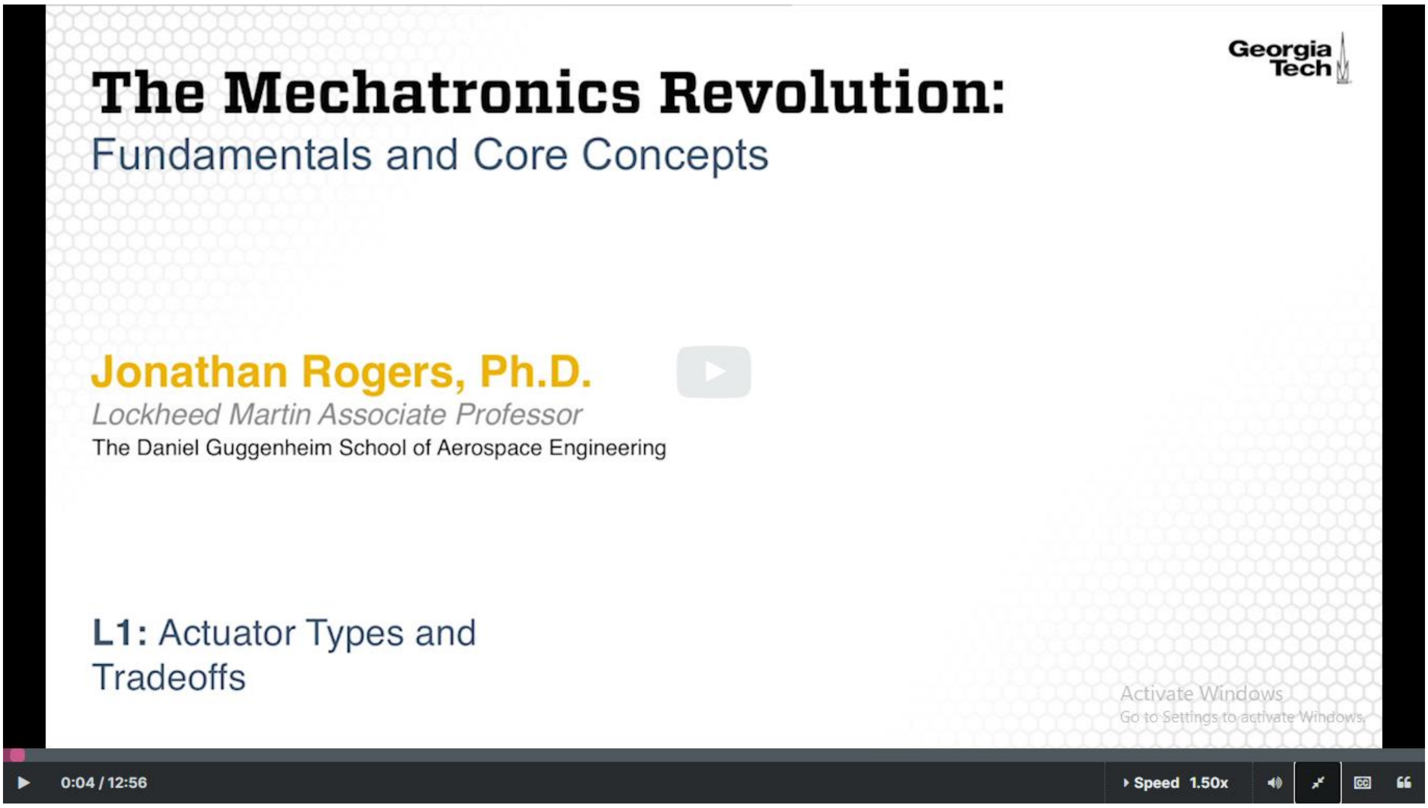
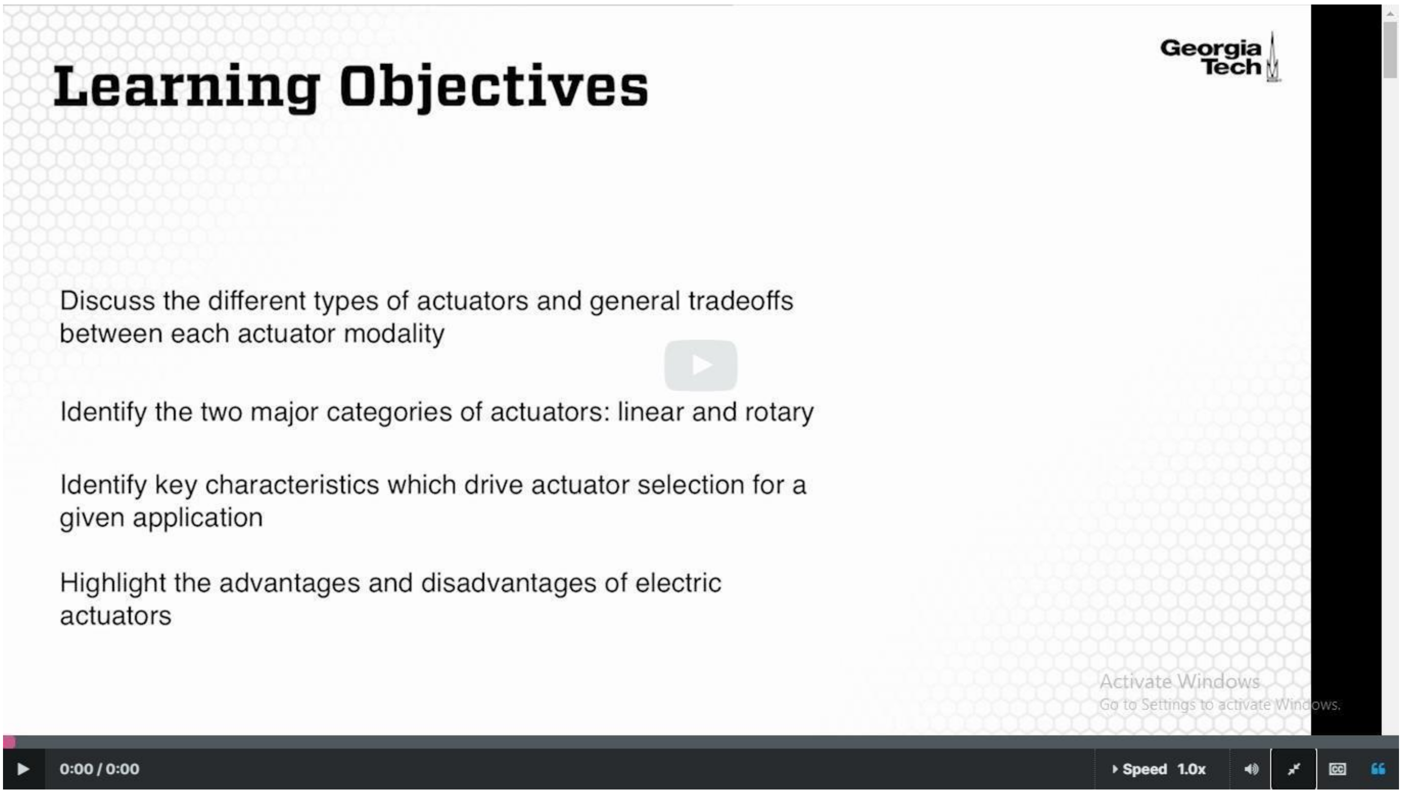
Module-4

Topic-1






Georgia Tech
Actuators: Key Elements of Mechatronic Devices
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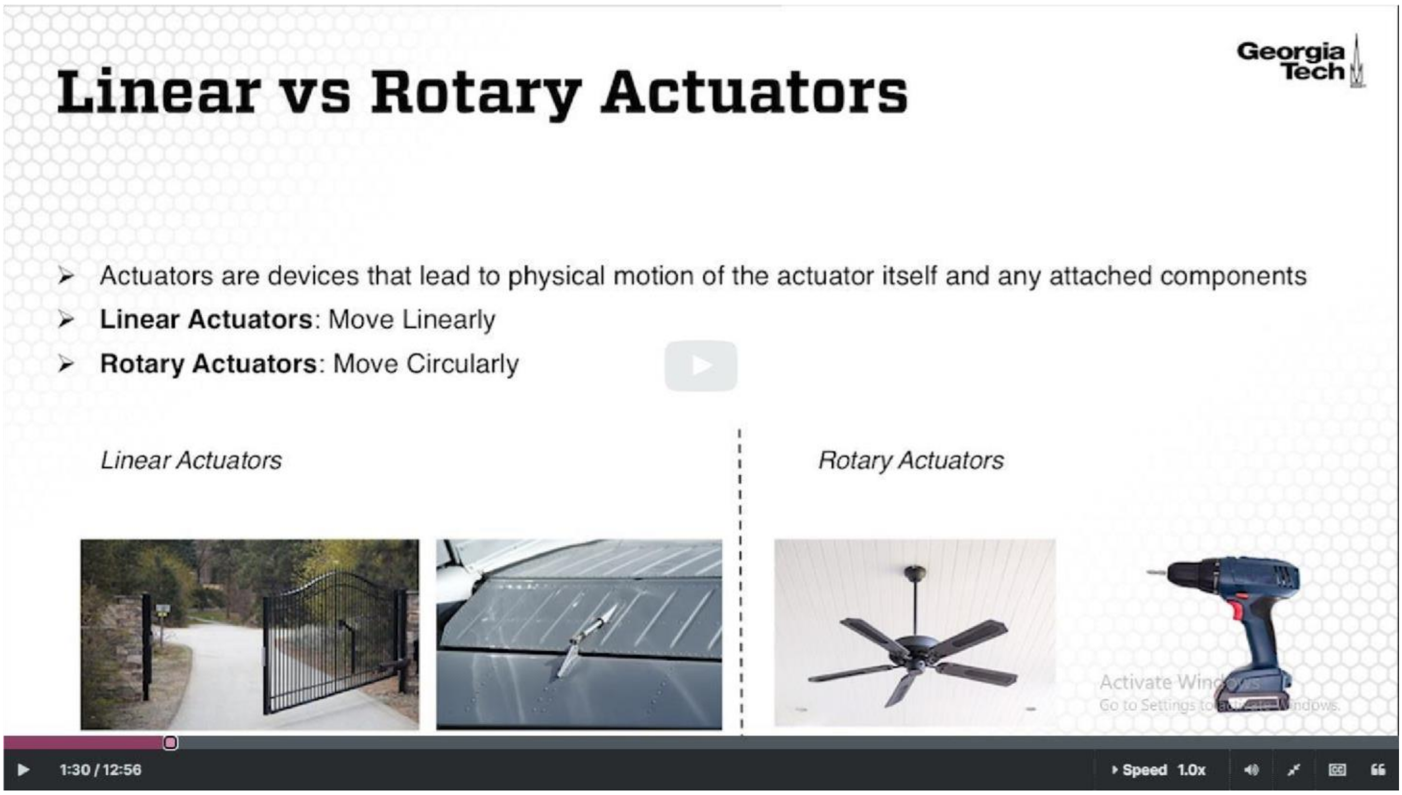
Speed 1.0x


Georgia Tech
Linear vs Rotary Actuators
➢ Actuators are devices that lead to physical motion of the actuator itself and any attached components
➢ Linear Actuators: Move Linearly
➢ Rotary Actuators: Move Circularly
Linear Actuators
Rotary Actuators
1:30 / 12:56
Speed 1.0x

Actuator Types

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- Actuators are required to move anything! Integral part of any mechatronic device.
- Actuator Types:
  - **Electric:** Electromagnetic effects
  - **Internal Combustion**: Burning fuel
  - **Pneumatic**: Pressurized air
  - **Hydraulic**: Pressurized fluid
  - **Piezoelectric**: Piezoelectric effect

2:15 / 12:56 Speed 1.0x

Actuator Key Characteristics

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- Maximum **extension** or linear/rotary **displacement**
- Maximum output **force** or **torque**
- Maximum **actuation speed** and/or **bandwidth**
- Actuator **size/volume**
- Actuator **efficiency**

3:20 / 12:56 Speed 1.0x

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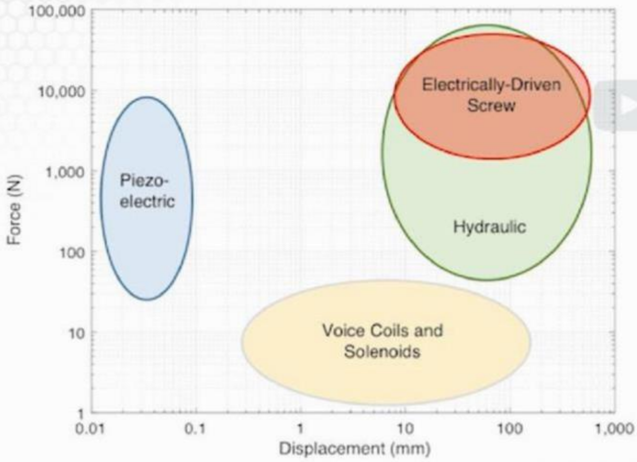
Linear Actuators: Force vs. Displacement



Graphs like these can assist in selection of an actuator type for a given application.

5:20 / 12:56 Speed 1.0x

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Electric Actuators

- Many smaller mechatronic devices use **electric motors** for actuation
- Advantages of electric actuators
  - Clean (do not require fluids, oil, etc.)
  - Require no extra equipment (no pressure tanks, etc.)
  - Can operate indoors (no emissions)
  - Can be made small economically
- Disadvantages of electric actuators
  - Low power-to-size ratio

7:50 / 12:56 Speed 1.0x

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Electric Actuators

Qualitative Comparison of Electric Motors

	Brushed DC Motor	Brushless DC Motor	Servo	Stepper Motor
Maximum Displacement	Unlimited	Unlimited	Limited	Unlimited
Maximum Torque	Medium*	High	High	High
Maximum Speed	Medium	High	Low	Low
Drive Complexity	Low	High	Medium	Low
Example Application	Car starter	Hand-held drill	Robot arm	Printer

** Torque of brushed motor is high at zero speed, then decreases rapidly at higher speeds. For brushless motors the torque profile is less sensitive to speed.*

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Linear Actuators

Qualitative Comparison of Electric vs Hydraulic Linear Actuators

	Electric Actuator	Hydraulic Actuator
Maximum Force	Low	High
Positioning Accuracy	High	Low
Complexity of Installation	Low	High
Cost	High (initial), Low maintenance	Low (initial), High maintenance
Example Application	CNC milling machine	Excavator

Summary

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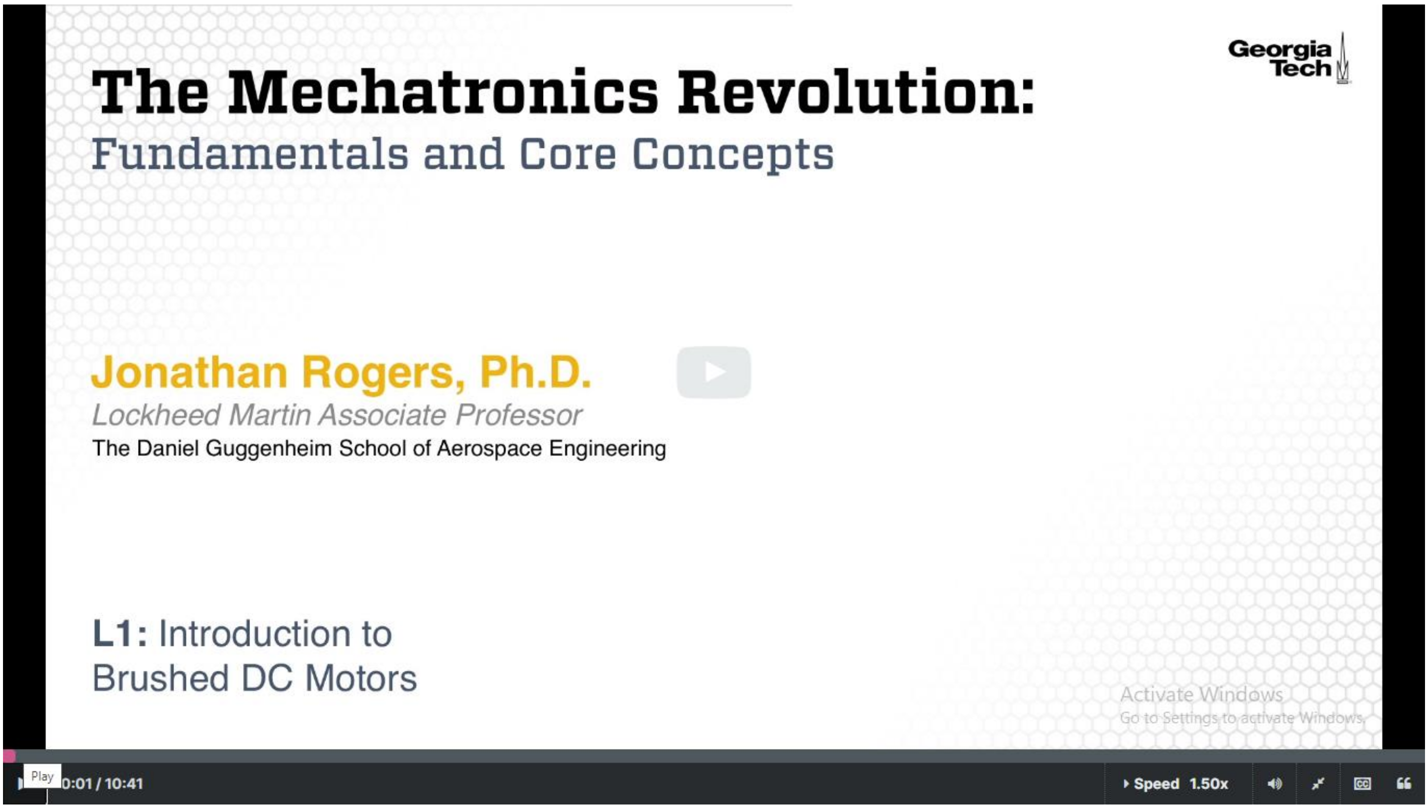
Actuation mechanisms generally fall into two categories: **linear** and **rotary**.

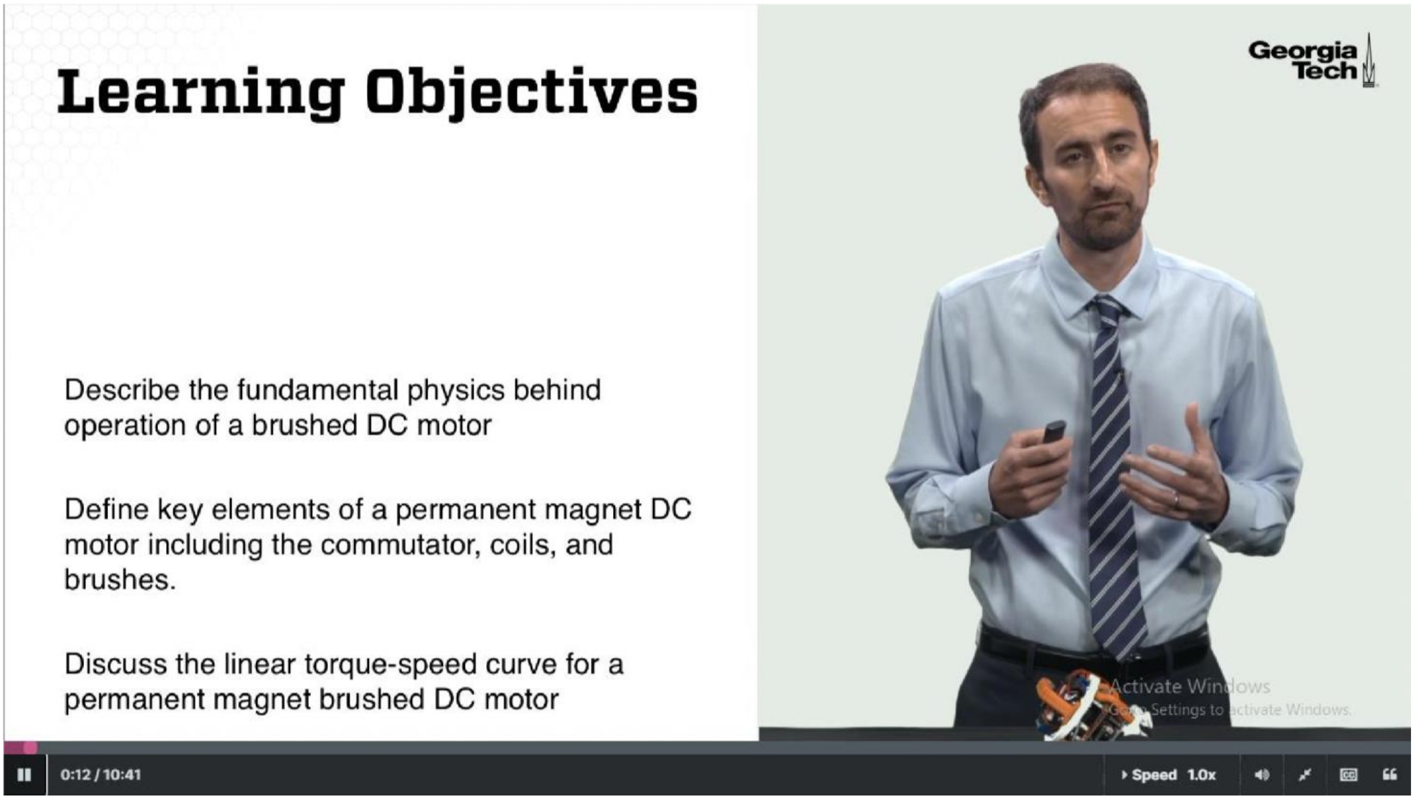
Actuators can be further categorized by their actuation type including: **electromagnetic**, **piezoelectric**, **hydraulic**, and **pneumatic**.

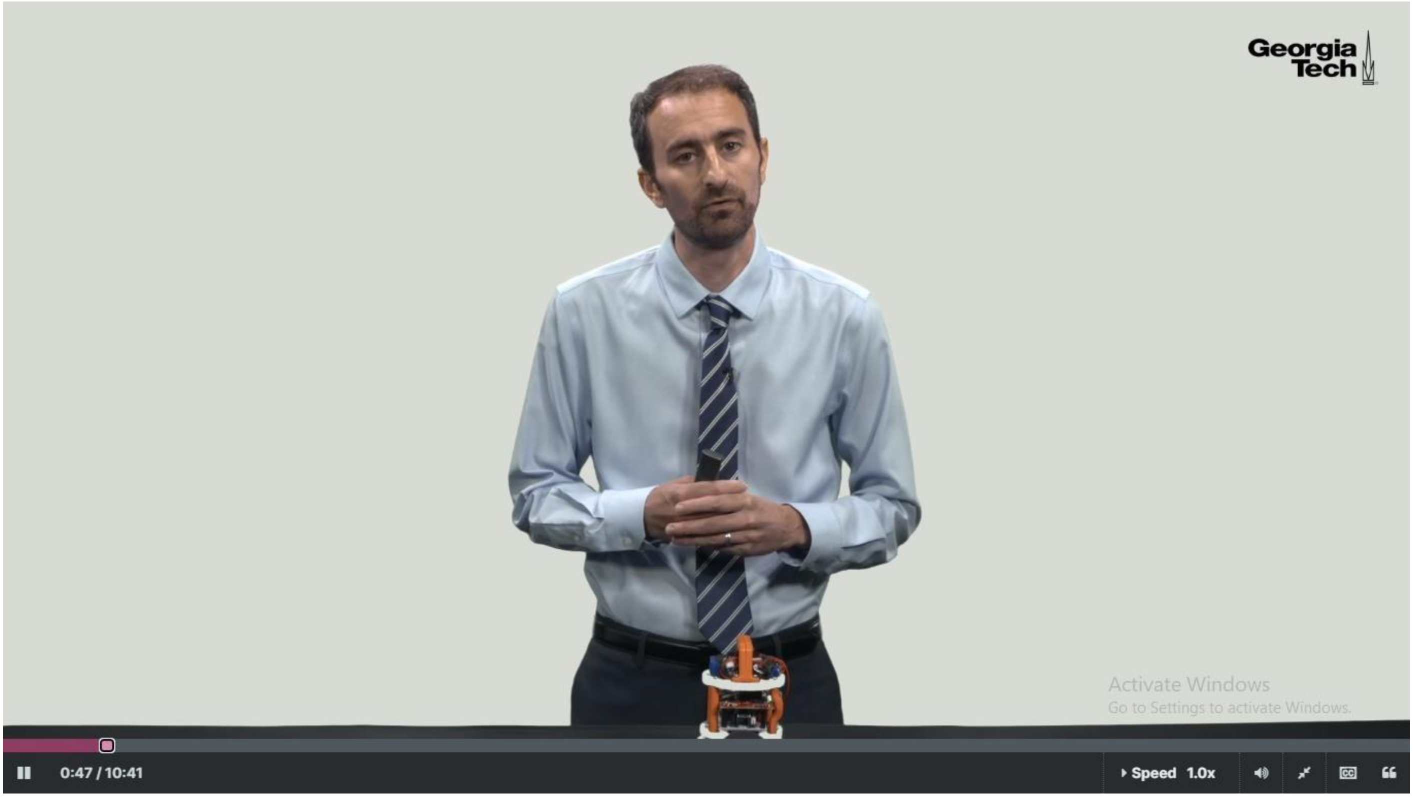
For a given application, actuators can be selected based on key characteristics. Some of these characteristics are maximum **force/torque**, **speed**, **cost**, **complexity** of installation and interfacing.

Topic-2

Lesson 1: Introduction to Brushed DC Motors



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Activate Windows
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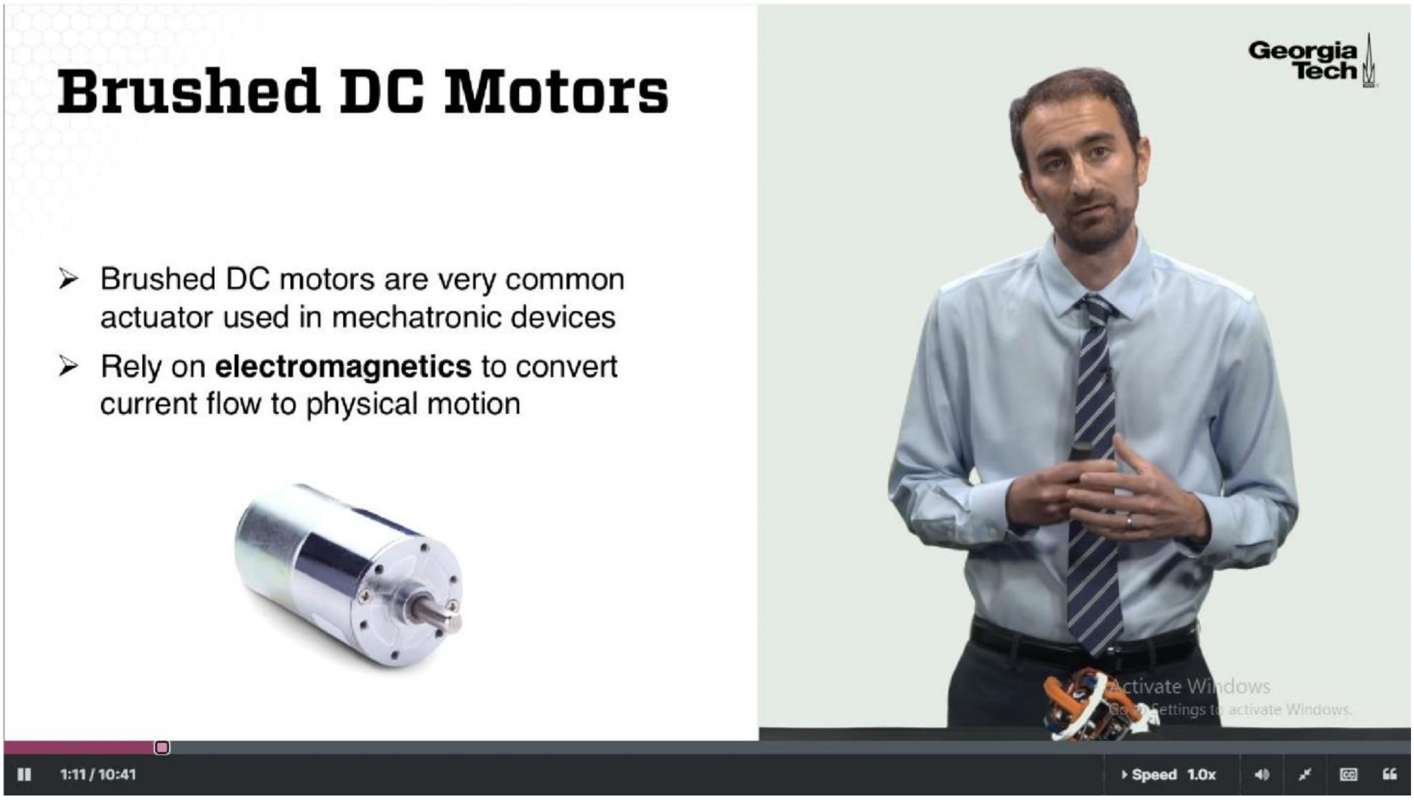
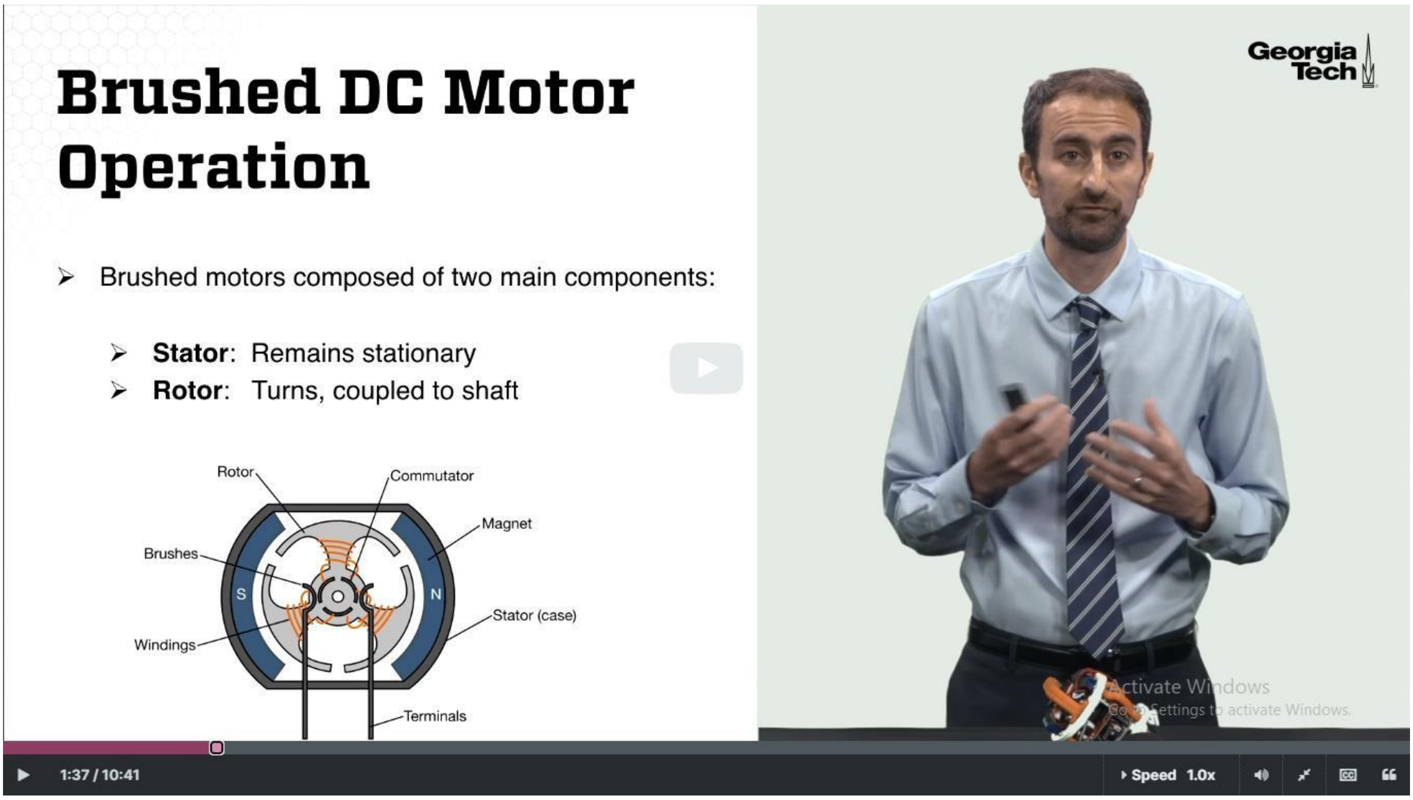
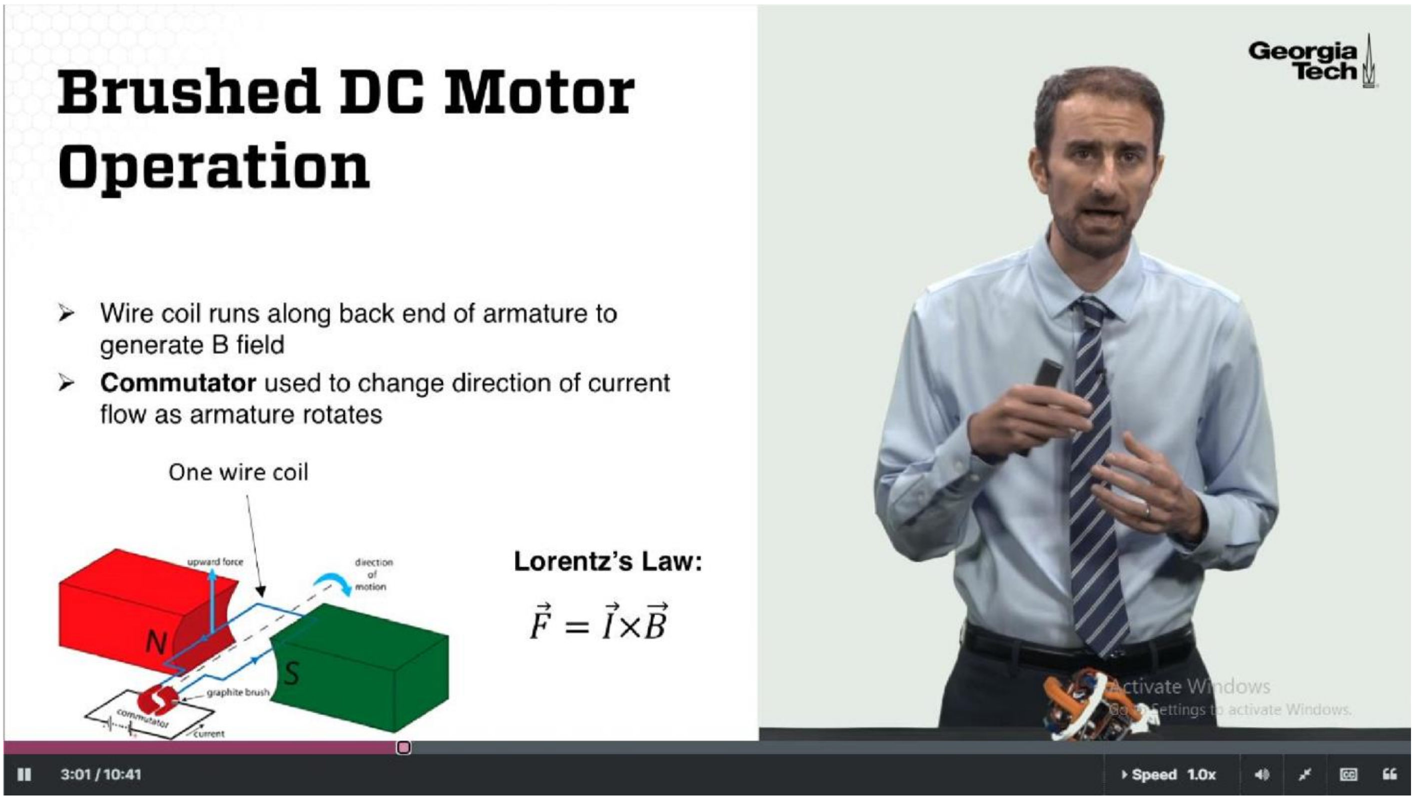
0:47 / 10:41
Speed 1.0x


Brushed DC Motors
➢ Brushed DC motors are very common actuator used in mechatronic devices
➢ Rely on **electromagnetics** to convert current flow to physical motion
Georgia Tech
1:11 / 10:41
Speed 1.0x


Brushed DC Motor Operation
Brushed motors composed of two main components:
Stator: Remains stationary
Rotor: Turns, coupled to shaft
Rotor
Commutator
Magnet
Brushes
S
N
Stator (case)
Windings
Terminals
Georgia Tech
1:37 / 10:41
Speed 1.0x


Brushed DC Motor Operation
Wire coil runs along back end of armature to generate B field
Commutator used to change direction of current flow as armature rotates
One wire coil
upward force
direction of motion
N
S
graphite brush
commutator
current
Lorentz's Law:
$\vec{F} = \vec{I} \times \vec{B}$
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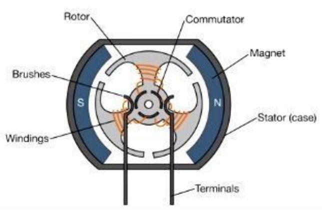
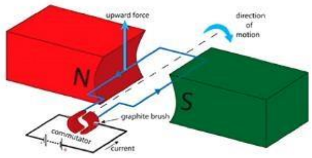
3:01 / 10:41
Speed 1.0x

Brushed DC Motor Operation

- Commutator must be composed of at least two segments
- Motors below have 3-piece commutator (left) and 2-piece commutator (right)





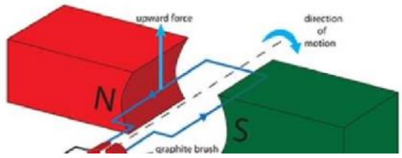
5:47 / 10:41   Speed 1.0x

Brushed DC Motor

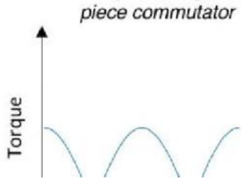
Brushed DC Motor Operation

- As motor turns, angle of energized coil with respect to magnet changes

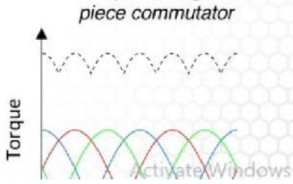
$\vec{F} = \vec{I} \times \vec{B}$ → Torque is function of sine of angle between B field and armature angle → Torque is not smooth using 2-piece commutator



Torque vs angle for 2-piece commutator



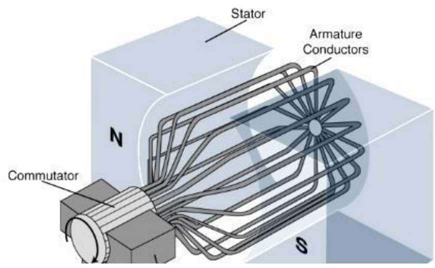
Torque vs angle for 6-piece commutator



Brushed DC Motor

Brushed DC Motor Operation

- Good drawing of a motor with multiple-piece commutator and coils

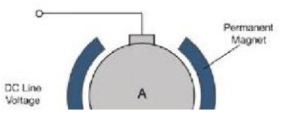


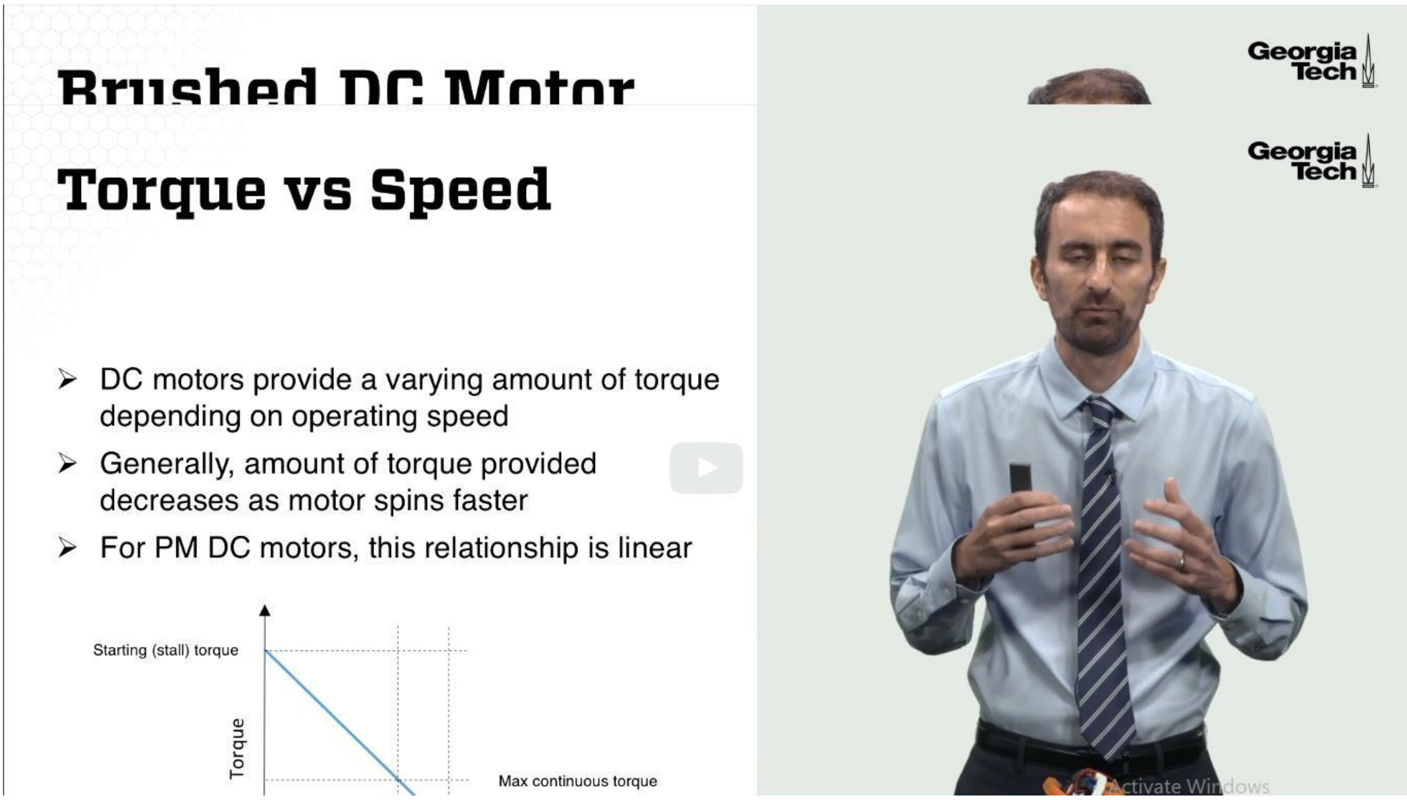
Brushed DC Motor

Permanent Magnet DC Motors

- Various different types of brushed DC motors exist - differing in how magnetic field is generated
- **Permanent magnet** (PM) DC motors use a permanent magnet to generate magnetic field
  - Other types: Series wound, shunt wound, compound wound
  - These types use inductive coils to generate magnetic field

PM DC Motor





Brushed DC Motor
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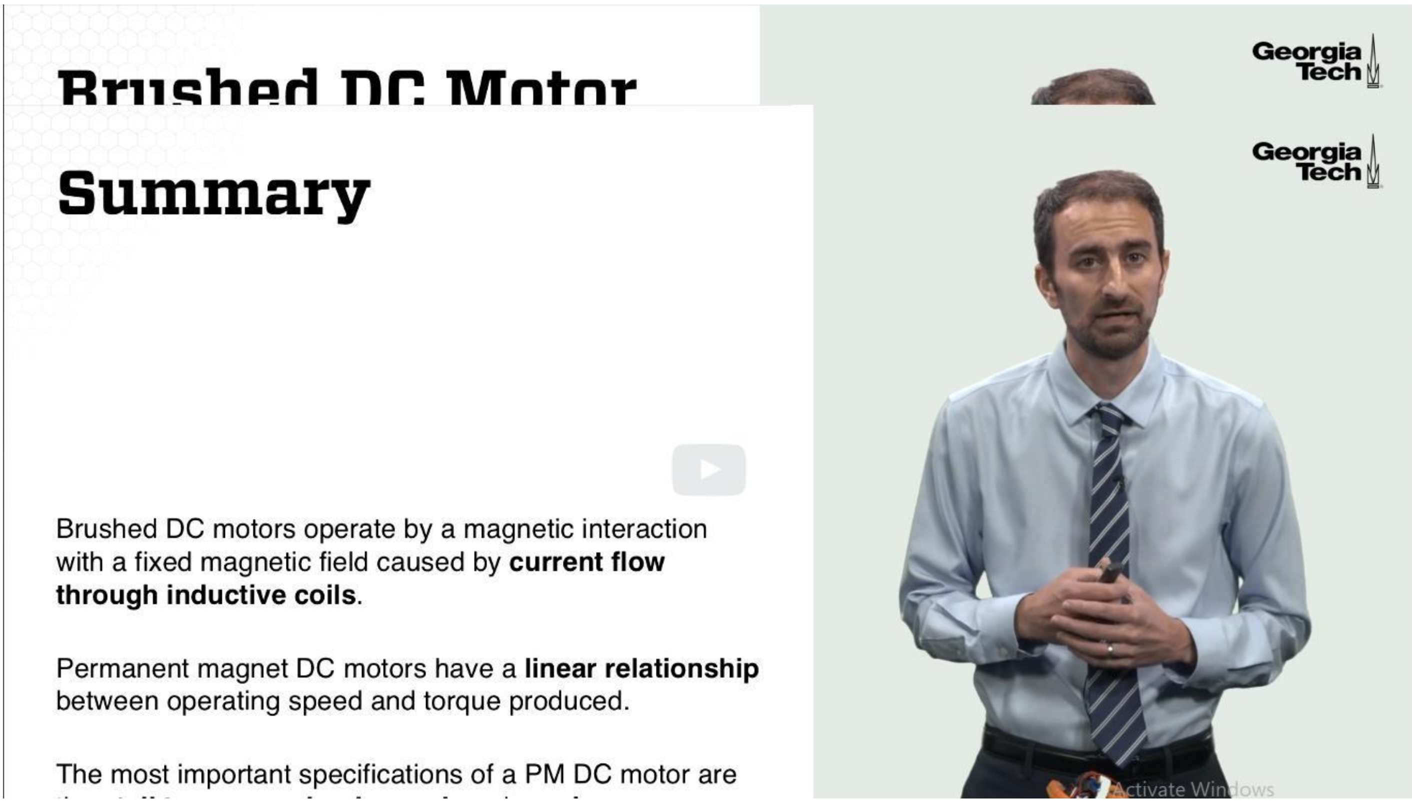
Torque vs Speed
➢ DC motors provide a varying amount of torque depending on operating speed
➢ Generally, amount of torque provided decreases as motor spins faster
➢ For PM DC motors, this relationship is linear
Starting (stall) torque
Torque
Max continuous torque
Activate Windows



Brushed DC Motor
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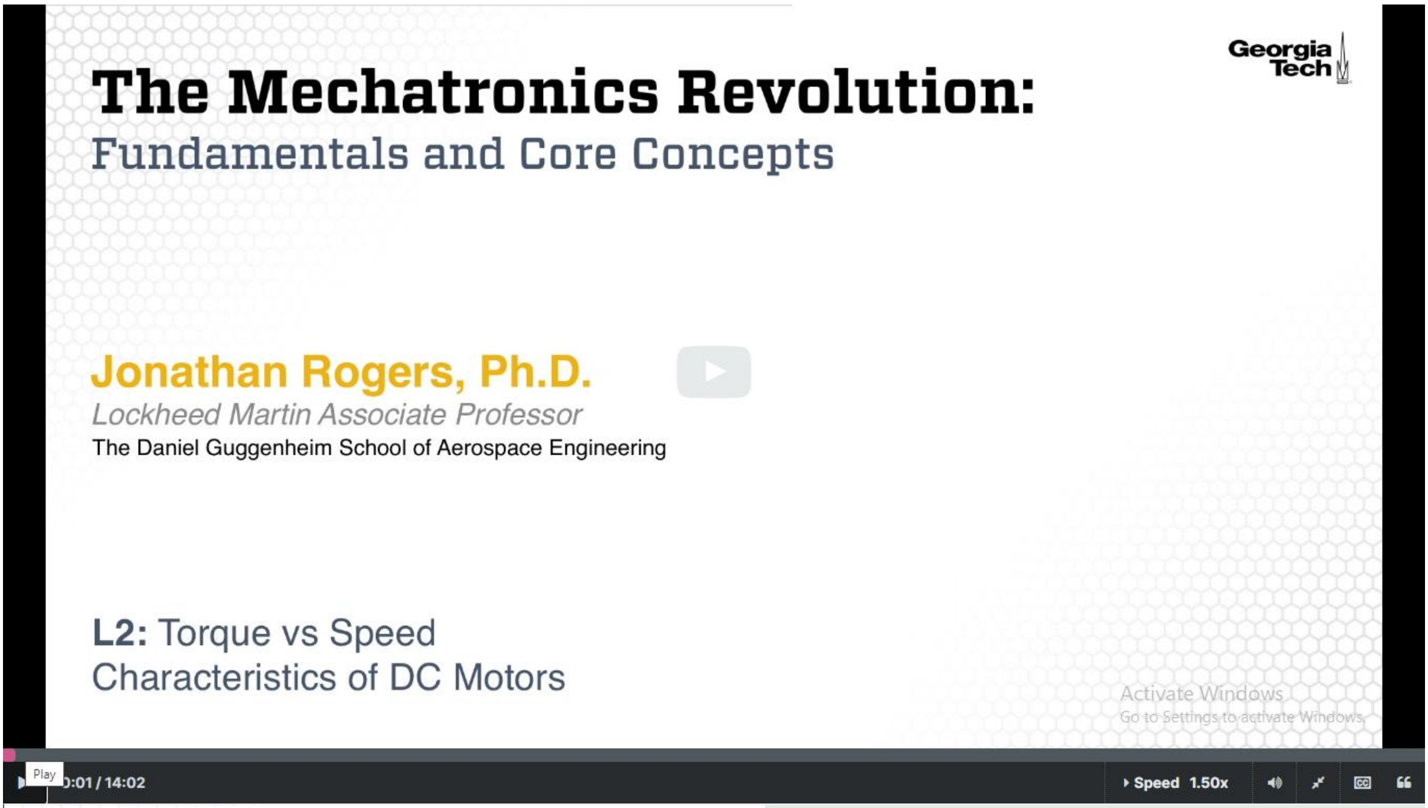
Summary
Brushed DC motors operate by a magnetic interaction with a fixed magnetic field caused by **current flow through inductive coils**.
Permanent magnet DC motors have a **linear relationship** between operating speed and torque produced.
The most important specifications of a PM DC motor are
Activate Windows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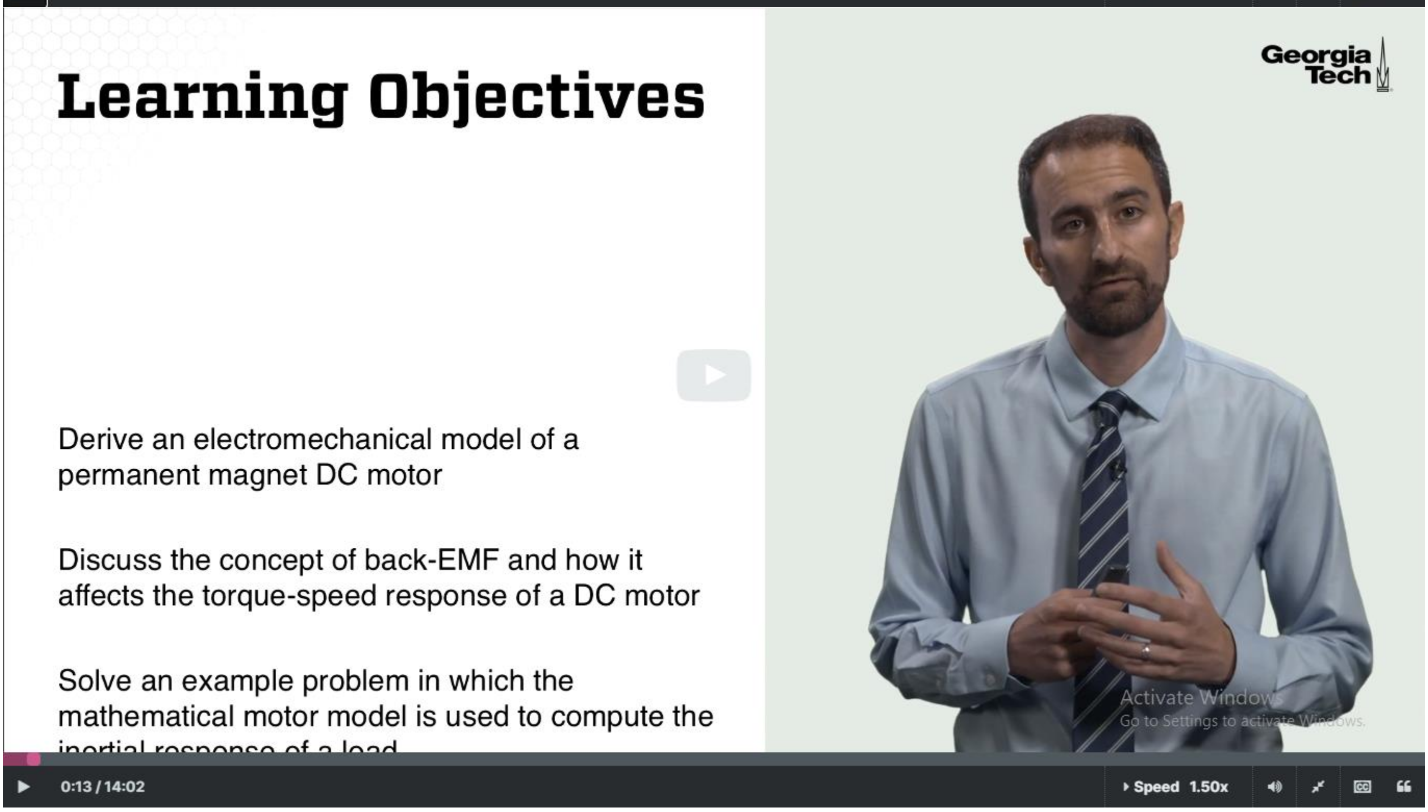
The Mechatronics Revolution:
Fundamentals and Core Concepts
Jonathan Rogers, Ph.D.
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering
L2: Torque vs Speed
Characteristics of DC Motors
Activate Windows
Go to Settings to activate Windows.
Play
0:01 / 14:02
Speed 1.50x


Learning Objectives
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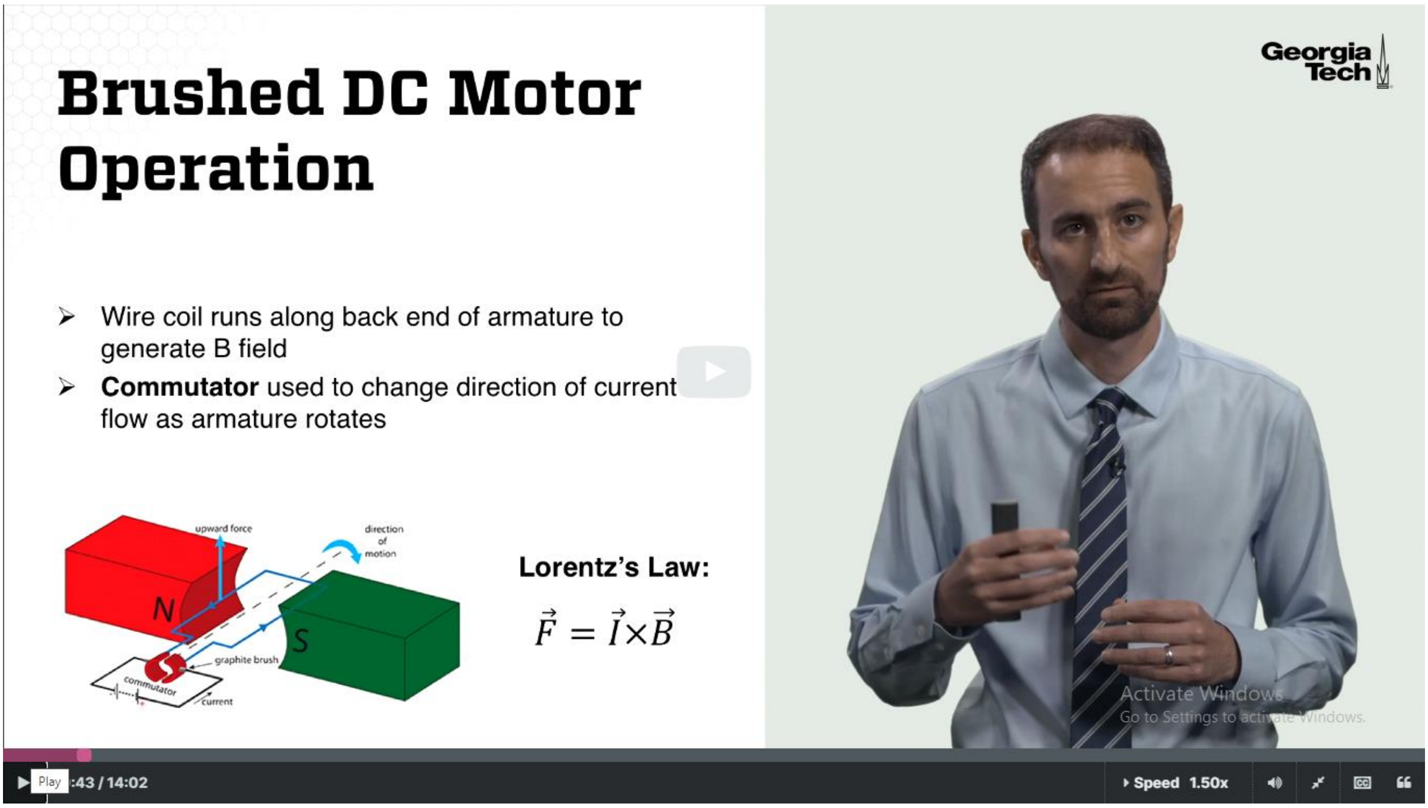
Derive an electromechanical model of a permanent magnet DC motor
Discuss the concept of back-EMF and how it affects the torque-speed response of a DC motor
Solve an example problem in which the mathematical motor model is used to compute the
Activate Windows
Go to Settings to activate Windows.
0:13 / 14:02
Speed 1.50x


Brushed DC Motor Operation
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upward force
direction of motion
N
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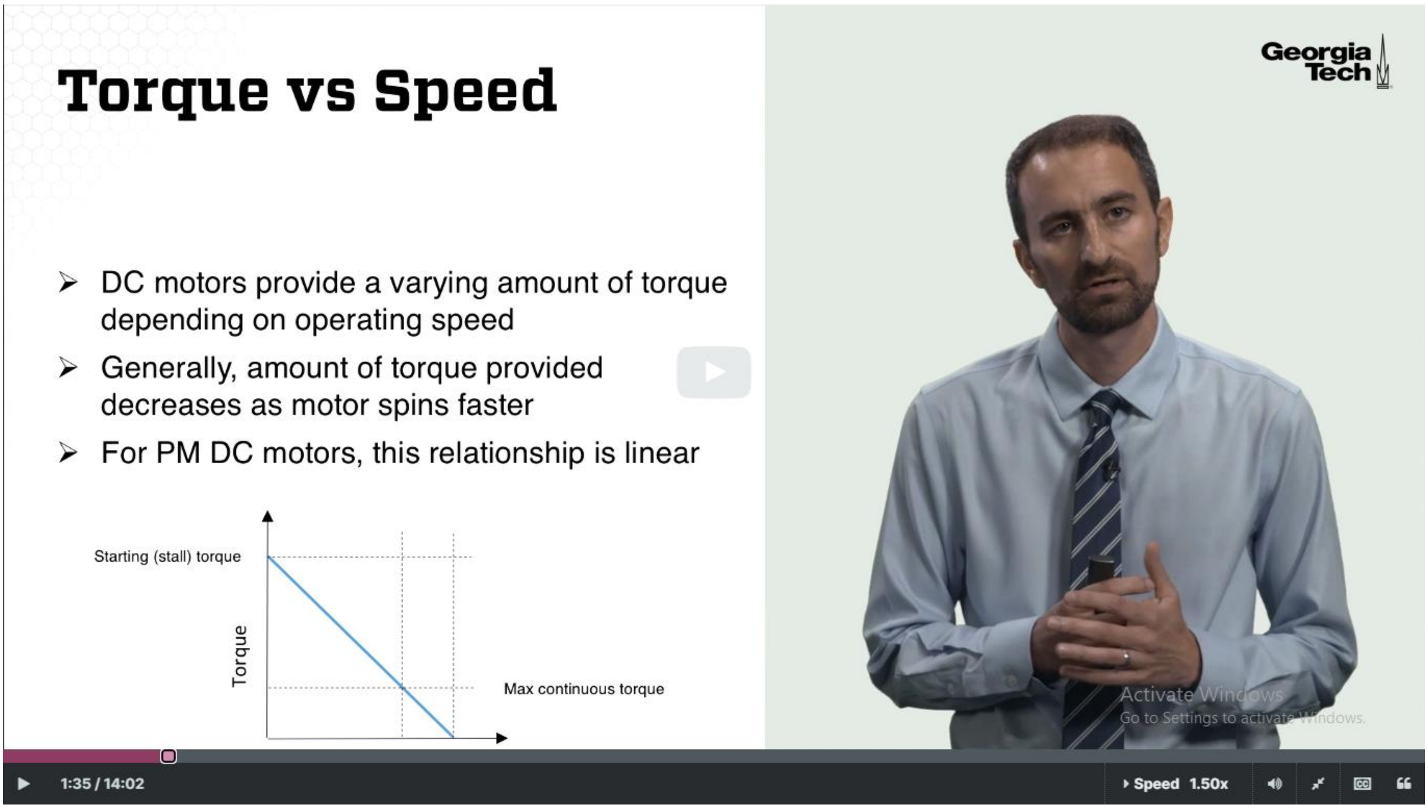
Georgia Tech
Activate Windows
Go to Settings to activate Windows.
Play :43 / 14:02
Speed 1.50x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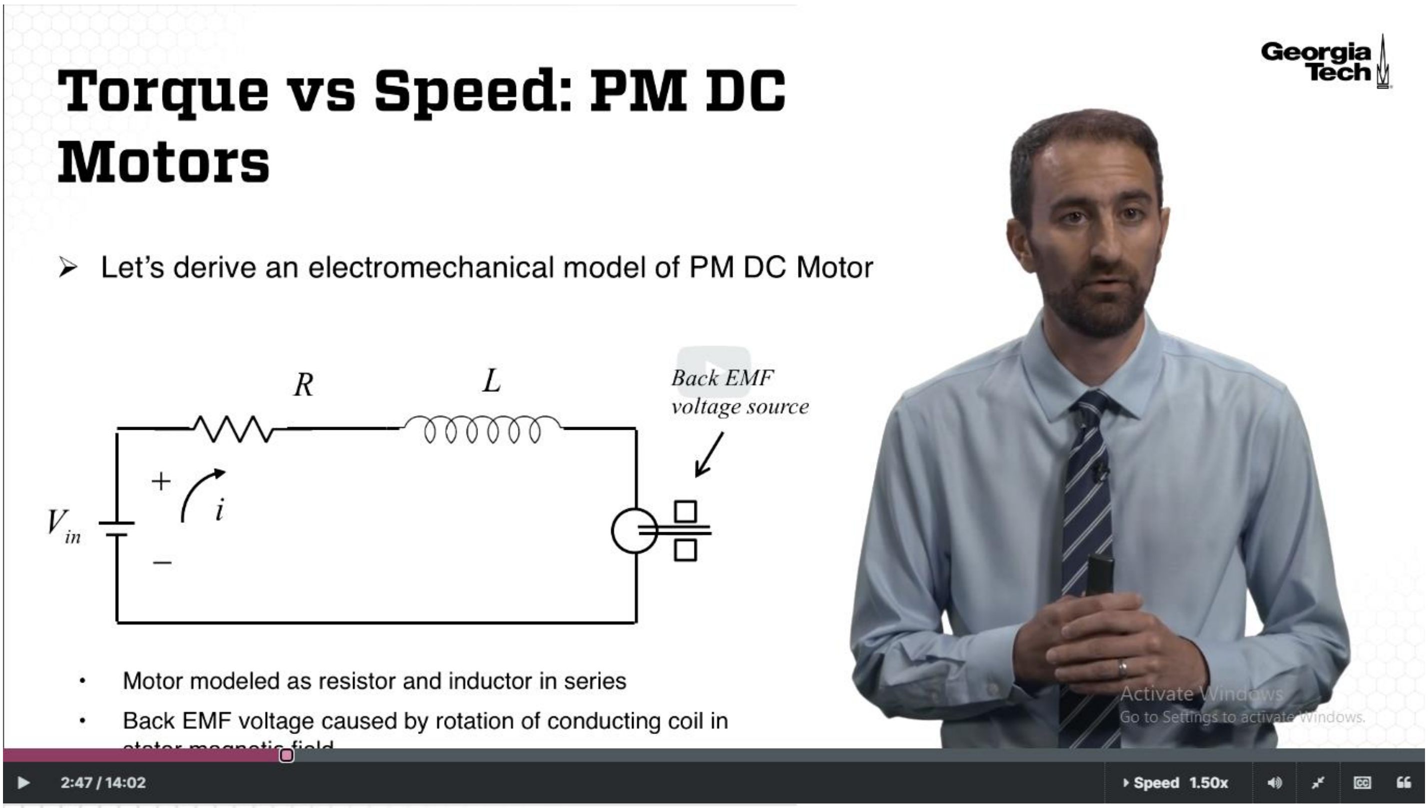
Starting (stall) torque
Torque
Max continuous torque
Georgia Tech
Activate Windows
Go to Settings to activate Windows.
1:35 / 14:02
Speed 1.50x


Georgia Tech
Torque vs Speed: PM DC Motors
➢ Let's derive an electromechanical model of PM DC Motor
R
L
Back EMF voltage source
+
i
−
V_{in}
• Motor modeled as resistor and inductor in series
• Back EMF voltage caused by rotation of conducting coil in
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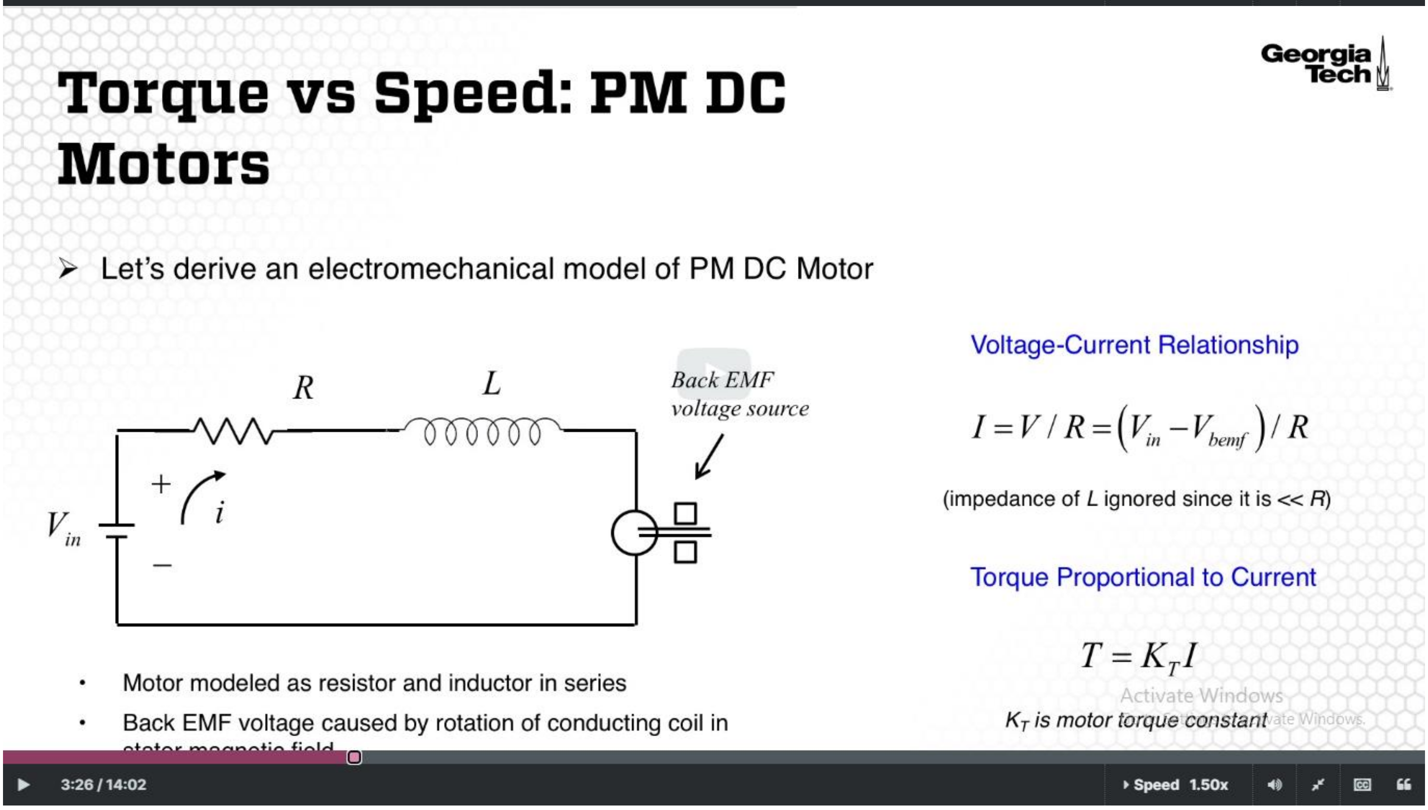
2:47 / 14:02
Speed 1.50x


Georgia Tech
Torque vs Speed: PM DC Motors
➢ Let's derive an electromechanical model of PM DC Motor
R
L
Back EMF voltage source
+
i
−
V_{in}
Voltage-Current Relationship
$I = V / R = \left(V_{in} - V_{bemf}\right) / R$
(impedance of L ignored since it is << R)
Torque Proportional to Current
$T = K_T I$
K_T is motor torque constant
• Motor modeled as resistor and inductor in series
• Back EMF voltage caused by rotation of conducting coil in
Activate Windows
3:26 / 14:02
Speed 1.50x

Torque vs Speed: PM DC Motors

Back EMF Voltage is Proportional to Motor Speed

$$V_{bemf} = K_E \omega$$

K_E is back EMF constant (or voltage constant) and ω is speed.

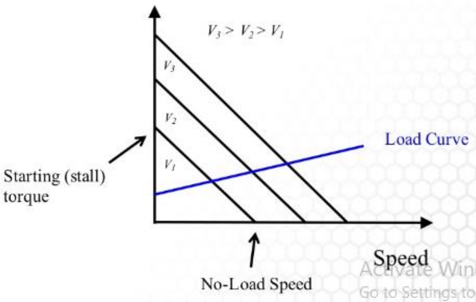
Combining equations:

$$T = \underbrace{K_T \frac{V_{in}}{R}}_{\text{Torque when } \omega = 0 \text{, called "starting torque" } T_S} - K_T K_E \frac{\omega}{R}$$

Linear Torque-Speed Relationship:

$$\Rightarrow \quad T = T_S - \alpha\omega \qquad \alpha = \frac{K_T K_E}{R}$$

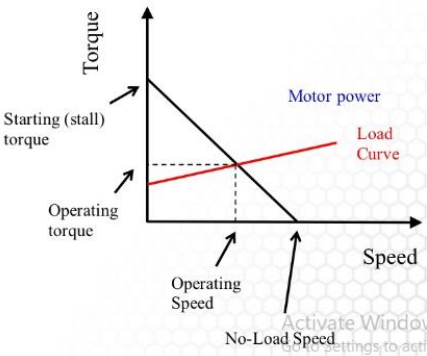
Torque-Speed Curve for DC Motor at Different Input Voltage (Vin) Values



5:29 / 14:02 ▸ Speed 1.50x

Torque vs Speed: PM DC Motors

- Torque-speed curve defined by two parameters:
  - **Starting (stall) torque**: Torque generated by motor at zero speed
  - **No-load speed**: Maximum speed achieved by motor, achieved when not connected to a load
- As motor rotates, back EMF generated due to rotation of coil within magnetic field reduces voltage across motor leads and thus current through motor
- This is why torque decreases with speed
- Torque continues to decrease as ω increases until torque is zero at maximum speed
- Motor delivers maximum power when it reaches half of its no load speed
- When motor drives a load, its operating speed will be where load torque equals motor torque
- If load torque increases linearly with speed, operating speed of motor will increase linearly with increase in supply voltage



Play

6:38 / 14:02 ▸ Speed 1.50x

Example Problem: Speed and Torque of a DC Motor

Problem: A PM DC motor is used to lift a 25 kg load via a pulley as shown. From the datasheet, the no-load motor speed is 200 RPM (20.9 rad/s) and starting torque is 31.2 N-m. Frictional resistance in pulley is 2 N-m/(rad/s). Neglect inertia of rotor, pulley, and cable. Determine the initial acceleration of the load and steady-state speed of the load.

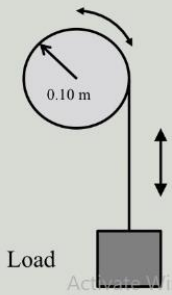
Total torque at startup:

(Total torque) = (Starting torque) – (Friction torque) – (Gravity torque)

$$T_0 = 31.2 - (25)(9.81)(0.1) = 6.67 \quad \text{N-m}$$

Acceleration of load due to this torque:

$$F_0 = 6.67/0.1 = 66.7 \quad \text{N} \quad \Rightarrow \quad \boxed{\alpha_0 = 66.7/25 = 2.67 \quad \text{m/s}^2}$$



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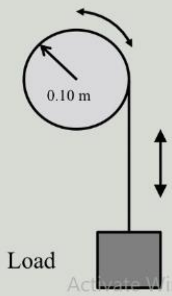
Torque exerted by load in steady-state:

(Total torque) = (Starting torque) – (Friction torque) – (Gravity torque)

$$T_{load} = 2\omega_{ss} + (25)(9.81)(0.1) = 2\omega_{ss} + 24.53$$

Use torque-speed curve to determine steady-state speed:

$$\underbrace{T_{motor} = 31.2 - \left(\frac{31.2}{20.9}\right)\omega_{ss}}_{T_{motor}} = \underbrace{2\omega_{ss} + 24.53}_{T_{load}} \quad \Rightarrow \quad \boxed{\omega_{ss} = 1.91 \text{ rad/s}}$$



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Example Problem: Speed and

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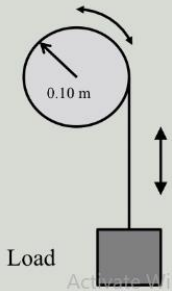
Use torque-speed curve to determine steady-state speed:

$$T_{motor} = 31.2 - \left(\frac{31.2}{20.9}\right)\omega_{ss} = 2\omega_{ss} + 24.53 \quad \Rightarrow \quad \boxed{v_{ss} = 19 \text{ cm/s}}$$



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Summary

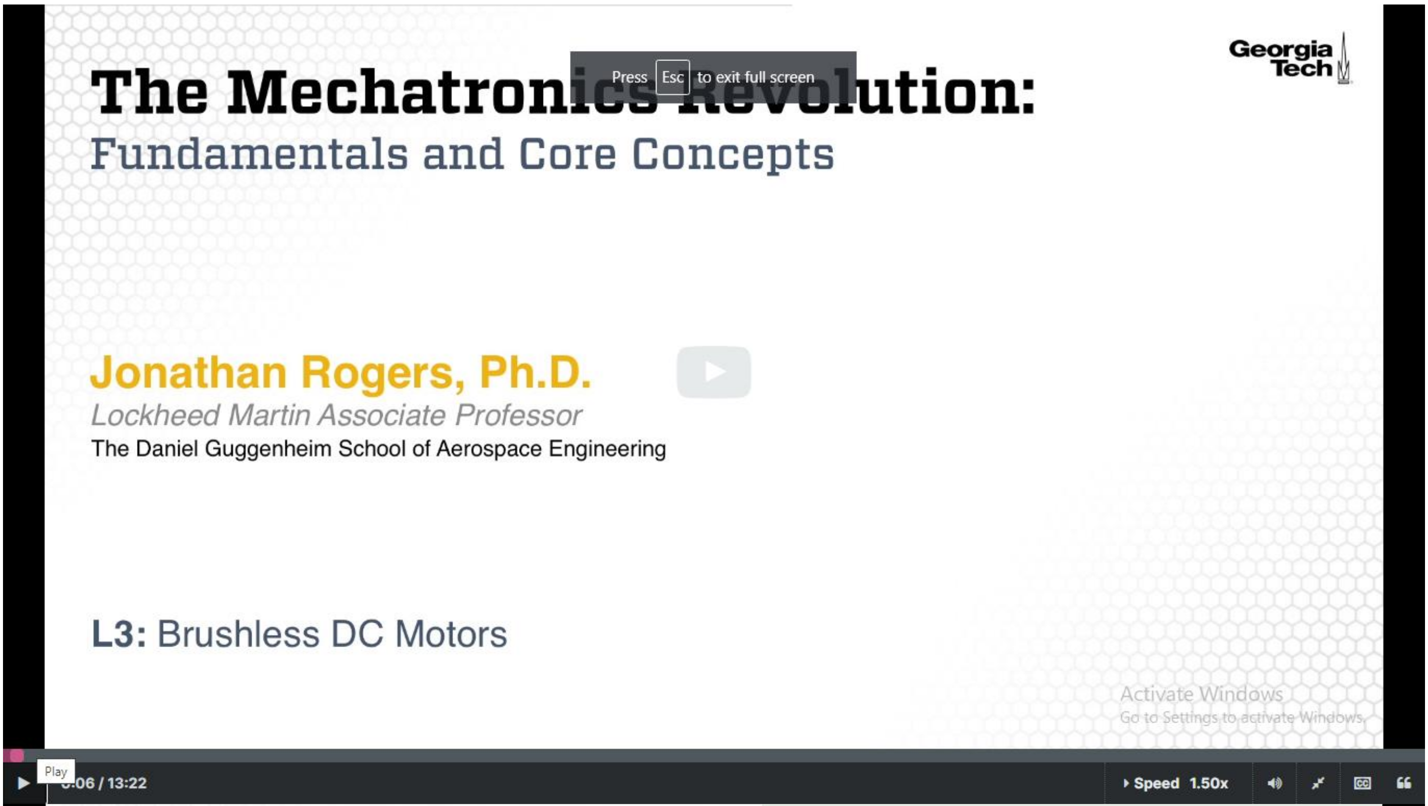
Permanent magnet DC motors have a **linear relationship** between operating speed and torque produced.

Back-EMF reduces the net magnetic field across the wire coils in a permanent magnet DC motor, reducing current through the coils as the motor spins faster

The most important specifications of a PM DC motor are the **stall torque**, **no-load speed**, and **maximum continuous torque**.

The torque-speed curve for a given motor provides a means to analyze the dynamics of a motor-driven device.

13:15 / 14:02 Speed 1.50x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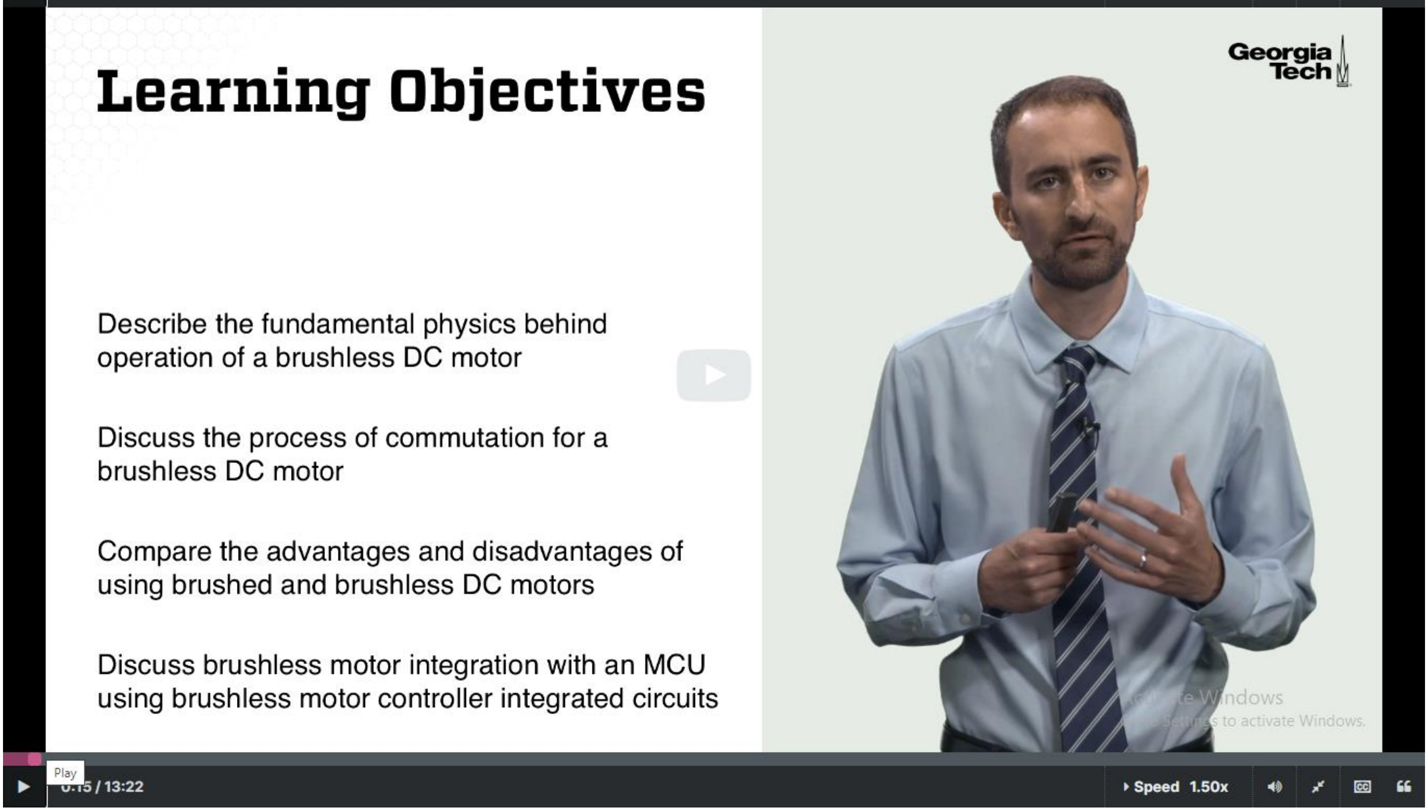
Press Esc to exit full screen
The Mechatronics Revolution:
Fundamentals and Core Concepts
Jonathan Rogers, Ph.D.
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering
L3: Brushless DC Motors
Activate Windows
Go to Settings to activate Windows.
Play
0:06 / 13:22
Speed 1.50x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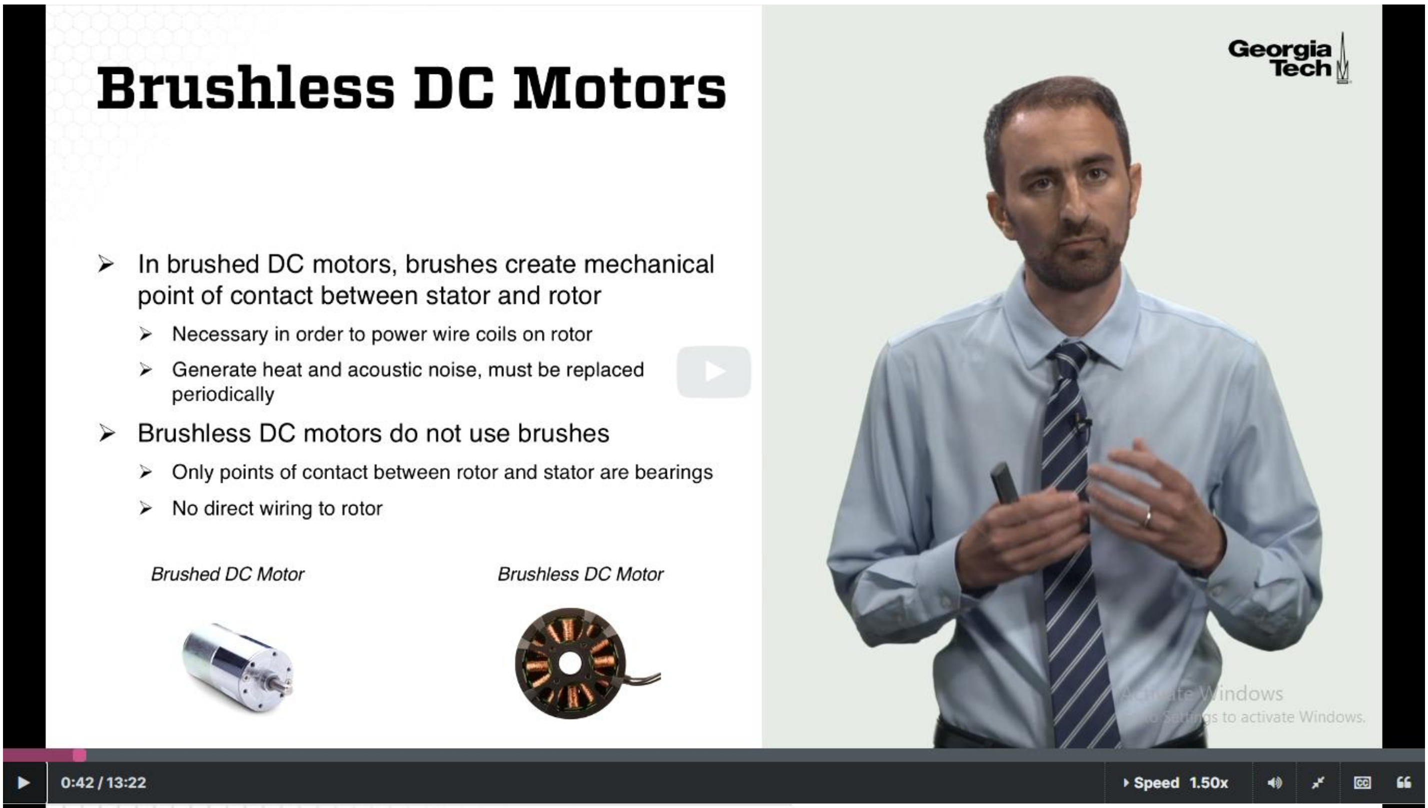
Learning Objectives
Describe the fundamental physics behind operation of a brushless DC motor
Discuss the process of commutation for a brushless DC motor
Compare the advantages and disadvantages of using brushed and brushless DC motors
Discuss brushless motor integration with an MCU using brushless motor controller integrated circuits
Play
0:15 / 13:22
Speed 1.50x


Brushless DC Motors
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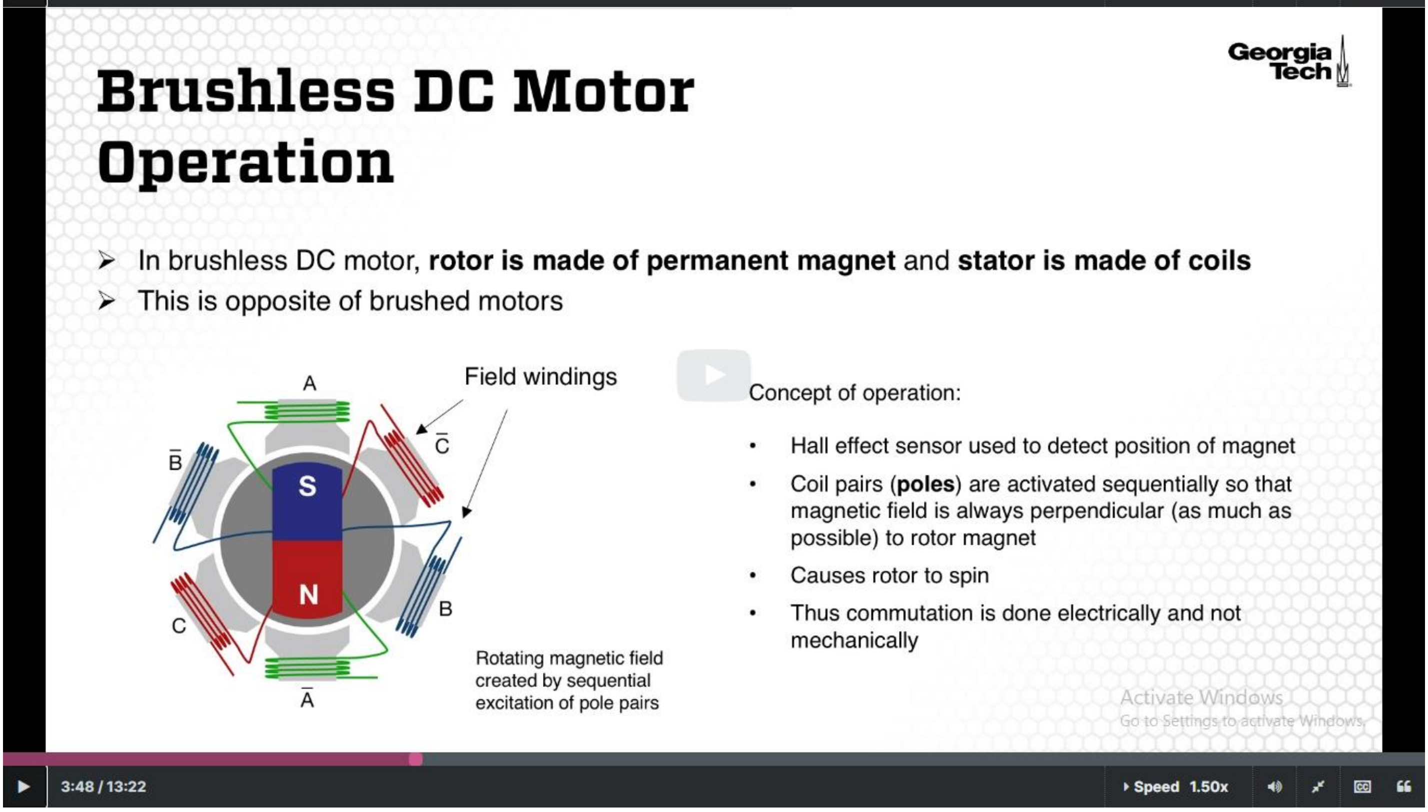
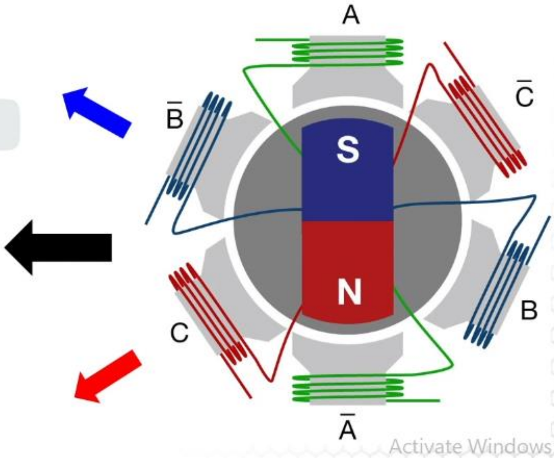
➢ In brushed DC motors, brushes create mechanical point of contact between stator and rotor
➢ Necessary in order to power wire coils on rotor
➢ Generate heat and acoustic noise, must be replaced periodically
➢ Brushless DC motors do not use brushes
➢ Only points of contact between rotor and stator are bearings
➢ No direct wiring to rotor
Brushed DC Motor
Brushless DC Motor
0:42 / 13:22
Speed 1.50x


Brushless DC Motor Operation
Georgia Tech
➢ In brushless DC motor, rotor is made of permanent magnet and stator is made of coils
➢ This is opposite of brushed motors
Field windings
A
B̄
C̄
S
N
C
B
Ā
Rotating magnetic field created by sequential excitation of pole pairs
Concept of operation:
• Hall effect sensor used to detect position of magnet
• Coil pairs (poles) are activated sequentially so that magnetic field is always perpendicular (as much as possible) to rotor magnet
• Causes rotor to spin
• Thus commutation is done electrically and not mechanically
3:48 / 13:22
Speed 1.50x

Brushless DC Motor Operation

3-Pole Brushless DC Motor

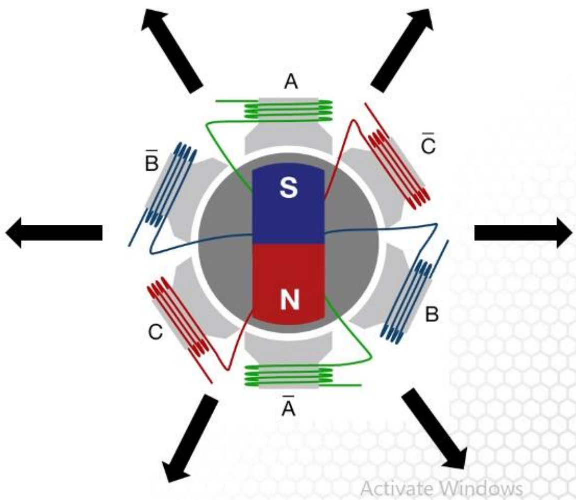
- A sensor is attached to each pair of coils which detects position of PM (rotor)
- Coils are activated so that resulting magnetic field across permanent magnet is as close to perpendicular to poles as possible
- In current configuration, coils B and C would be activated (A is off)



Brushless DC Motor Operation

3-Pole Brushless DC Motor

- For a 3-pole BLDC in this configuration, there are 6 possible magnetic field vectors that can be produced by the coils
- How often does the commutator sequence through them (in terms of deg rotation of rotor)?

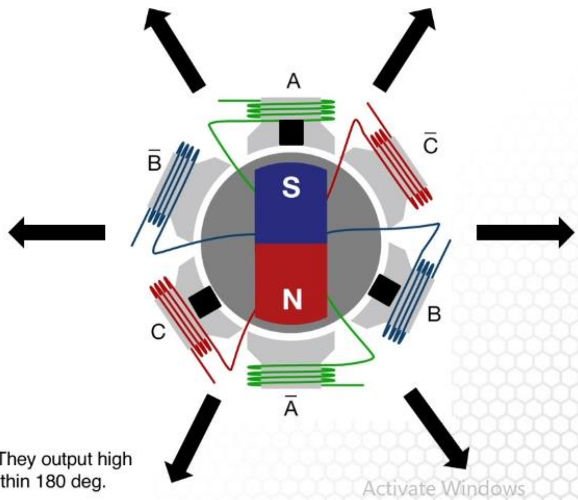


Brushless DC Motor Operation

3-Pole Brushless DC Motor - Commutation Sequence

Sensor Output			CW Rotation		
C	*B*	*A*	*A*	*B*	*C*
1	0	0	NC	Hi	Low
1	0	1	Low	Hi	NC
0	0	1	Low	NC	Hi
0	1	1	NC	Low	Hi
0	1	0	Hi	Low	NC
1	1	0	Hi	NC	Low

NC = No Current
Hi = +Voltage
Low = -Voltage



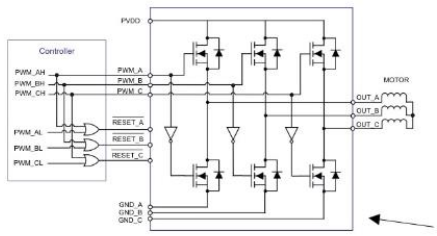
Black boxes indicate sensors. They output high (1) when N pole of magnet is within 180 deg.

BLDC Motor Control

- Brushless DC motors require a special chip that implements drive timing diagram - **BLDC motor driver**
  - Phase changes happen too fast for implementation on MCU that is performing other functions - requires dedicated IC or MCU
- Example: Texas Instruments DRV8312 3-Phase Motor Driver
  - Comprised of 3 half H-bridges

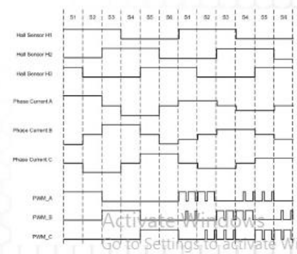
Courtesy of Texas Instruments

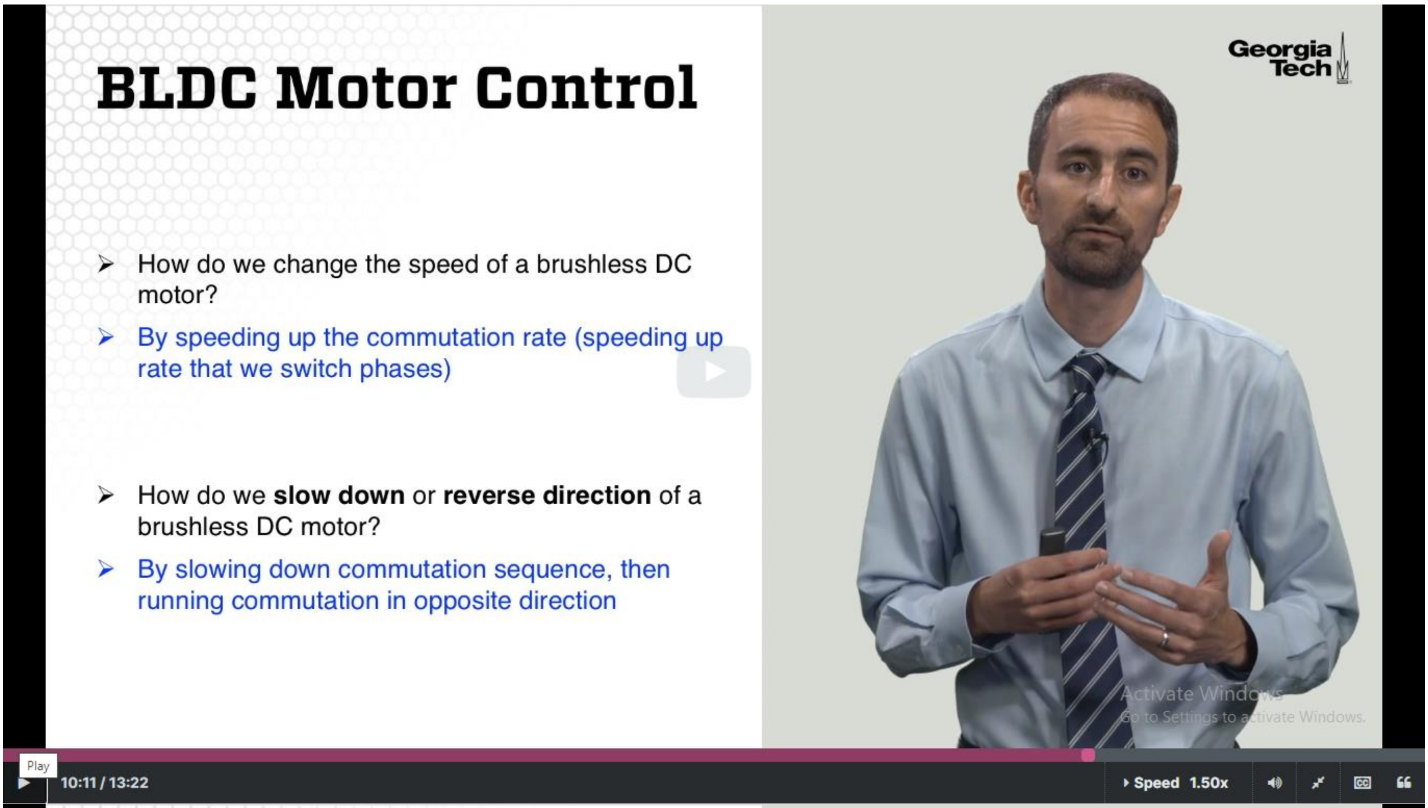
MCU

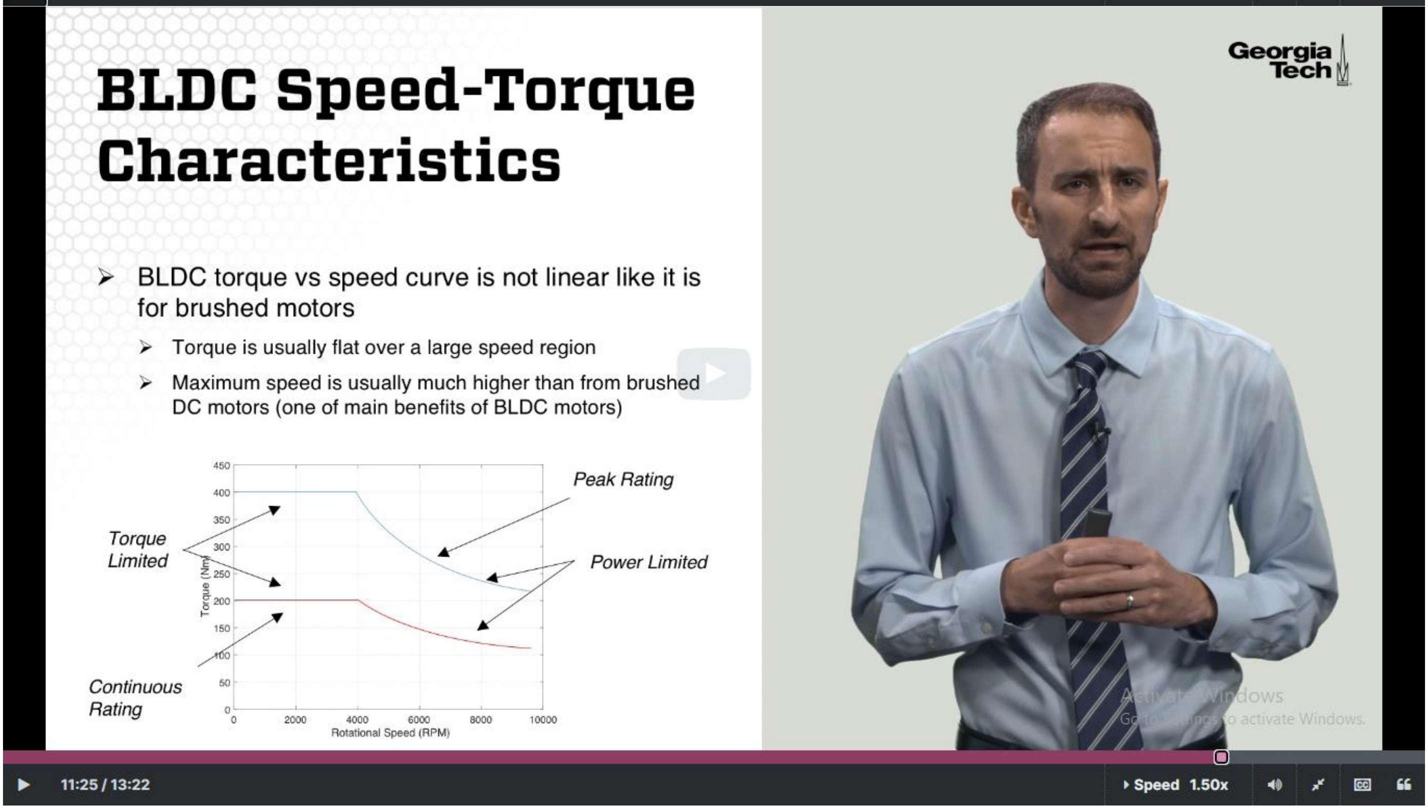


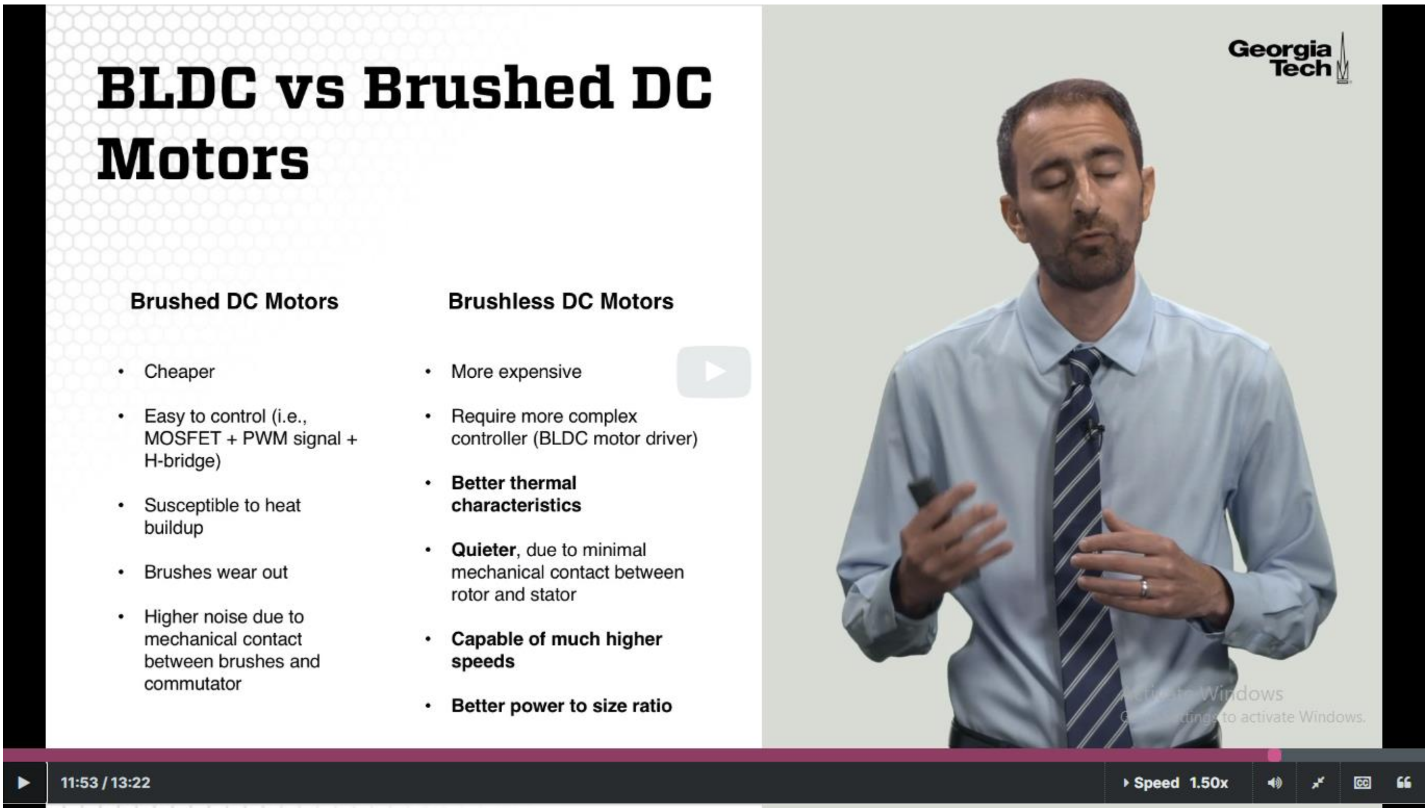
DRV8312

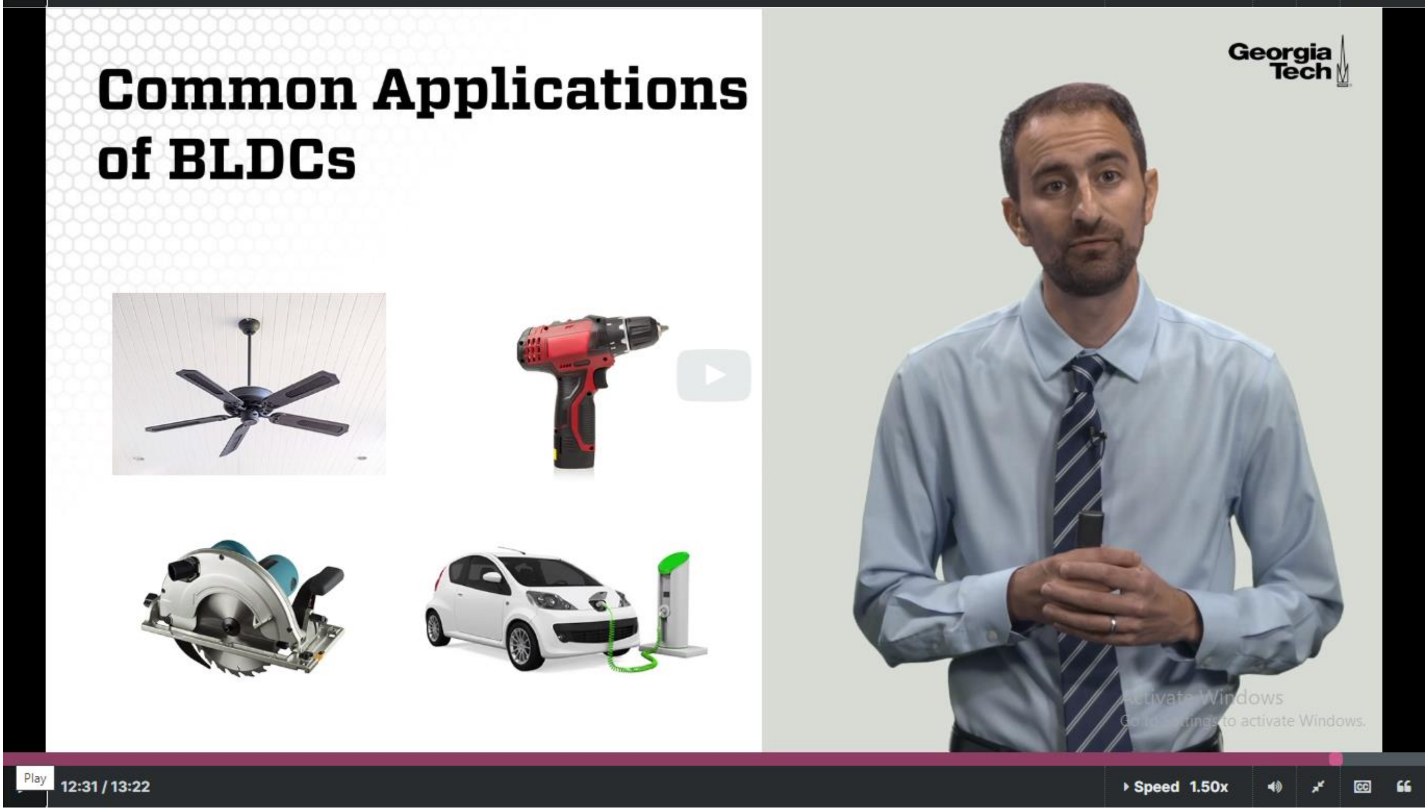
DRV8312 Drive Timing Diagram

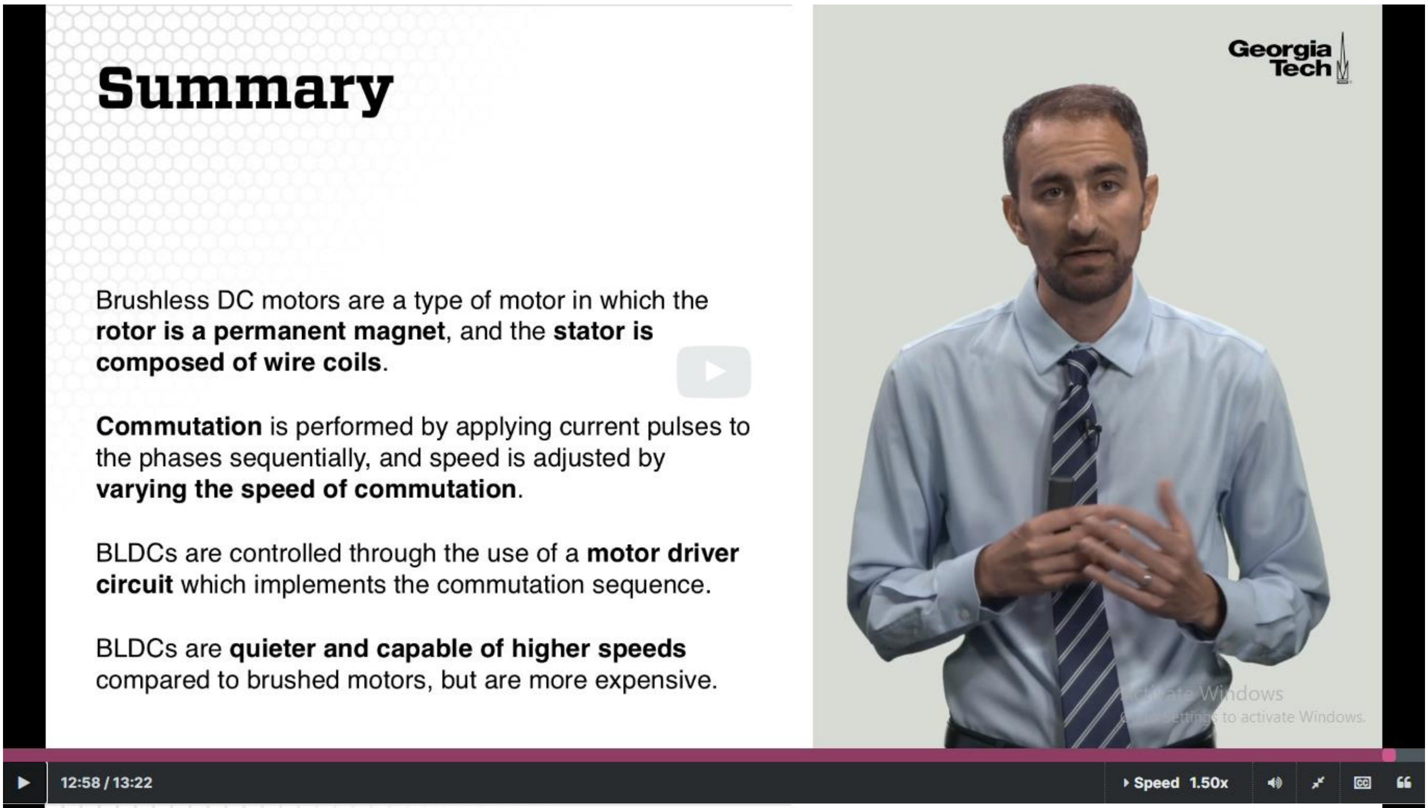


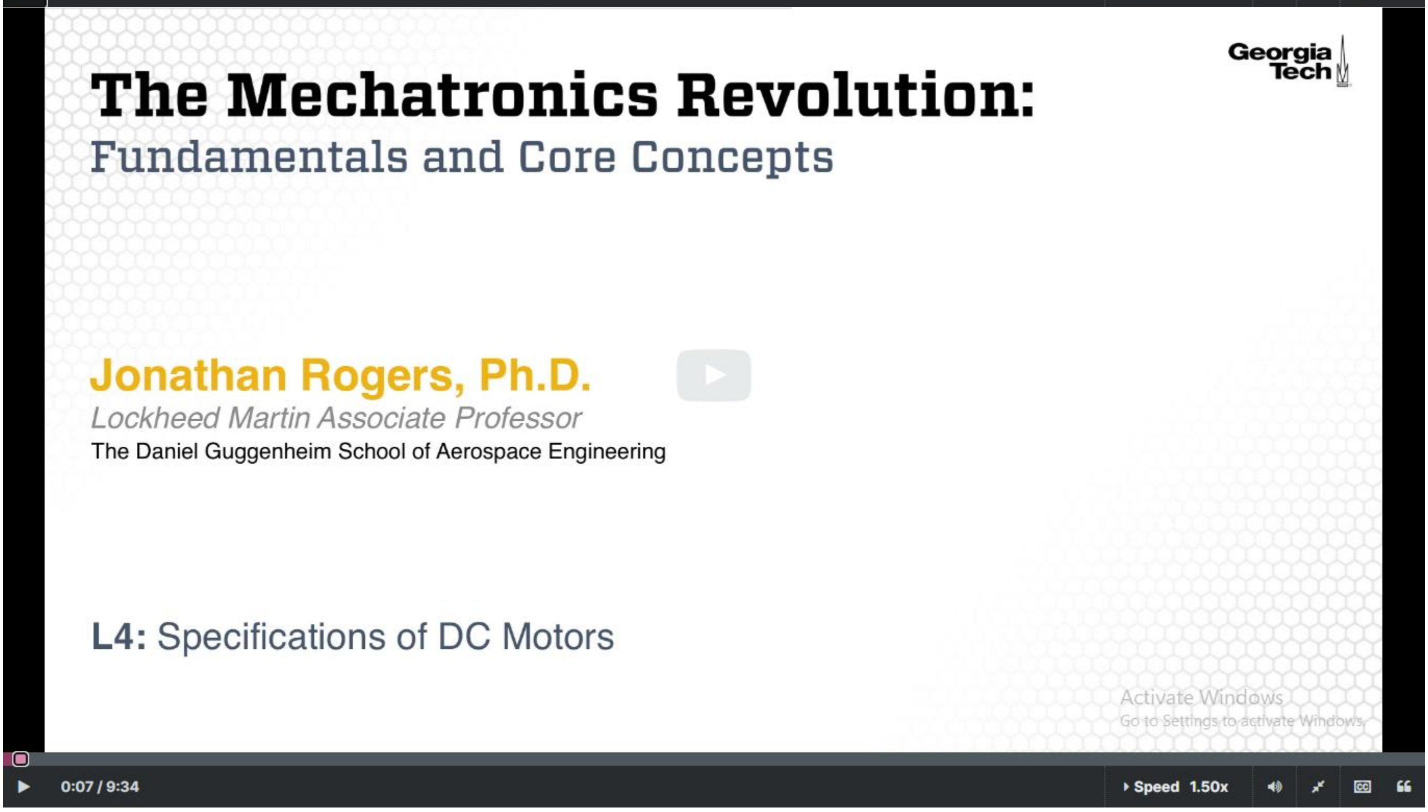

BLDC Motor Control
Georgia Tech
How do we change the speed of a brushless DC motor?
By speeding up the commutation rate (speeding up rate that we switch phases)
How do we slow down or reverse direction of a brushless DC motor?
By slowing down commutation sequence, then running commutation in opposite direction
Activate Windows
Go to Settings to activate Windows.
Play
10:11 / 13:22
Speed 1.50x

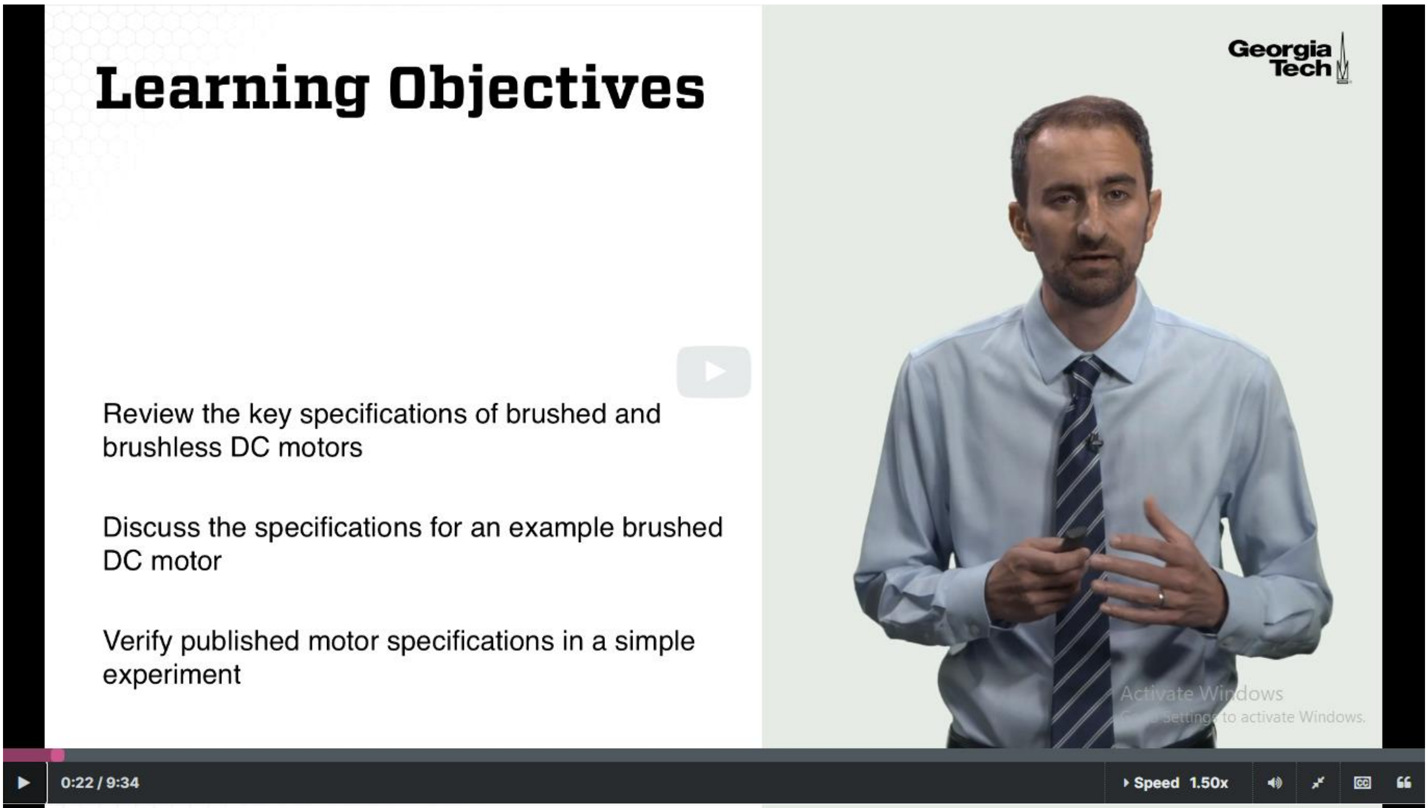

BLDC Speed-Torque Characteristics
Georgia Tech
BLDC torque vs speed curve is not linear like it is for brushed motors
Torque is usually flat over a large speed region
Maximum speed is usually much higher than from brushed DC motors (one of main benefits of BLDC motors)
Peak Rating
Torque Limited
Power Limited
Continuous Rating
Torque (Nm)
Rotational Speed (RPM)
0
50
100
150
200
250
300
350
400
450
0
2000
4000
6000
8000
10000
11:25 / 13:22
Speed 1.50x

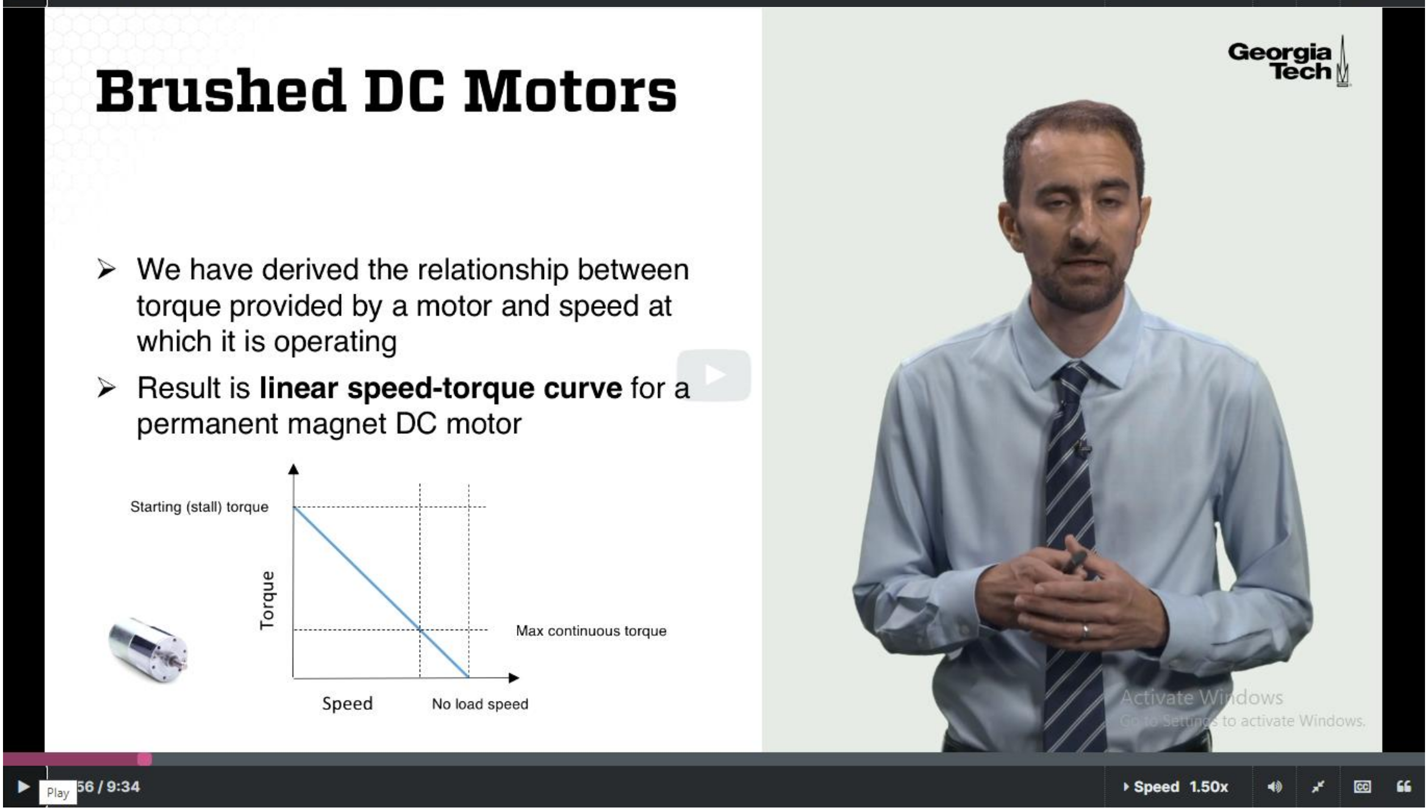

BLDC vs Brushed DC Motors
Brushed DC Motors
• Cheaper
• Easy to control (i.e., MOSFET + PWM signal + H-bridge)
• Susceptible to heat buildup
• Brushes wear out
• Higher noise due to mechanical contact between brushes and commutator
Brushless DC Motors
• More expensive
• Require more complex controller (BLDC motor driver)
• Better thermal characteristics
• Quieter, due to minimal mechanical contact between rotor and stator
• Capable of much higher speeds
• Better power to size ratio
Georgia Tech
11:53 / 13:22
Speed 1.50x


Common Applications of BLDCs
Georgia Tech
Play
12:31 / 13:22
Speed 1.50x


Summary
Brushless DC motors are a type of motor in which the **rotor is a permanent magnet**, and the **stator is composed of wire coils**.
Commutation is performed by applying current pulses to the phases sequentially, and speed is adjusted by **varying the speed of commutation**.
BLDCs are controlled through the use of a **motor driver circuit** which implements the commutation sequence.
BLDCs are **quieter and capable of higher speeds** compared to brushed motors, but are more expensive.
Georgia Tech
12:58 / 13:22
Speed 1.50x


The Mechatronics Revolution:
Fundamentals and Core Concepts
Georgia Tech
Jonathan Rogers, Ph.D.
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering
L4: Specifications of DC Motors
0:07 / 9:34
Speed 1.50x


Georgia Tech
Learning Objectives
Review the key specifications of brushed and brushless DC motors
Discuss the specifications for an example brushed DC motor
Verify published motor specifications in a simple experiment
Activate Windows
Go to Settings to activate Windows.
0:22 / 9:34
Speed 1.50x


Georgia Tech
Brushed DC Motors
➢ We have derived the relationship between torque provided by a motor and speed at which it is operating
➢ Result is **linear speed-torque curve** for a permanent magnet DC motor
Starting (stall) torque
Torque
Max continuous torque
Speed
No load speed
Activate Windows
Go to Settings to activate Windows.
Play
56 / 9:34
Speed 1.50x

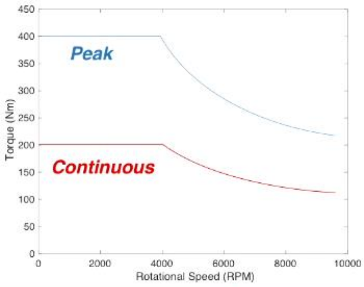
Brushed DC Motor Specifications

- Key specifications of a brushed DC motor:
  - **No-load speed**: Speed motor turns when there is no frictional resistance from a load
  - **Stall torque**: Torque produced by motor when not turning
  - **Terminal resistance**: Resistance across motor leads when motor not turning
  - **Maximum continuous torque**: Torque level safe for long-term operation (10-25% of stall torque)
  - **Speed at max continuous torque**: Minimum speed safe for long-term operation (75-90% of no-load speed)
  - **Operating voltage**: Voltage (range) that can be applied to motor for safe operation
  - **Peak or Stall current**: Maximum current drawn by motor, at stall

Georgia Tech

Brushless DC Motor Specifications

- Key specifications of brushless DC motors:
  - **Continuous stall torque**: Safe torque value applied continuously at stall (motor should be heat-sinked)
  - **Peak torque**: Maximum torque motor can generate
  - **Maximum speed**: Max operating speed of motor



Georgia Tech

Example: DC Motor Specifications

Georgia Tech

- Pololu Metal Gearmotor (25 mm Diameter, 34:1 gear ratio, High Power)

www.pololu.com

Courtesy of Pololu

Basic Specifications

Nominal Voltage	6 V
Stall Torque @ 6 V	90 oz-in
No-Load Speed @ 6V	280 RPM
Stall Current @ 6 V	6.5 A

Play :32 / 9:34 Speed 1.50x

Example: DC Motor Specifications

Georgia Tech

- Derived specifications of Pololu motor:

Terminal Resistance (*R*)

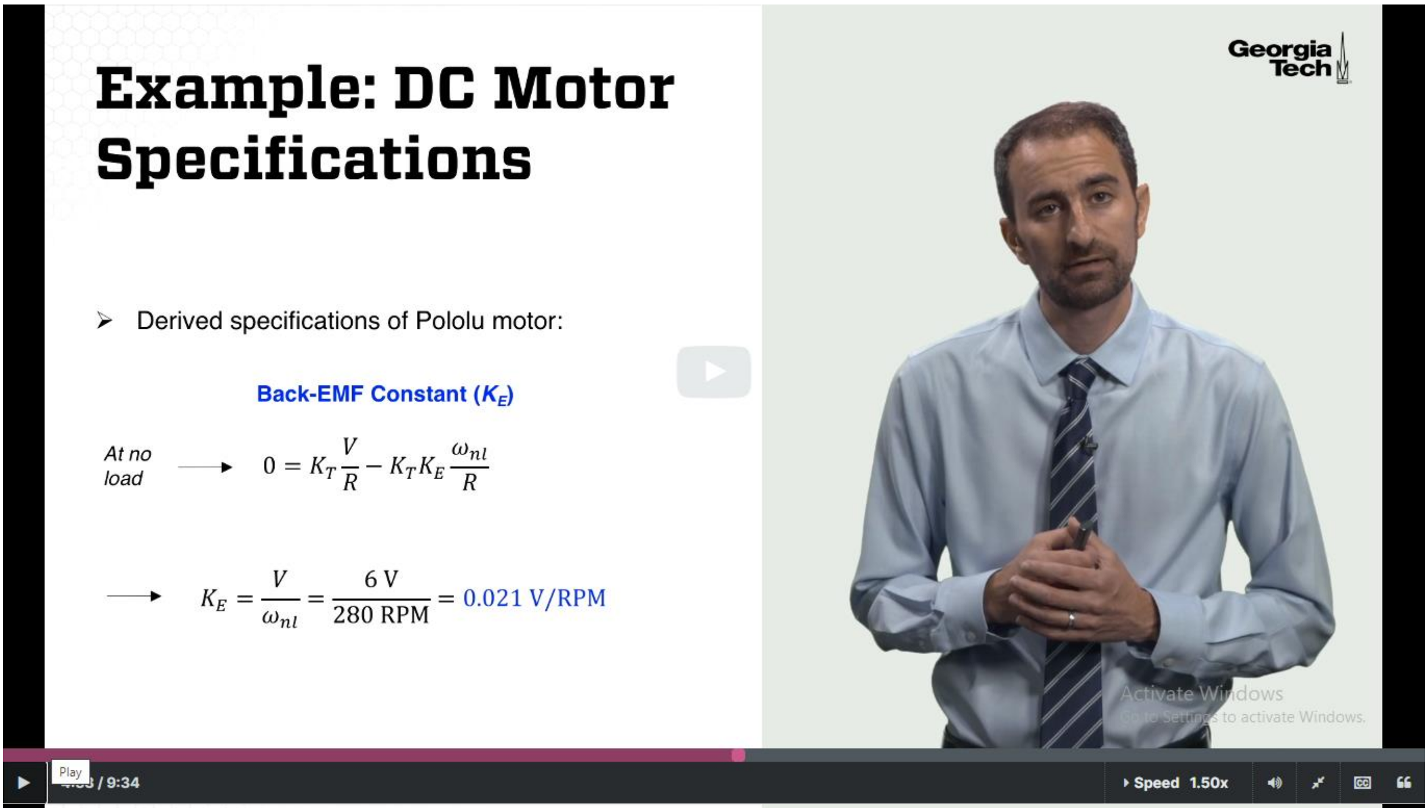
At stall $\longrightarrow \frac{V}{I} = \frac{6\text{ V}}{6.5\text{ A}} = 0.923\ \Omega$

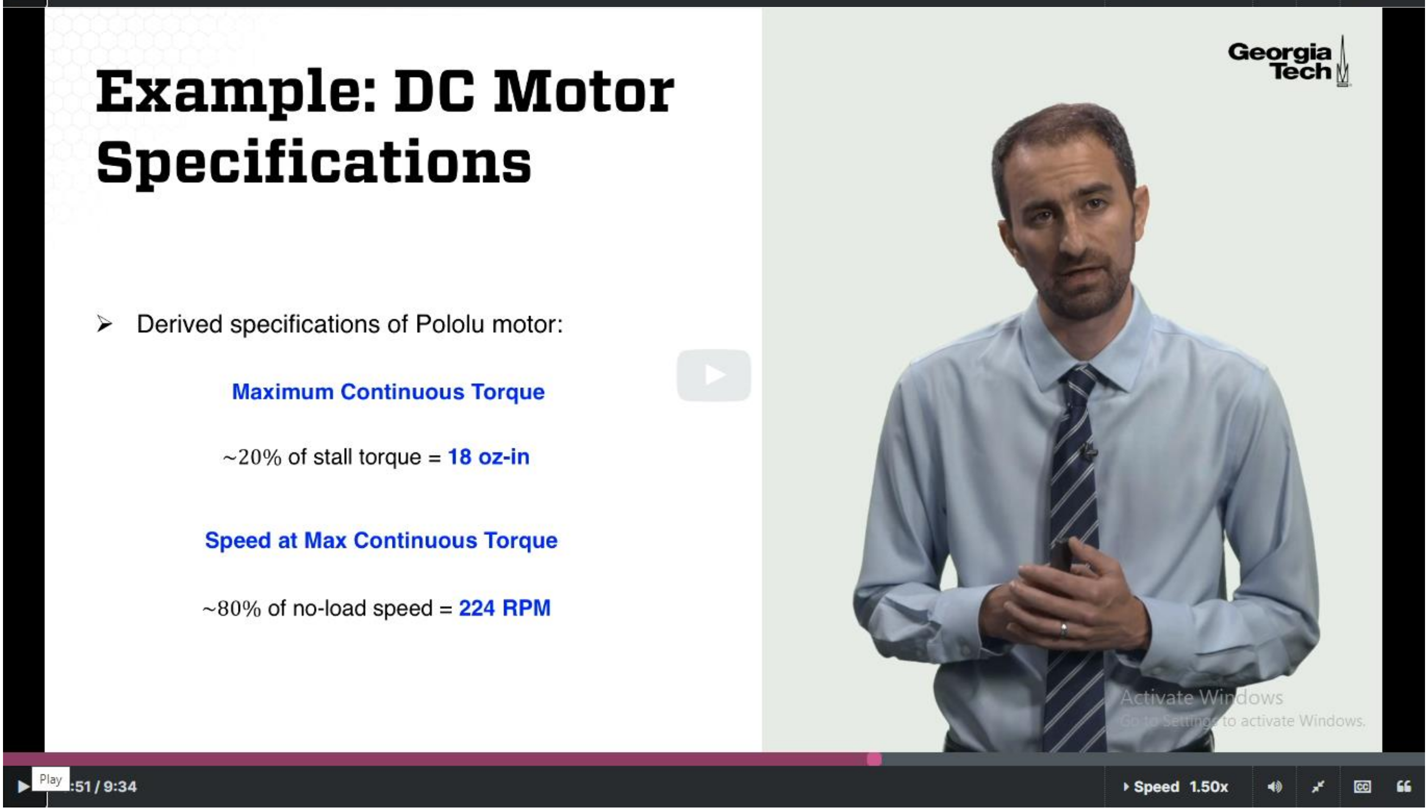
Torque Constant (K_T)

$T_{start} = K_T \frac{V}{R} \longrightarrow K_T = 90\text{ oz-in}\frac{0.923\ \Omega}{6\text{ V}}$

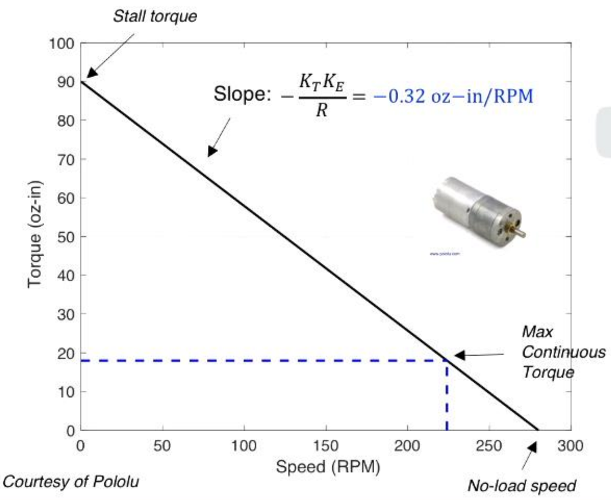
$\longrightarrow K_T = 13.84\text{ oz-in/A}$

3:53 / 9:34 Speed 1.50x


Example: DC Motor Specifications
Georgia Tech
➢ Derived specifications of Pololu motor:
Back-EMF Constant (K_E)
At no load → $0 = K_T \frac{V}{R} - K_T K_E \frac{\omega_{nl}}{R}$
→ $K_E = \frac{V}{\omega_{nl}} = \frac{6\ \text{V}}{280\ \text{RPM}} = 0.021\ \text{V/RPM}$
Play
/ 9:34
Speed 1.50x


Example: DC Motor Specifications
Georgia Tech
➢ Derived specifications of Pololu motor:
Maximum Continuous Torque
~20% of stall torque = **18 oz-in**
Speed at Max Continuous Torque
~80% of no-load speed = **224 RPM**
Play
:51 / 9:34
Speed 1.50x

Example: DC Motor Specifications

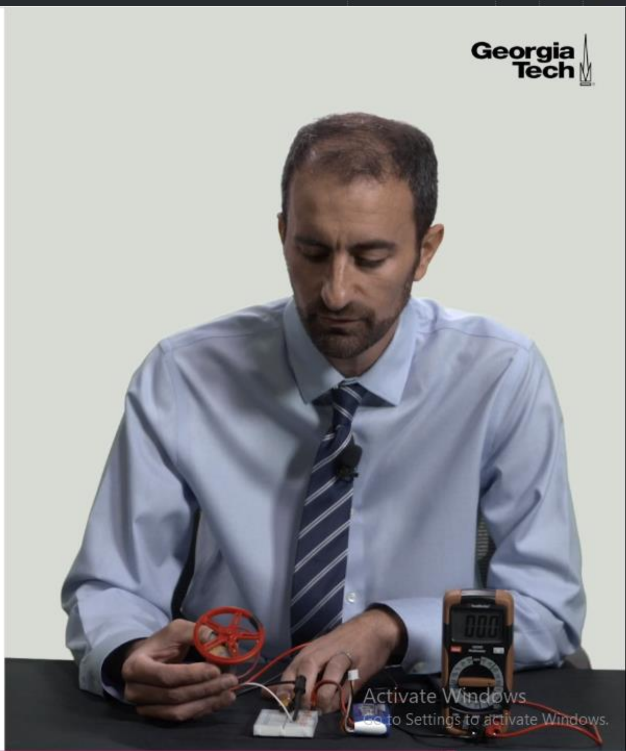


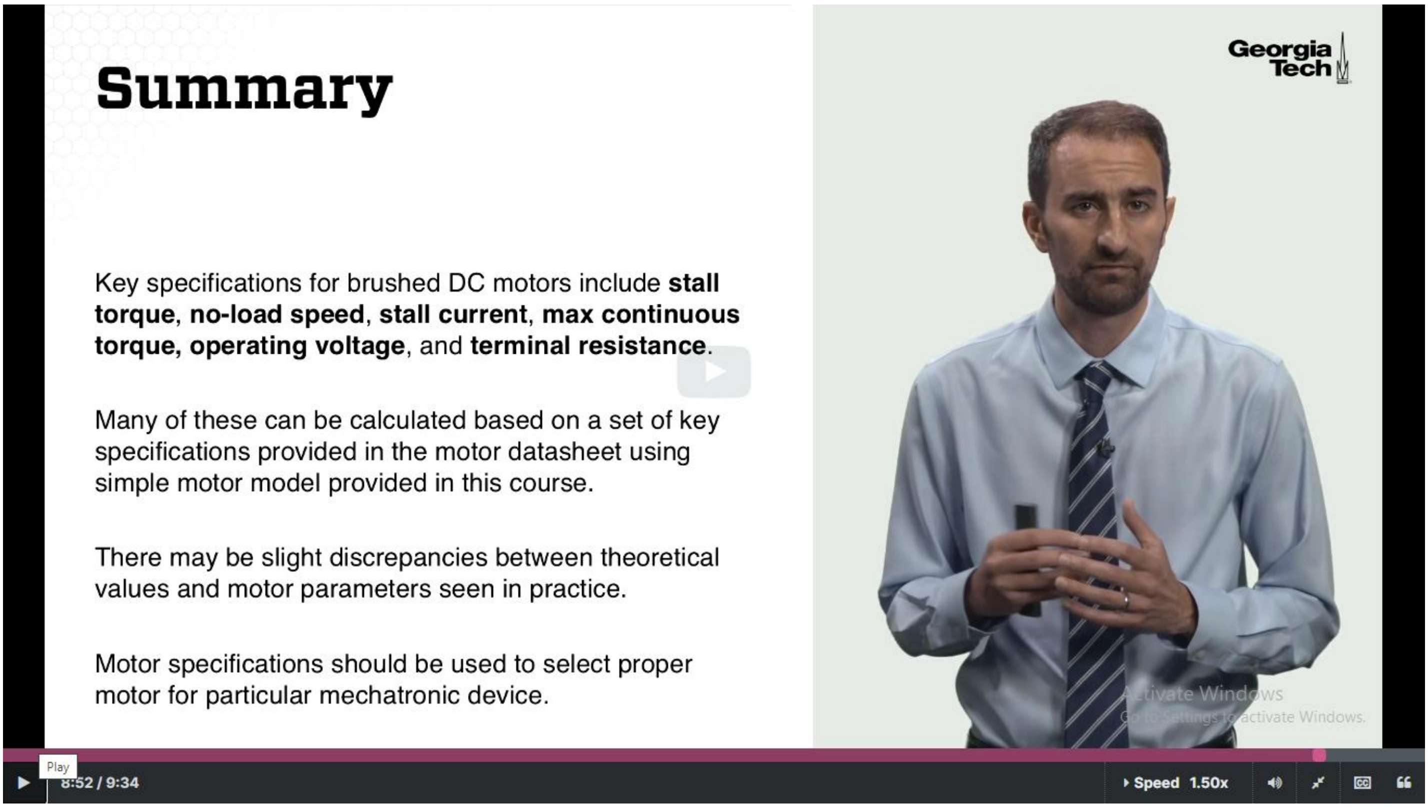
Courtesy of Pololu

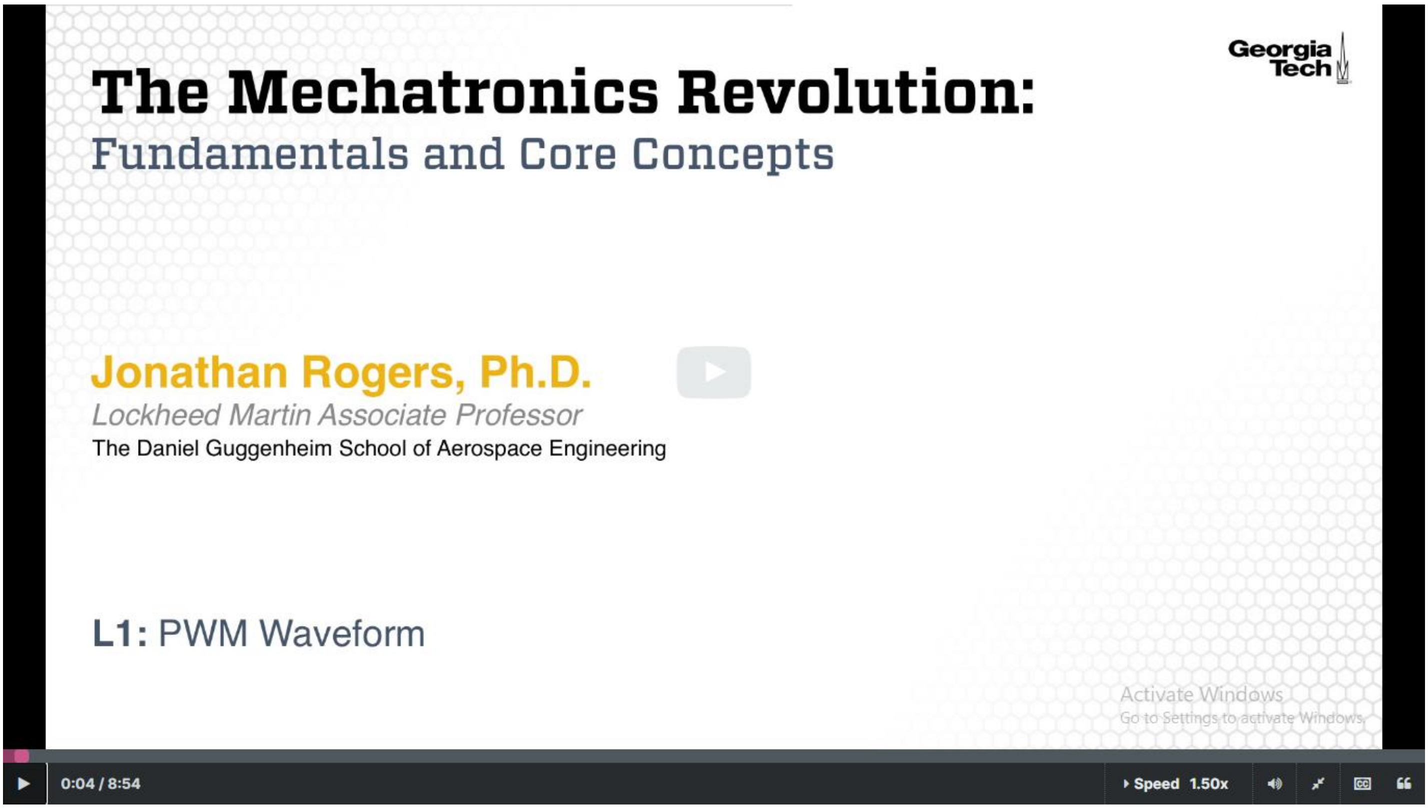
Motor Demonstration

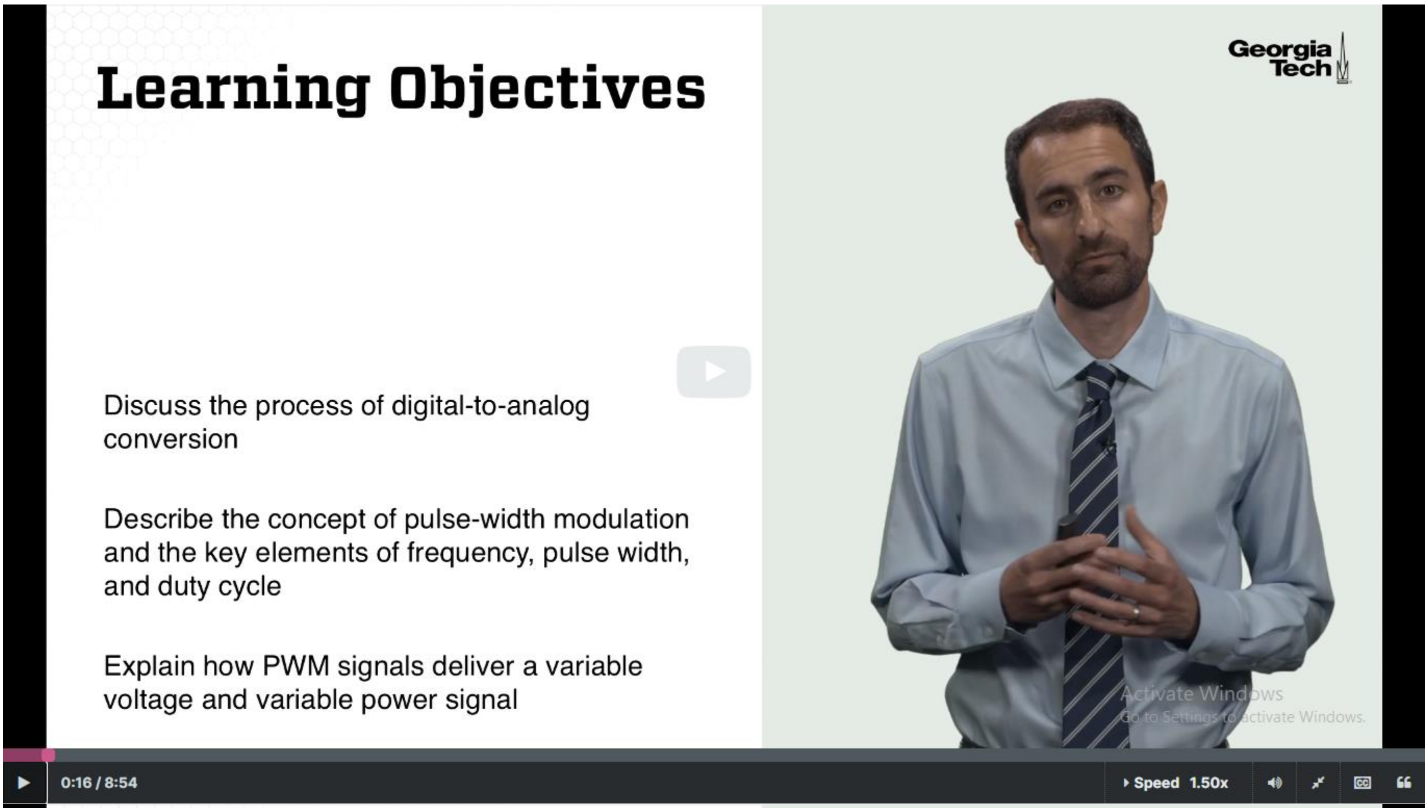
Example Motor Specifications:

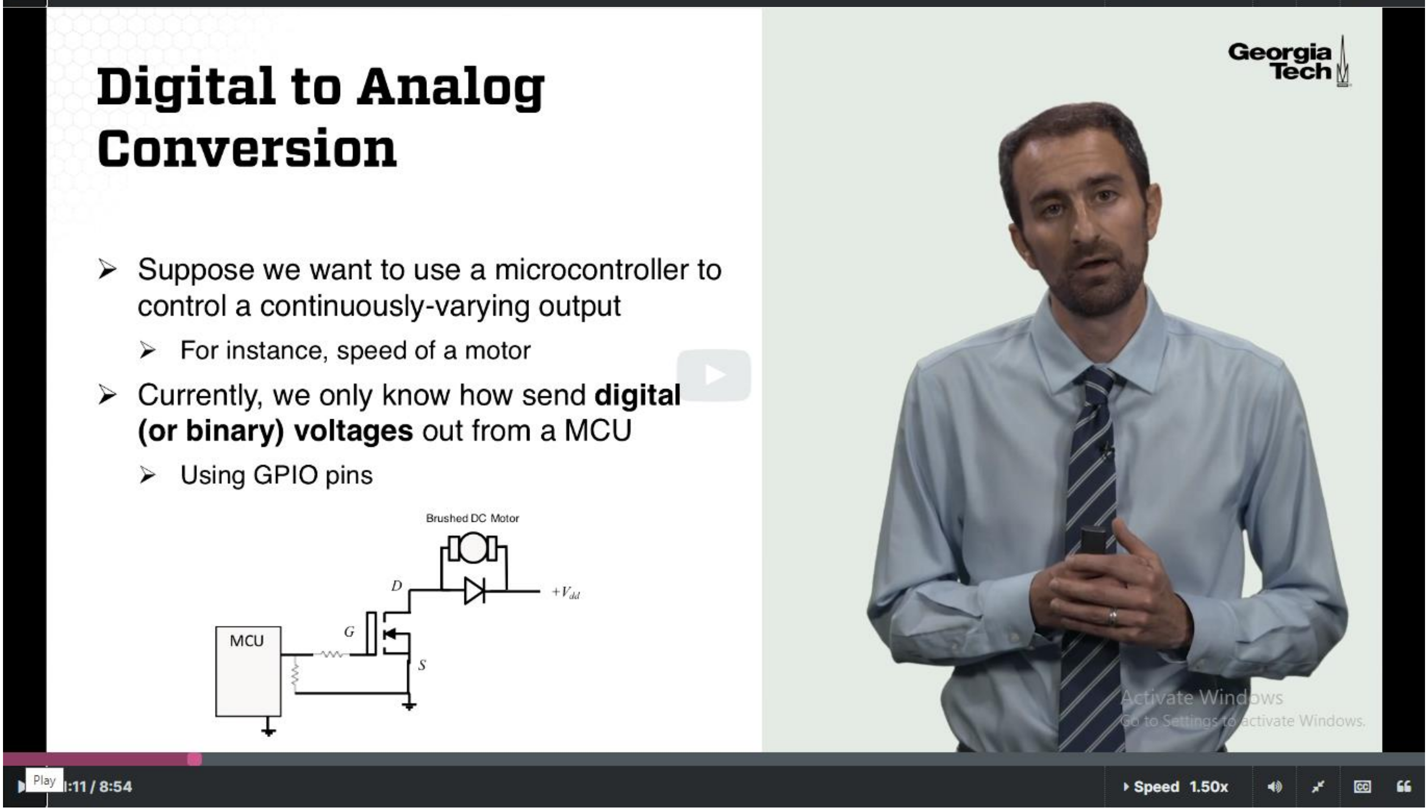
Operating Voltage	12 V
No-Load Current @ 12V	55 mA
No-Load Speed @ 12V	20 RPM
Rated Current @ 12 V	115 mA




Summary
Key specifications for brushed DC motors include **stall torque**, **no-load speed**, **stall current**, **max continuous torque, operating voltage**, and **terminal resistance**.
Many of these can be calculated based on a set of key specifications provided in the motor datasheet using simple motor model provided in this course.
There may be slight discrepancies between theoretical values and motor parameters seen in practice.
Motor specifications should be used to select proper motor for particular mechatronic device.
Georgia Tech
Activate Windows
Go to Settings to activate Windows.
Play
8:52 / 9:34
Speed 1.50x


The Mechatronics Revolution:
Fundamentals and Core Concepts
Jonathan Rogers, Ph.D.
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering
L1: PWM Waveform
Georgia Tech
Activate Windows
Go to Settings to activate Windows.
0:04 / 8:54
Speed 1.50x

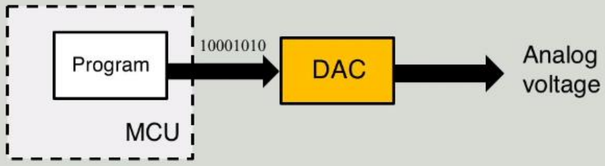

Learning Objectives
Georgia Tech
Discuss the process of digital-to-analog conversion
Describe the concept of pulse-width modulation and the key elements of frequency, pulse width, and duty cycle
Explain how PWM signals deliver a variable voltage and variable power signal
Activate Windows
Go to Settings to activate Windows.
0:16 / 8:54
Speed 1.50x


Digital to Analog Conversion
Georgia Tech
➢ Suppose we want to use a microcontroller to control a continuously-varying output
➢ For instance, speed of a motor
➢ Currently, we only know how send **digital (or binary) voltages** out from a MCU
➢ Using GPIO pins
Brushed DC Motor
D
$+V_{dd}$
G
MCU
S
Activate Windows
Go to Settings to activate Windows.
Play
:11 / 8:54
Speed 1.50x

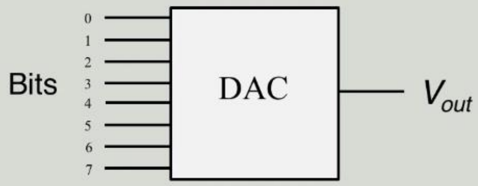
Digital to Analog Conversion

Georgia Tech

- A digital to analog converter (DAC) converts digital signals to analog ones
- DACs are special integrated circuits that generate a variable voltage output given a binary number input



DAC Chip Functional Diagram



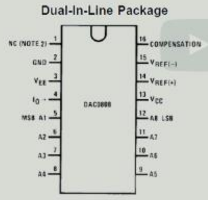
Play 2:07 / 8:54 Speed 1.50x

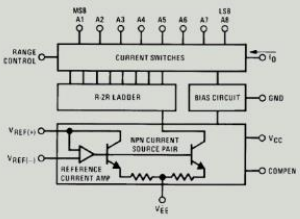
Digital to Analog Conversion

Georgia Tech

- Example: Texas Instruments DAC0808 8-bit D/A Converter

Courtesy of Texas Instruments





- Problem: D/A converters use a lot of MCU output pins (most MCU's do not have DAC's built in)
- For instance, using 0808 chip we would need to use all pins from one entire port just to generate one analog voltage signal

Play 3:06 / 8:54 Speed 1.50x

Pulse Width Modulation (PWM)

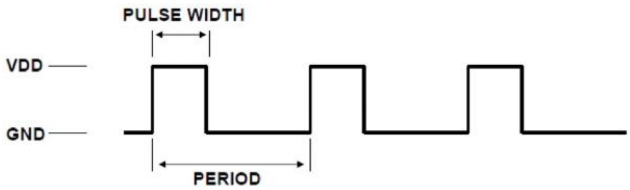
- Pulse width modulation (PWM) is very common method of generating a variable power signal using single output pin
- Used often in motor and servo control
- Three quantities define PWM signal:

$$\text{Duty Cycle} = \frac{\text{Pulse Width}}{\text{Period}} \times 100\%$$

Pulse width

Period

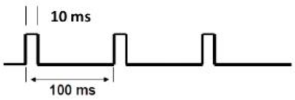
Voltage



Pulse Width Modulation (PWM)

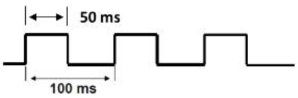
- Consider following 3 cases:

A)



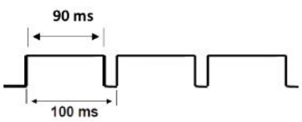
Duty Cycle = 10%

B)



Duty Cycle = 50%

C)

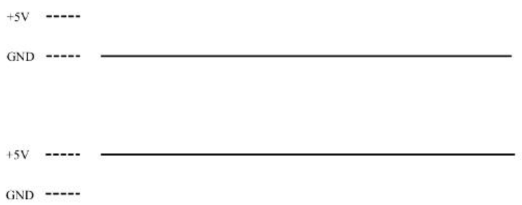


Duty Cycle = 90%

Pulse Width Modulation (PWM)

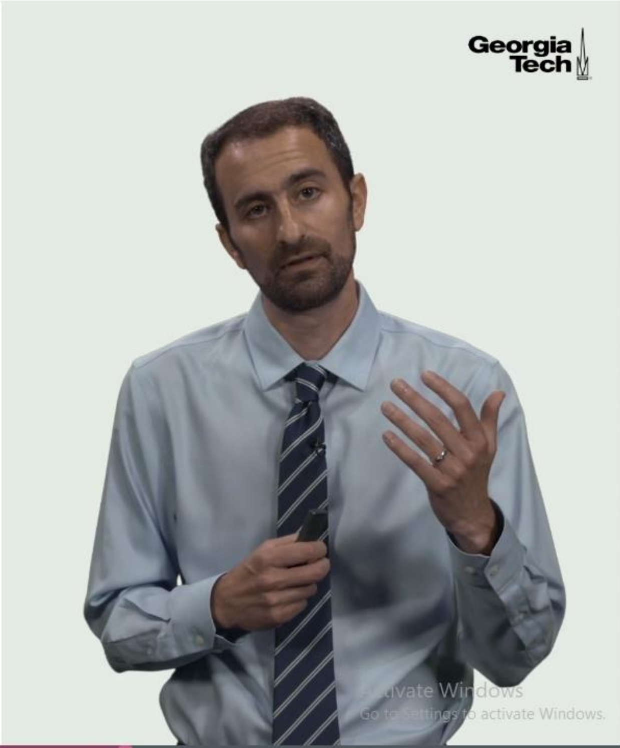
Georgia Tech

➢ What is the duty cycle of the below two PWM signals?



0%

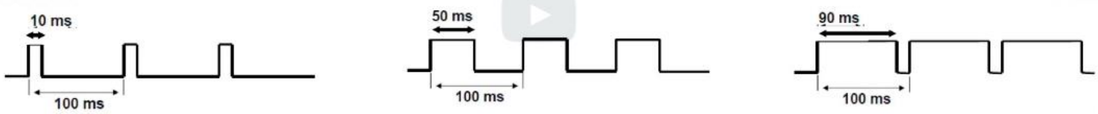
100%



Pulse Width Modulation (PWM)

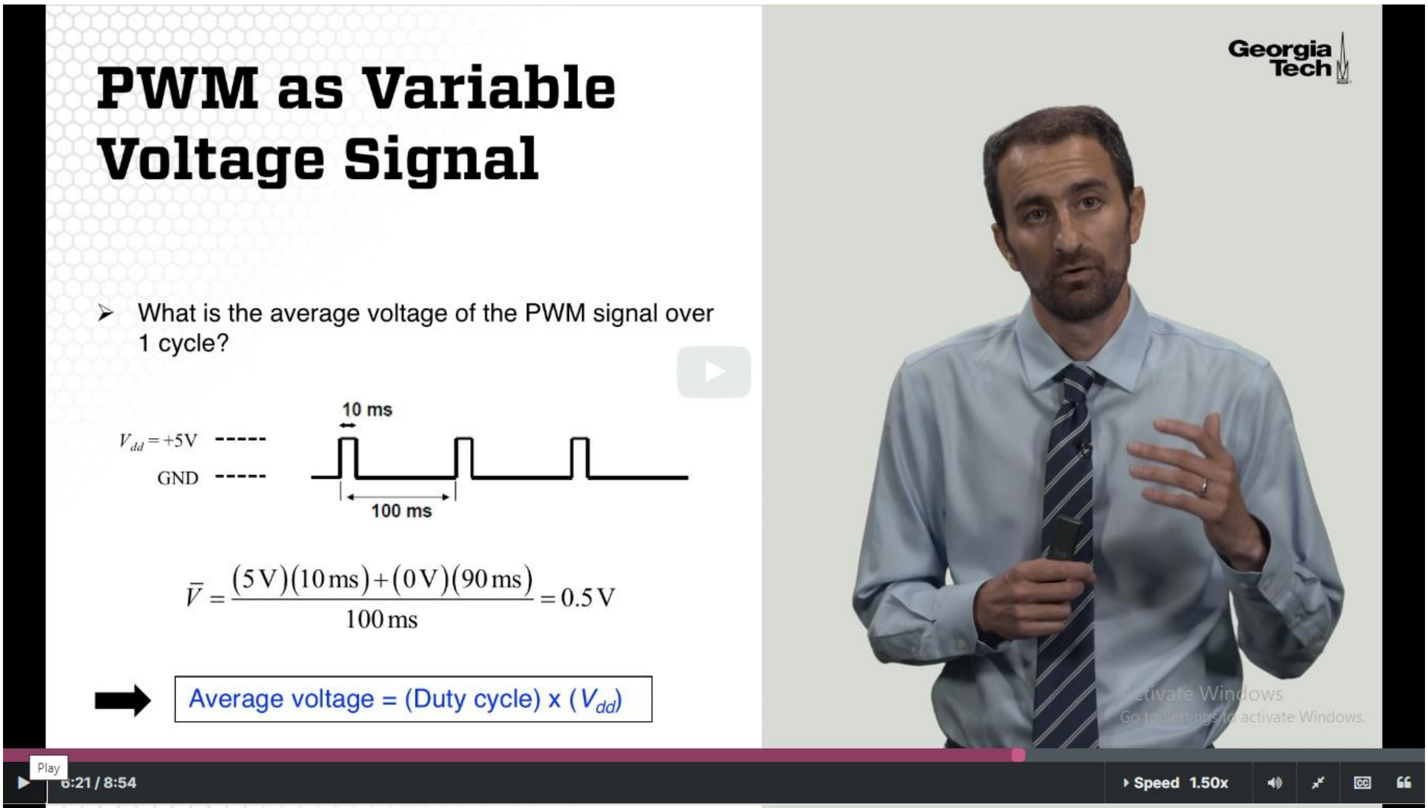
Georgia Tech

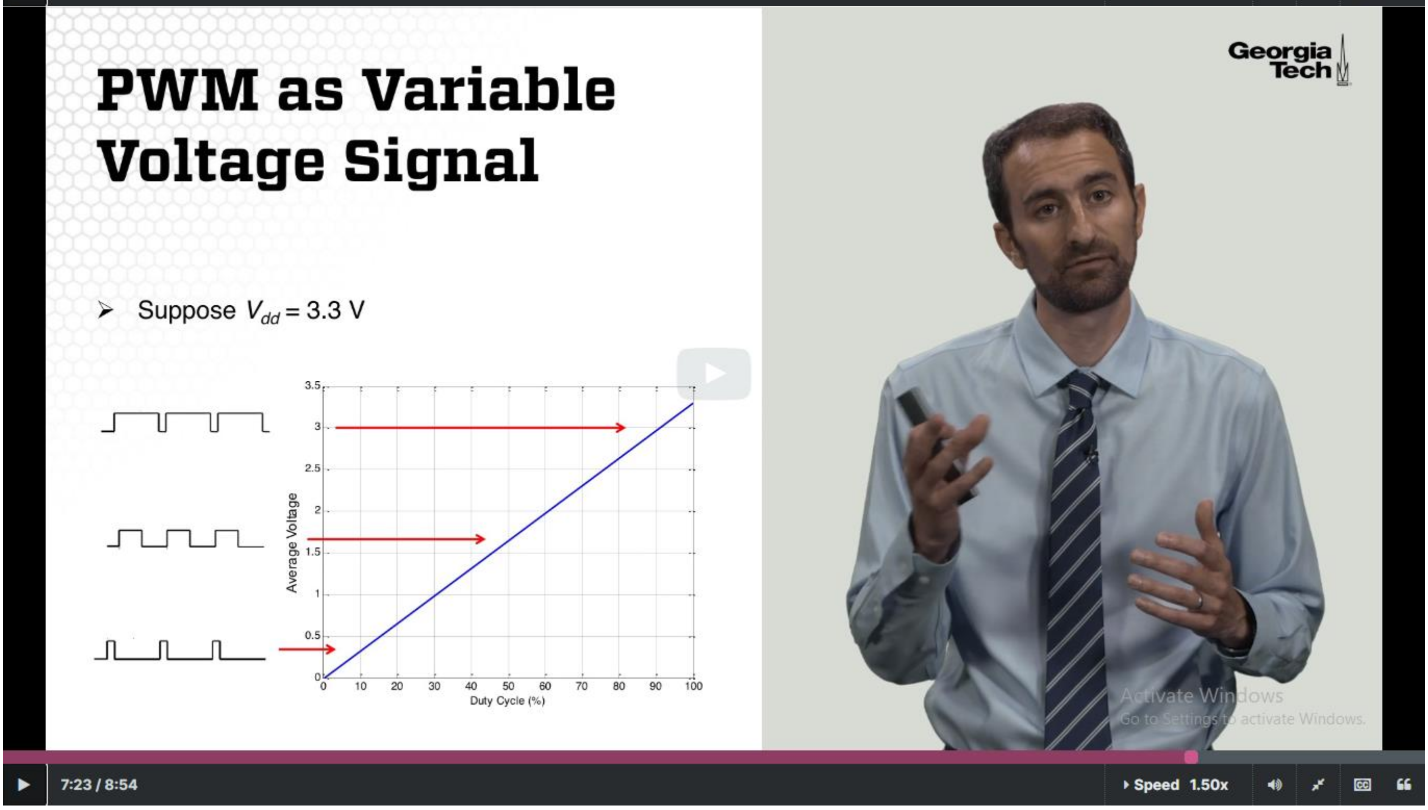
➢ PWM signal has a **fixed frequency** that is independent of the duty cycle

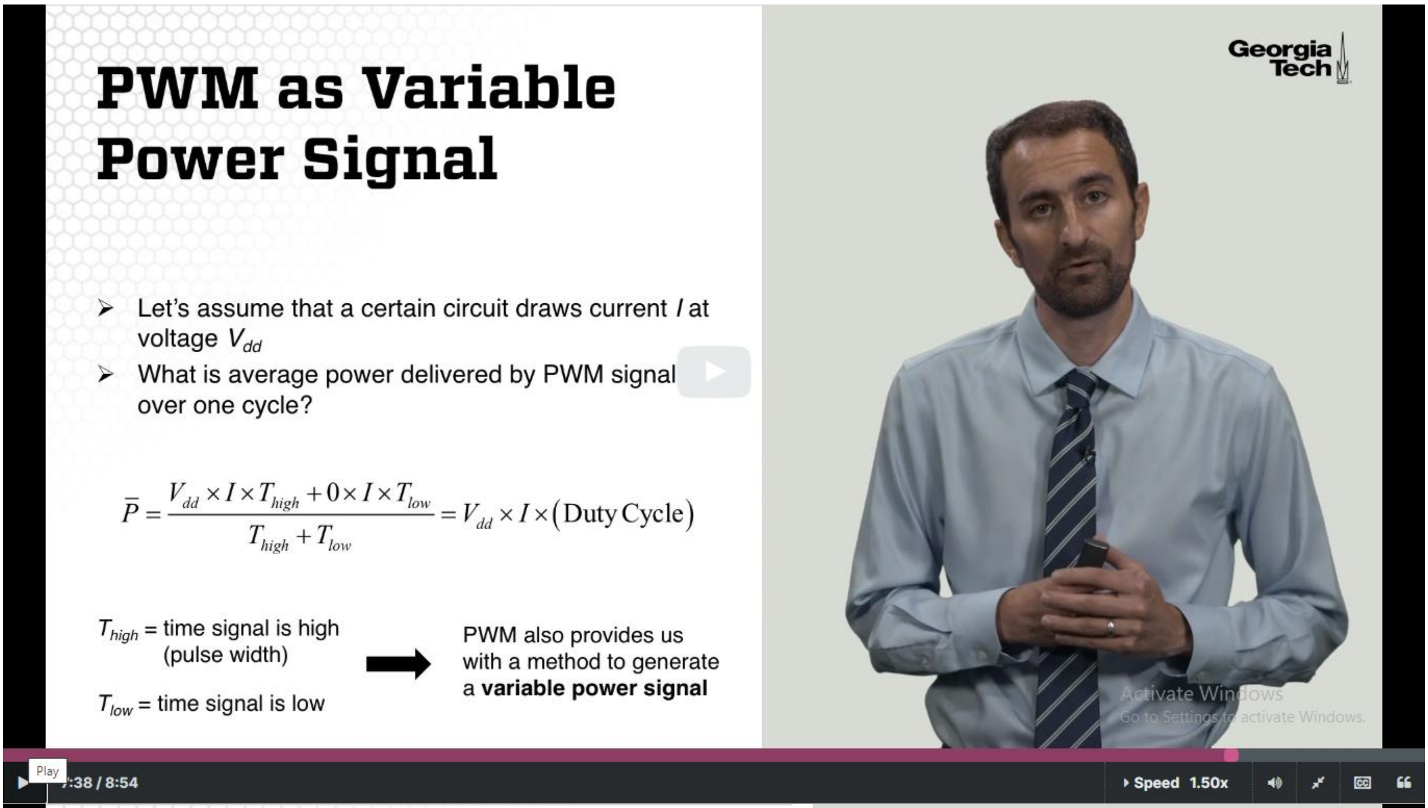


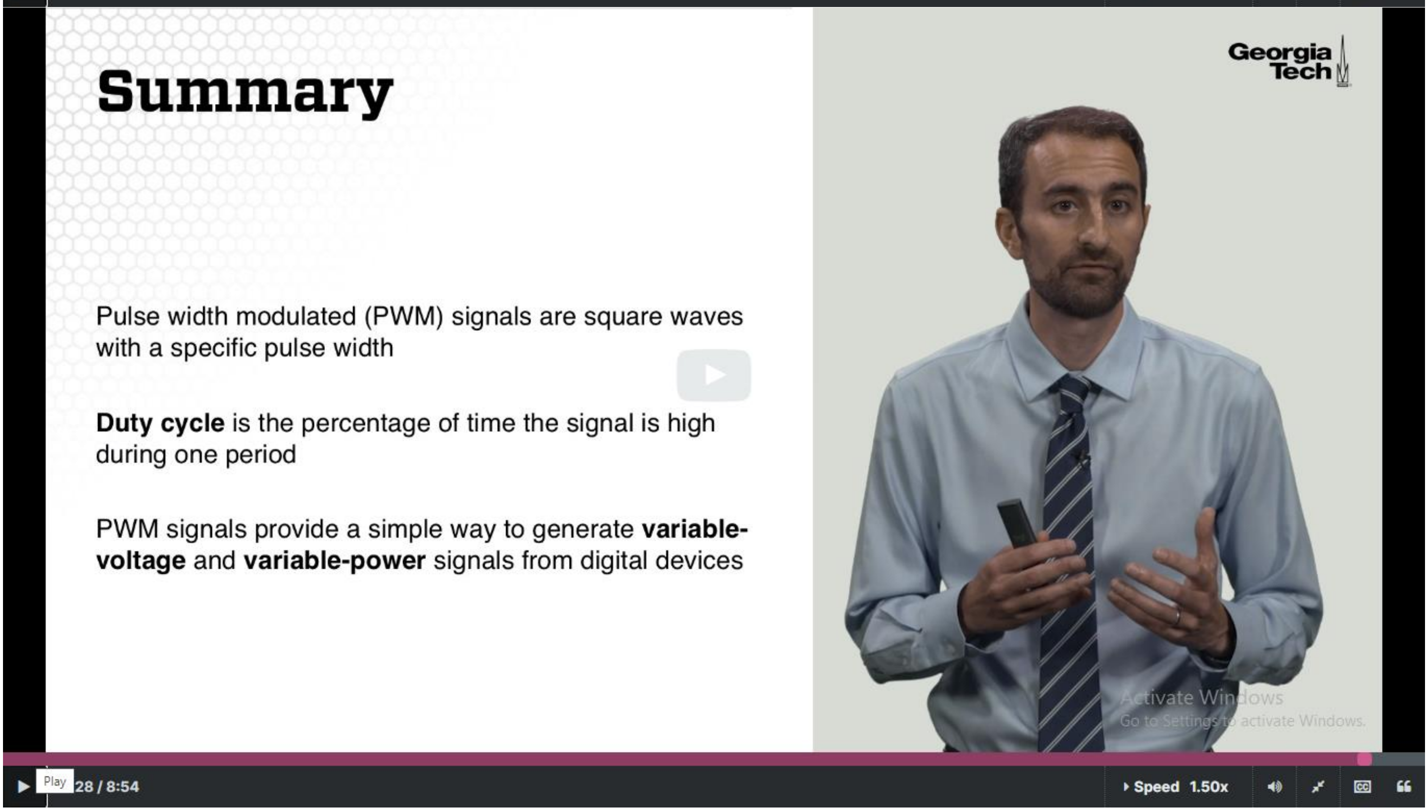
All these signals have a frequency of 1/100 ms = 10 Hz

➢ PWM signal can be generated using a digital output pin by rapidly setting pin high/low (square wave signal)


PWM as Variable Voltage Signal
What is the average voltage of the PWM signal over 1 cycle?
10 ms
$V_{dd} = +5\text{V}$
GND
100 ms
$\bar{V} = \frac{(5\,\text{V})(10\,\text{ms}) + (0\,\text{V})(90\,\text{ms})}{100\,\text{ms}} = 0.5\,\text{V}$
Average voltage = (Duty cycle) x (V_{dd})
Georgia Tech
Play
6:21 / 8:54
Speed 1.50x


PWM as Variable Voltage Signal
Suppose $V_{dd} = 3.3$ V
Average Voltage
Duty Cycle (%)
0
0.5
1
1.5
2
2.5
3
3.5
0 10 20 30 40 50 60 70 80 90 100
Georgia Tech
7:23 / 8:54
Speed 1.50x


Georgia Tech
PWM as Variable Power Signal
➢ Let's assume that a certain circuit draws current *I* at voltage V_{dd}
➢ What is average power delivered by PWM signal over one cycle?
$$\overline{P} = \frac{V_{dd} \times I \times T_{high} + 0 \times I \times T_{low}}{T_{high} + T_{low}} = V_{dd} \times I \times (\text{Duty Cycle})$$
T_{high} = time signal is high (pulse width)
T_{low} = time signal is low
PWM also provides us with a method to generate a **variable power signal**
Play
:38 / 8:54
Speed 1.50x


Georgia Tech
Summary
Pulse width modulated (PWM) signals are square waves with a specific pulse width
Duty cycle is the percentage of time the signal is high during one period
PWM signals provide a simple way to generate **variable-voltage** and **variable-power** signals from digital devices
Play
28 / 8:54
Speed 1.50x

The Mechatronics Revolution:
Fundamentals and Core Concepts

Georgia Tech

Jonathan Rogers, Ph.D.
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering

L2: PWM Control of Mechanical Devices

Play
0:02 / 10:31
Speed 1.50x

The Mechatronics Revolution:
Fundamentals and Core Concepts

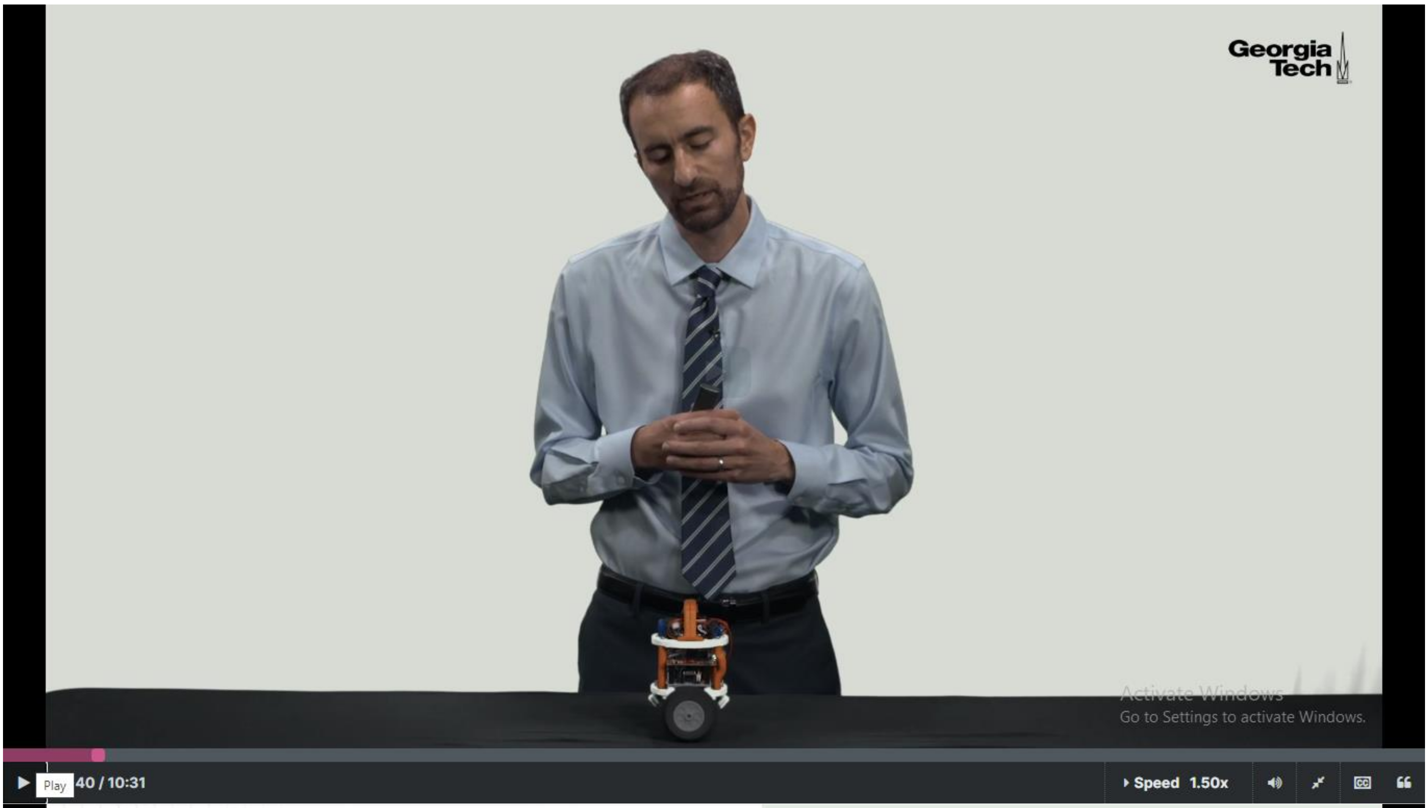
Georgia Tech

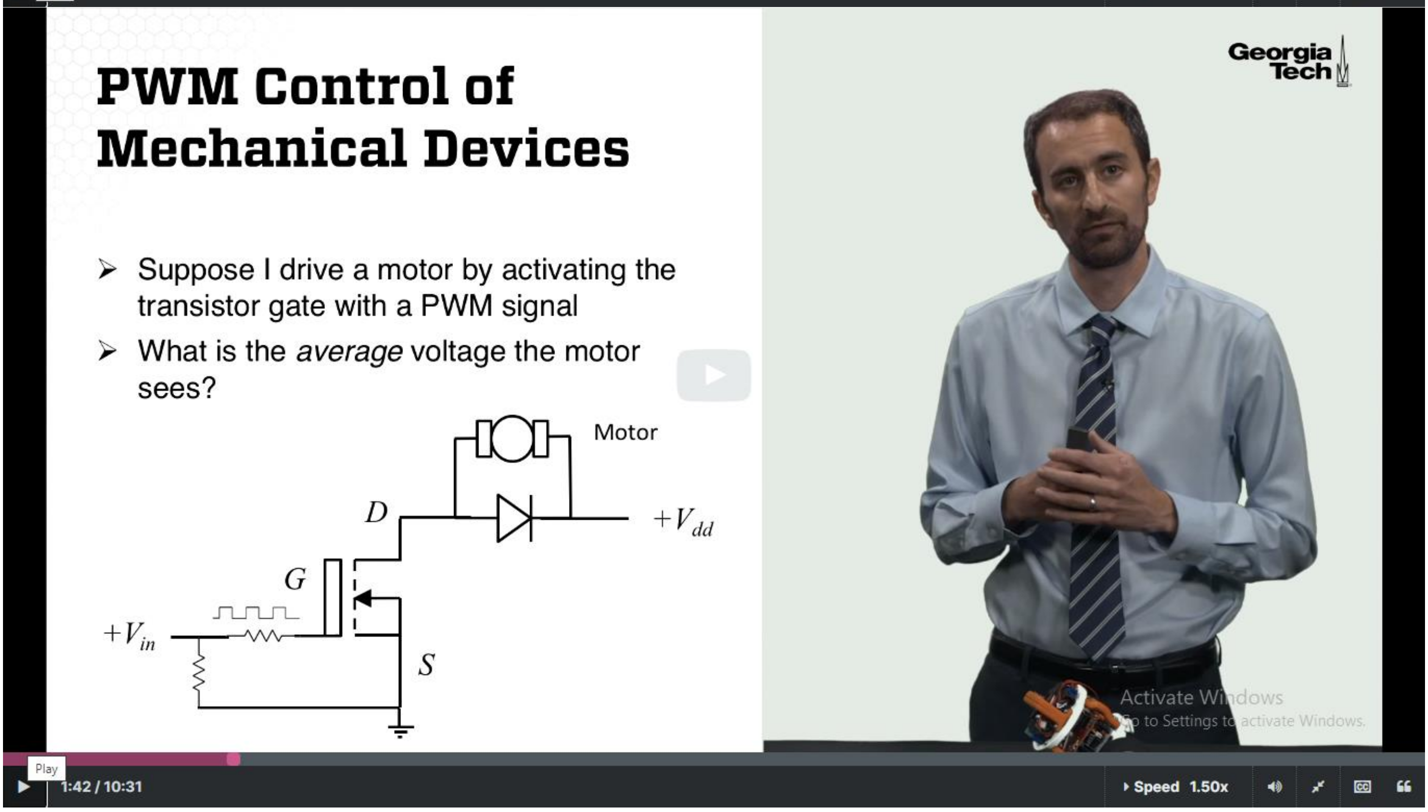
Learning Objectives

Georgia Tech

Describe how PWM signals are used to generate variable voltage signals for motor control

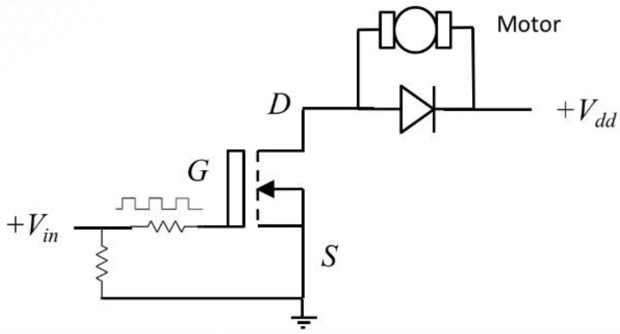
Explain how PWM signals are used in H-Bridge


Georgia Tech
Activate Windows
Go to Settings to activate Windows.
Play
40 / 10:31
Speed 1.50x


PWM Control of Mechanical Devices
➢ Suppose I drive a motor by activating the transistor gate with a PWM signal
➢ What is the *average* voltage the motor sees?
Motor
D
G
S
$+V_{dd}$
$+V_{in}$
Georgia Tech
Activate Windows
Go to Settings to activate Windows.
Play
1:42 / 10:31
Speed 1.50x

PWM Control of Mechanical Devices

- Suppose I drive a motor by activating the transistor gate with a PWM signal
- What is the *average* voltage the motor sees?



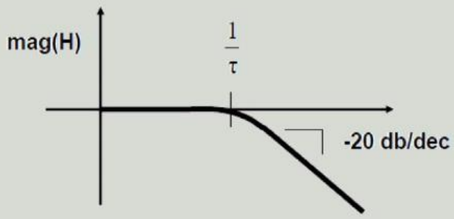
$$\bar{V} = \frac{V_{dd} \times T_{high} + 0 \times T_{low}}{T_{high} + T_{low}}$$
$$= V_{dd} \times (\text{Duty Cycle})$$

- Thus, if V_{dd} = 12 V, we can produce a signal with any average voltage in 0-12 V range by adjusting duty cycle between 0-100%.
- Note: Switching times of transistors are in the ~10 ns range. PWM signal periods are in the 10's of ms range, so MOSFET switching time is negligible.

PWM Control of Mechanical Devices

- **Question**: When you give a PWM input voltage signal to a motor, why doesn't it respond to each square wave peak and valley?
  - i.e., Why doesn't it slow down and speed up with every pulse?
  - Explain in terms of frequency response.
- **Answer**: PWM frequency is well beyond the cutoff frequency for a motor.

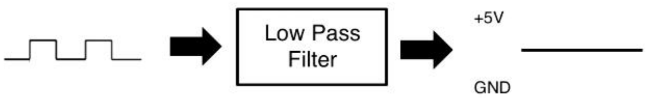
Bode Plot for RL Circuit

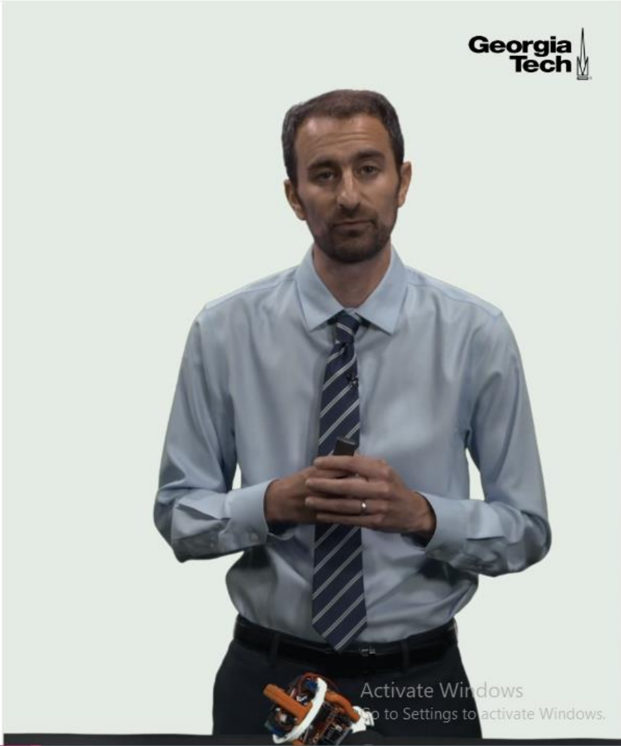


- RL circuit such as a motor has can be modeled as a first-order system with time constant τ.
- *Cutoff frequency* for such a system is $1/\tau$.
- Inputs with frequency higher than cutoff frequency get attenuated – meaning system does not exhibit oscillatory response.

PWM Control of Mechanical Devices

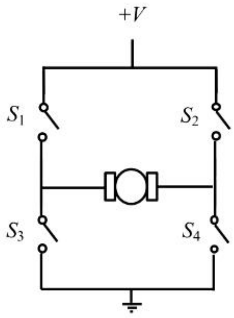
- Like motors, most mechanical devices act as a low-pass filter
- If you low pass filter a PWM signal, the periodic content is lost and just the mean value of the signal is left
- Thus, PWM + low pass filter = analog voltage signal

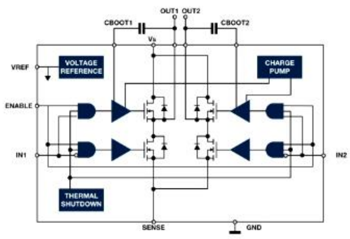


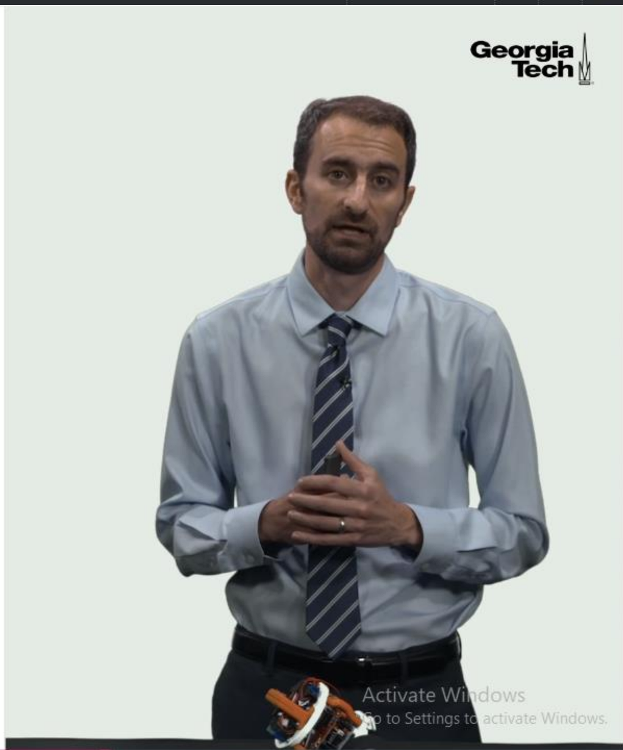


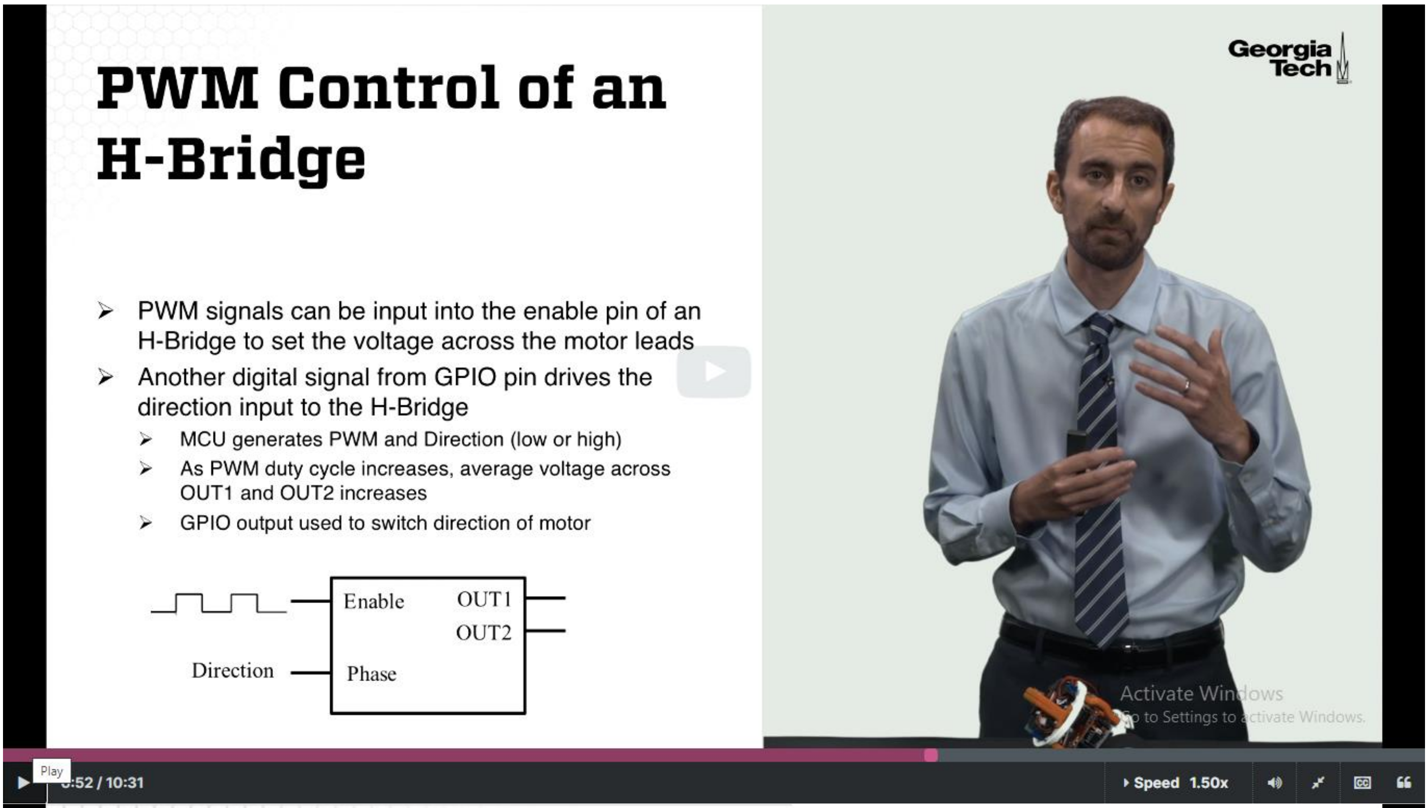
PWM Control of an H-Bridge

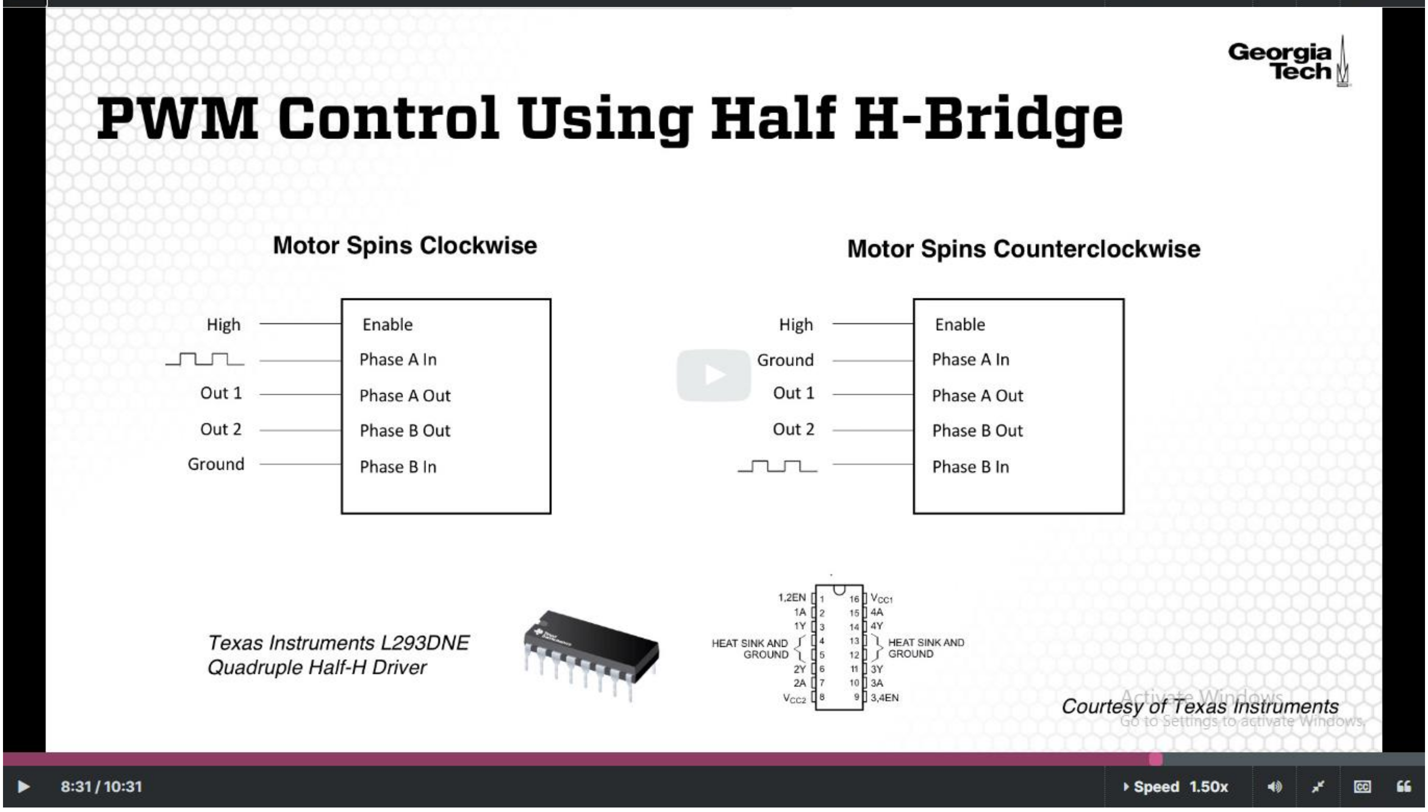
- Recall that H-Bridge circuits are commonly used to flip the polarity of the voltage across a load








Georgia Tech
PWM Control of an H-Bridge
PWM signals can be input into the enable pin of an H-Bridge to set the voltage across the motor leads
Another digital signal from GPIO pin drives the direction input to the H-Bridge
MCU generates PWM and Direction (low or high)
As PWM duty cycle increases, average voltage across OUT1 and OUT2 increases
GPIO output used to switch direction of motor
Enable
OUT1
OUT2
Direction
Phase
Activate Windows
Go to Settings to activate Windows.
Play
6:52 / 10:31
Speed 1.50x


Georgia Tech
PWM Control Using Half H-Bridge
Motor Spins Clockwise
High
Out 1
Out 2
Ground
Enable
Phase A In
Phase A Out
Phase B Out
Phase B In
Motor Spins Counterclockwise
High
Ground
Out 1
Out 2
Enable
Phase A In
Phase A Out
Phase B Out
Phase B In
Texas Instruments L293DNE
Quadruple Half-H Driver
1,2EN
1A
1Y
HEAT SINK AND GROUND
2Y
2A
VCC2
VCC1
4A
4Y
HEAT SINK AND GROUND
3Y
3A
3,4EN
Courtesy of Texas Instruments
Activate Windows
Go to Settings to activate Windows.
8:31 / 10:31
Speed 1.50x

Summary

PWM signals are commonly used to provide a **varying voltage signal to mechanical loads** such as brushed DC motors.

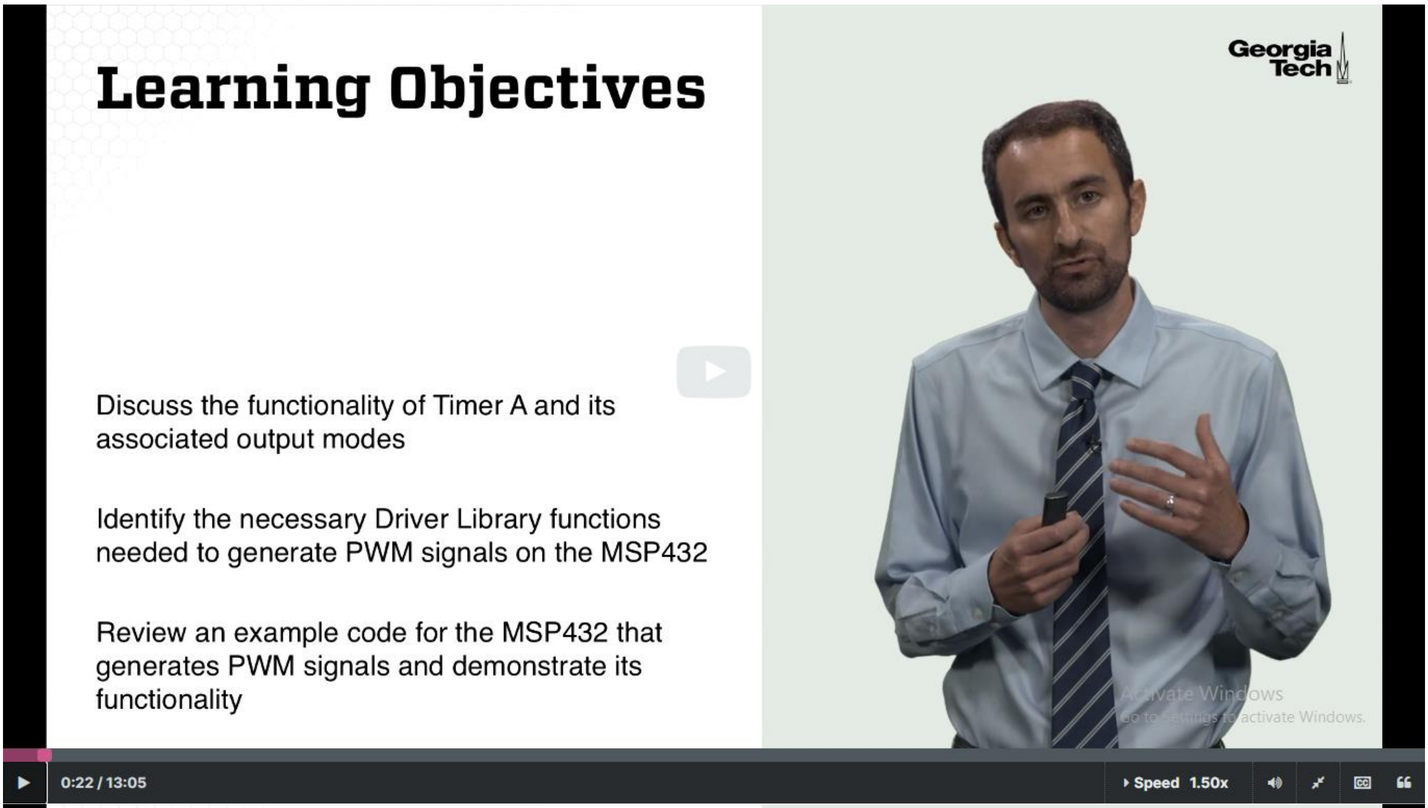
This works as long as PWM frequency is much faster than the response rate of the mechanical load.

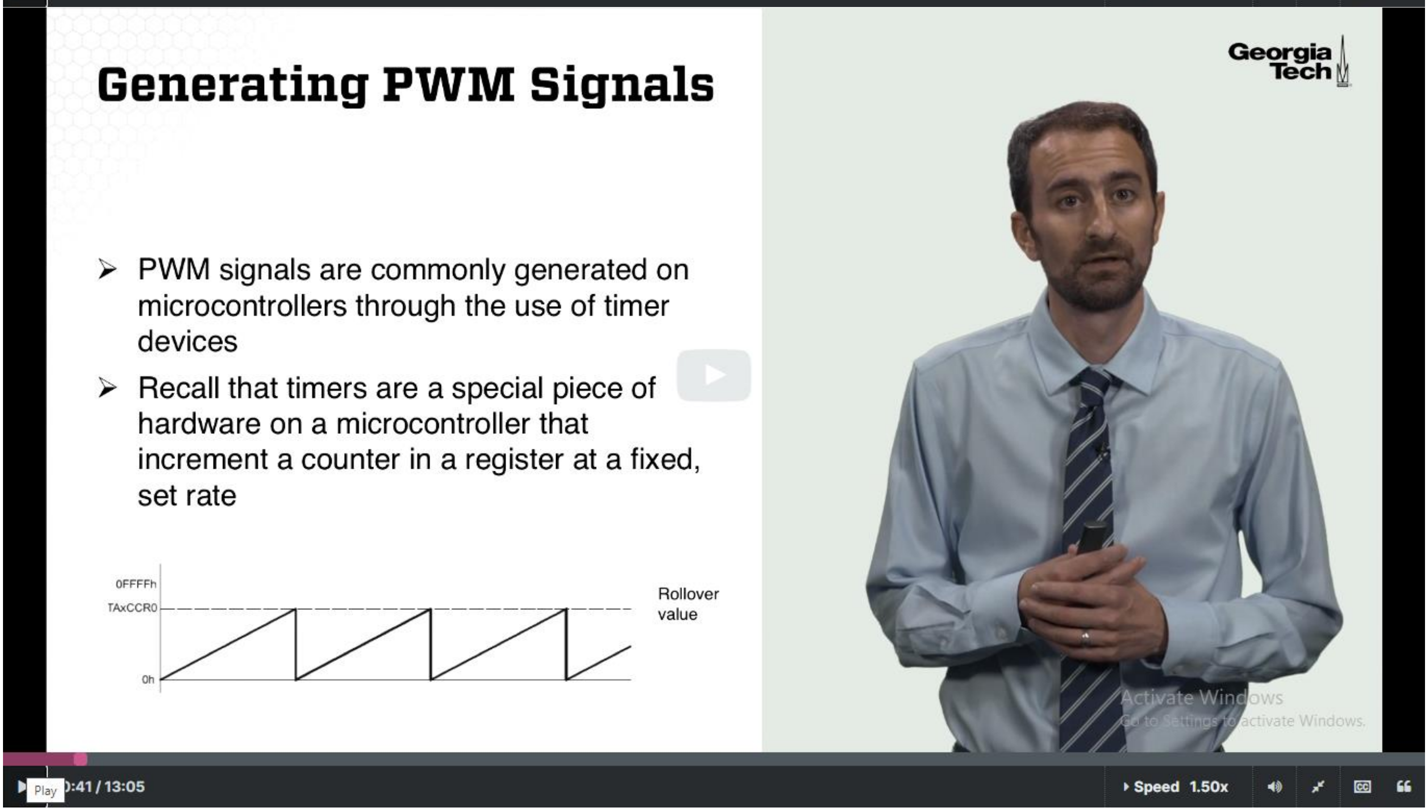
A PWM signal can be used in conjunction with an H-Bridge to achieve **variable speed, bidirectional control** of a DC motor.

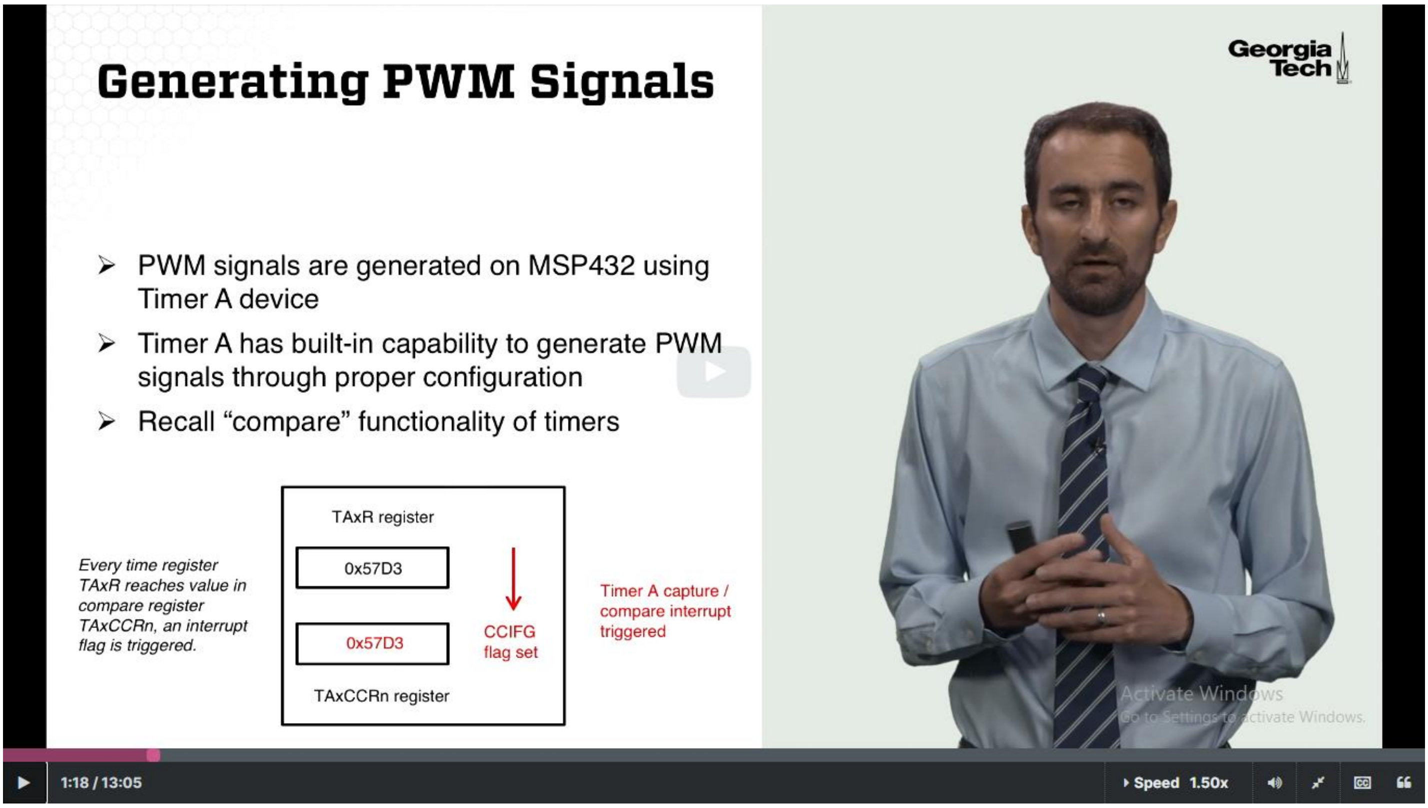
The Mechatronics Revolution:
Fundamentals and Core Concepts

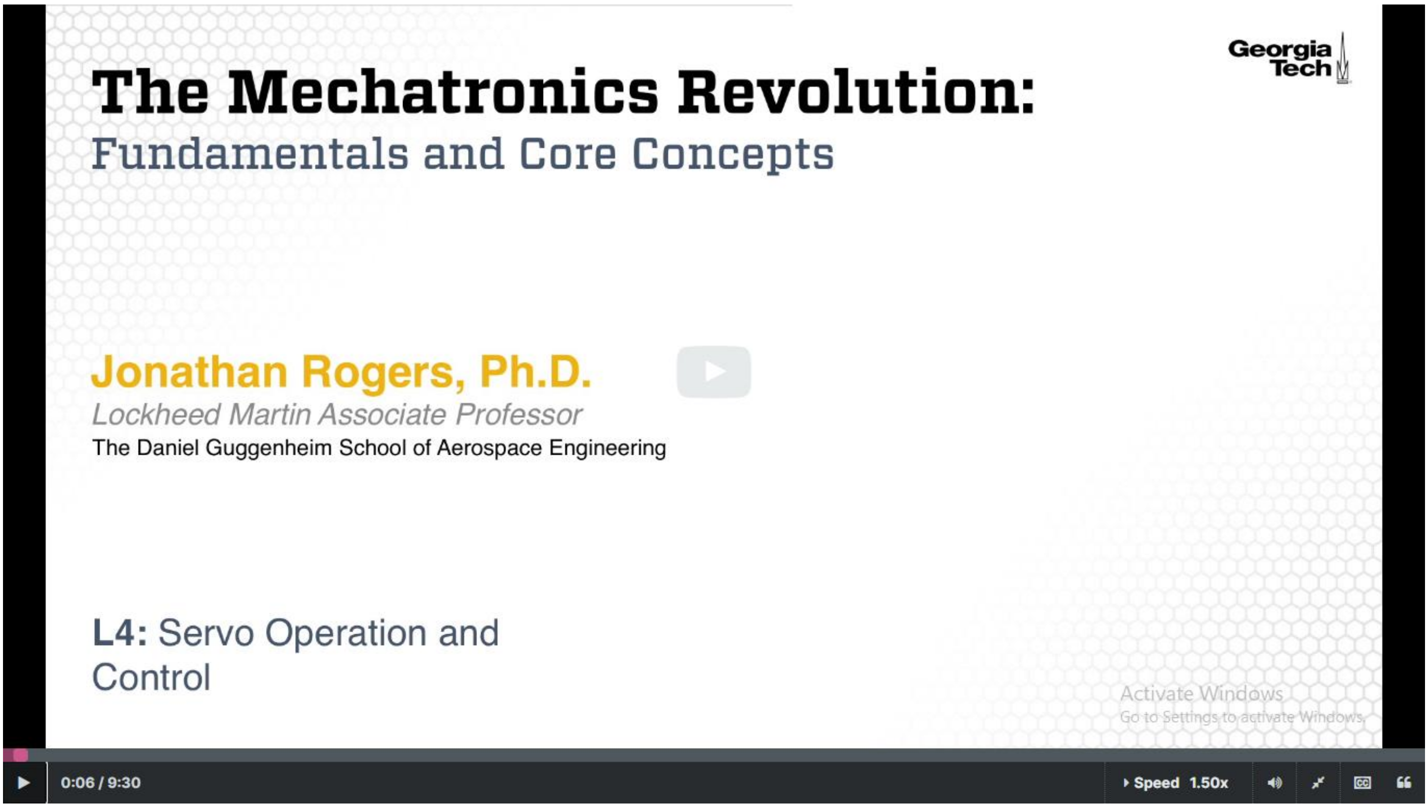
Jonathan Rogers, Ph.D.
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering

L3: Generating PWM Signals on the MSP432


Learning Objectives
Georgia Tech
Discuss the functionality of Timer A and its associated output modes
Identify the necessary Driver Library functions needed to generate PWM signals on the MSP432
Review an example code for the MSP432 that generates PWM signals and demonstrate its functionality
Activate Windows
Go to Settings to activate Windows.
0:22 / 13:05
Speed 1.50x


Generating PWM Signals
Georgia Tech
PWM signals are commonly generated on microcontrollers through the use of timer devices
Recall that timers are a special piece of hardware on a microcontroller that increment a counter in a register at a fixed, set rate
0FFFFh
TAxCCR0
0h
Rollover value
Activate Windows
Go to Settings to activate Windows.
Play
0:41 / 13:05
Speed 1.50x


Generating PWM Signals
Georgia Tech
➢ PWM signals are generated on MSP432 using Timer A device
➢ Timer A has built-in capability to generate PWM signals through proper configuration
➢ Recall "compare" functionality of timers
Every time register TAxR reaches value in compare register TAxCCRn, an interrupt flag is triggered.
TAxR register
0x57D3
0x57D3
TAxCCRn register
CCIFG flag set
Timer A capture / compare interrupt triggered
1:18 / 13:05
Speed 1.50x


The Mechatronics Revolution:
Fundamentals and Core Concepts
Georgia Tech
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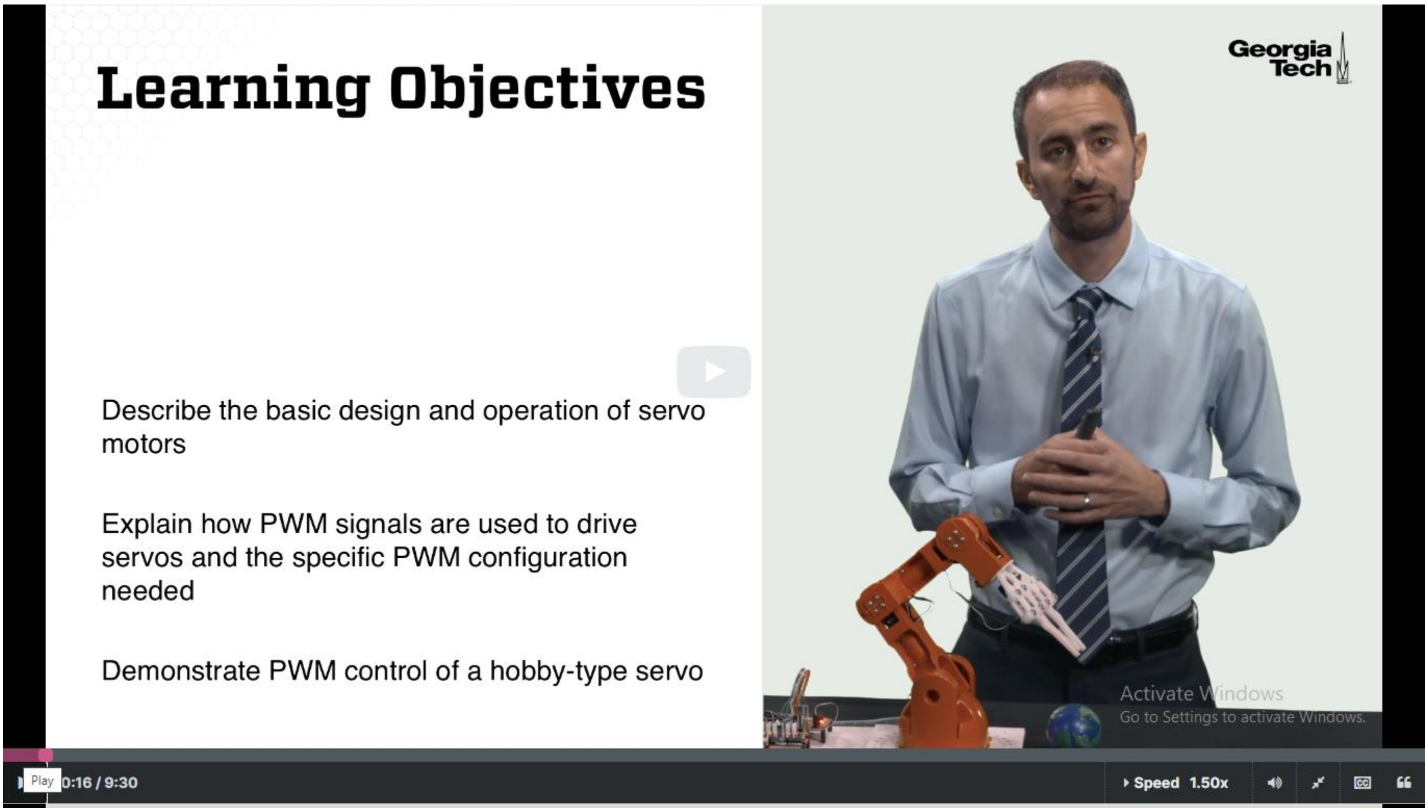
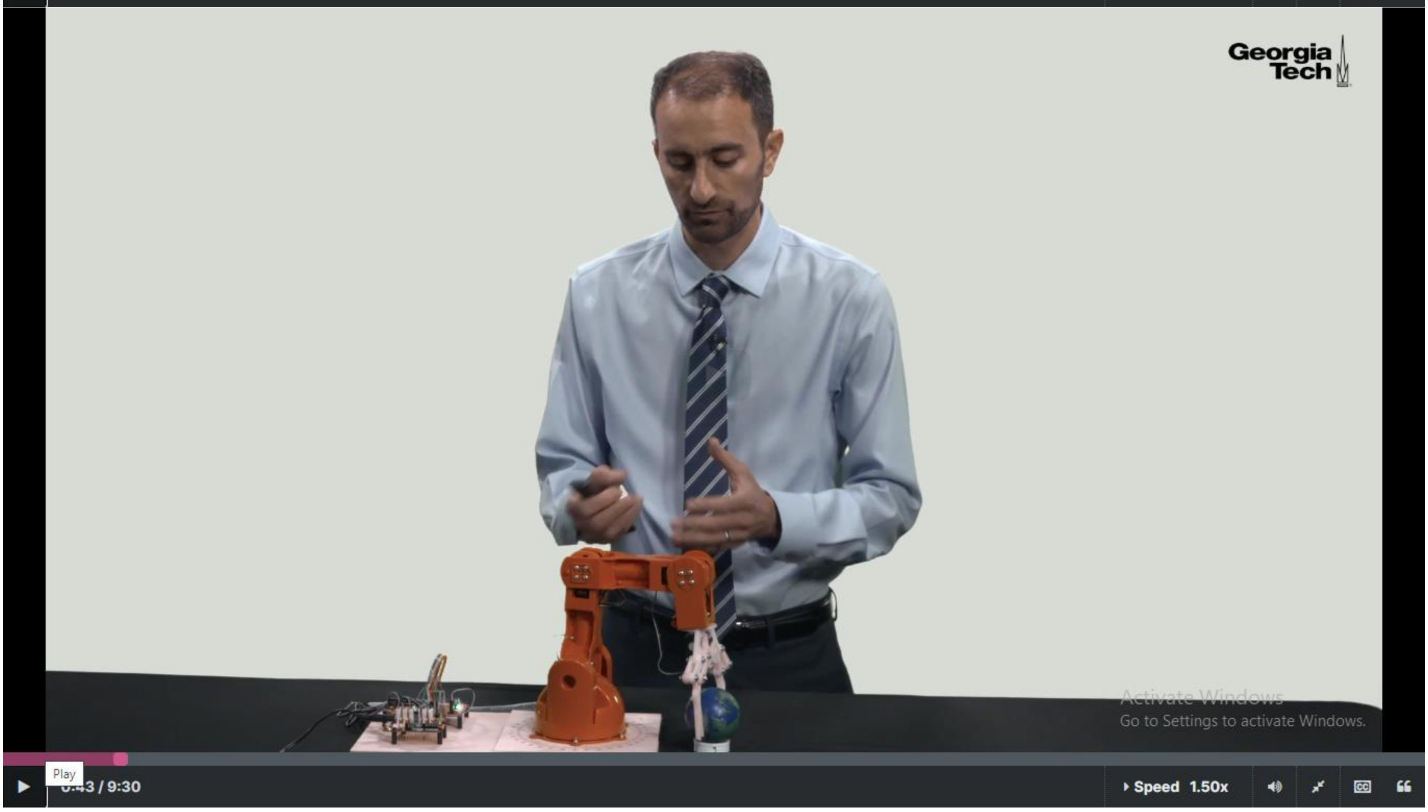
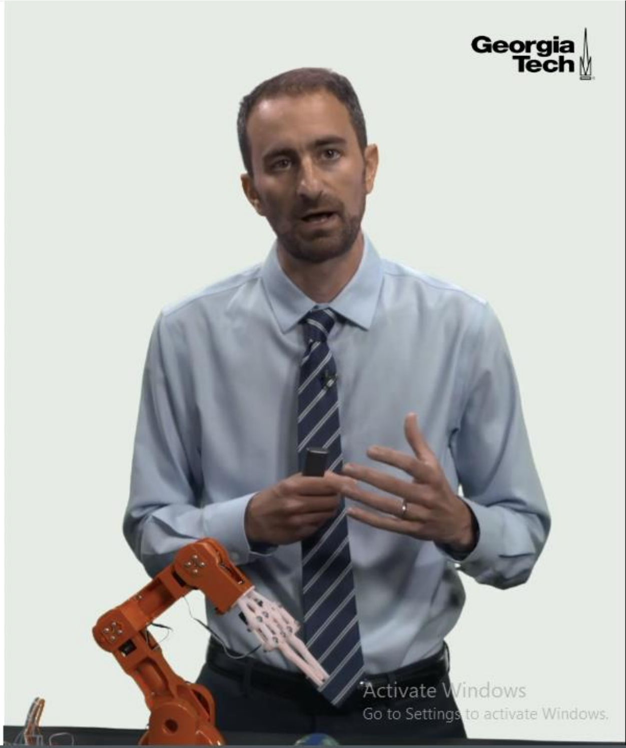
Lockheed Martin Associate Professor
The Daniel Guggenheim School of Aerospace Engineering
L4: Servo Operation and Control
0:06 / 9:30
Speed 1.50x


Learning Objectives
Describe the basic design and operation of servo motors
Explain how PWM signals are used to drive servos and the specific PWM configuration needed
Demonstrate PWM control of a hobby-type servo
Georgia Tech
Activate Windows
Go to Settings to activate Windows.
Play
0:16 / 9:30
Speed 1.50x


Georgia Tech
Activate Windows
Go to Settings to activate Windows.
Play
Speed 1.50x

Servos

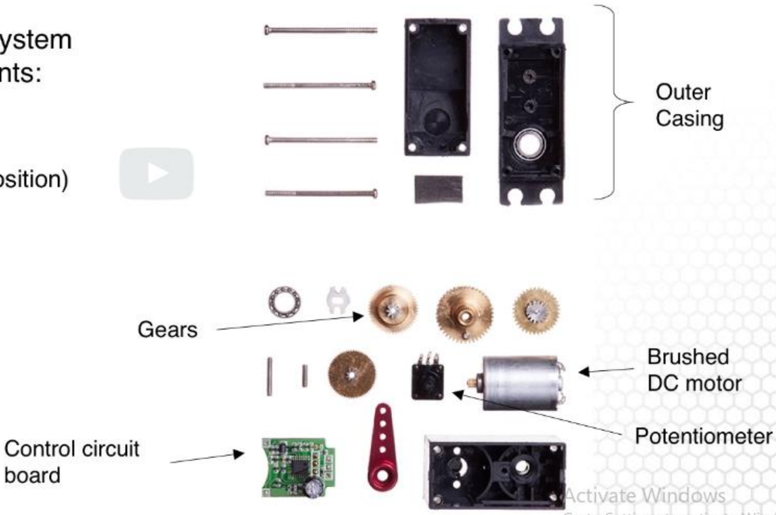
- Servos are used in many industrial and robotics applications
  - Provides **precise positioning**
  - Used often in mechatronic system requiring precise position control
  - Convenient packaging allows enables easy integration



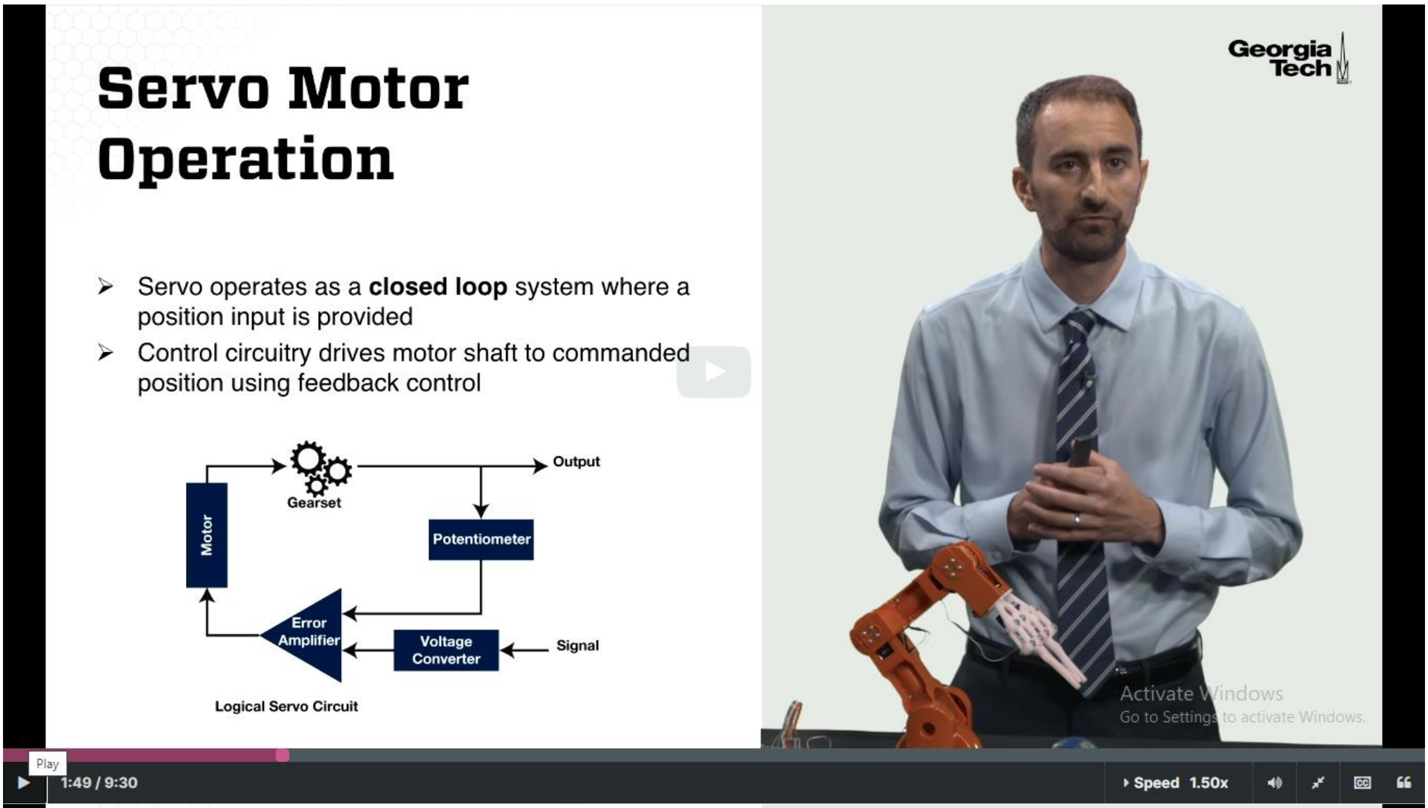
Play 1:02 / 9:30 Speed 1.50x

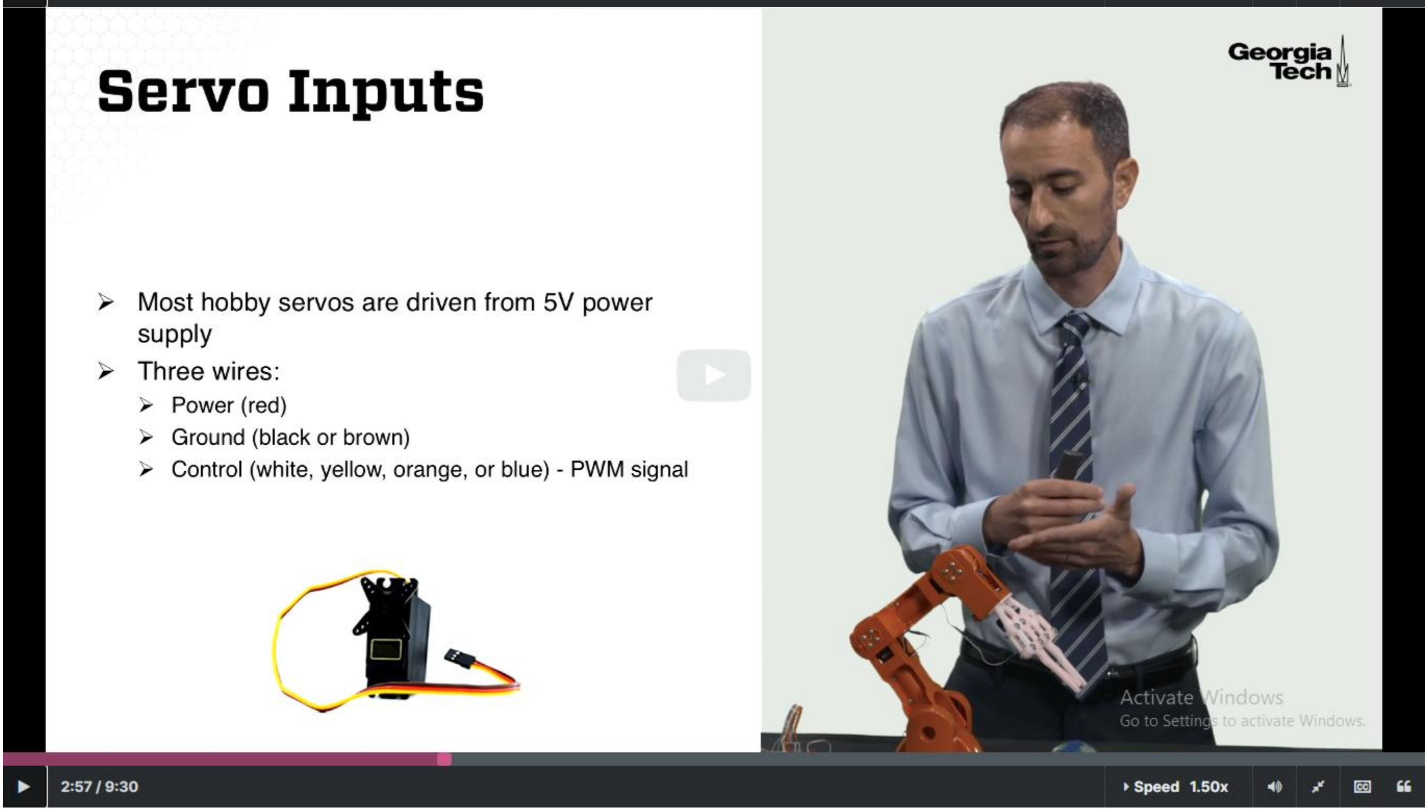
Servo Motor Operation

- Servos are complete positioning system incorporating four major components:
  - Brushed DC motor
  - Gear set
  - Potentiometer (for detecting shaft position)
  - Control circuit board



Play 1:46 / 9:30 Speed 1.50x

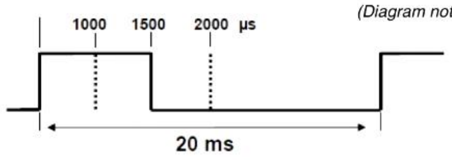

Servo Motor Operation
Servo operates as a **closed loop** system where a position input is provided
Control circuitry drives motor shaft to commanded position using feedback control
Gearset
Output
Motor
Potentiometer
Error Amplifier
Voltage Converter
Signal
Logical Servo Circuit
Georgia Tech
Play
1:49 / 9:30
Speed 1.50x

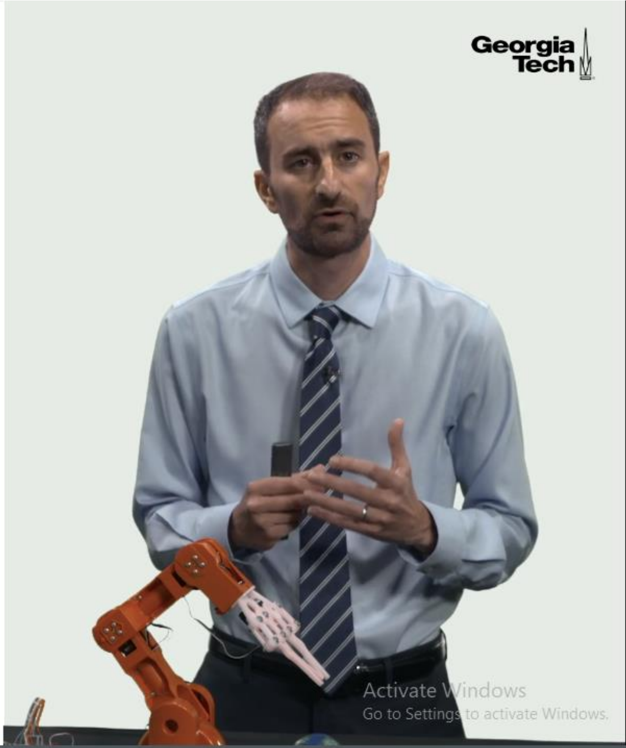

Servo Inputs
Most hobby servos are driven from 5V power supply
Three wires:
Power (red)
Ground (black or brown)
Control (white, yellow, orange, or blue) - PWM signal
Georgia Tech
2:57 / 9:30
Speed 1.50x

Servo Control

- How do you command a servo to a specific rotational position?
- <u>PWM signal</u>
- Servos require PWM signal of specific format
  - Signal period of **20 ms** (frequency of **50 Hz**)
  - Valid duty cycle is **5%** (full neg. throw) to **10%** (full pos. throw)
  - Equates to pulse width between 1000 μs and 2000 μs

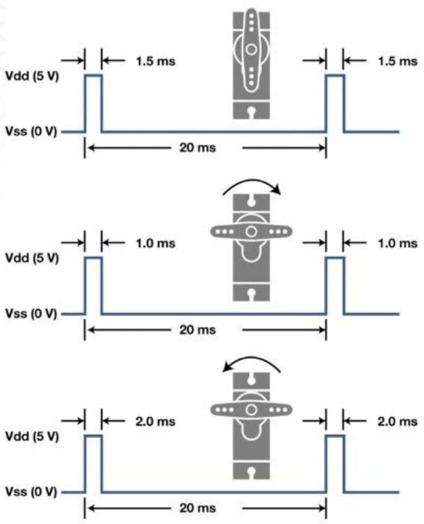
(Diagram not to scale)





Play / 9:30 Speed 1.50x

Servo Control



Pulse width of 1500 μs (1.5 ms) is neutral or centered position. This is 7.5% duty cycle.

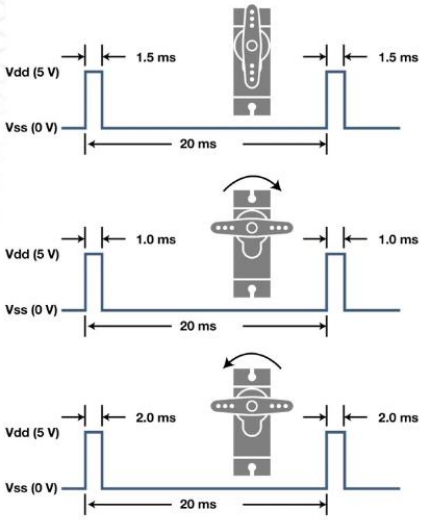
Pulse width of 1000 μs (1.0 ms) is full clockwise position (usually 90 deg). This is 5% duty cycle.

Pulse width of 2000 μs (2.0 ms) is full counter-clockwise position (usually -90 deg). This is 10% duty cycle.

Play 06 / 9:30 Speed 1.50x

Servo Control

Georgia Tech

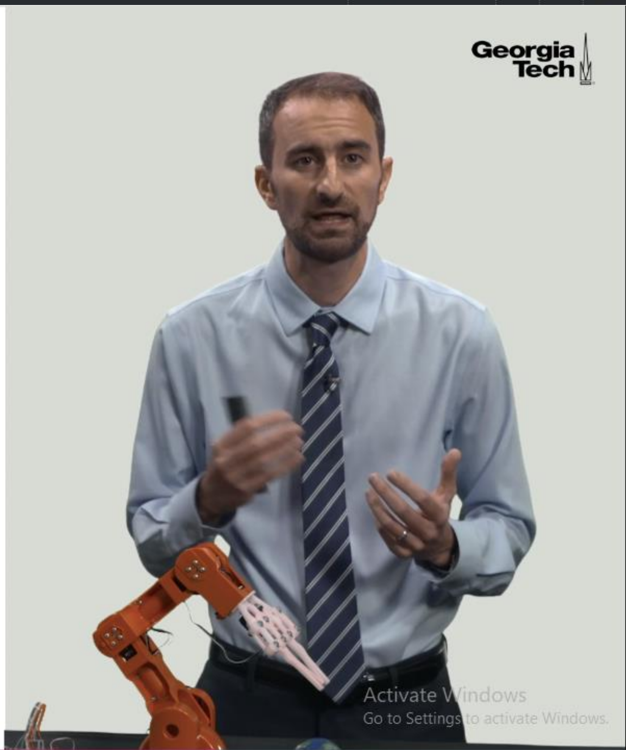


Note: You must maintain PWM signal to servo continuously during operation.

Common Servo Specifications

Georgia Tech

Specification	Typical Values
Power voltage	4.8-7.2 V
PWM voltage	5V
PWM frequency	20-60 Hz
Travel range	180 deg - 360 deg
Min. Pulse Width	700-1000 µs
Max. Pulse Width	2000-2300 µs
Rotational Speed	300 deg/s



Summary

Servo motors are special type of packaged actuator device used for **position control**.

Used commonly in **robotic arms, remote-control vehicles**, and other mechatronic devices.

Consist of **DC motor, potentiometer, gear set**, and **control circuit** that implements feedback controller.

Servos are driven using **PWM signal** with specific frequency and pulse width characteristics.