SJSU SAN JOSÉ STATE UNIVERSITY

Charles W. Davidson College of Engineering

Department of Computer Engineering

Real-Time Embedded System Co-Design

CMPE 146 Section 1

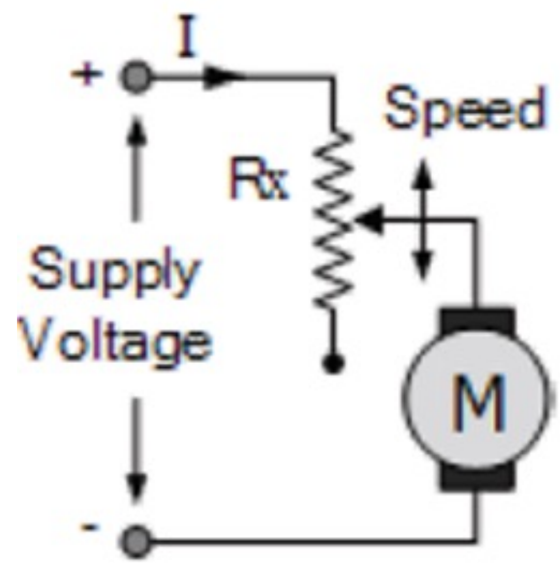
Fall 2024

Pulse Width Modulation

Pulse Width Modulation (PWM)

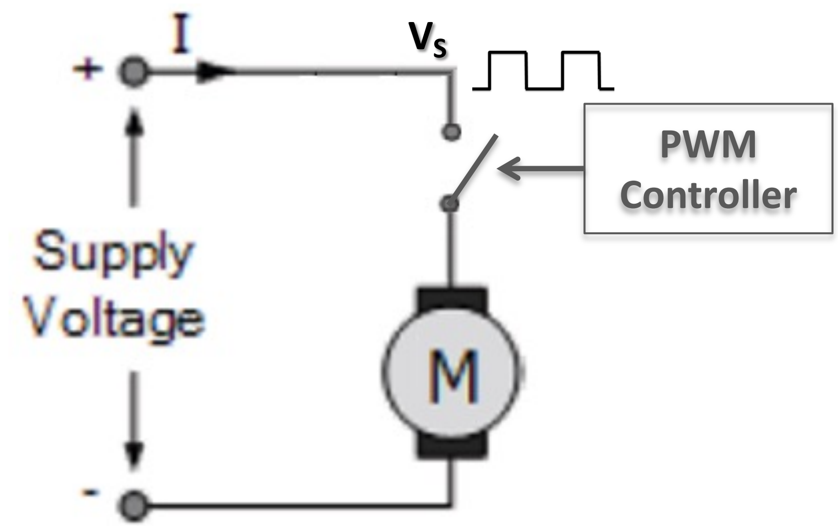
- A technique to control the output of only two states, ON and OFF, by varying the width of the ON state

- Commonly used as an efficient way to deliver power to a load
- Example: One way to control the speed of a motor is to vary the supply voltage to the motor through a rheostat R_X
  - A voltage divider approach
  - Voltage dropped across the resistor generates heat and wasted
  - If only a small portion of the input supply voltage ends up on the motor, the power efficiency would be quite low



PWM Example

- We can replace the rheostat with a switch that can be turned ON and OFF rapidly by a PWM controller
  - When switch is ON, motor receives full voltage
  - When switch is OFF, no current goes through motor



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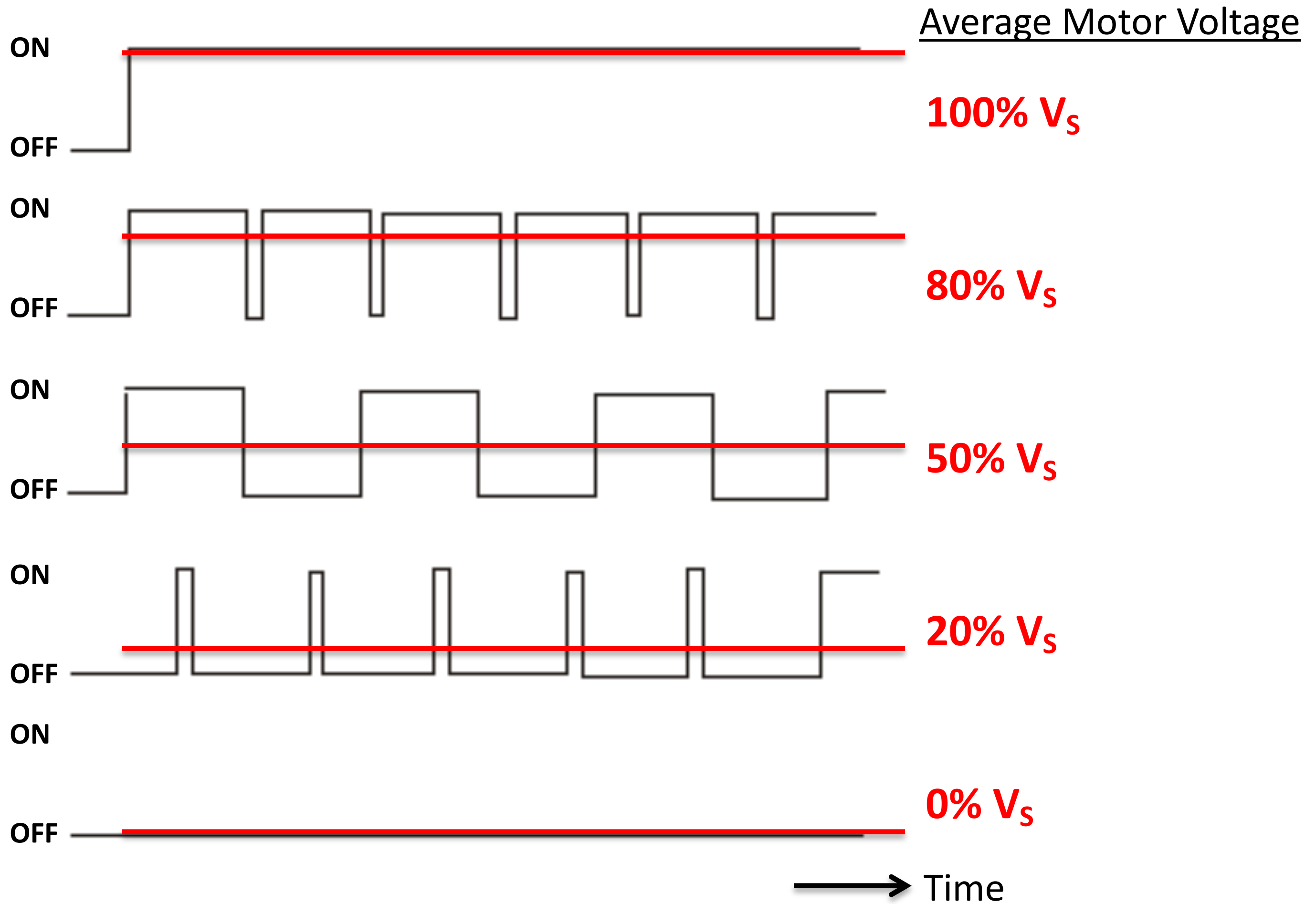
PWM Example (cont'd)

- We can effectively vary the average voltage delivered to the motor by modulating the how long the switch stays close
  - It would appear that a constant voltage is applied to the load
  - Percentage of the full supply voltage V_S sets the motor speed



PWM Example (cont'd)

- Modulating rate can be very high, in hundreds of kHz
- Supply voltage is almost solely used on the motor
  - No energy wasted on major components like rheostat
- Power efficiency can be very high, in the high 90%'s
- Switch closing and opening is not instantaneous
  - Generates some amount of heat during state transition

PWM Attributes

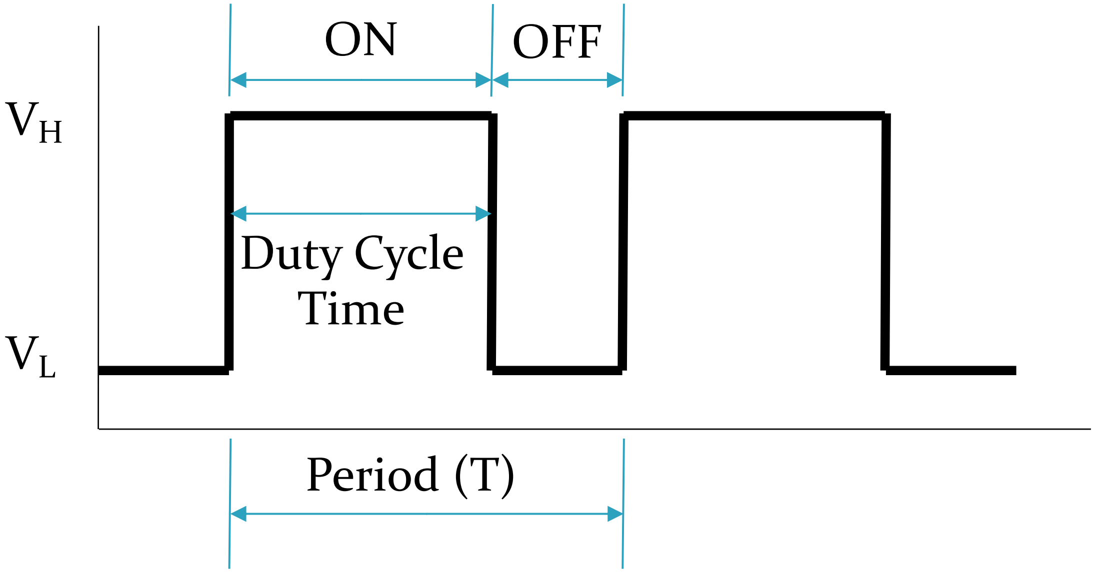
- Duty cycle
- Frequency
- Resolution

PWM Duty Cycle

- The modulated signal in ON state is generated periodically
- Duty cycle is a measure of time when the modulated signal is on the ON state within a period
- Generally expressed as the percentage of the period

  Duty Cycle, D = On_Time / Period x 100%

- Average output voltage = $D(V_H - V_L) + V_L$,
  where V_H = On-state voltage and V_L = Off-state voltage



PWM Frequency

- Output signal is varied at a certain interval, or period
  - A time that is chosen to give the best results for an application
- The term frequency is more often used than the period
- The frequency being used depends on the response time of the load being applied to
- Some applications' typical frequency ranges:
  - Heating or lighting elements: 10-100 Hz
  - DC electric motors: 5-10 kHz
  - Power supplies or audio amplifiers: 20-200 kHz
- If the load is only resistive, the frequency has no effect
  - Impedance (load) of inductive and capacitive elements depends on frequency
  - Resistor: Impedance = R
  - Inductor: Impedance = ωL
  - Capacitor: Impedance = $1/(\omega C)$

PWM Resolution

- Resolution is the granularity with which the duty cycle can be modulated
- Defined as the number of possible duty cycle values in a period
  - Often is expressed as number of bits used in a register that can contain the number of possibilities
  - For example, 1024 (2^{10}) different duty cycles values can be expressed in a 10-bit register, so the resolution is 10 bits
- It also depends on the operating frequency F_C of the controller and the PWM frequency F_{PWM}

$$\text{Resolution} = F_C \,/\, F_{PWM}$$

  - For example, if the controller is running at 16 MHz and PWM frequency is 250 kHz, then resolution is 16000 / 250 = 64, i.e., 6 bits ($2^6 = 64$)
- PWM frequency and resolution are interdependent
  - Controller bandwidth (operating frequency) is limited
  - The higher the PWM frequency, the lower resolution is available, and vice versa
  - For example, if you want finer control of the motor speed, you have to reduce the rate you can modulate the voltage

PWM Signal Generation on MSP432

- Timer_A counter can be used to generate PWM signal automatically
- Set counter to count-up mode
  - Register TAxCCR0 determines the period
  - Register TAxCCR1 determines when to set state to ON
  - Duty cycle = (TAxCCR0 - TAxCCR1) / TAxCCR0
- Use compare mode and enable the output unit to generate the PWM signal

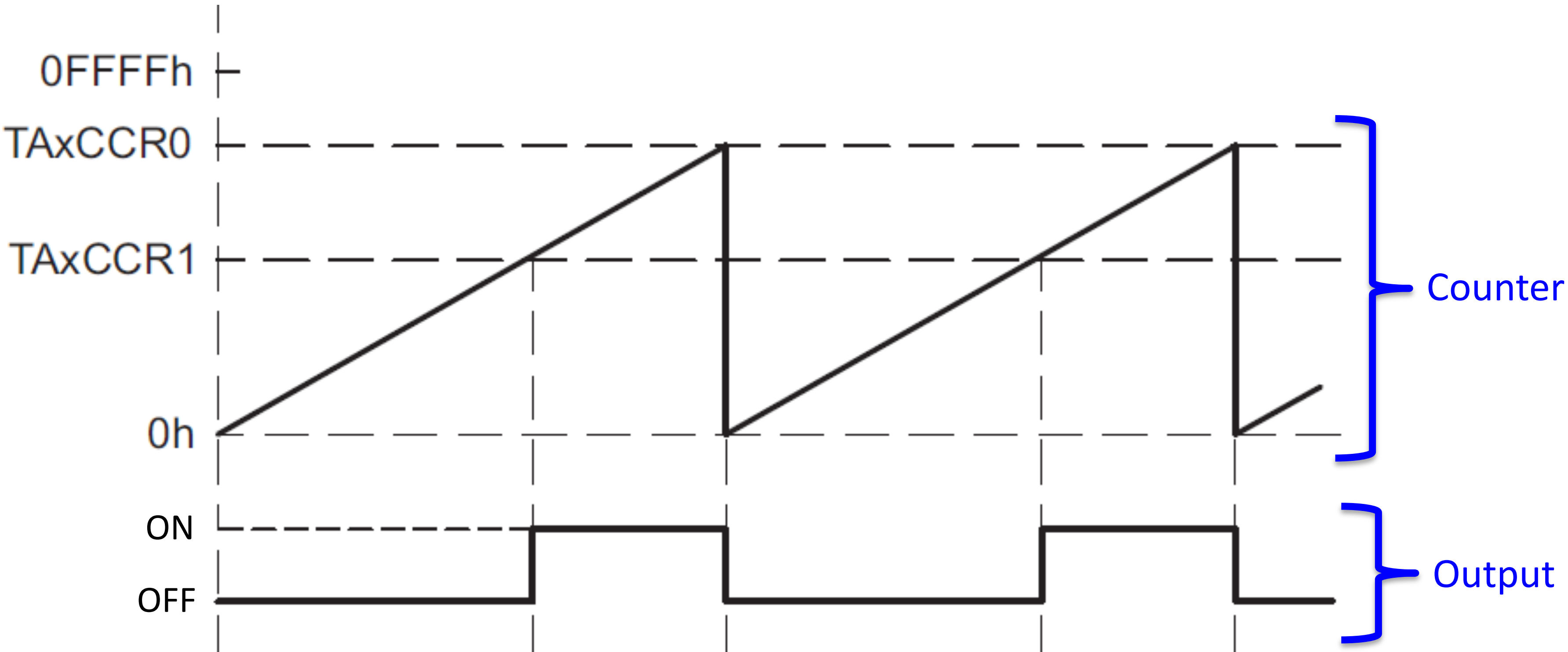


Diagram source: TI MSP432P4xx SimpleLink Microcontrollers Technical Reference Manual

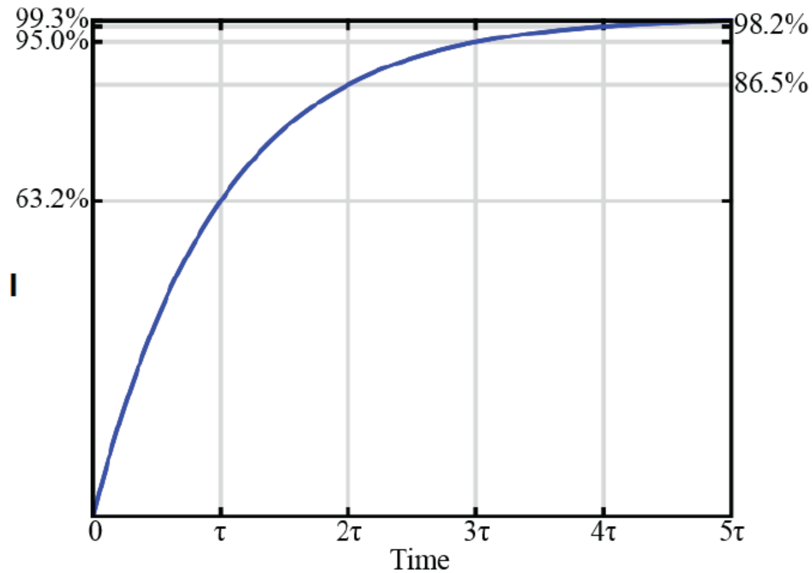
Applications

Some common applications

- Motor control
- Light intensity control
- Voltage regulation
- Data communication

DC Motor Control

- PWM is an efficient method for driving DC motors
- PWM controls current in the windings, which determines the output torque
  - Torque is proportional to the average winding current
- Change of current in the windings produces a back EMF (ElectroMotive Force) that resists the current flow
- The motor can be modeled as a RL circuit
  - Motor current I does not reach its top value instantaneously
  - The delay depends on the time constant, $\tau = L/R$



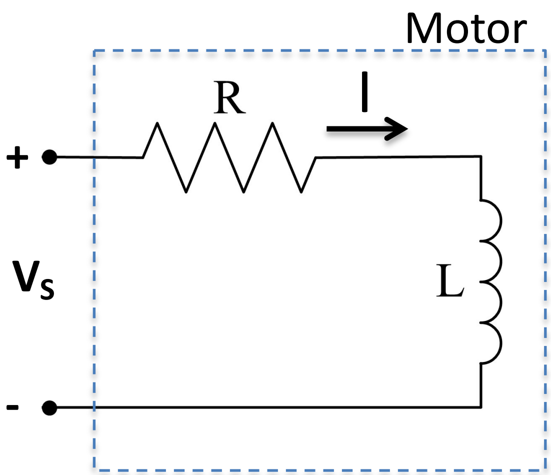
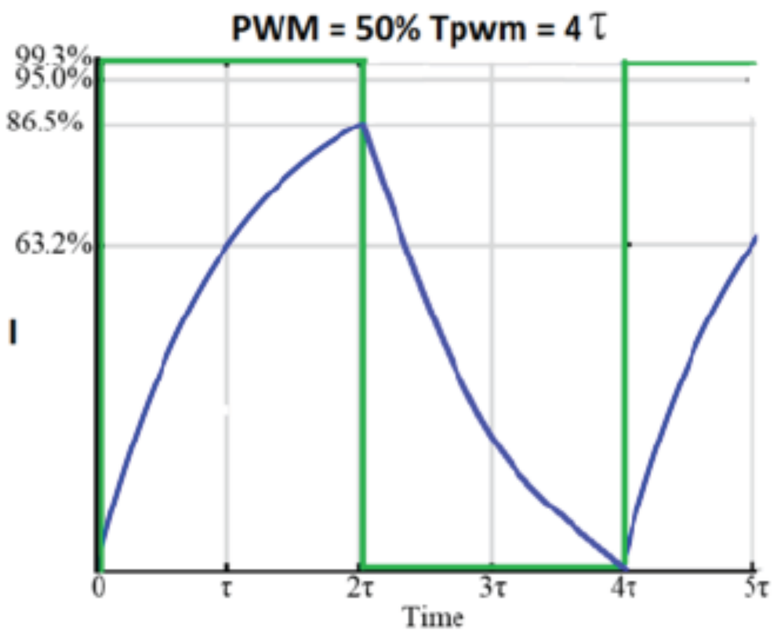
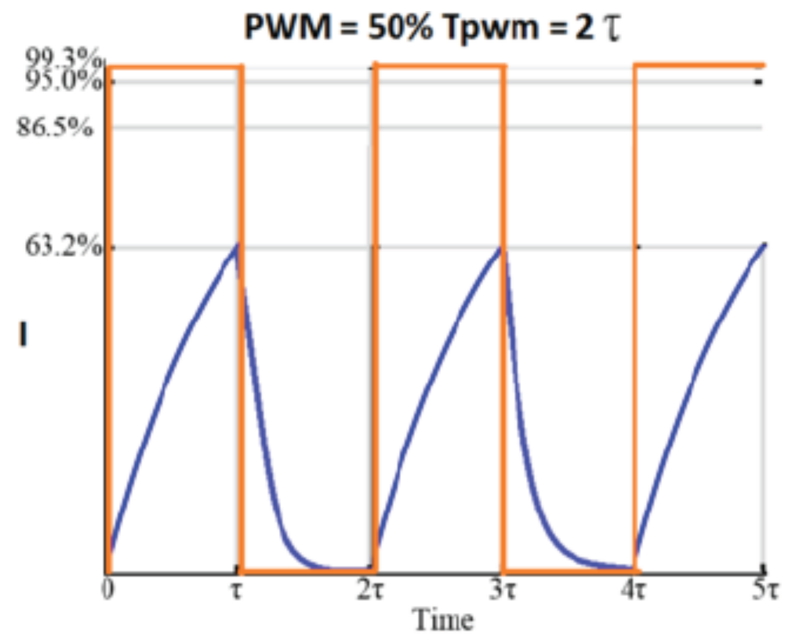


Diagram source: https://www.precisionmicrodrives.com/content/ab-022-pwm-frequency-for-linear-motion-control/

Motor Control (cont'd)

- This means the choice of PWM frequency has direct impact on the motor performance
  - If the PWM cycle is too narrow (high frequency), the current is not able to reach a high value





- PWM frequency cannot be too low
  - Motion may become jerky
  - May produce a (annoying) whining sound

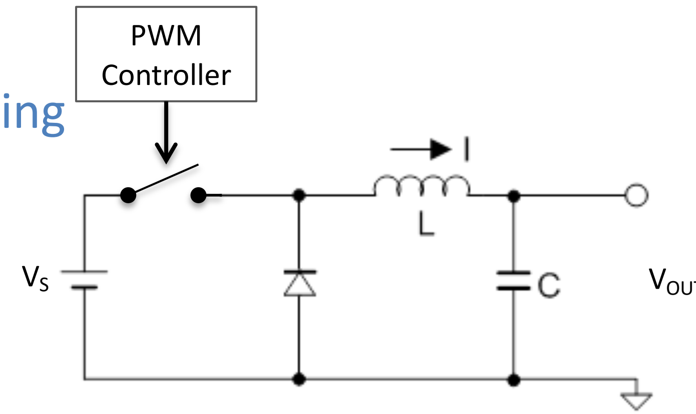
Diagram source: https://www.precisionmicrodrives.com/content/ab-022-pwm-frequency-for-linear-motion-control/

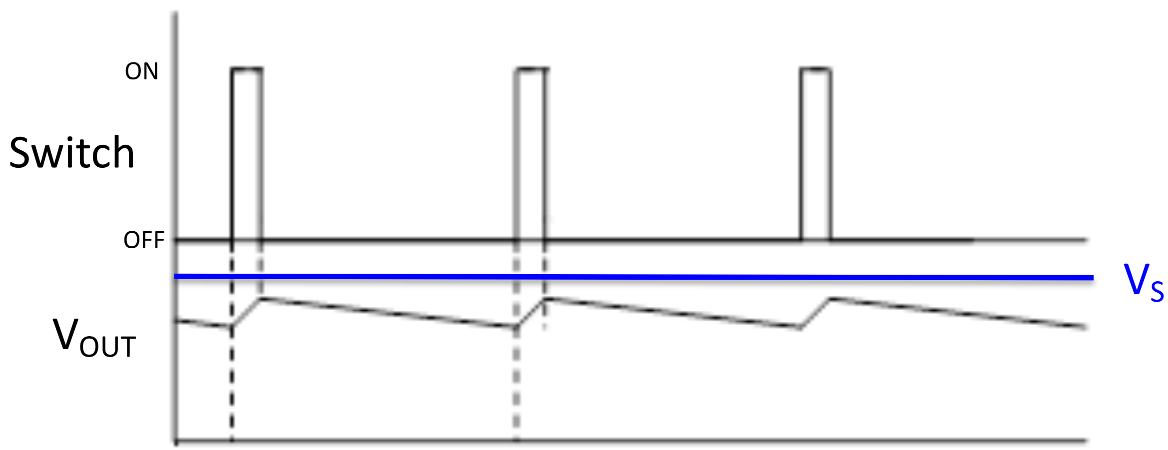
Light Intensity Control

- Most lighting elements don’t have much capacitive or inductive load
  - Response from elements is almost instantaneous
- PWM frequency higher than 1 kHz can be easily achieved
  - Well above the flickering rate human can detect
- These two factors make light intensity control an ideal application for PWM
- PWM can produce many levels of accurate and linear intensity control
  - Any intensity level can be selected at any time
    - No need to go through a sequence (no ramping up or down)
  - Can effectively produce different lighting effects, like gradual dimming, flashing, color setting, etc.
- Power efficiency is very high

Voltage Regulation

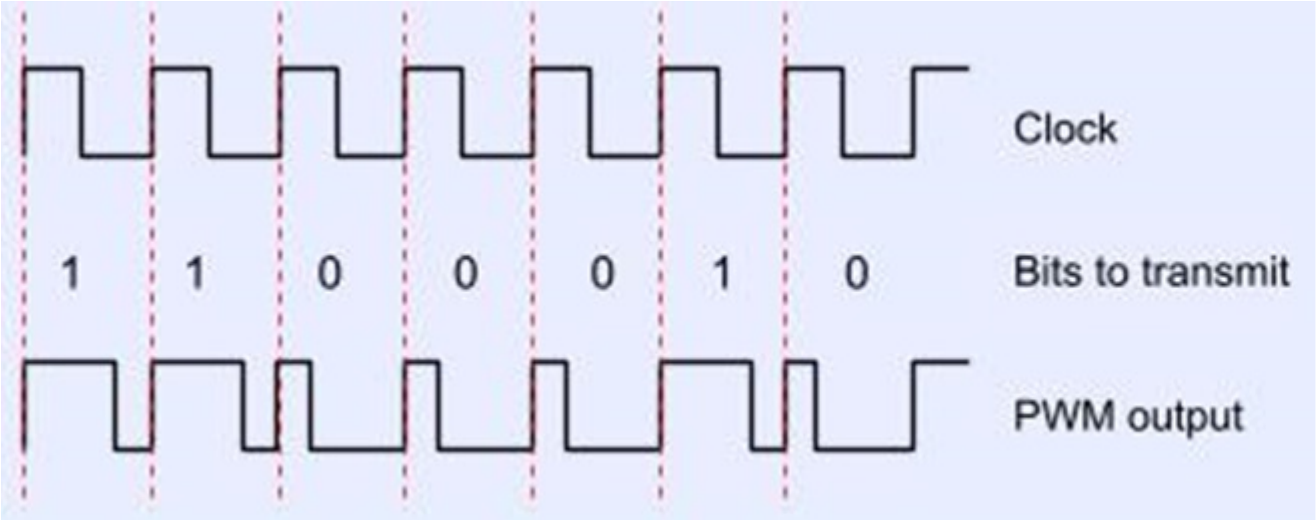
- Step-down converter
- When switch is turned ON and current is increasing
  - Inductor L develops a magnetic field and a voltage V_L
  - $V_{OUT} = V_S - V_L$
- When switch is OFF, no current from V_S
  - L releases its stored energy to provide current to the load
- PWM controller rapidly turns the switch ON and OFF to provide a V_{OUT} consistently lower than V_S
  - Average $V_{OUT} = DV_S$, where D = duty cycle of the switching signal





Data Communication

- PWM can be used to transmit data
- Data bits can be encoded as duty cycle
  - For example, duty cycle > 50% represents a ‘1’; otherwise a ‘0’



- Clock signal is included in the PWM output
  - A rising edge is the clock edge
- Can be expanded to encode multiple bits in a cycle to increase bandwidth
  - For example, 20%, 40%, 60% and 80% represent 00, 01, 10 and 11, respectively