11080 BDC

Intelligently Controlling Brushed DC Motors

Objectives

- Further your understanding of brushed DC motors and how to control them
- Understanding Pulse Width Modulation
- Familiarize you with a couple of Microchip's development tools
- Show you an application of brushed DC motor control

Agenda

1. Brushed DC Motor Basics
   A). Principles of Operation
   B). 4 Types of BDCMs

2. Motor Control
   A). Drive Topologies
   B). CCP (PWM Mode)
   C). Speed Measuring
   D). ECCP (Enhanced PWM)

Brushed DC Motor Basics

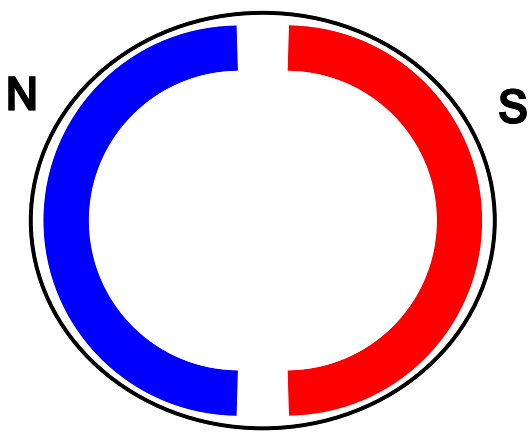
Principles of Operation

1. Stator
2. Rotor / Armature
3. Brushes and Commutator

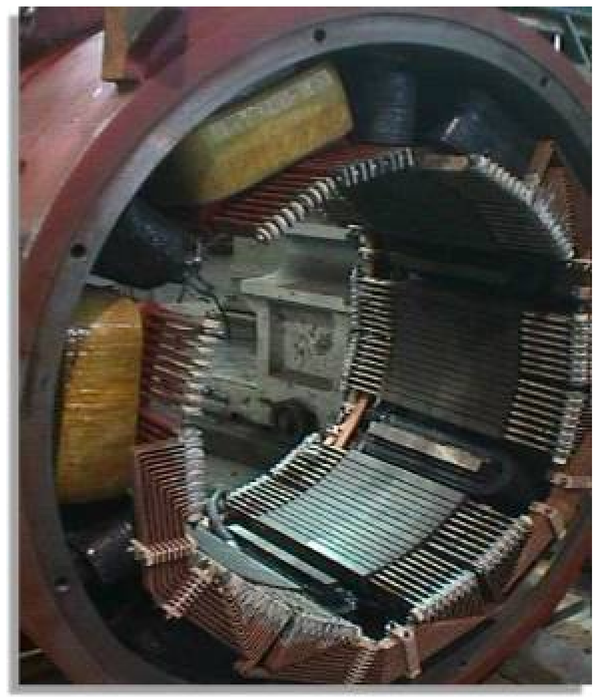
Stator

- Generates a stationary magnetic field that surrounds the rotor, this field is generated by either:

permanent magnets

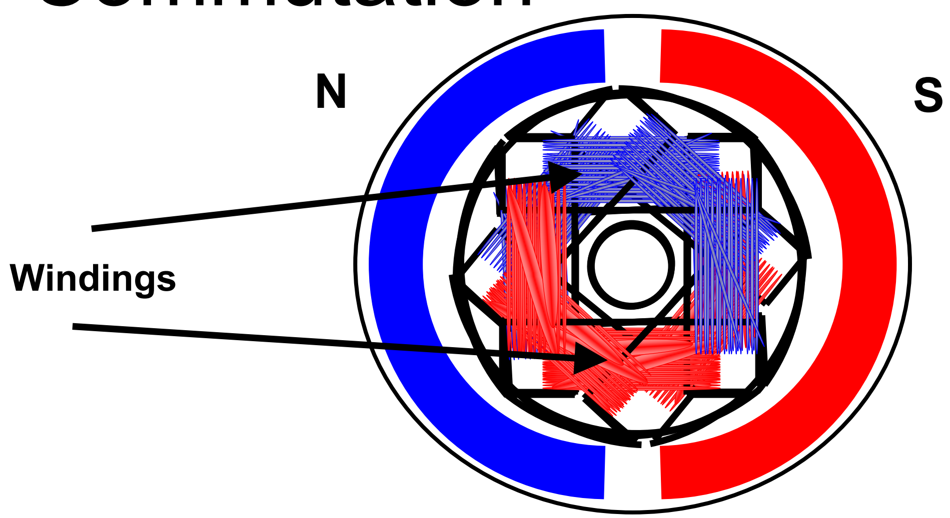


electromagnetic windings

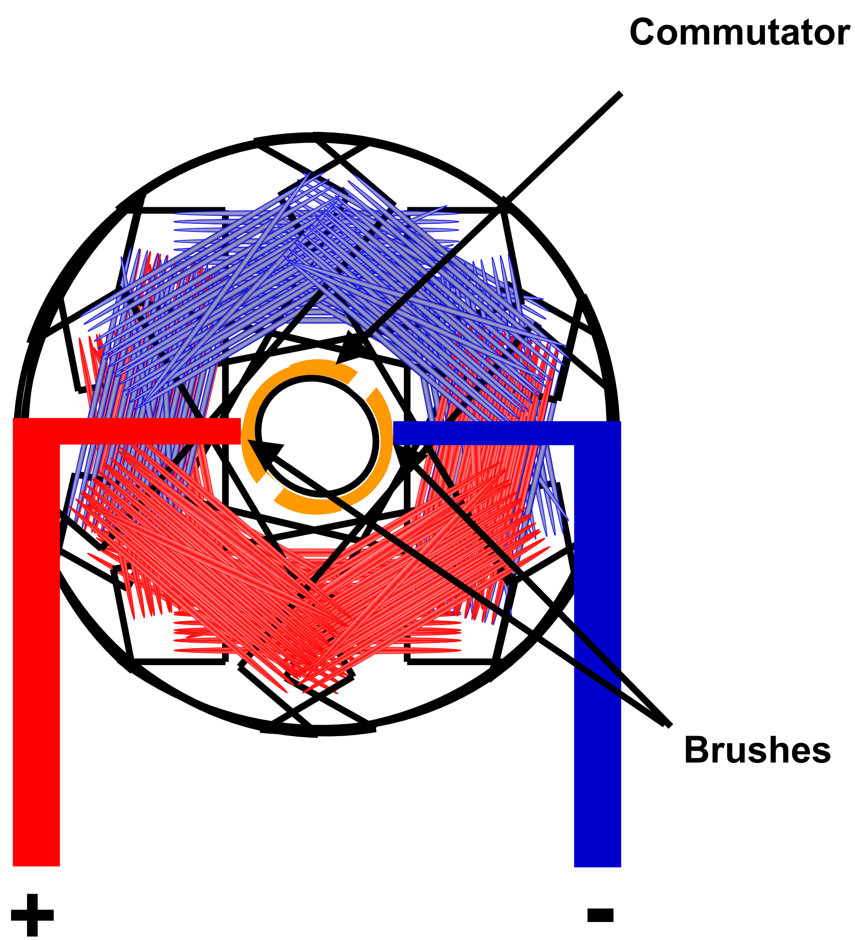


Rotor

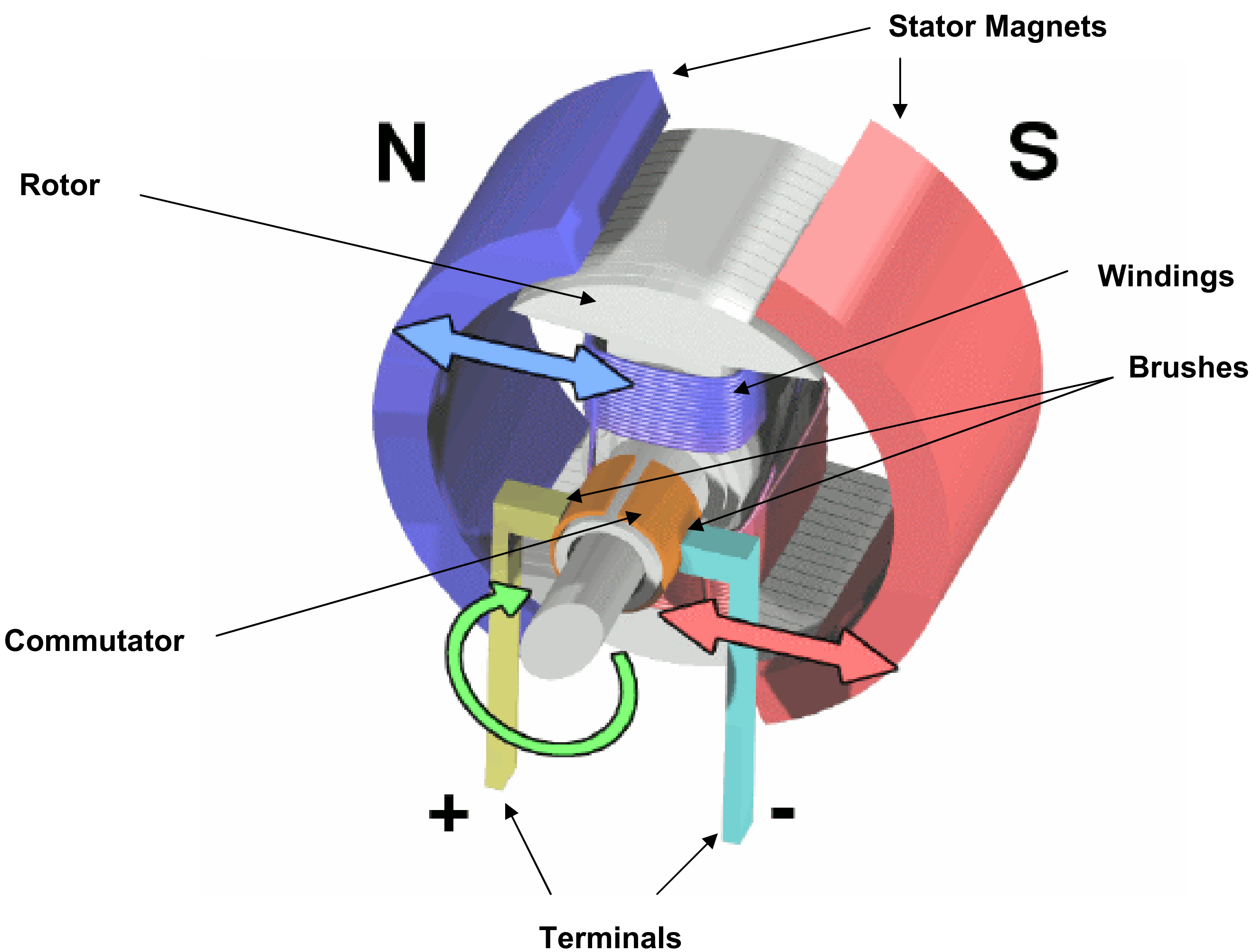
- Also known as the Armature
- Made up of one or more windings
- Commutation



Brushes and Commutator



Brushed DC Motor

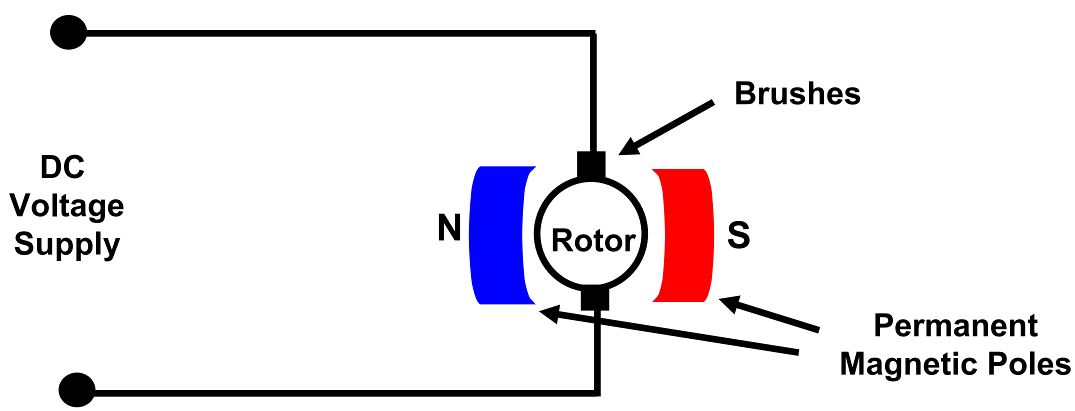


Four Types of BDCMs

1. Permanent Magnet
2. Shunt - wound
3. Series - wound
4. Compound - wound
    - Shunt + Series

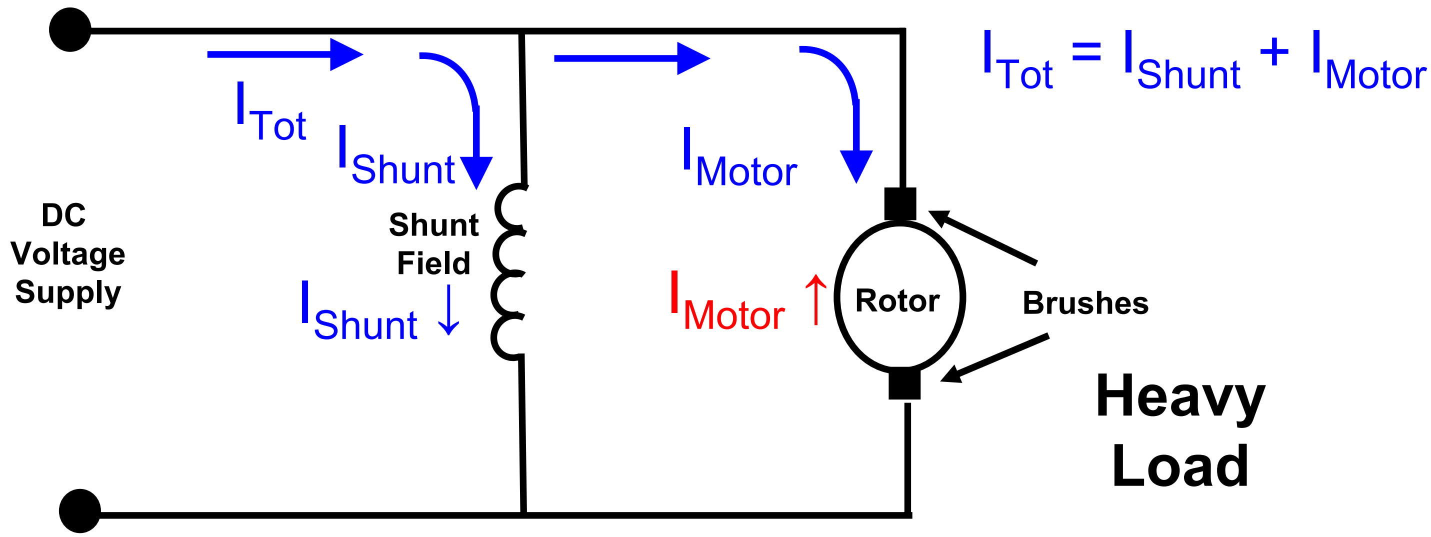
Permanent Magnet
(PMDC)

- Most common
- Used in fractional horsepower applications
  Examples: Toys, RC app., Slot cars, Appliances, etc…
- More cost effective than wound stators
- Torque, limited b/c of stator field
  - Good low end (low speed) torque
  - Limited high end (high speed) torque
- Responds very quickly to voltage changes due to constant stator field (good speed control)
- Drawback, Magnets lose their magnetic properties over time



Shunt-Wound

(SHWDC)



- As V_{Supply} ↑, I_{Tot} ↑, speed ↑, stator/rotor field ↑, thus Torque ↓
- As motor load ↑, I_{Motor} ↑, I_{Shunt} ↓, stator field ↓, rotor field ↑, speed ↓, thus Torque ↑

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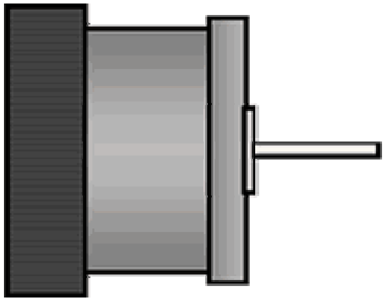
Shunt-Wound

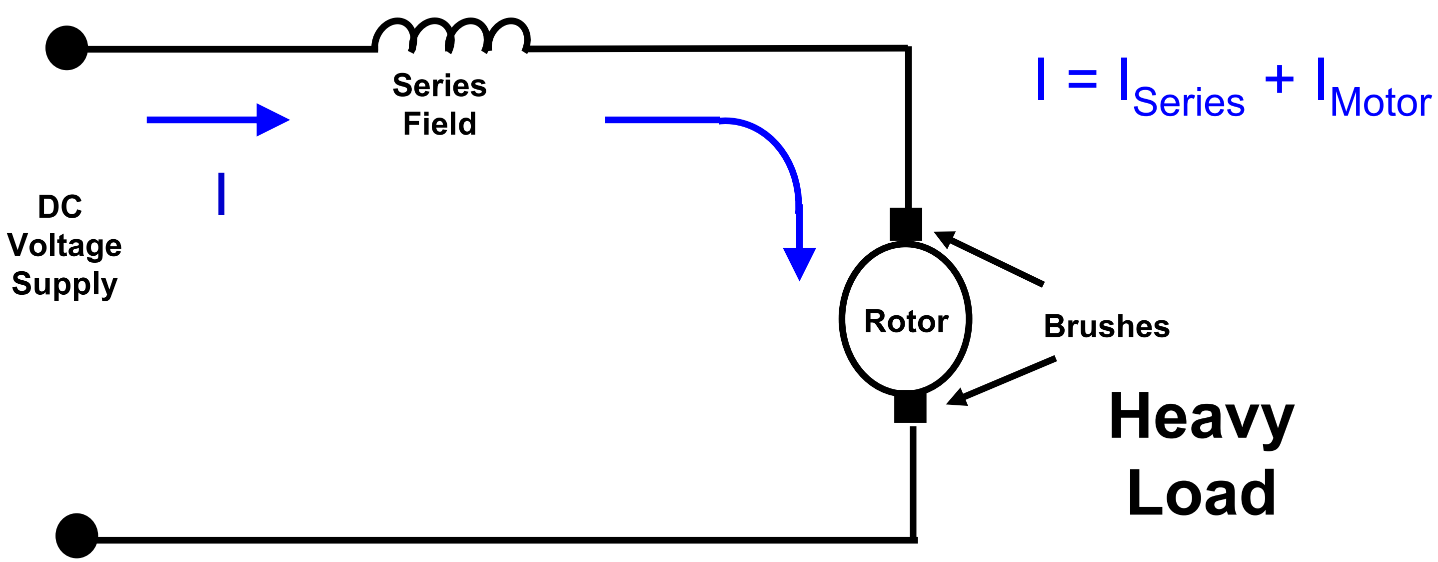
(SHWDC)

- Decreasing torque at high speed
- At low speed, higher more consistent torque
- Excellent speed control
- Typically used in Industrial and automotive applications
- No loss of magnetism over time as with PMDC motors
- More expensive than PMDC motors
- Motor Runaway, if the shunt current goes to zero



Series-Wound

(SWDC)



- As V_{Supply} ↑, I ↑, Stator/Rotor field ↑, speed ↑, thus torque ↓
- As motor load ↑, I ↑, Stator/Rotor field ↑, speed ↓, thus torque ↑

Series-Wound

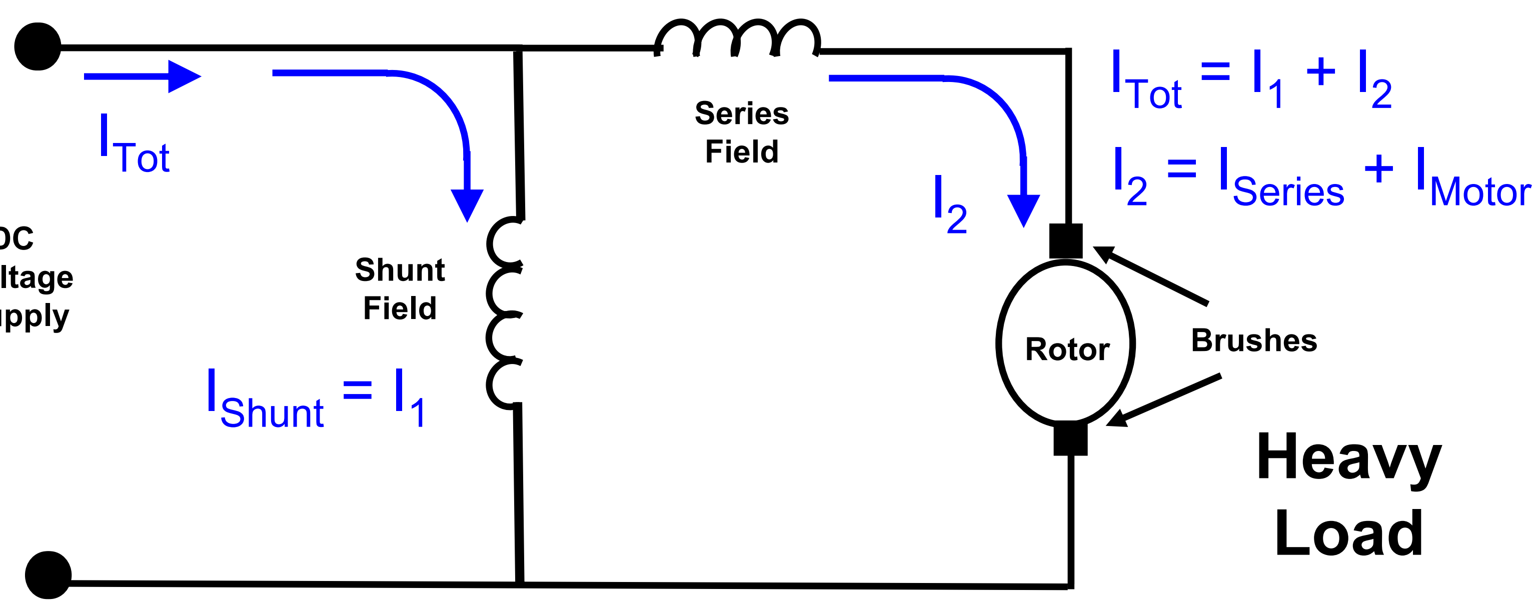
(SWDC)

- Great slow speed torque (low end)
  - But, as load is removed, speed increases sharply
- Ideally suited for heavy loads, examples: cranes and winches

- Poor high speed torque (high end)
- More expensive than PMDC
- Poor speed control due to the series stator field
- Motor Runaway, if the series field is shorted

Compound-Wound

(CWDC)



Heavy Load

- As motor load ↑, I_{Shunt} ↓, shunt field ↓, I_2 ↑, Series field/Rotor field ↑, speed ↓, thus torque ↑

Compound-Wound
(CWDC)

- Has the performance properties of both SHWDC and SWDC motors
- High torque at low speed w/ heavy loads, SHWDC motors
- Great speed control, SWDC motors
- Great for Industrial and automotive applications, example: generators
- Motor Runaway, less likely b/c shunt current must go to zero and series field must short
- More expensive than PMDC, SHWDC, and SWDC

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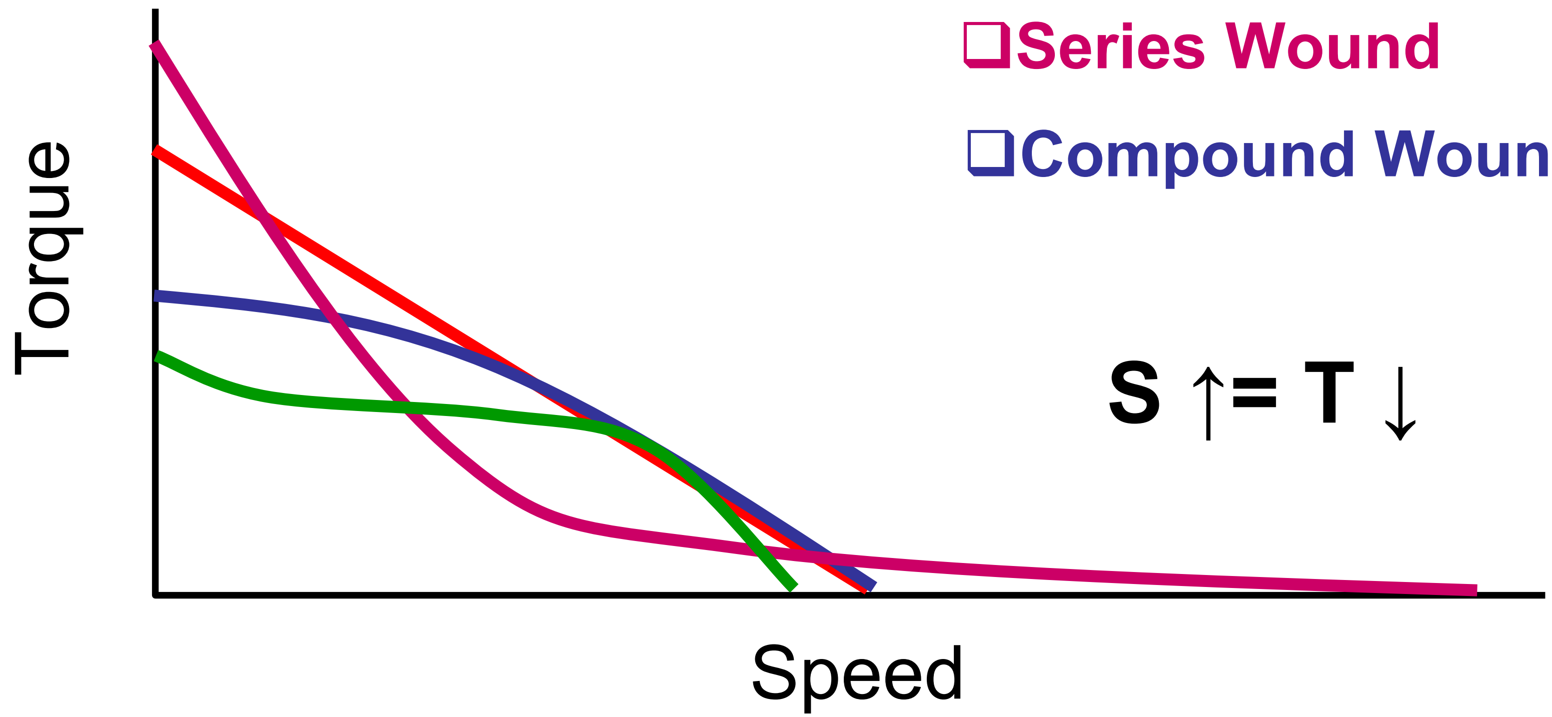
Performance Comparison

- ❑Permanent Magnet
- ❑Shunt Wound
- ❑Series Wound
- ❑Compound Wound



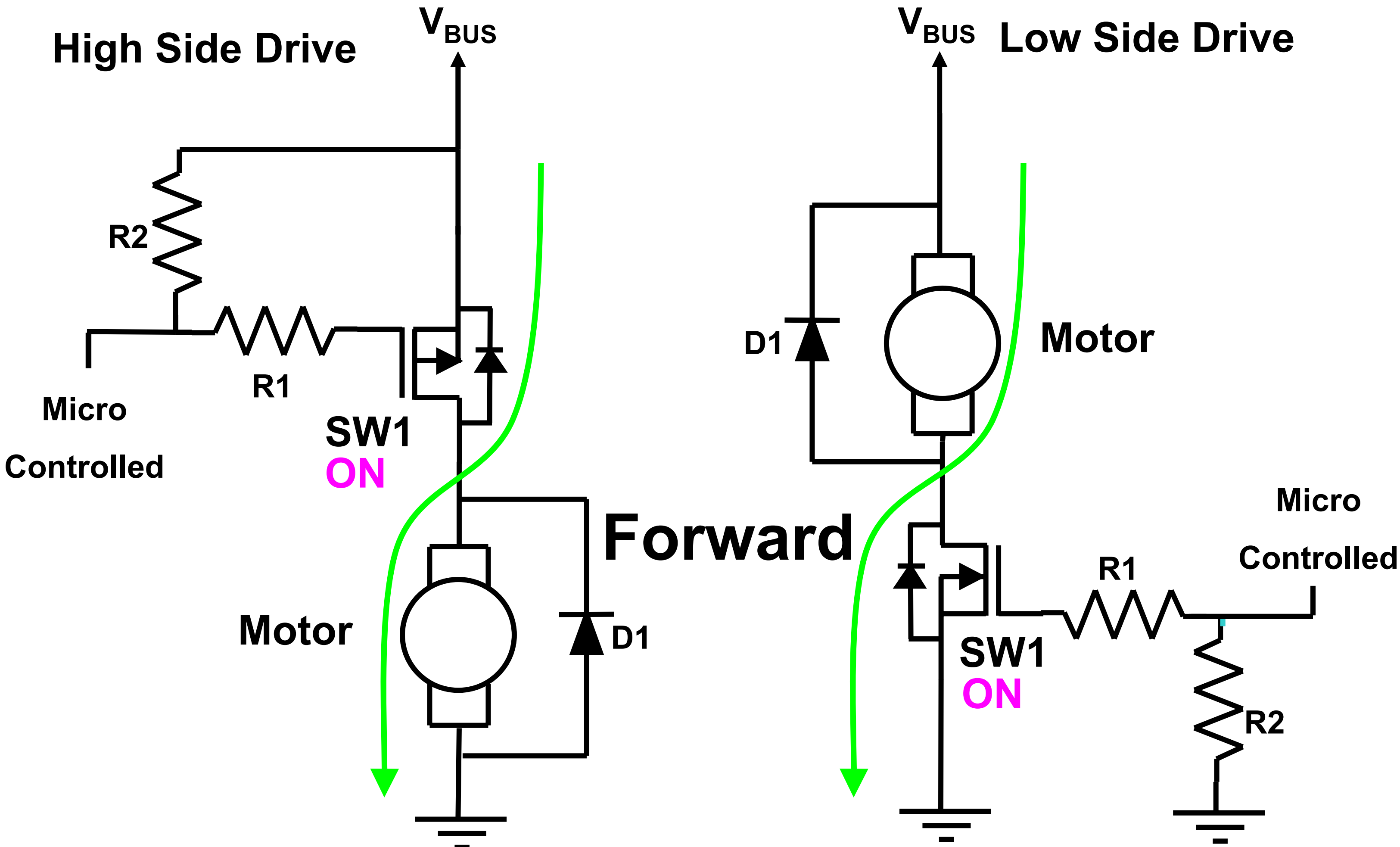
S ↑= T ↓

Motor Control

Motor Control Topologies

- Chopper
  - Low Side Drive
  - High Side Drive
- Half Bridge
  - Low Side Drive
  - High Side Drive
- Full Bridge (H-Bridge)

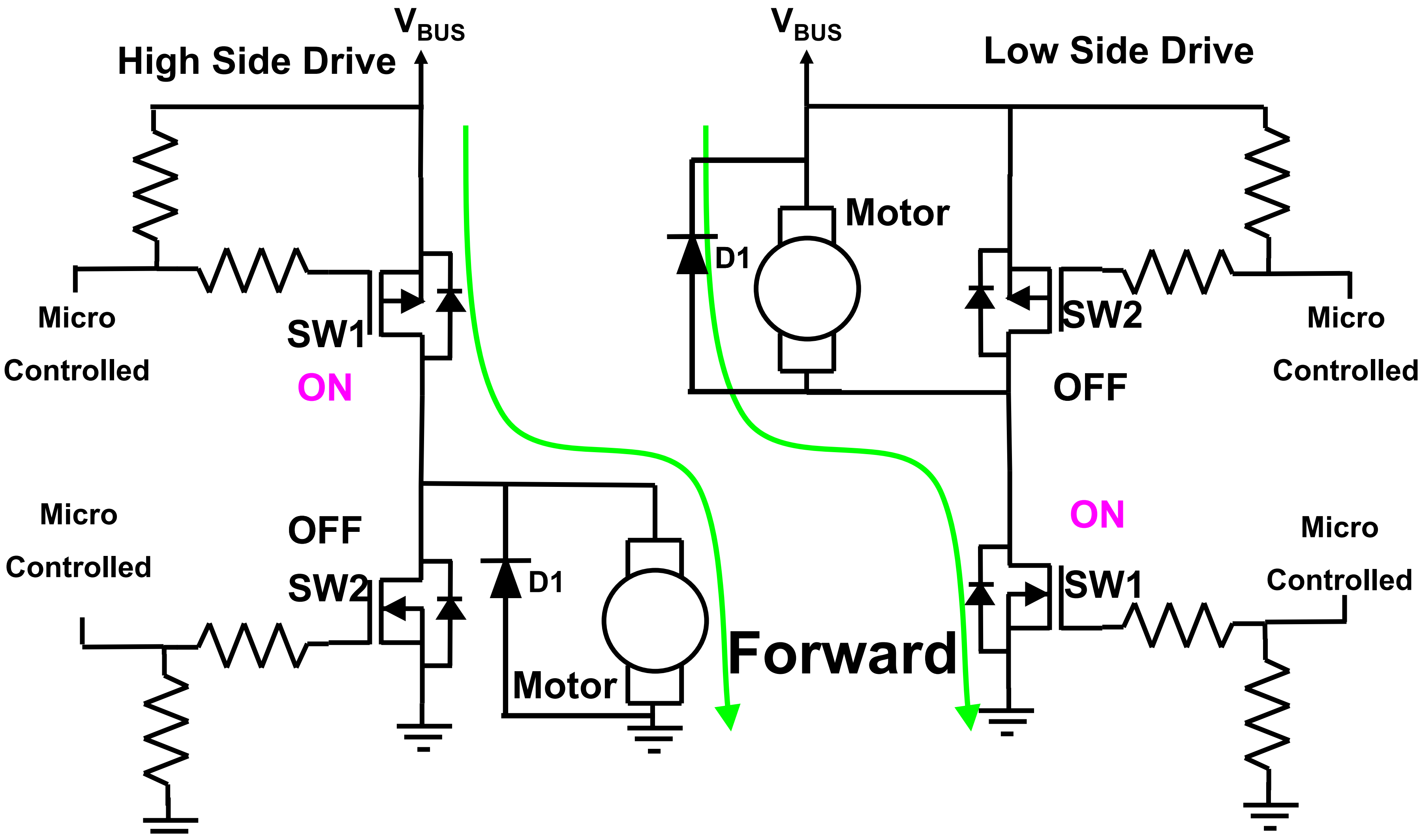
Chopper


High Side Drive
V_BUS
R2
R1
Micro
Controlled
SW1
ON
Motor
D1
Forward
V_BUS
Low Side Drive
D1
Motor
Micro
Controlled
R1
SW1
ON
R2

Chopper

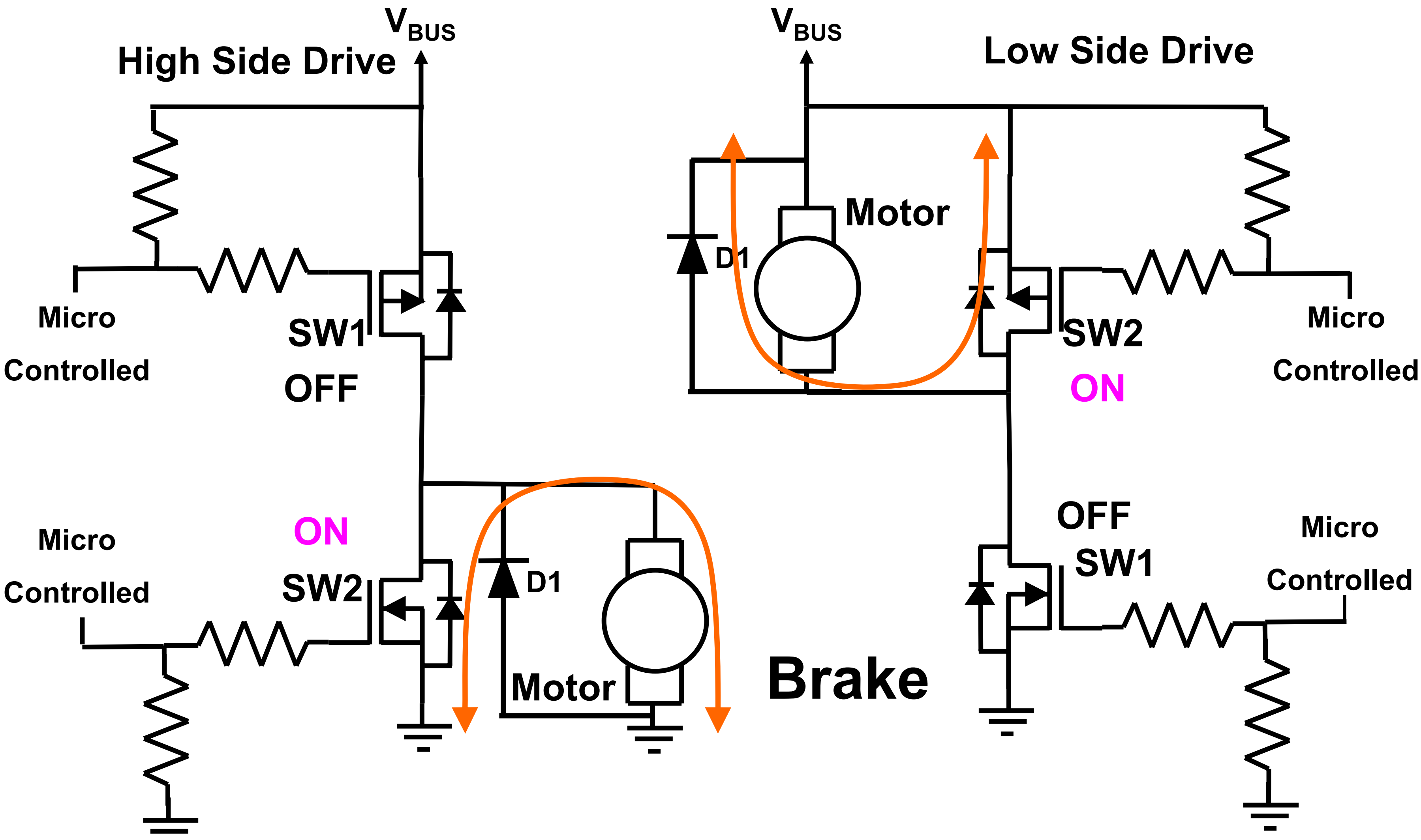
- Example: Fan controller
- Advantages
  - Simplest drive circuit for driving the switch
  - Less expensive, 1 MOSFET
- Safety (High side drive)
- Disadvantages of the Chopper Topology
  - Can only go forward
  - No braking

Half Bridge



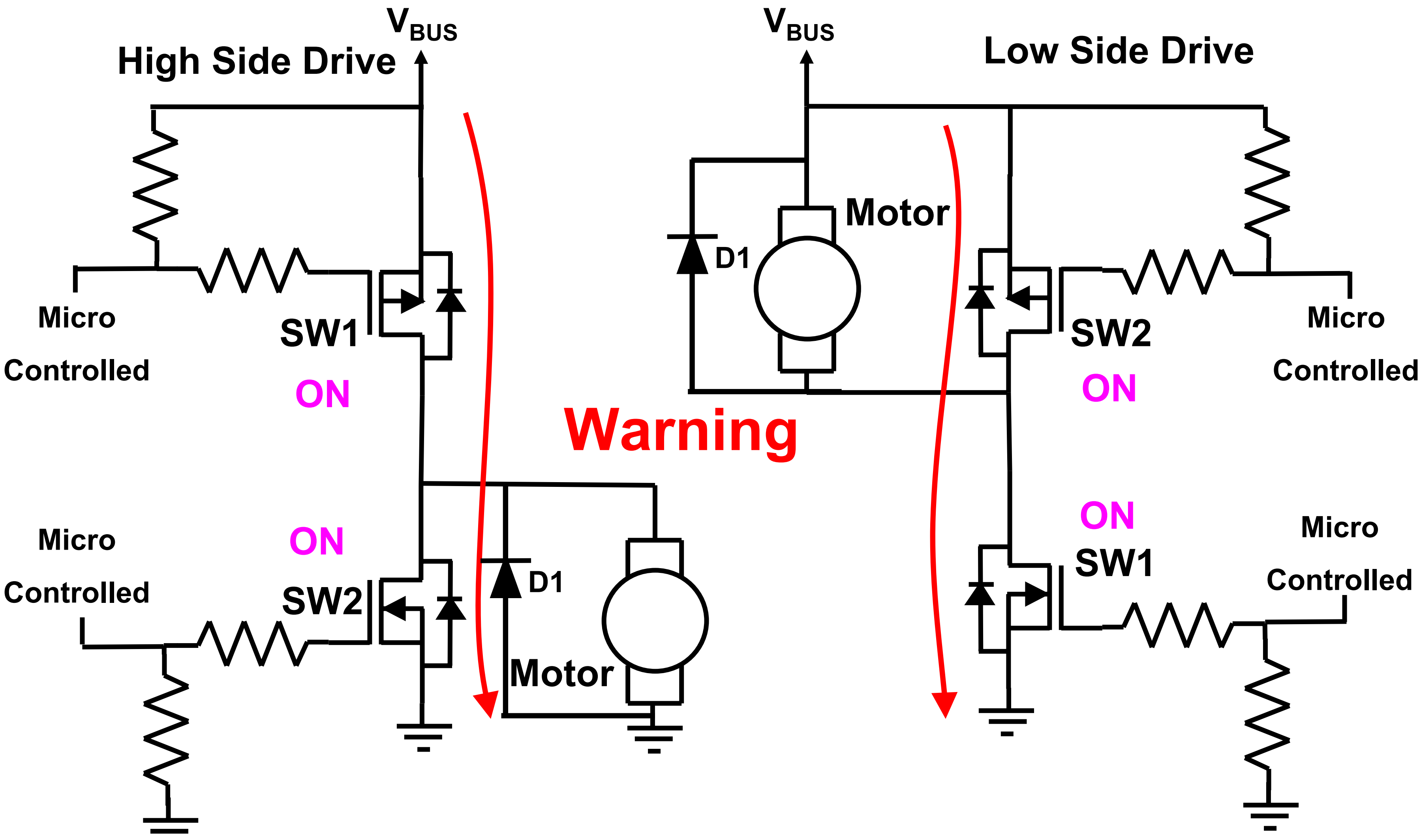
High Side Drive
V_{BUS}
Micro
Controlled
SW1
ON
Micro
Controlled
OFF
SW2
D1
Motor
Forward
V_{BUS}
Low Side Drive
D1
Motor
SW2
OFF
Micro
Controlled
ON
SW1
Micro
Controlled

Half Bridge



V_{BUS}
High Side Drive
Micro
Controlled
SW1
OFF
Micro
Controlled
ON
SW2
D1
Motor
V_{BUS}
Low Side Drive
Motor
D1
SW2
ON
Micro
Controlled
OFF
SW1
Micro
Controlled
Brake

Half Bridge

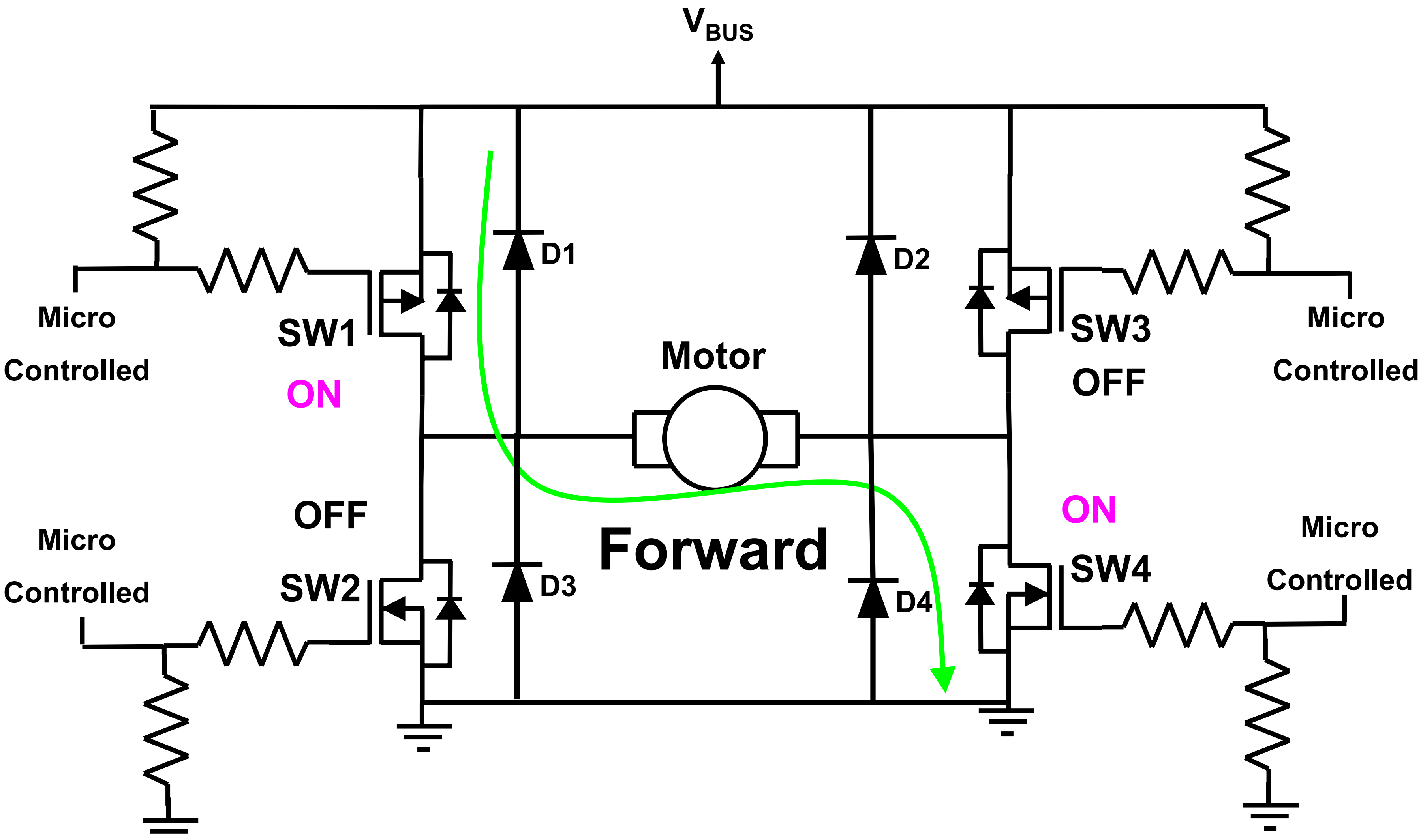


High Side Drive
V_{BUS}
Micro
Controlled
SW1
ON
Micro
Controlled
ON
SW2
D1
Motor
Warning
V_{BUS}
Low Side Drive
Motor
D1
SW2
ON
Micro
Controlled
ON
SW1
Micro
Controlled

Half Bridge

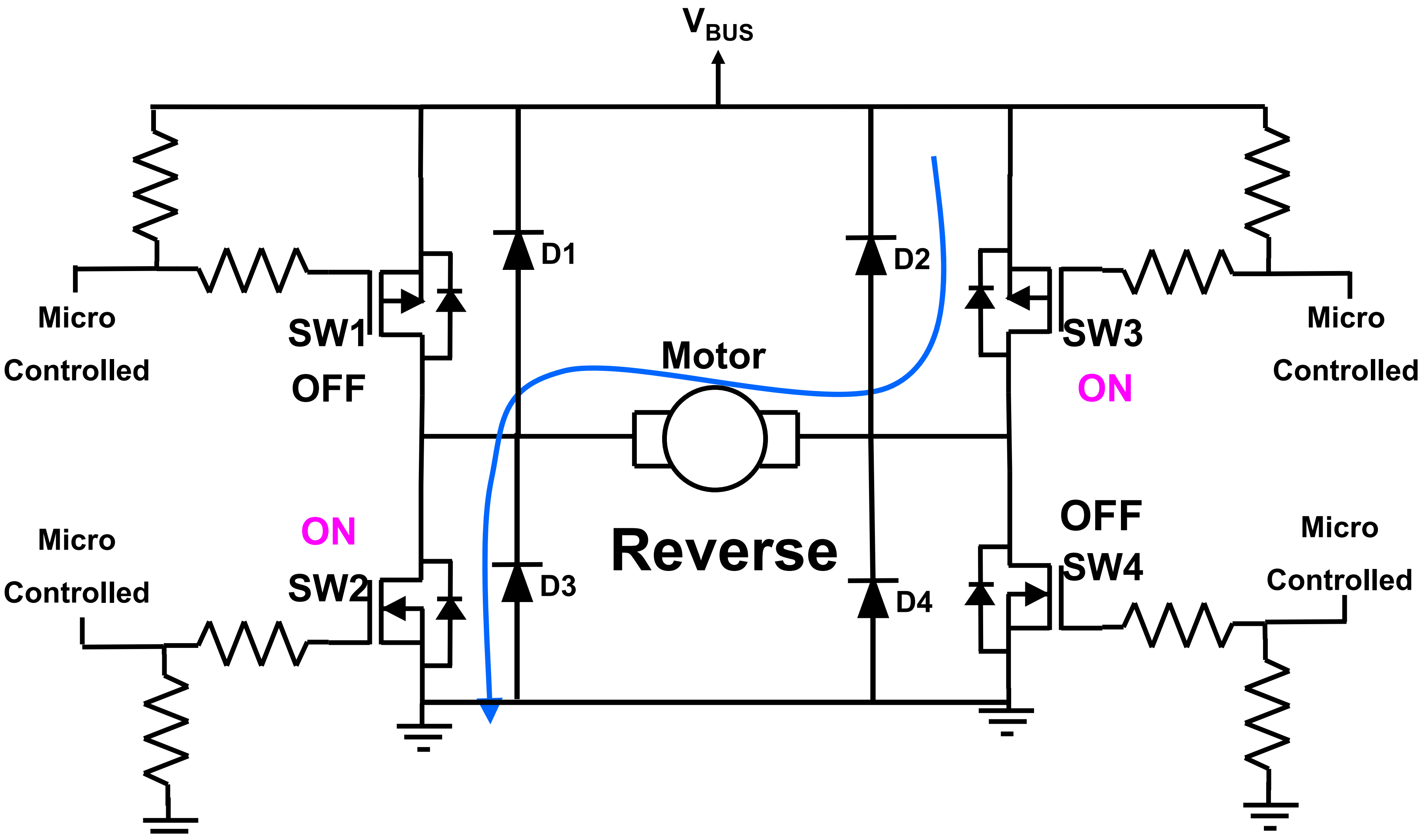
- Example: Slot car
- Advantages
  - Ability to brake the motor
  - Safety (High Side Drive)
- Disadvantages
  - Can only go forward
  - More parts, 2 outputs to control
  - Can have both the N-channel and P-channel on at the same time

Full Bridge



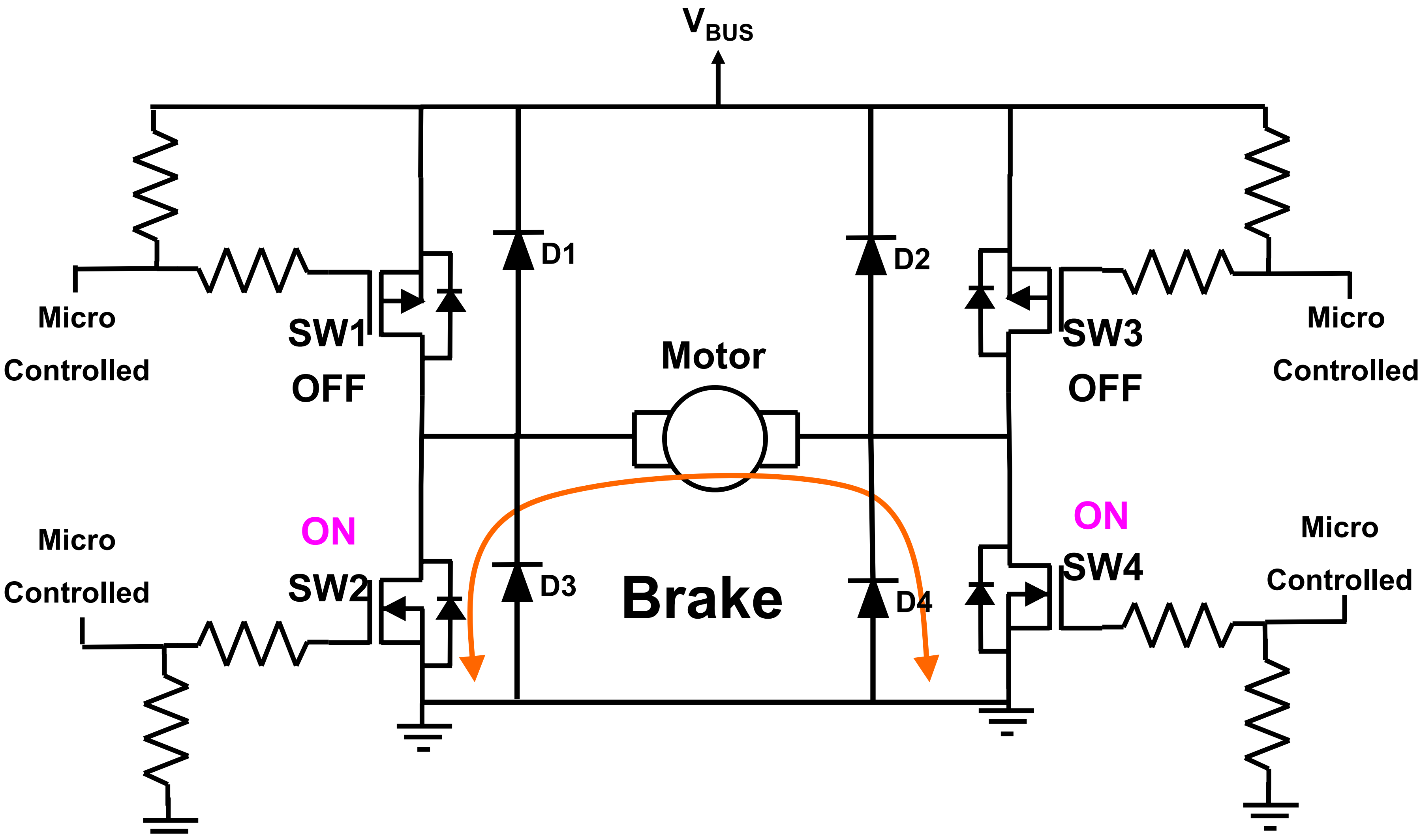
V_{BUS}
D1
D2
Micro
Controlled
SW1
ON
Motor
SW3
OFF
Micro
Controlled
D3
D4
OFF
Micro
Controlled
SW2
Forward
ON
SW4
Micro
Controlled

Full Bridge



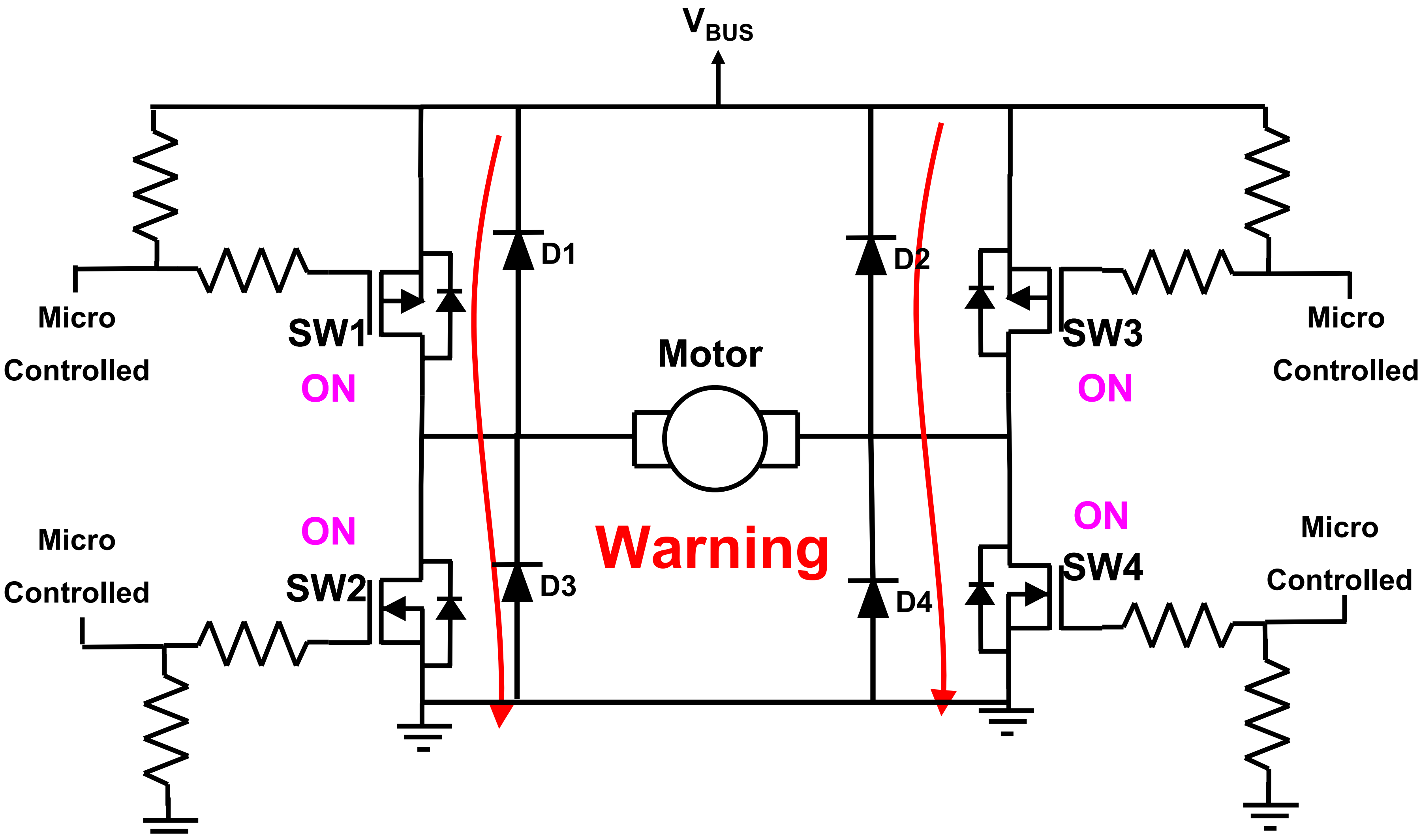
VBUS
Micro
Controlled
SW1
OFF
D1
D2
Motor
SW3
ON
Micro
Controlled
Micro
Controlled
ON
SW2
D3
Reverse
D4
OFF
SW4
Micro
Controlled

Full Bridge



V_{BUS}
D1
D2
Micro
Controlled
SW1
OFF
Motor
SW3
OFF
Micro
Controlled
Micro
Controlled
ON
SW2
D3
Brake
D4
ON
SW4
Micro
Controlled

Full Bridge


V BUS
D1
D2
D3
D4
Motor
Micro Controlled
SW1
ON
Micro Controlled
SW3
ON
Micro Controlled
ON
SW2
ON
SW4
Micro Controlled
Warning

Full Bridge

- Example: Cordless drill
- Advantages
  - Ability to drive the motor in reverse & brake
  - Safety (High side drive)
- Disadvantages of the Full Bridge Topology
  - Most complicated
  - 4 outputs to control
  - Can have all N-channels and P-channels on at the same time

Topology Review

- Chopper
  - Example: Fan control
  - Simplest, only one output to control
  - Fewest features
- Half Bridge
  - Example: Slot cars
  - More complex than the Chopper
  - Adds the Braking feature
- Full Bridge
  - Example: Cordless drill
  - Most complicated
  - Adds the features of Braking and Reverse

Motor Control

How do we control the speed of a Brushed DC Motor?

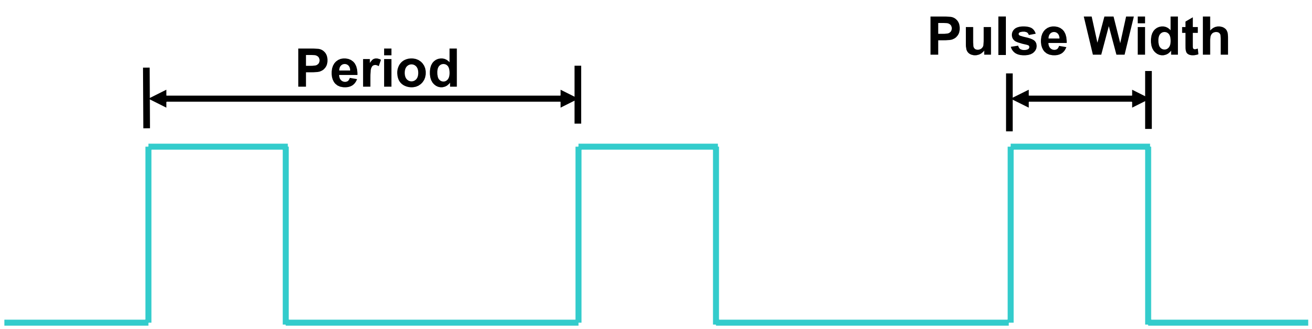
PWM

(Pulse Width Modulation)

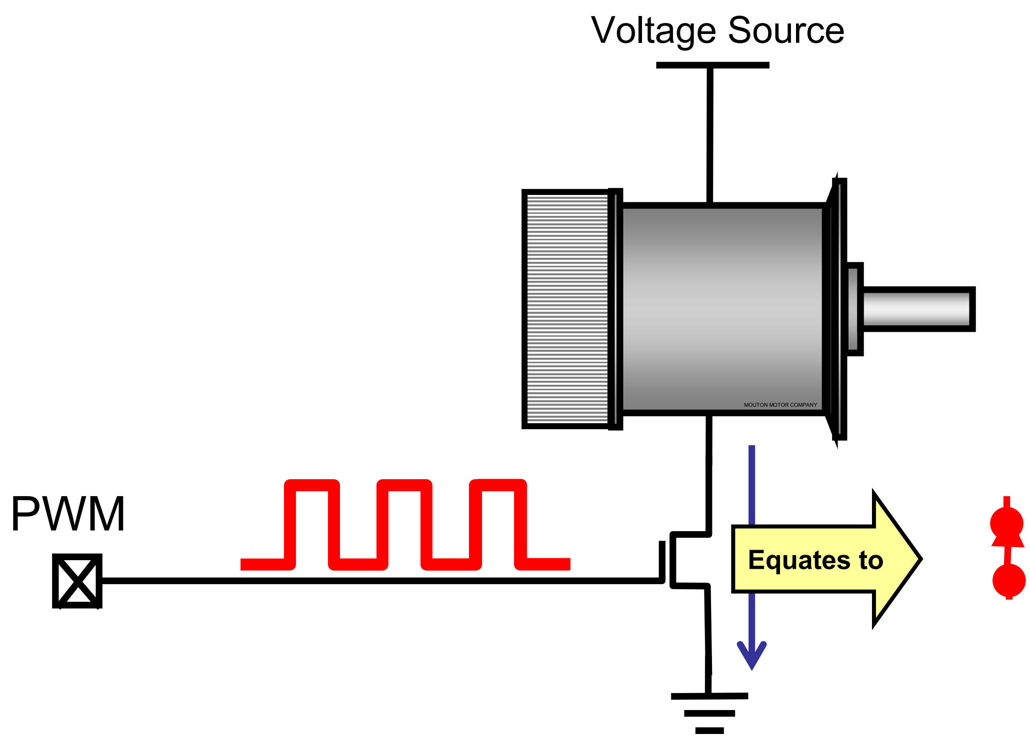
- We control the speed by varying the voltage across the motor

Voltage Across Motor$_{Avg.Volt}$ = Voltage$_{Supply}$• Duty Cycle

= VDD • (Pulse Width / Period)



PWM



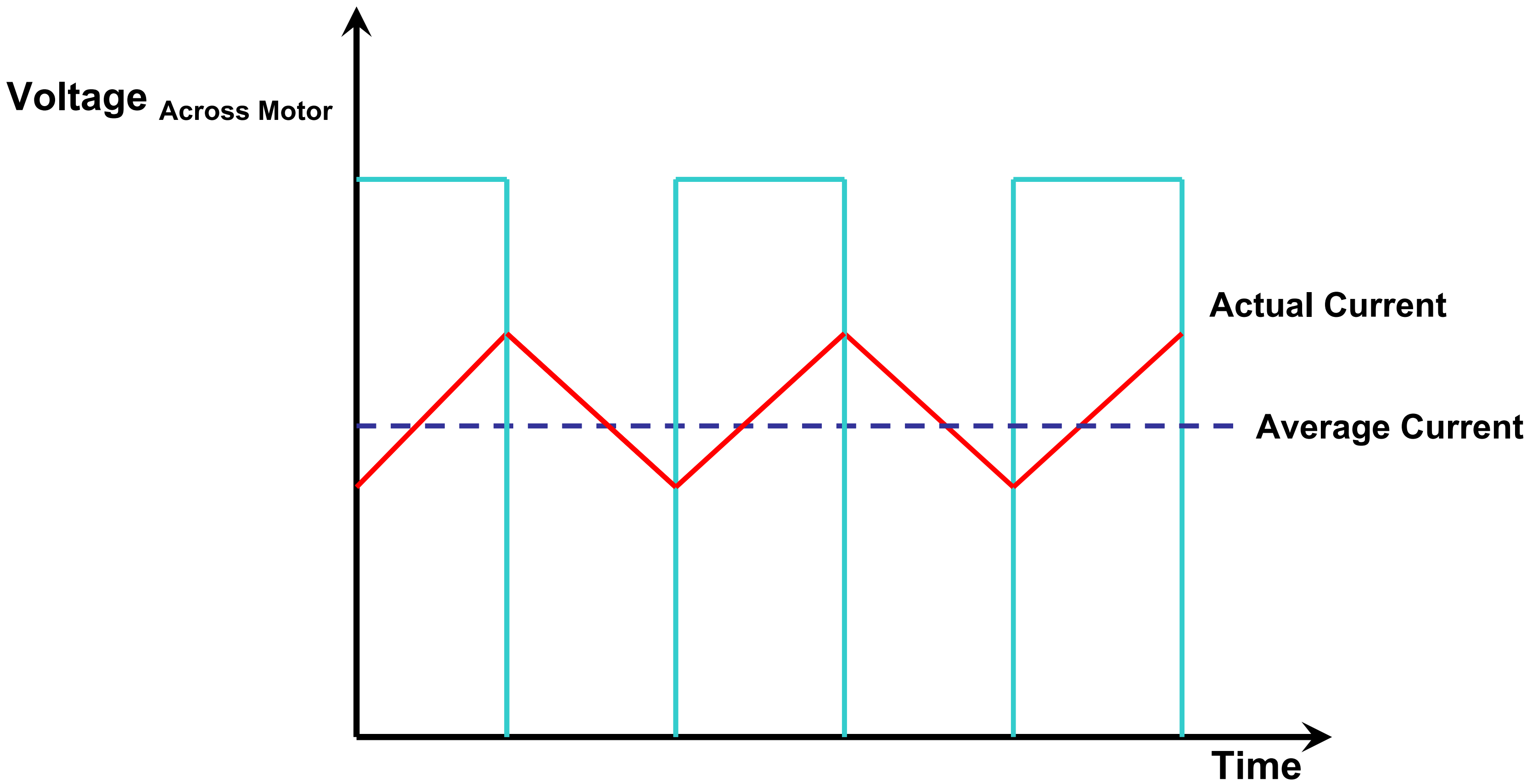
Motor Control

- Brushed DC Motor acts like an Inductor
  - Current doesn't change instantaneously
  - As inductance increases, the slower the current changes

$$V(t) = L \bullet di/dt$$

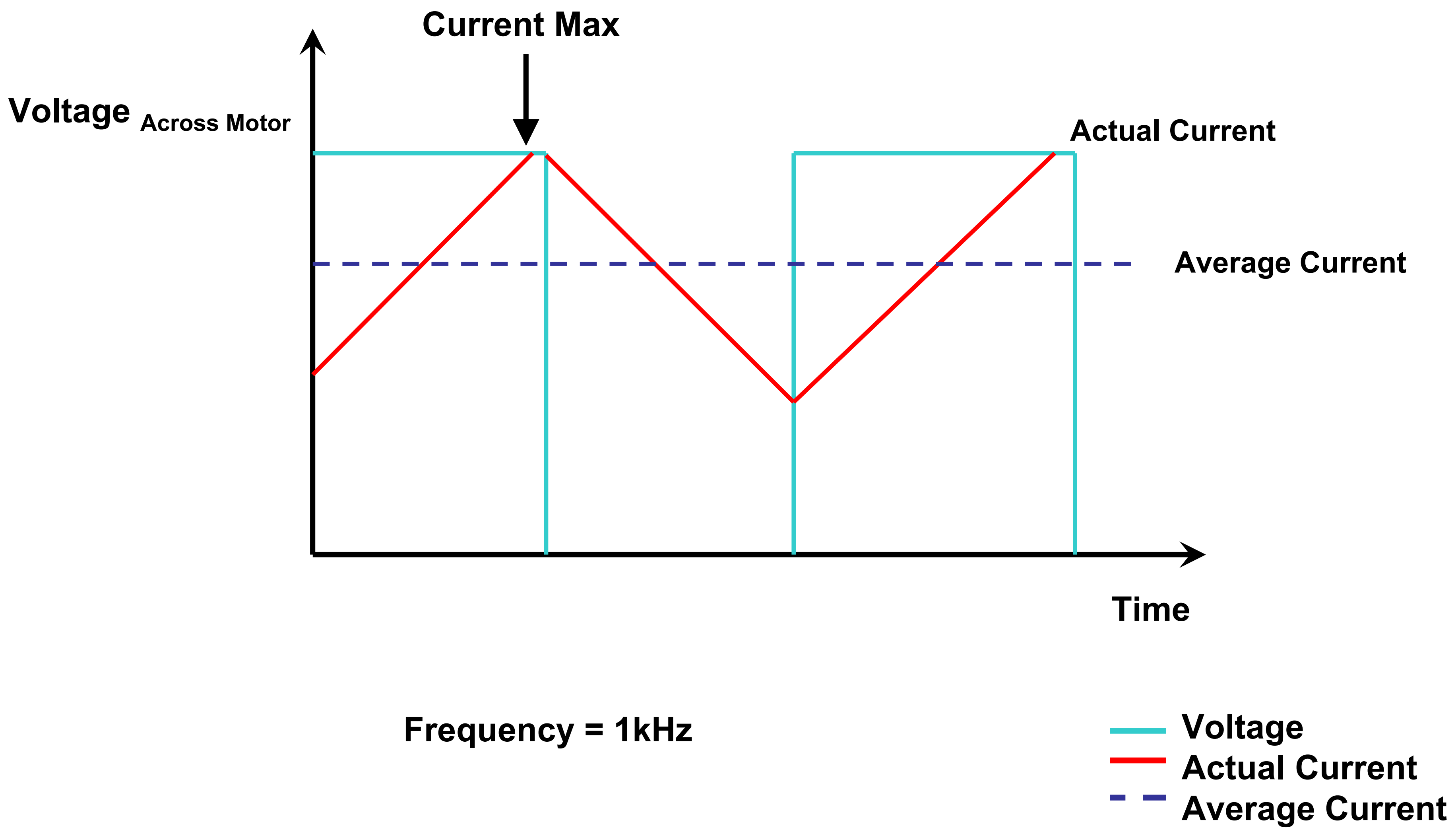
- Voltage across motor is directly proportional to RPM
  - 100%RPM = 100% Duty cycle

Motor Control



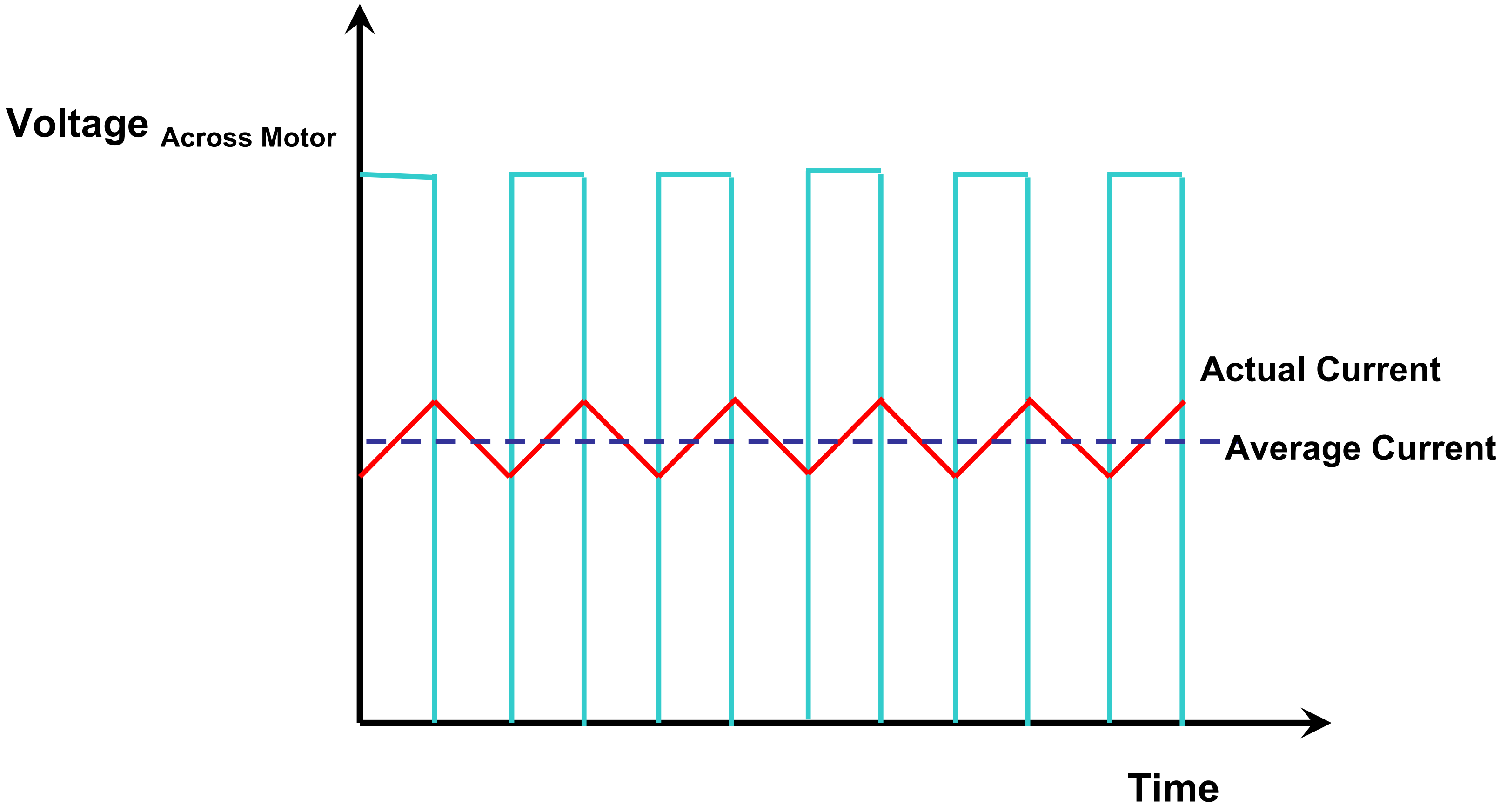
Accelerate **Decelerate**

Motor Control



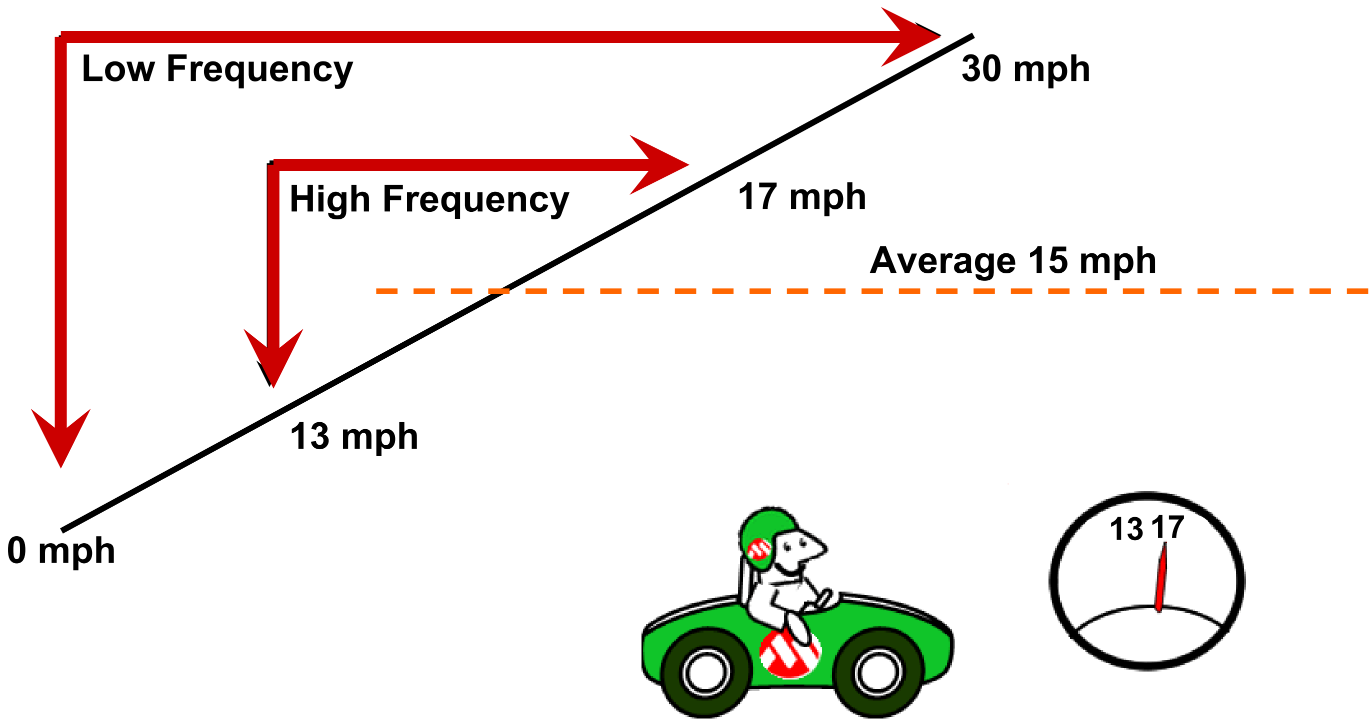
Frequency = 1kHz

Motor Control



Frequency = 4kHz

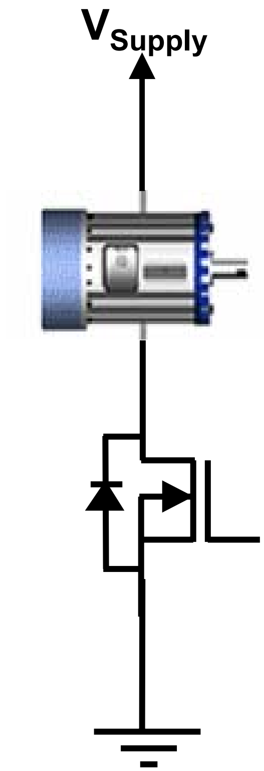
Motor Control

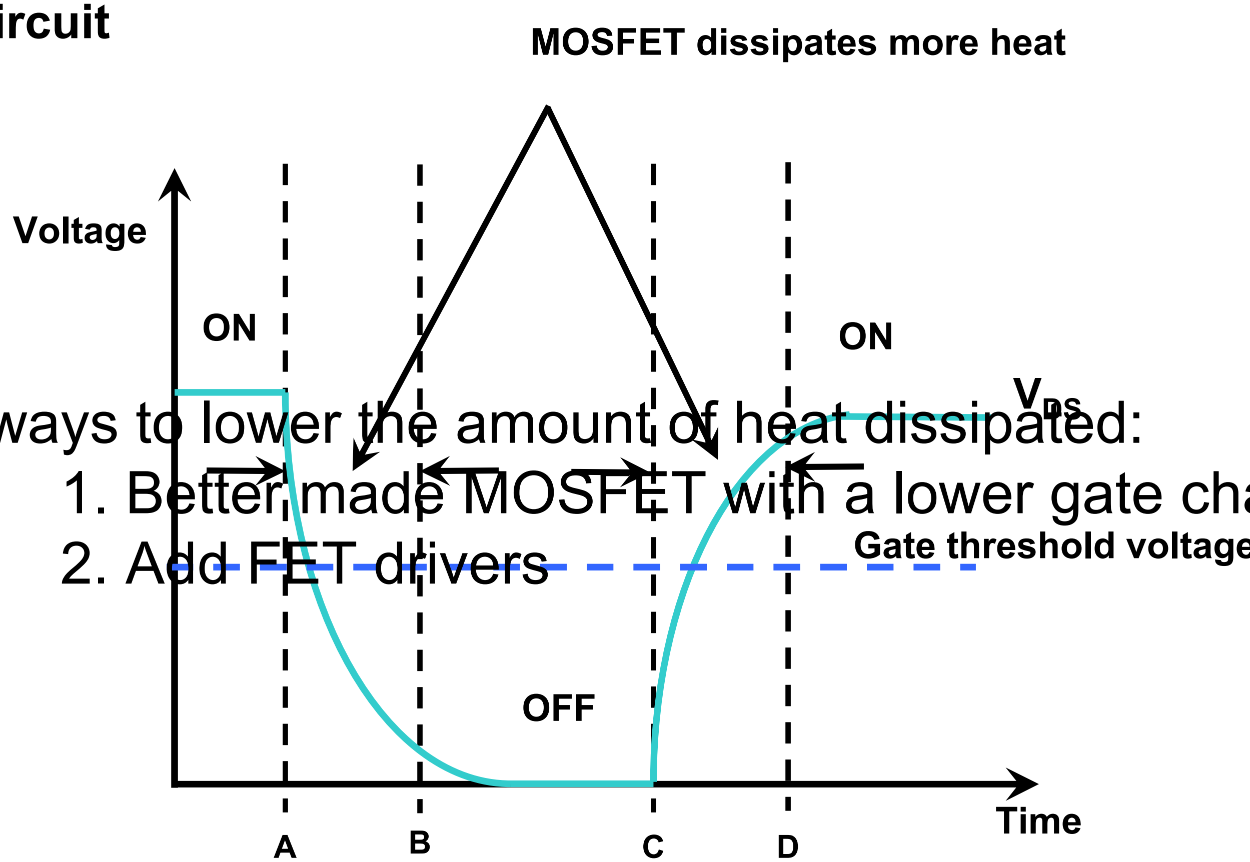


So, is a higher frequency better?

Motor Control

MOSFET Drive Circuit





- 2 ways to lower the amount of heat dissipated:
  1. Better made MOSFET with a lower gate charge
  2. Add FET drivers

Deciding on a PWM Frequency

- 2 considerations when choosing PWM frequency

1). Heat dissipated in the MOSFETs
- Switching speed

2). Responsiveness of the motor
- A motor responds faster to changes in duty cycle at higher frequencies

3). Sound generated by the motor
- Motor whines at 20Hz to 4kHz range
- To avoid motor whine set frequency above 4kHz

4). Speed at which the motor is operating
- At lower speeds you want a higher frequency, constant torque

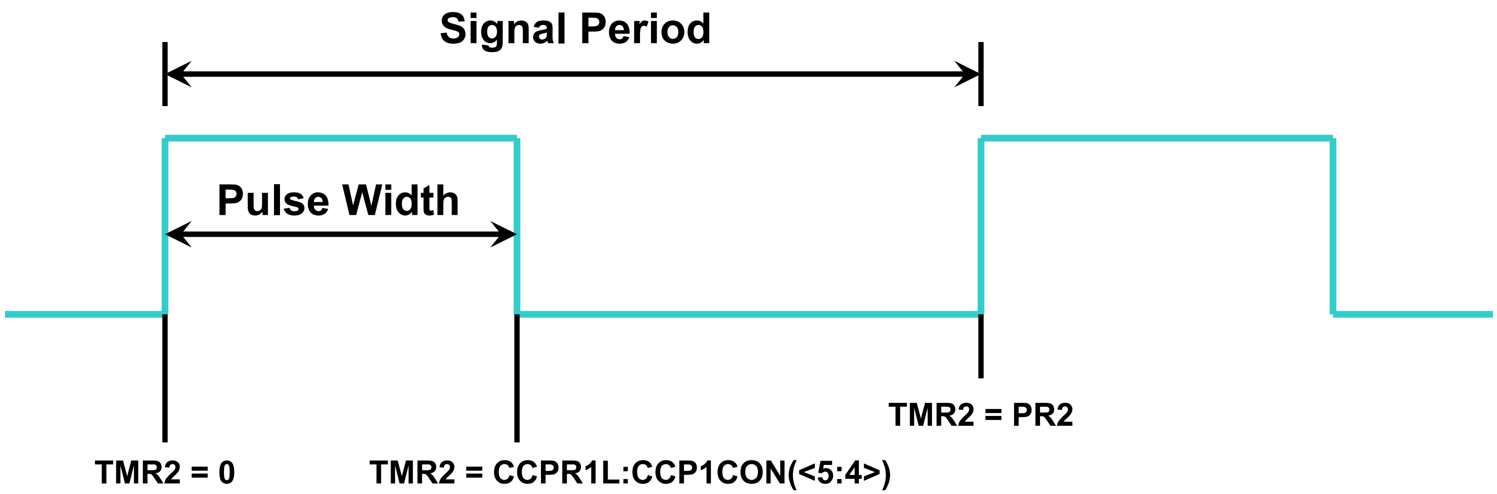
CCP
Capture/Compare/PWM

CCP Module

- What is it?
  The Capture/Compare/PWM module is a peripheral which allows the user to time and control different events

- What does it consist of?
  - Capture mode: allows timing of an events duration
  - Compare mode: allows the user to trigger an external event when a predetermined amount of time has expired
  - PWM mode: generates a pulse-width modulated signal of varying freq. and duty cycle on a single output
    - ► TMR2
    - ► PR2
    - ► CCPR1L
    - ► CCP1CON

Hardware PWM



Equations

Period $_{PWM}$(seconds) = (PR2 + 1) • 4 • Tosc • TMR2 Prescaler

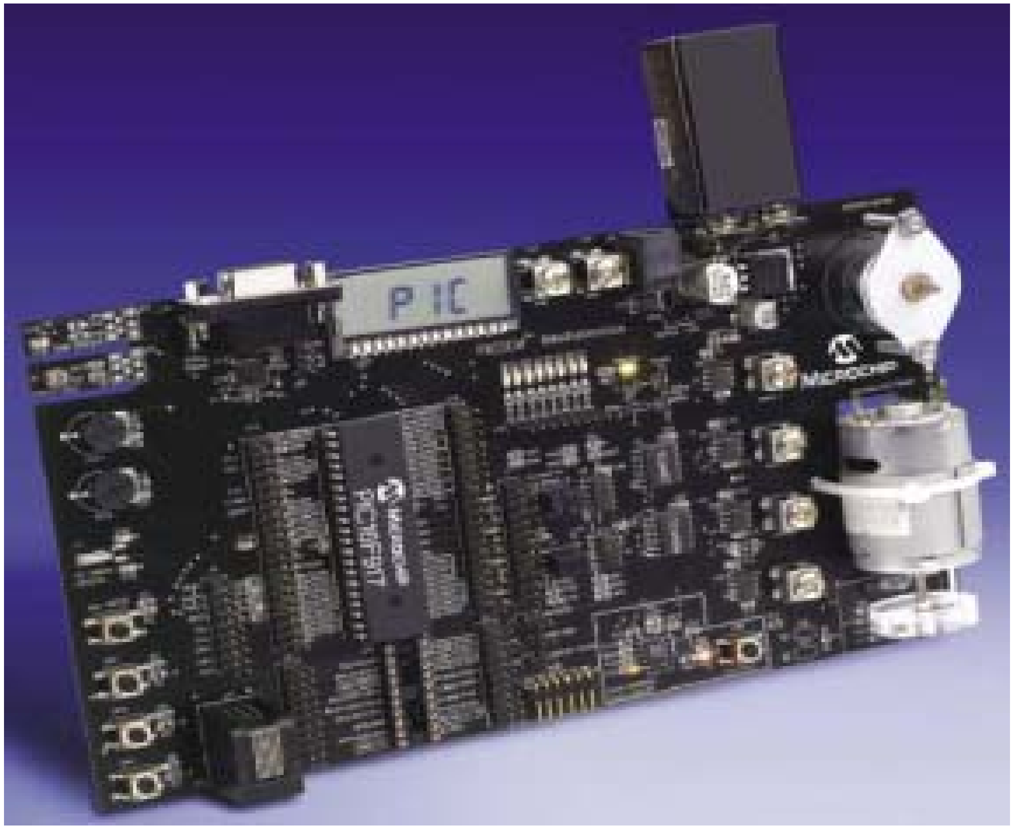
Duty Cycle $_{PWM}$(ratio) = (CCPR1L:CCP1CON<5:4>) / 4 (PR2 + 1)

Lab 1

Hardware PWM

Lab 1

- Use CCP to create a Hardware PWM
- Vary Duty Cycle via POT1
- Increase Frequency
- Vary the Duty Cycle and observe effects on motor



Back EMF

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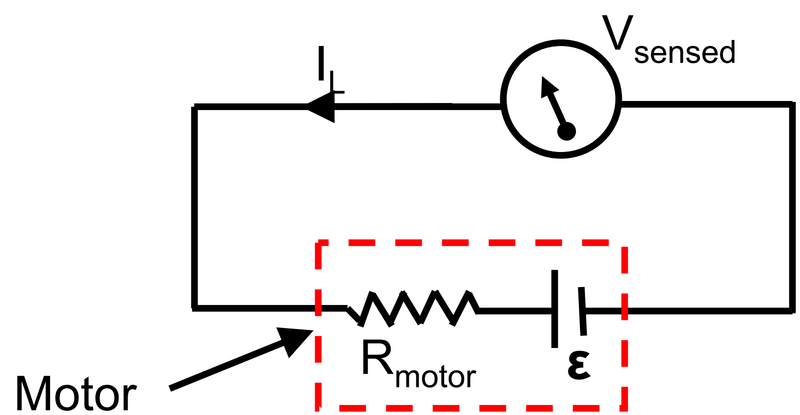
Back EMF

What is it?

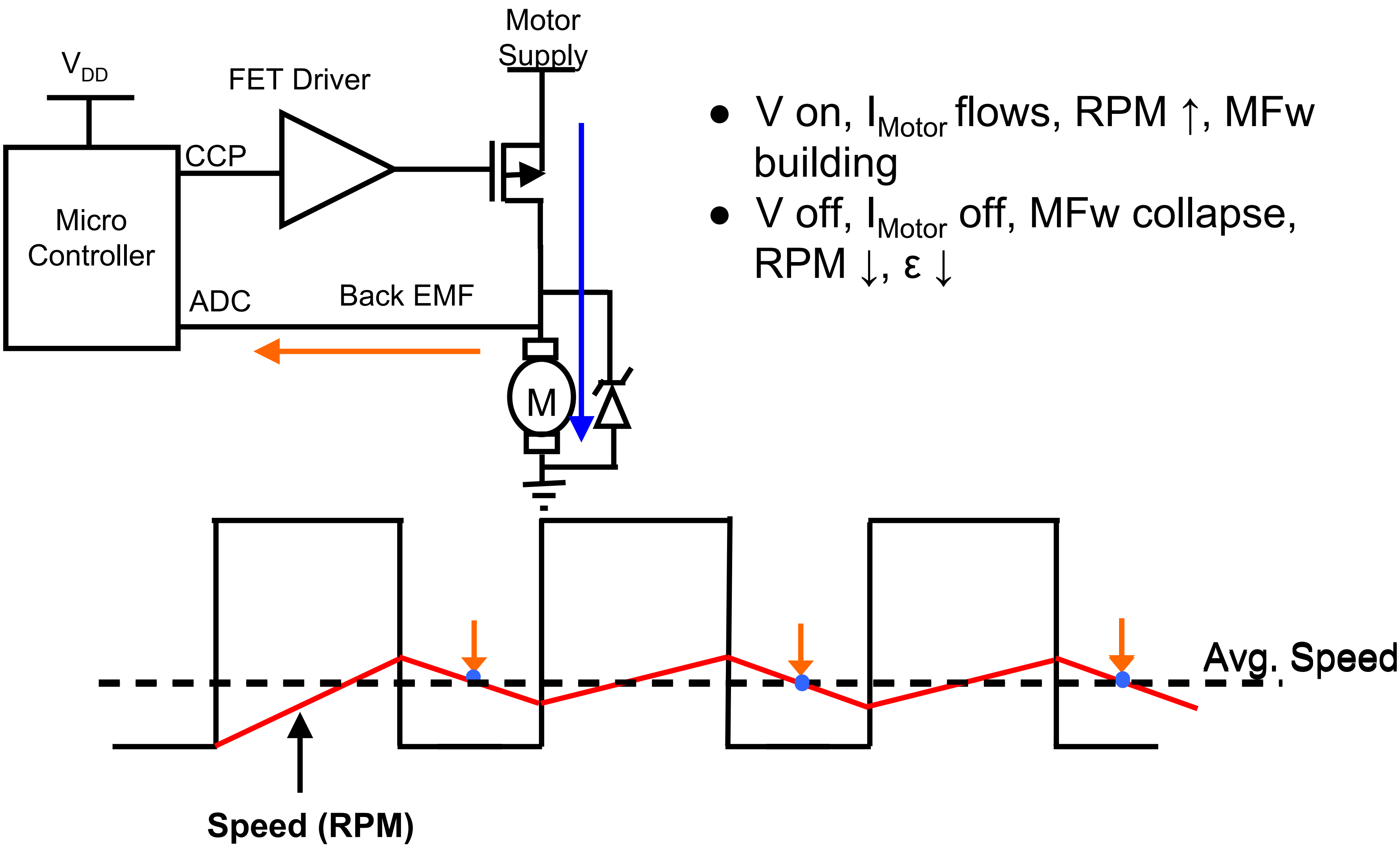
- It is the Electro-Motive Force (EMF) or electrical kickback that results from a coil (rotor) turning inside a magnetic field (stator) and is sensed as a voltage

$$V_{sensed} = I_L \bullet R_{motor} + \varepsilon$$

V_{sensed} = Voltage Sensed
I_L = Leakage Current
R_{motor} = Motor Resistance
ε = Back EMF



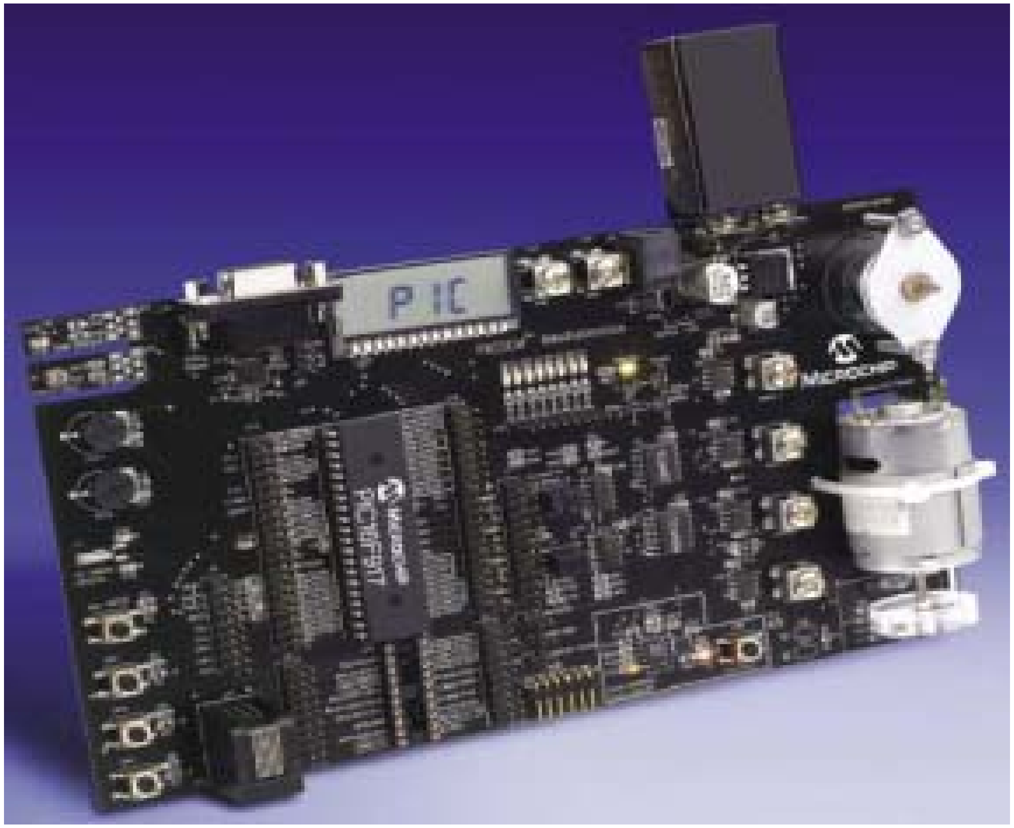
Back EMF



- V on, I_{Motor} flows, RPM ↑, MFw building
- V off, I_{Motor} off, MFw collapse, RPM ↓, ε ↓

Lab 2

Brushed DC Motor Control with Back EMF Feedback

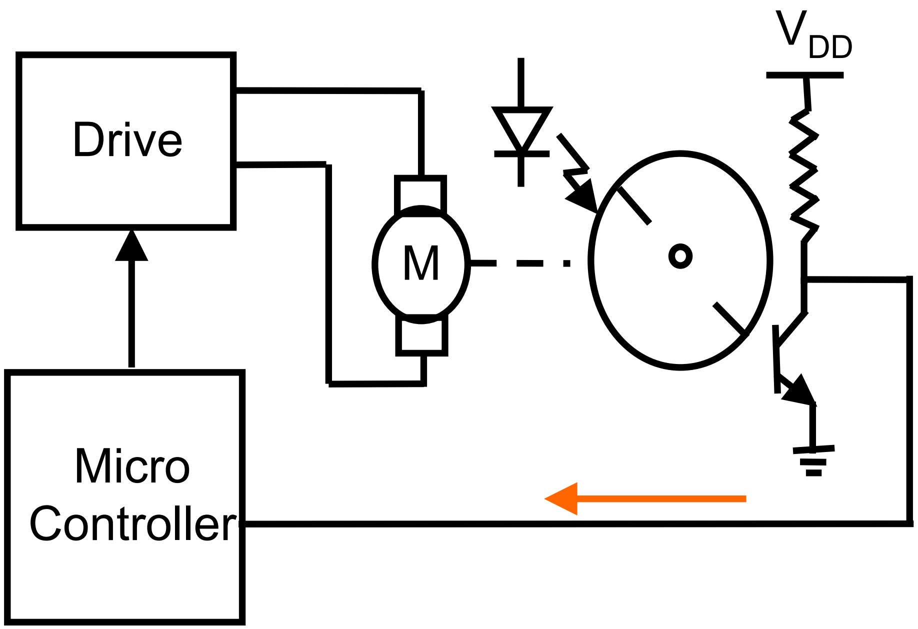


Lab 2

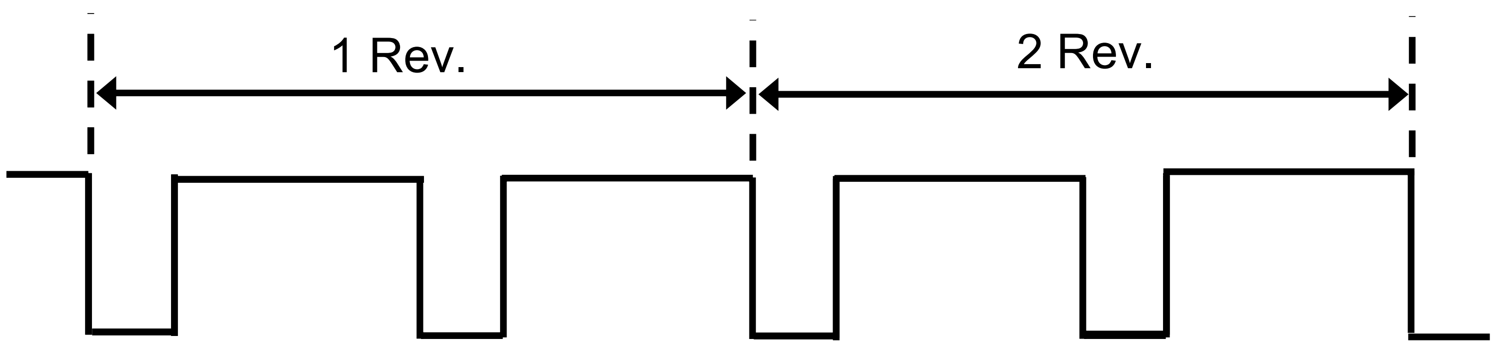
- Use CCP to create a Hardware PWM
- Use the ADC to measure Back EMF off the motor
- Vary the motor speed via POT1

Optical Encoder

Rotary Encoder

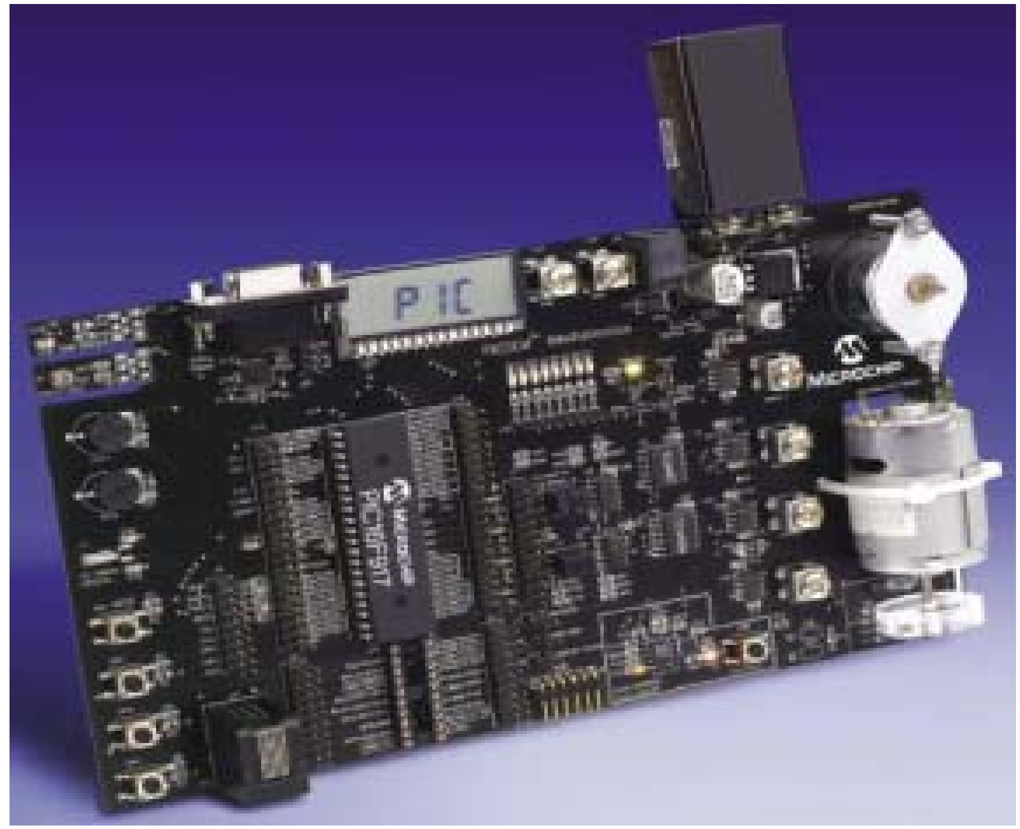


- As the LED shines through the disc, the Photo transistor acts as a switch and closes allowing a ‘0’ to be read
- Therefore, the time between every other rising edges of pulse correspond to the speed of motor



Lab 3

Brushed DC Motor Control with Optical Encoder Feedback



Lab 3

- Use CCP to create a Hardware PWM
- Use Optical Encoder to measure time of motor rotation
- Vary the motor speed via POT1

Positives and Negatives

- Measuring motor speed using Back EMF

  Positive: - Can sense speed faster

  - Low cost, Fewer parts

  Negative: - Can't sense while motor is on thus, not as accurate

- Measuring motor speed using Optical Encoder

  Positive: - No signal calibration thus, more accurate

  Negative: - Can be affected by other light sources

  - Limited by the time it takes to complete 1 rev.

  - Higher cost, more parts and code maybe more involved

ECCP
(Enhanced Compare/Capture/PWM)

ECCP Module

- What is it?
  The Enhanced Capture/Compare/PWM module is a peripheral which allows the user to time and control different events

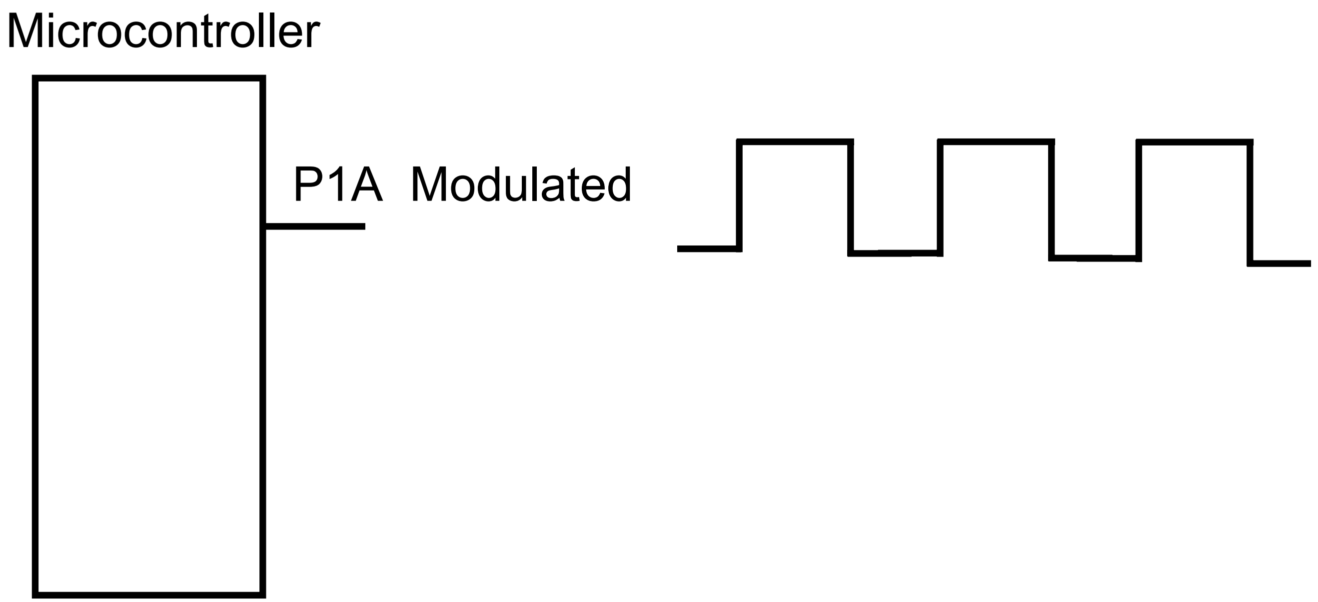
- What does it consist of?
  - Capture mode: allows timing of an events duration
  - Compare mode: allows the user to trigger an external event when a predetermined amount of time has expired
  - PWM mode: generates a pulse-width modulated signal of varying freq. and duty cycle

Enhanced PWM Modes

- The Enhanced PWM Mode can generate a PWM signal on up to four different output pins
  - ► Four different PWM Output modes:
    - Single PWM
    - Half-Bridge PWM
    - Full-Bridge PWM, Forward mode
    - Full-Bridge PWM, Reverse mode
  - ► Auto-Shutdown Mode
  - ► Auto-Restart Mode
  - ► Programmable Dead-Band Delay Mode
  - ► Pulse Steering Mode

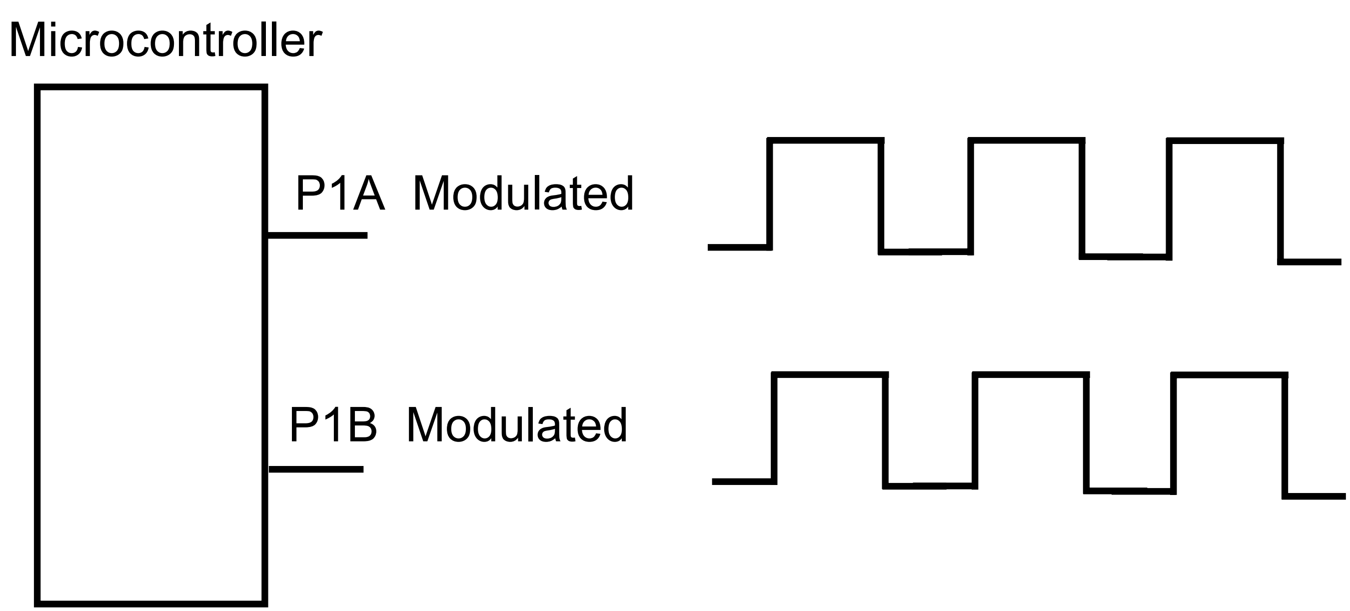
PWM Output Modes

- Single PWM
  - Generates a pulse-width modulated signal of varying freq. and duty cycle on a single output



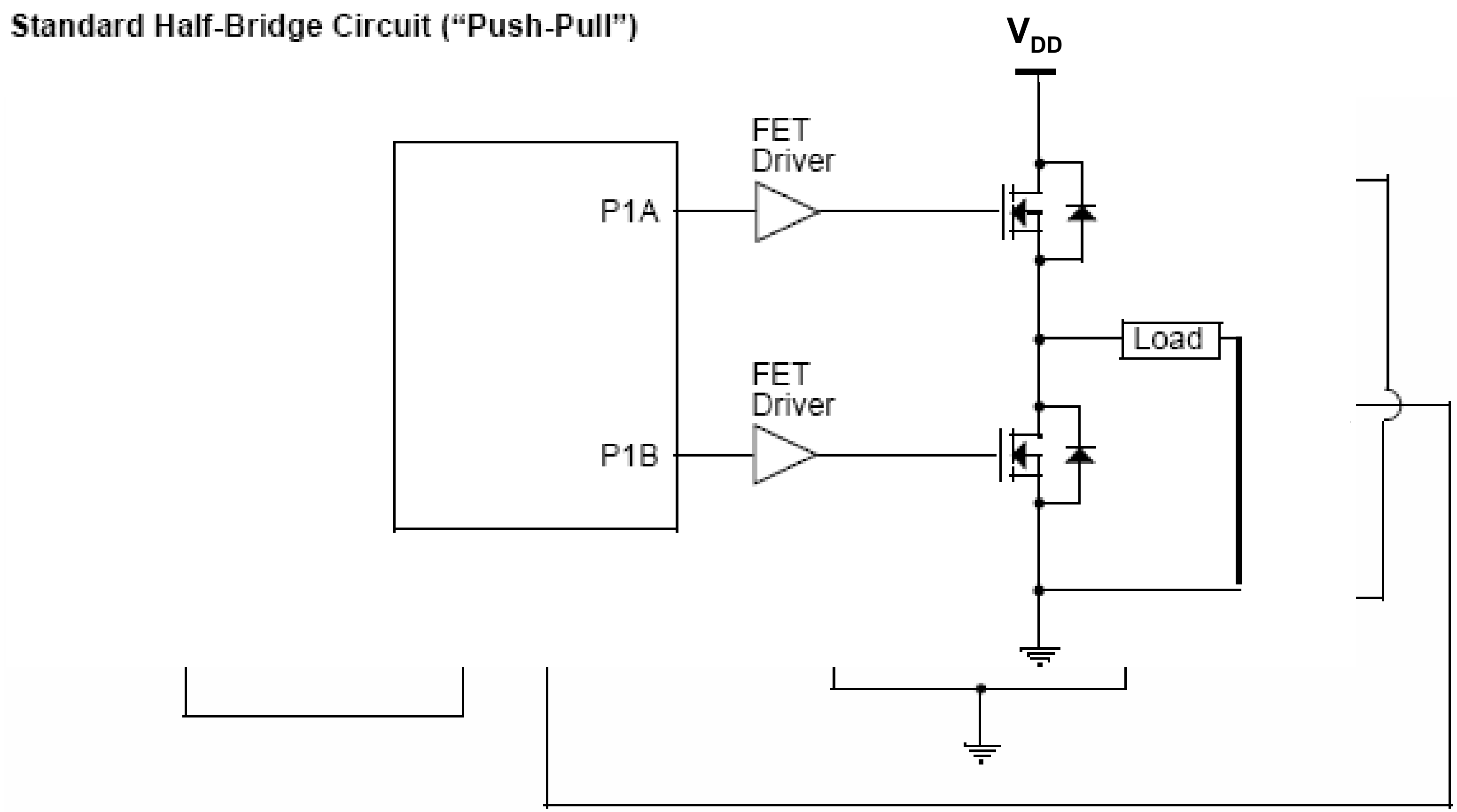
PWM Output Modes

- Half-Bridge PWM
  - Generates a PWM signal on two outputs



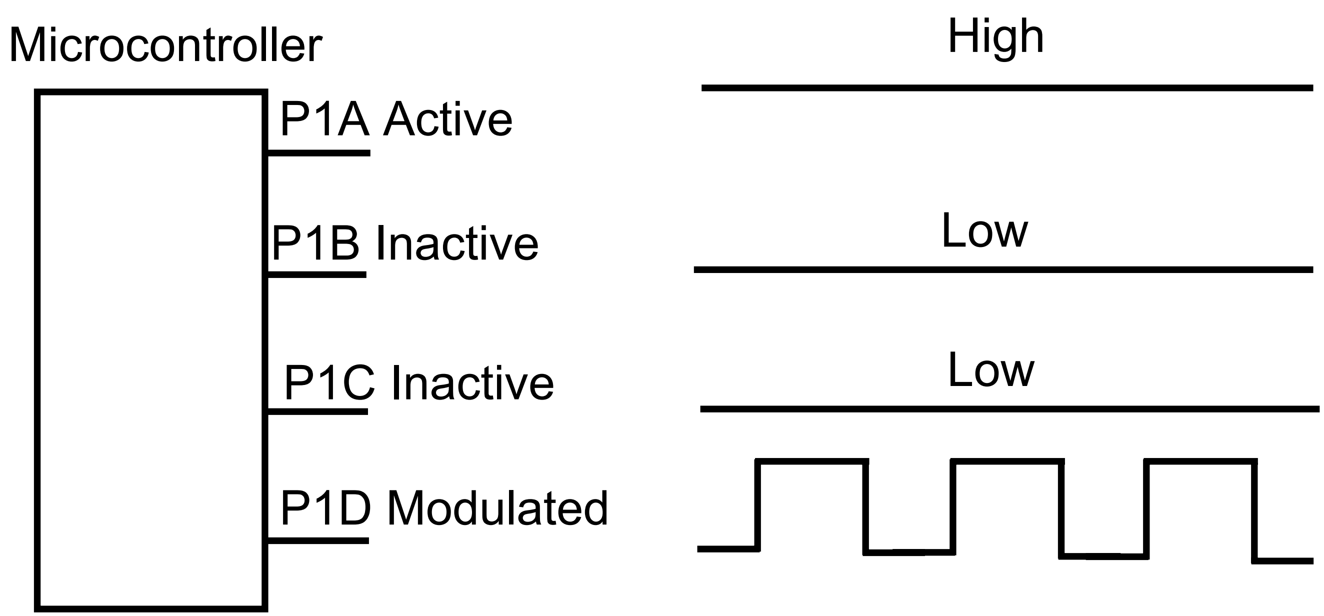
PWM Output Modes

- Application examples:



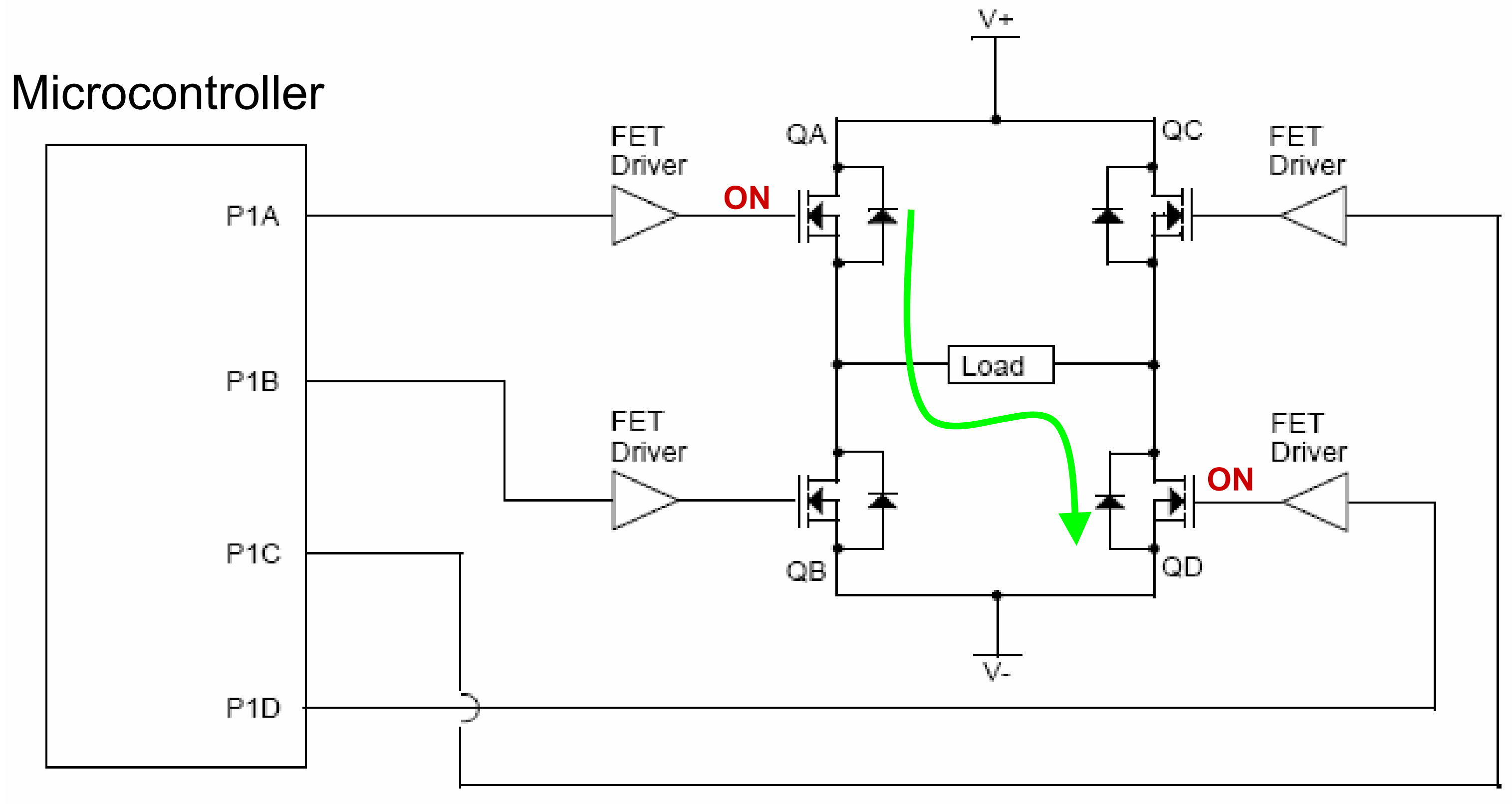
PWM Output Modes

- Full-Bridge PWM, Forward Mode
  - All four pins are used as outputs



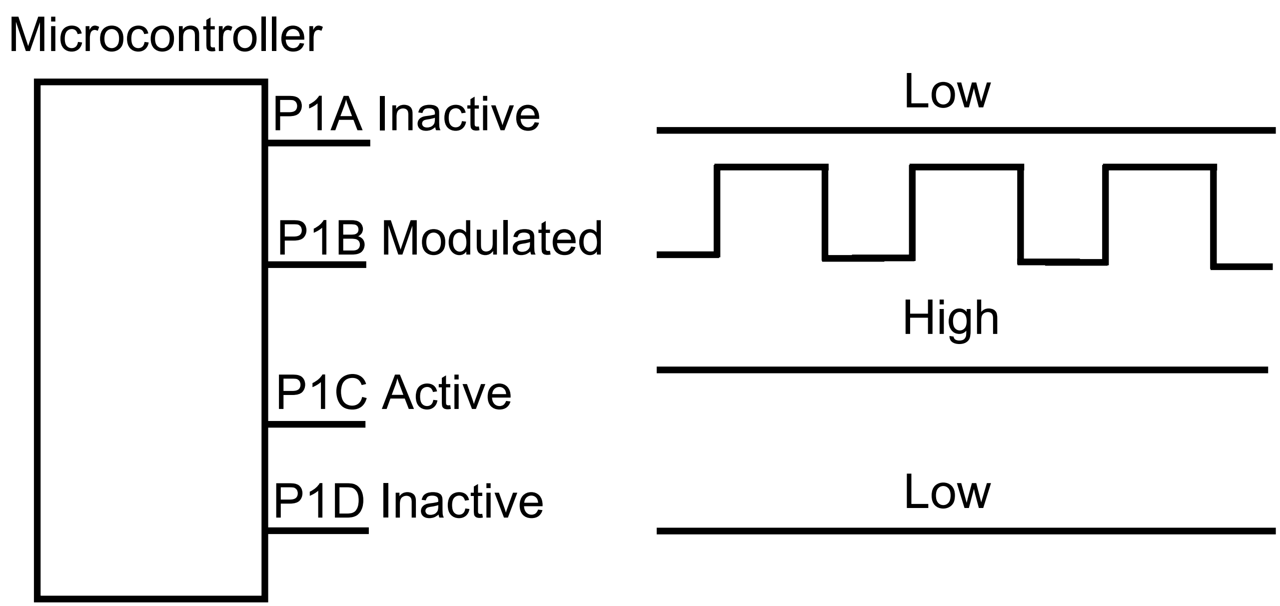
PWM Output Modes

- Example:



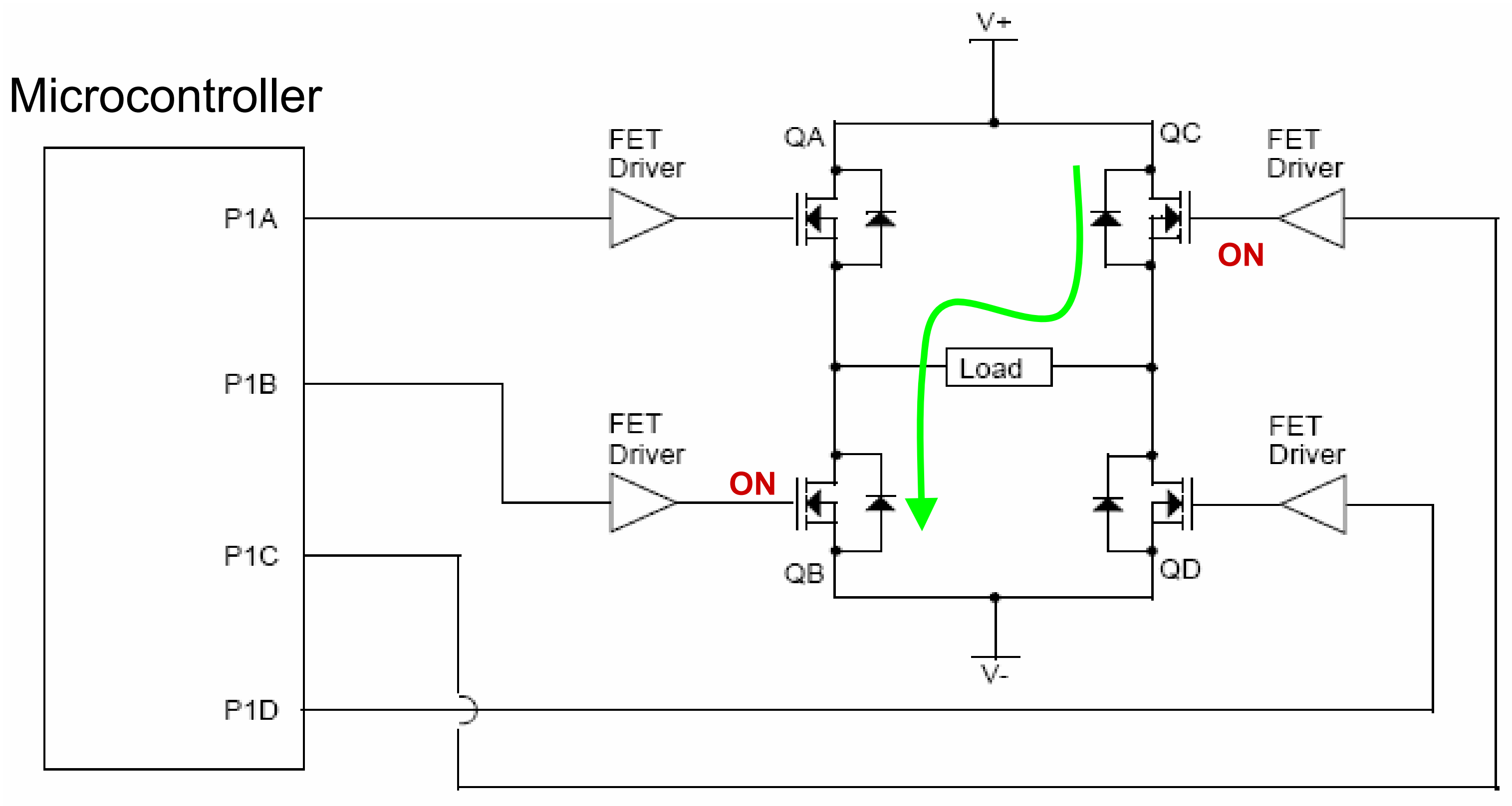
PWM Output Modes

- Full-Bridge PWM, Reverse Mode
  - All four pins are used as outputs



PWM Output Modes

- Example:

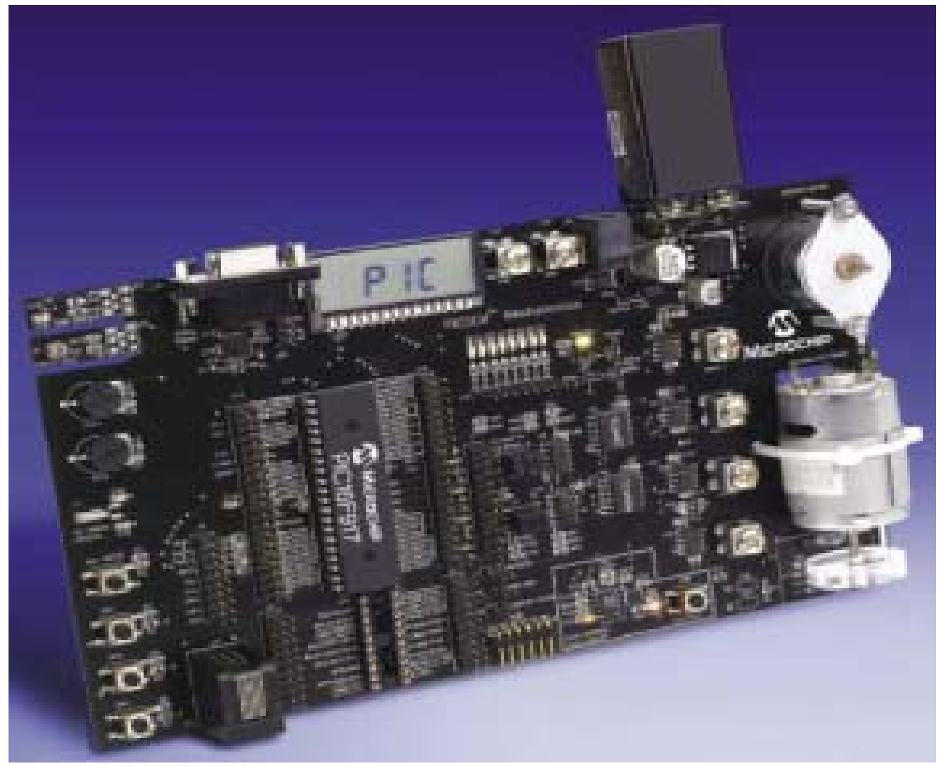


Lab 4

Brushed DC Motor Control Using the Enhanced PWM to change motor direction

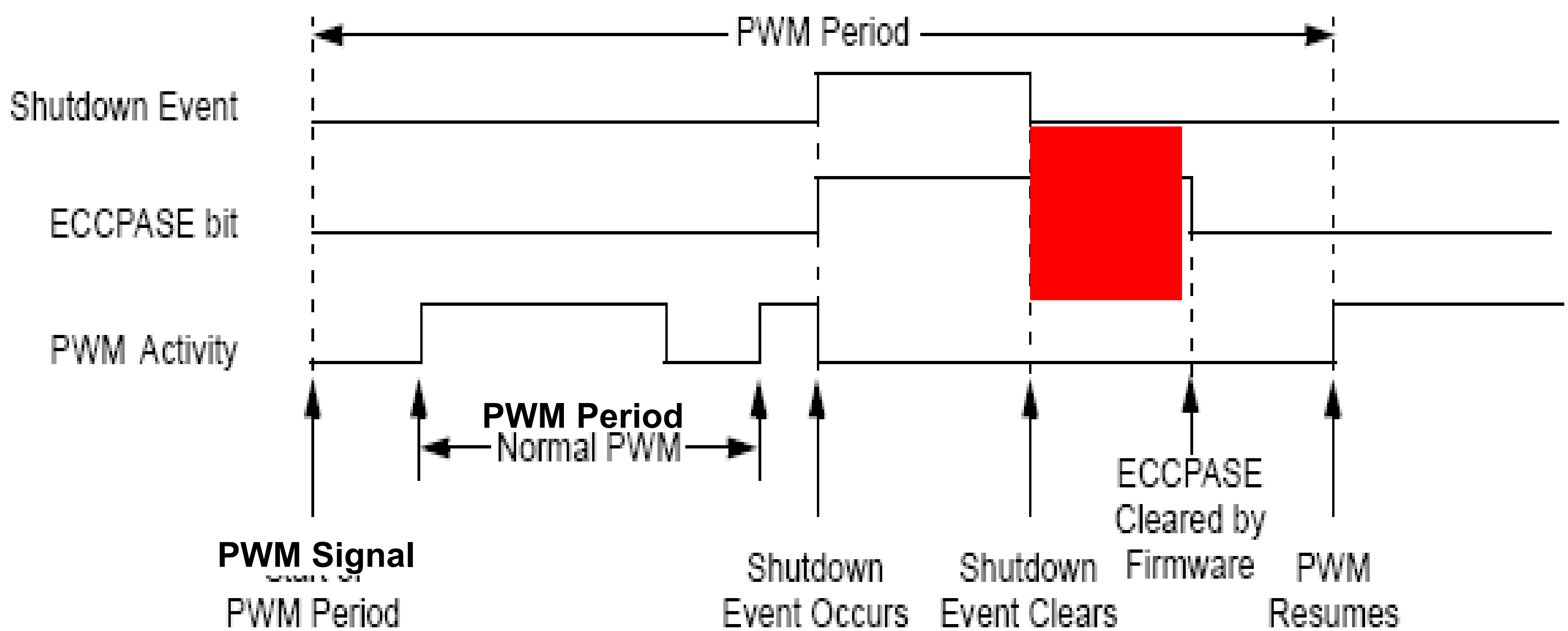
Lab 4

- Use the Enhanced PWM mode of the ECCP to drive a motor
- Use a Full-Bridge PWM mode to drive the motor forward, brake and reverse



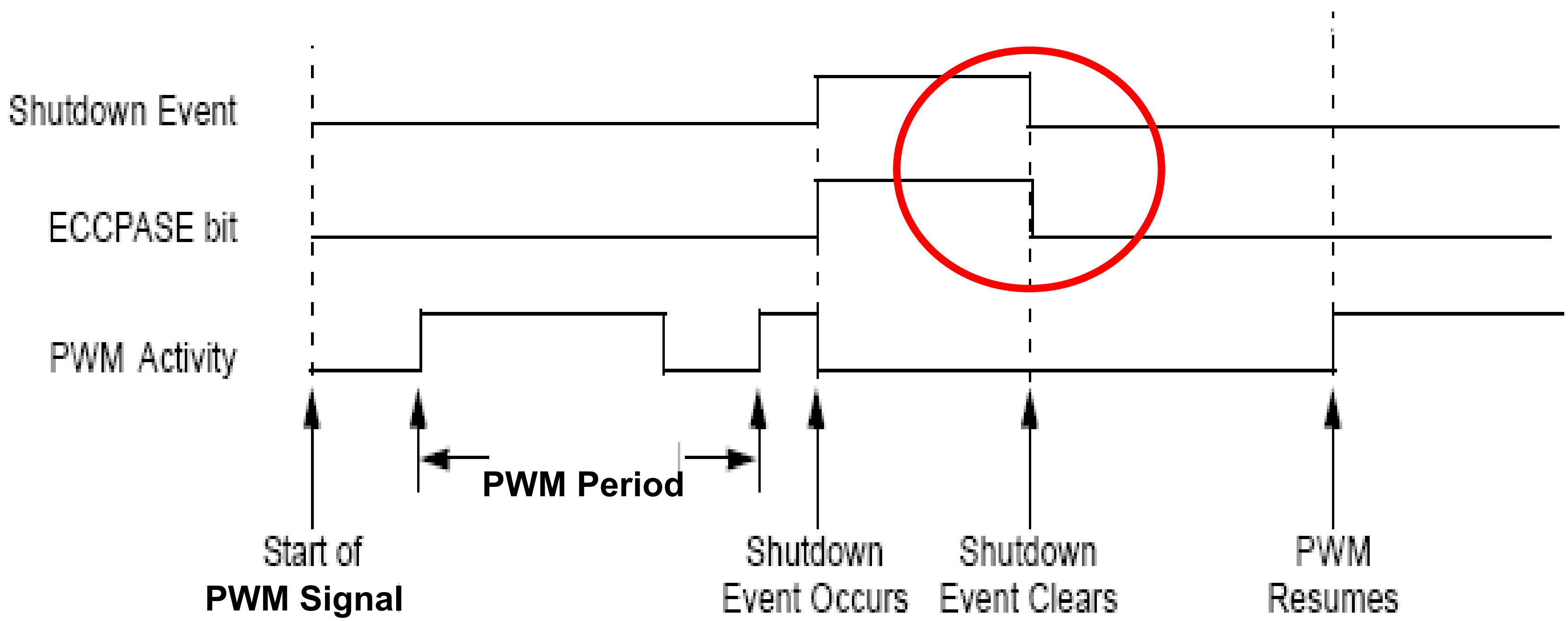
Auto-Shutdown Mode

- What does it do?
  - It is a feature that will disable the PWM outputs when an external shutdown event occurs
    - ► Shutdown events: - A logic '0' on the INT pin



Auto-Restart Mode

- What does it do?
  - The Auto-Restart can be configured to automatically restart the PWM signal once the Auto-Shutdown condition has been removed



Current Sensing

Current Sensing

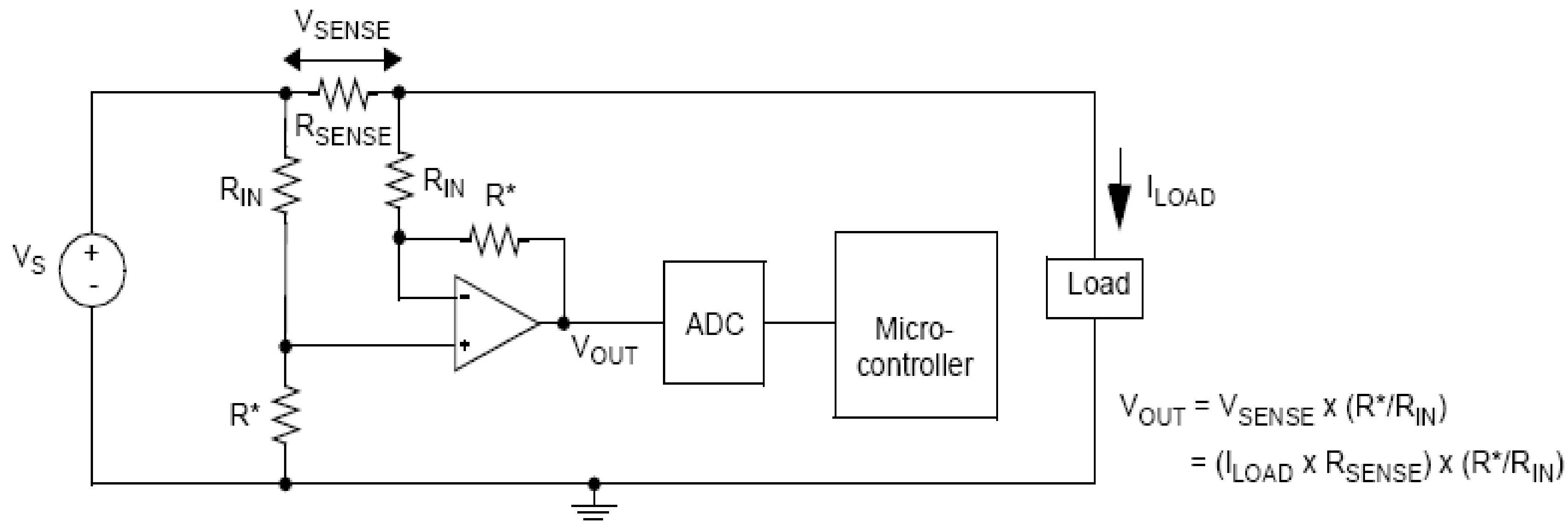
- What can sensing the current flowing through a motor tell us?
  - Torque (When you control current you control torque)

- How can current be sensed in a given application?
  Current can be sensed by measuring:
  1). The voltage drop through a known resistor value
  2). The magnetic field strength of a known inductor value

- Where can current be sensed?
  Current is generally sensed at one of two places:
  1). The supply side of the drive circuit (High Side Current Sense)
  2). The sink side of the drive circuit (Low Side Current Sense)

Current Sensing

High Side Resistive Circuit



- As I_{Load} ↑ or ↓, V_{Out} will ↑ or ↓
- If R_{Sense} ↑ or ↓, I_{Load} and V_{Out} will act the same proportionally

Current Sensing

High Side Advantages:

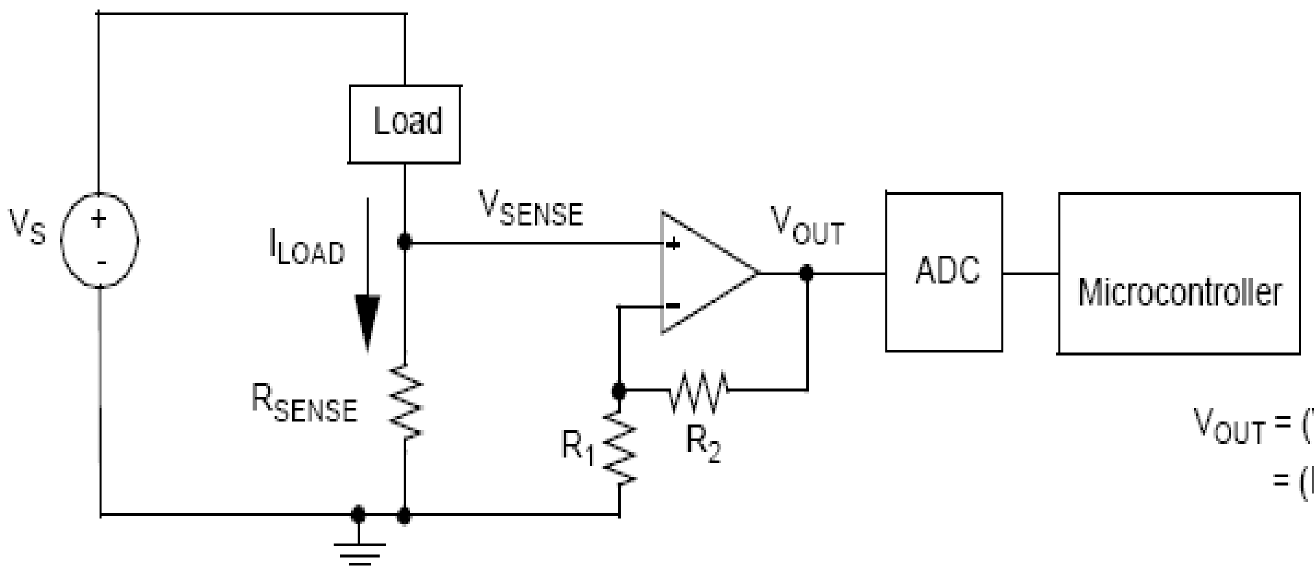
- Can detect over current faults that can occur by short circuits
- Differential amplifier circuit will filter noise via the common-mode-rejection-ratio (CMRR) of the amplifier

High Side Disadvantages:

- V_{SENSE} voltage is approx. equal to the Vs, which may be beyond the max input voltage range of op-amp
- A differential amplifier's CMRR will be degraded by mismatches in amplifier resistors

Current Sensing

Low Side Resistive Circuit



$V_{OUT} = (V_{SENSE}) \times (1 + R_2/R_1)$

$= (I_{LOAD} \times R_{SENSE}) \times (1 + R_2/R_1)$

- As I_{Load} ↑ or ↓, V_{Out} will ↑ or ↓
- If R_{Sense} ↑ or ↓, I_{Load} and V_{Out} will act the same proportionally

Current Sensing

Low Side Advantages:

- V_{SENSE} is referenced to ground, thus a low voltage amplifier can be used
- A non-inverting amplifier can be used and the input impedance of the circuit will be equal to the large input impedance of the amplifier

Low Side Disadvantage:

- Low-side current monitors are unable to detect a fault where the load is accidentally connected to ground via an alternative ground path

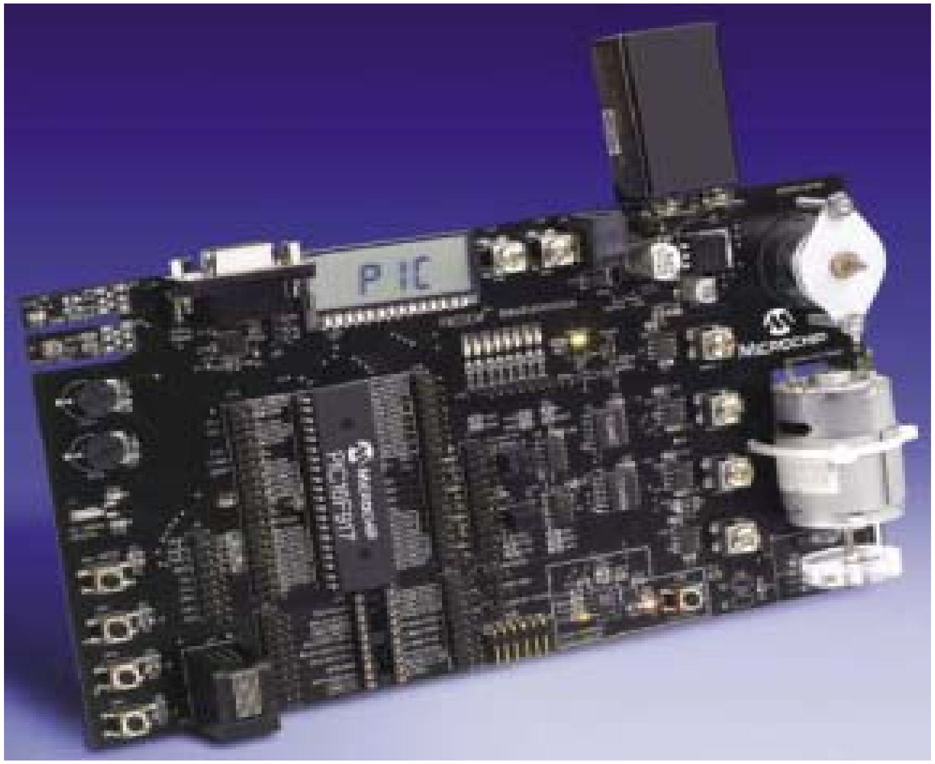
Lab 5

Using Current Sensing to detect current loading on a brushed DC motor

University of Microchip UofM MASTERs 2007

Lab 5

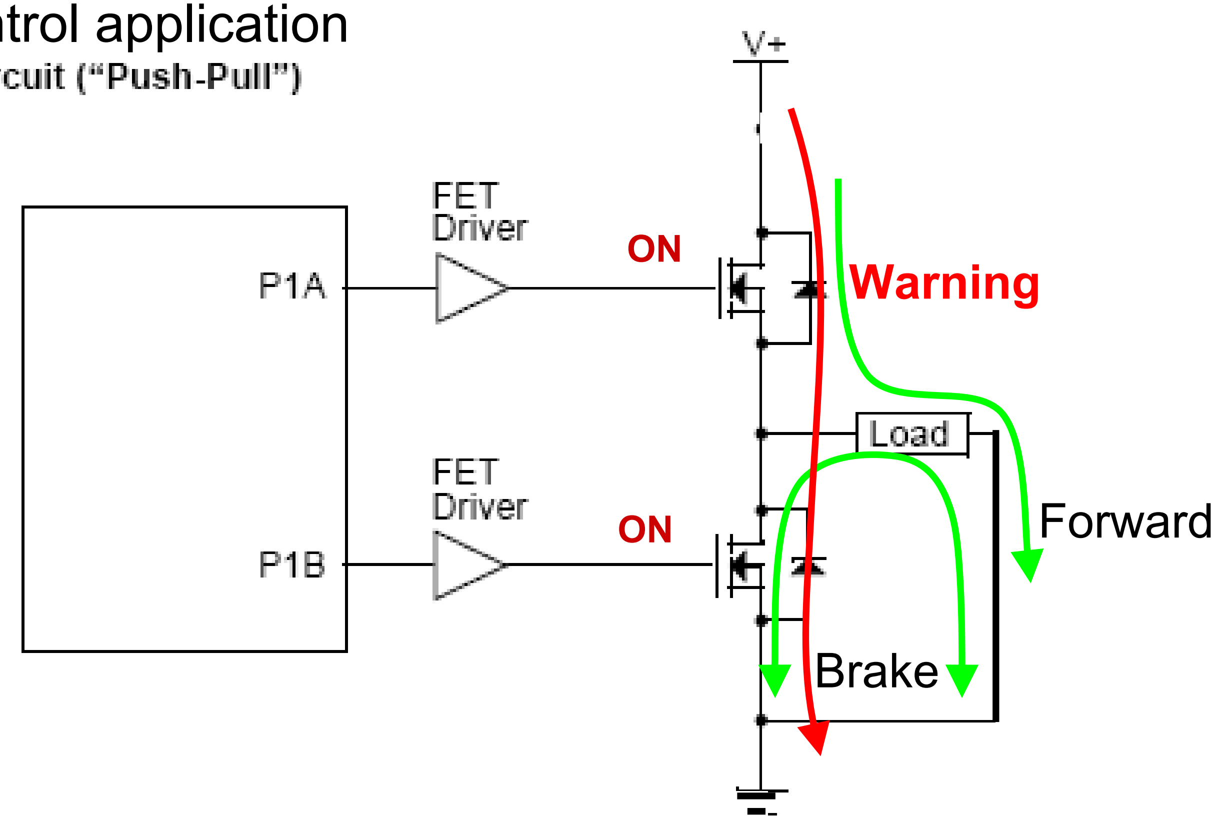
- Use a Low-side Resistive current sensing circuit to detect a load on the motor
- Use Auto-Shutdown mode to shut the motor off at a given load
- Use Auto-Restart mode to restart the motor when the load is removed



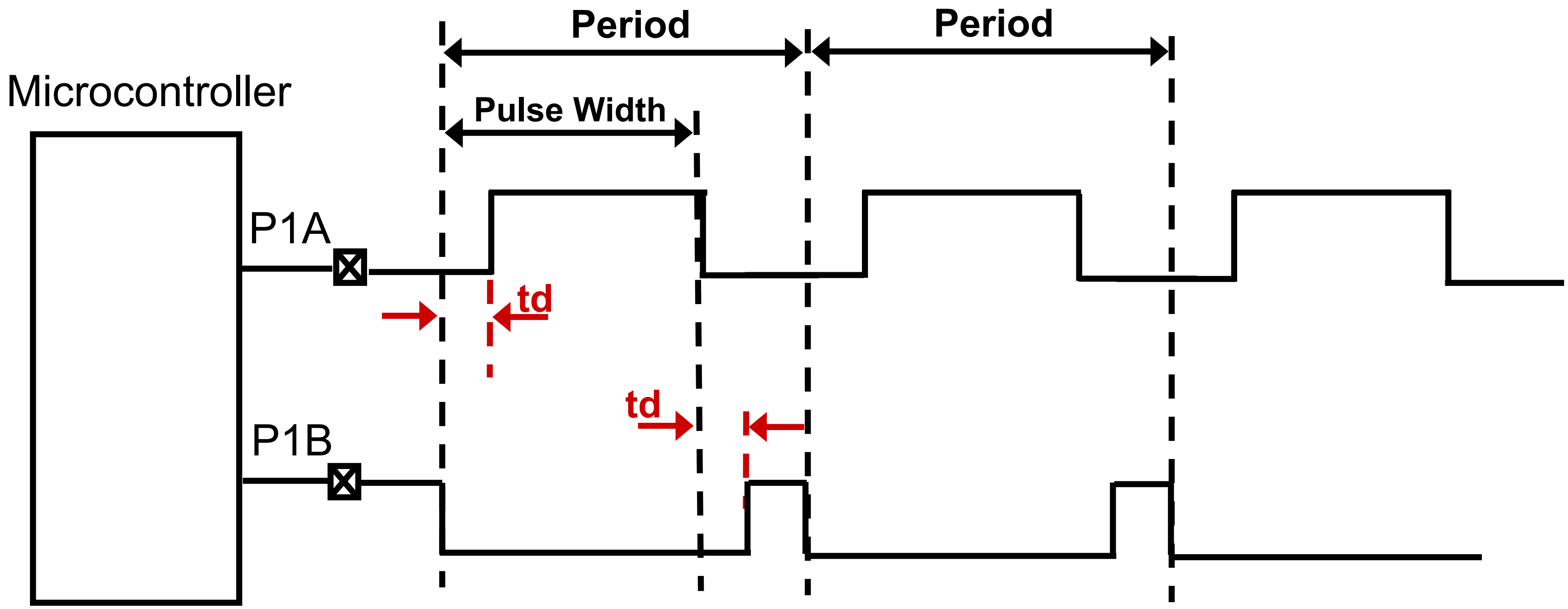
Programmable Dead Band Delay

- Why do I need it?
  - To avoid Shoot-Through Current from shorting the bridge supply of your motor control application

Standard Half-Bridge Circuit ("Push-Pull")



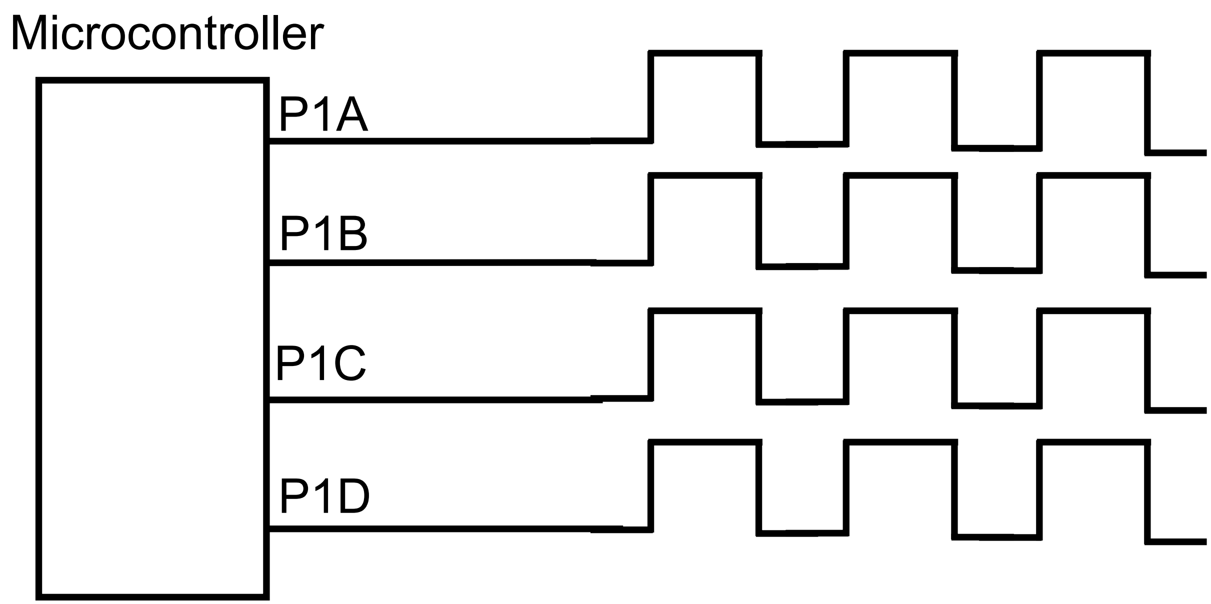
Programmable Dead Band Delay



td = Dead Band Delay

Pulse Steering Mode

- What does it do?
  - Pulse Steering Mode allows any of the PWM output pins to carry a PWM signal (Basically, it's a single PWM)
  - The same PWM signal can be put on one, two, three or four output pins at the same time

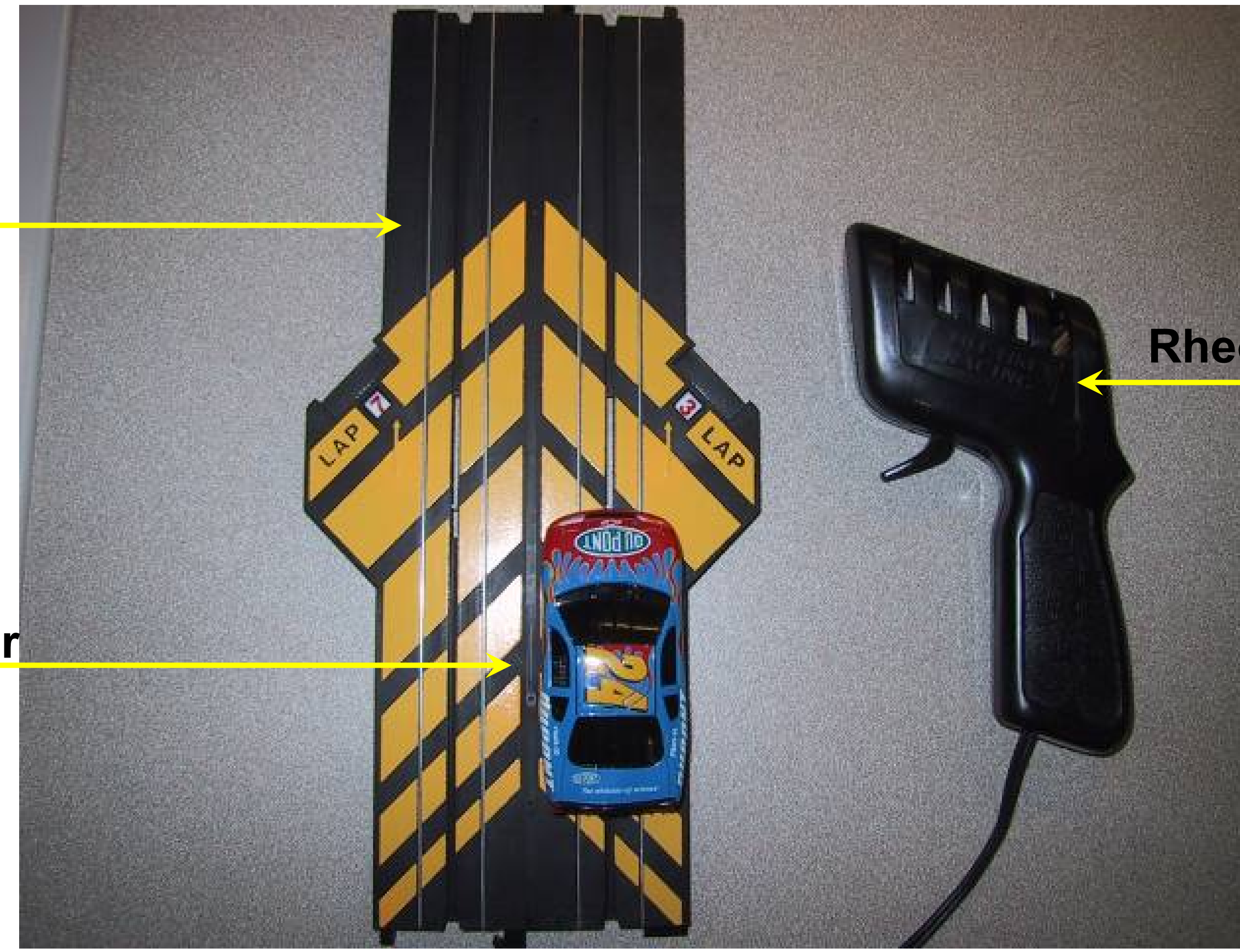


Slot Car Demo

Brushed DC motor control of an electric

Slot car and track

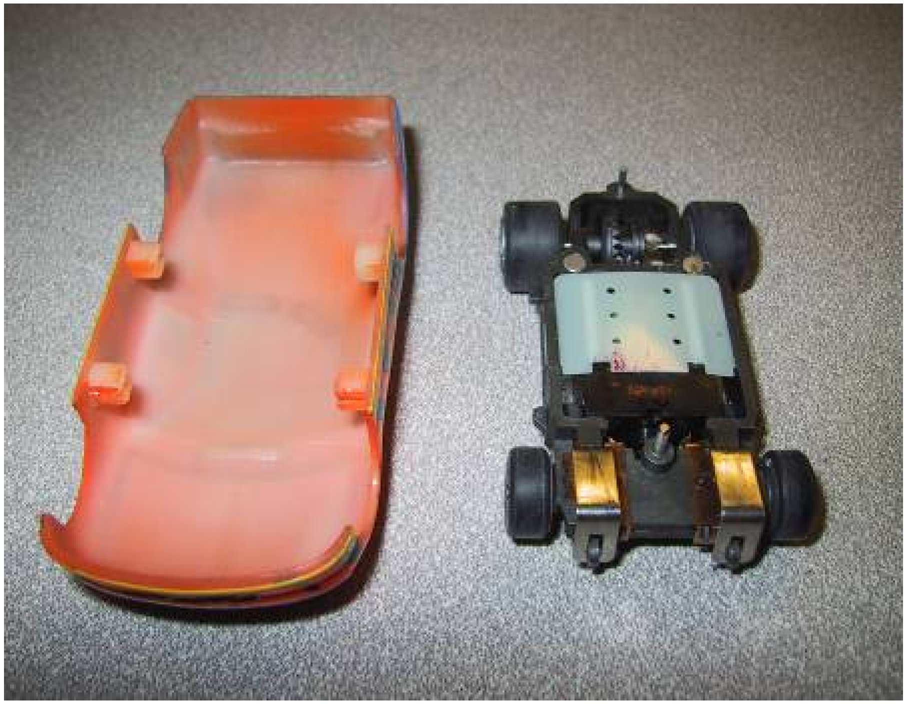
Slot Car Demo



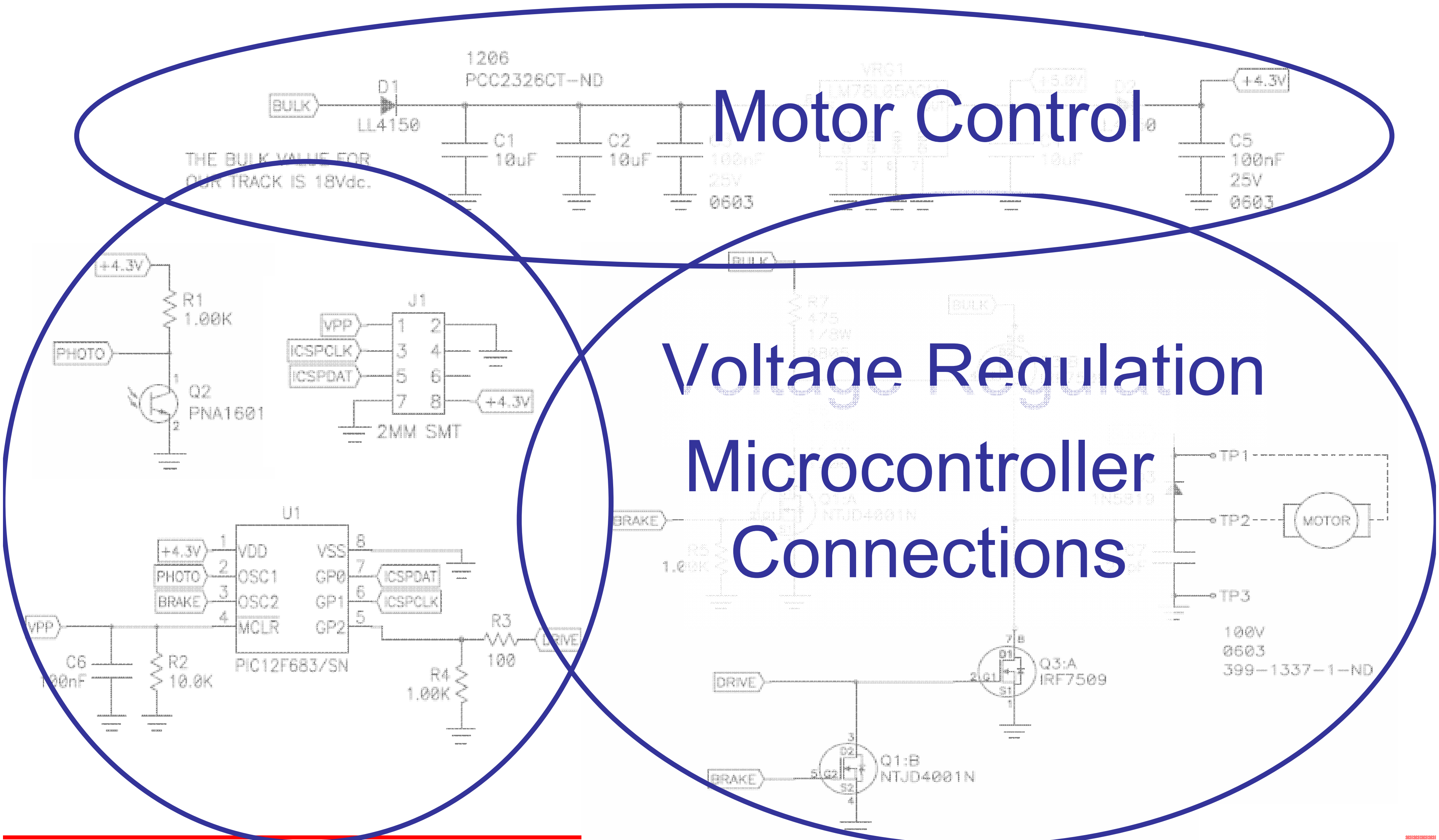
Slot Car Demo

Original Car (Top)

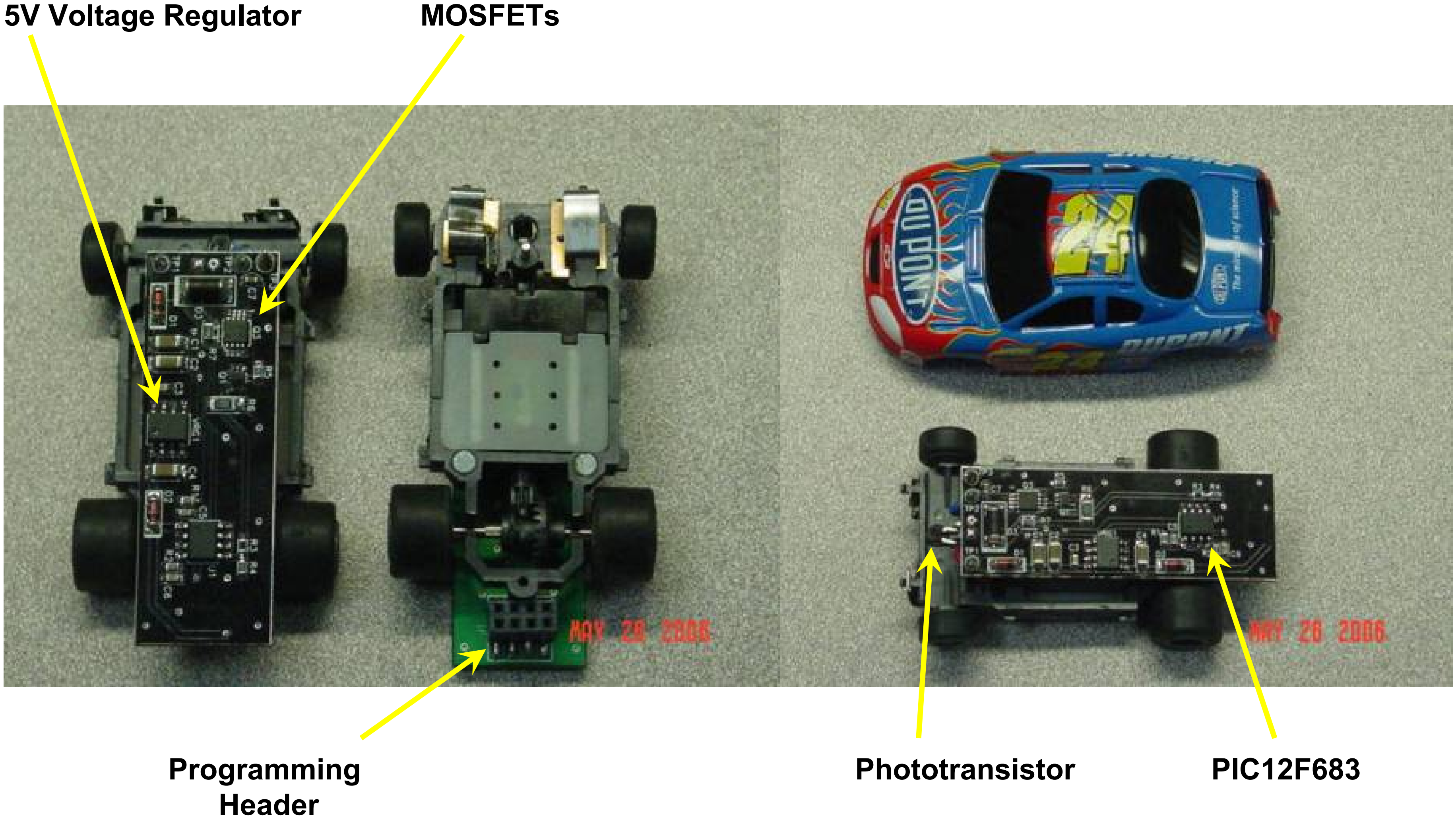
Original Car (Bottom)



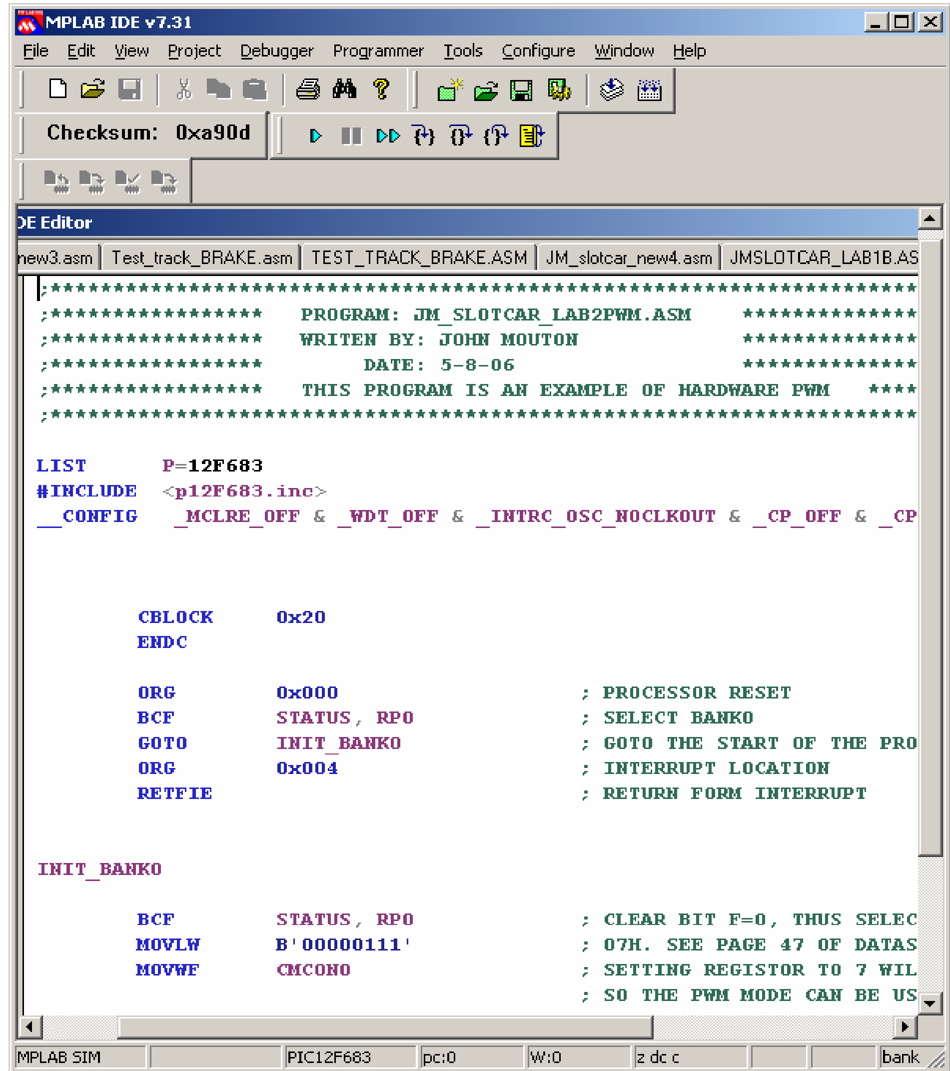
Slot Car Demo



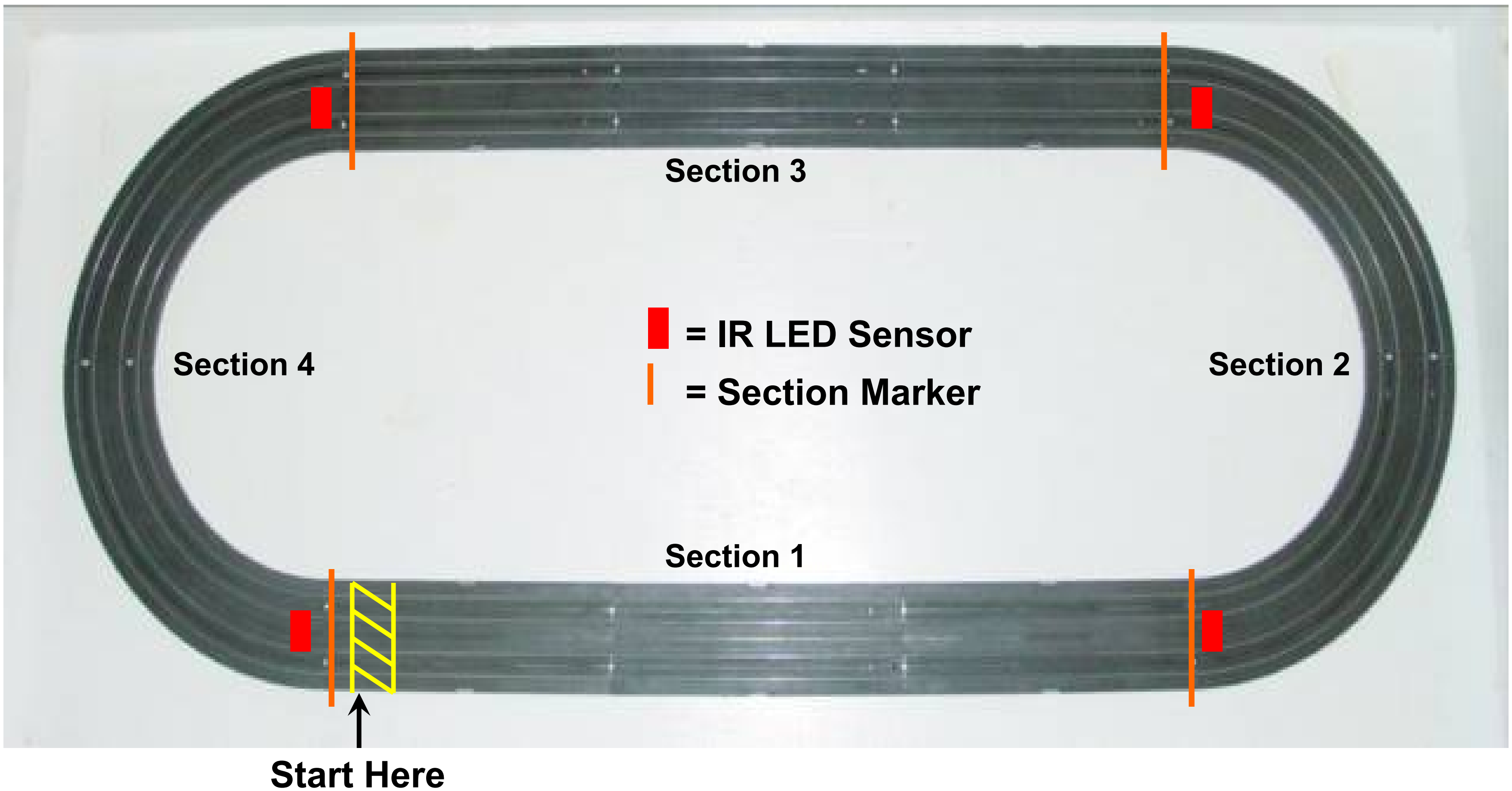
Slot Car Demo



Slot Car Demo

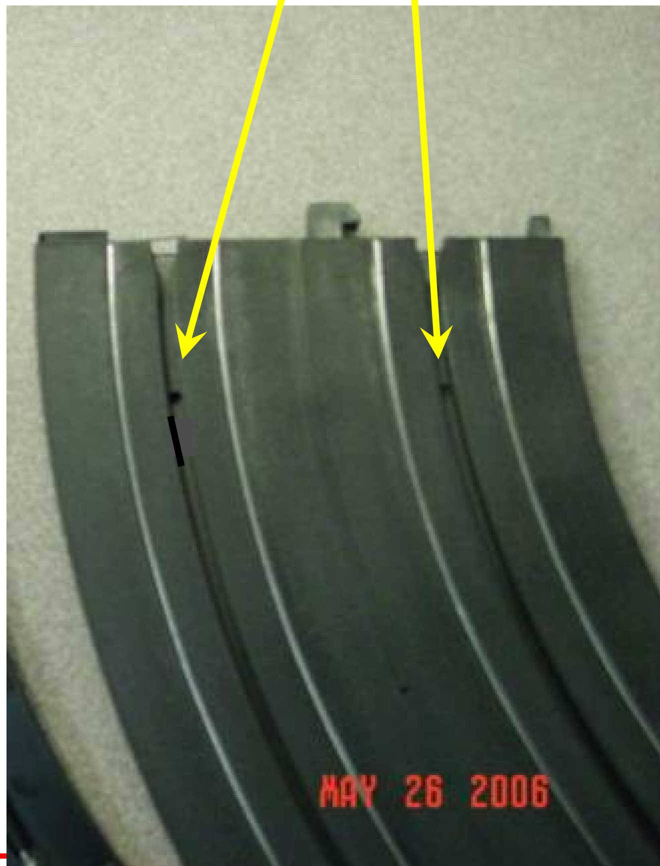


Track Layout

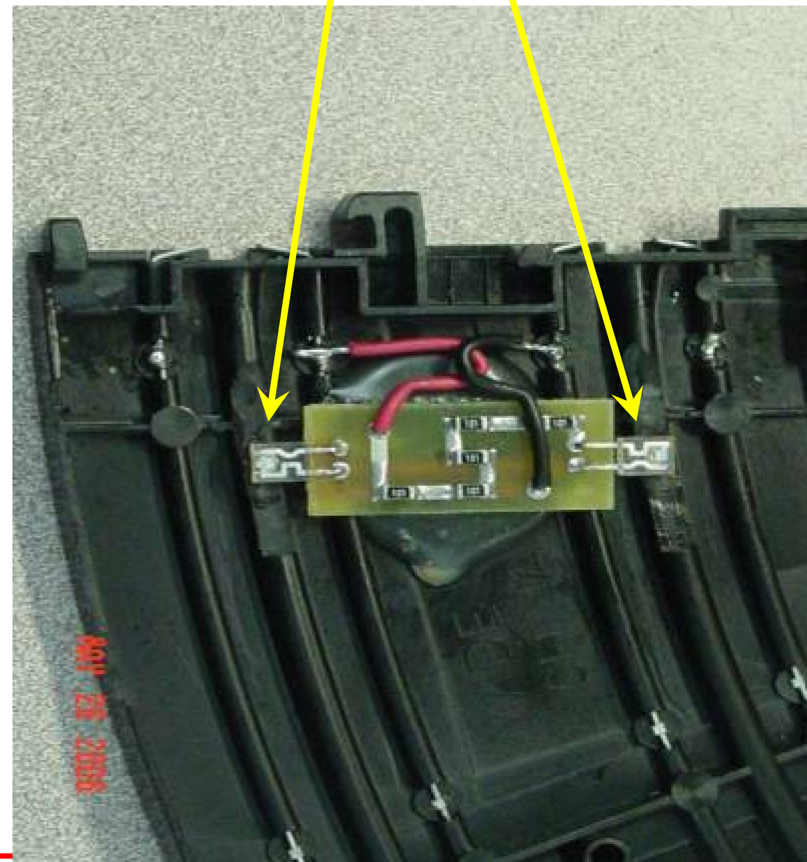


Track Modification

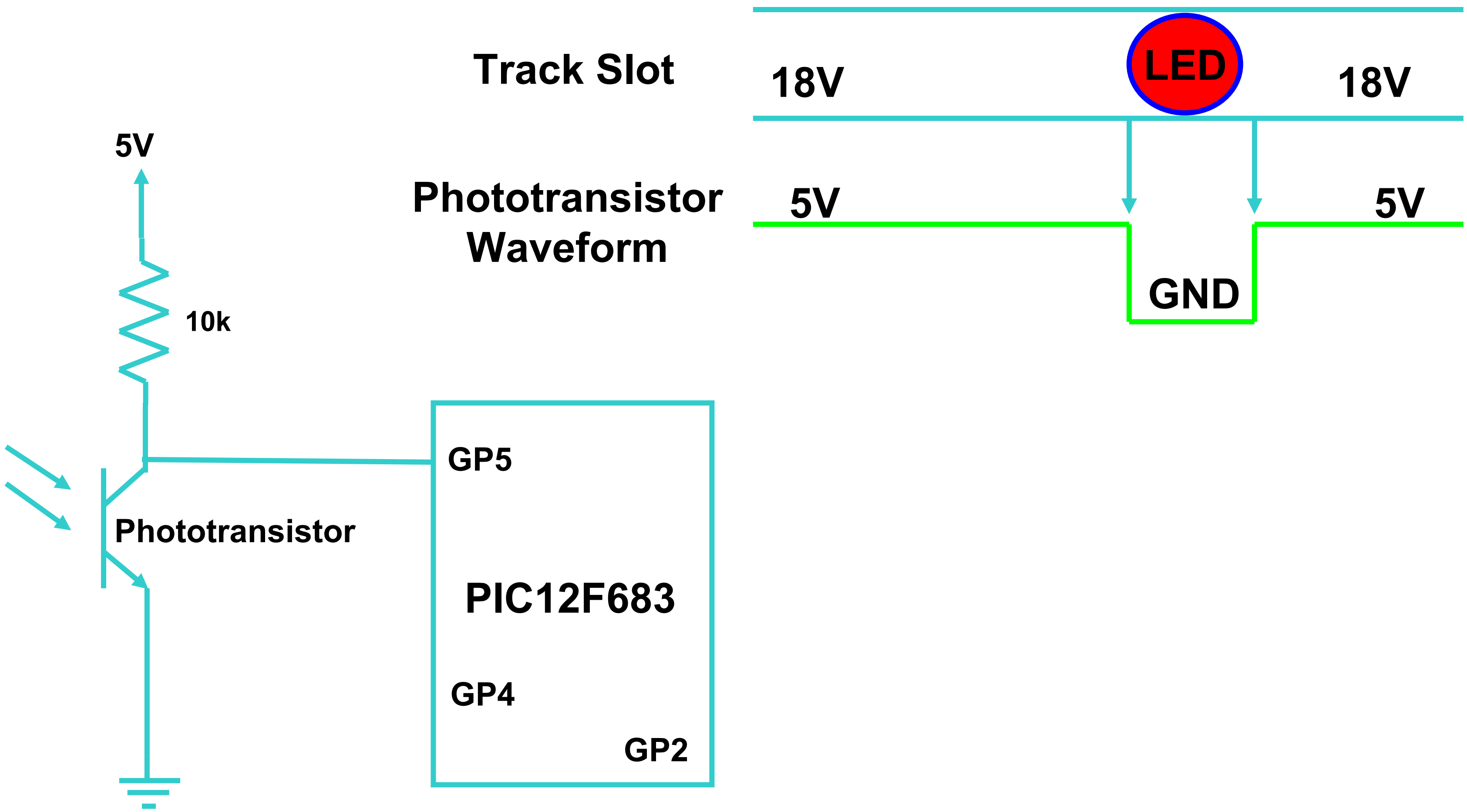
Drilled Holes



Infrared LEDs



Track Modifications



Summary

- Basic brushed DC motor operation, 4 types, and 3 methods of driving them
- How to control speed using CCP and measure speed using Back EMF and Optical Encoder
- How to use ECCP (Enhanced PWM) with all of its modes

Dev Tools Used

Labs:

- PICDEM™ Mechatronics Demo Board (DM163029)
- MPLAB® ICD 2 In-Circuit Debugger Kit (DV164005)

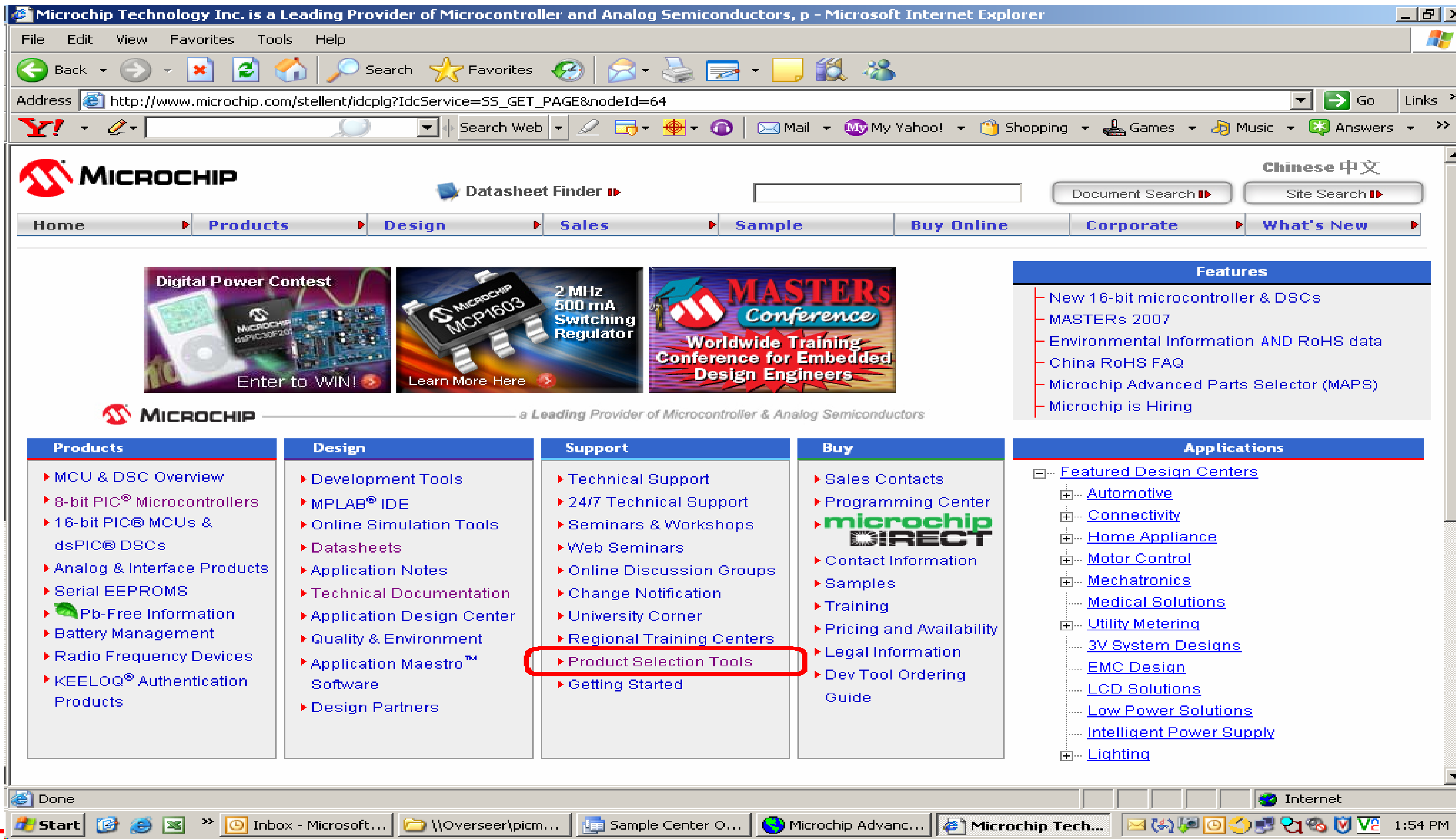
Slot Car Demo:

- PICkit™ 1 Flash Starter Kit (DV164101)

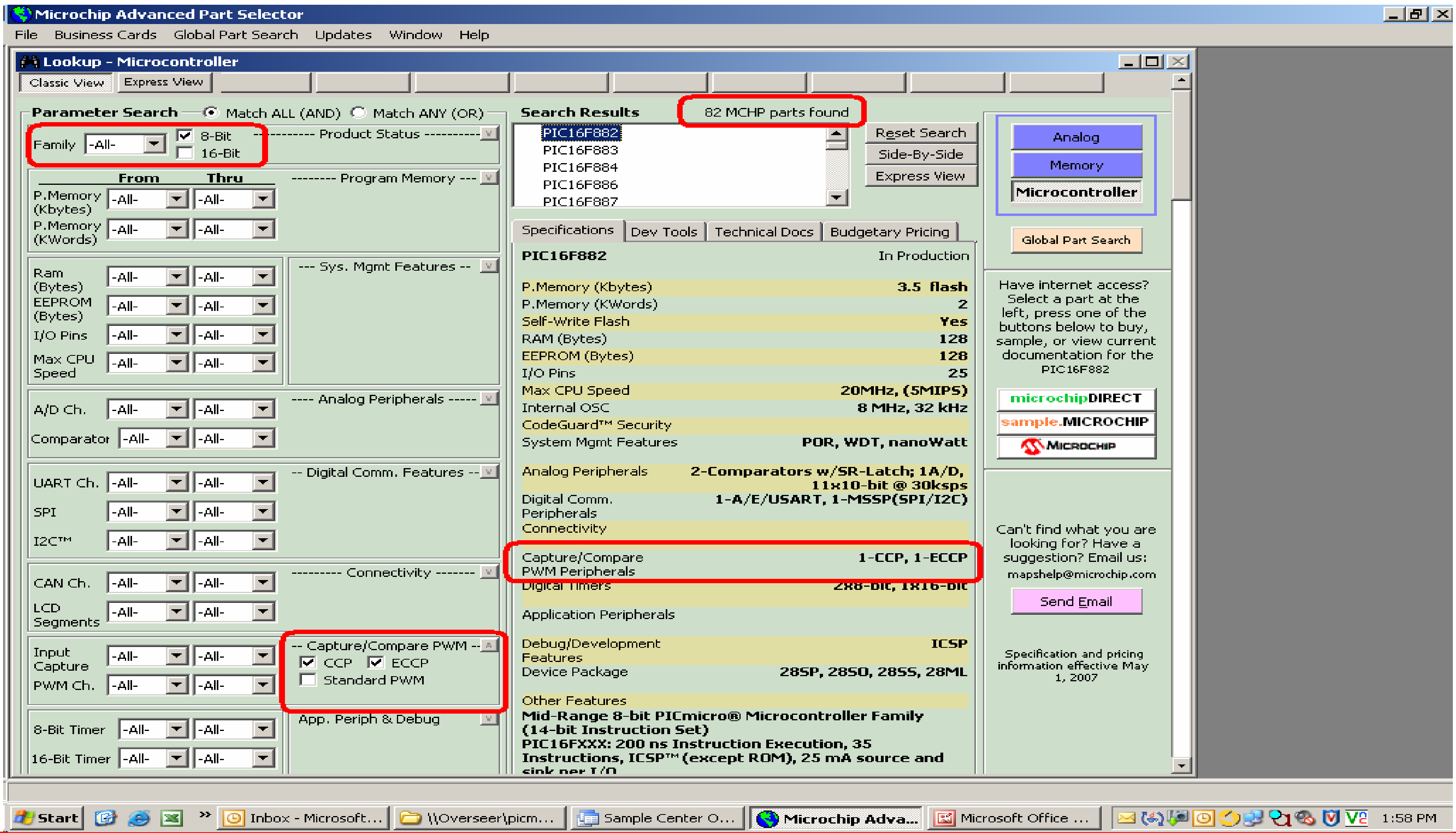
Additional Reading

- AN847 – RC Model Aircraft Motor Control
- AN893 – Low-Cost Bidirectional Brushed DC Motor Control Using the PIC16F684
- AN894 – Motor Control Sensor Feedback Circuits
- AN898 – Determining MOSFET Driver Needs for Motor Drive Applications
- AN905 – Brushed DC Motor Fundamentals
- DS41233 – DC Motor Control Tips ‘n Tricks
- DS41214 – CCP and ECCP Tips ‘n Tricks

Microchip's Advanced Parts Selector (MAPS)



Microchip's Advanced Parts Selector (MAPS)



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