Mechatronics (ROB-GY 5103 Section A)

- **Today's lecture:**
  - H-bridge
  - Control
  - Miscellaneous
- (See Topics #4 and #7 from Main Text for details)

Next Week

- **Final Exam (2:00 to 2:45)**
  - 45 minutes for 8 written questions
  - Only on content covered after midterm

- **Break/Intermission (2:45 to 3:00)**

Next Week

- **Early presentations (3:00 onwards)**
  - Presentations (~10-15 minutes followed by Q&A)
    - Must bring physical prototype to demonstrate
    - Submit your presentation files on Brightspace
  - I encourage you to present early!
    - Sign up sheet here
      - Indicate special accommodations
    - You can still submit project report on NYU Brightspace at the official deadline Dec 19.

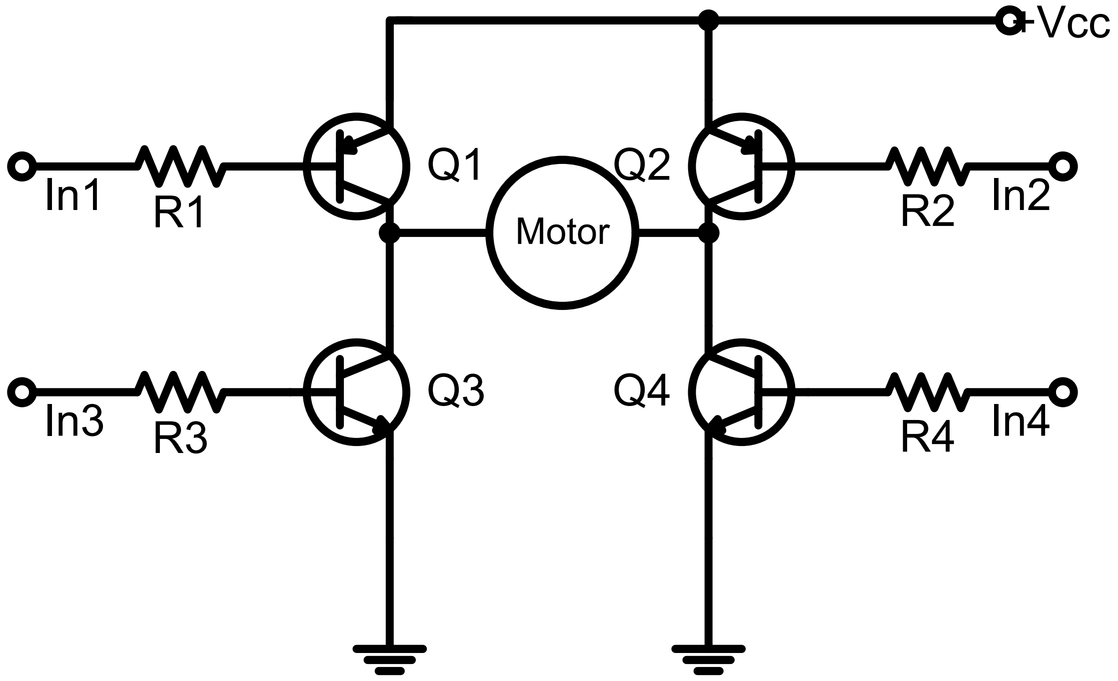
H-Bridge

- Why is it called an H-bridge (Full-bridge)?

H

Full-Bridge: Version 1

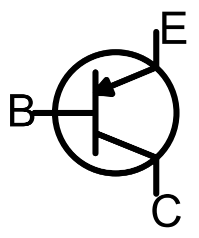
- 4 BJTs, 1 voltage source, and a DC motor.
    - Switches: transistors Q1-Q4.



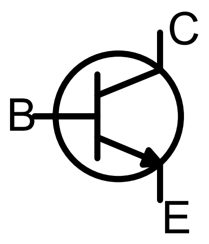
Full-Bridge: Version 1

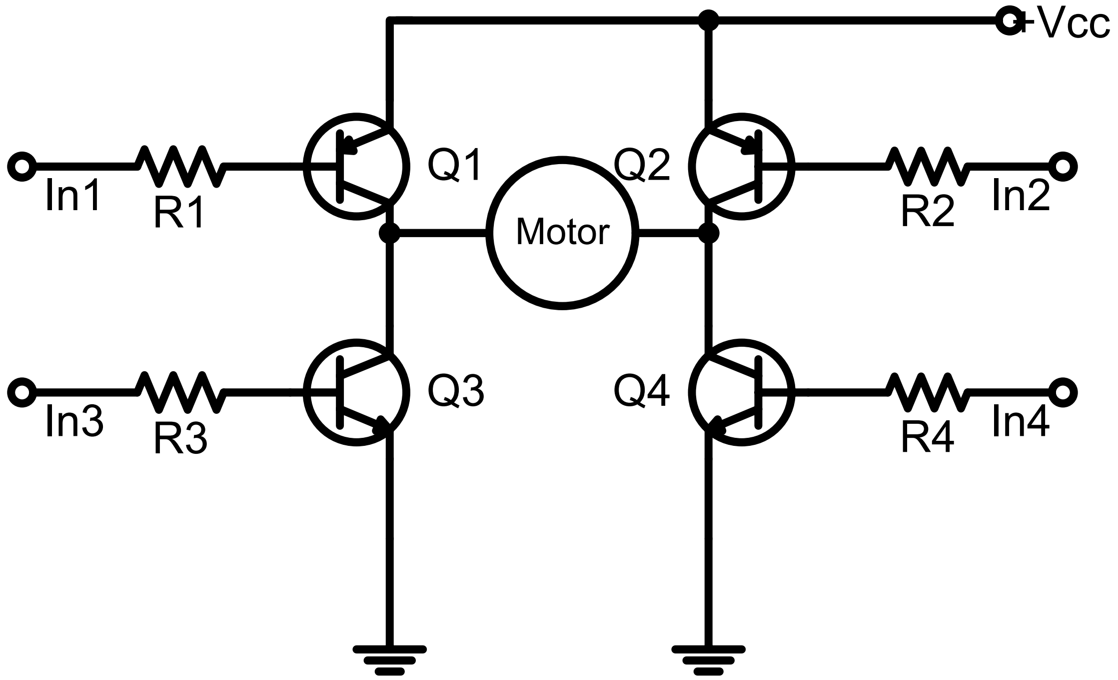
- NPN transistor. **Normally off**. When base potential higher than emitter potential, collector-emitter pair conducts. $V_c > V_e$.
- PNP transistor. **Normally off**. When base potential is lower than emitter potential, emitter-collector pair conducts. $V_e > V_c$.

PNP



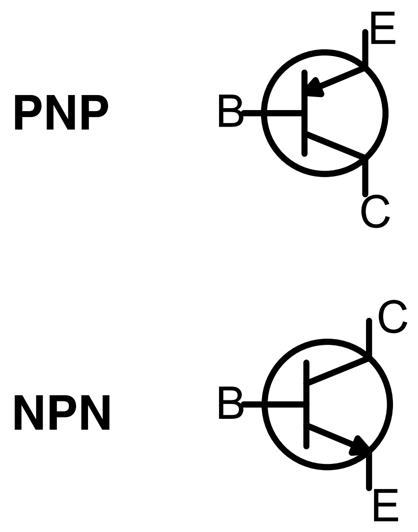
NPN

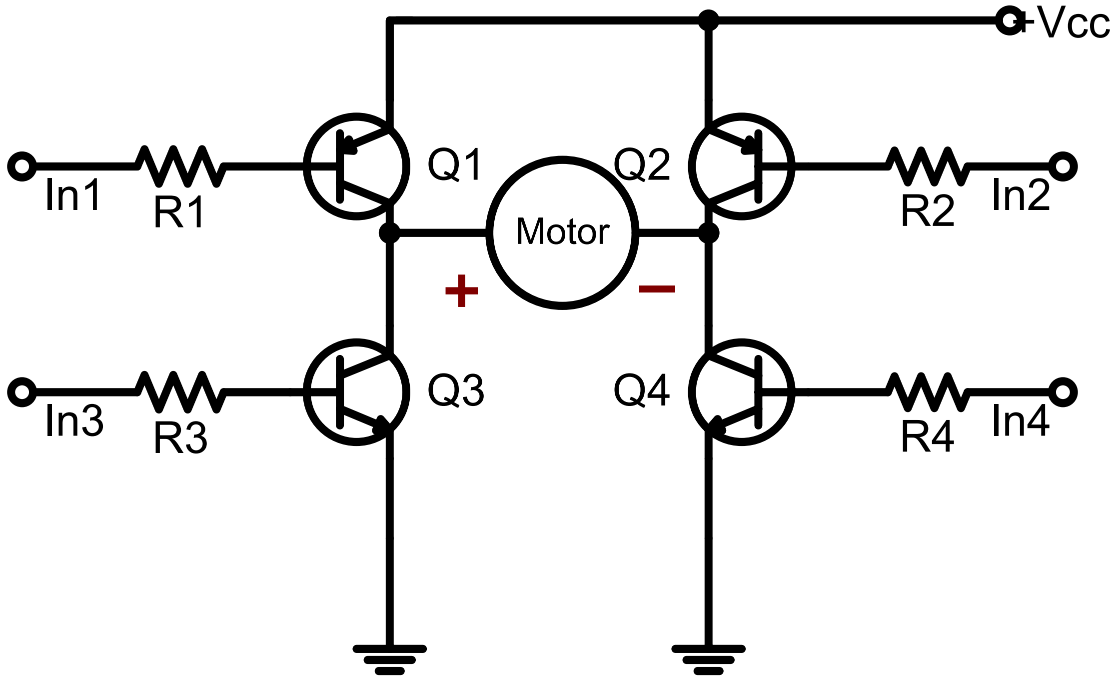




Full-Bridge: Version 1 (4 inputs)

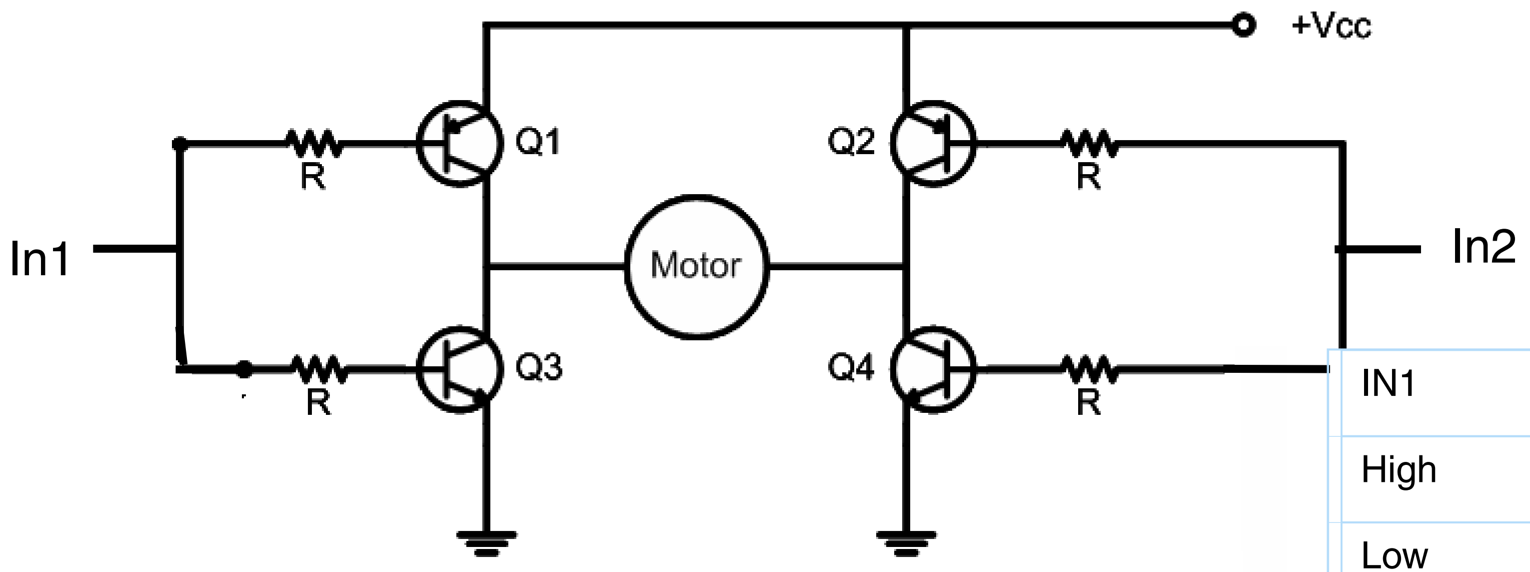
- $V_{in1} \leq V_{cc} - 0.6V$ and $V_{in4} \geq 0.6$ V: Motor turns forward.
- $V_{in2} \leq V_{cc} - 0.6V$ and $V_{in3} \geq 0.6$ V: Motor turns backward.
- **4 inputs** are being used to appropriately switch the transistors.





Full-Bridge: Version 2 (2 inputs)

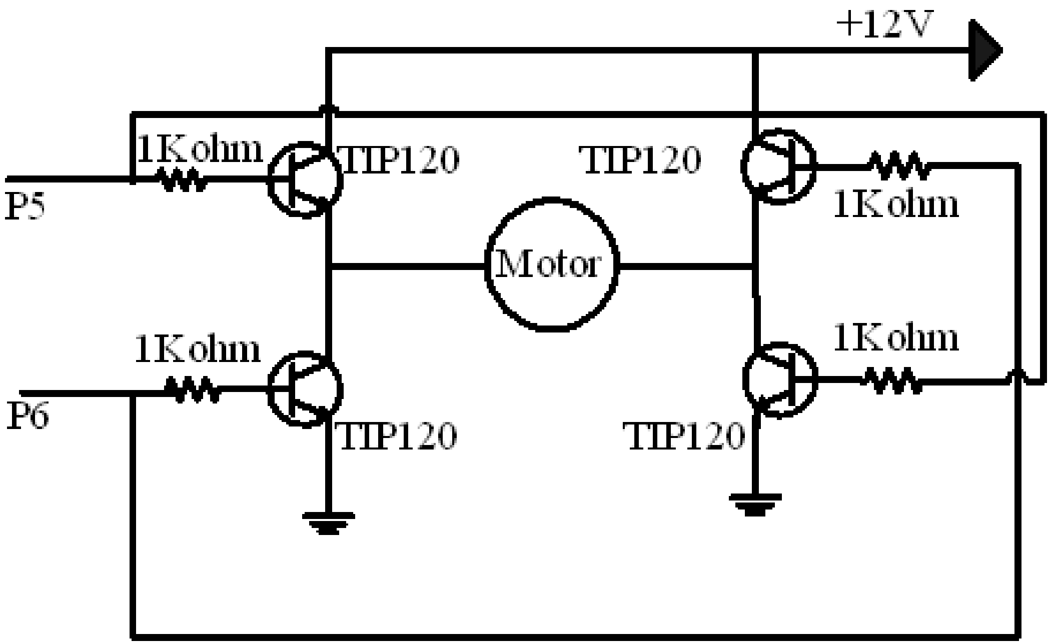
- **2 inputs** are being used to appropriately switch the transistors.



IN1	IN2	Motor	Notes
High	Low	Forward	
Low	High	Backward	
Low	Low	No motion	
High*	High*	*	Forbidden

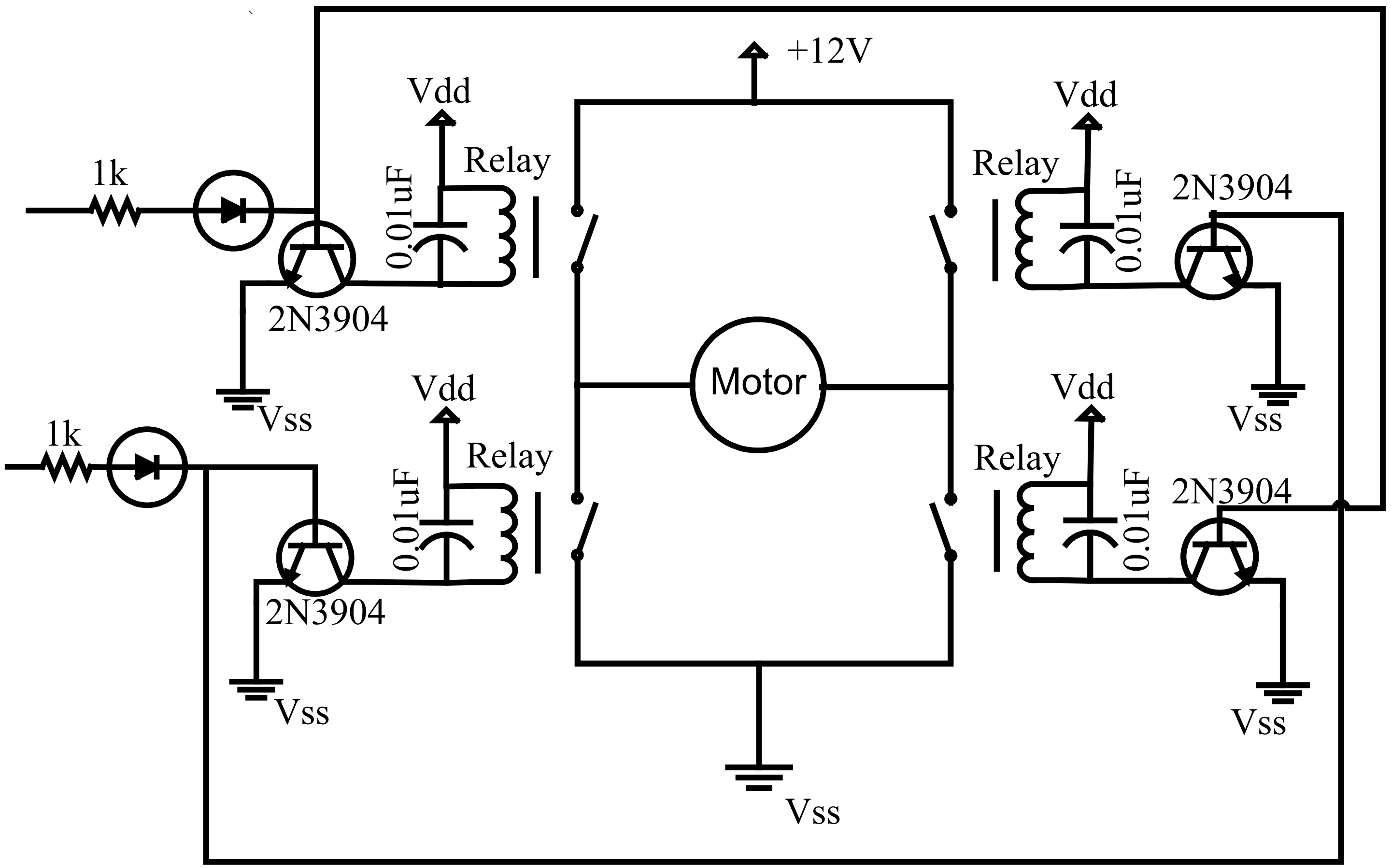
Full-Bridge: Version 3 (2 inputs)

- **2 inputs** are being used to appropriately switch the transistors.
  - Only NPN transistors



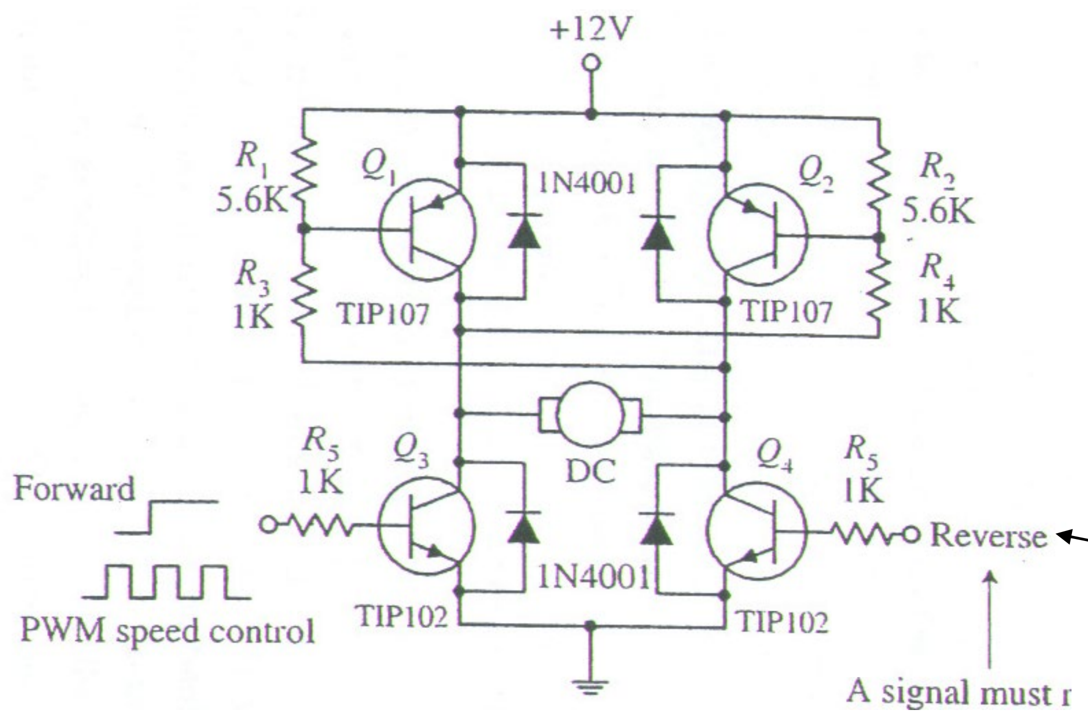
P5	P6	Motor	Notes
Positive	Ground	Forward	
Ground	Positive	Backward	
Ground	Ground	No motion	
Positive	Positive	*	Forbidden

H-bridge: Relays



H-bridge: BJTs

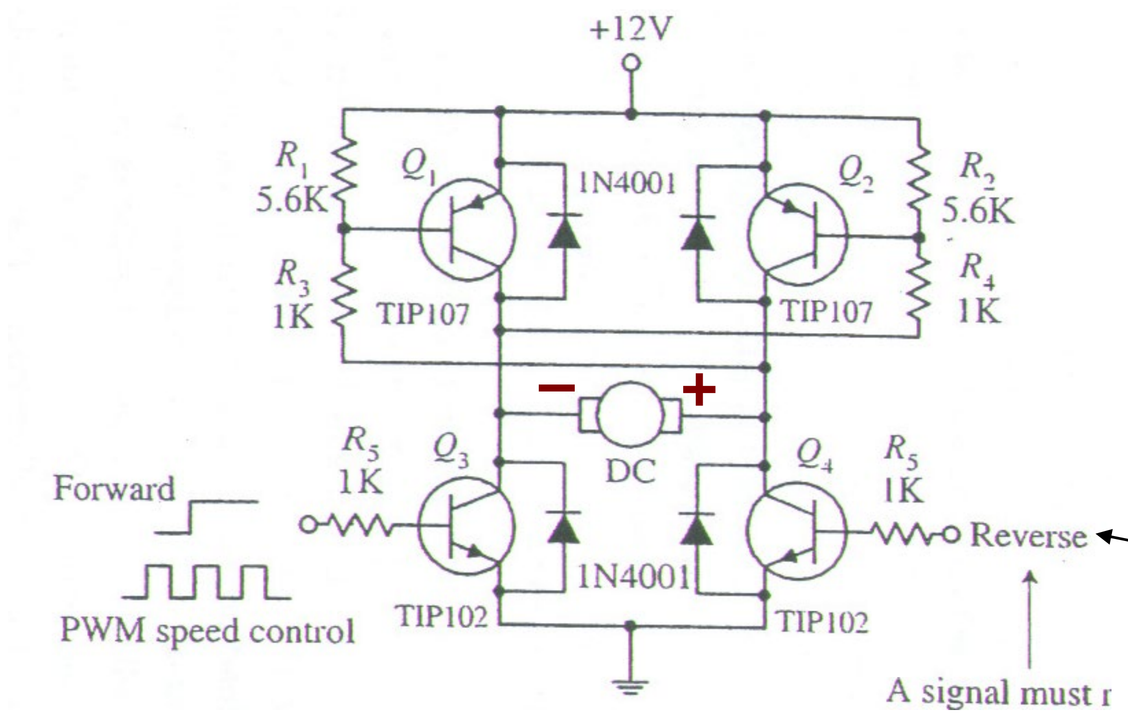
- Diodes are being used to prevent BJTs being damaged by inductive kickback.



A signal must not be applied here when a signal is being applied to the forward lead.

H-bridge: BJTs

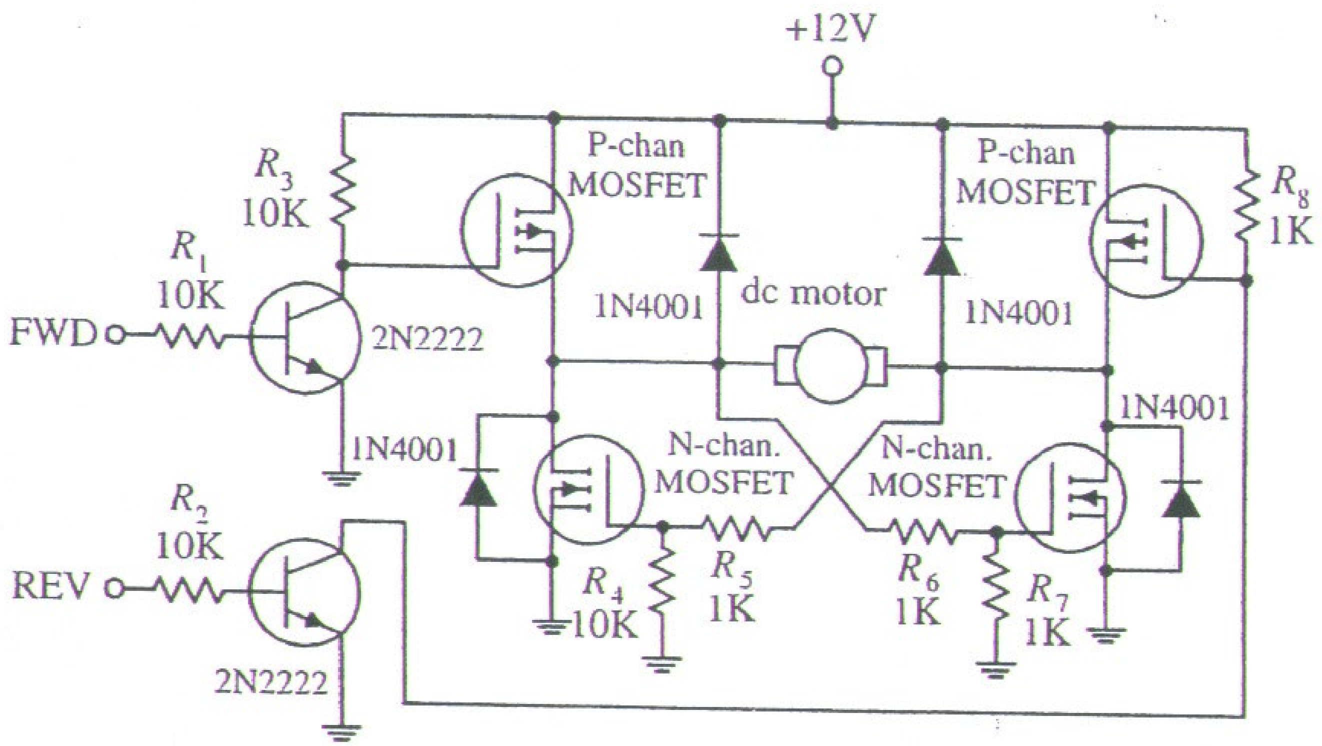
- High signal enters Q3's base, Q3 conducts, which allows Q2 to conduct.
    - Current flows from +12 V supply through the motor from right to left (forward).
- To reverse the direction, remove High signal from Q3, and apply to Q4 instead.



A signal must not be applied here when a signal is being applied to the forward lead.

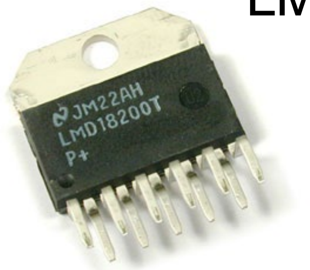
H-bridge: MOSFETs

MOSFET H-Bridge

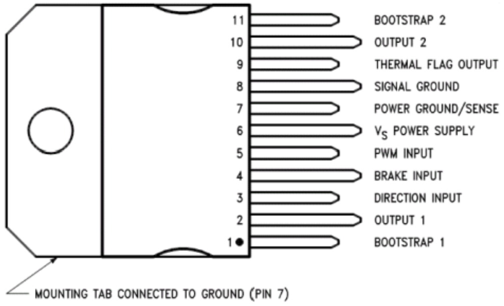


H-Bridge Motor Driver ICs

LMD18200



- Common H-Bridge solutions include:
  - National Semiconductor's LMD18200, LMD18201, LM15200
- LMD18200
  - High-current, easy-to-use H-bridge chip (3A, 12-55V).
  - TTL and CMOS compatible.
  - Comes with clamping diodes, shorted load protection, and a thermal warning interrupt output lead.



LMD18201

- L293D (Unitrode)
  - Very easy to use, cheaper than LMD18200
  - Can't handle as much current
  - Not many functions available.

L293D

Speed Control

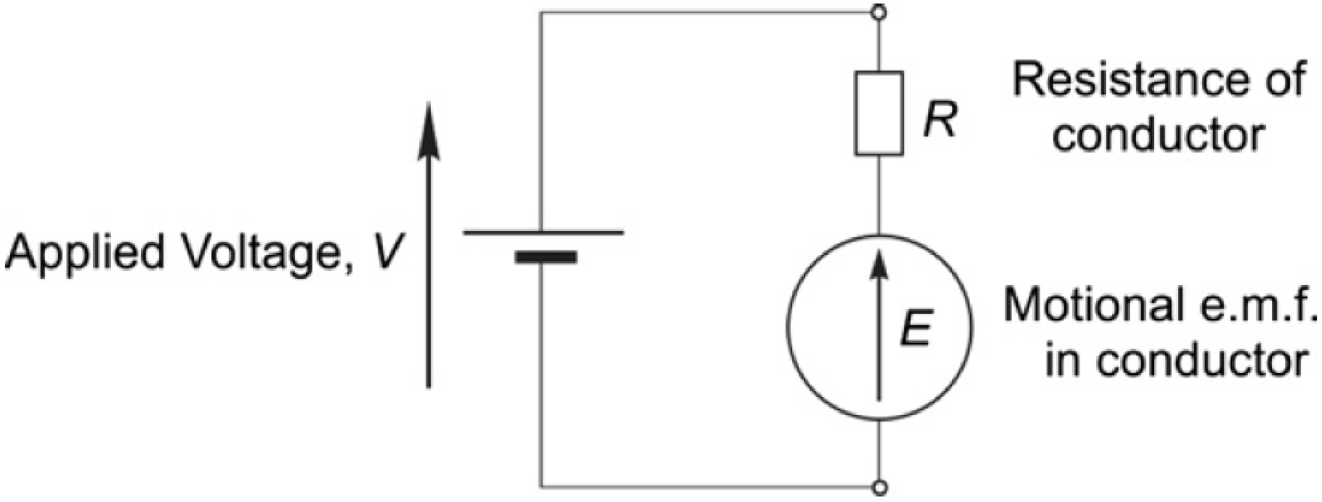
- Apply voltage to motor:
  - Lower than the nominal voltage $\rightarrow$ motor runs slower.
  - Larger than nominal voltage $\rightarrow$ motor runs faster.

Speed Control: DC motor dynamics

- Equivalent Circuit Model

$$V = E + IR$$

$$\tau = kI \qquad E = k\omega$$



- E: Motional EMF or electromotive force)
- I: Motor Current
- V: Applied Voltage (at motor terminals)
- R: Motor Resistance
- k: motor (torque) constant

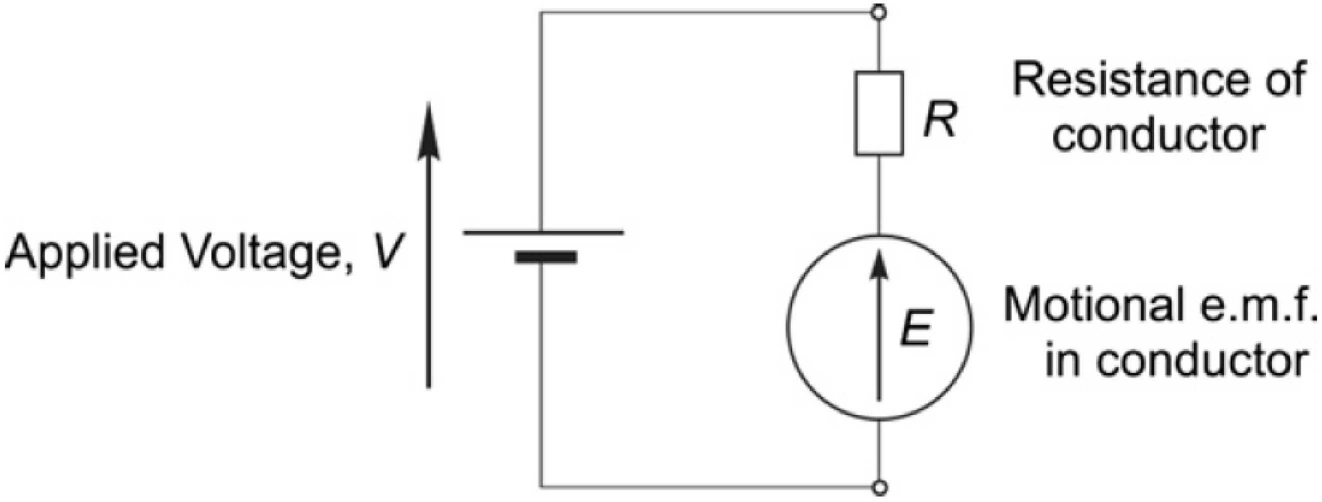
Speed Control: DC motor dynamics

- Equivalent Circuit Model

$$V = E + IR$$

$$\tau = kI \qquad E = k\omega$$

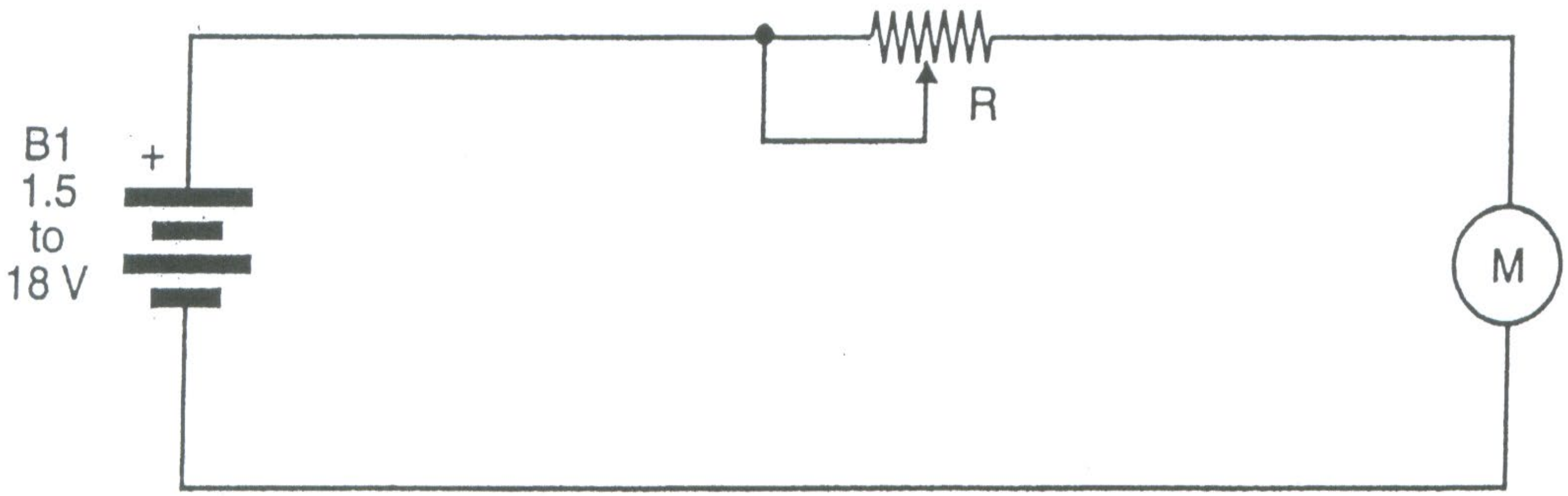
Lorenz Force **Faraday's law of induction**



- E: Motional EMF or electromotive force)
- I: Motor Current
- V: Applied Voltage (at motor terminals)
- R: Motor Resistance
- k: motor (torque) constant

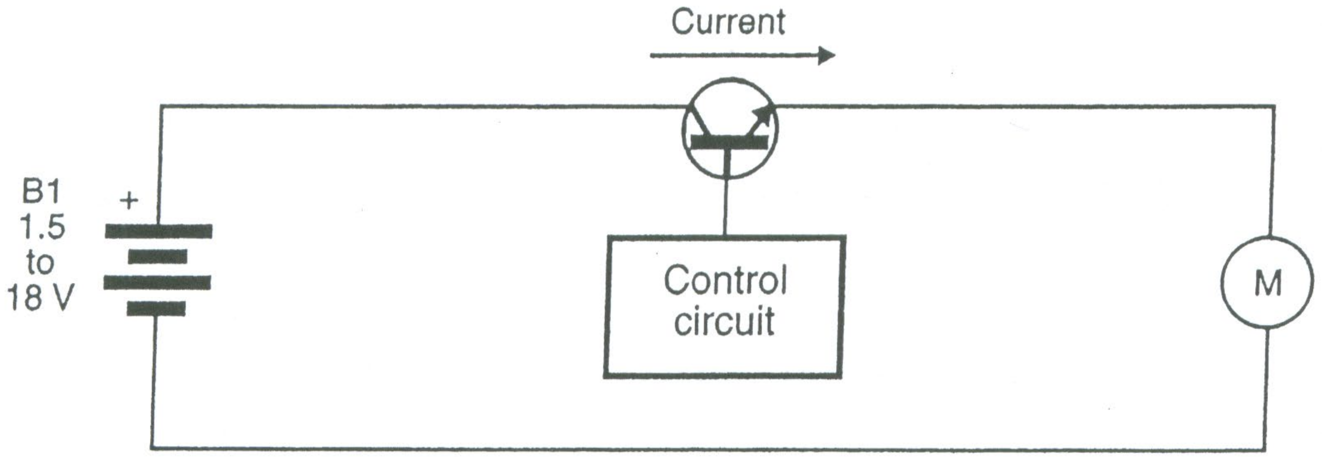
Speed Control: Potentiometer

- Despite the linearity of the control, don’t do this. Not recommended.
- Highly inefficient:
  - Resistance wastes energy
- Use of pot as described does not allow soft start of the motor while keeping the torque constant. It leads to a hard start which may induce jerk behavior.



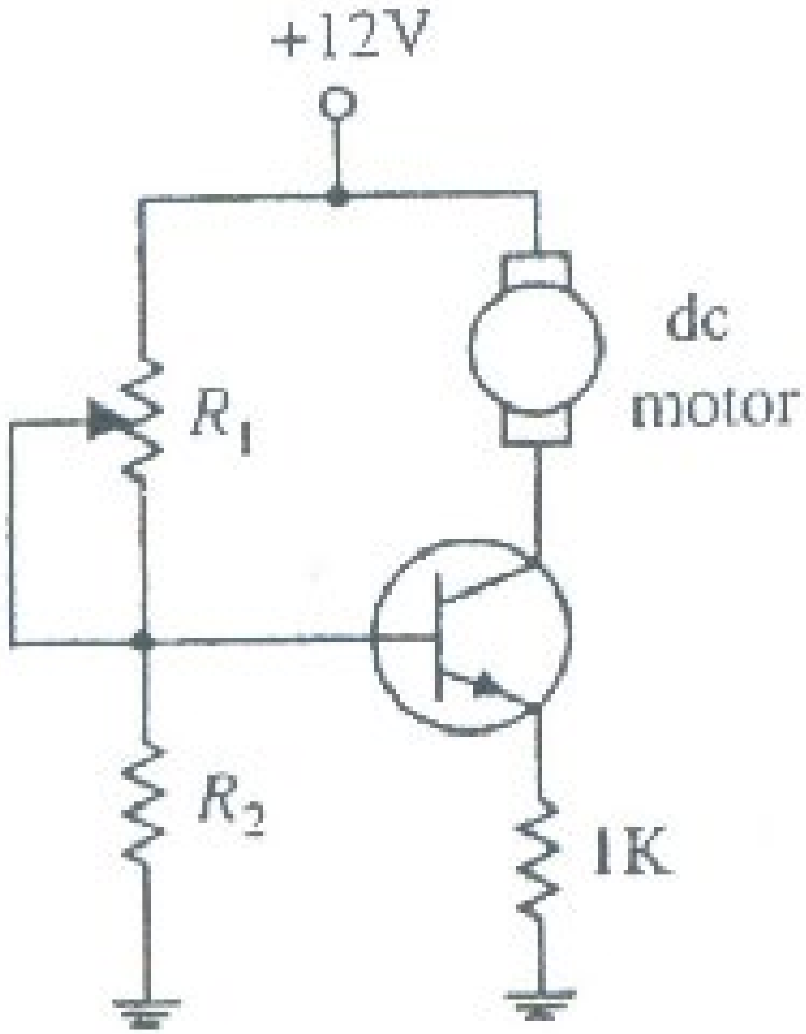
Speed Control: BJT

- Don’t do this. Not recommended.
  - Base voltage/current changes the resistance across collector-emitter pair thus varying the current flow through the circuit connected through collector-emitter pair.
  - Now the BJT must dissipate heat.
  - Power dissipated by transistor = (voltage drop across transistor) x (current flow through the transistor)



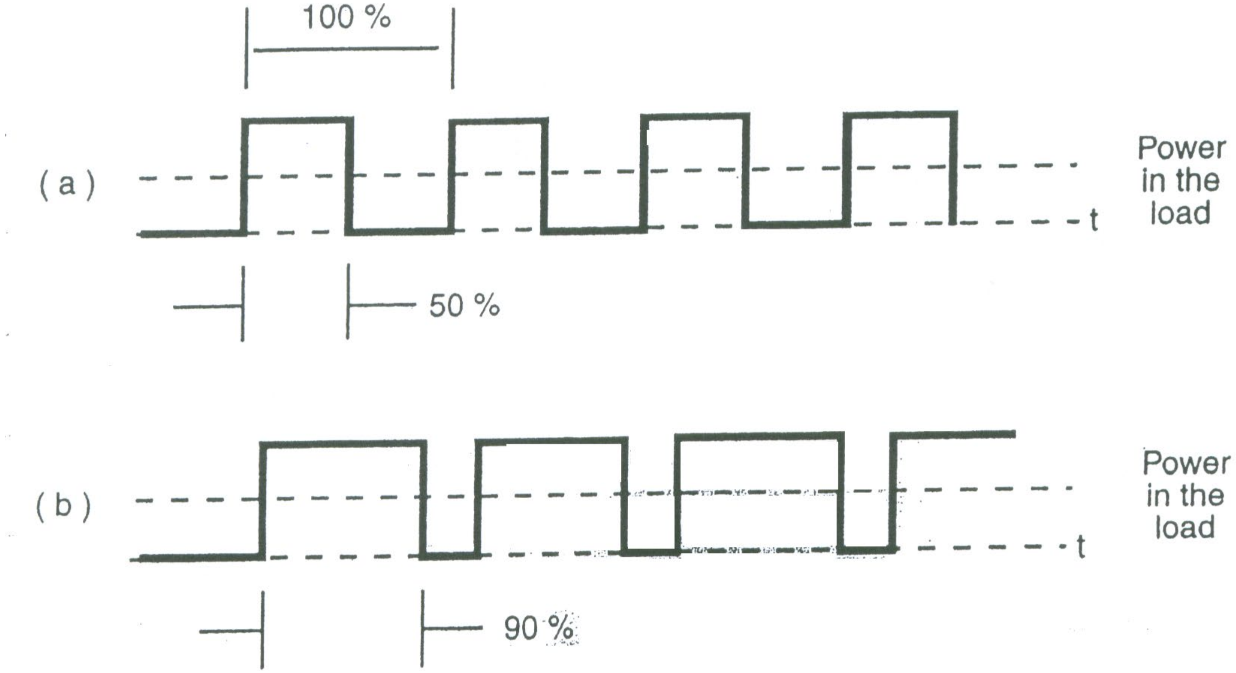
Speed Control: Potentiometer BJT

- Don't do this. Not recommended.



Speed Control: PWM

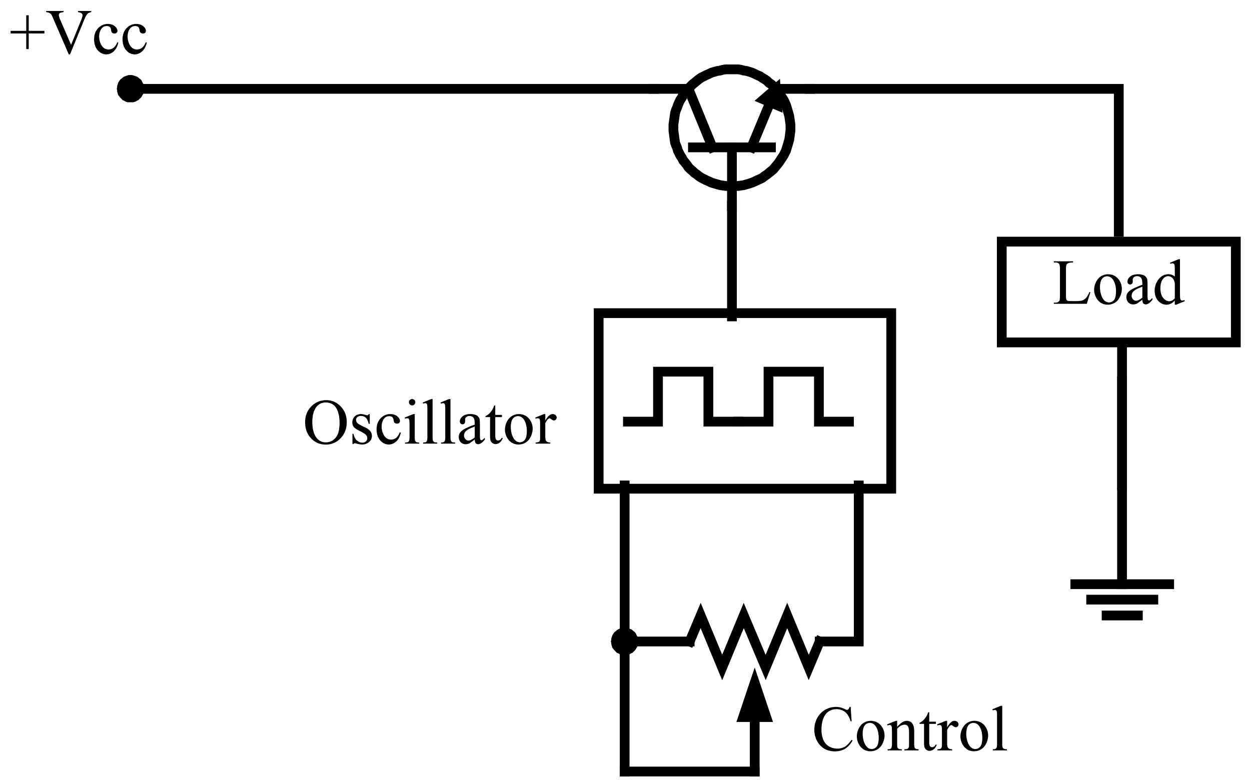
- Yes, please do this.
  Recommended



The power depends on the pulse width

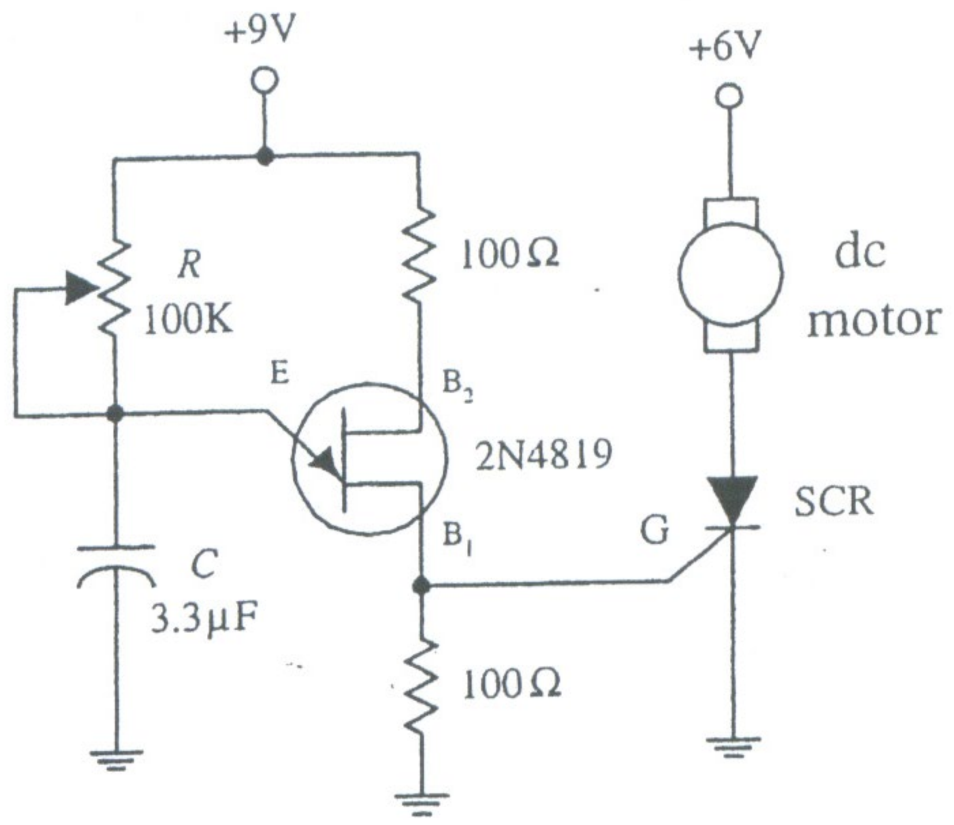
Pulse Width Modulator

- The output of a variable duty oscillator is fed to the control lead “base” of a power transistor.



DC Motor Speed Control using PWM: Version 1

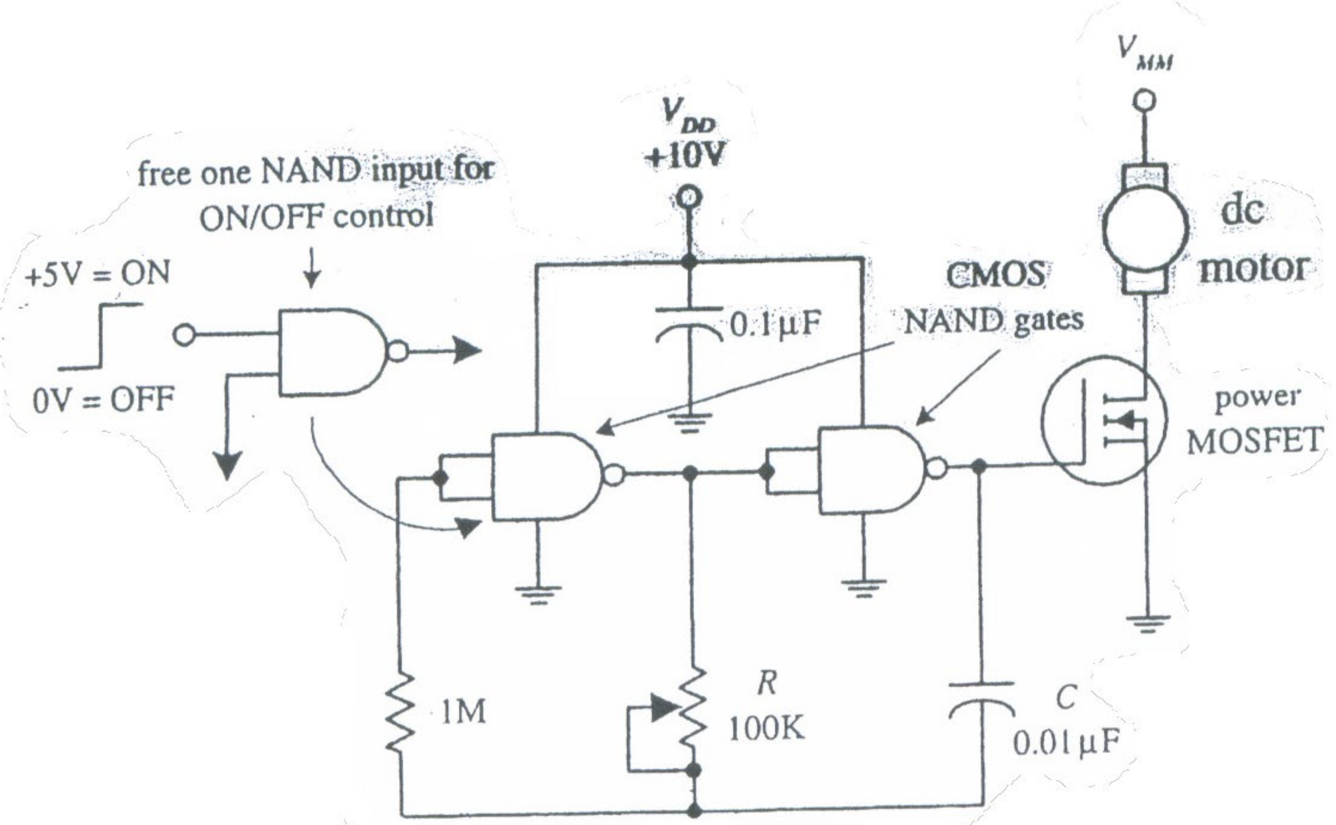
- Here a UJT relaxation oscillator is used to generate a series of pulses that drive an SCR on and off.
- To vary the speed of the motor, the UJT oscillator's frequency is adjusted by changing the RC time constant.



UJT/SCR Control Circuit

DC Motor Speed Control using PWM: Version 2

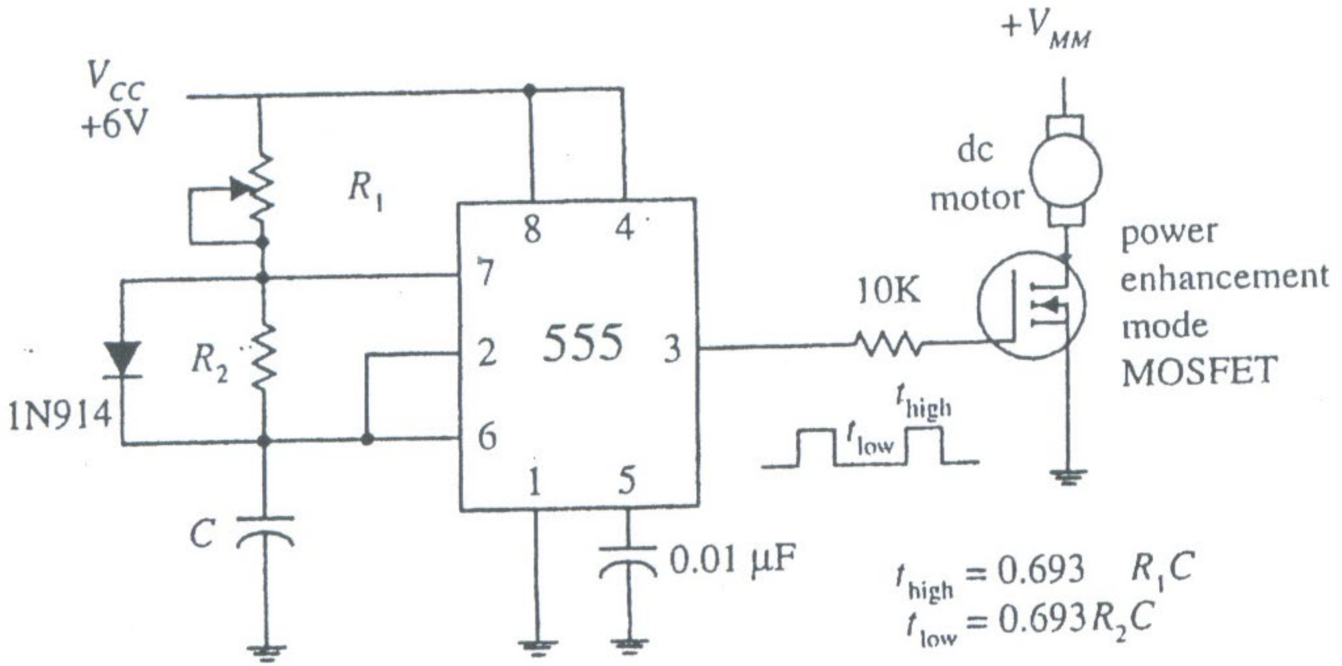
- A pair of NAND gates make up the relaxation oscillator section, while an enchantment-type power MOSFET is used to drive the motor.
- Like the preceding circuit, the speed of the motor is controlled by the oscillator's RC time constant.



CMOS/MOSFET Control Circuit

DC Motor Speed Control using PWM: Version 3

- 555 timer in astable mode to generate pulses that drive a power MOSFET.
- By inserting a diode between pins 7 and 6, as shown, the 555 timer is placed into low-duty cycle operation.
  - R_1, R_2, and C set the frequency and on/off duration of the output pulses



DC Motor Speed Control using PWM: Version 3

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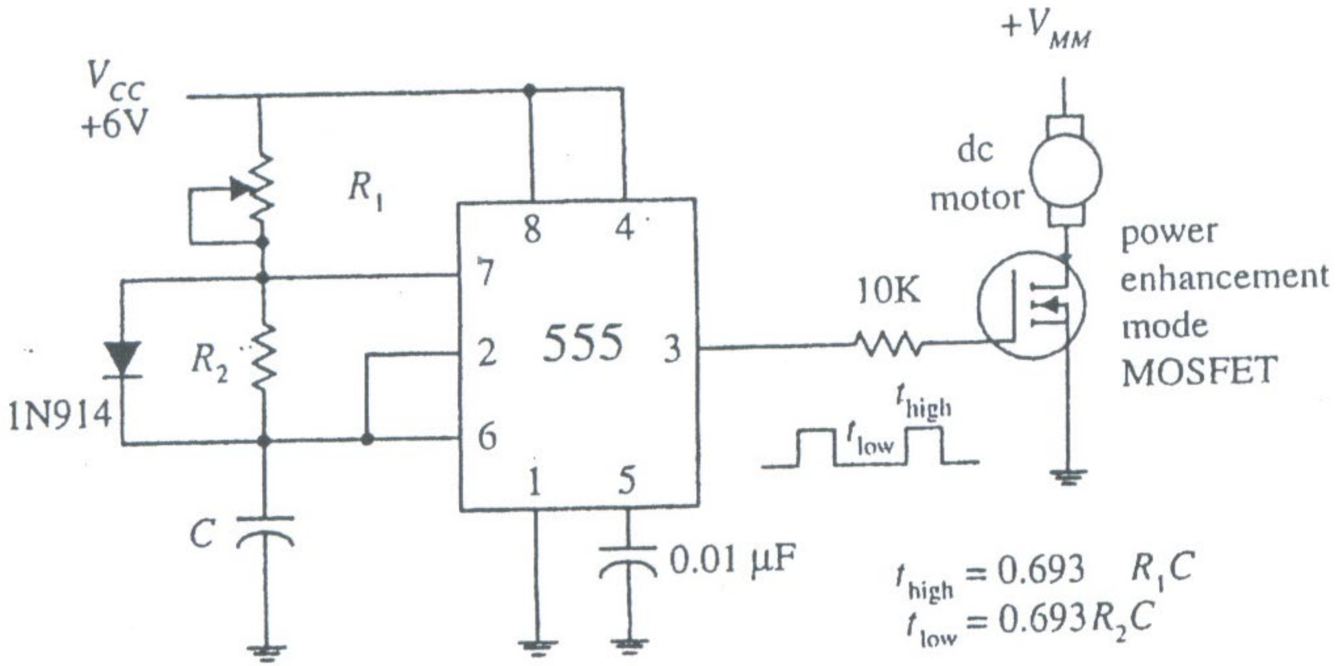
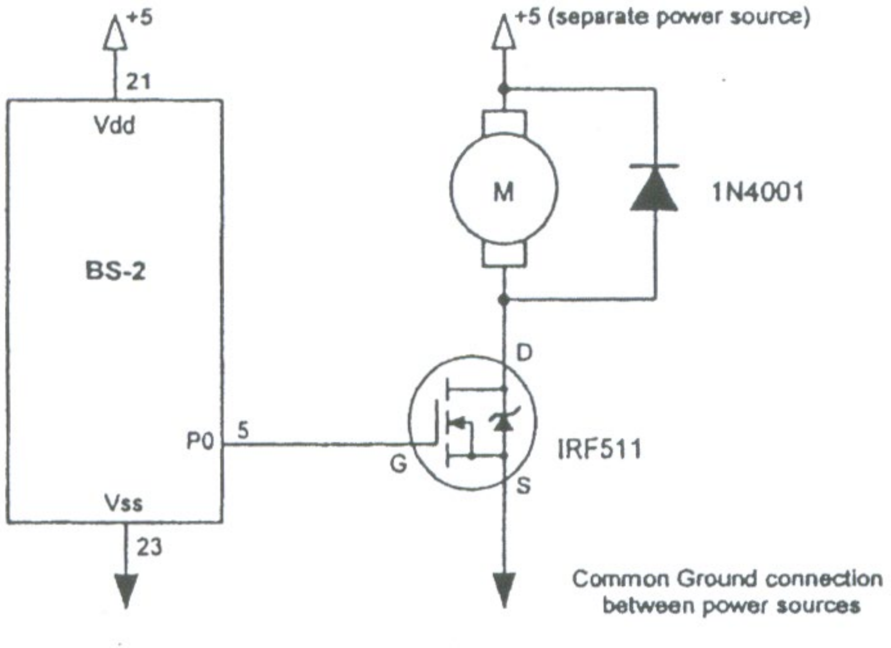


Without diode, $t_{high} = 0.693\ (R_1 + R_2)\ C$

Interfacing DC Motor with BS2: On/Off Control Circuit #1

- Interface an N-channel MOSFET IRF511 to BS2 as shown.
- Interface the motor between the +5V of power supply and the drain of MOSFET, with MOSFET source connected to ground.
- Place a 1N4001 diode in reverse biased mode parallel to motor.
- With BS2 o/p high on P0 → MOSFET gate is driven positive relative to source of MOSFET.
  - The drain source pair of the MOSFET conducts and motor turns on.
- With BS2 o/p low on P0 → MOSFET stops conducting, a reverse voltage spike is generated in the motor which conducts through a diode.
- A low voltage (5VDC) motor is being used in this circuit.

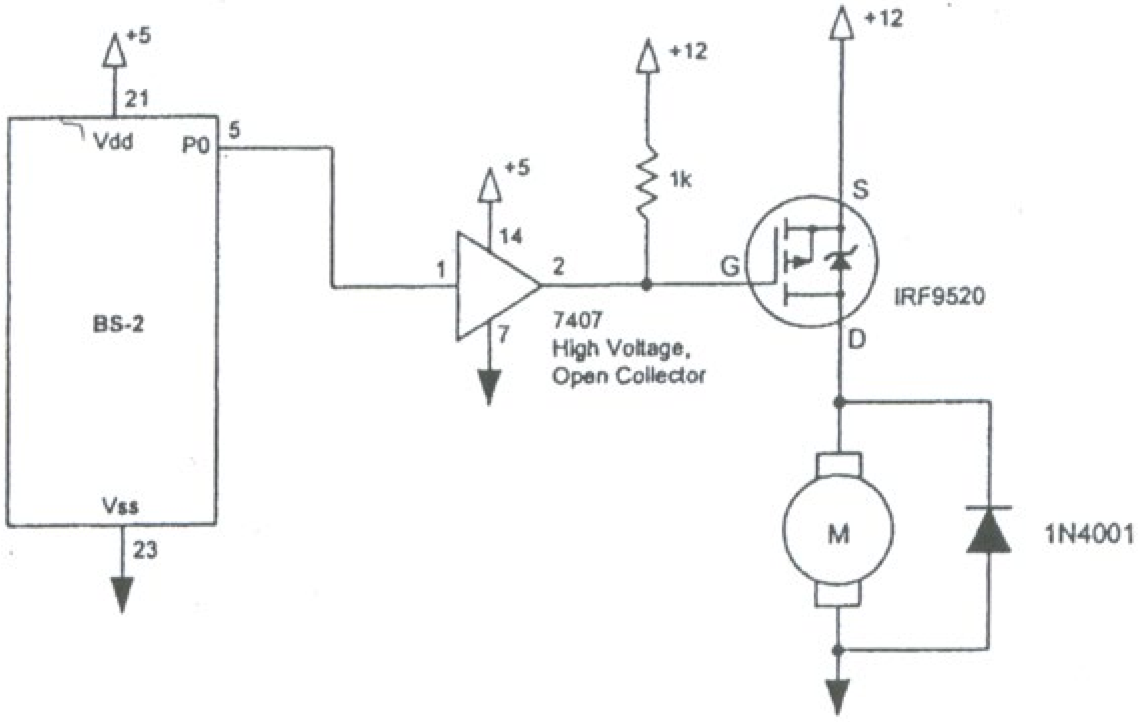


Figure

A simple DC motor driver circuit

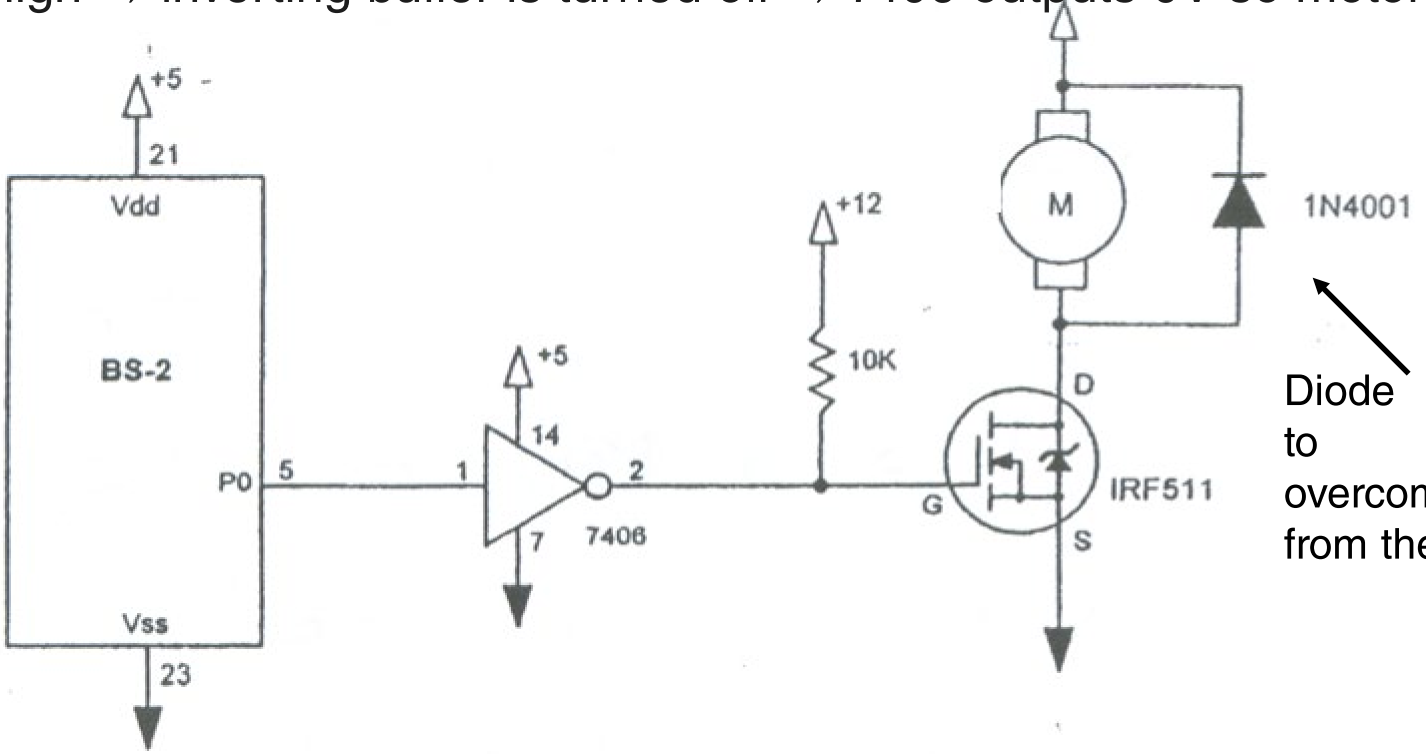
Interfacing DC Motor with BS2: On/Off Control Circuit #2

- BS2 drives the open collector, non-inverting buffer whose output is tied to 12VDC.
- When BS2 is low, 7407 buffer outputs 0V DC which drives a P-channel MOSFET.
- The 12VDC potential difference between source-gate yields higher drive capability.
- P0 low → motor turns on
  P0 high → motor turns off.



Interfacing DC Motor with BS2: On/Off Control Circuit #3

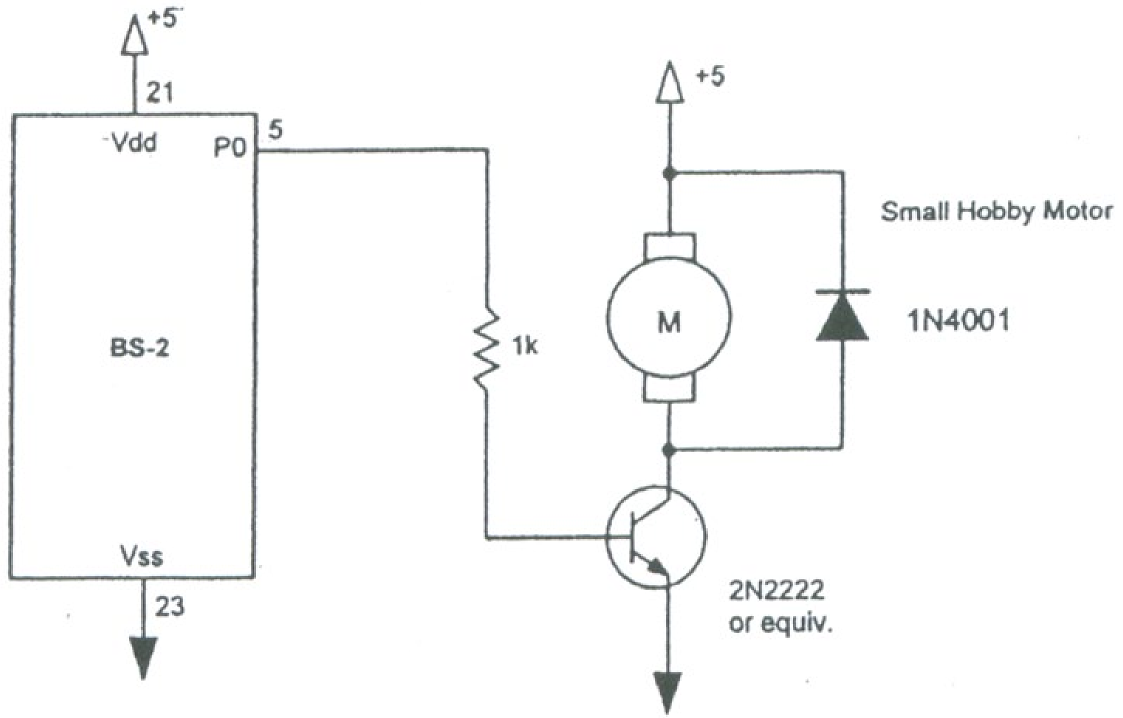
- In this circuit: P0 low → inverting buffer is turned on → 7406 outputs 12V which appears at the gate of an N-channel MOSFET IRF511.
  - The motor is turned on.
  - With Vg – Vs = 12V, the MOSFET provides high drive capability.
- With P0 high → inverting buffer is turned off → 7406 outputs 0V so motor turns off.



Diode prevents damage to MOSFET by overcoming inductive kick from the motor.

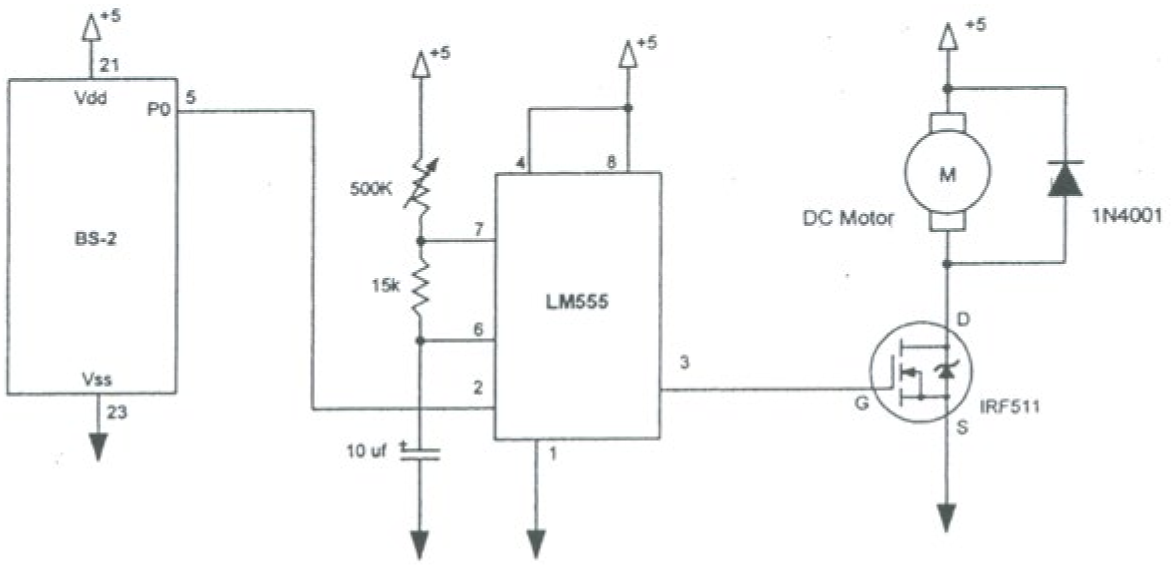
Interfacing DC Motor with BS2: On/Off Control Circuit #4

- In this circuit, an NPN BJT is used to turn on/off a low voltage, low current hobby motor.
- The current rating of BJT must be appropriately selected to provide the drive current required by the motor.



DC Motor: On-Time Control Circuit #1

- DC motor is turned on for a period of time, determined by the 500k pot and 10μF capacitor.
- When a low going pulse appears at PIN2 of the LM555 timer, the IRF511 MOSFET is turned on which turns the motor on.
- PIN2 of LM555 timer should be turned high immediately after being turned low.
- This circuit allows us to off-load the task of running the motor for a certain period and then stopping it.
- BS2 simply turns the motor on, it does not have to monitor time to turn the motor off, since LM555 takes care of the timing issue (monostable operation mode).

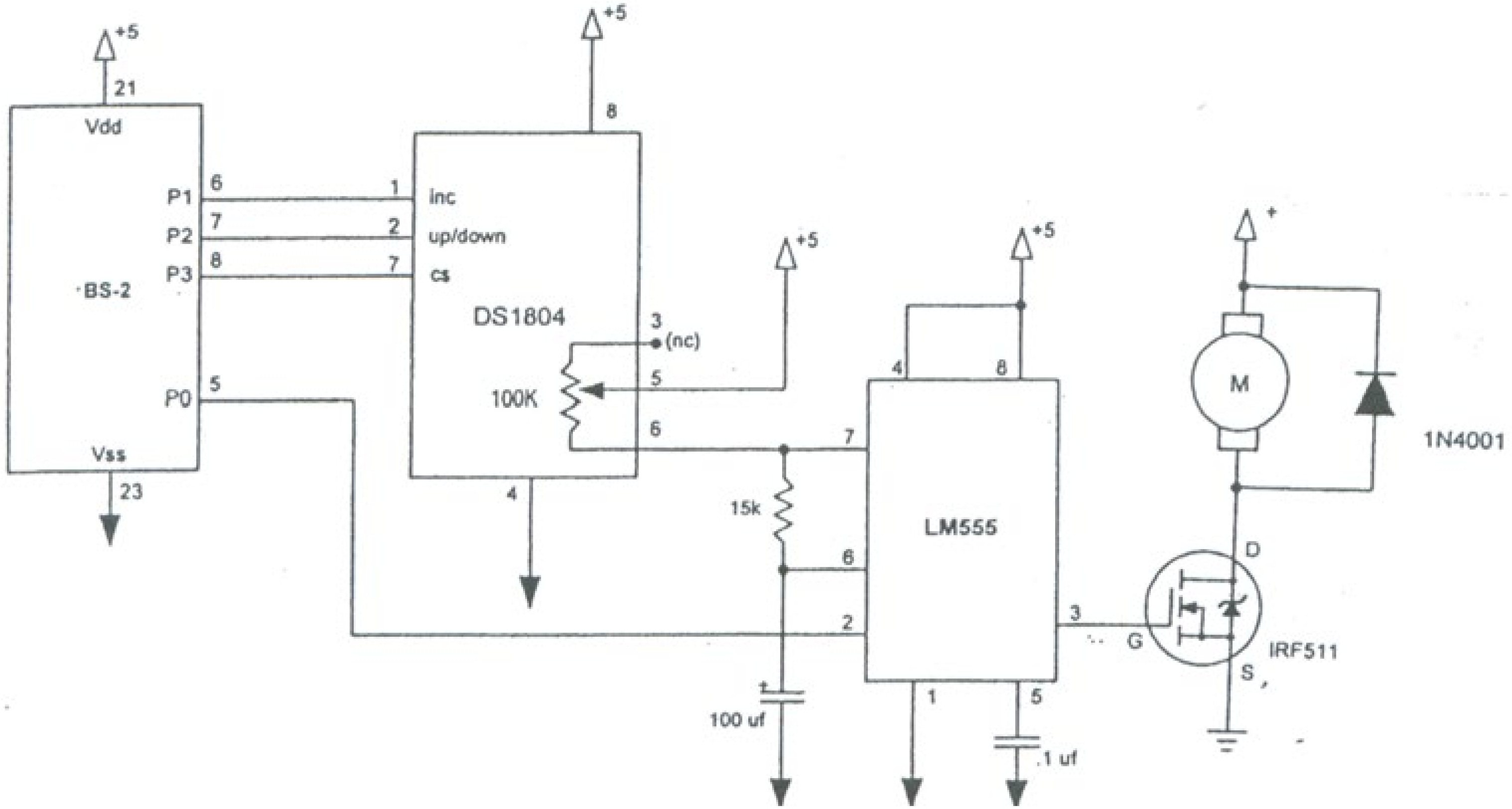


- Sample code:

```
low 0
high 0
'(rest of the code here)
```

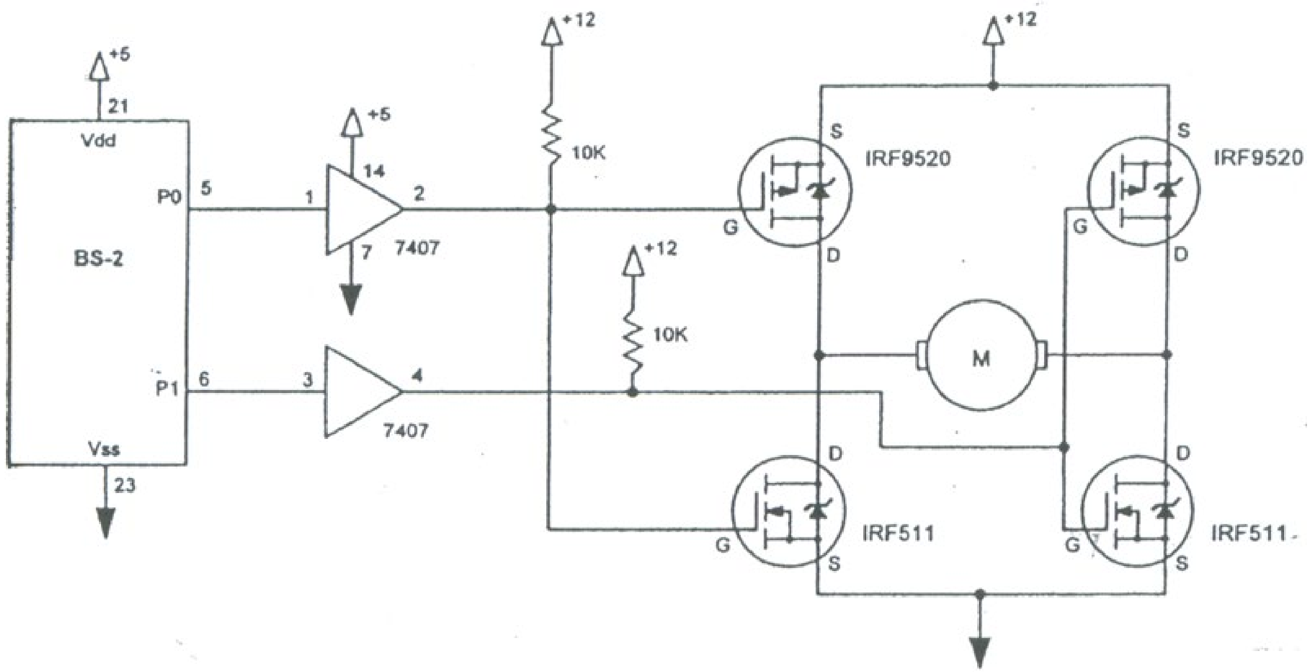
DC Motor: On-Time Control Circuit #2

- To allow automatic control of ON-time duration of motor, here a digital pot is used.
- By selecting a proper setting for solid state pot, the motor ON-time duration is controlled.



Interfacing DC Motor with BS2: H-Bridge Circuit

- MOSFET-based H-bridge for the direction control of a DC motor.
- The outputs from P0 and P1 of BS2 are processed by the 7407 non-inverting buffers. The buffer outputs control two pairs of two MOSFET's each to perform direction control.

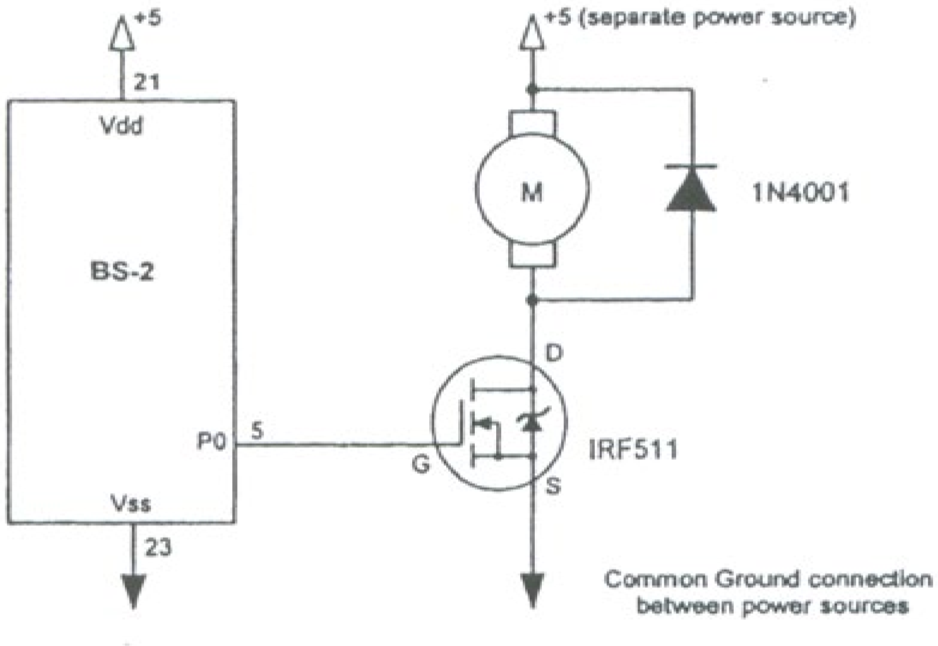


Sample Code:

```
loopstart:
high 0
low 1
pause 2000
low 0
high 1
pause 2000
goto loopstart
```

DC Motor Speed Control using PWM

- Consider DC Motor on/off control circuit #1 (reproduced below).
- We can use the PWM technique to control the speed of motor.
- Sample code shown below can be used to get:
  - Motor on at full speed (on all the time).
  - Motor on only 50% of time (slower speed compared to 100%).
  - Motor on only 25% of time (slower speed compared to 50%).
  - Motor accelerating

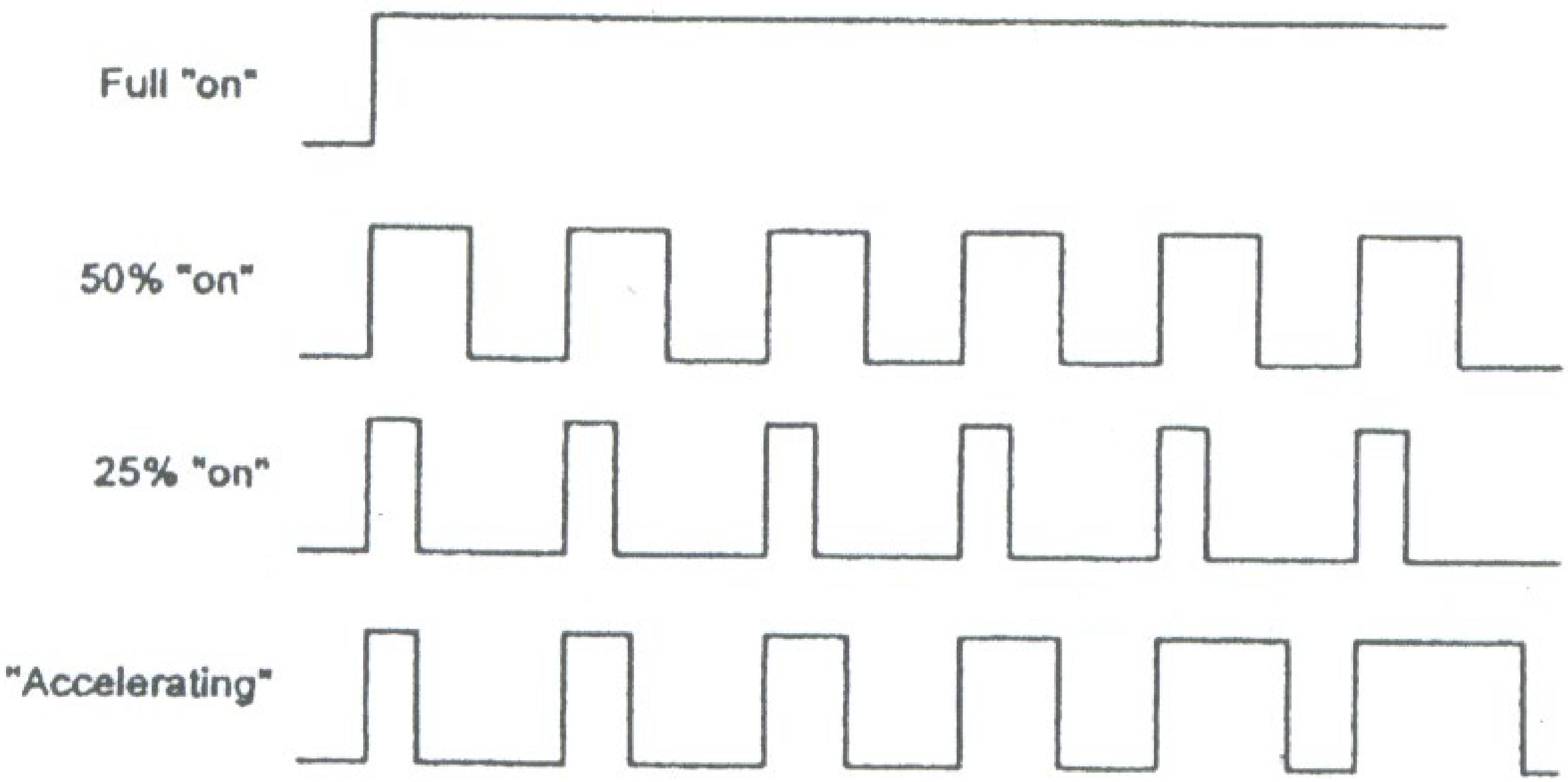


Sample PWM Code

```
x var word
y var word
here:
debug “This is full-on”
debug cr
high 0     ’On all the time.
pause 2000
debug “This is 50% on”
debug cr
for x = 1 to 200
high 0
pause 5        ’ON for 5 milliseconds
low 0
pause 5        ’OFF for 5 milliseconds
next
```

```
debug “This is 25% on”
debug cr
for x = 1 to 100
high 0
pause 5   ’ON for 5 milliseconds
low 0
pause 15      ’OFF         for         15
milliseconds
next
pause 2000
debug “This is accelerating”
debuc cr
for y = 100 to 1
high 0
pause 15
low 0
pause y
next
goto here
```

PWM Signal Produced by the Sample Code



DC Motor Challenges

- Issues: rechargeability, energy density, capacity, voltage, internal resistance, etc.
- **Power supply noise:**
  - Current demand varies as motor starts or changes direction.
  - Commutator brush noise introduced due to breaking/making of contact that leads to inductive kickback.
  - PWM noise which also causes motor to turn on/off leading to inductive kickback.
    - **Advised to use separate power supplies or motor and microcontroller.**
- Electromagnetic interference may be produced as PWM pulses current in motor coil or as motor brushes make/break contact with the power supply.
- **Audible noise:**
  - When PWM frequency matches up with one of the resonant frequencies of motor structure (in the audible range).
  - Gearbox and other mechanical components.

Servomotor

- Position control rather than speed control
  - Servomechanism with feedback control
    - Example: potentiometer as angle sensor (encoder)

Parallax Standard Servo Motor

- DC motors with feedback position control
- As long as the coded signal exists on the input line, the servo will maintain the angular position of the shaft
- As the coded signal changes, the angular position of the shaft changes

Parallax Standard Servo Motor Specifications

Technical Specifications

> Power 6vdc max

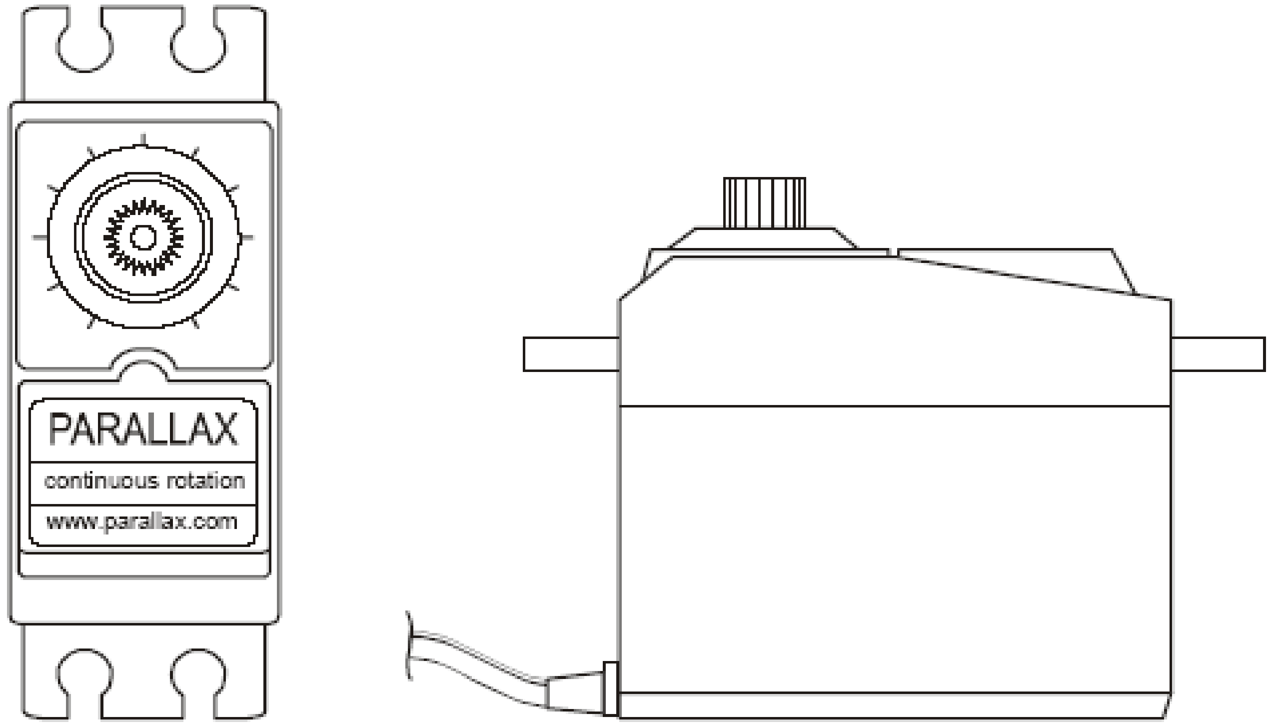
> Speed 0 deg to 180 deg in 1.5 seconds on average

> Weight 45.0 grams/1.59oz

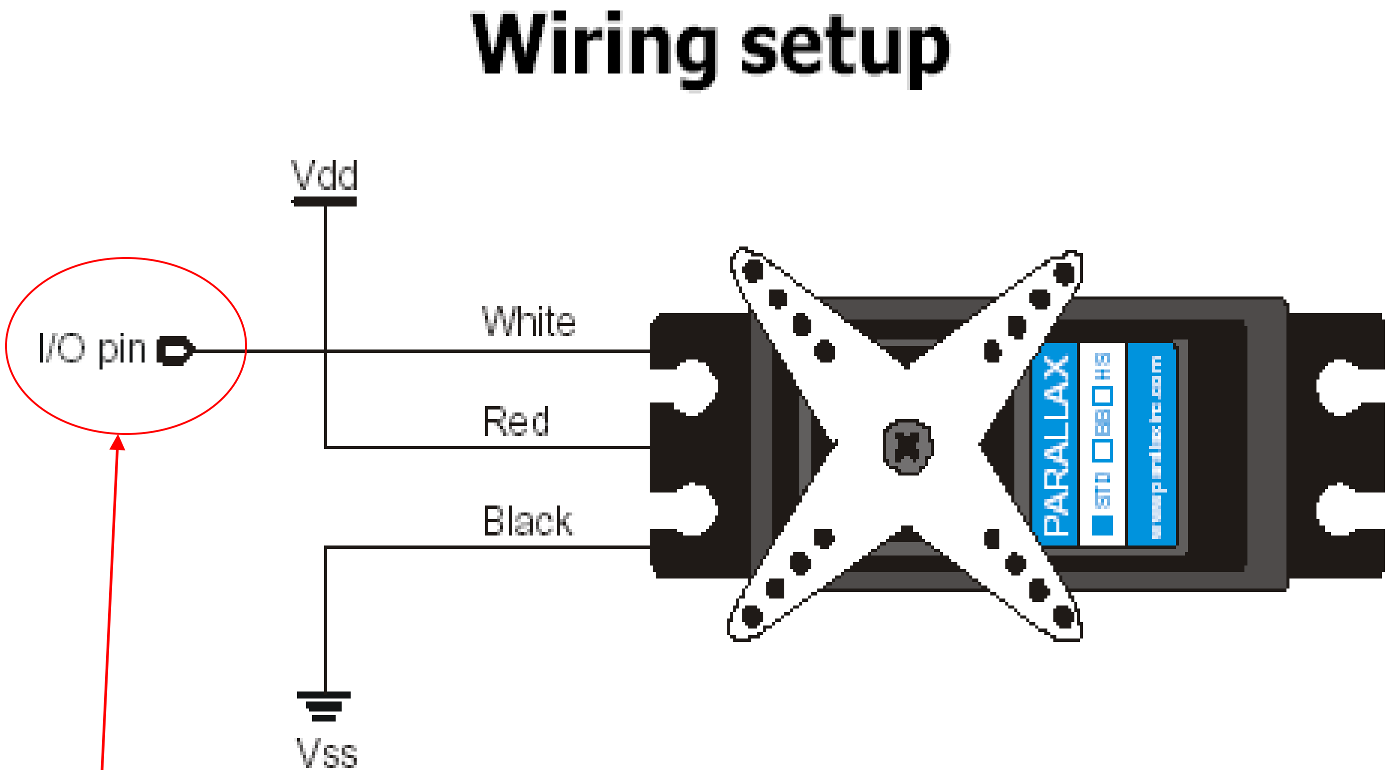
> Torque 3.40 kg-cm/47oz-in

> Size mm (L x W x H) 40.5x20.0x38.0

> Size in (L x W x H) 1.60x.79x1.50



Servomotor Wiring

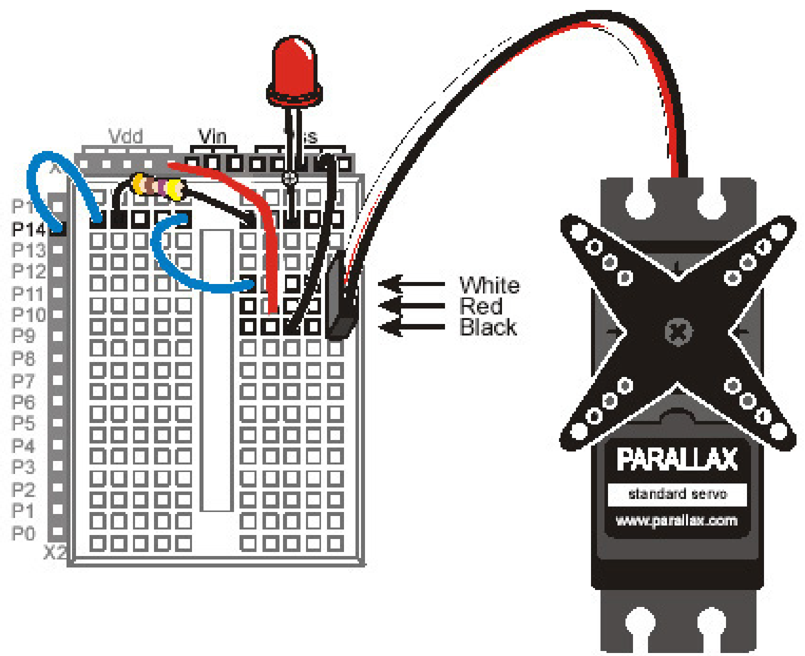


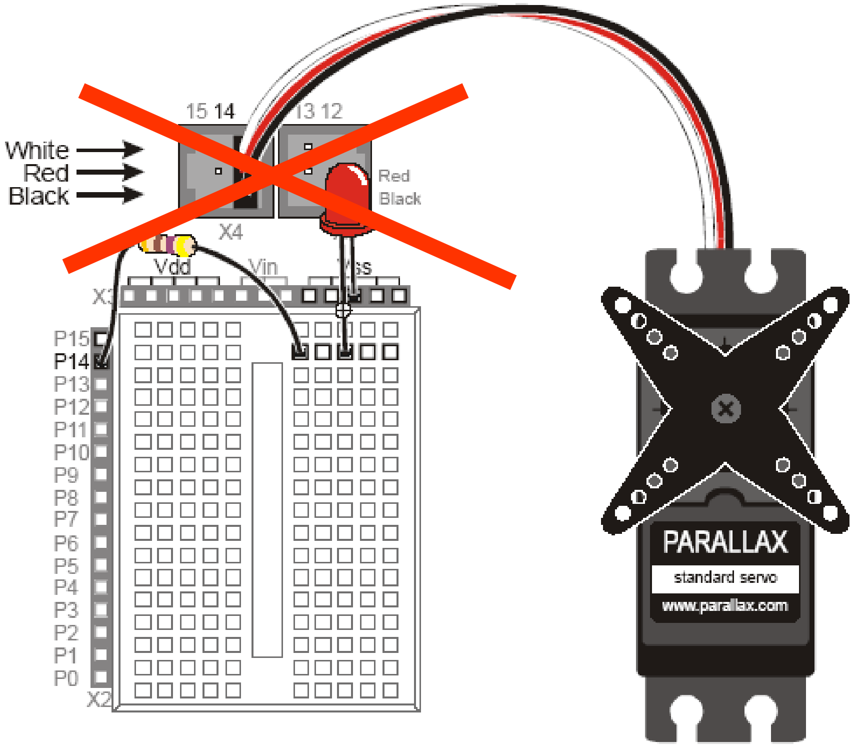
This pin can be any I/O pin

Servomotor with BS2

Board of Education Rev B

Caution: Do not connect servo here when using wall transformer or 9V battery. Servo is to be connected here only when using AA battery pack with ≤ 6V.





When more than 2 servos are to be connected, need to use additional capacitors across V_{dd} and V_{ss}.

Servomotor with BS2: Code

```
X var byte
Output 12

Here:
For X = 1 to 100
Pulsout 12, 500
Pause 10
Next
Pause 500

For X = 1 to 100
Pulsout 12, 1000
Pause 10
Next
Pause 500

Goto Here
```

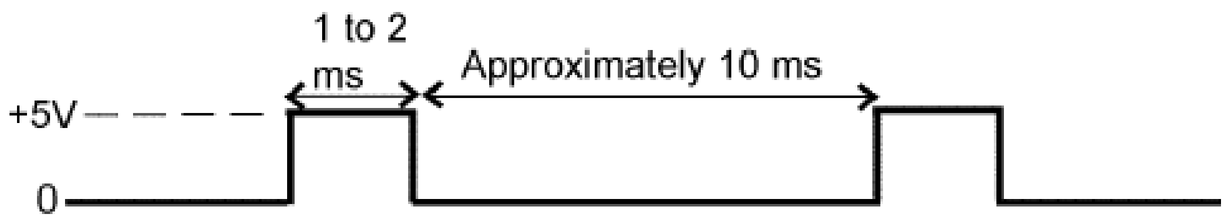
Pulsout Pin #, Duration

12 is pin number of BS2

500 means 1 millisecond

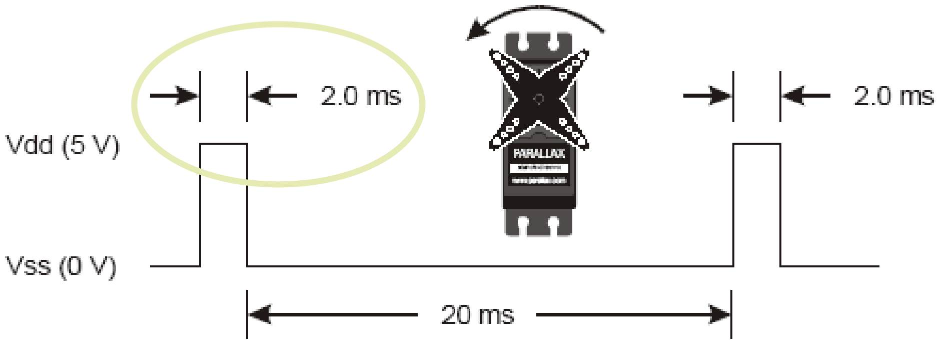
!! Caution

Fix the Duration between 500 to 1000

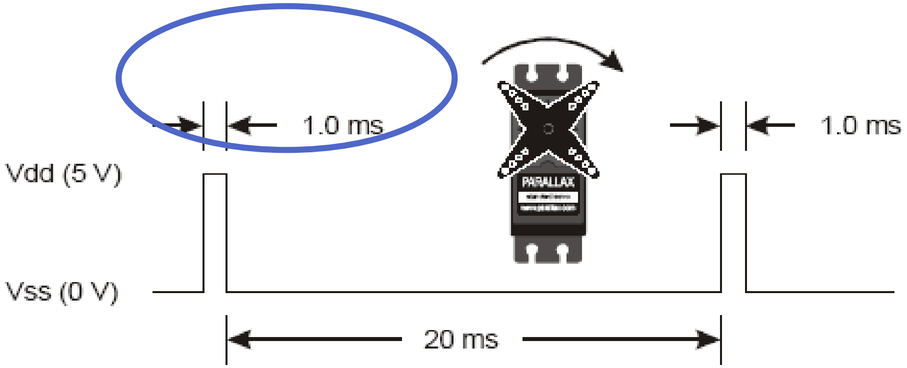


Servomotor with BS2: Code

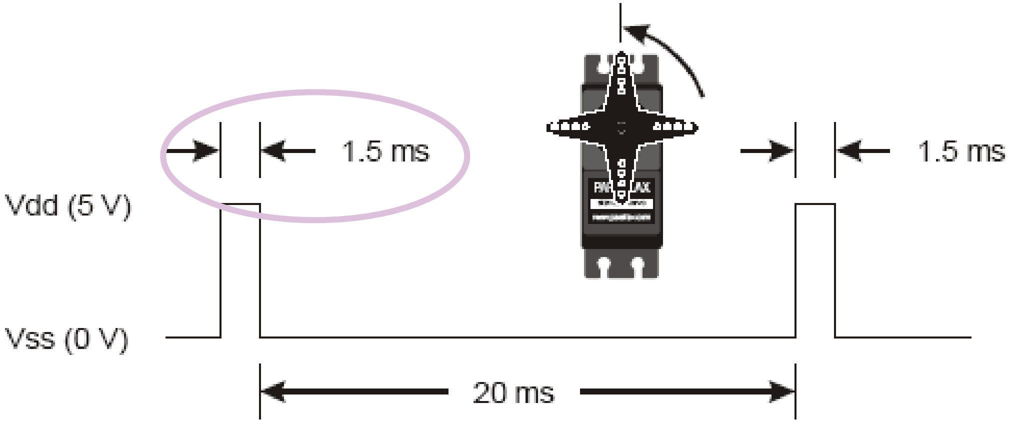
```
FOR counter = 1 to 150
    pulsout 14, 1000
    pause 20
NEXT
```




```
FOR counter = 1 to 150
    pulsout 14, 500
    pause 20
NEXT
```




```
FOR counter = 1 to 150
    pulsout 14, 750
    pause 20
NEXT
```



Control Theory

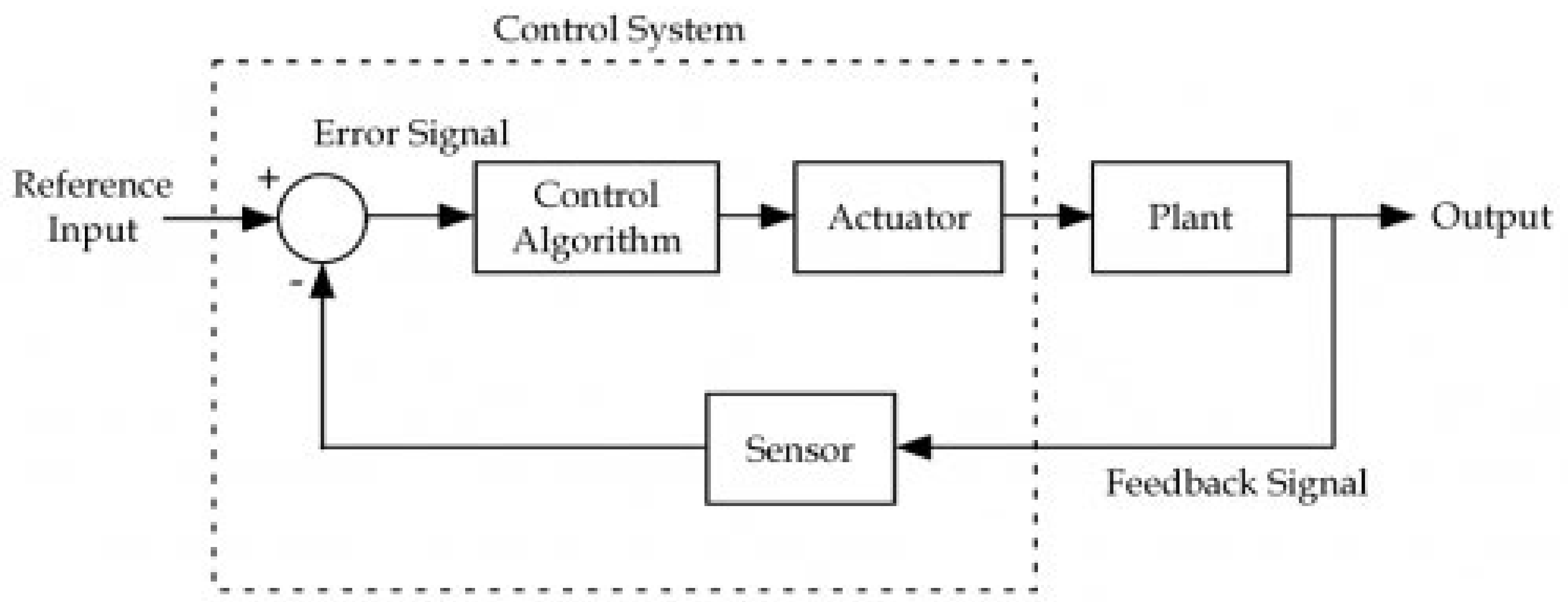
- How to ride a bike

PID Simulator

- https://grauonline.de/alexwww/ardumower/pid/pid.html

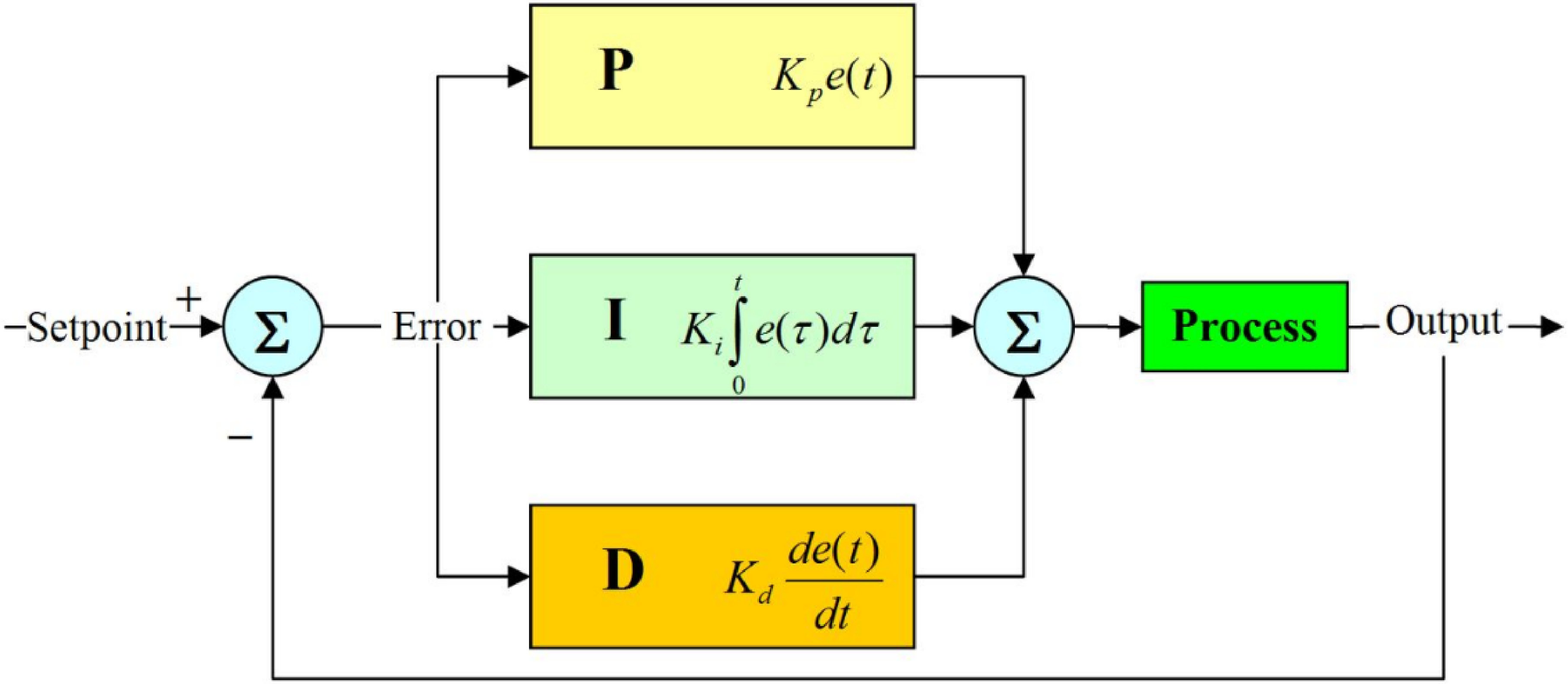
Control Theory

- Block diagram

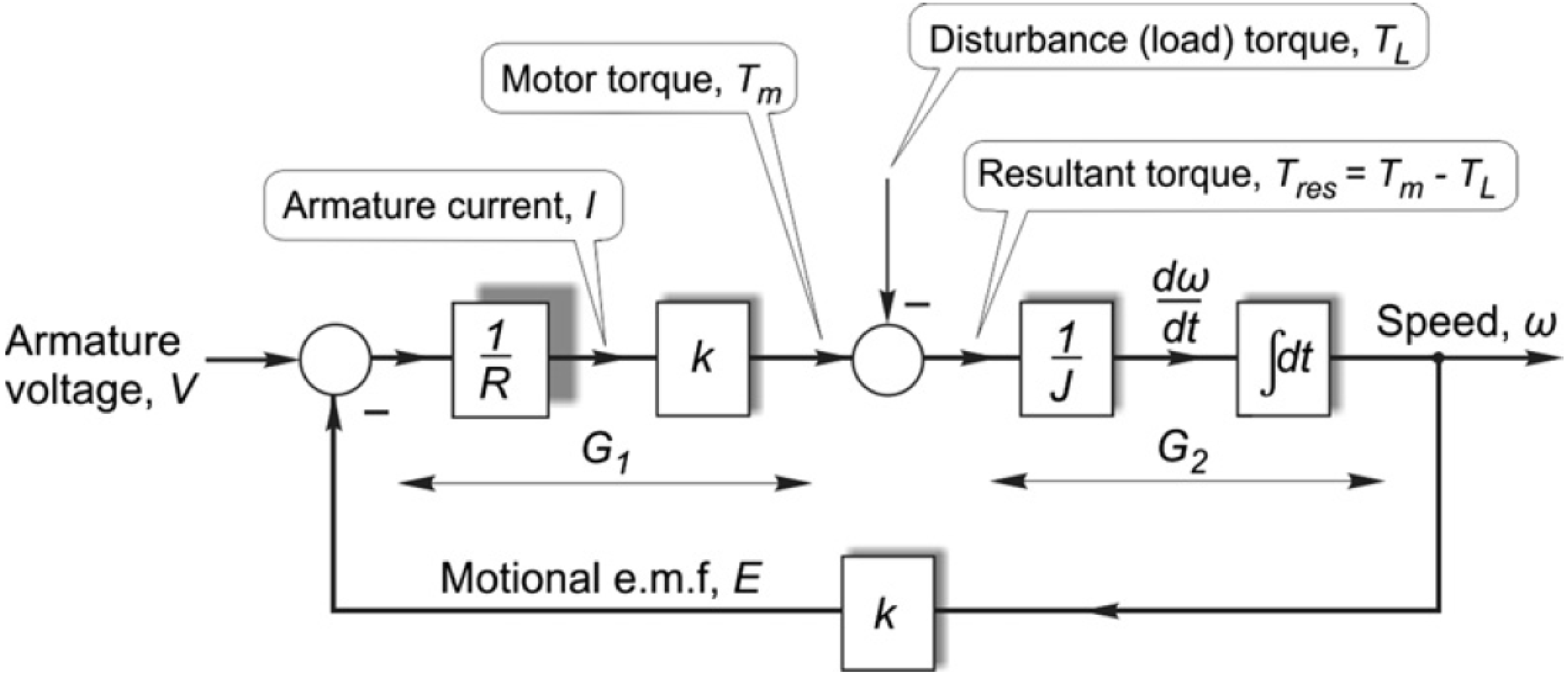


PID Control

- Proportional, Derivative, Integral Control



DC Motor Block Diagram



Miscellaneous

Dead Reckoning

- **Dead Reckoning:** derived from deduced reckoning of sailing days
  - Establish present location by advancing over a previous known position through known course and velocity information over a given length of time
- **Measure vehicle displacement:**
  - Wheel rotation (odometry using pot, encoder, magnetic/inductive proximity sensor, etc.).
  - Doppler navigation (motion relative to ground)
  - Inertial navigation (accelerometers)
- **Measure vehicle heading:**
  - Onboard steering
  - Magnetic compass
  - Rate gyro
  - Differential odometry

Doppler Effect

- Stationary Observer, moving source

$$f_{\text{rec}} = f\left(\frac{s}{s \pm v_{\text{s}}}\right)$$

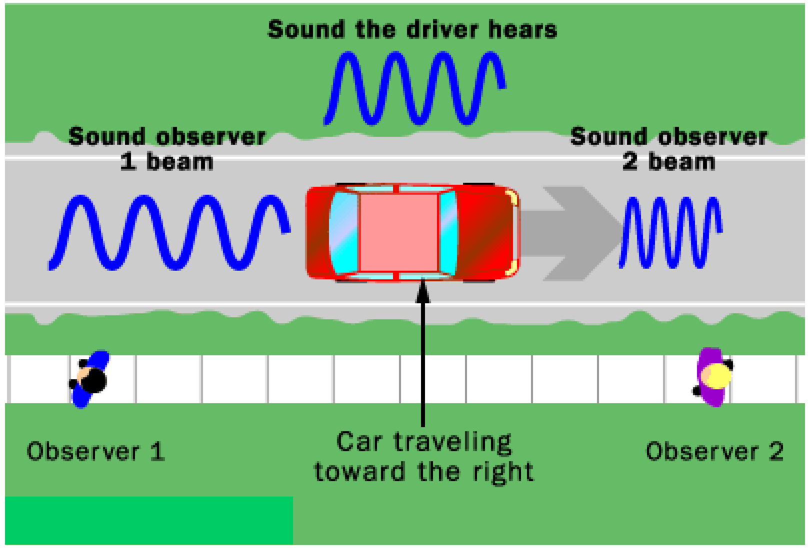
  - f: source frequency, f_{rec}: frequency @ observer (Doppler frequency), s: speed of sound in air, v_{s}: velocity of source

  - +/- sign: source moving away from/toward observer

- Moving observer, stationary source

$$f_{\text{rec}} = f\left(\frac{s \pm v_{\text{o}}}{s}\right)$$

  - v_{o}: velocity of observer



- For reflected wave, instead of Doppler frequency, we consider the change in frequency (Doppler shift)

$$\Delta f = f - f_{rec} = \frac{2 f\, v \cos\theta}{s}$$

  – f: source frequency, f_{rec}: frequency received, s: speed of sound in air, v: velocity of target object, ϑ: relative angle between direction of motion and beam axis

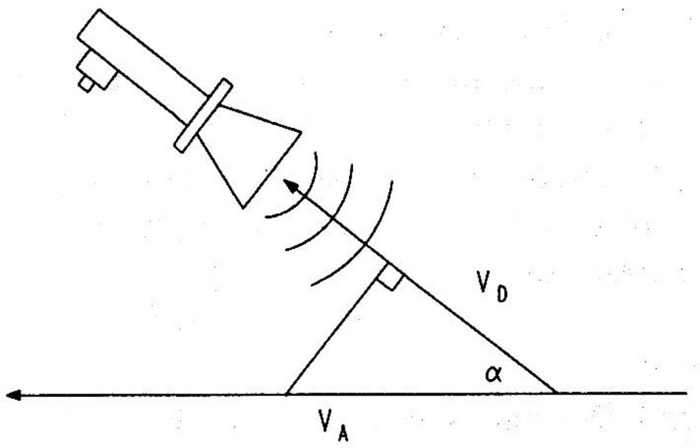
Doppler Navigation

- Use ultrasonic sensor aimed downward at a prescribed angle to sense ground movement
- Use Doppler shift equation to determine the ground speed V_A of the vehicle as follows:

$$\Delta f = f - f_{rec} = \frac{2 f V_D}{s}$$

$$\Rightarrow V_D = \frac{s \Delta f}{2 f}$$

$$\Rightarrow V_A = \frac{V_D}{\cos\alpha} = \frac{s \Delta f}{2 f \cos\alpha}$$



Doppler ground speed sensor

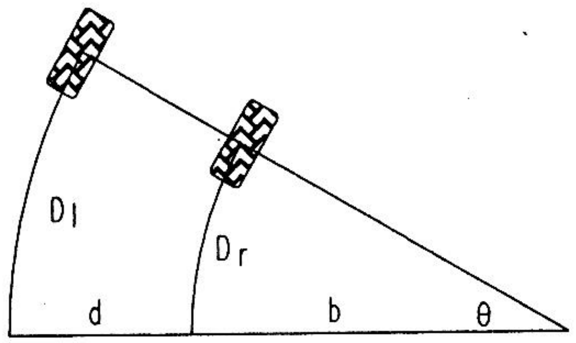
- f: transmitted frequency, Δf: Doppler shift, s: speed of sound in air, V_D: measured velocity, α: declination angle

Vehicle heading via Differential Odometry

- Displacement *D* of a differential-drive robot platform:

$$D = \frac{D_L - D_R}{2}$$

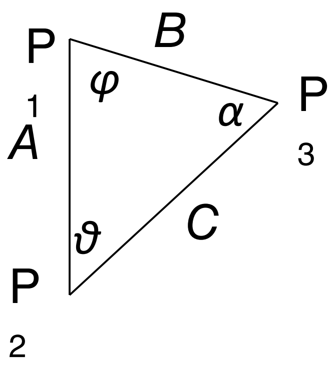
- D_L and D_R: displacements of left and right wheels, respectively
- D_L: portion of the circumference of a circle with radius $d+b$, $C_L = 2\pi(d+b)$
- D_R: portion of the circumference of a circle with radius b, $C_R = 2\pi b$
    - d: distance between left and right wheels, b: inner turn radius
- Moreover: $D_L = \left(\frac{C_L}{2\pi}\right)\theta \rightarrow C_L = \frac{2\pi D_L}{\theta} \rightarrow \theta = \frac{D_L}{d+b}$



- Similarly, $D_R = \left(\frac{C_R}{2\pi}\right)\theta \rightarrow C_R = \frac{2\pi D_R}{\theta} \rightarrow \theta = \frac{D_R}{b} \rightarrow b = \frac{D_R}{\theta}$
- Finally, $\theta = \frac{D_L - D_R}{d}$

Triangulation Ranging

- Basis (Law of sines): If the sides of a triangle are a, b, and c and the angles opposite to those sides are *α, θ,* and *φ*, then



$$\frac{A}{\sin\alpha} = \frac{B}{\sin\theta} = \frac{C}{\sin\varphi}$$

$$\rightarrow \quad B = A\frac{\sin\theta}{\sin\alpha} = A\frac{\sin\theta}{\sin(180-\theta-\varphi)} = A\frac{\sin\theta}{\sin(\theta+\varphi)}$$

- Therefore, given the length of a side and two angles of a triangle, the length of the other two sides and the third angle can be determined.

- In ranging applications, length *B* represents the distance to the object of interest at point P_3.

- In a passive ranging system, directional detectors can be placed at P_1 and P_2 to view the object point P_3, forming an imaginary triangle.

- Measurement of angles *θ* and *φ* along with the known orientation and lateral separation of the detectors allows the calculation of range to the object at P_3.

Time-of-Flight Ranging

Measure the round-trip time required for a pulse (burst) of emitted energy (acoustic, radio, or optical) to travel to an object and then reflect/echo back to a receiver.

Range to the object: $d=v(T/2)$, where v is the speed of the propagated wave, T=round-trip time of travel

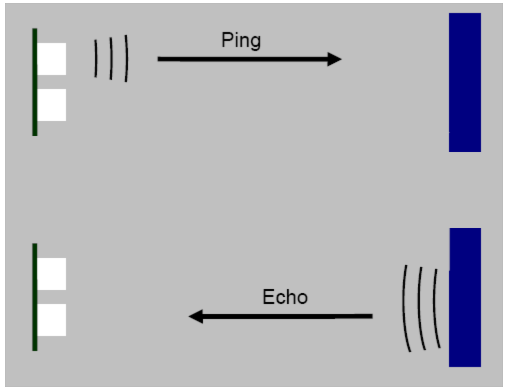
Ultrasonic emitter/detector pairs (transceivers) are commonly used

- Common ultrasonic transducers: capacitive, electrostatic, and piezoelectric

Laser-based time-of-flight systems

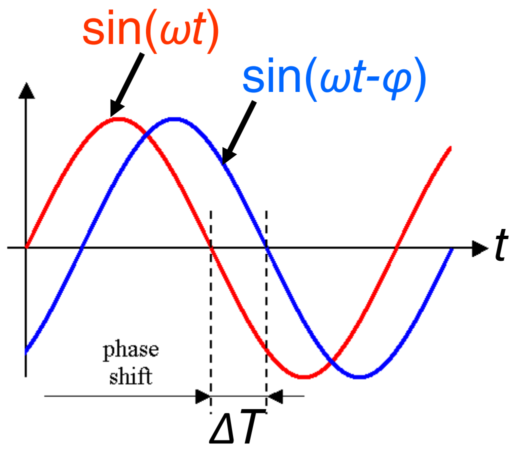
Speed of sound ≈ 0.3m/ms, speed of light ≈ 0.3m/ns

- Time of flight for 3 meters: ultrasonic system: 10ms; laser system: 10ns
- → sophisticated timing circuitry necessitated in laser-based time-of-flight ranging instruments.



Ranging by Phase Shift Measurement

- A continuous-wave (e.g., amplitude-modulated laser, RF, or acoustic) energy source is directed towards a target.
- The reflected signal that strikes back at the detector is compared to a reference signal (tapped off from the transmitted signal).
- The relative phase shift between the reference and reflected signal is measured to determine the round-trip distance from the object.
- Notation: *T*: period (sec), *f*: frequency (Hz), *ω*: radial frequency (radian/sec), *λ*: wavelength (m), *ω=2πf, λ=s/f, s*: speed of sound.



$$\phi = \omega \Delta T = 2\pi f \Delta T = 2\pi \left(\frac{s}{\lambda} \right) \Delta T$$

$$= \frac{2\pi}{\lambda} s \Delta T = \frac{2\pi(2d)}{\lambda} = \frac{4\pi d}{\lambda}$$

$$\Rightarrow d = \frac{\phi \lambda}{4\pi}$$

The End