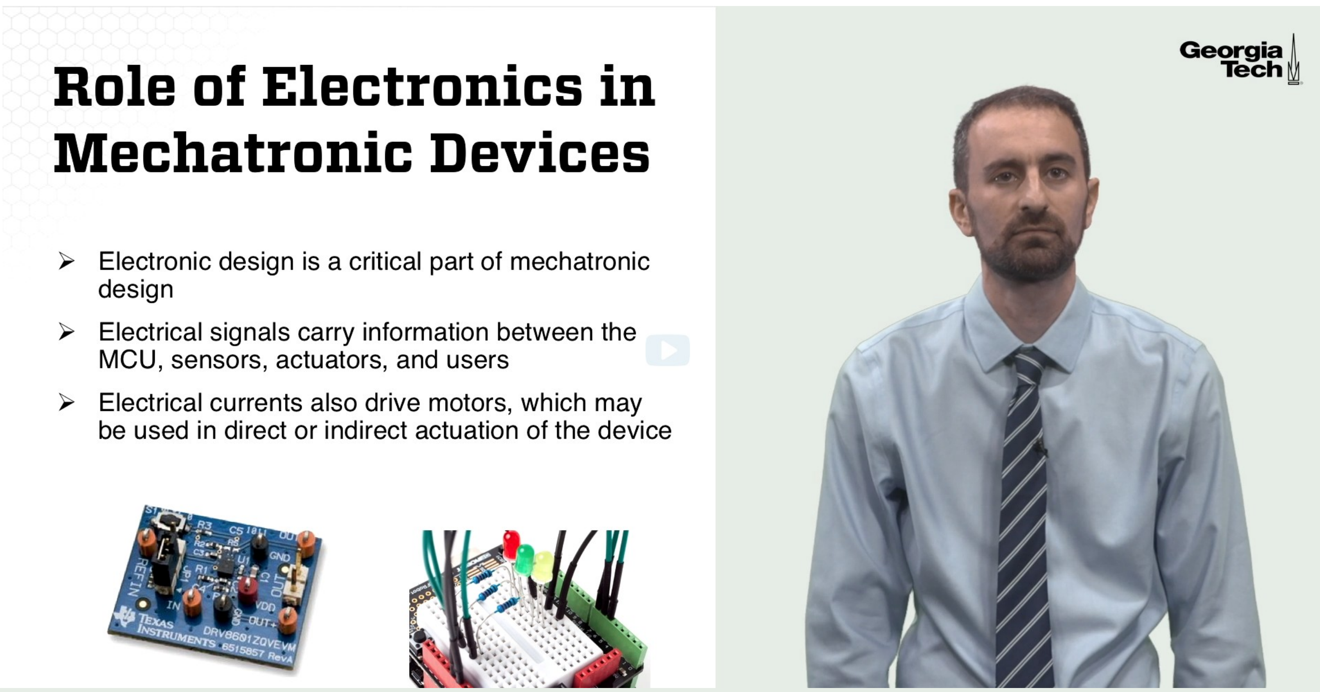
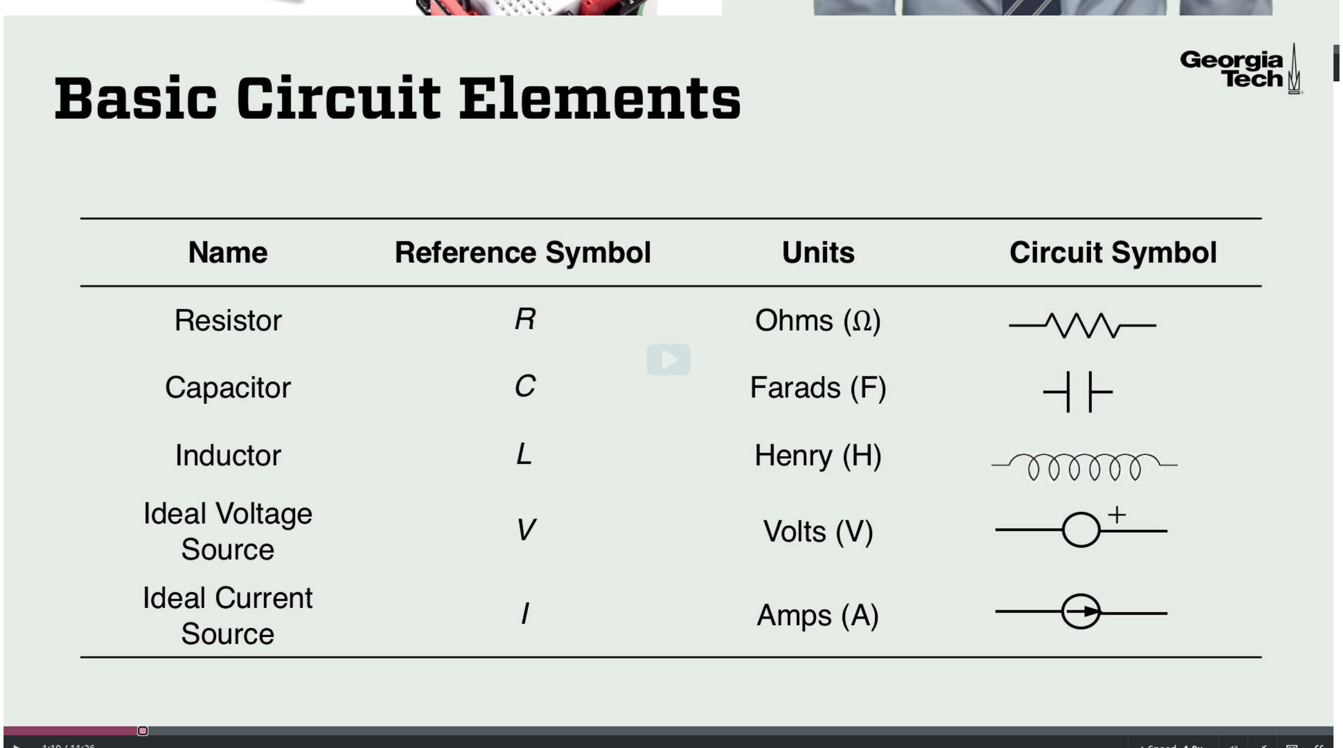
Module 2 – Circuits and Electrical Components

Topic 1 – Basic Circuit Concepts

Lesson 1: Circuit Elements and Constitutive Relationships





Basic Circuit Elements

Name	Reference Symbol	Units	Circuit Symbol
Resistor	*R*	Ohms (Ω)	
Capacitor	*C*	Farads (F)	
Inductor	*L*	Henry (H)	
Ideal Voltage Source	*V*	Volts (V)	
Ideal Current Source	*I*	Amps (A)	

Constitutive Relationships

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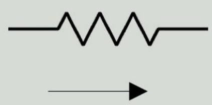
Resistance

R



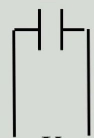
I

$$\boxed{V = IR}$$

Ohm's Law

Capacitance

C

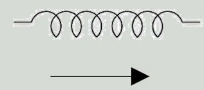


V

$$\boxed{\frac{dV}{dt} = \frac{1}{C} I}$$

Inductance

L



I

$$\boxed{\frac{dI}{dt} = \frac{1}{L} V}$$

Switches

Georgia Tech

Switches may be either **toggle** or **push-button** switches

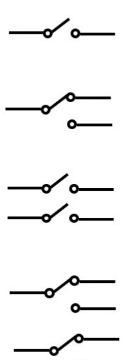
Toggle Switches

Single Pole, Single Throw (SPST)

Single Pole, Double Throw (SPDT)

Double Pole, Single Throw (DPST)

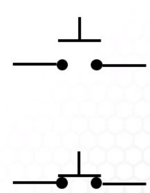
Double Pole, Double Throw (DPDT)

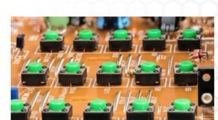


Push-Button Switches

Normally Open (NO)

Normally Closed (NC)

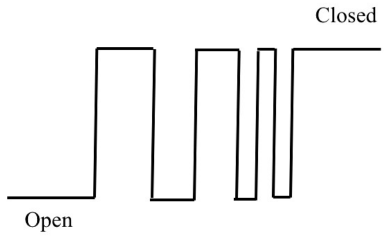




Switch Bouncing

- When switches are toggled, mechanical contacts rebound off of each other
- This happens over very short timescales - too fast for us, but not too fast for a microcontroller
- MCU may see switch toggle several times very quickly - can result in unwanted behavior

*Switch **debouncing** circuits or algorithms can fix this*



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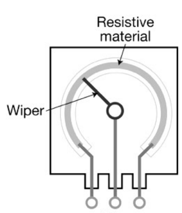
Potentiometers

- Potentiometers and rheostats are **variable resistors** that can be tuned to precise values
- Useful for **user interfaces**, or to adjust resistance to precise level in circuit design (resistors only come in discrete values)

Potentiometer Symbol



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Alternating Current (AC) vs Direct Current (DC)

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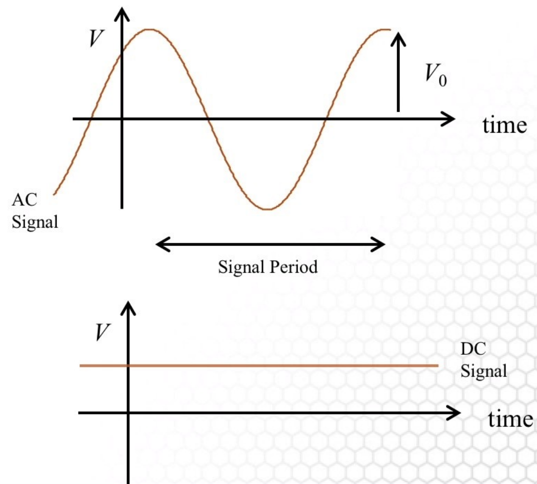
- AC signals have sinusoidally varying voltage
- DC signals have a constant voltage over time - DC is a special case of AC with a frequency of zero

AC voltage signal: $V = V_0 \sin(\omega t + \theta)$

Root Mean Square (RMS) Voltage: $V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V^2 dt} = 0.707 V_0$

Root Mean Square (RMS) Current: $I_{RMS} = \sqrt{\frac{1}{T}\int_0^T I^2 dt} = 0.707 I_0$



Impedance

Georgia Tech

- When dealing with AC signals, concept of resistance must be generalized to impedance
- Impedance is a generalized form of resistance - it measures the opposition that a circuit presents to a current when an AC voltage is applied

Ohm's Law for AC Circuits $Z = \frac{V}{I}$ Complex values

Complex number

Impedance

- When dealing with AC signals, concept of resistance must be generalized to impedance
- Impedance is a generalized form of resistance - it measures the opposition that a circuit presents to a current when an AC voltage is applied

Impedance is an imaginary quantity:

$$Z = R + jX$$

R = **resistance** $\quad$ X = **reactance**

Power

- Power dissipated by a circuit element is the current that flows through the element multiplied by the voltage drop across the element

$$\boxed{P(t) = I(t)V(t)} \xrightarrow{\text{DC Voltage}} \boxed{P = IV = I^2R}$$

AC Voltage

Instantaneous Power

$$P(t) = V_0 I_0 \sin(\omega t + \theta_v)\sin(\omega t + \theta_I)$$

Average Power

$$P(t) = V_0 I_0 \cos(\theta_v - \theta_I)$$

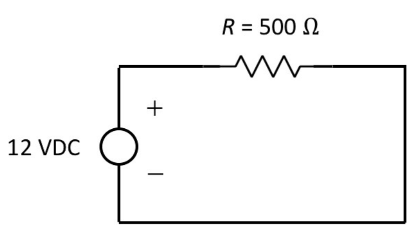
Power Dissipation

- The heat generated by circuit elements depends on the **power dissipated** by the circuit element
- When designing circuits, must make sure that all elements can handle the expected power dissipation - otherwise elements will overheat
- Power is measured in Watts

5.1Ω resistor, rated at 0.25 Watts

Power Dissipation

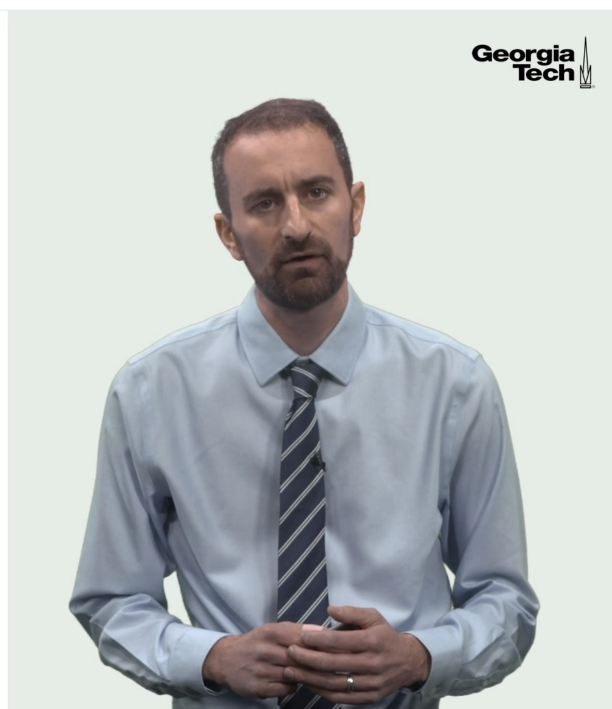
- Example: For the example circuit below, what resistor power rating is needed for the resistor *R*?



$$I = \frac{V}{R} = \frac{12\ V}{500\ \Omega} = 24\ \text{mA}$$

$$P = I^2R = 0.29\ \text{Watts}$$

The resistor must have a power rating **greater than 0.29 W**.



Lesson 2 – Circuits Analysis and Voltage Regulation

Kirchhoff's Voltage Law

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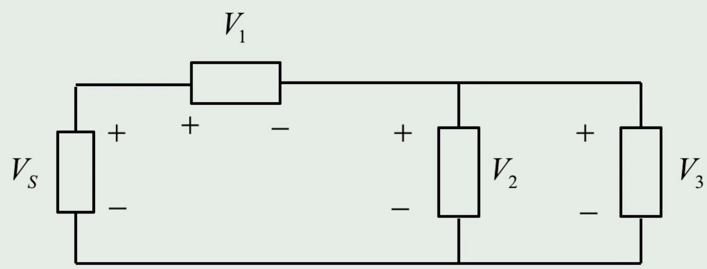
- Sum of voltage drops and rises around any closed path in a circuit is equal to zero.

$$\boxed{\sum_{i=1}^{N} V_i = 0}$$

Kirchhoff's Voltage Law



$$V_S - V_1 - V_2 = 0 \qquad V_S - V_1 - V_3 = 0$$

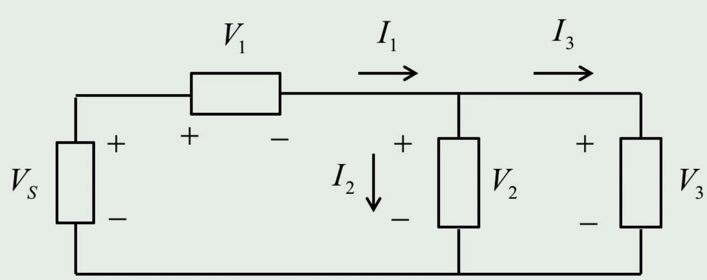
Kirchhoff's Current Law

Georgia Tech

- Sum of current into (or out of) a node is zero
- A node is the junction between different branches of a circuit

$$\boxed{\sum_{i=1}^{N} I_i = 0}$$

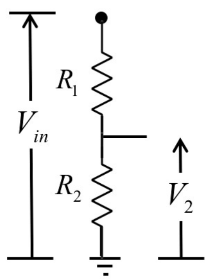
Kirchhoff's Current Law



$$I_1 - I_2 - I_3 = 0$$

Voltage Dividers

- Sometimes we need to step down a source voltage to power a circuit element (such as a sensor or processor)
- A **voltage divider**, created by placing two resistors in series, can be used for this purpose



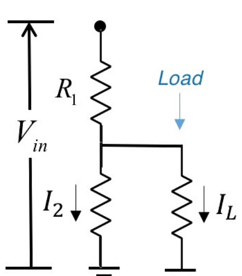
$$V_2 = \frac{R_2}{R_1 + R_2} V_{in}$$

(derived using Kirchhoff's Laws)

2:37 / 12:16 Speed 1.0x

Voltage Dividers

- **Caveat:** Do not use a voltage divide to power a load. Any current passing through load (R_2) will also pass through R_1, dissipating power and generating heat
- If you need to step down voltage to power a load, use a voltage regulator instead
- Only for use in **low-current applications**. Use high values of R_1 and R_2 (in the 1 kΩ - 10 kΩ range)



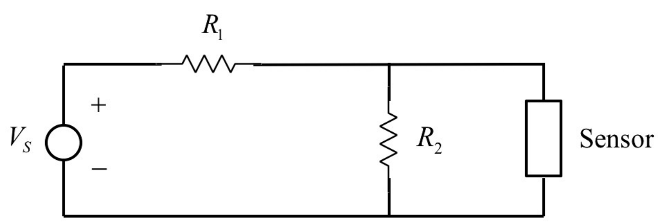
Power Dissipated by R_1: $R_1(I_2 + I_L)^2$

Voltage dividers are commonly used for sensor interfacing or reading potentiometer values.

4:06 / 12:16 Speed 1.0x

Example: Designing a Voltage Divider

Problem: A certain sensor requires an input voltage of 5 VDC. You have a voltage source available which only provides 15 VDC. Design a voltage divider (find R_1 and R_2) that will allow you to power the sensor from this power supply.



$$V_2 = \frac{R_2}{R_1 + R_2} V_S \quad \Rightarrow \quad 5\ V = \frac{R_2}{R_1 + R_2} 15\ V$$

Select R_1 = 1 kΩ $\Rightarrow$ $\frac{1}{3} = \frac{R_2}{1000 + R_2}$

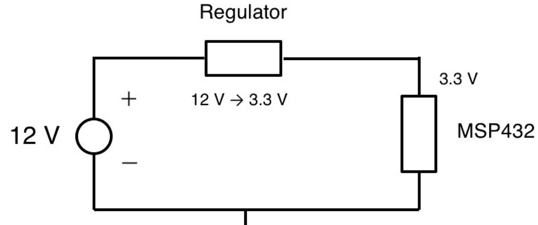
$\Rightarrow$ R_2 = 500 Ω

If a 500 Ω resistor is not available or we need tight tolerances, we can use a potentiometer.

7:05 / 12:16 Speed 1.0x

Voltage Regulators

- Voltage regulators are semi-conductor devices provide an efficient, stable mechanism for stepping down input voltages
- Regulators provides a **single output voltage** (e.g., 5 V) for a **range of input** voltages (e.g., 7-35 V)
- Useful when powering components / processors from a battery

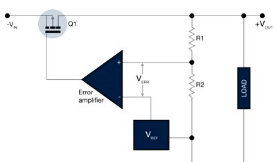


7:41 / 12:16 Speed 1.0x

Voltage Regulators

- **Linear voltage regulators** use an op-amp and transistor to achieve stable output voltage
- **Power is dissipated** as heat continuously during operation
- Must ensure that regulator has adequate power rating for particular application, and should **attach to heat sink**
- **Power dissipation** computed as: $P = I(V_{in} - V_{out})$

Linear Regulator Schematic

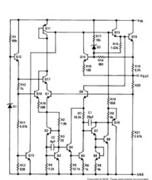


Linear Regulators have a **dropout voltage**: how much higher input voltage must be than desired output voltage

8:54 / 12:16 Speed 1.0x

Voltage Regulators

- Typical linear voltage regulator: Texas Instruments LM7805



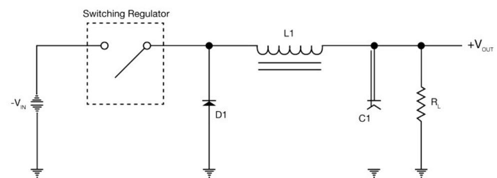
Courtesy of Texas Instruments

- Output voltage: 5V
- Input voltage range: 7-35V
- Maximum current provided: 1.5A
- Dropout voltage: 2V
- Cost: ~$1

10:17 / 12:16 Speed 1.0x

Voltage Regulators

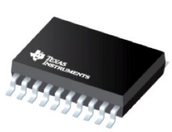
- **Switching regulators** uses a switching element to transform input voltage into a periodic signal with lower average voltage
- Capacitors, inductors, and other elements are used to smooth pulsed voltage
- Switching regulators are **more efficient** and generate **less heat** than linear regulators

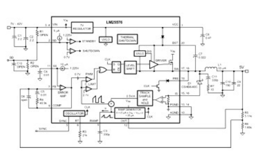


10:51 / 12:16 Speed 1.0x

Voltage Regulators

- Typical switching voltage regulator (Buck Converter): Texas Instruments LM25576



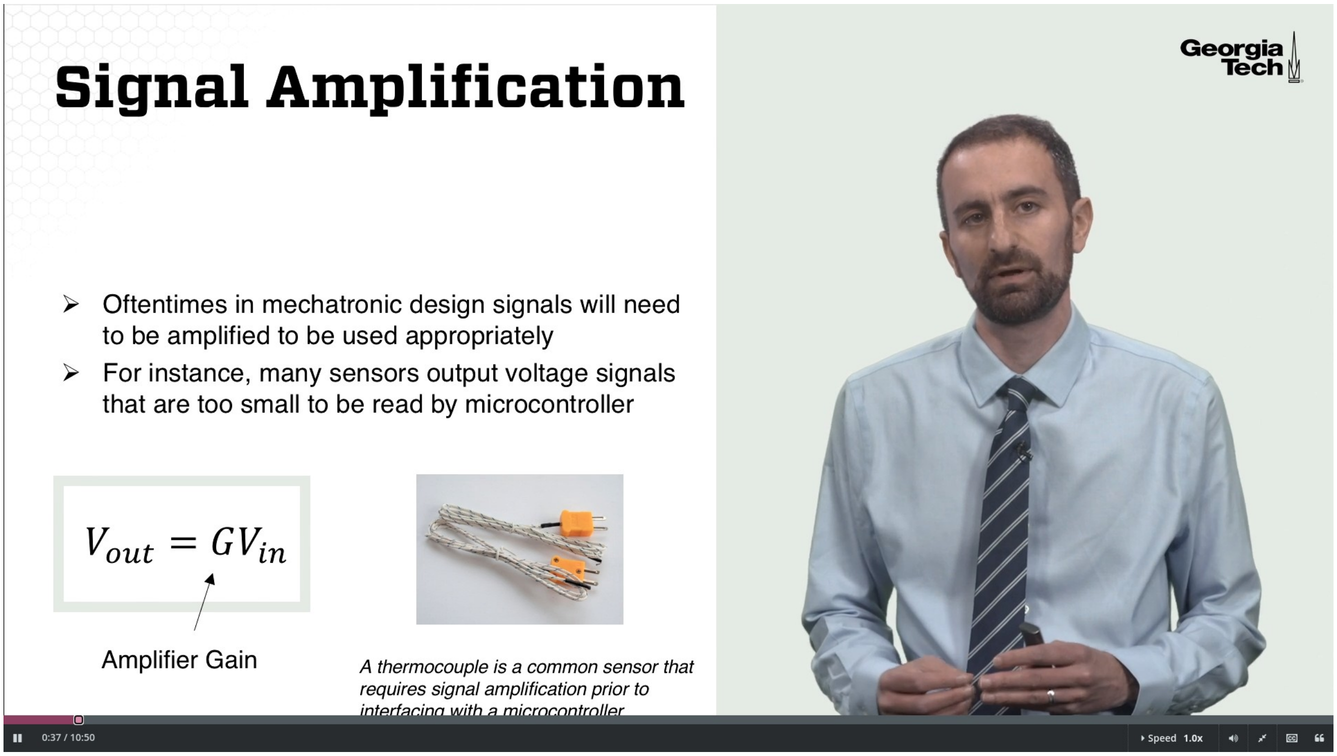


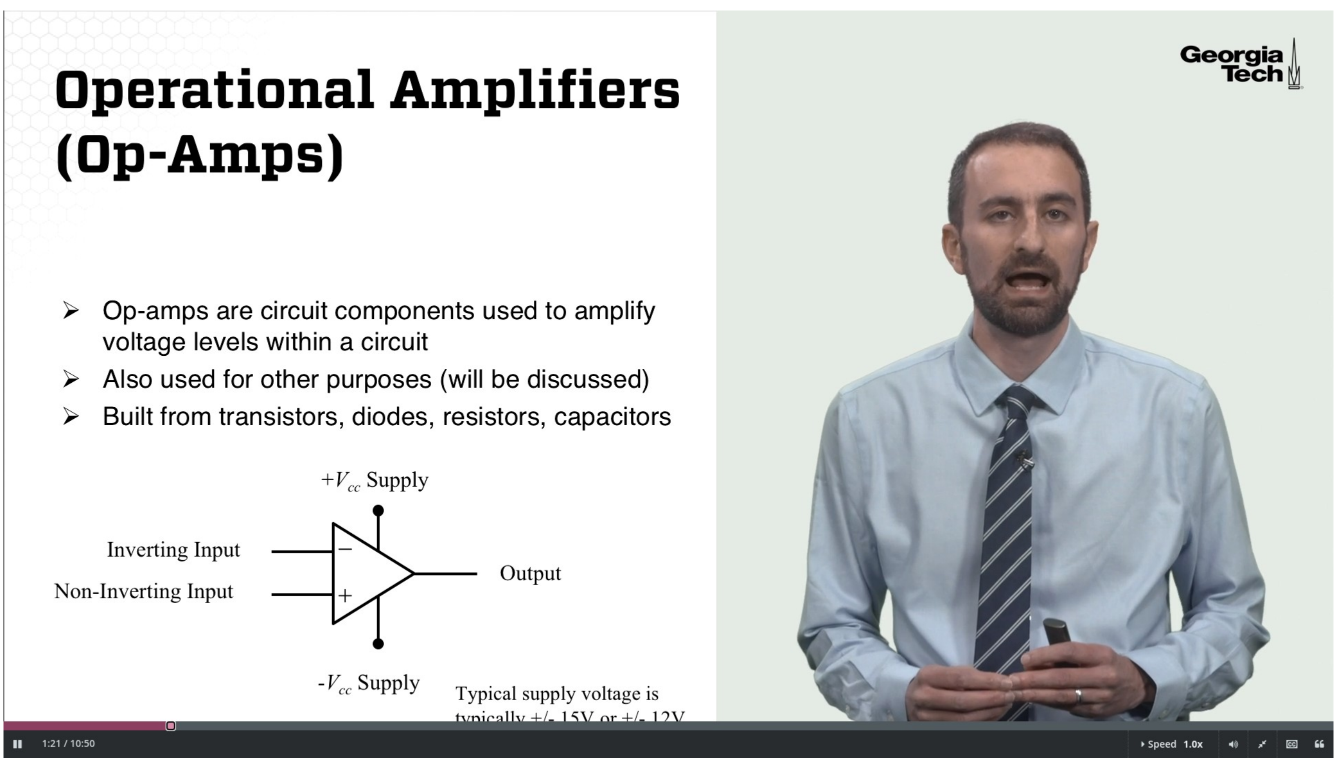
Courtesy of Texas Instruments

- Output voltage: Adjustable down to 1.225V
- Input voltage range: 6-42V
- Maximum current provided: 3A
- Cost: ~$4.80

11:12 / 12:16 Speed 1.0x

Lesson 3 – Amplifier Circuits

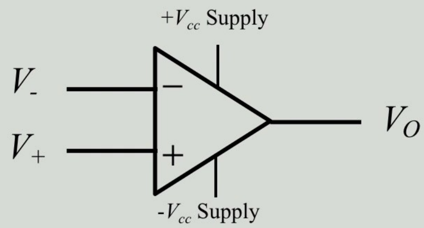




Operational Amplifiers (Op-Amps)

Georgia Tech

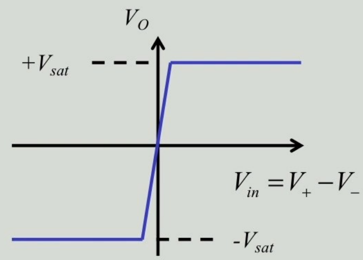
- **Open-loop** operation of op-amps



$$\boxed{V_O = K_{OL}\left(V_+ - V_-\right)}$$

$$K_{OL} \approx 10^5 \text{ or } 10^6$$

V_O saturates at V_{sat} which is typically slightly smaller than supply voltage (~13V)

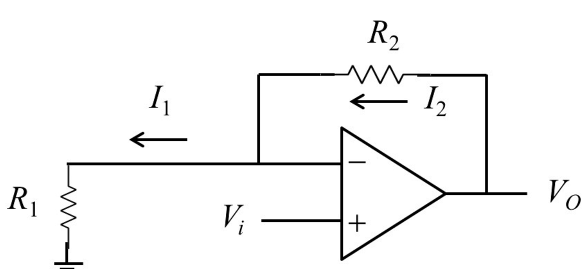


Op-amps in “open loop” configuration are called ***comparators***.

Operational Amplifiers (Op-Amps)

Georgia Tech

- **Non-inverting** op-amp circuit - uses closed-loop configuration
- Used to amplify voltage signal
- **Amplifier gain** determined by resistance values R_1 and R_2



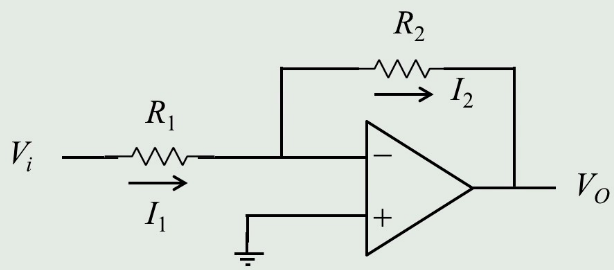
Note: Rail (supply) voltages no longer shown.

$$V_O = \frac{R_1 + R_2}{R_1} V_i = \underbrace{\left(1 + \frac{R_2}{R_1}\right)}_{\text{Amplifier Gain}} V_i$$

- By sizing R_1 and R_2 appropriately, can amplify V_i to value we need at output V_O
- Since resistors only come in discrete values, sometimes need to make R_1 or R_2 a **potentiometer** so it can be tuned to precise value we need.

Operational Amplifiers (Op-Amps)

- **Inverting** op-amp circuit
- Used to amplify voltage signal **and invert it**
- Gain determined by resistance values R_1 and R_2



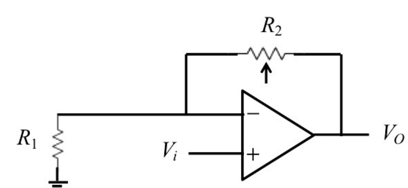
Amplifier Gain

$$V_O = \underbrace{-\frac{R_2}{R_1}}_{\text{Amplifier Gain}} V_i$$

- By sizing R_1 and R_2 appropriately, can amplify V_i to value we need at output V_O
- Inverting op-amps are sometimes used **current-to-voltage converters** to convert a current output from a sensor to a voltage output

Example: Amplifier Design

Using an op-amp, design a circuit that takes an input voltage V_i and produces an output voltage $V_O = kV_i$ which is tunable from $1 \leq k \leq 10$. Determine the circuit components needed and an expression for the value of k in terms of the circuit component values.



- Use a non-inverting op-amp circuit to amplify the voltage
- Because we want a variable (or tunable) gain, make one (or both) of the resistors a potentiometer

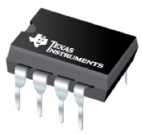
$$V_O = \left(1 + \frac{R_2}{R_1}\right) V_i$$

$$\Rightarrow \quad k = 1 + \frac{R_2}{R_1}$$

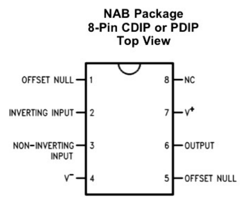
- If we select R_1 = 1 kΩ, then R_2 can be a potentiometer that can be tuned between 0 and 9 kΩ

Common Op-Amp: LM741

- Supply ("rail") voltage of +/- 15V
- Cost: ~$0.87
- Note: Input terminals to op-amps are very high impedance (MΩ range) - almost no current flows into input terminals

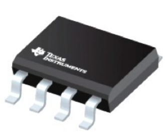


Courtesy of Texas Instruments

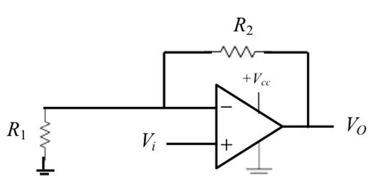


Single Supply Op-Amps

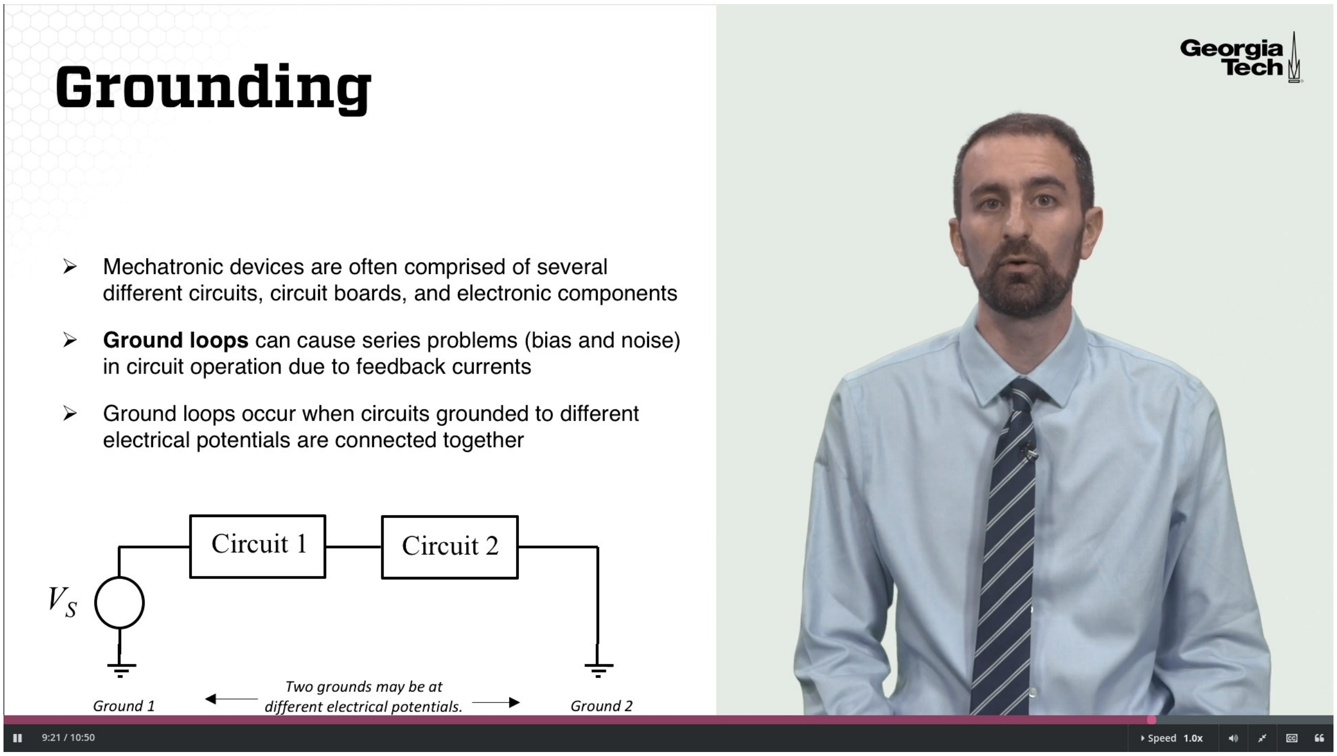
- Sometimes it can be hard to generate a large negative supply voltage in a circuit to use for rail input
- **Single-supply** op-amps eliminate the need for negative rail voltage. Negative supply can be tied to ground.
- Example: Texas Instruments TLE2022 single supply op-amp

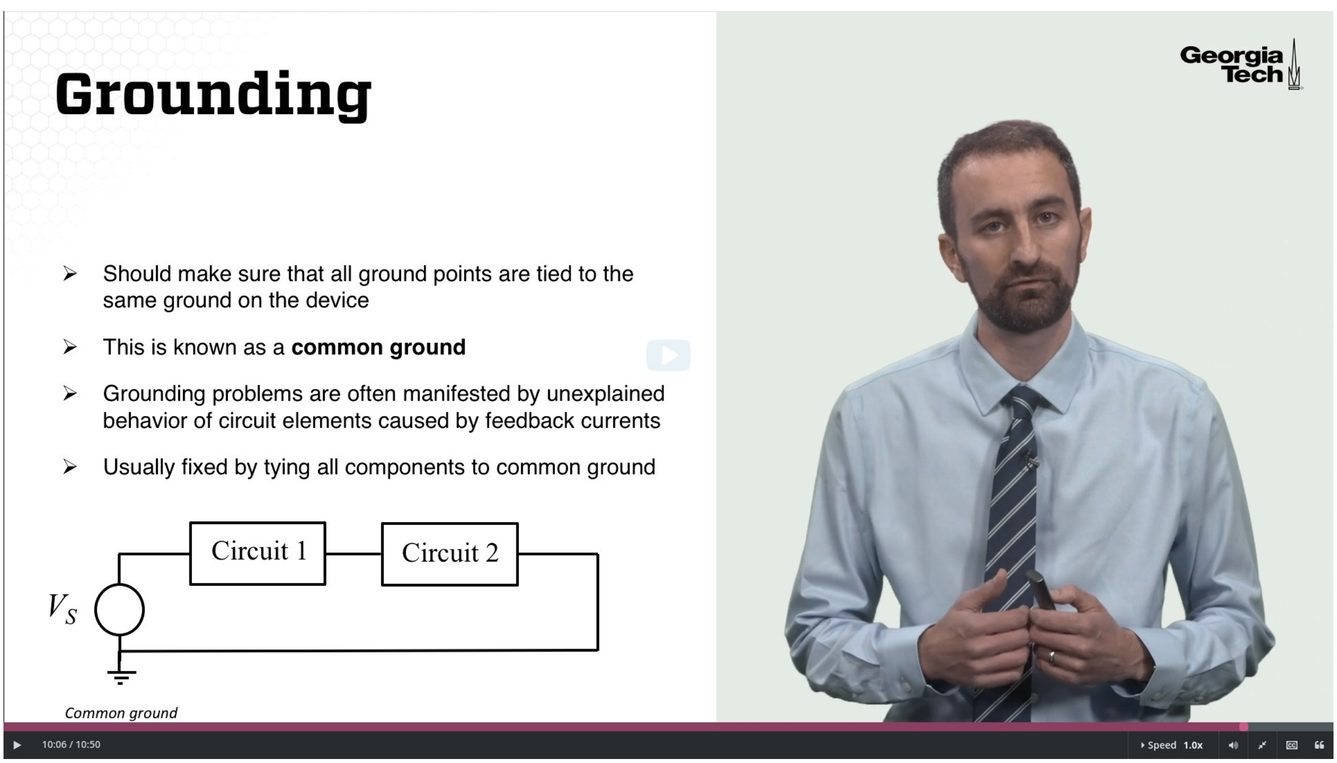


Courtesy of Texas Instruments



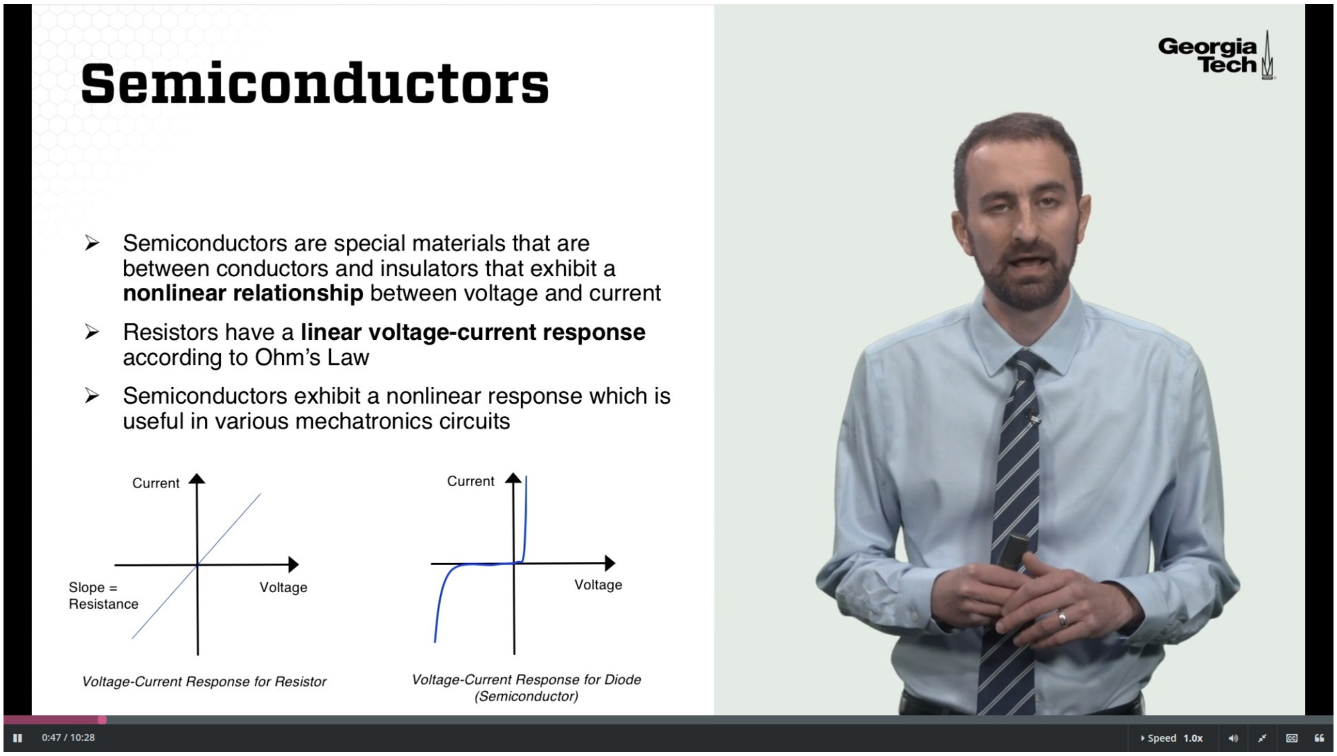
Non-inverting amplifier using single

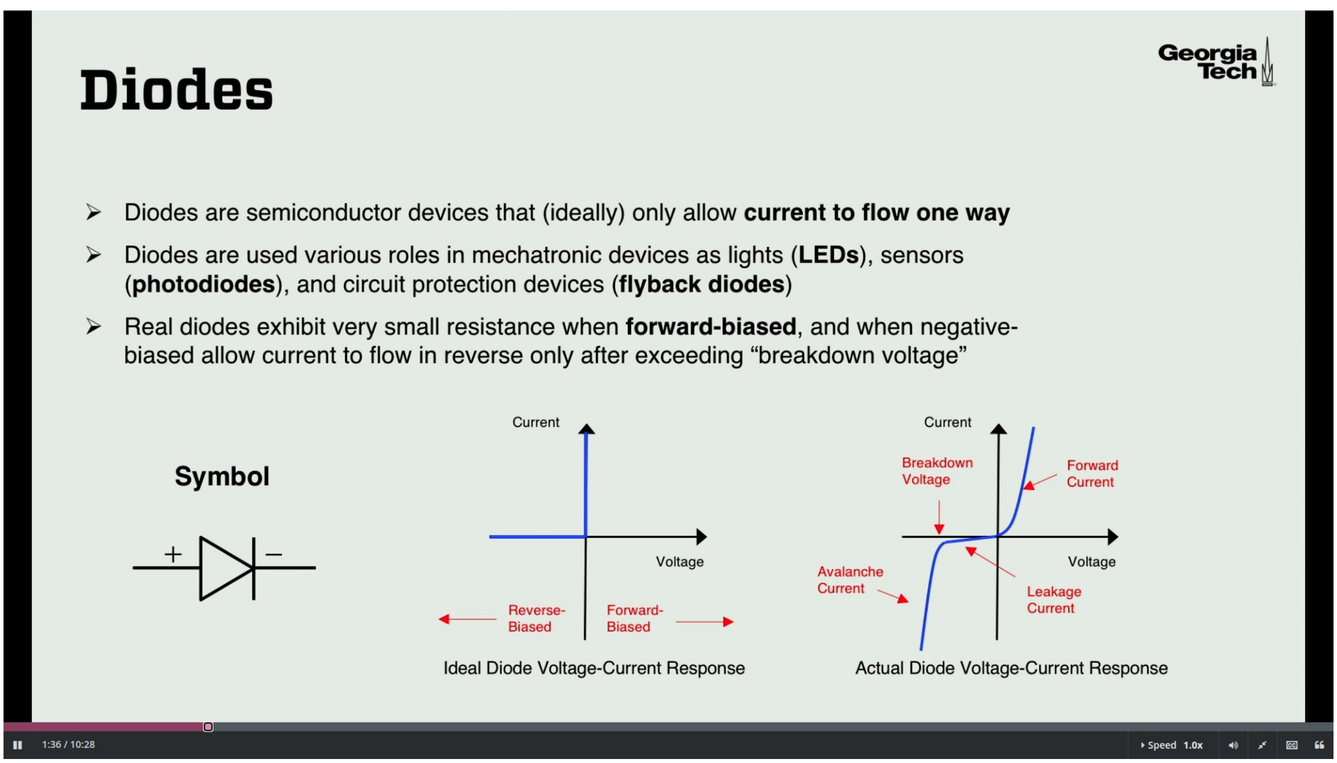

Grounding
Georgia Tech
➢ Mechatronic devices are often comprised of several different circuits, circuit boards, and electronic components
➢ **Ground loops** can cause series problems (bias and noise) in circuit operation due to feedback currents
➢ Ground loops occur when circuits grounded to different electrical potentials are connected together
Circuit 1
Circuit 2
V_S
Ground 1
Two grounds may be at different electrical potentials.
Ground 2
9:21 / 10:50
Speed 1.0x


Grounding
Georgia Tech
➢ Should make sure that all ground points are tied to the same ground on the device
➢ This is known as a **common ground**
➢ Grounding problems are often manifested by unexplained behavior of circuit elements caused by feedback currents
➢ Usually fixed by tying all components to common ground
Circuit 1
Circuit 2
V_S
Common ground
10:06 / 10:50
Speed 1.0x

Topic 2 – Semiconductors Circuits Elements

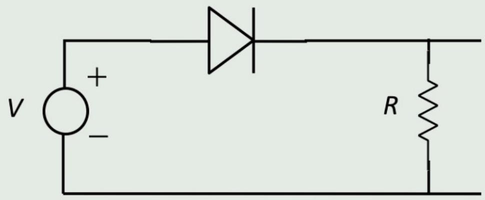
Lesson 1 – Diodes , LEDs and Photodiodes





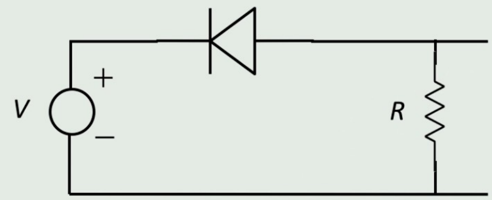
Diodes

Diode in **Forward-Biased** Configuration



- Current flows through circuit approximately according to $V = IR$
- Resistance of diode when forward-biased is very low (a few Ohms)

Diode in **Reverse-Biased** Configuration

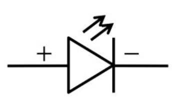


- Very little current flows through circuit unless V is higher than the breakdown voltage
- Reverse-biasing is usually used to try to eliminate current flow in a certain direction

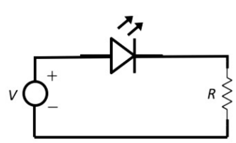
Light Emitting Diodes (LEDs)

- Light emitting diodes (LEDS) are diodes which **emit light** when forward-biased
- Static voltage drop of about 2-4V occurs when current flows through LED (forward-biased)
- Color of LED determined either by semiconductor material of plastic housing over diode

Symbol

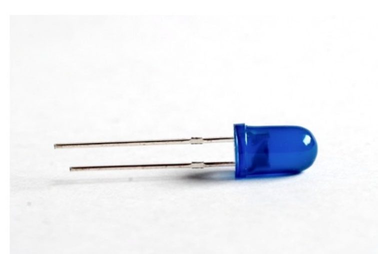


Basic LED Circuit



Typical blue LED:

- 3.4V drop when forward biased
- Maximum current of 30 mA
- Cost: ~$0.50

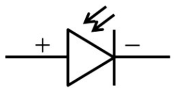


Photodiodes

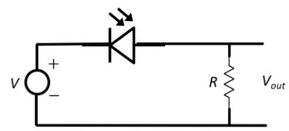
Georgia Tech

- Photodiodes are the opposite of LEDs - they allow current to pass through when light shines on them
- Amount of current passed by diode is proportional to the amount of light it receives
- Commonly used as ambient light sensors (i.e., night lights, etc.)

Symbol

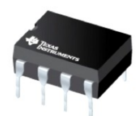


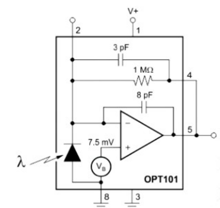
Light Measurement Circuit



Texas Instruments
OPT101 Photodiode

- Integrated combination of photodiode and amplifier
- Easy to integrate with MCU for light detection
- Cost: ~$9



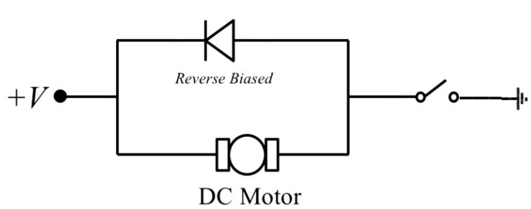


Courtesy of Texas Instruments

Flyback Diodes

Georgia Tech

- Consider following circuit in which motor is activated using mechanical switch (or transistor)

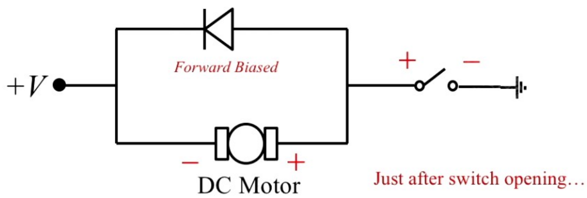


- Motor has high inductance *L*
- *When motor switched off, voltage develops across motor terminals according to:*

$$V = L\frac{di(t)}{dt}$$

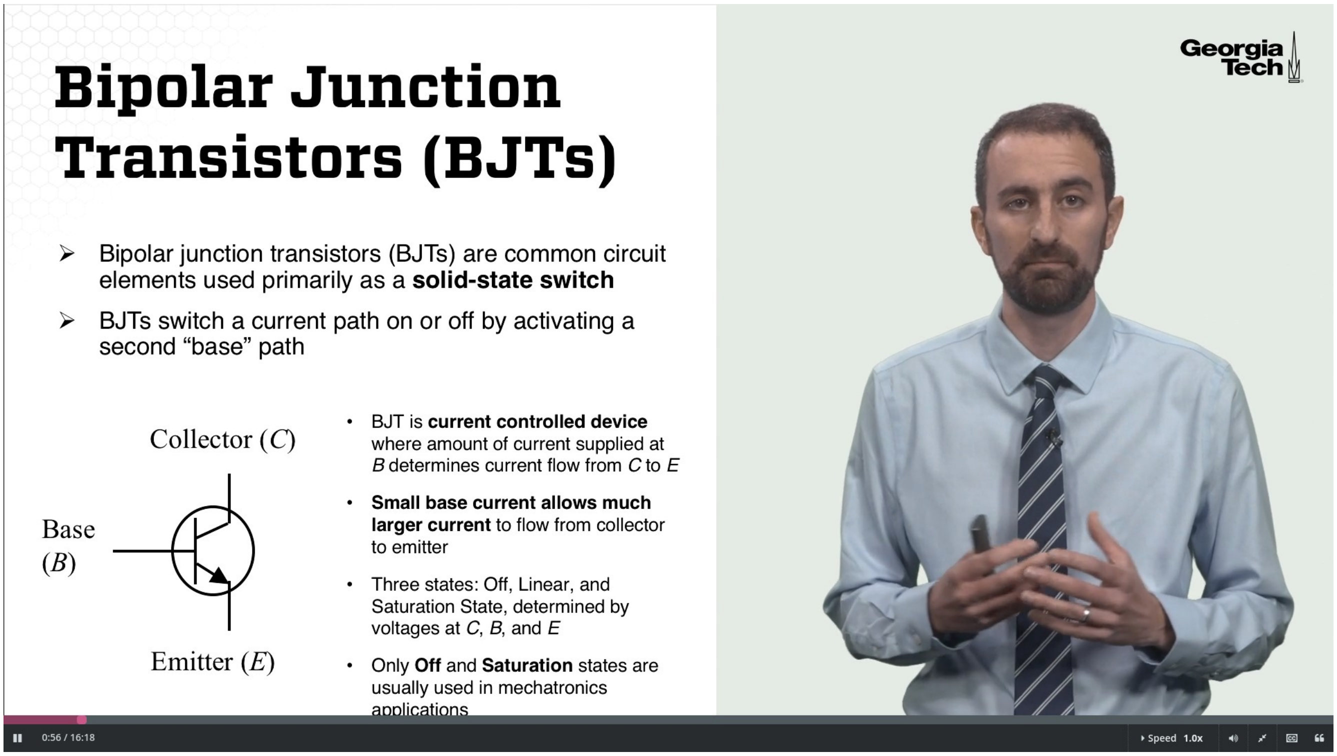
Flyback Diodes

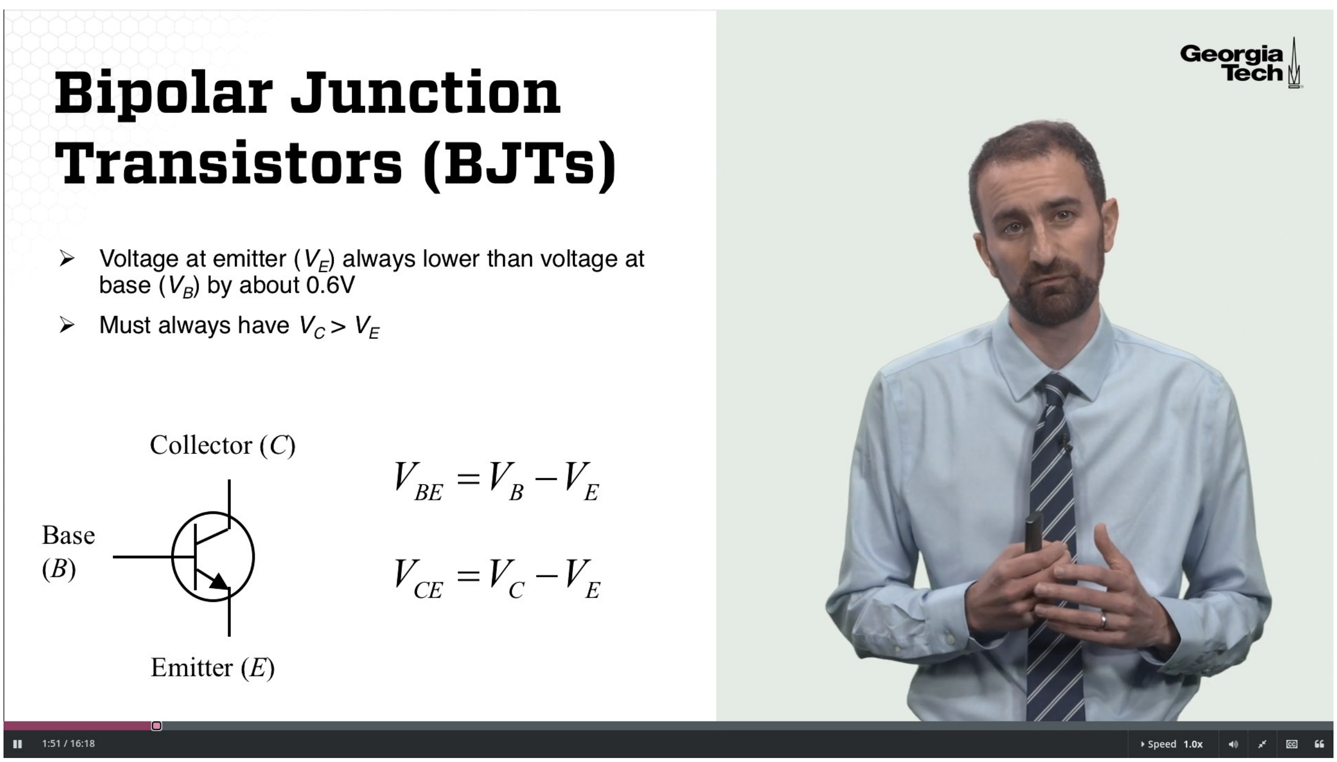
- Consider following circuit in which motor is activated using mechanical switch (or transistor)



- High voltage of opposite polarity across switch terminals just after switch opening
- May cause wear on switch due to arcing, or blow out transistor
- **Flyback diode** provides alternative path for current in motor coil and mitigates arcing / excessive current through transistor

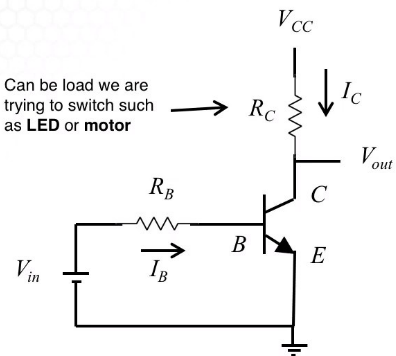
Lesson 2 – Bipolar Junction Transistors (BJTs)

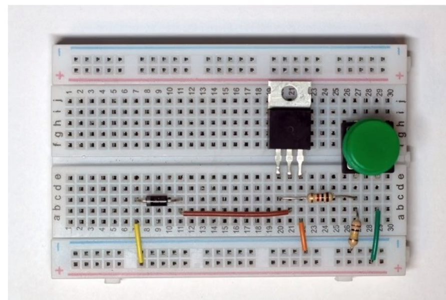




Transistor Switch Circuits

- In many mechatronic devices, loads that require **high current** (motors, LEDs, etc) must be switched on and off by devices that only accept and provide low current (MCUs)
- Transistor switch circuits are used to **switch high power loads from low-power devices**

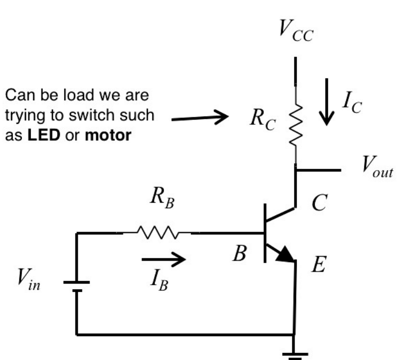




Transistor switch circuit using BJT (Darlington) transistor

Transistor Switch Circuits

- In many mechatronic devices, loads that require **high current** (motors, LEDs, etc) must be switched on and off by devices that only accept and provide low current (MCUs)
- Transistor switch circuits are used to **switch high power loads from low-power devices**



Three States of BJT Transistors

Off state: $V_{BE} < \sim 0.6$ V $\longrightarrow$ $I_C = 0$ $\quad V_{out} = V_{cc}$

(No current flows through load)

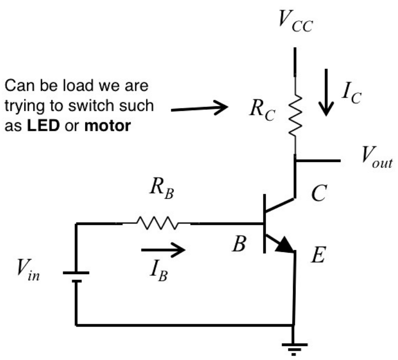
Linear state: $\sim 0.6 \text{ V} < V_{BE} < \sim 0.7$ V, $V_{CE} > 0.2$ V $\longrightarrow$ $I_C = \beta I_B$ $\quad \beta \approx 100$

Saturation state: $V_{BE} > \sim 0.7$ V $\longrightarrow$ $I_C > 0$ $\quad V_{out} = V_{CE} = 0.2$ V

(Current flows through load)

Transistor Switch Circuits

- Let's design a transistor switch circuit to control current flow I_C using input voltage V_{in}
- When $V_{in} = 0$ (off state) no current flows between collector and emitter and thus $I_C = 0$ (and $V_{out} = V_{CC}$)
- Question: What voltage V_{in} is required to switch transistor **from off state to saturation state**, allowing current to flow through load?



Solution:

Kirchhoff's Voltage Law: $V_{in} = I_B R_B + V_{BE}$

Kirchhoff's Current Law: $I_C = (V_{CC} - V_{CE})/R_C$

Property of BJTs just before saturation: $I_B = I_C/\beta$

3 equations, 3 unknowns

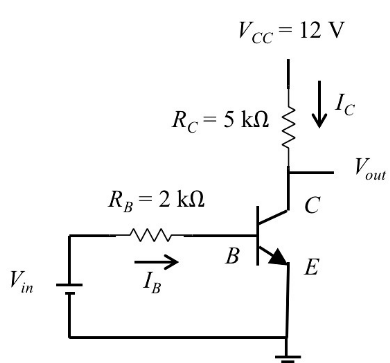
Knowns: $\beta \approx 100$, V_{CC}, V_{CE}, $V_{BE} = 0.7$, R_B, R_C

Unknowns: I_B, I_C, V_{in}

3 equations can be solved to yield required value of V_{in}

Example: Transistor Switch Circuits

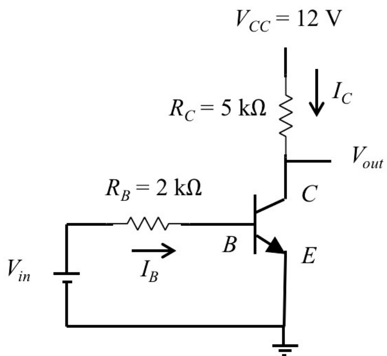
- Consider the **2N3904 BJT transistor**. Several parameters from the datasheet for this transistor are below.
- What is the input voltage needed to switch on the load (initiate saturation) if the load resistance is $R_C = 5$ kΩ and $R_B = 2$ kΩ? Assume $V_{CC} = 12$ V.



Parameter	2N3904 Value
V_{CE} at saturation	0.2 V
β	100
V_{BE} at saturation	0.7 V

Example: Transistor Switch Circuits

- Consider the **2N3904 BJT transistor**. Several parameters from the datasheet for this transistor are below.
- What is the input voltage needed to switch on the load (initiate saturation) if the load resistance is $R_C = 5$ kΩ and $R_B = 2$ kΩ? Assume $V_{CC} = 12$ V.



Step 1: $I_C = \frac{(V_{CC}-V_{CE})}{R_C} = \frac{(12-0.2)}{5000} = 2.4$ mA

Step 2: $I_B = \frac{I_C}{\beta} = \frac{0.024}{100} = 0.024$ mA

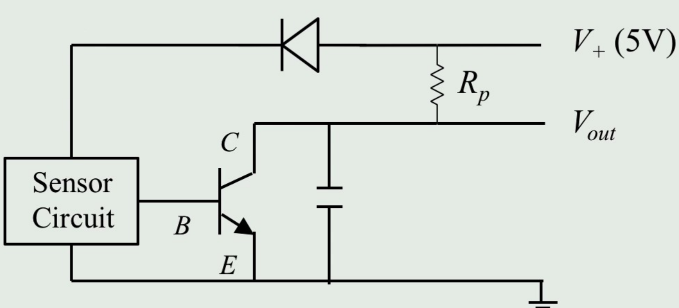
Step 3: $V_{in} = I_B R_B + V_{BE} = 0.000024 \times 2000 + 0.7$

➡ $V_{in} = 0.747$ V

To switch on load, input voltage must be greater than 0.74 V.

Open Collector Output

- BJT transistors are also commonly used to build **open collector output** circuits
- These are used to connect certain sensors to digital input pins on the MCU, allowing sensors with different output ranges to be read as **digital high or low** at the desired logic voltage (usually 3.3V or 5V)



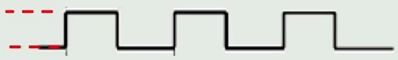
- Output of sensor drives base of transistor
- R_p is "pull-up" resistor connected from reference voltage V_+ to output V_{out}
- When sensor is low, transistor is in OFF state and no current flows from C to E → $V_{out} = 5$V
- When sensor is high, transistor is in saturation and current flows from C to E → $V_{out} \approx 0$
- Reference voltage V_+ can be set to any desired voltage (e.g., 3.3V for MSP432)

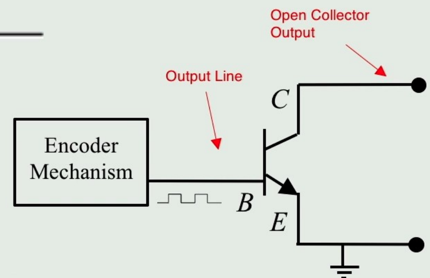
Example: Encode Open Collector Outputs

- **Encoders** are sensors that connect to rotating devices to measure angular speed or position
- They output a **square wave** as the shaft rotates - alternating between high and ground
- To be able to interface with logic levels at different voltages, most encoders have **open collector outputs.** They can be attached to pull-up resistors at the desired logic-high voltage.

High (3.3V, 5V, or other)

Low (0V)





Open collector output means high voltage value of signal is ***determined by circuit it is connected to***

Example: Encode Open Collector Outputs

- **Encoders** are sensors that connect to rotating devices to measure angular speed or position
- They output a **square wave** as the shaft rotates - alternating between high and ground
- To be able to interface with logic levels at different voltages, most encoders have **open collector outputs.** They can be attached to pull-up resistors at the desired logic-high voltage.

High (3.3V, 5V, or other)

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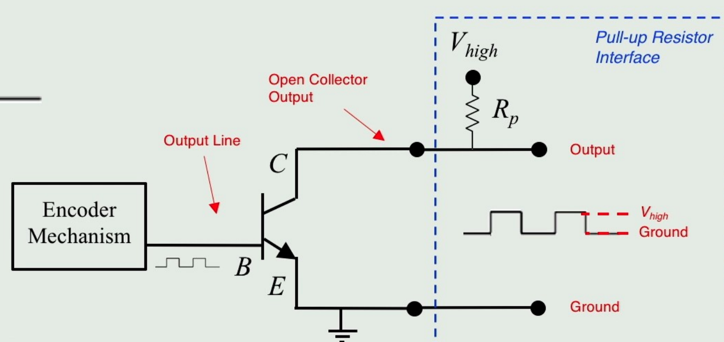
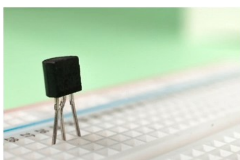
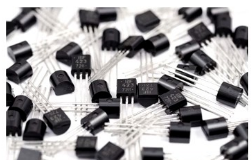
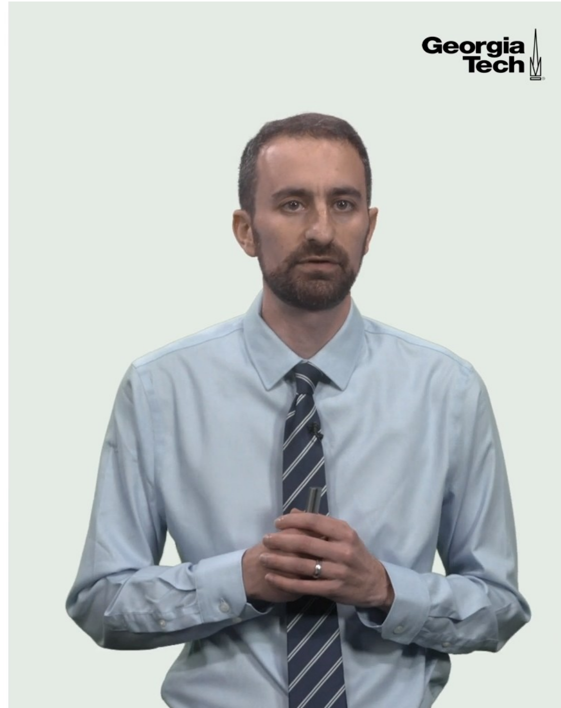


Common BJTs

Part No.	Max V_{CE}	Max V_{BE}	Max I_C	Power Dissipation at 25 deg C
2N2222	30 V	5 V	800 mA	0.5 W
2N3904	40 V	6 V	200 mA	0.625 W
MJE51	40 V	4 V	4 A	40 W
TIP3055	60 V	7 V	15 A	90 W



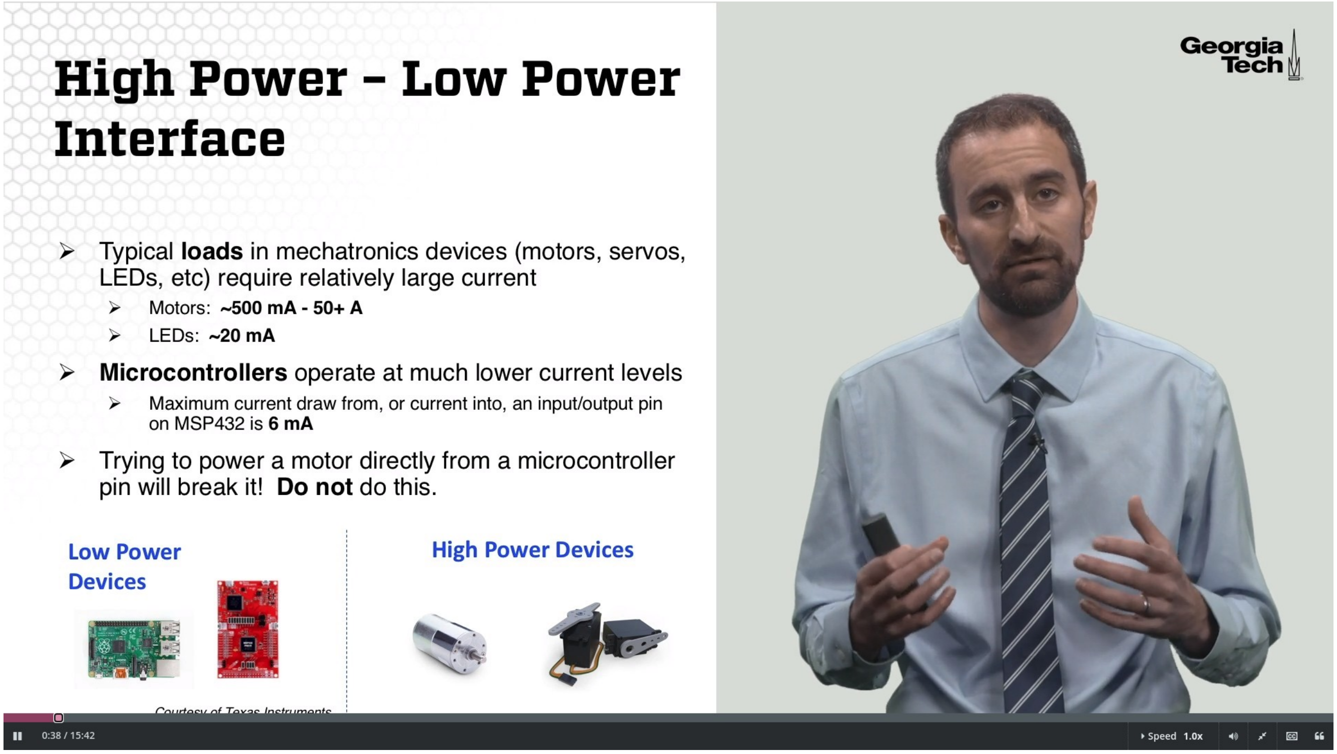


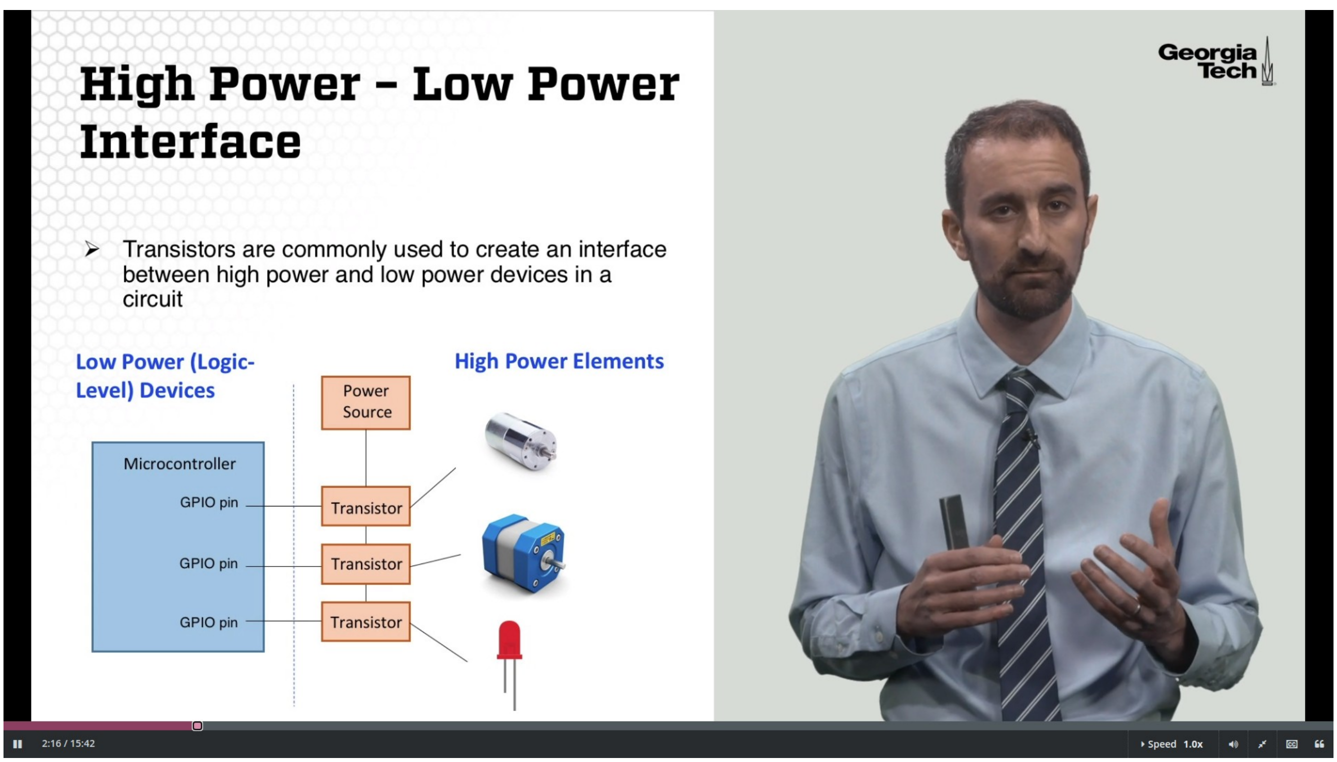


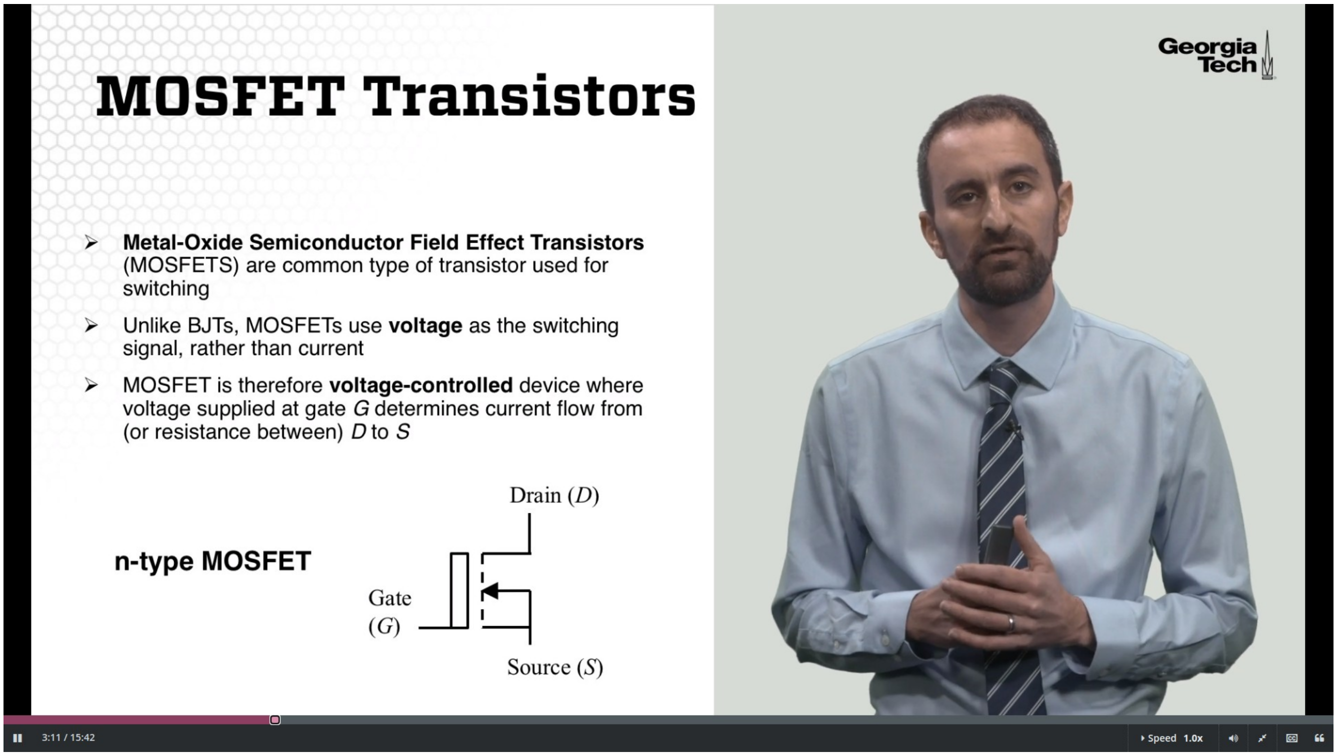
14:30 / 16:18

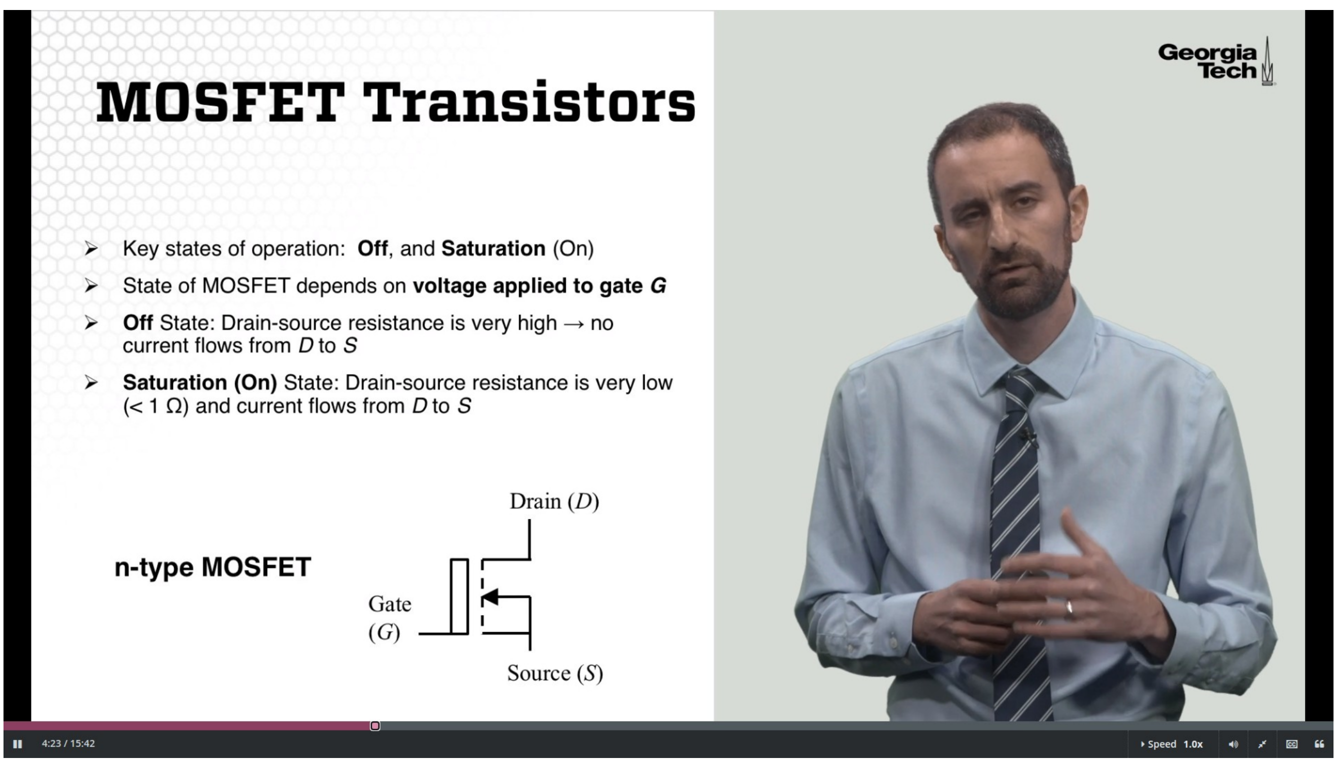
Speed 1.0x

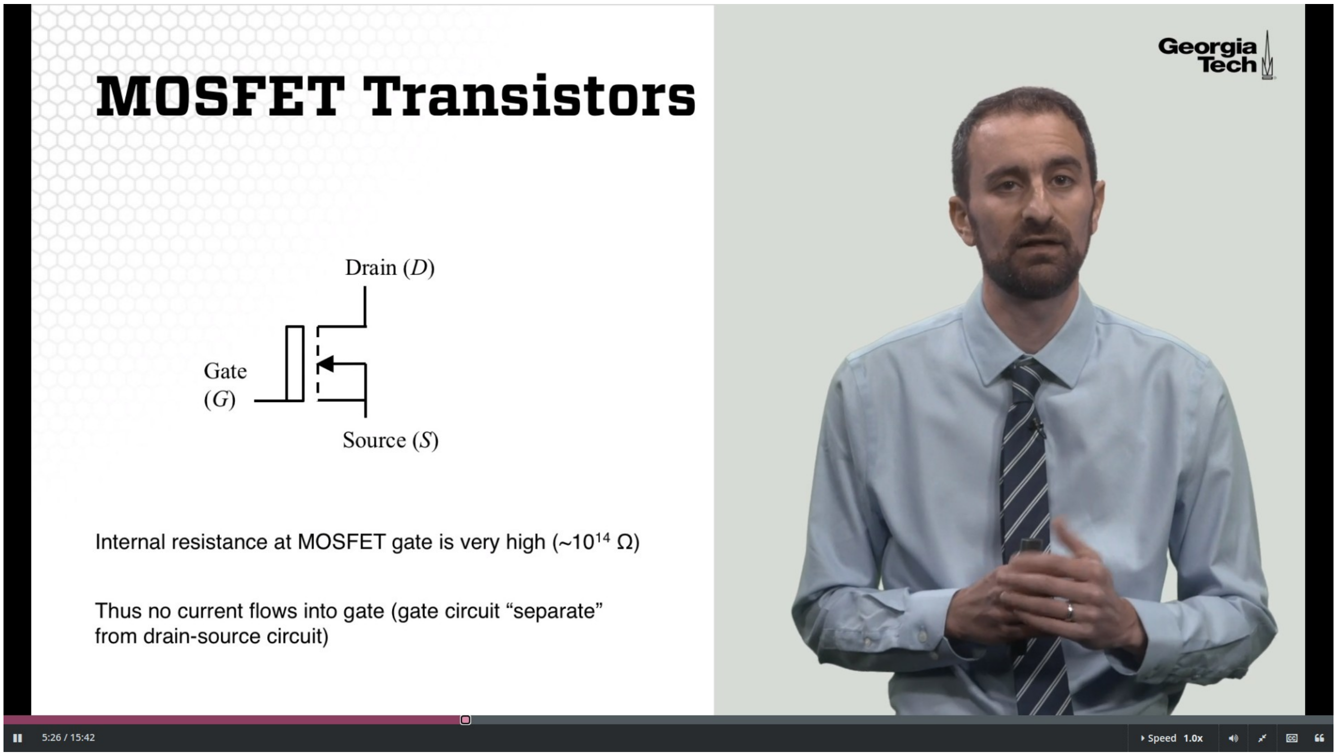
Lesson 3 – Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs)

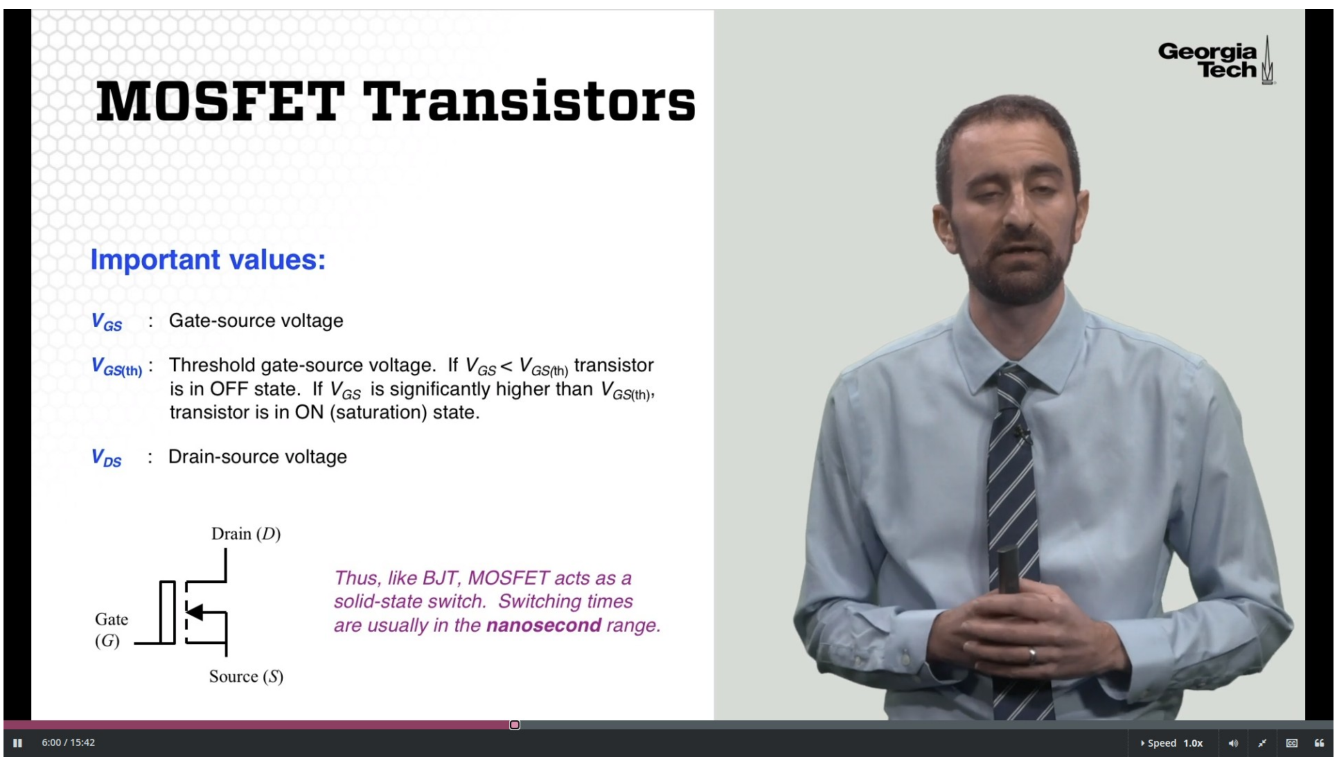





Georgia Tech
MOSFET Transistors
➢ Metal-Oxide Semiconductor Field Effect Transistors (MOSFETS) are common type of transistor used for switching
➢ Unlike BJTs, MOSFETs use voltage as the switching signal, rather than current
➢ MOSFET is therefore voltage-controlled device where voltage supplied at gate G determines current flow from (or resistance between) D to S
n-type MOSFET
Drain (D)
Gate (G)
Source (S)
3:11 / 15:42
Speed 1.0x


Georgia Tech
MOSFET Transistors
➢ Key states of operation: Off, and Saturation (On)
➢ State of MOSFET depends on voltage applied to gate G
➢ Off State: Drain-source resistance is very high → no current flows from D to S
➢ Saturation (On) State: Drain-source resistance is very low (< 1 Ω) and current flows from D to S
n-type MOSFET
Drain (D)
Gate (G)
Source (S)
4:23 / 15:42
Speed 1.0x

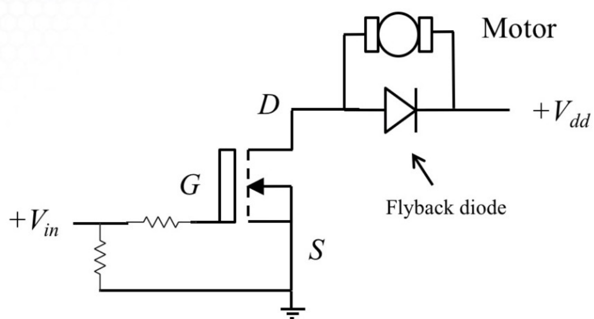

MOSFET Transistors
Georgia Tech
Drain (D)
Gate (G)
Source (S)
Internal resistance at MOSFET gate is very high (~10^{14} Ω)
Thus no current flows into gate (gate circuit "separate" from drain-source circuit)
5:26 / 15:42
Speed 1.0x


MOSFET Transistors
Georgia Tech
Important values:
V_{GS} : Gate-source voltage
$V_{GS(th)}$: Threshold gate-source voltage. If $V_{GS} < V_{GS(th)}$ transistor is in OFF state. If V_{GS} is significantly higher than $V_{GS(th)}$, transistor is in ON (saturation) state.
V_{DS} : Drain-source voltage
Drain (D)
Gate (G)
Source (S)
Thus, like BJT, MOSFET acts as a solid-state switch. Switching times are usually in the **nanosecond** range.
6:00 / 15:42
Speed 1.0x

MOSFET Switching Circuits

Georgia Tech

- MOSFETs are commonly used to **switch high-power loads** (motors, LEDs, etc) **from logic-level devices** such as microcontrollers
- They act to separate high-power and low-power portions of circuit
- Typical **motor driver** circuit using a MOSFET



- When V_{in} is below threshold voltage, transistor is OFF and no current flows through motor
- When V_{in} is well above threshold voltage, transistor is ON and current flows through motor
- Flyback diode protects MOSFET from large voltage buildup when transistor is switched from on to off
- Resistor used to ground gate terminal when $V_{in} = 0$ to turn transistor completely off

8:46 / 15:42 Speed 1.0x

Example MOSFETs

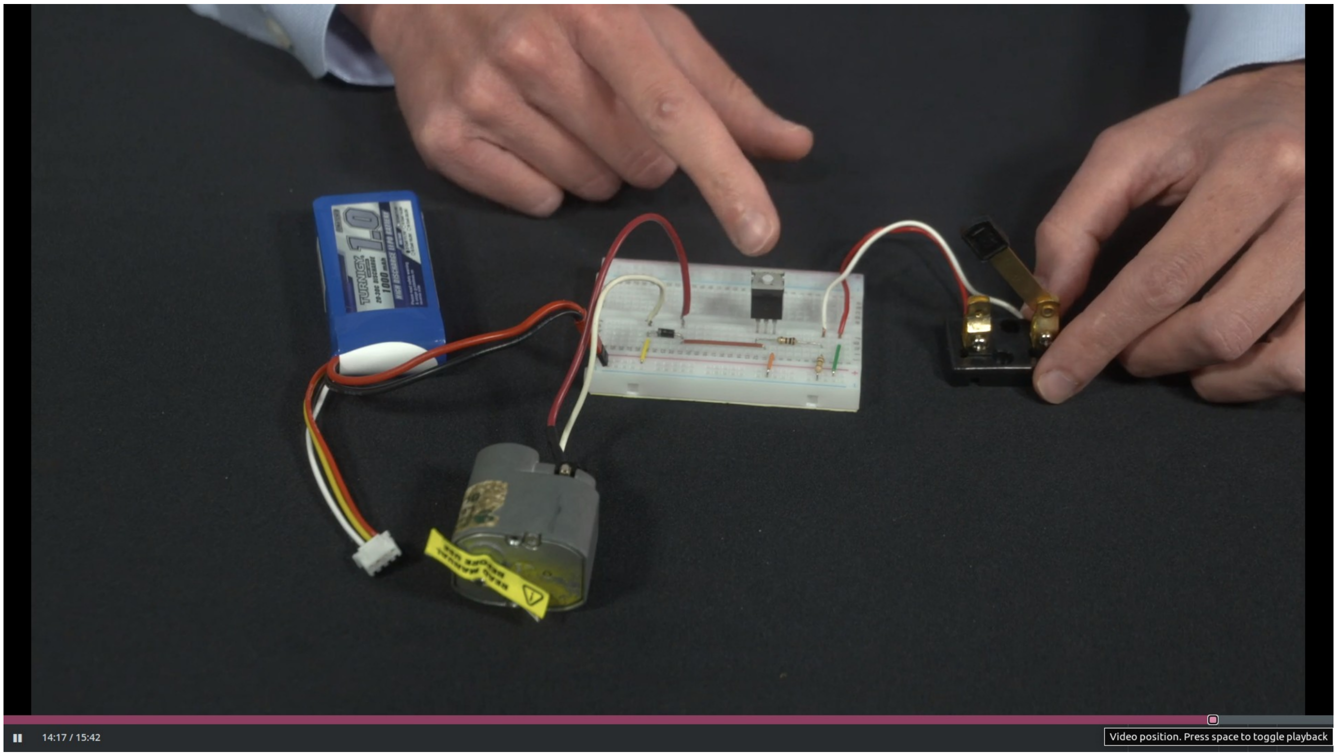
Georgia Tech

Part No.	On Resistance $R_{DS\,(on)}$	Max Drain Current I_D (max)	Power Dissipation P_D	Gate Threshold Voltage $V_{GS(th)}$
2N7002	1.7 Ω	115 mA	200 mW	2.1 V
4N60	2.5 Ω	4 A	38 W	4 V
IRL540	0.077 Ω	28 A	150 W	2 V

$R_{DS\,(on)}$: Resistance between drain and source terminals when MOSFET is fully on.

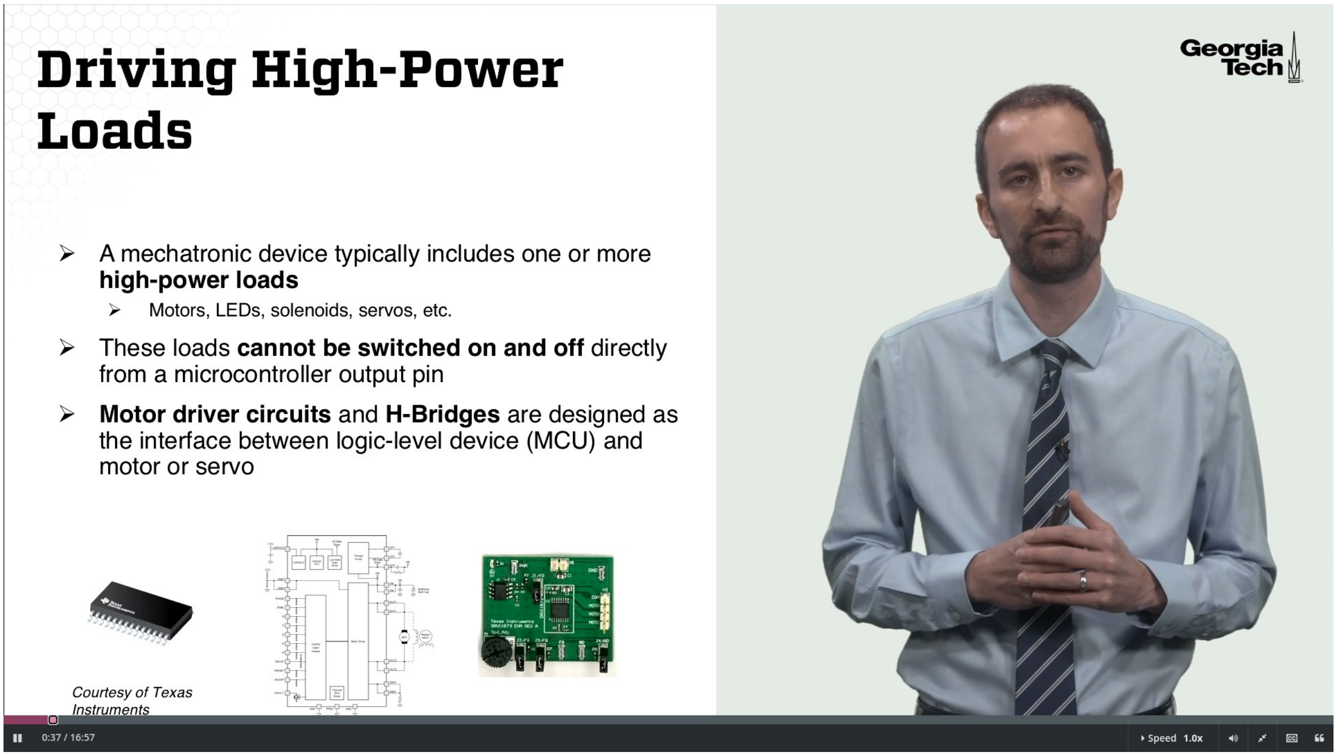
$I_{D\,(max)}$: Max current that can be passed between drain and source.

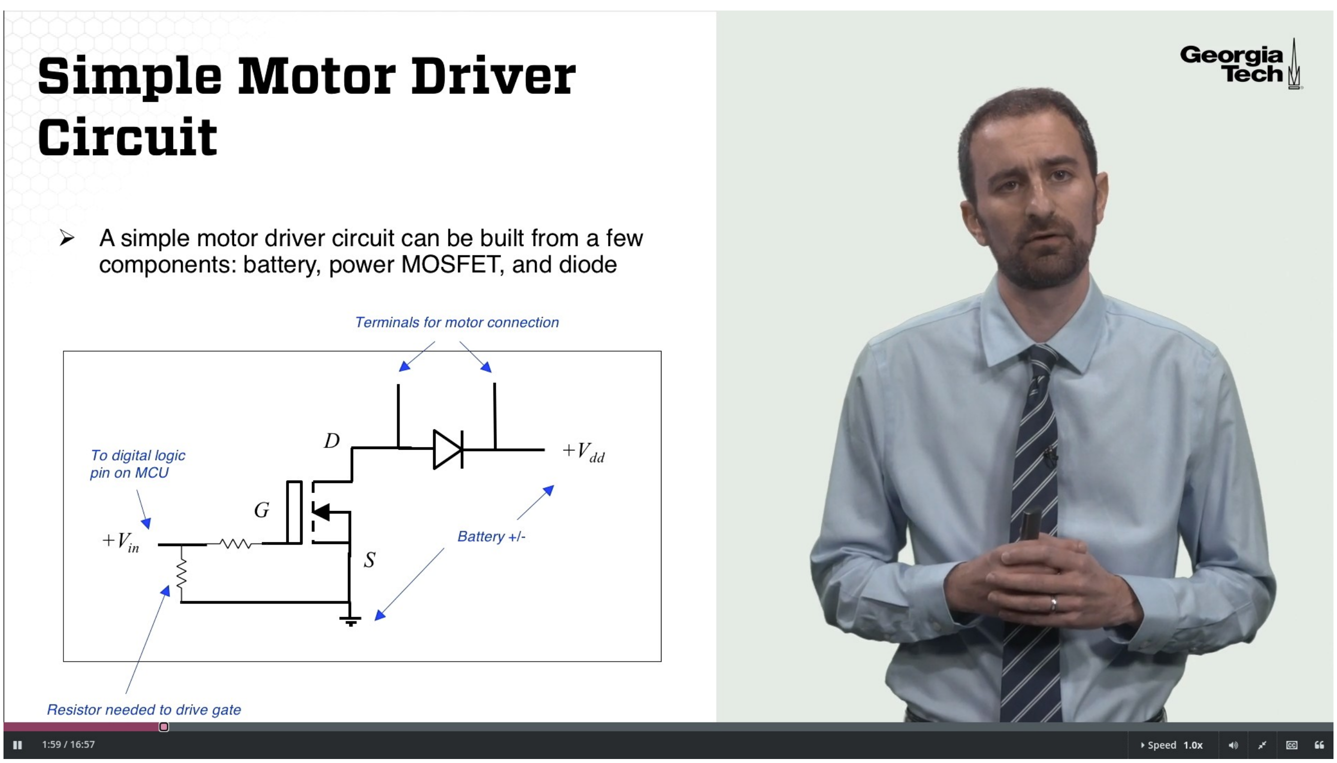
10:41 / 15:42 Speed 1.0x

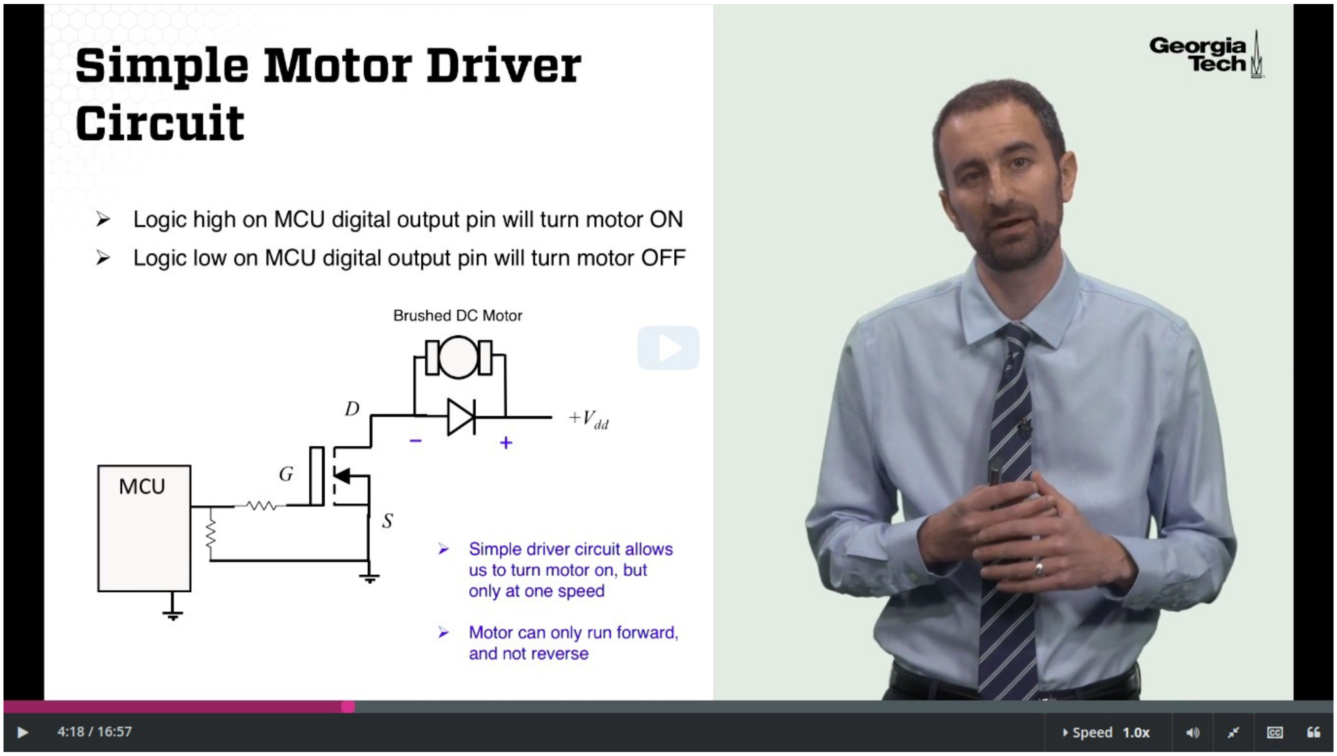

14:17 / 15:42
Video position. Press space to toggle playback

Example Circuits For Mechatronic Devices

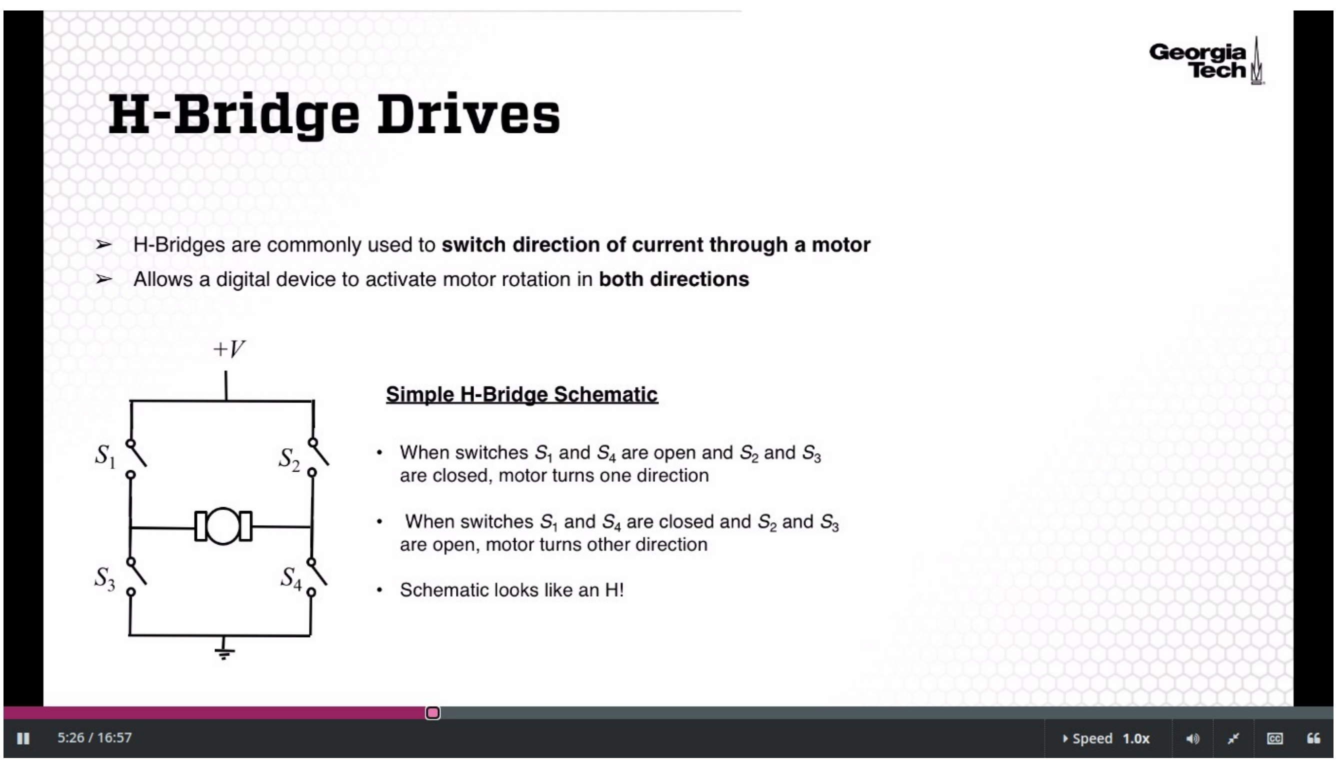
Lesson 1 – H-Bridges And Motor Driver Circuits







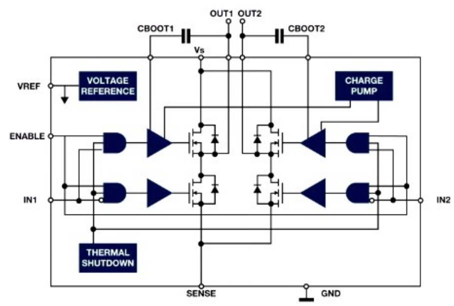
Simple Motor Driver Circuit
Logic high on MCU digital output pin will turn motor ON
Logic low on MCU digital output pin will turn motor OFF
Brushed DC Motor
D
G
S
MCU
+Vdd
Simple driver circuit allows us to turn motor on, but only at one speed
Motor can only run forward, and not reverse
Georgia Tech
4:18 / 16:57
Speed 1.0x



H-Bridge Drives
H-Bridges are commonly used to switch direction of current through a motor
Allows a digital device to activate motor rotation in both directions
+V
S1
S2
S3
S4
Simple H-Bridge Schematic
When switches S1 and S4 are open and S2 and S3 are closed, motor turns one direction
When switches S1 and S4 are closed and S2 and S3 are open, motor turns other direction
Schematic looks like an H!
Georgia Tech
5:26 / 16:57
Speed 1.0x

H-Bridge Drives

- Real H-Bridges are built from transistors, diodes, and logic gates. Transistors act as switching elements.
- They have very fast switching times (~ nanosecond range)
- Many have **built-in flyback diodes**

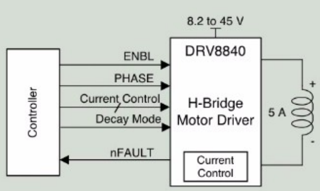


Typical H-Bridge circuit schematic

TI DRV8840 Motor Driver IC (H-Bridge)

- Integrated circuit consisting of H-Bridge and supporting components
- Made to drive brushed DC motors and stepper motors
- Cost: ~$2.95

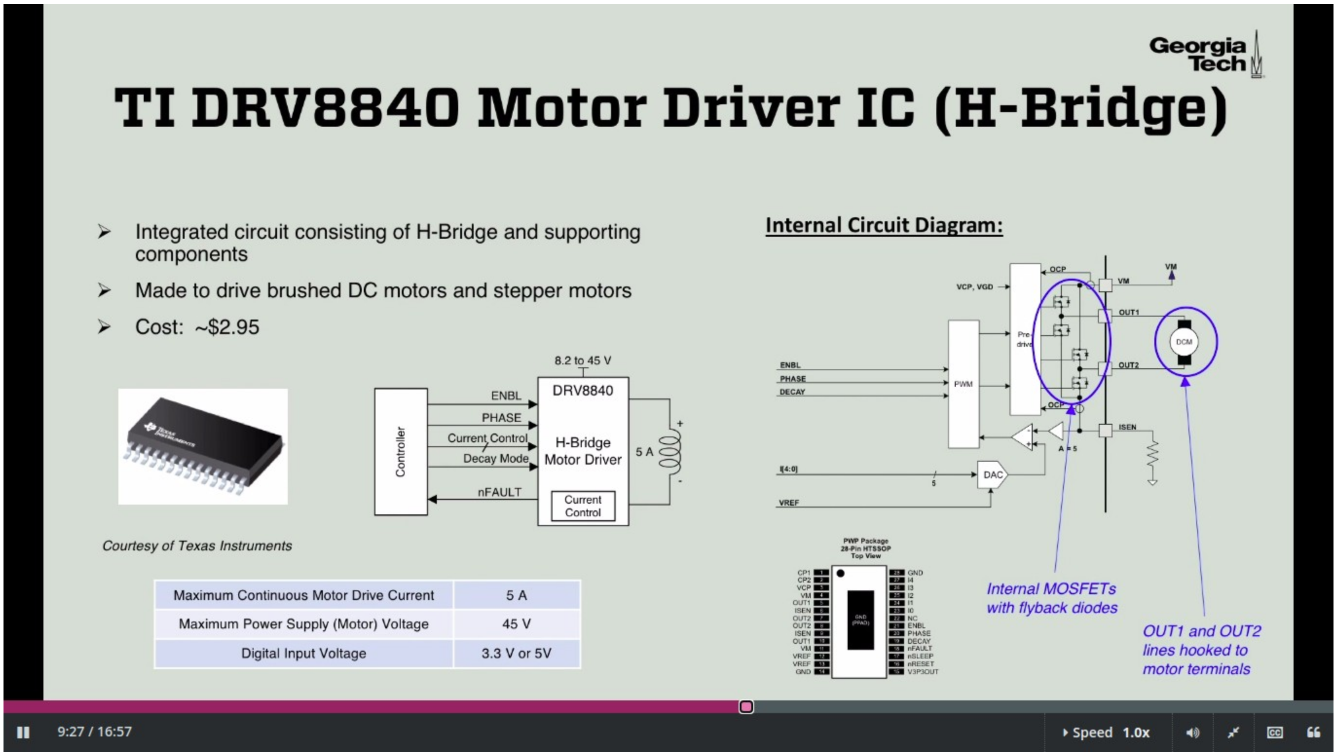
Courtesy of Texas Instruments



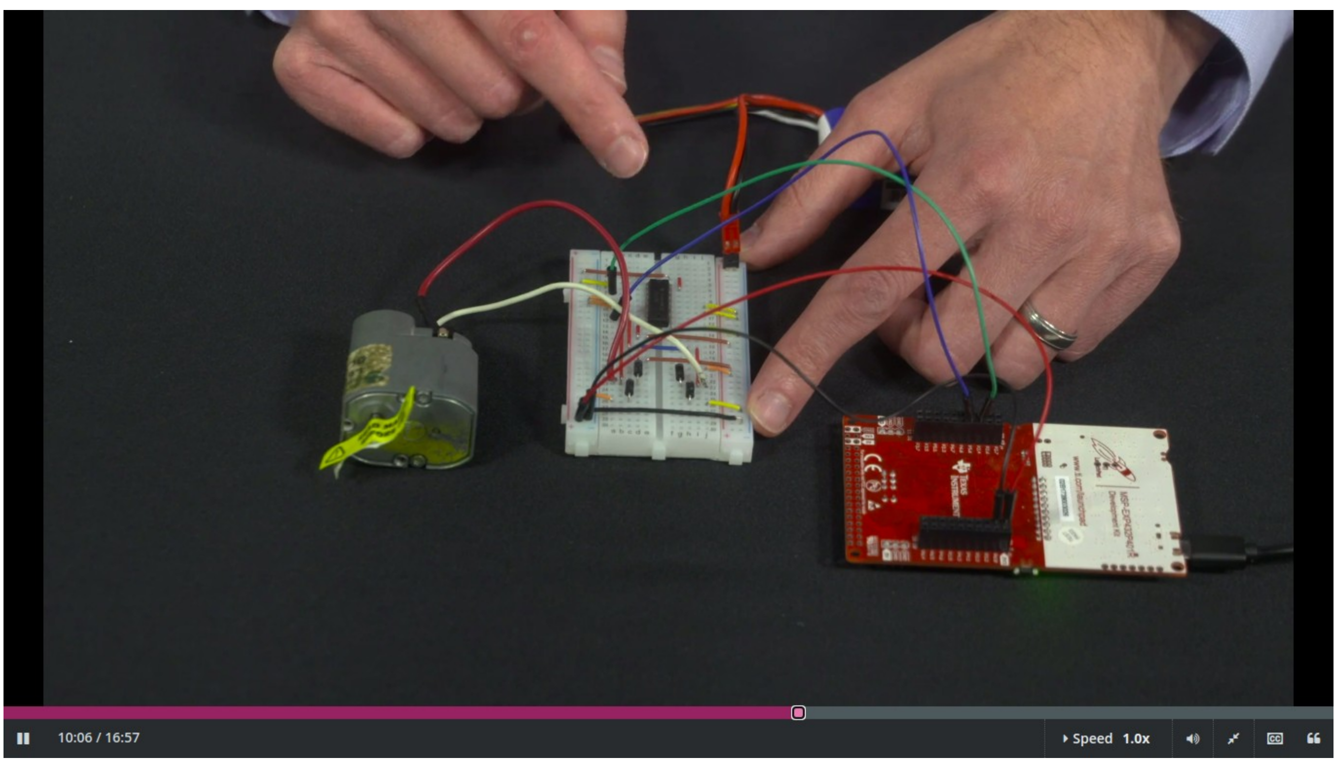
Maximum Continuous Motor Drive Current	5 A
Maximum Power Supply (Motor) Voltage	45 V
Digital Input Voltage	3.3 V or 5V

Simple Brushed DC Motor Setup:

- Enable (ENBL) line connected to MCU digital input/output pin - used to **switch motor on and off**
- Phase (PHASE) line connected to MCU digital input/output pin - used to **set direction of rotation**
- Other lines not needed - used for more advanced functionality



Georgia Tech
TI DRV8840 Motor Driver IC (H-Bridge)
Integrated circuit consisting of H-Bridge and supporting components
Made to drive brushed DC motors and stepper motors
Cost: ~$2.95
Courtesy of Texas Instruments
8.2 to 45 V
Controller
ENBL
PHASE
Current Control
Decay Mode
nFAULT
DRV8840
H-Bridge Motor Driver
Current Control
5 A
Maximum Continuous Motor Drive Current | 5 A
Maximum Power Supply (Motor) Voltage | 45 V
Digital Input Voltage | 3.3 V or 5V
Internal Circuit Diagram:
Internal MOSFETs with flyback diodes
OUT1 and OUT2 lines hooked to motor terminals
9:27 / 16:57
Speed 1.0x

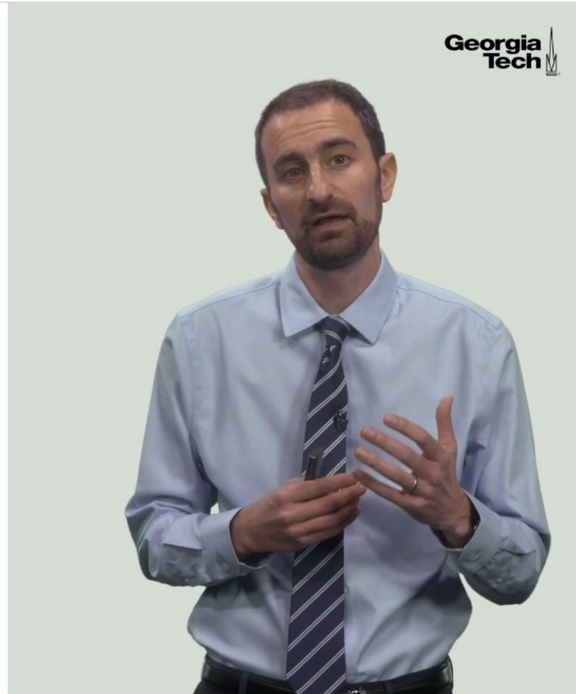


10:06 / 16:57
Speed 1.0x

Example H-Bridges

- Note: When driving a load, the load current **passes through H-Bridge** and transistors heat up
- H-Bridge should have **power dissipation rating** sufficient for particular load it is driving – use spec sheet values to calculate power dissipation for your application

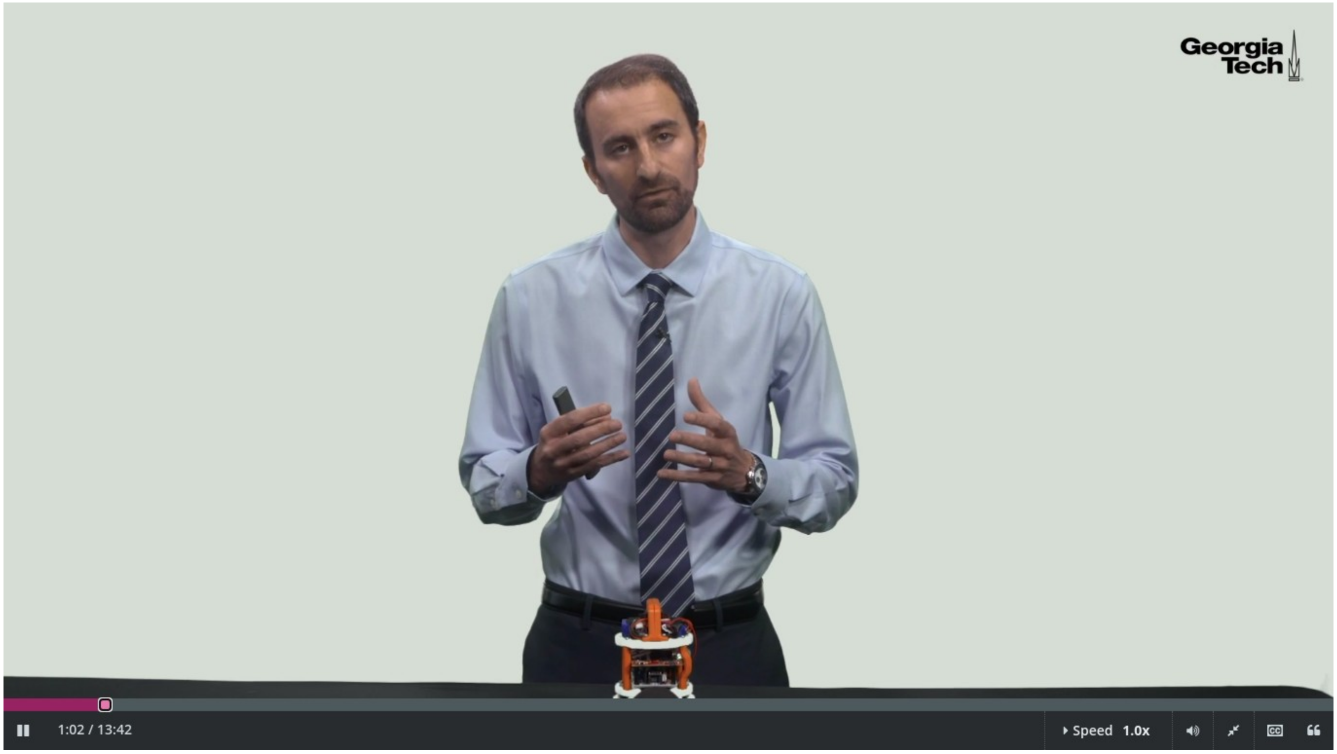
Part No.	Maximum Drive Current	Operating Supply Voltage
34931	5 A	5-36 V
SN754410	1 A	0-36 V
L298	4 A	0-46 V

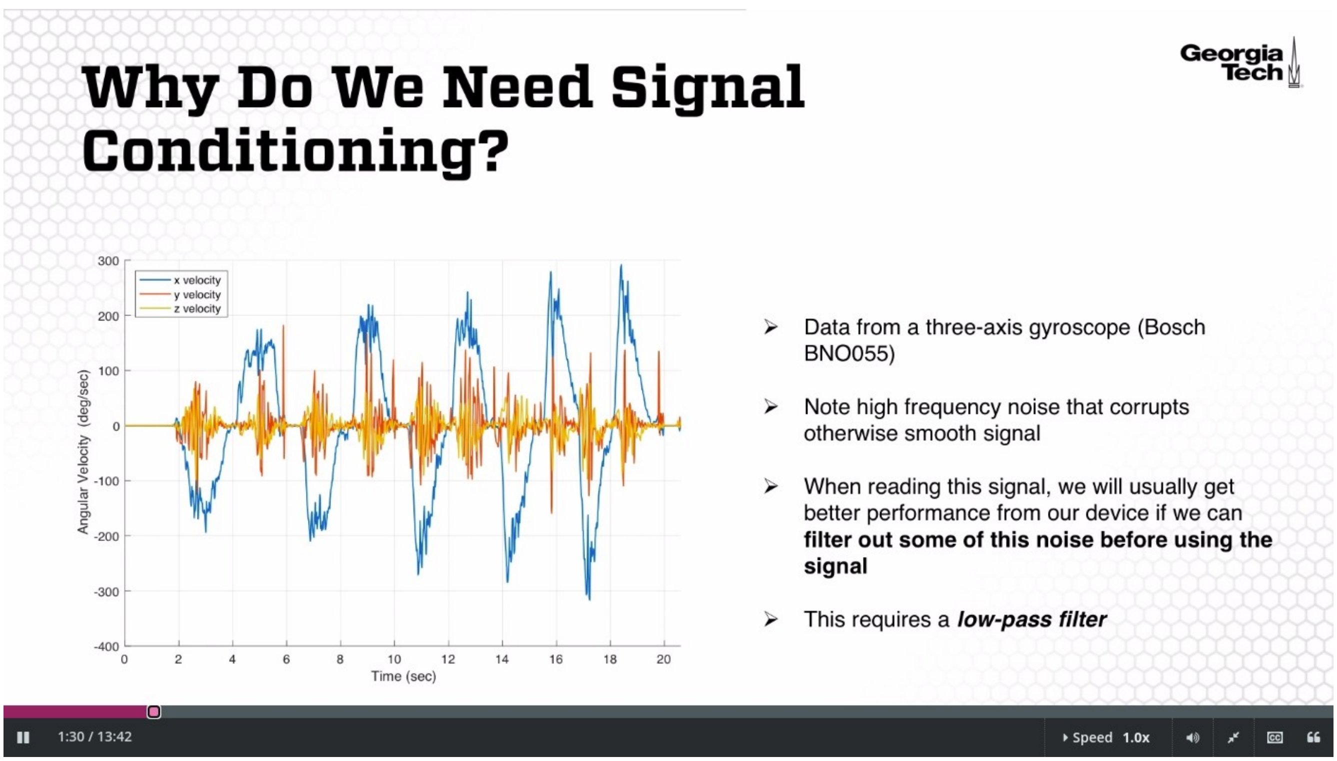


14:41 / 16:57

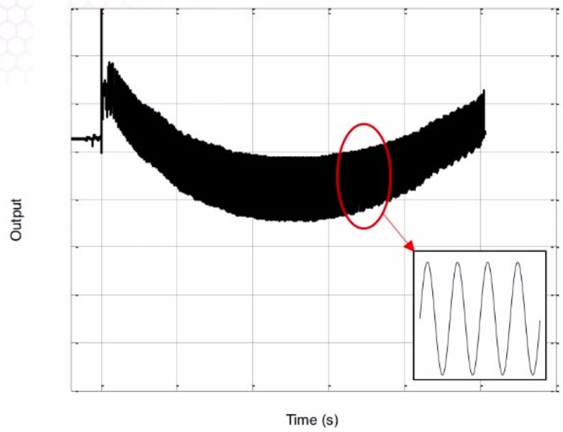
Speed 1.0x

Lesson 2 – Signal Conditioning Circuits





Why Do We Need Signal Conditioning?

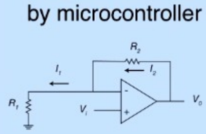


- Data from a thermopile sensor looking at sky and ground repeatedly at high frequency
- Ambient temperature changes over longer time-scales, add a **moving bias** to signal
- Signal of interest is **high-frequency**, want to remove moving bias *before reading* by microcontroller
- This requires a ***high-pass filter***

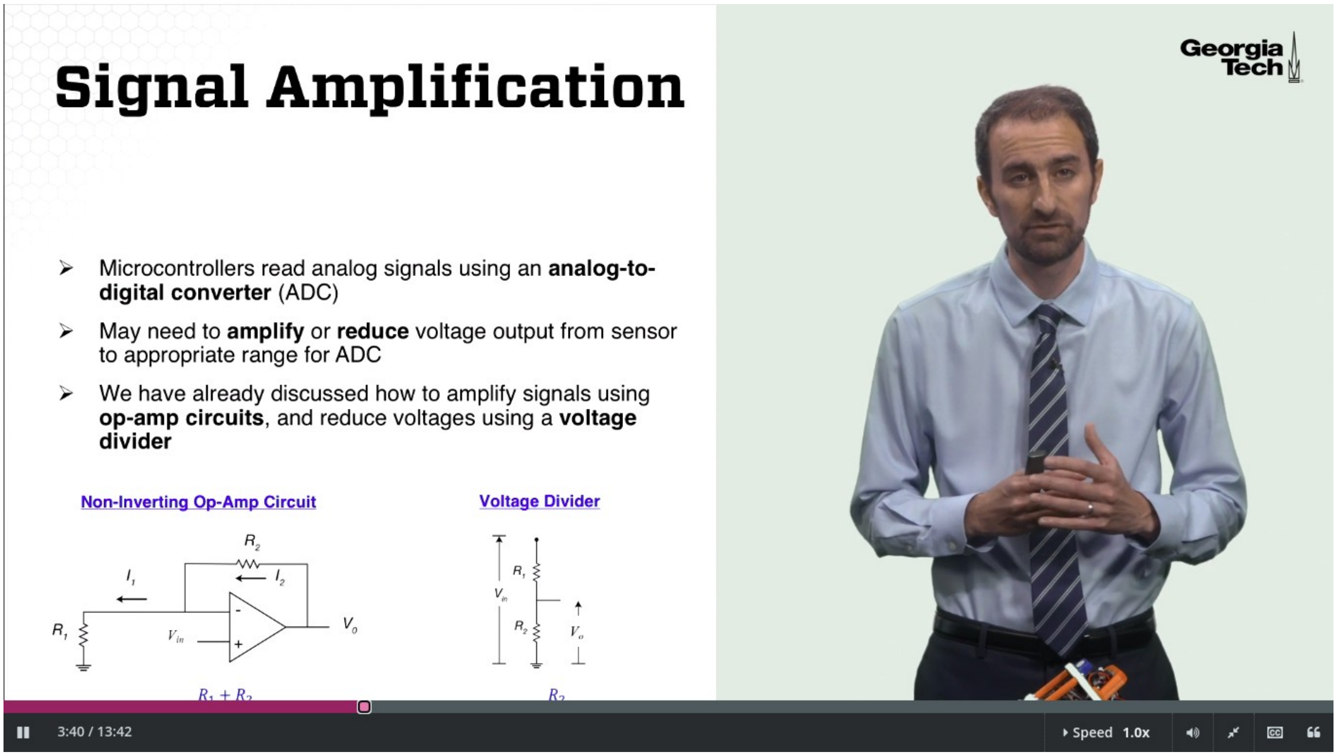
Signal Conditioning

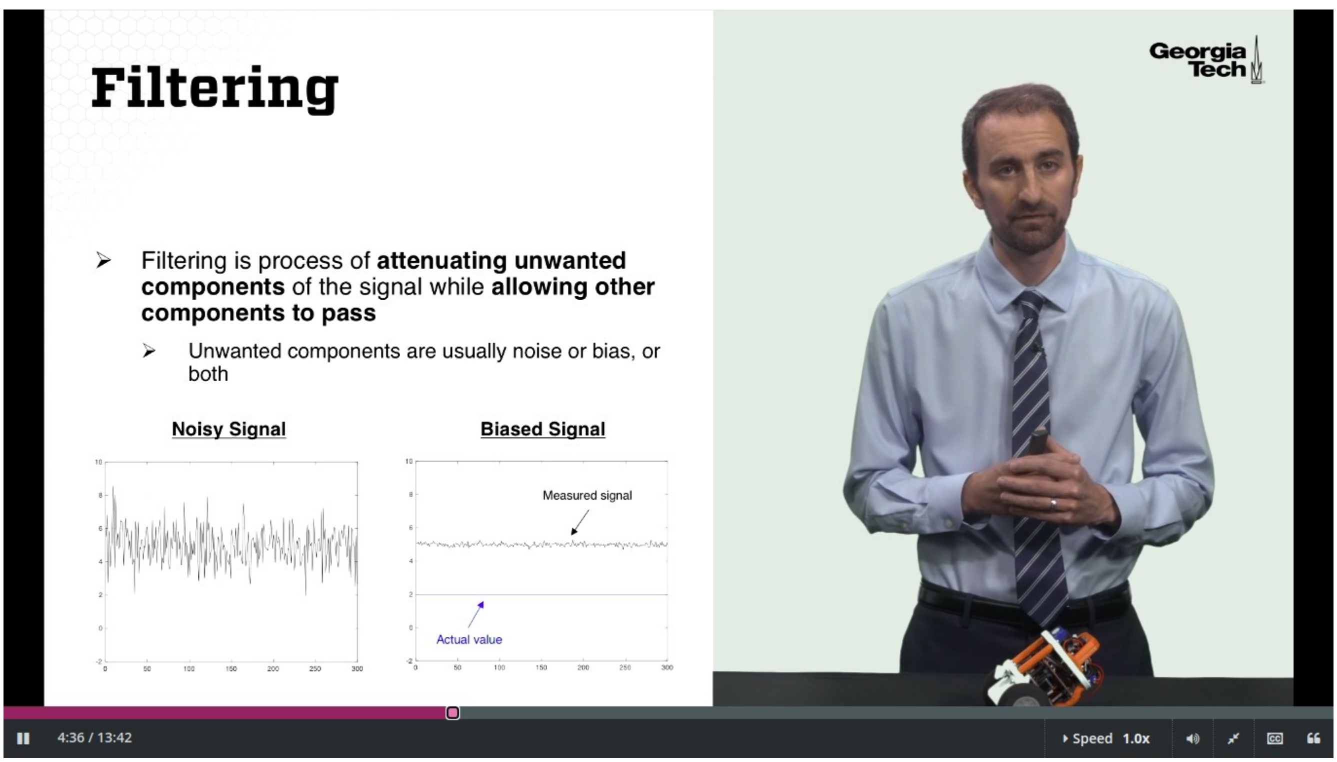
- Signal conditioning is often a necessary aspect of sensor integration
- **Two components** of signal conditioning:

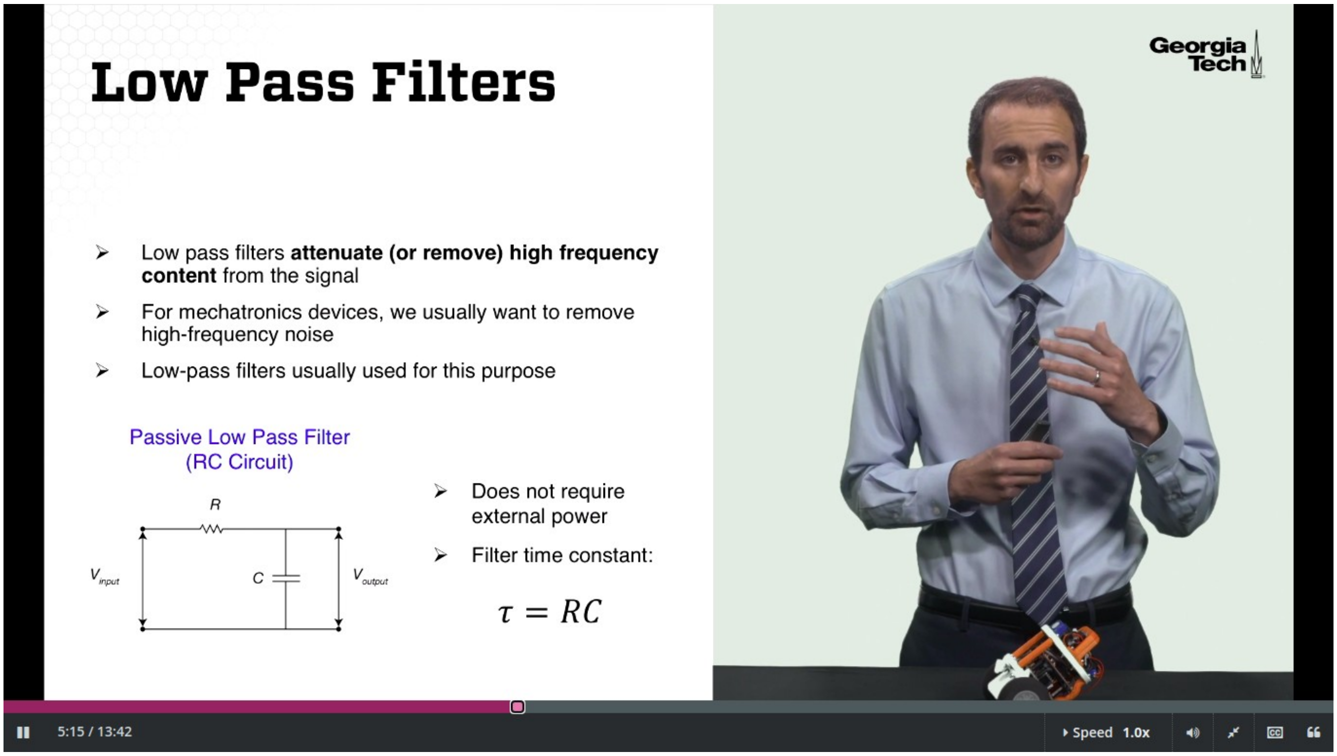
Amplifying sensor outputs to appropriate range for reading by microcontroller

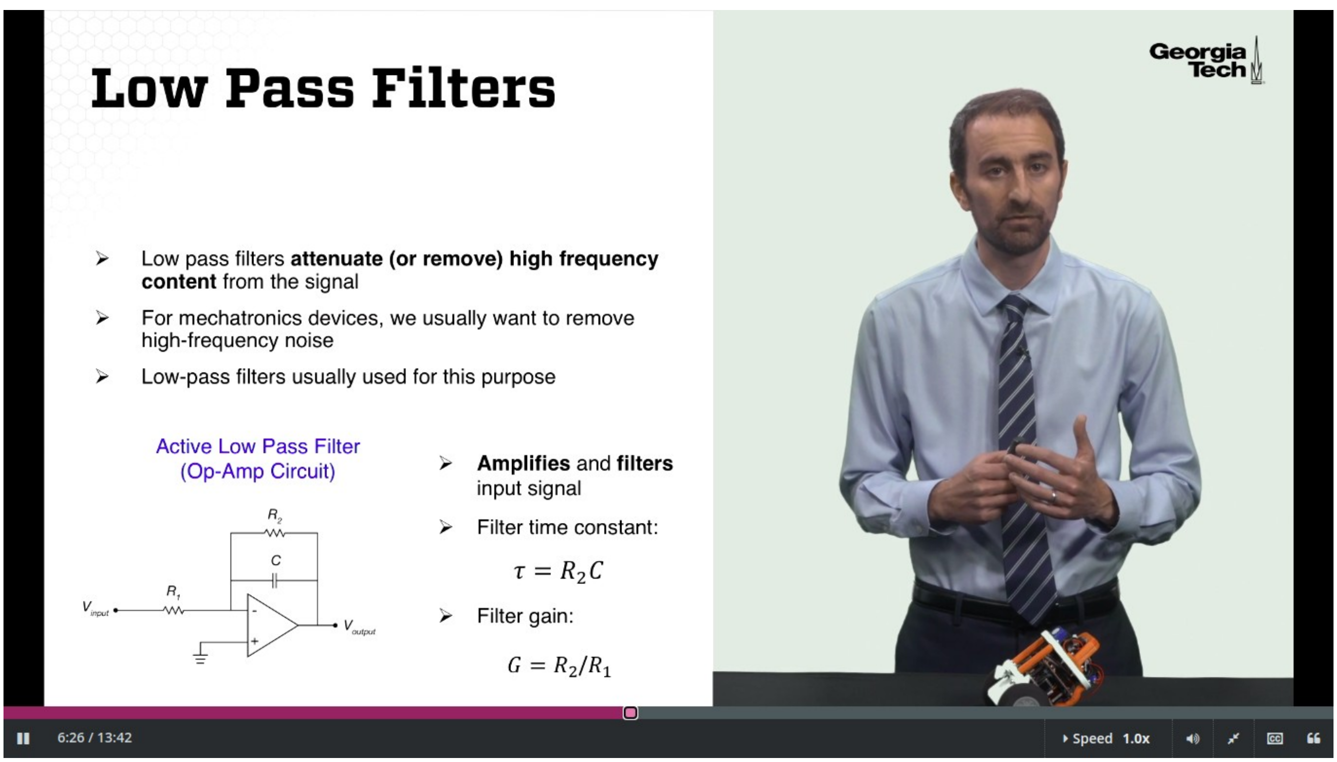


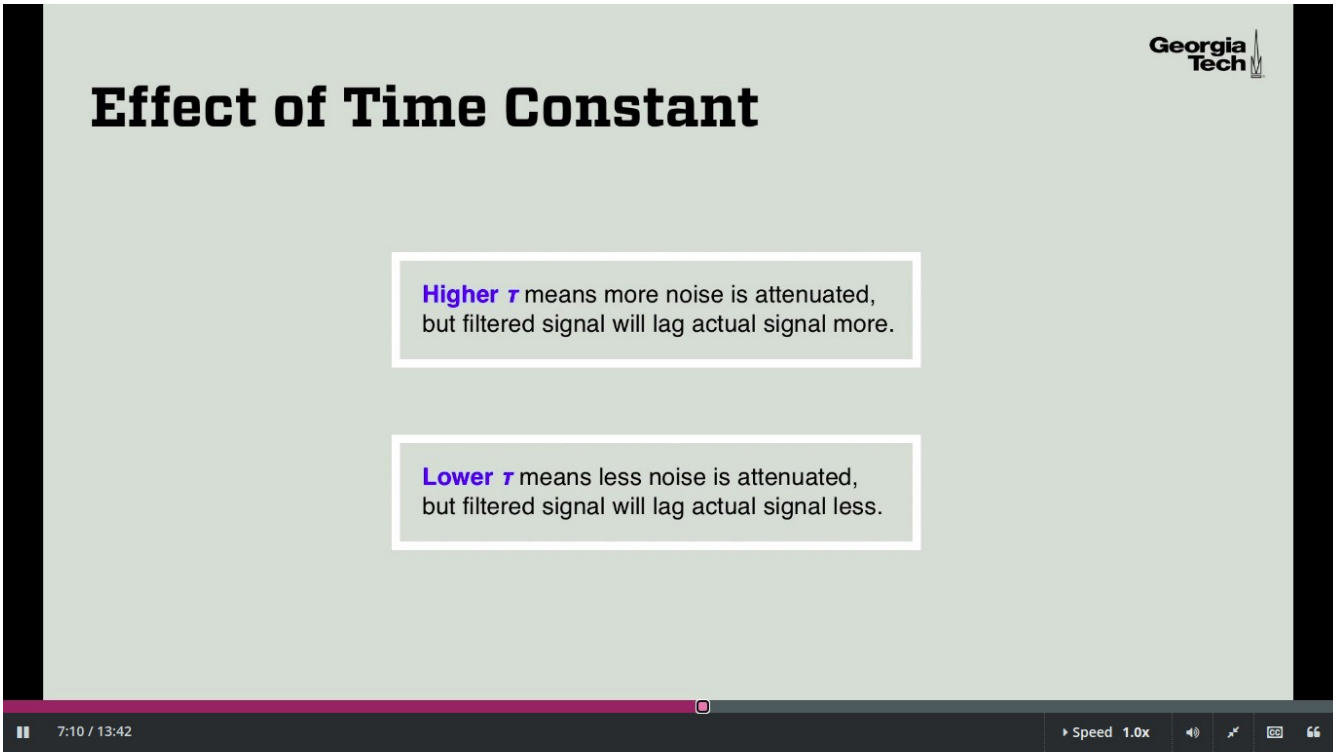
Reducing noise and bias in an output signal

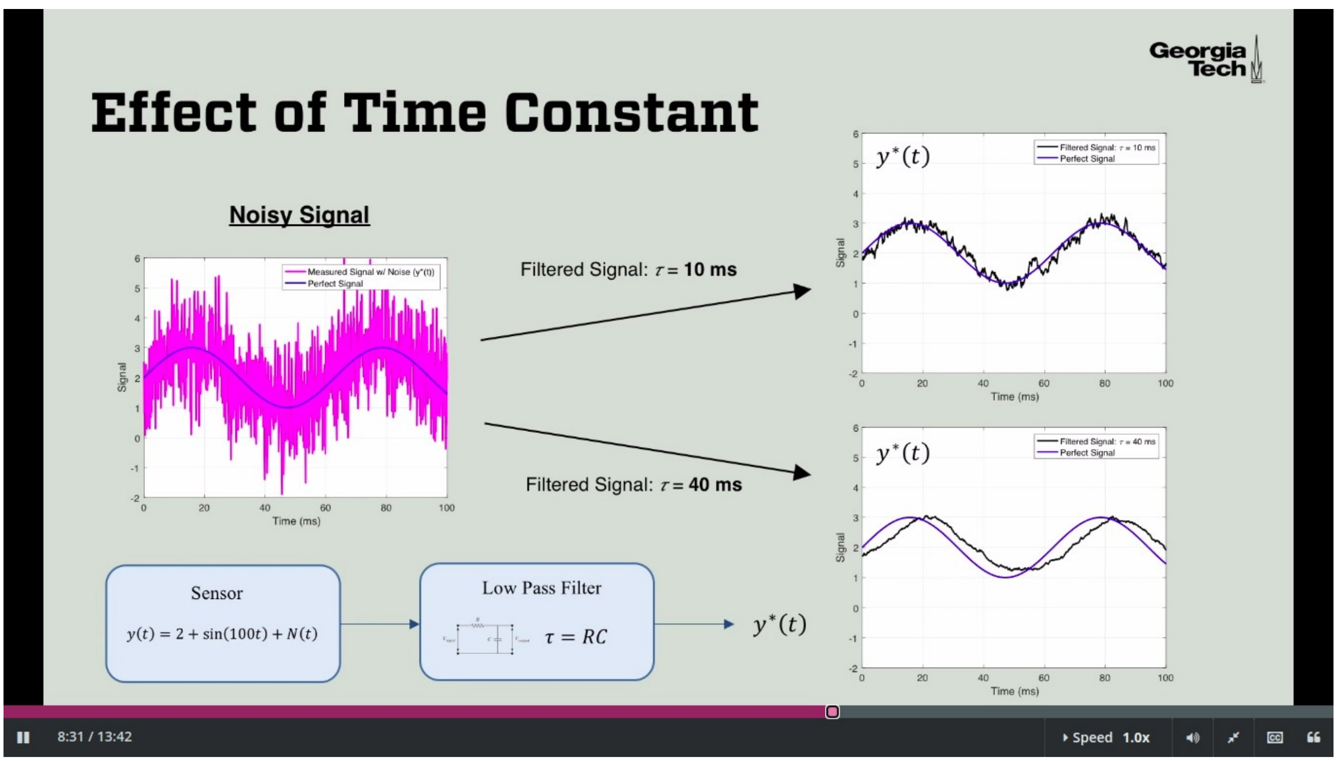

Georgia Tech
Signal Amplification
Microcontrollers read analog signals using an **analog-to-digital converter** (ADC)
May need to **amplify** or **reduce** voltage output from sensor to appropriate range for ADC
We have already discussed how to amplify signals using **op-amp circuits**, and reduce voltages using a **voltage divider**
Non-Inverting Op-Amp Circuit
R_2
I_1
I_2
R_1
V_{in}
V_o
Voltage Divider
R_1
V_{in}
R_2
V_o
3:40 / 13:42
Speed 1.0x


Georgia Tech
Filtering
Filtering is process of **attenuating unwanted components** of the signal while **allowing other components to pass**
Unwanted components are usually noise or bias, or both
Noisy Signal
Biased Signal
Measured signal
Actual value
4:36 / 13:42
Speed 1.0x


Low Pass Filters
Georgia Tech
Low pass filters attenuate (or remove) high frequency content from the signal
For mechatronics devices, we usually want to remove high-frequency noise
Low-pass filters usually used for this purpose
Passive Low Pass Filter (RC Circuit)
R
C
V_{input}
V_{output}
Does not require external power
Filter time constant:
$\tau = RC$
5:15 / 13:42
Speed 1.0x


Low Pass Filters
Georgia Tech
Low pass filters attenuate (or remove) high frequency content from the signal
For mechatronics devices, we usually want to remove high-frequency noise
Low-pass filters usually used for this purpose
Active Low Pass Filter (Op-Amp Circuit)
R_2
C
R_1
V_{input}
V_{output}
Amplifies and filters input signal
Filter time constant:
$\tau = R_2 C$
Filter gain:
$G = R_2/R_1$
6:26 / 13:42
Speed 1.0x


Georgia Tech
Effect of Time Constant
Higher τ means more noise is attenuated, but filtered signal will lag actual signal more.
Lower τ means less noise is attenuated, but filtered signal will lag actual signal less.
7:10 / 13:42
Speed 1.0x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Effect of Time Constant
Noisy Signal
Measured Signal w/ Noise (y*(t))
Perfect Signal
Signal
Time (ms)
Filtered Signal: τ = 10 ms
Filtered Signal: τ = 40 ms
y*(t)
Filtered Signal: τ = 10 ms
Filtered Signal: τ = 40 ms
Sensor
y(t) = 2 + sin(100t) + N(t)
Low Pass Filter
τ = RC
8:31 / 13:42
Speed 1.0x

Digital Low Pass Filter

- Low pass filter can also be implemented in ***software*** rather than in circuitry
- Let's look at a first-order low pass filter implemented in software

Formula for first-order digital filter

$$y(k) = (1-\alpha)x(k) + \alpha y(k-1)$$

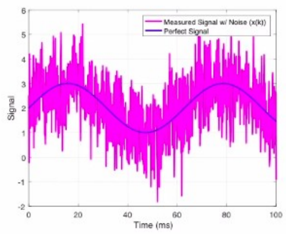
$y(k)$ = filtered signal at timestep k

$x(k)$ = signal at timestep k

$\alpha = e^{-2\pi T/\tau}$ (constant)

T = sampling interval

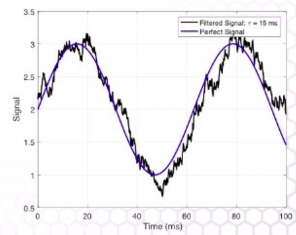
Raw Signal



T = 0.1 ms

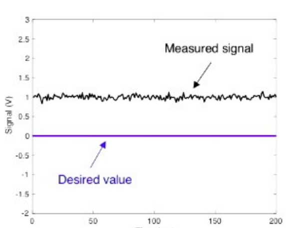
τ = 15 ms

Digitally Filtered Signal

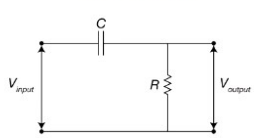


Removing Biases

- A **DC bias** is a fixed voltage offset that we would like to remove
- Example: A certain sensor produces a **1 V output** when reading an **input of zero**.
- What type of circuit will remove this bias, so that the output is 0 V when the input is zero?



High Pass Filter
(RC Circuit)



Removes bias from signal (V_{in}) to produce unbiased output (V_{out})