Lecture 8:
Pulse-width modulation (PWM)

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CpE 301

Embedded System Design

February 14, 2017

Today's Topics

- Logistics
- Pulse-width modulation (PWM)
  - Wave characteristics
  - Timer0 review
  - Wave generating using Timer0
  - Wave generating using Timer2
  - Wave generating using Timer1
- DC Motors
- Debugging

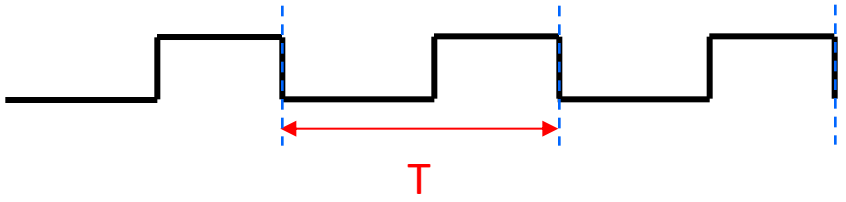
Logistics

- **Reminders:**
  - Lecture on 2/21 will be a video (available on WebCampus by 2/21 @ 8:30am).
  - I will be at a conference that day (back on 2/22) – so no office hours on 2/21.
  - You are allowed 1 free late day for each design assignment (i.e., until Tuesday @ 11:59pm)

Wave characteristics

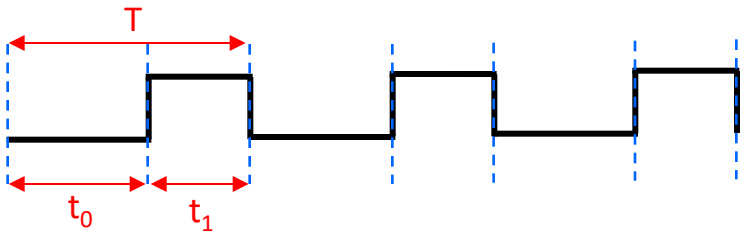
- Period
  - Frequency

$$f = \frac{1}{T}$$



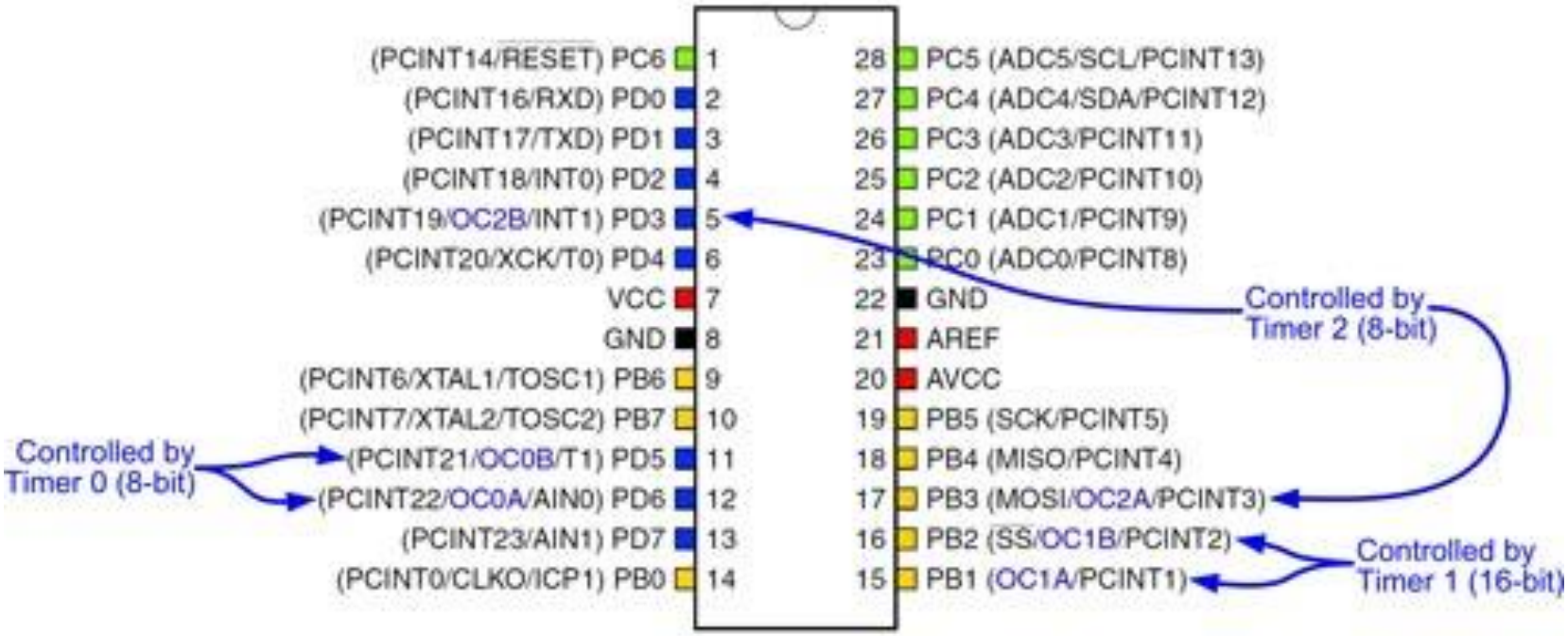
- Duty cycle

$$\text{duty cycle} = \frac{t_1}{T} \times 100 = \frac{t_1}{t_0 + t_1} \times 100$$

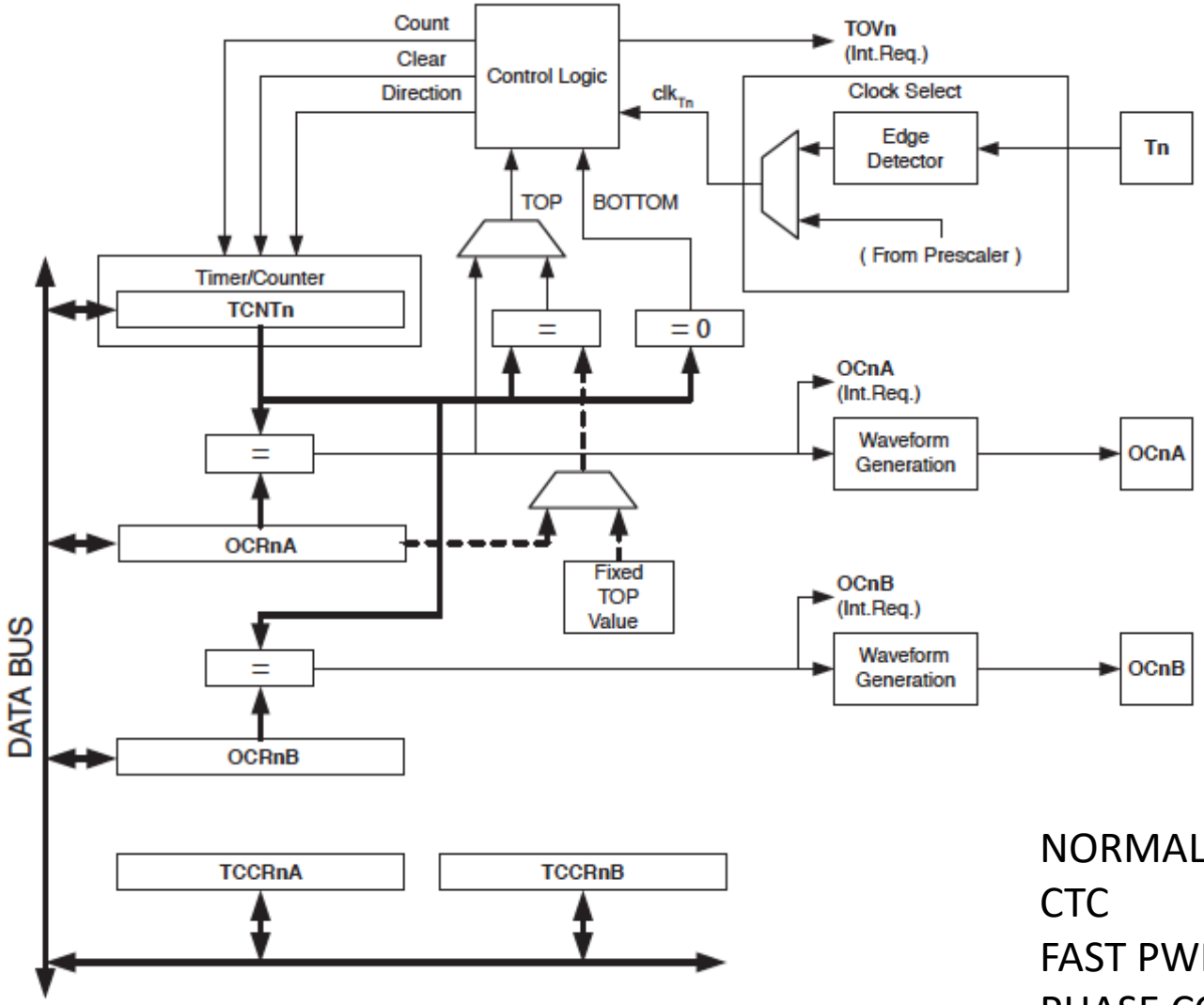


- Amplitude

PWM pins

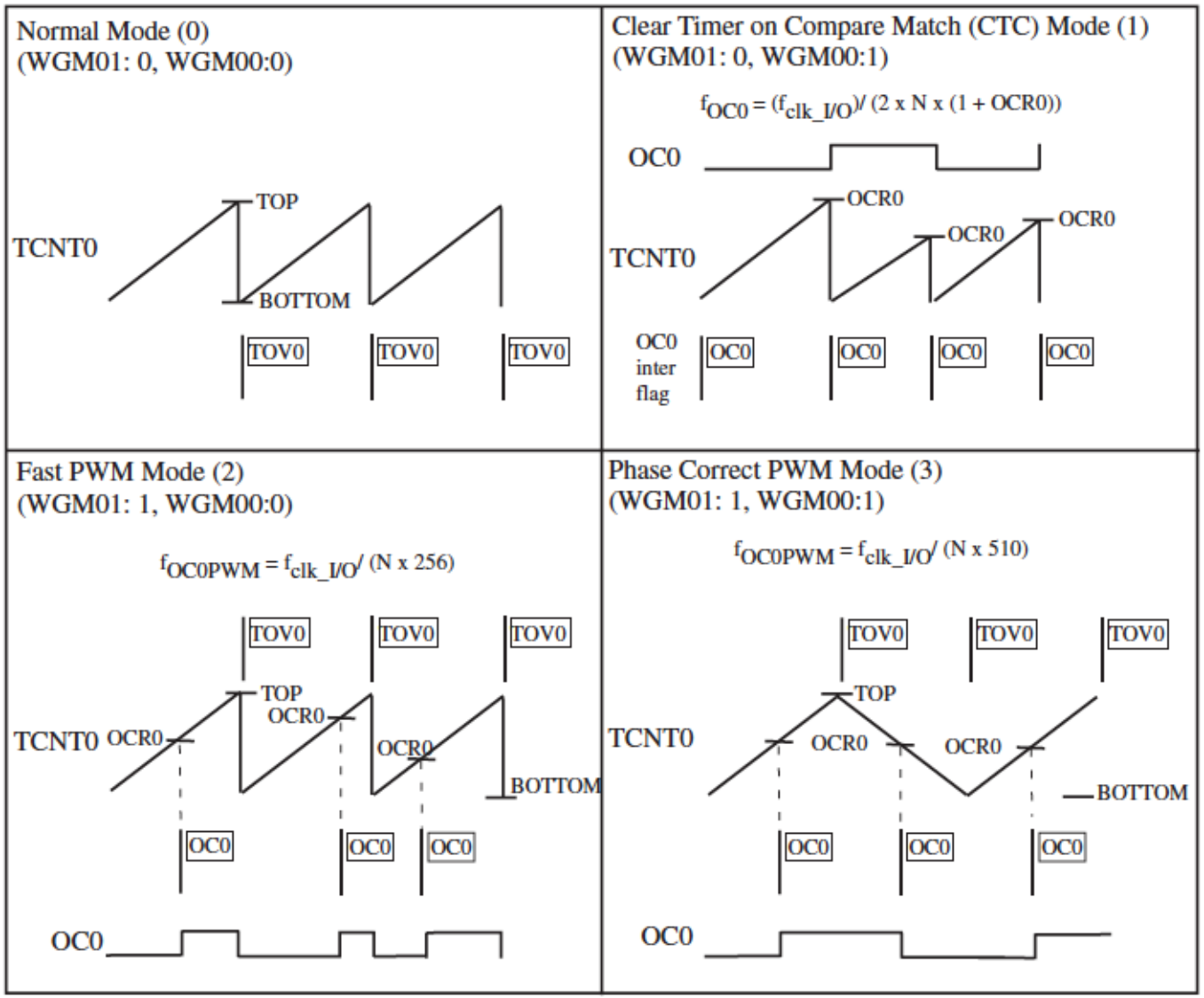

(PCINT14/RESET) PC6 1
(PCINT16/RXD) PD0 2
(PCINT17/TXD) PD1 3
(PCINT18/INT0) PD2 4
(PCINT19/OC2B/INT1) PD3 5
(PCINT20/XCK/T0) PD4 6
VCC 7
GND 8
(PCINT6/XTAL1/TOSC1) PB6 9
(PCINT7/XTAL2/TOSC2) PB7 10
(PCINT21/OC0B/T1) PD5 11
(PCINT22/OC0A/AIN0) PD6 12
(PCINT23/AIN1) PD7 13
(PCINT0/CLKO/ICP1) PB0 14
28 PC5 (ADC5/SCL/PCINT13)
27 PC4 (ADC4/SDA/PCINT12)
26 PC3 (ADC3/PCINT11)
25 PC2 (ADC2/PCINT10)
24 PC1 (ADC1/PCINT9)
23 PC0 (ADC0/PCINT8)
22 GND
21 AREF
20 AVCC
19 PB5 (SCK/PCINT5)
18 PB4 (MISO/PCINT4)
17 PB3 (MOSI/OC2A/PCINT3)
16 PB2 (SS/OC1B/PCINT2)
15 PB1 (OC1A/PCINT1)
Controlled by Timer 2 (8-bit)
Controlled by Timer 0 (8-bit)
Controlled by Timer 1 (16-bit)

Timer 0

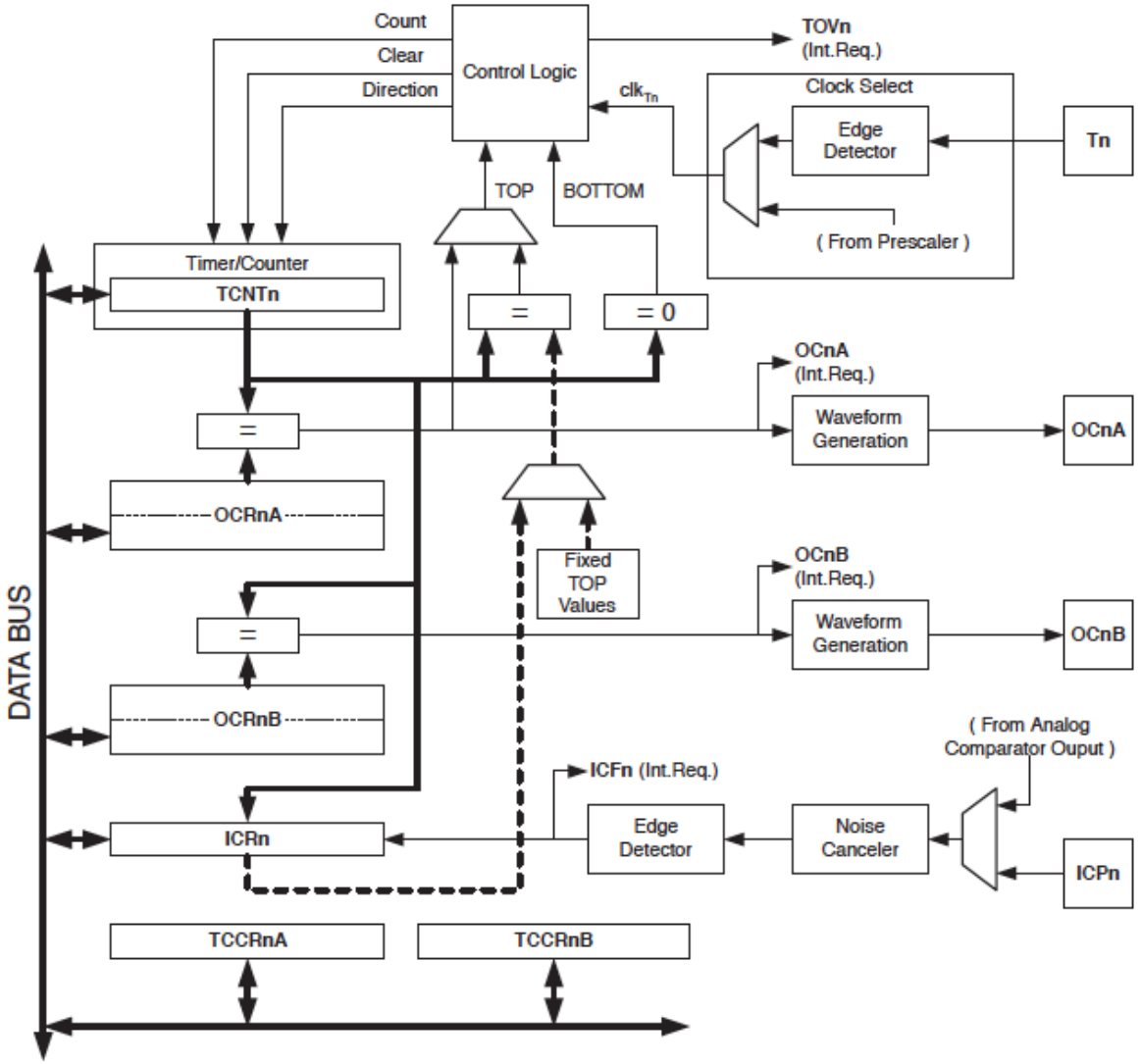


NORMAL
CTC
FAST PWM
PHASE CORRECT PWM

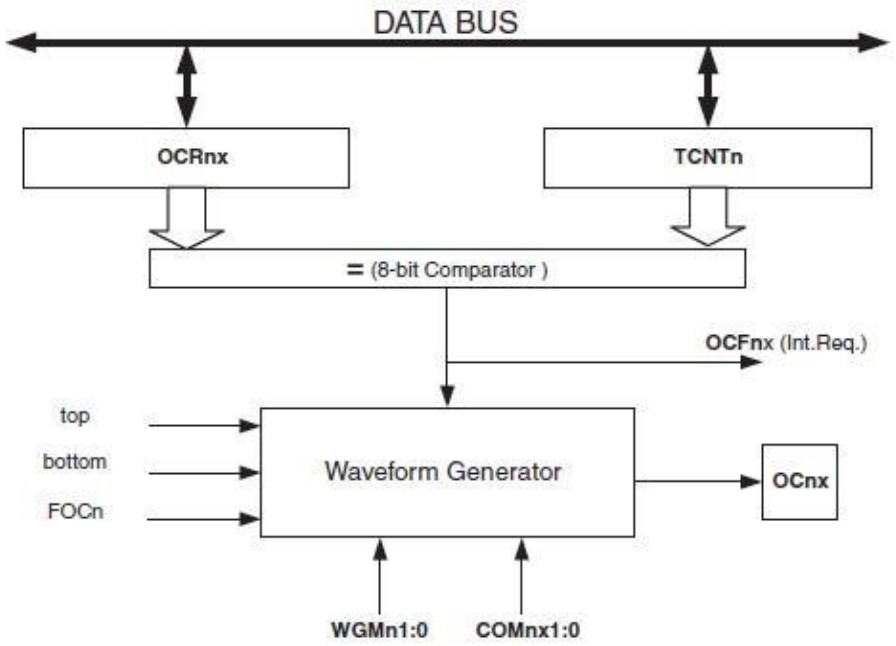
Timer Modes


Normal Mode (0)
(WGM01: 0, WGM00:0)
TCNT0
TOP
BOTTOM
TOV0
TOV0
TOV0
Clear Timer on Compare Match (CTC) Mode (1)
(WGM01: 0, WGM00:1)
$f_{OC0} = (f_{clk\_I/O})/ (2 \times N \times (1 + OCR0))$
OC0
TCNT0
OCR0
OCR0
OCR0
OC0 inter flag
OC0
OC0
OC0
OC0
Fast PWM Mode (2)
(WGM01: 1, WGM00:0)
$f_{OC0PWM} = f_{clk\_I/O}/ (N \times 256)$
TOV0
TOV0
TOV0
TCNT0
OCR0
TOP
OCR0
OCR0
BOTTOM
OC0
OC0
OC0
OC0
Phase Correct PWM Mode (3)
(WGM01: 1, WGM00:1)
$f_{OC0PWM} = f_{clk\_I/O}/ (N \times 510)$
TOV0
TOV0
TOV0
TCNT0
TOP
OCR0
OCR0
BOTTOM
OC0
OC0
OC0
OC0

Timer 1


Count
Clear
Direction
Control Logic
TOVn
(Int.Req.)
clk$_{Tn}$
Clock Select
Edge
Detector
Tn
(From Prescaler)
TOP
BOTTOM
Timer/Counter
TCNTn
=
= 0
OCnA
(Int.Req.)
Waveform
Generation
OCnA
OCRnA
Fixed
TOP
Values
OCnB
(Int.Req.)
Waveform
Generation
OCnB
OCRnB
(From Analog
Comparator Ouput)
ICFn (Int.Req.)
Edge
Detector
Noise
Canceler
ICPn
ICRn
TCCRnA
TCCRnB
DATA BUS

TIMER0PWM



Timer/Counter0 has 2 outputs, OC0A and OC0B. Since both of these outputs run off the same timer and waveform generators both OC0A and OC0B are synchronized

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0A	COM0A1	COM0A0	COM0B1	COM0B0	-	-	WGM01	WGM00

Timer/Counter Control Register 0 A

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0B	FOC0A	FOC0B	-	-	WGM02	CS02	CS01	CS00

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TIFR0	-	-	-	-	-	OCF0B	OCF0A	TOV0

Timer/Counter Interrupt Flag Register

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TIMSK0	-	-	-	-	-	OCIE0B	OIE0A	TOIE0

Timer/Counter Interrupt Mask Register

TIMER0PWM– ATm328

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0A	COM0A1	COM0A0	COM0B1	COM0B0	-	-	WGM01	WGM00

Timer/Counter Control Register 0 A

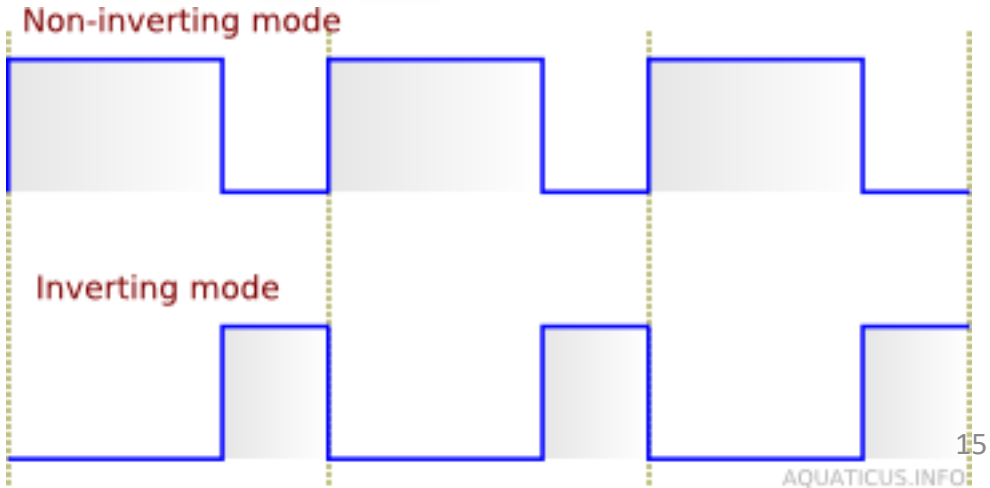
PWM MODES

COM0A1	COM0A0	DESCRIPTION
0	0	OC0A disabled
0	1	WGM02 = 0: Normal Port Operation, OC0A Disconnected WGM02 = 1: Toggle OC0A on Compare Match
1	0	None-inverted mode (HIGH at bottom, LOW on Match)
1	1	Inverted mode (LOW at bottom, HIGH on Match)

Applies only to PWM modes

COM0B1	COM0B0	DESCRIPTION
0	0	OC0B disabled
0	1	Reserved
1	0	None-inverted mode (HIGH at bottom, LOW on Match)
1	1	Inverted mode (LOW at bottom, HIGH on Match)

Applies only to PWM modes



PRE-SCALAR + PWM MODE

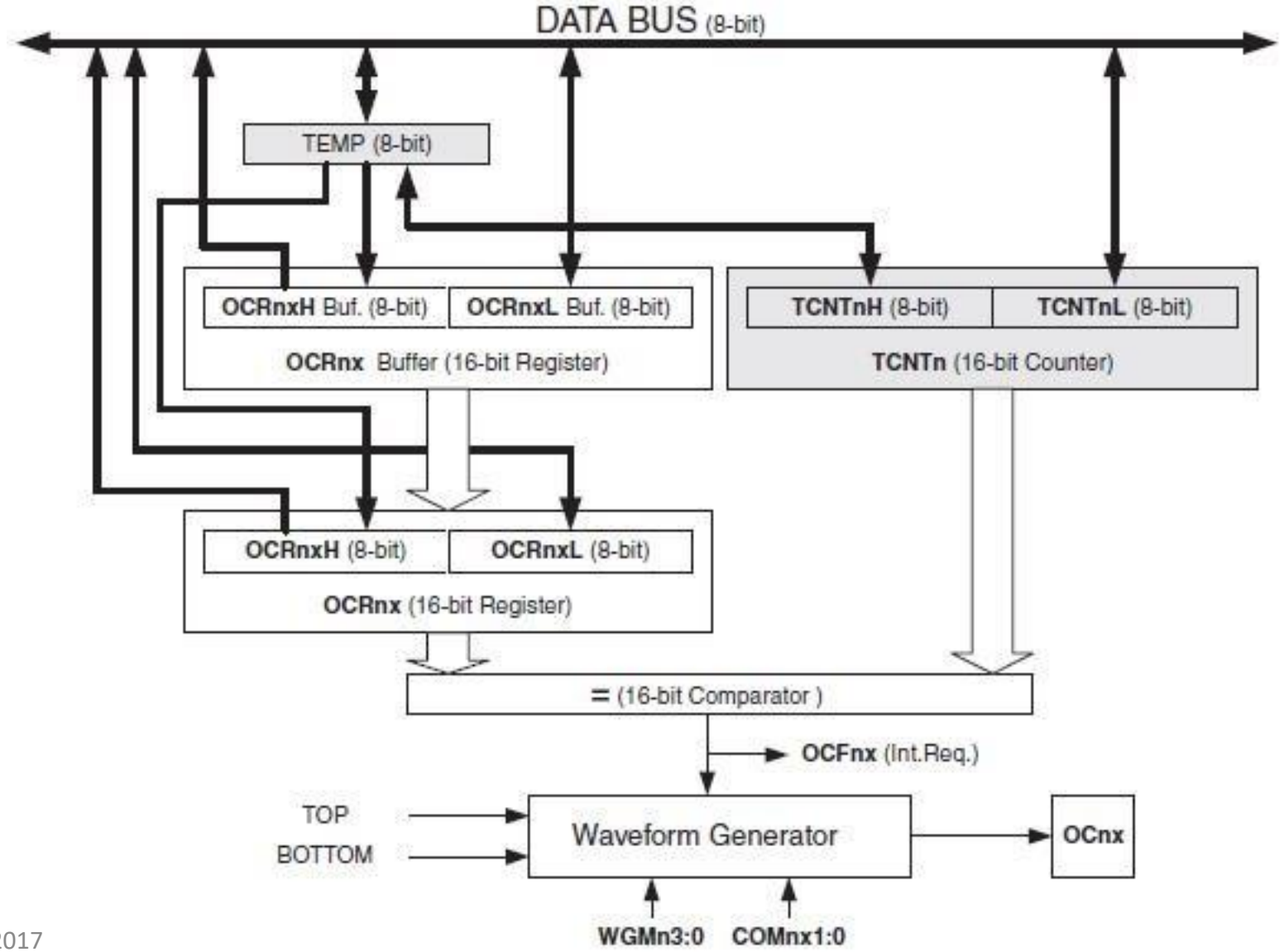
CS02	CS01	CS00	DESCRIPTION
0	0	0	Timer/Counter2 Disabled
0	0	1	No Prescaling
0	1	0	Clock / 8
0	1	1	Clock / 64
1	0	0	Clock / 256
1	0	1	Clock / 1024

CS bits

MODE	WGM02	WGM01	WGM00	TOP	DESCRIPTION
0	0	0	0		Normal
1	0	0	1	0xFF	PWM Phase Corrected
2	0	1	0	OCRA	CTC
3	0	1	1	0xFF	Fast PWM
4	1	0	0	-	Reserved
5	1	0	1	OCR0A	PWM Phase Corrected
6	1	1	0	-	Reserved
7	1	1	1	OCR0A	Fast PWM

Waveform Generator Mode bits

TIMER1PWM


DATA BUS (8-bit)
TEMP (8-bit)
OCRnxH Buf. (8-bit)
OCRnxL Buf. (8-bit)
OCRnx Buffer (16-bit Register)
TCNTnH (8-bit)
TCNTnL (8-bit)
TCNTn (16-bit Counter)
OCRnxH (8-bit)
OCRnxL (8-bit)
OCRnx (16-bit Register)
= (16-bit Comparator)
OCFnx (Int.Req.)
TOP
BOTTOM
Waveform Generator
OCnx
WGMn3:0
COMnx1:0

TIMER1PWM

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR1A	COM1A1	COM1A0	COM1B1	COM1B0	-	-	WGM11	WGM10

Timer/Counter Control Register 1 A

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR1B	ICNC1	ICES1	-	WGM13	WGM12	CS12	CS11	CS10

Timer/Counter Control Register 1 B

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR1C	FOC1A	FOC1B	-	-	-	-	-	

Timer/Counter Control Register C

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TIMSK1	-	-	ICIE1	-	-	OCIE1B	OCIE1A	TOIE1

Timer/Counter Interrupt Mask Register

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TIFR	OCF2	TOV2	ICF1	OCF1A	OCF1B	TOV1	-	TOV0

Timer/Counter Interrupt Flag Register

TIMER1 MODES

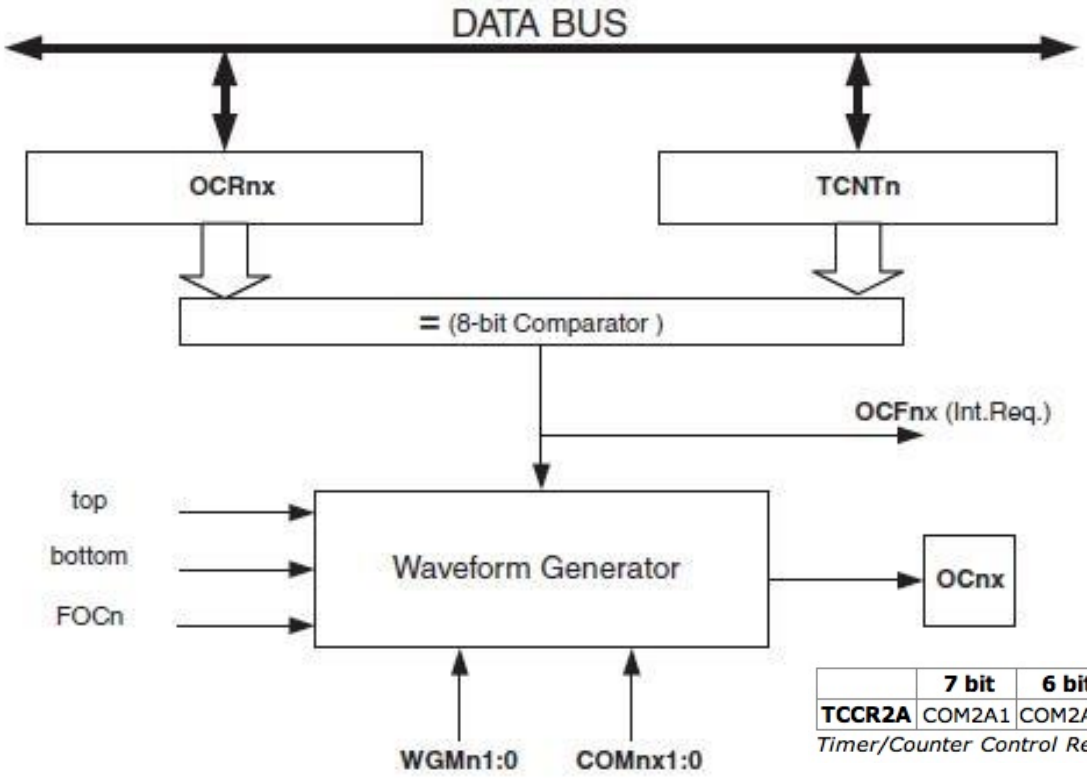
COM1A1 COM1B1	COM1A0 COM1B0	DESCRIPTION
0	0	Normal port operation, OC1A/OC1B disconnected.
0	1	Mode 9,11,14,15 only: Enable OCR1A only (OC1B disconnected)
1	0	None-inverted mode (HIGH at bottom, LOW on Match)
1	1	Inverted mode (LOW at bottom, HIGH on Match)

Applies only to PWM modes

MODE	WGM13	WGM12	WGM11	WGM10	DESCRIPTION	TOP
0	0	0	0	0	Normal	0xFFFF
1	0	0	0	1	PWM, Phase Corrected, 8bit	0x00FF
2	0	0	1	0	PWM, Phase Corrected, 9bit	0x01FF
3	0	0	1	1	PWM, Phase Corrected, 10bit	0x03FF
5	0	1	0	1	Fast PWM, 8bit	0x00FF
6	0	1	1	0	Fast PWM, 9bit	0x01FF
7	0	1	1	1	Fast PWM, 10bit	0x03FF
8	1	0	0	0	PWM, Phase and Frequency Corrected	ICR1
9	1	0	0	1	PWM, Phase and Frequency Corrected	OCR1A
10	1	0	1	0	PWM, Phase Correct	ICR1
11	1	0	1	1	PWM, Phase Correct	OCR1A
14	1	1	1	0	Fast PWM	ICR1
15	1	1	1	1	Fast PWM	OCR1A

Waveform Generator Mode bits (Abbreviated)

TIMER2PWM



	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR2A	COM2A1	COM2A0	COM2B1	COM2B0	-	-	WGM21	WGM20

Timer/Counter Control Register 2 A

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR2B	FOC2A	FOC2B	-	-	WGM22	CS22	CS21	CS20

Timer/Counter Control Register 2 A

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TIMSK2	-	-	-	-	-	OCIE2B	OIE2A	TOIE2

Timer/Counter Interrupt Mask Register

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TIFR2	-	-	-	-	-	OCF2B	OCF2A	TOV2

Timer/Counter Interrupt Flag Register

TIMER2 MODES

CS22	CS21	CS20	DESCRIPTION
0	0	0	Timer/Counter2 Disabled
0	0	1	No Prescaling
0	1	0	Clock / 8
0	1	1	Clock / 32
1	0	0	Clock / 64
1	0	1	Clock / 128
1	1	0	Clock / 256
1	1	1	Clock / 1024

CS bits

MODE	WGM22	WGM21	WGM20	TOP	DESCRIPTION
0	0	0	0	0xFF	Normal
1	0	0	1	0xFF	PWM Phase Corrected
2	0	1	0	OCRA	CTC
3	0	1	1	0xFF	Fast PWM
4	1	0	0	-	Reserved
5	1	0	1	OCR0A	PWM Phase Corrected
6	1	1	0	-	Reserved
7	1	1	1	OCR0A	Fast PWM

Waveform Generator Mode bits

Assuming XTAL = 8 MHz, make the following pulse duty cycle = 75% and frequency = 31.250KHz

$$F_{OC0} = \frac{f_{clk}}{N(256)} \Rightarrow 31.250KHz = \frac{8MHz}{N(256)} \Rightarrow N = \frac{8MHz}{31.250K*256} = 1$$

75/100 = (OCRnX+1)/256 ➔ OCRnX+1 = 191 = 0xBF ➔ OCR0 = 0xBE

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0A	COM0A1	COM0A0	COM0B1	COM0B0	-	-	WGM01	WGM00

Timer/Counter Control Register 0 A

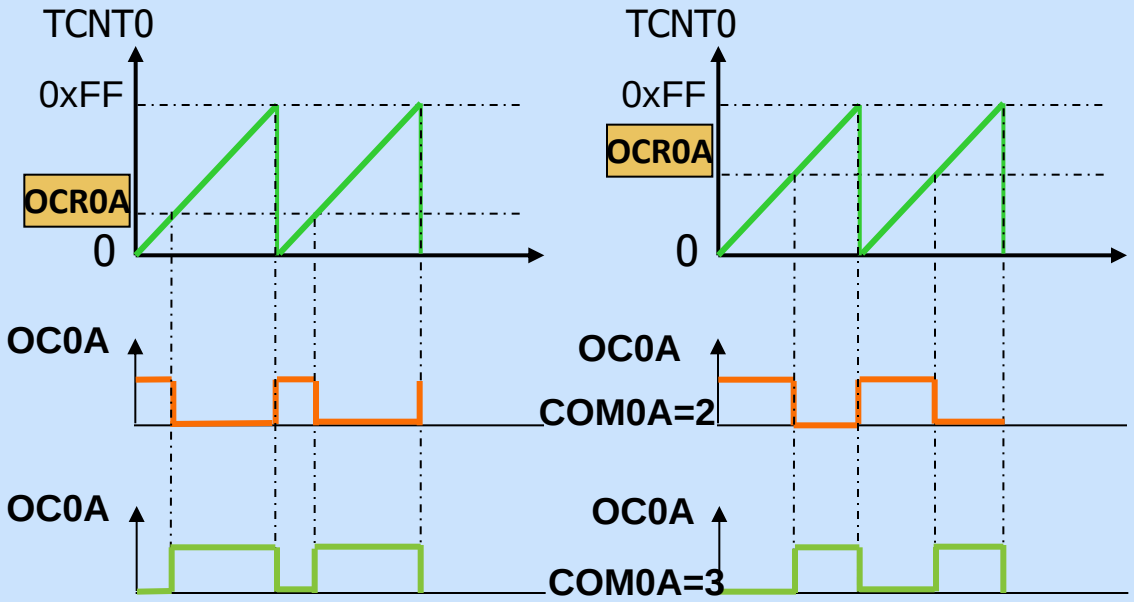
	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0B	FOC0A	FOC0B	-	-	WGM02	CS02	CS01	CS00

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0A	COM0A1	COM0A0	COM0B1	COM0B0	-	-	WGM01	WGM00

Timer/Counter Control Register 0 A

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0B	FOC0A	FOC0B	-	-	WGM02	CS02	CS01	CS00

Fast PWM
Duty cycle = changeable (0% to 100%)
Frequency = selectable between limited choices



OCR0A

$$\text{Duty Cycle} = \frac{\text{OCR0} + 1}{256} \times 100$$

$$\text{Duty Cycle} = \frac{255 - \text{OCR0}}{256} \times 100$$

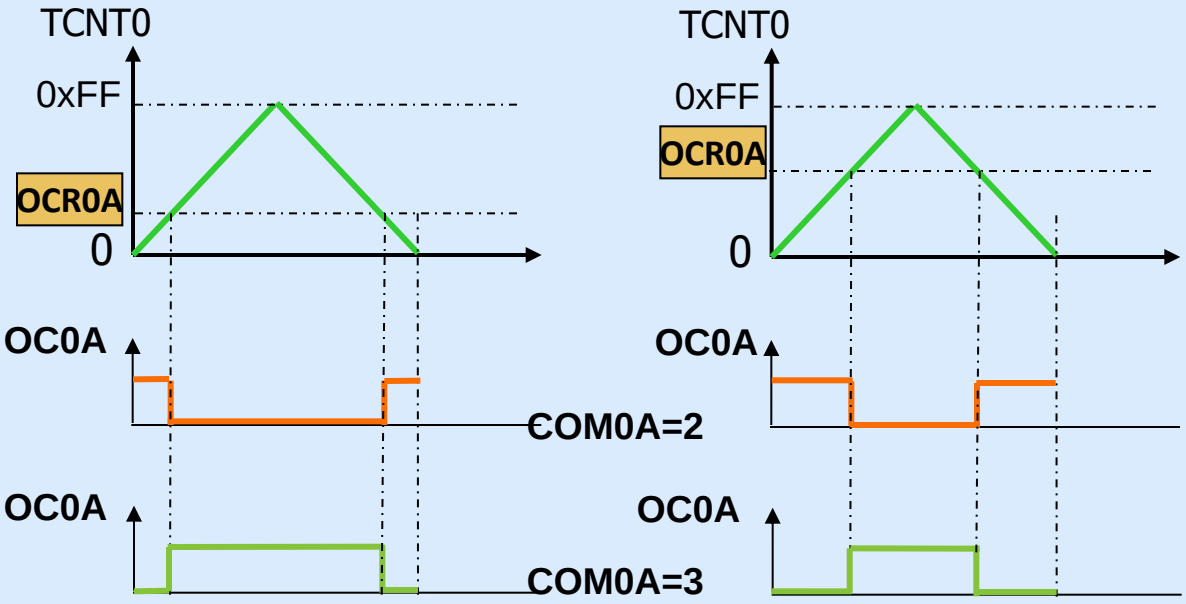
$$F_{OC0} = \frac{f_{clk}}{N(256)}$$

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0A	COM0A1	COM0A0	COM0B1	COM0B0	-	-	WGM01	WGM00

Timer/Counter Control Register 0 A

	7 bit	6 bit	5 bit	4 bit	3 bit	2 bit	1 bit	0 bit
TCCR0B	FOC0A	FOC0B	-	-	WGM02	CS02	CS01	CS00

Phase Correct PWM
Duty cycle = changeable (0% to 100%)
Frequency = selectable between limited choices



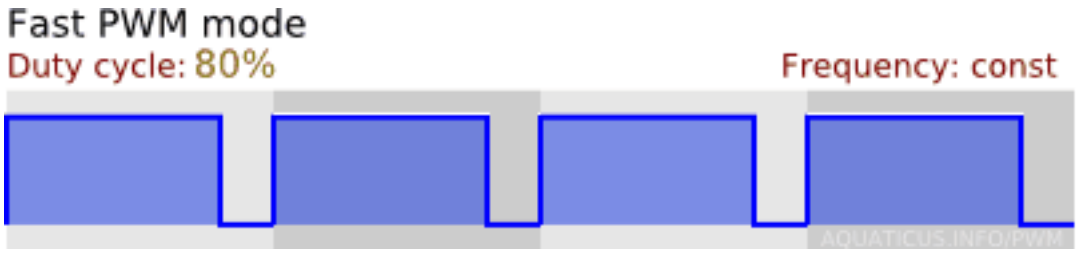
OCR0A

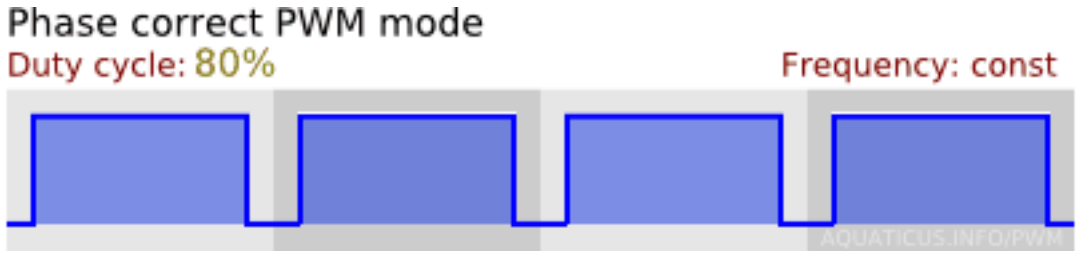
$$\text{Duty Cycle} = \frac{OCRx}{255} \times 100$$

$$\text{Duty Cycle} = \frac{255 - OCR0}{255} \times 100$$

$$F_{OC0} = \frac{f_{clk}}{N(510)}$$

FAST & PHASE CORRECTED PWM

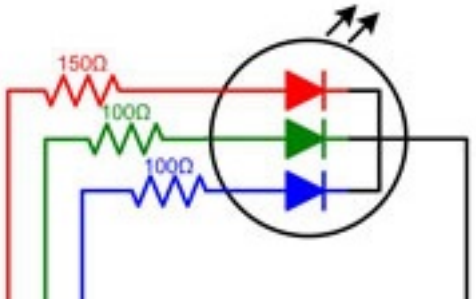




Design Assignment 3

RGB LED

What you need to do:
You need 3 independent PWMs
Change Color by varying frequency of each PWM.
For a single color change DC to vary intensity/brightness!



http://www.protostack.com/blog/2011/06/atmega168a-pulse-width-modulation-pwm/

https://www.adafruit.com/blog/2012/03/14/constant-brightness-hsb-to-rgb-algorithm/

Embedded/Robotic Systems

Systems typically consist of

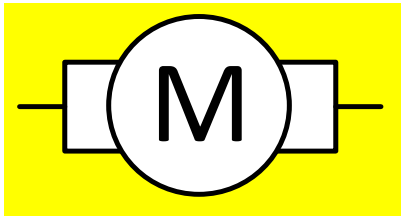
- **Sensors** (i.e., switches, photoresistor, distance sensor, temperature sensor, etc.)
- **Actuators** (i.e., motors, etc.)

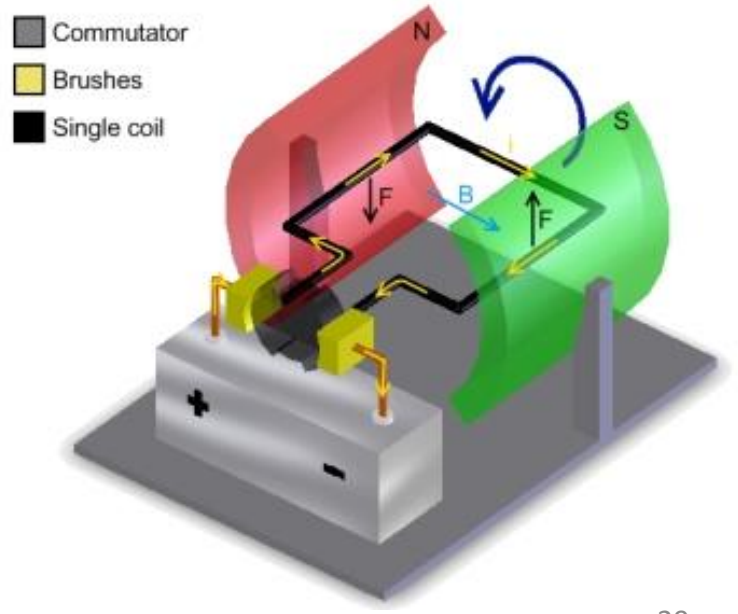
Actuators & Sensors

- **Actuators**
  - DC Motor
  - Servo Motor
  - Stepper Motor
- **Sensors**
  - Phototransistor
  - Reflectance Sensor
  - IR Distance Sensor
  - Contact Switch
  - Bend Sensor
  - Other Sensors

DC Motor

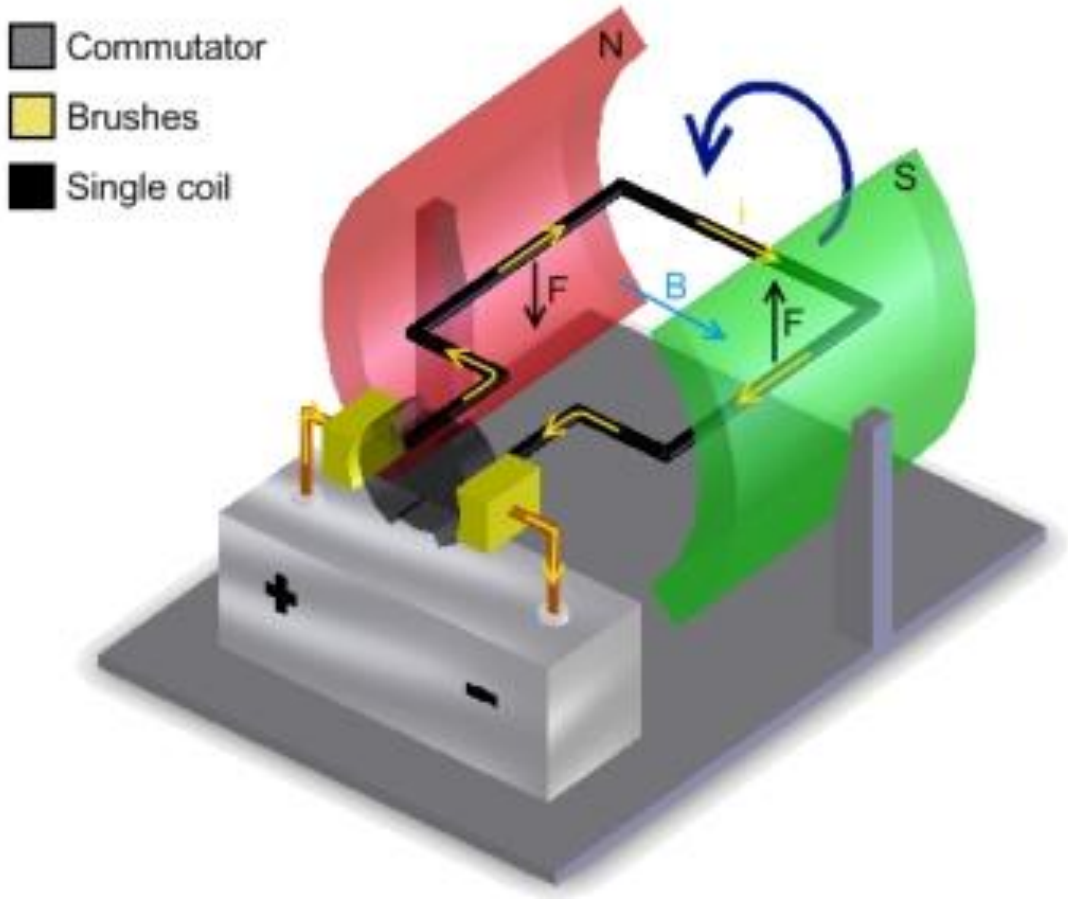
- DC motors spin when a steady voltage is applied
  - Can draw significant current (~ 1A or more)
- Fixed permanent magnet (stator)
- Rotating coil (rotator)
- Brushes/Commutator





http://humanoids.dem.ist.utl.pt/servo/overview.html

DC Motor



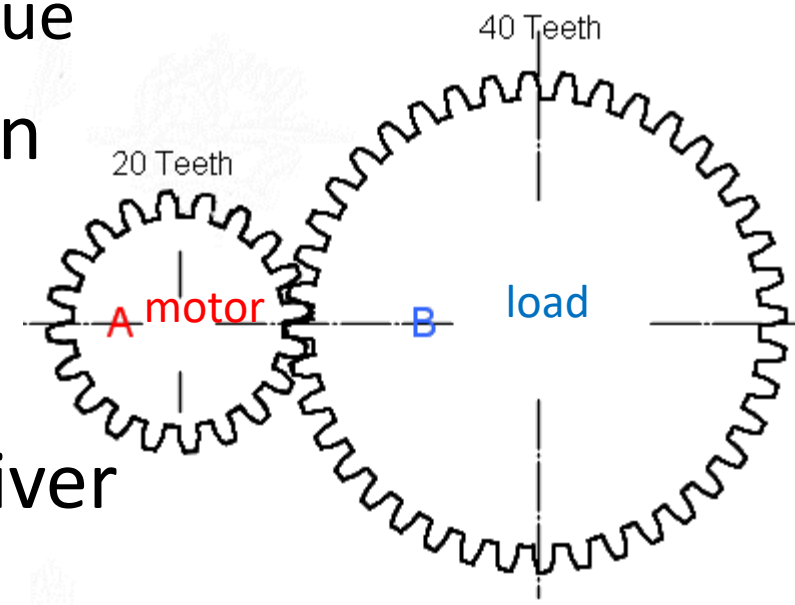
http://humanoids.dem.ist.utl.pt/servo/overview.html

DC Motors

- Operating Voltage: 3-12 V
- At 6 V operation:
  - Free run speed: 11,500 RPM
  - Unloaded current: 70 mA
  - Stall current: 800 mA
  - ~0.5 oz-in torque

Gearing

- DC motors spin too fast
  - And they have too little torque
- Gears slow the load rotation
  - Also increase torque
- In this example, load spins at half the speed of the driver
- Gear ratio: $\frac{\omega_B}{\omega_A} = \frac{N_A}{N_B}$



Gearing

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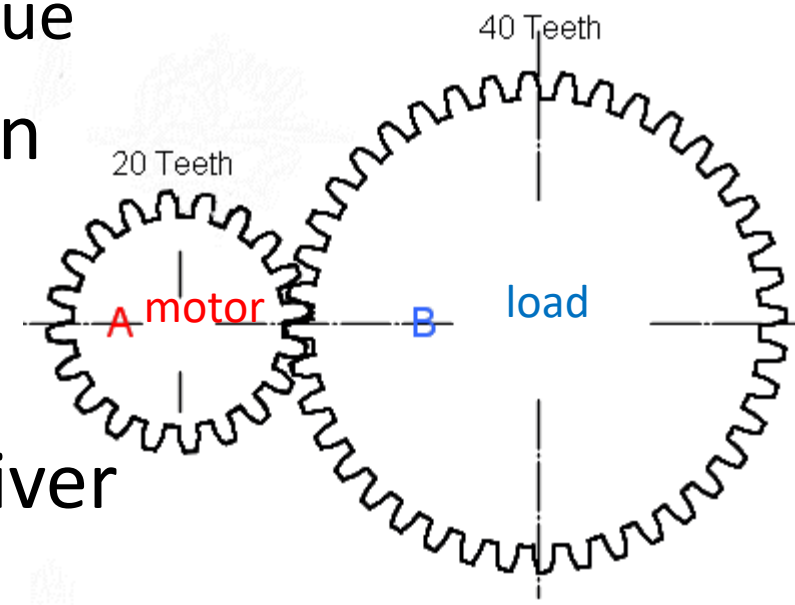
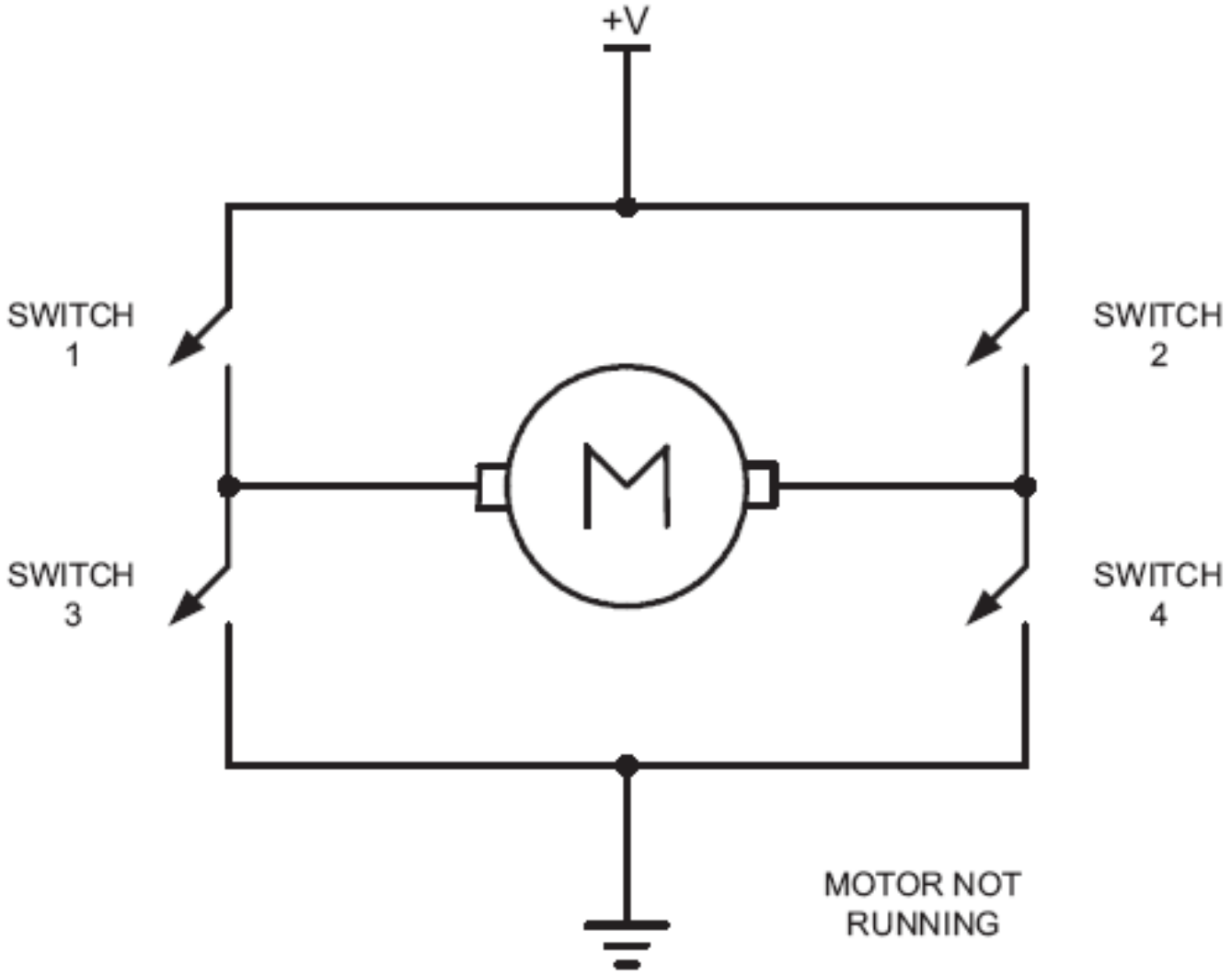
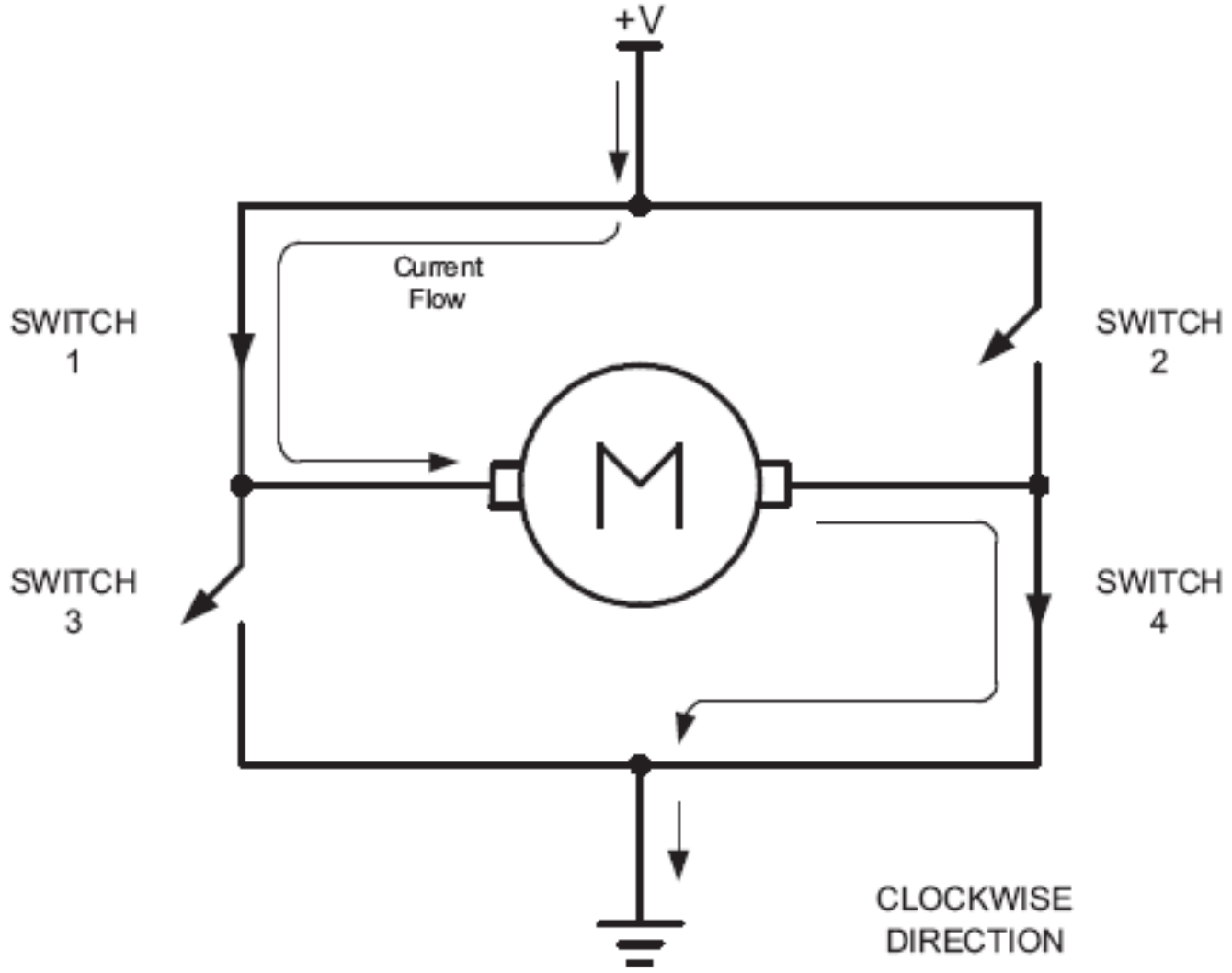


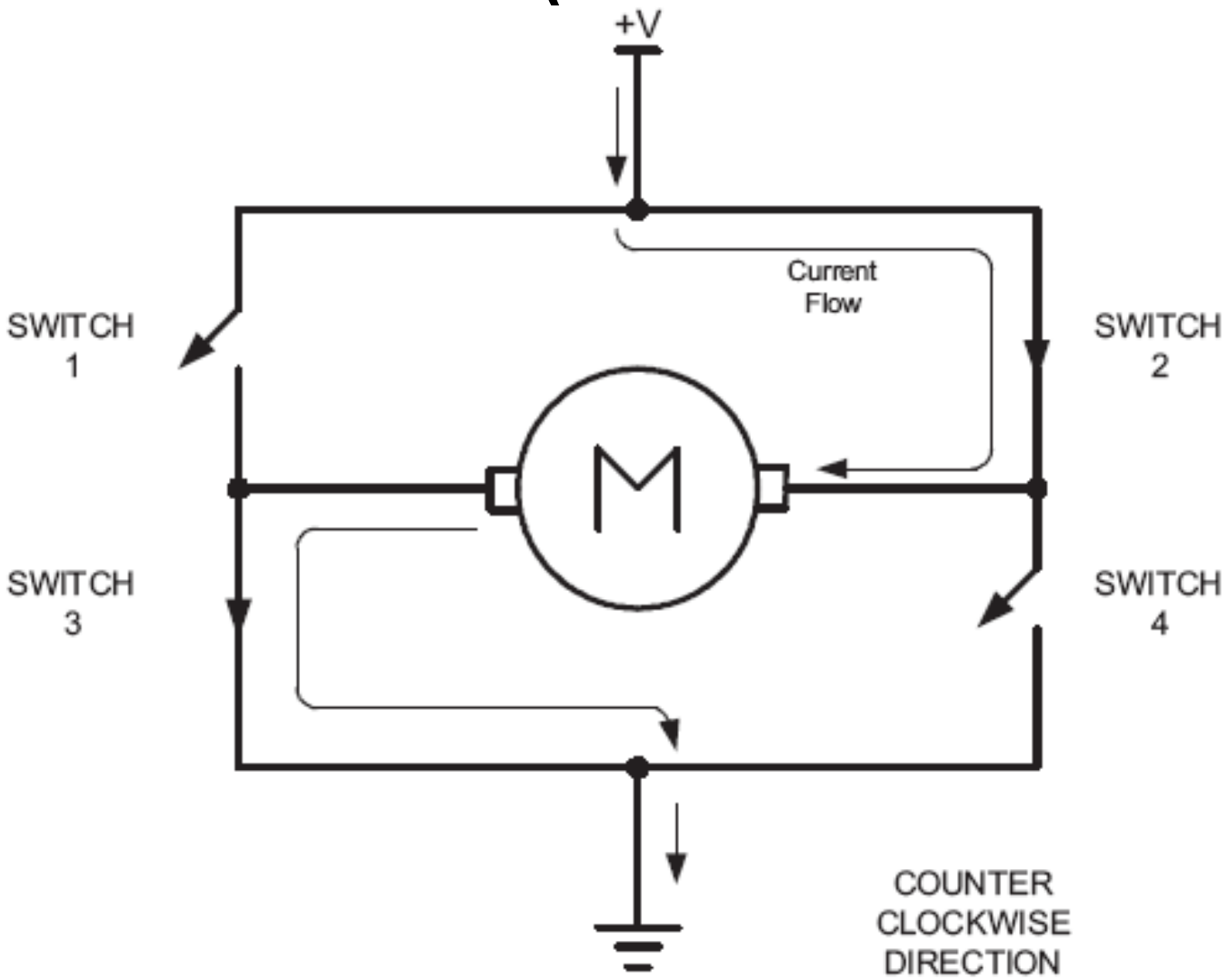
Bidirectional control



Bidirectional (clock wise)

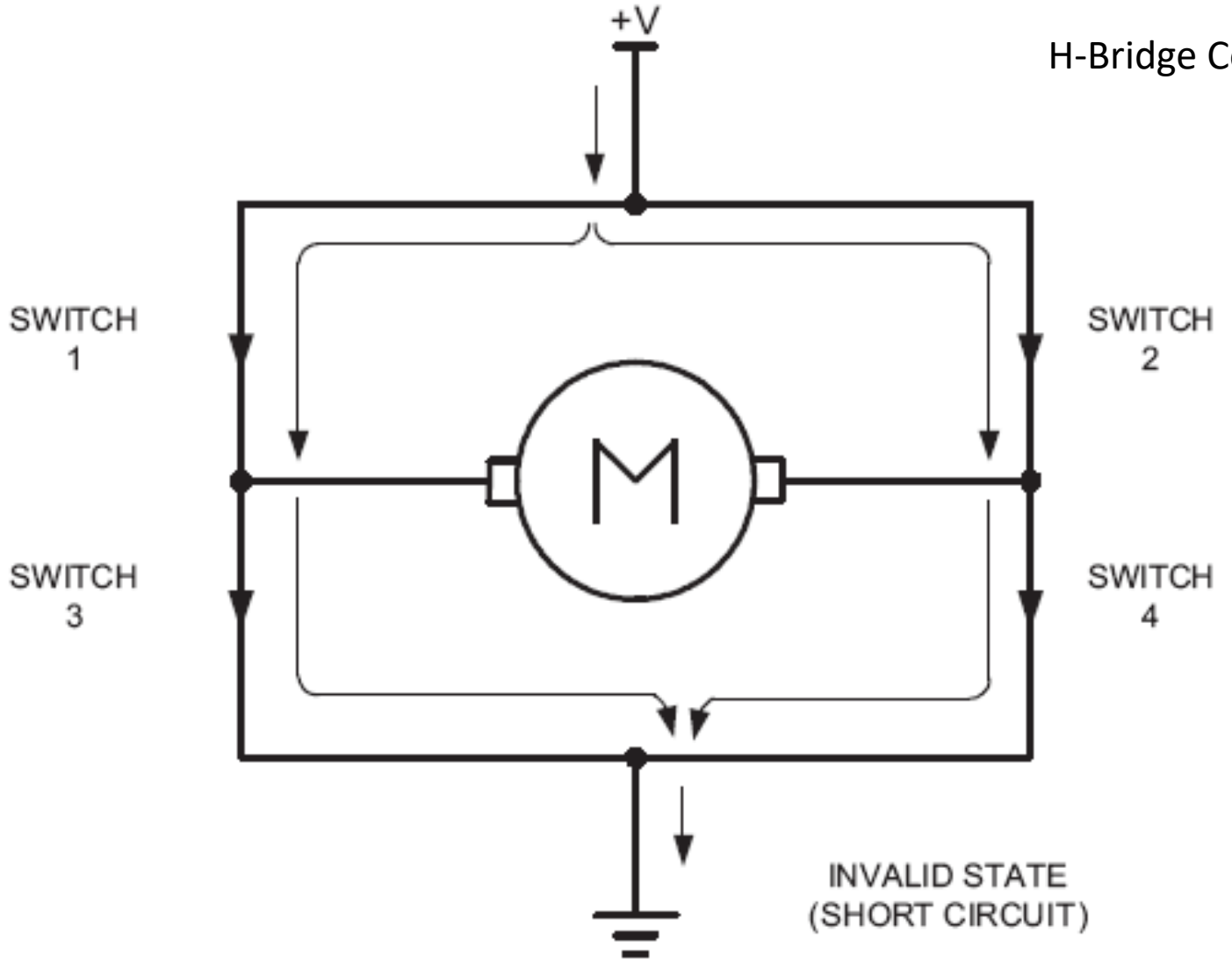


Bidirectional (counter clockwise)



Bidirectional

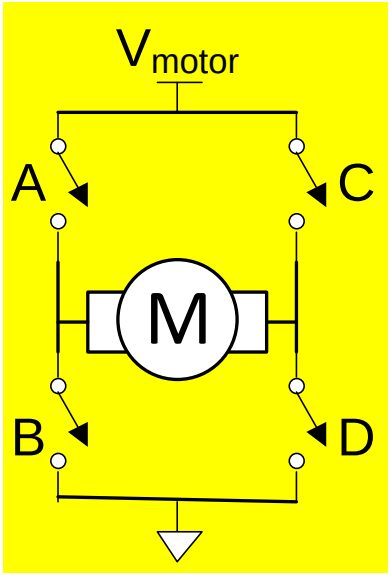
H-Bridge Configuration



H-Bridge

- Motors require large current to operate
  - But Atmega328p outputs only offer ~mAs
- H-Bridges are used to drive the large current

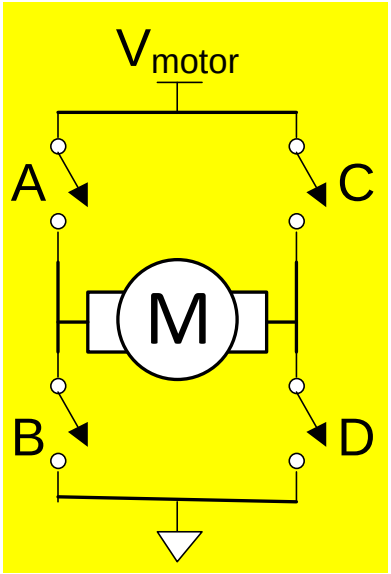
A	B	C	D	Motor
ON	OFF	OFF	ON	
OFF	ON	ON	OFF	
ON	OFF	ON	OFF	
OFF	OFF	OFF	OFF	
ON	ON	OFF	OFF	



H-Bridge

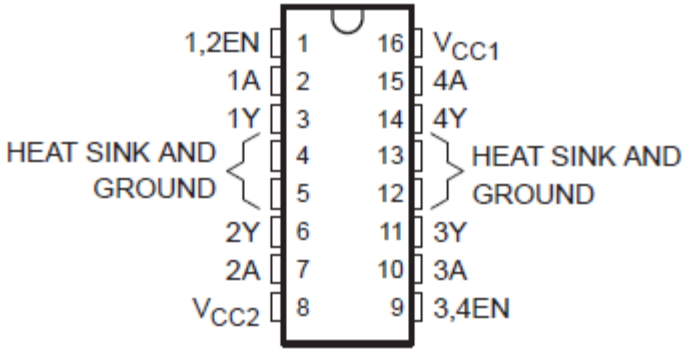
- Motors require large current to operate
  - But Atmega328p outputs only offer ~mAs
- H-Bridges are used to drive the large current

A	B	C	D	Motor
ON	OFF	OFF	ON	Forward
OFF	ON	ON	OFF	Backward
ON	OFF	ON	OFF	Brake
OFF	OFF	OFF	OFF	Coast
ON	ON	OFF	OFF	H-Bridge Magic Smoke

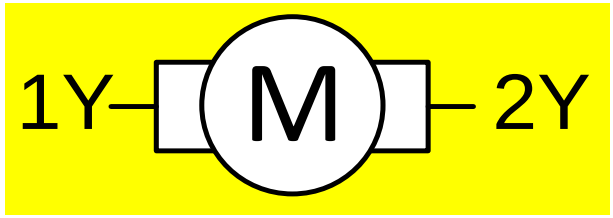


SN754410 H-Bridge

- 754410 Dual H-Bridge is easy to control with digital logic
  - V_{CC1} = Logic Supply (5V)
  - V_{CC2} = Motor Supply (4.5-36 V)

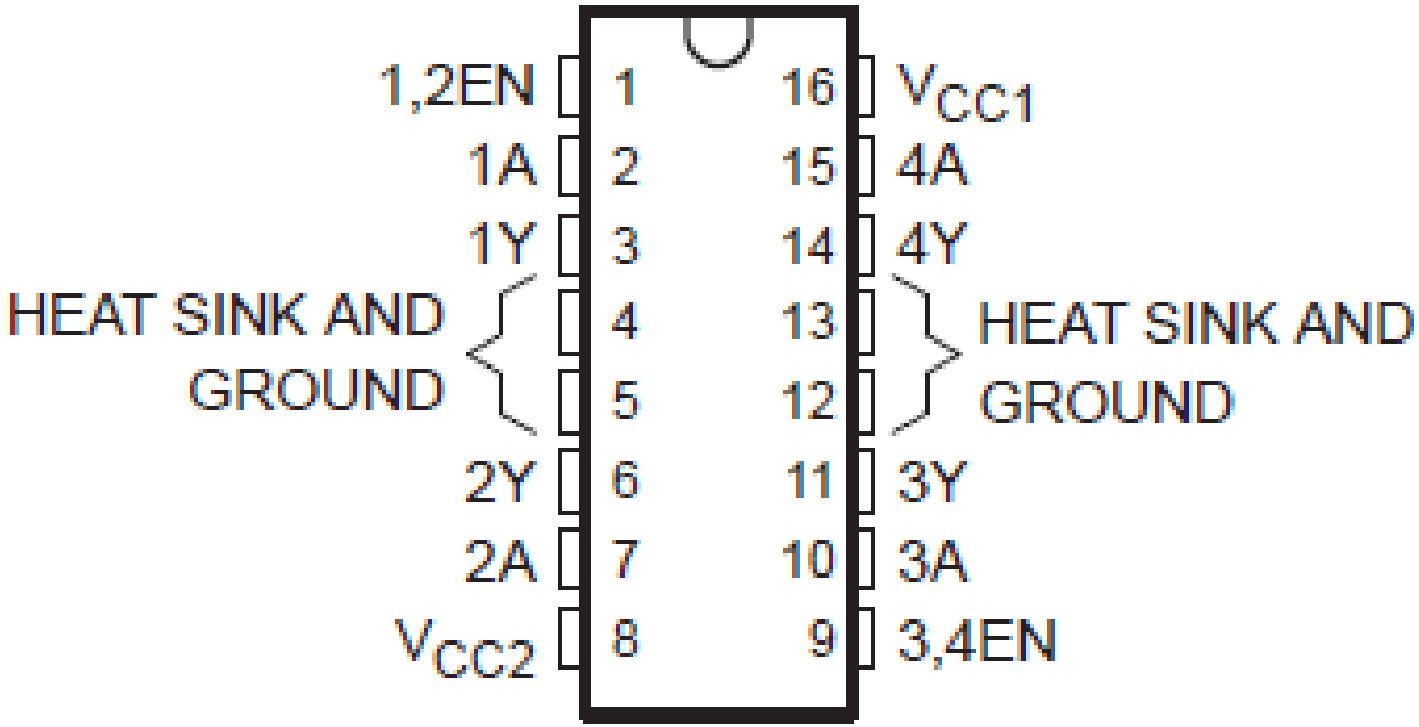


12En	1A	2A	Motor
0	X	X	Coast
1	0	0	Brake
1	0	1	Backward
1	1	0	Forward
1	1	1	Brake

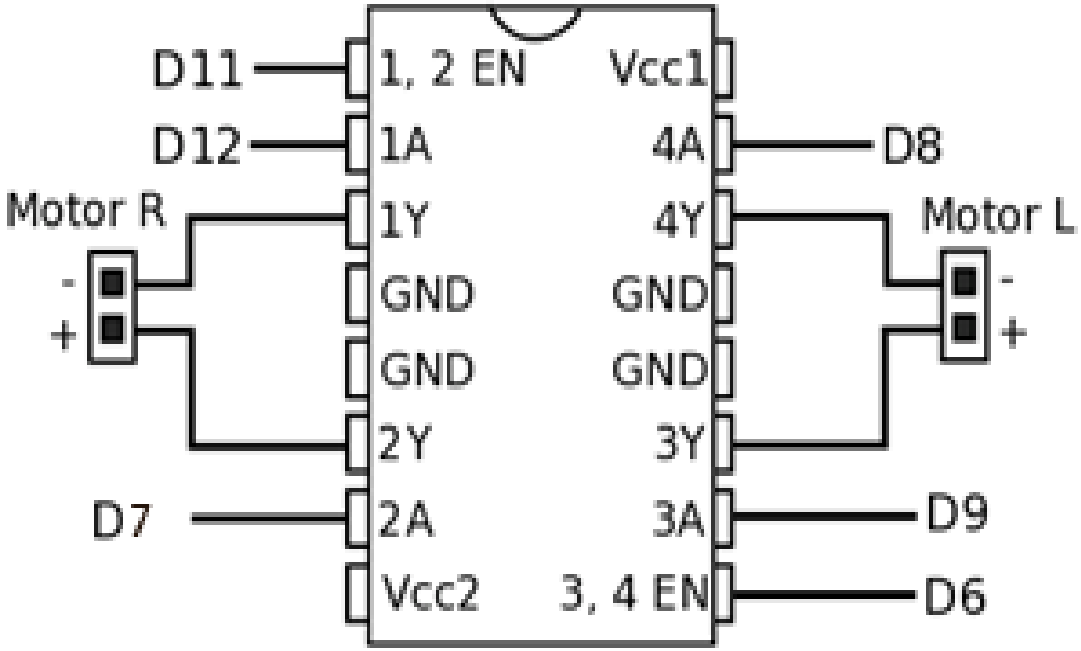


- Contains two H-Bridges to drive two motors

H-Bridge Interface



H-Bridge Interface



Shaft Encoding

- Sometimes it helps to know the position of the motor
- Optical shaft encoder
  - Disk with slits attached to motor shaft
  - Light and optical sensor on opposite sides of disk
  - Count light pulses as the disk rotates
- Analog shaft encoder
  - Connect potentiometer (variable resistor) to shaft
  - Resistance varies as shaft turns
- Our DC motors don’t have shaft encoders built in