I like to bring in, just to show you the kind of things we're going to look at this term. This is a piece of commercial hardware, from a company called MKS Instruments, that I just happen to have in my office.

This input piece is a filter, so you don't create electromagnetic interference and you don't generate noise you don't want.

Then this piece, here, takes energy from the 60 hertz grid and generates DC from it. And it has to do it while making the whole thing look like a resistor to the grid, so that you don't mess up the grid. OK? That's what this part does.

Then it has these isolated DC to DC converters, that can take that DC voltage and generate other DC voltages, referenced in other ways, and without worrying about currents going back to ground. OK? It's galvanically isolated.

And then, it takes that energy, and it goes back DC to AC. OK? Now, in some systems, you might go DC to AC for 60 hertz to generate into the grid, or for a motor, or something else. This particular one has these outputs that are at 13 megahertz, for driving plasmas to process semiconductors.

But you get all these kinds of functions-- AC to DC, DC to DC, DC to AC. And we're going to learn the-- first of all, the underlying principles of doing all these things and how to design them.

So the real goal is, by the time you walk out of here, you should have all the tools to go off and design power electronics for all kinds of applications. And, in fact, graduates of this class have worked on electric vehicles, battery chargers, solar, communication systems, data centers.

The-- in fact, the power supply I usually use for my laptop and, in fact, the wireless charger for my iWatch were all designed, or the teams were led, by graduates of this class. So this-- the goal is to give you the tools you need to go do these things.

So, with that, let me start by just giving you a sense of what goes on inside power electronics.

So let's think of the simplest case. I have some DC input voltage, and I'd like some other DC voltage.

So suppose I have some input that's-- maybe it's 9 volts to 16 volts. I'm making that up arbitrarily, but that's, roughly, what you might get in a typical vehicle, out of the cigarette lighter.

And suppose I want-- and I'll call this V in-- and suppose I want-- here's some load, that I'm going to represent with a resistor. I'm going to call that V out. And suppose I want Vg 5 volts. Right? To power something that takes 5 volts.

What's the most obvious and simple way to get 5 volts at my output from some higher voltage?

Voltage divider. Precisely.

I could come up here, and I could say, OK. Let me put in some variable resistor, and I'll drop down this voltage, to give me the voltage I want. And I'm done.

And, in fact, a lot of systems, that's exactly, more or less, what they have inside them. In fact, inside most integrated circuits, there's lots of these things going on. OK?

Well, OK. They don't do it quite this way. What do they really do? They-- we'll take V in. And what they will do is they'll use some kind of transistor, a MOSFET or a bipolar transistor, and they will treat that, essentially, as a variable resistor.

So I implement the variable resistor with a controlled transistor, and I will come and I'll have some feedback loop. I'll feed in a reference voltage. And I'll measure the output voltage. And I'll control the gate of this transistor and, essentially, make that transistor look like a variable resistor and control the voltage division, so that, even if this voltage varies between 9 and 16 volts, I always get my 5 volts output.

And, like I said, that's very common. But what's the problem with this? Well, there's a whole lot of problems with this. Why wouldn't you want to do this in typical operation?

AUDIENCE: Low efficiency.

DAVID PERREAULT: Terrible efficiency. Yes, exactly.

So let's think about this. If I accept the fact-- let me call this current I in and this current I out. If this thing does act exactly like a variable resistor, the input currents equal the output current. Now, this-- actually, a real system might have some current that actually also goes to the ground, but let's take the best case, where the output current is equal to the input current.

What would be the efficiency of this beast?

Well, the efficiency-- the efficiency is equal to the output power over the input power. I'm drawing energy, maybe, from my car battery, or whatever my battery source is, and I'm delivering it to the output. But not all of it's getting to the output.

So the output power is V out times I out, and my input power is V in times I in. And I just told you that I out was equal to I in, in the best case. So that's V out over V in. Right?

So if I'm coming in from 15 volts, and I'm getting 5 volts, that's 33% efficiency. I've taken 2/3 of my energy and thrown it away.

Now, if I've got lots of energy floating around, and I'm processing a microwatt, maybe I don't care. Maybe I'll live with that because this thing's pretty simple. Right? It's a transistor-- it's a power transistor and some controls.

And they can, often, put all that on one integrated circuit, or as even as a sub-block on an integrated circuit. I might still need some filtering. It's not quite as easy as it sounds, but pretty much. It's relatively simple. But my efficiency is miserable.

Now, if I thought about in your computer, your desktop computer, typically, the intermediate supply that you're getting after, it's sort of come in from the grid and been transformed down. You get 12 volts.

And let's say your computer is at sort of-- it depends on what it's doing, but say it's operating at a volt. So then you're less than 10% efficient.

And if you think that you can have a microprocessor that's taking 200 amps at a volt, so a few hundred watts, suddenly, if I've got less than 10% efficiency on 200 watts, that means I need to put in a few kilowatts.

Well, you can't even plug that into the wall, never mind the fact that you've just made a massive room heater. That's, like-- that'd be great for heating your dorm room, but pretty terrible for the overall system.

So the number one reason we don't like this solution is efficiency. Good thing, it's simple. Bad thing, it's terrible efficiency.

This technique, I should have noted, is what's known, for historical reasons, as a, quote unquote, linear power supply. Why linear? I think only because analog circuits, kind of a category of them, became known as, quote unquote, linear circuits. There's nothing really that linear about it, but this would be called a linear power converter, or sometimes a linear regulator is what it would be called.

For obvious reasons, I hate throwing away energy. We're not going to talk about linear regulators at all in this class, and there's plenty of classes where you can learn about that. We want to do things some better way, that's not going to burn lots of energy.

So, ideally, in my world, the goal is to take as much of the input energy in and put it to the output. And that's important because-- think about it this way. I showed you a photograph of something that was really tiny, maybe that big and that thick, and it was processing a kilowatt. Right? If I don't do that at really high efficiency, that thing will burn up.

So, in order to make something small, I need to make it efficient. So we want almost all of the energy at the input to get to the output.

Well, how can we do that?

Let's think of a completely different way we might achieve this same function.

And here's the idea. Here's my input.

I'm going to create a switch here, a single pole double throw switch.

Now, we're not going to go get physical switches. We're probably going to get semiconductor devices and make it do something like this. But we could use anything-- any technology that was practical-- as a switch.

And let me just define. I'm going to define a switching function that I'm going to call q of t. If q of t is 1, I'll connect the switch to the input. If q of t is 0, I'll connect the switch to the ground.

So this notion, this voltage-- maybe I'll call this voltage Vx.

So one thing I could do is I could say, OK. Let me just hook this up to my load. Here's my resistive load, whatever it is, and I'll call this V out.

Well, all right. What would that look like? Well, let me define my switching function.

I'm going to put the switch in the up position for a little while, and then I'll put it in the down position by setting the switching function to 0. And then I'll just repeat that. So I said we're going to operate in some kind of repetitive fashion here. And so forth.

Let me operate with some period T. That's going to be my switching period. In this example, I'm showing it as a fixed switching period.

And I will keep the switch in the up position some fraction of the time that I'll call DT.

So D is a fraction. 0 is less than D is less than 1.

So if I do that, then what do I get for Vx? Vx is going to look something like this.

When the switch is in the up position, Vx equals V in. So this is Vx.

When the switch is in the down position, Vx is equal to 0.

And I rinse and repeat, and I get this. Now, I have this pulsating voltage Vx.

What's the average value of that voltage Vx?

I can take simple integration, 1 over t, the integral of Vx of t, over a period T. And what I would find is the average voltage of Vx is equal to D times V in.

So I can create a waveform here whose average value is something different than V in, just by controlling this timing, D.

So now, if my load resistor here was a space heater-- you know, maybe this is some load resistance RL-- and I wanted to modulate the power to that load resistance by controlling the average voltage on the load resistance, then this technique would work great.

If, on the other hand, my load was a microprocessor, and I start pulsing 12 volts-- between 12 volts and 0 on it, I'm probably going to blow it up. So that's no good.

But this notion is at least that I can control an average voltage by pulsing a switch. And this would be known as PWM, or pulse width modulation, because I control the average voltage by the fraction of the time the switch is in one position versus the other.

So that's the basic concept we're going to be using.

How do I fix this little problem of-- in practice? What I wanted was a DC voltage, and what I got was a pulsating voltage, that just happened to have the right average value.

Well, I could go do something like this. Maybe I'll go back and say, OK. Let me throw in a filter and extract out the component I want. I want the average value of Vx. So maybe I'll come back here and say, OK. Let me throw in a filter. And I'll use an inductor here, an L. And if I want, optionally, I can put a capacitor here, C. OK?

And I think people can look at this filter block and recognize that as a low-pass filter. The DC component of Vx passes through the filter to the output, and the AC component of Vx gets rejected by the filter and doesn't get to the output.

So, in this case, I might get an output voltage V out that looks something like this.

I'm going to sort of make this up, but-- I'm amplifying the ripple. But, eventually, it's going to filter the energy content of that. And the fundamental and higher harmonic terms of Vx are going to go away, and the DC term is going to go through. And I get an output voltage V out that's very close to whatever value I want.

And if I, basically, make the filter cutoff hard enough, I can't distinguish between V out and the average value of Vx, and I get exactly what I wanted.

So we've, essentially, now created a voltage converter that lets me use this pulse width modulation, by controlling this duty cycle D, to regulate the output just the way I wanted.

So instead of-- here, I'm just changing the gate voltage on my transistor to control the output. Here I'm changing timing. I'm going to control timing. And by controlling timing, I control average value. And then I get what I want.

All right. Any questions about that?

AUDIENCE: What's the efficiency of the supply?

DAVID PERREAULT: That is an excellent question. The answer is, ideally, theoretically, the efficiency can be 100%. In reality, it can't be.

Why do I say the efficiency can ideally be 100%? Well, how would I implement this box in the real world? Usually, I don't get semiconductor single pole double throw switches. The way I would usually build this beast is like this. OK? I would usually have a first switch and a second switch implemented like this.

So I close this when q of t is equal to 1, and I close this one when q of t is equal to 0.

And then I build my filter.

And then I put my load on here.

So what would be the efficiency of this thing? Well, let's think about this.

This is voltage V sub x and this is voltage V sub out.

All right.

What power is theoretically dissipated in my switch?

If I have an ideal switch, a 0 resistance when it's on and it has infinite resistance when it's off.

What's that? 0 power. Why?

Because the power dissipated. The power that goes into this box-- let me call this V switch, and let me call this I switch. OK? Well, P switch, the power going into the switch, the power being dissipated in the switch, is going to be V switch times I switch. OK?

Well, if it's an ideal switch, then, If the switch is on, V switch is 0. Right? It's ideal, so it has no voltage drop when it's on. So the power when it's on is 0. When the switch is off, it has infinite resistance. So the switch is current 0. So, basically, the power going into the switch, if it's an ideal switch, is, ideally, 0. So these elements, this ideal switch, is a lossless element.

Likewise, I wasn't-- I didn't just randomly choose any filter here. I chose an LC filter. Why did I choose an LC filter? I chose an LC filter because inductors and capacitors are energy storage elements. If they're ideal, then they store energy, but they don't dissipate energy.

So, basically, everything in the white box here-- everything between the input and the output-- is a lossless element.

So then, one would assume that, if every element is lossless, any energy walking in to the left comes out to the right. And that's how that kilowatt-- little 400 volt to 12 volt converter I showed you in the photo is about 97% efficient.

It's not 100% because the wires have some resistance, and the switches have some on-state resistance. There's a whole bunch of things that contribute to loss, and we'll talk about that. But I can make it really close to 100%, even though I might be doing a huge step down.

So if I tried to build a linear regulator that was going from 400 to 12 volts, that would be about 2.5% efficient. So if I want to generate a kilowatt at 2.5% efficiency, what is that? 40 kilowatt input? And instead, what I get is, sort of, like, 1.03 kilowatts input to generate a kilowatt output.

So the whole magic that we're going to talk about this term is, how can I use perfectly lossless elements to draw energy in, process it, and put it out the other side?

And, by the way, I should say, not only did I say inductors and capacitors are lossless in principle, lossless elements, it wasn't an accident that we put an inductor here.

Because think about it. When this switch is closed, I have V in on this side of the inductor and V out on this side of the inductor. And I have current flowing this way.

Well, what's happening, when this switch is closed?

Basically, there's voltage across this inductor and current going through it. We are storing energy in that inductor. So the difference in voltage between the input and the output is, basically, putting energy in the inductor.

In the other part of the cycle, when I turn this switch off and this switch on, basically, I'm taking-- now I have a negative voltage across the inductor. I'm taking energy out of the inductor and putting it in the output. So, essentially, I'm using this inductor as a filter, but it's also an intermediate store of energy, that lets me take energy from the input and transfer it to the output, with a voltage conversion, without losing any of the energy.

Excellent question. Long answer to a short question. Any other questions?

OK. So, as I said, my goal is to, first of all, teach you a lot of the underlying principles. This is the world's, if you will, simplest switching power converters. So we use this technique. We also often say we're switched-mode. All right? With the notion that we're going to use switches and energy storage elements to process energy. And that's sort of what sits at the core of power electronics. OK?

And, as I said, we're going to look at all of the aspects. How do you design these things? How do you control them? How do you design the components? And, by the time we're done, you should be able to put it all together and start designing power electronics of your own. And you will, for the final project.

So, any final questions?

OK. We'll wrap up today, and I will see everybody on Wednesday.