POWER CONSIDERATIONS

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OUTLINE

- Overview
- Voltage Regulation and DC/DC Converters
- Utility Power Considerations
- Battery Power Considerations
- Alternative Power Considerations
- Power Design Techniques
- Other Power Considerations
- Thermal Considerations

OVERVIEW

- Why is power circuitry important?
  - All electrical circuits need voltage/power/current
  - All electrical components have strict V/I/P limits which must be adhered to
  - Limited range of input voltage levels (utility power, battery voltage levels, etc.)
  - Digital circuits often operate at one (or more) voltage levels (5V, 3.3V, 2.5V, 1.8V, 1.2V, 0.9V, etc.)
  - Need to convert from input levels to appropriate output levels

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VOLTAGE REGULATION

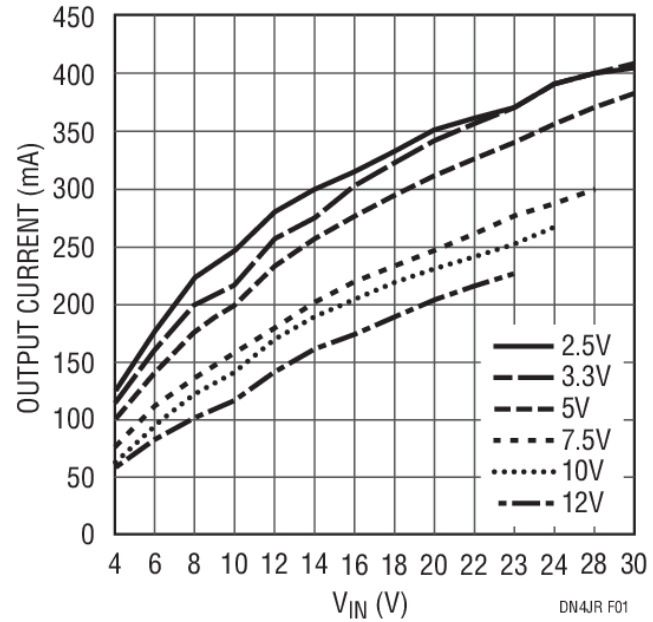
Overview

- Objective: accept a given input voltage and convert it to a desired output voltage level
- Provide a “flat” voltage with minimal transients
- Common Regulator Approaches:
  - Linear regulators and Low Dropout (LDO) regulators
  - Switching regulators:
    - Buck converters
    - Boost converters
    - Buck-Boost converters
    - Flyback converters
    - Other converters (Cuk, SEPIC, Push-Pull, etc.)

VOLTAGE REGULATION

Regulator Considerations

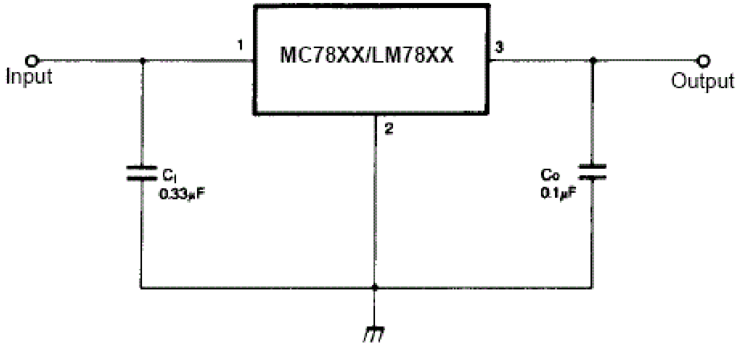
- Power/Voltage/Current: Maximum device ratings (W/V/A)
- Efficiency: % input power transferred to regulator output
- Ripple/Regulation: "Smoothness" of output voltage (transient suppression)
- Isolation: Amount of isolation provided by device (V or kV)
- Dropout: Depending on desired output current and output voltage levels, a certain minimum input voltage is required (example: obtaining 5V@200mA might require 5.5V Vin but 5V@4A might require 7V or 8V Vin)

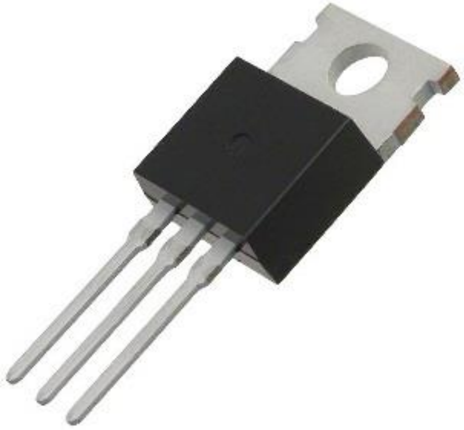


VOLTAGE REGULATION

Regulator Types: Linear Regulators

- Regulator acts as a resistive divider with a fixed input voltage, dissipating excess input power as heat
- Common parts: LM7805, LM78xx and variants
- <u>Pros:</u> Extremely simple, cheap
- <u>Cons:</u> Generate significant amounts of heat, require high input voltages, require external components (resistors, caps), inefficient (typical efficiencies of 30%~50%)
- Legacy design; largely obsolete





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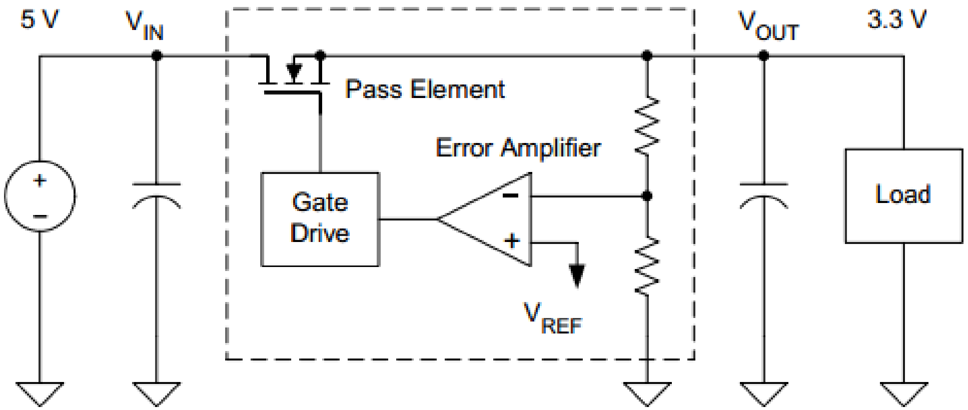
VOLTAGE REGULATION

Regulator Types: Low Dropout Regulators

- Similar operation to a linear regulator, but designed to operate with a lower dropout than traditional linear regs.
- Used when a fixed voltage level is needed but current demands are low (generally < 0.5A) (dropout < 3V)
- Pros: Simple, cheap, improved efficiency, lower dropout
- Cons: Significant power lost as heat, require external components, inefficient at high output currents



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VOLTAGE REGULATION

Regulator Types: Switching Regulators

- Operate by switching power to load at high speeds
- High efficiencies: (80%+ efficiency typical)
- Recommended for most digital design applications
- Separated by energy storage mode: (forward vs. flyback)
  - Forward: Energy delivered directly to load (no delay)
  - Flyback: Energy stored in magnetic fields, later delivered to load
- Separated by input/output (buck vs. boost vs. buck-boost)
  - Buck: Higher Vin is "stepped down" to lower Vout
  - Boost: Lower Vin is "boosted up" to higher Vout
  - Buck-Boost: Topology offering buck and/or boost operation

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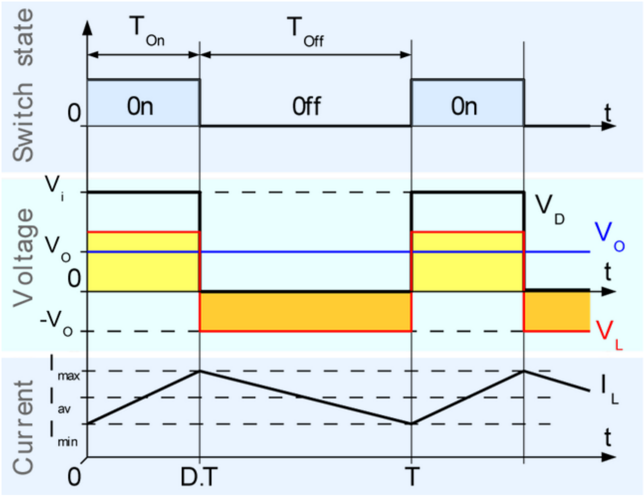
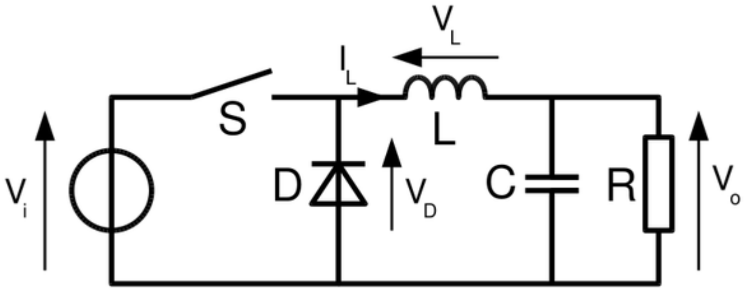
VOLTAGE REGULATION

Switching Regulators: Buck Converters

- Switch an inductor on and off:
  - <u>Switch Closed:</u> Inductor V_L opposes input voltage V_{in}
  - <u>Switch Open:</u> Inductor discharges stored energy through load
- "Steps down" voltage ($V_O < V_I$)
- <u>Pros:</u> Efficient, no need for large transformers, lower thermal requirements
- <u>Cons:</u> Switching introduces voltage ripple and EMI, current can vary significantly over switching cycle, complexity





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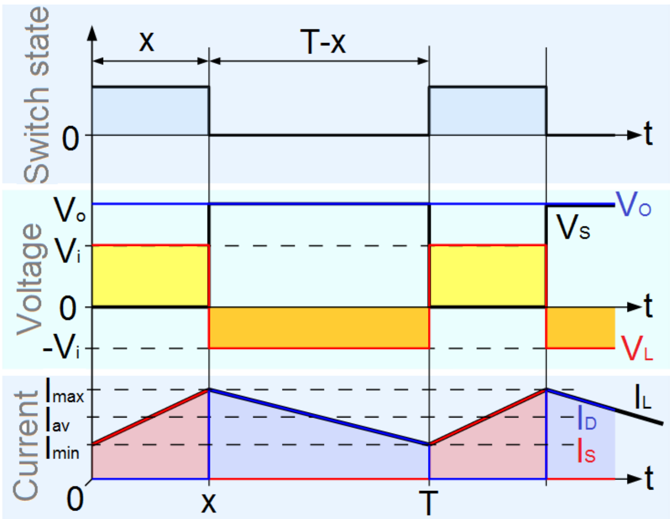
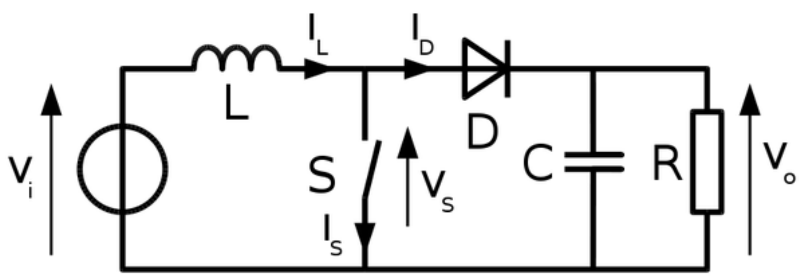
VOLTAGE REGULATION

Switching Regulators: Boost Converters

- Switch an inductor on and off:
  - <u>Switch Closed:</u> Inductor charged via Vin
  - <u>Switch Open:</u> Inductor discharges into capacitor/load
- Output voltage is "stepped up" ($V_O > V_I$)
- <u>Pros:</u> Efficient, can power systems from small power sources, lower thermal requirements
- <u>Cons:</u> Switching introduces voltage ripple and EMI, complexity (ICs available)





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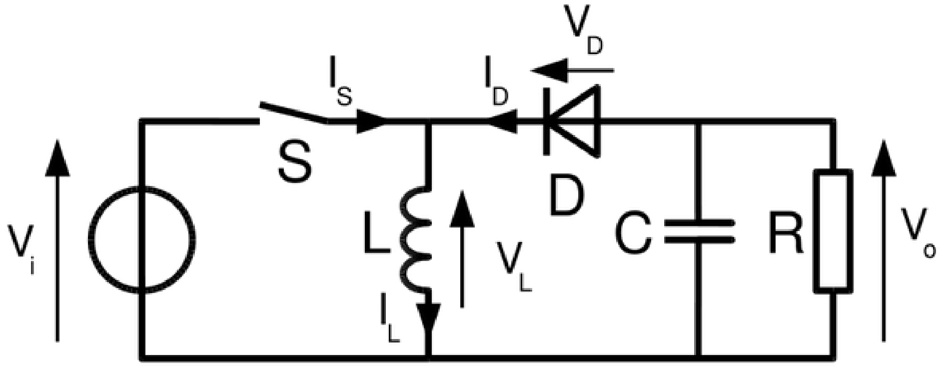
VOLTAGE REGULATION

Switching Regulators: Buck-Boost Converters

- Circuit operation:
  - Switch Closed: Inductor charges, capacitor supplies power to load
  - Switch Open: Inductor supplies power to capacitor and load
  - Output voltage can be bucked or boosted
- Pros: Efficient, versatile, lower thermal requirements
- Cons: Switching introduces voltage ripple and EMI, complexity, output voltage polarity reversed



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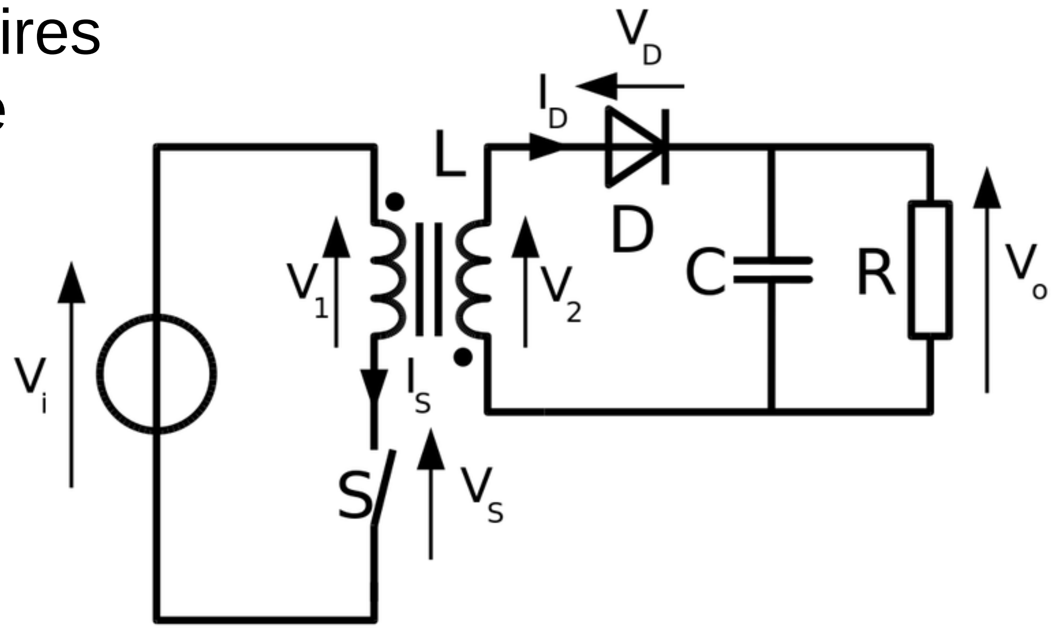
VOLTAGE REGULATION

Switching Regulators: Flyback Converters

- Similar in operation to a buck-boost converter, but inductor is split to form a transformer
- Capable of doing AC/DC or DC/DC conversion
- Pros: Efficient, versatile, provides isolation
- Cons: Switching introduces voltage ripple and EMI, complexity, requires (potentially large and heavy) transformer



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VOLTAGE REGULATION

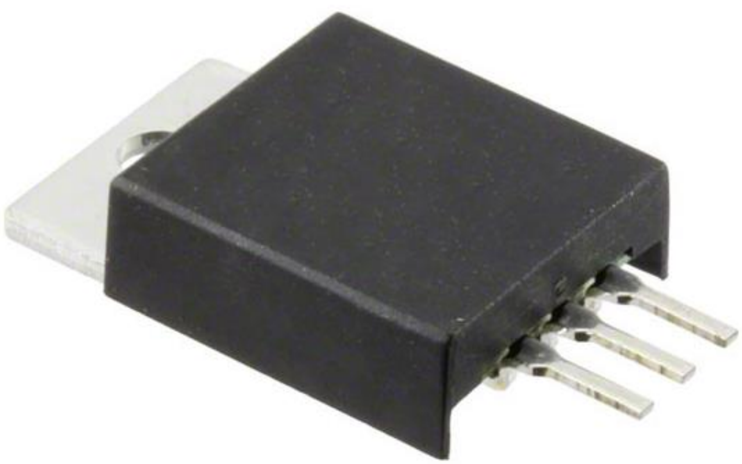
Switching Regulators: Other Topologies

- Other common switching converter topologies:
  - Ćuk: Boost stage followed by buck stage with shared capacitor for energy storage, continuous output current
  - SEPIC: Similar to Buck-boost, but capable of shutdown (0V output) and output is non-inverting
  - Push-Pull: Smoother current, higher efficiencies, less noise, higher cost (than Buck-boost)
  - Charge Pump: Uses capacitors (rather than inductors) as primary storage elements, low complexity, high efficiency (up to 95%), load-dependent output voltage

VOLTAGE REGULATION

Switching Regulators: COTS Converter Examples

- A few commercial off-the shelf (COTS) DC/DC converter examples:
  - Murata OKL-T-W12: 2.9-14Vin, 0.9-5Vout, 1A, 5W max, $3.10/unit
  - Rohm BP5275-50: 6-14Vin, 5Vout, 0.5A, 3W max, direct replacement to TO-220 linear regulators, $5.63/unit



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UTILITY POWER CONSIDERATIONS

Overview

- Utility power: (sometimes known as “mains electricity”)
  - AC power drawn from wall outlets
  - US power grid standards:
    - 110-127V @ 60Hz
    - Max circuit current draw: 10A, 15A, 20A common (check your breaker box!)
  - Power grid characteristics and plug types vary from region to region

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UTILITY POWER CONSIDERATIONS

Anatomy of an AC Adapter

- Rectifier: A circuit which converts AC electricity to DC. (This current is not necessary constant, but it flows in a single direction)
- As of the mid-2000s, mostly switching supplies are used. Two (deprecated) analog techniques:
  - Half-Wave: Current flows during one-half of the phase of the AC voltage waveform (deprecated)
  - Full-Wave: Current flows during both phases of the AC voltage waveform (deprecated)

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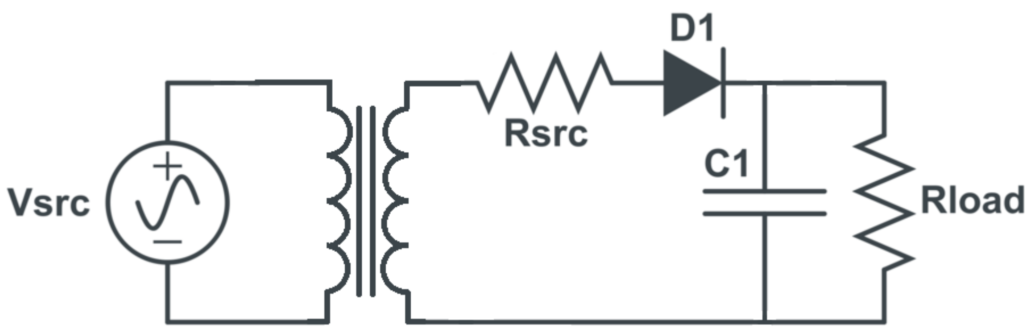
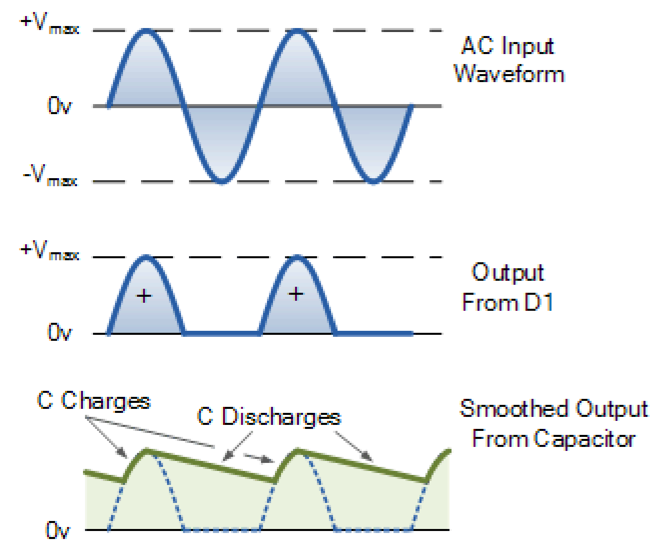
UTILITY POWER CONSIDERATIONS

Anatomy of an AC Adapter: Half-Wave Rectifier

- Half-wave rectifiers use specialized diodes rated for high voltage, current, and power
- <u>Pros:</u> Extremely simple and (comparatively) cheap
- <u>Cons:</u> Half-wave designs introduce significant amounts of voltage ripple at the output (more difficult to keep capacitor charged between phases)





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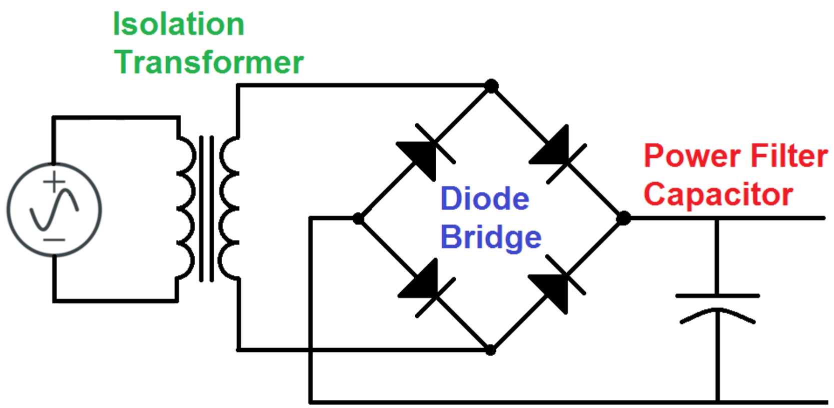
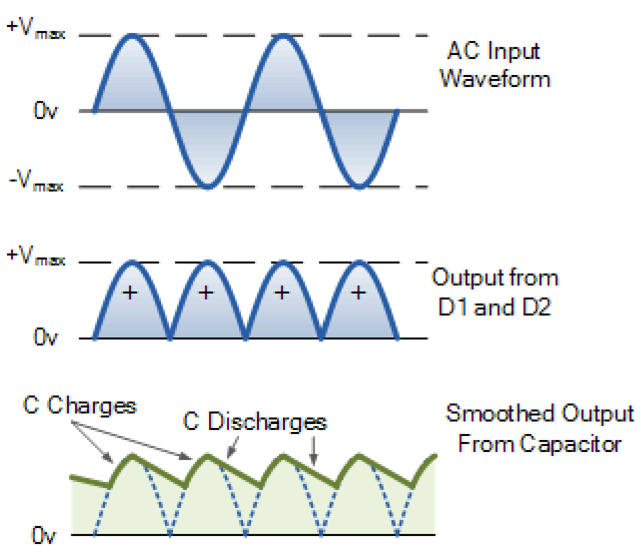
UTILITY POWER CONSIDERATIONS

Anatomy of an AC Adapter: Full-Wave Rectifier

- Full-wave rectifiers typically use a group of 4 diodes (sometimes known as a “diode bridge”)
- Pros: Simpler/cheaper than AC/DC converters (flyback), less output voltage ripple than half-wave
- Cons: More expensive than half-wave, typically use (large, heavy, expensive) transformers (flyback designs can reduce transformer size)





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UTILITY POWER CONSIDERATIONS

Full-Wave Rectifier: Considerations

- Depending on your circuit demands a full-wave rectifier may need to be followed by additional power filtering and/or regulation circuitry
- Need to choose components rated for desired voltages and currents
- The filter capacitor must be appropriately sized to achieve a desired level of ripple voltage:

$$\Delta V_{out} = \frac{I_{out}}{f_{in} C}$$

$$\begin{aligned} \Delta V_{out} &: \text{Output voltage ripple(V)} \\ I_{out} &: \text{Load current(A)} \\ f_{in} &: \text{Input frequency(Hz)} \\ C &: \text{Power filter capacitance(F)} \end{aligned}$$

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BATTERY POWER CONSIDERATIONS

Battery Considerations

- Capacity(C): Charge storeable in battery (Ah or mAh)
- Current(I): Max charge/discharge rates often expressed in terms of battery capacity (e.g. 1C, 5C, 0.65C, etc.) or A
- Voltage(V): Voltage provided by battery (V). Based on battery chemistry. Varies with time, temperature
- Rechargeability: Some chemistries can be recharged
- Shelf Life: How well the battery retains its charge when not in use
- Cycles (for rechargeables): How many charging cycles the battery can sustain and retain its life
- Chemistry: Alkaline? Lithium? NiMH? Li-Ion? $LiFePO_4$? Other?

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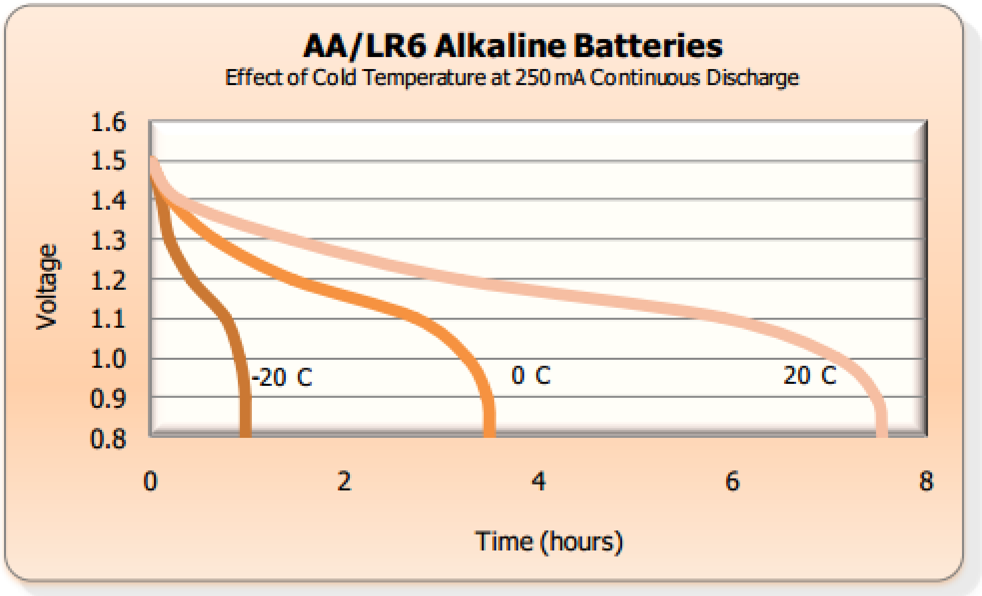
BATTERY POWER CONSIDERATIONS

Battery Discharge Curves

- As a battery is used, its voltage decreases. The rate of this decrease depends on temperature, rate of current draw, and battery chemistry
- Voltage decrease is nonlinear, therefore simple measurement of battery voltage may be a poor technique for predicting remaining battery life.
- Some chemistries (such as Li-Ion) have minimum voltages needed for safe operation



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BATTERY POWER CONSIDERATIONS

Battery Chemistries: Alkaline

- Electrodes: Zinc (-) and Manganese Dioxide (+)
- Chemical Reaction:

$$Zn_{(s)} + 2MnO_{2(s)} \rightleftharpoons ZnO_{(s)} + Mn_2O_{3(s)}[e^o = 1.43V]$$

- Capacity: Load and cell size dependent, 700-1500mAh common (for AA cells)
- Voltage: 1.5V (nominal), 1.65V (max, no load), 1.1 – 1.3V (average, under load), 0.8V – 1.0V (fully discharged)
- Current: Size dependent; 700mA for AA cells typical
- Other: Shelf life of 10+ years, generally not rechargeable

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BATTERY POWER CONSIDERATIONS

Battery Chemistries: Lithium

- Electrodes: Various materials but lithium anodes
- Capacity: Varies by specific chemistry, 30mAh - 1000mAh
- Voltage: Varies by chemistry, 1.5V – 3.7V nominal
- Other: High capacity, not rechargeable, long shelf life, more expensive
- Common Types: CRxxxx coin cells and “button cells”

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BATTERY POWER CONSIDERATIONS

Battery Chemistries: Nickel Metal Hydride (NiMH)

- Electrodes: NiOOH (+), hydrogen absorbing alloy (-)
- Chemical Reaction: (M: metal, MH: metal hydride)

$$NiO(OH) + MH \leftrightharpoons Ni(OH)_2 + M(e^0 = 1.2V)$$

- Capacity: Varies by size, ~3000mAh AA cells common
- Voltage: 1.2V nominal, 1.4V fresh, 1.0-1.1V discharged
- Notes: High self-discharge rates (up to 4%/day), high cycle life (can be repeatedly recharged without substantial memory effects), recyclable, environmentally friendly, high energy densities (improvement over NiCd)

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BATTERY POWER CONSIDERATIONS

Battery Chemistries: Lithium Ion (Li-Ion)

- Electrodes: Lithium cobalt oxide ($LiCoO_2$) (+), various alloys (-). Pass lithium ions between anode and cathode when charging/discharging
- Capacity: 2000mAh+ common (pack below is 6000mAh)
- Voltage: 3.7V nominal, 4.2V fresh, ~3.0V discharged
- Notes: High energy densities, no memory effects, low self discharge rates
- Pressurized and flammable – can pose safety risks (especially when damaged)

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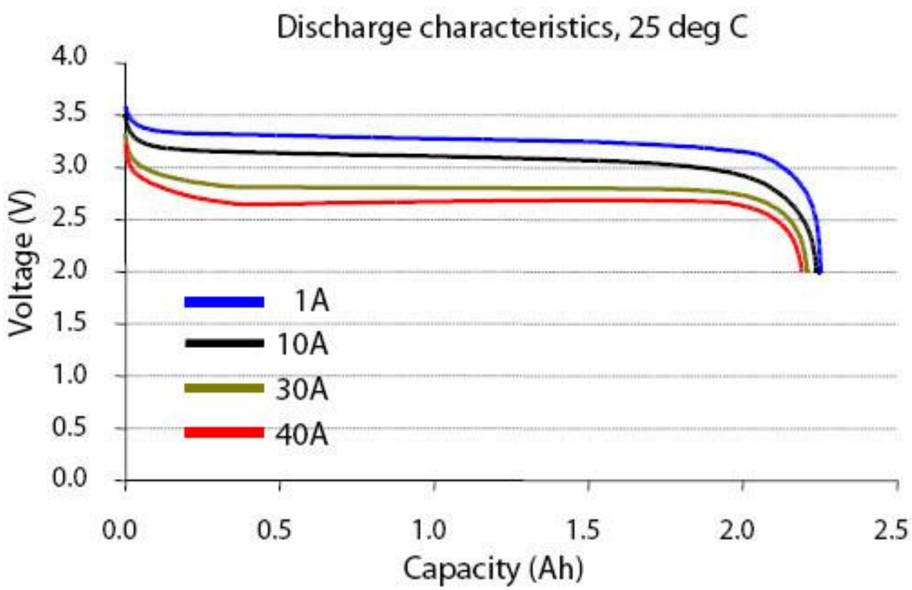
BATTERY POWER CONSIDERATIONS

Battery Chemistries: Lithium Iron Phosphate ($LiFePO_4$)

- <u>Electrodes:</u> Lithium Iron Phosphate ($LiFePO_4$) (+), various alloys (-). Variant of conventional Lithium Ion batteries
- <u>Capacity:</u> 2000mAh+ common (pack below is 6000mAh)
- <u>Voltage:</u> 3.2V nominal, 3.6V fresh, 2.0-2.5V discharged
- <u>Notes:</u> Lower energy density than Li-Ion, but improved cycle life, longer lasting, and considerably safer



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BATTERY POWER CONSIDERATIONS

Battery Chemistries: Other Battery Chemistries

- Zinc: Non-rechargeable chemistry. Worse performance than alkaline but substantially cheaper
- Silver Oxide: Non-rechargeable chemistry. Safer and more energy dense than lithium-ion tech. $$$$$$
- Nickel Cadmium (NiCd): Rechargeable chemistry. Less energy dense than NiMH but lower discharge rate
- Lead-Acid: Rechargeable chemistry. Most commonly found in cars. Heavy but capable of supplying very high surge currents. Cheap vs. comparable Li-Ion.
- Lithium-Sulfur Battery (Li-S): Potential emerging battery technology, offers substantial energy density improvements over conventional Li-Ion battery tech

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BATTERY POWER CONSIDERATIONS

Battery Charging Techniques

- Depending on battery chemistry, different charging techniques are available to charge cells safely (cells can be severely damaged from excessive voltage, current, temperature, etc.):
  - Trickle charging: Provide small amount of current to maintain present battery state (often used for battery backups)
  - Fast charging: Utilize built-in safety features within certain batteries to charge batteries more quickly
  - CC/CV charging: 2-step charging process, in which a battery is initially charged with a constant current. Once a threshold is reached, the charger switches over to a fixed voltage to complete charging

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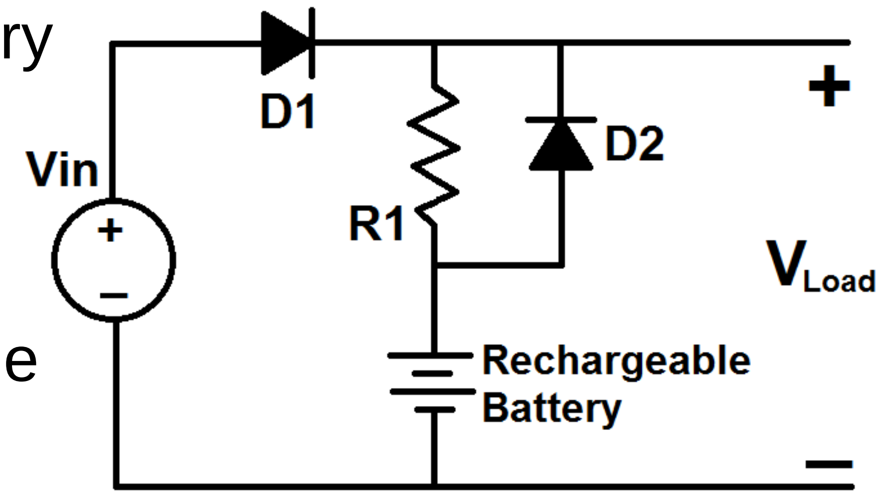
BATTERY POWER CONSIDERATIONS

Battery Charging: Trickle Charging



- Simple trickle charger battery backup example
- R1 must be sized properly to allow for safe charging current to be delivered to the battery
- Power normally supplied via Vin (regulated AC adapter or other source)
- When device is unplugged or power source for Vin otherwise fails, D1 is reverse biased and D2 forward biased, allowing the rechargeable battery to power the load

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BATTERY POWER CONSIDERATIONS

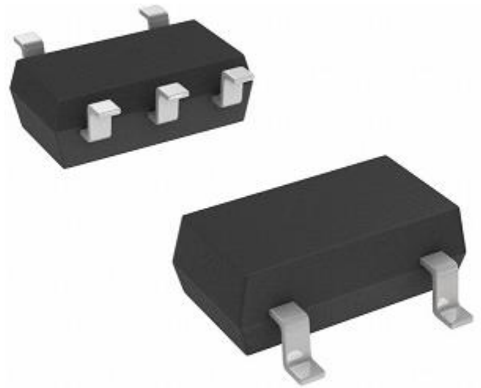
Charging, Monitoring, and Power Management ICs (PMICs)

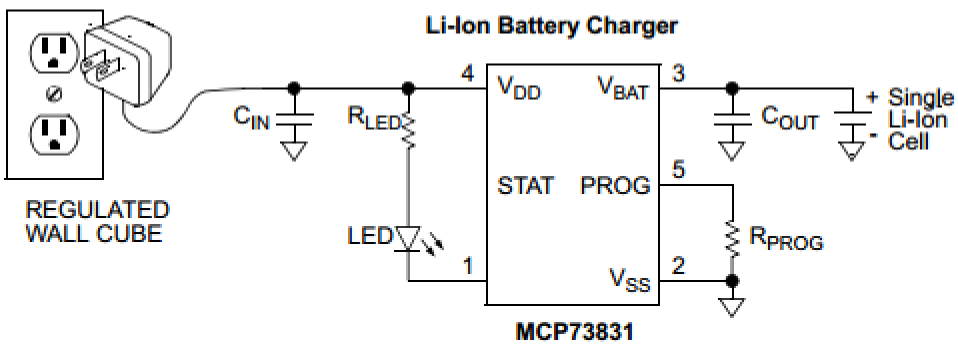
- Modern electronics systems can have complicated power requirements, such as:
  - Battery Charging: Needed for safely charging some chemistries, especially lithium ion variants
  - Power Source Selection: Multiple power sources (utility, USB, battery backup, solar, etc.) may exist; need to select the appropriate power source at a given time
  - Power Sequencing: Depending on the application, some systems/circuits/devices may need to be powered on (or off) before others
  - Battery Monitoring: Determine remaining battery life at a given time (simple voltage measure often insufficient)

BATTERY POWER CONSIDERATIONS

Charging, Monitoring, and Power Management ICs (PMICs)

- Solution to power management issues? Dedicated ICs.
  - Battery Charger: Used to charge batteries with a particular charging algorithm
  - Battery Monitoring: Used to measure battery level and estimate remaining battery life
  - Battery Protection: Used to protect battery from excessive voltages and/or currents





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AMBIENT POWER CONSIDERATIONS

Energy Harvesting

- Depending on device power demands and environment, ambient sources of power may be available:
  - Solar: Draw energy from light sources with solar cells
  - RF: Draw power from TV, radio, satellite, etc. signals
  - Motion and Vibration: Harvest power from natural motion (small turbines, footsteps, etc.)
  - Heat: Harvest energy from heat sources (waste heat from an engine, body heat, etc.)

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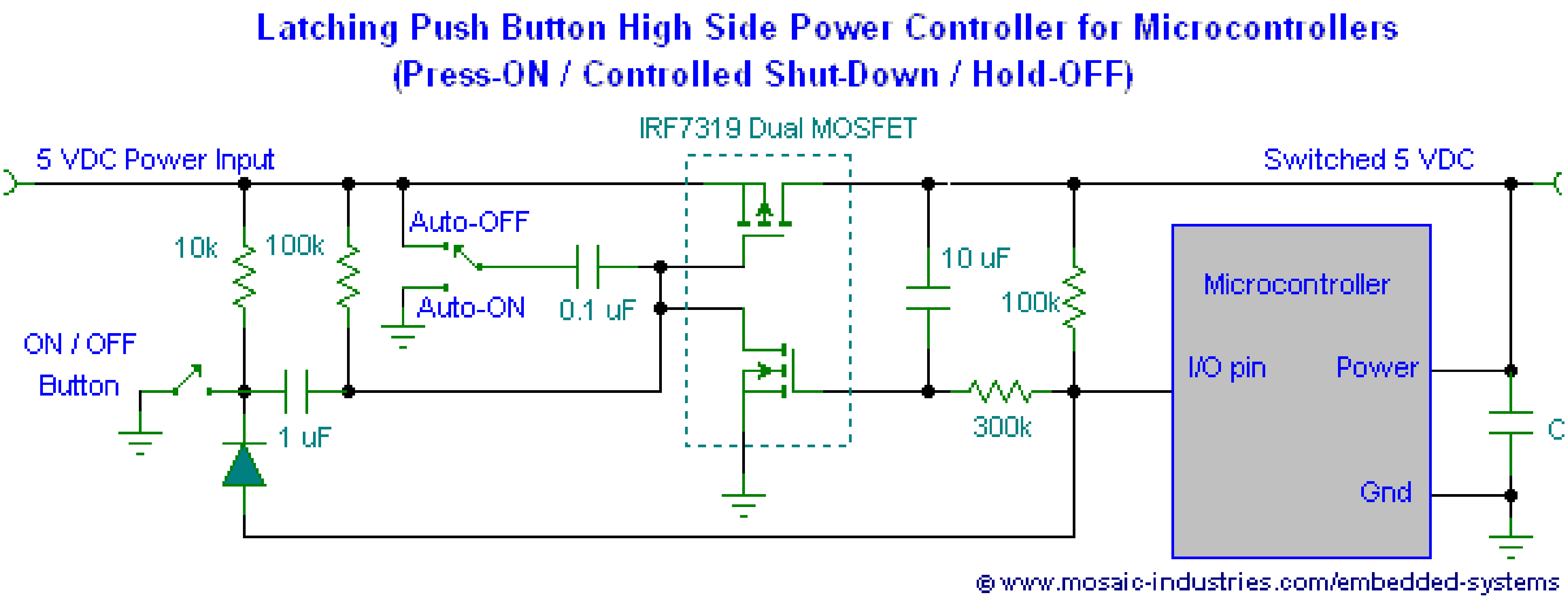
POWER DESIGN TECHNIQUES

Simple Programmable Shutdown



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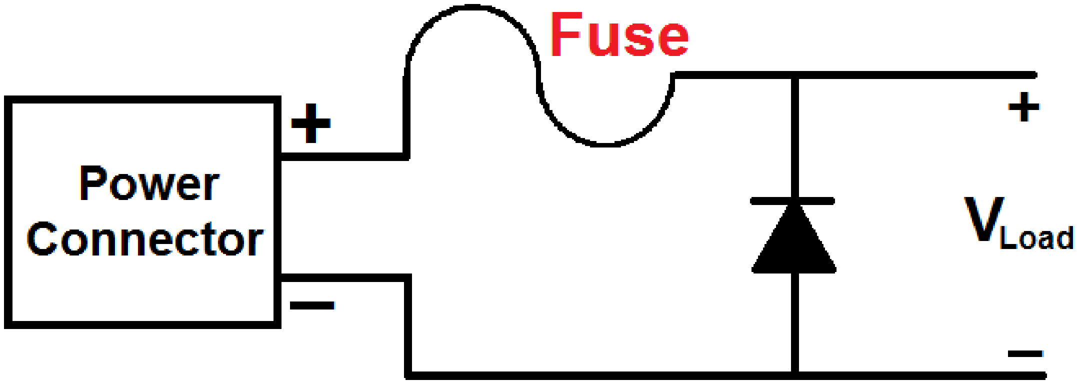
POWER DESIGN TECHNIQUES

Simple Reverse Polarity Protection

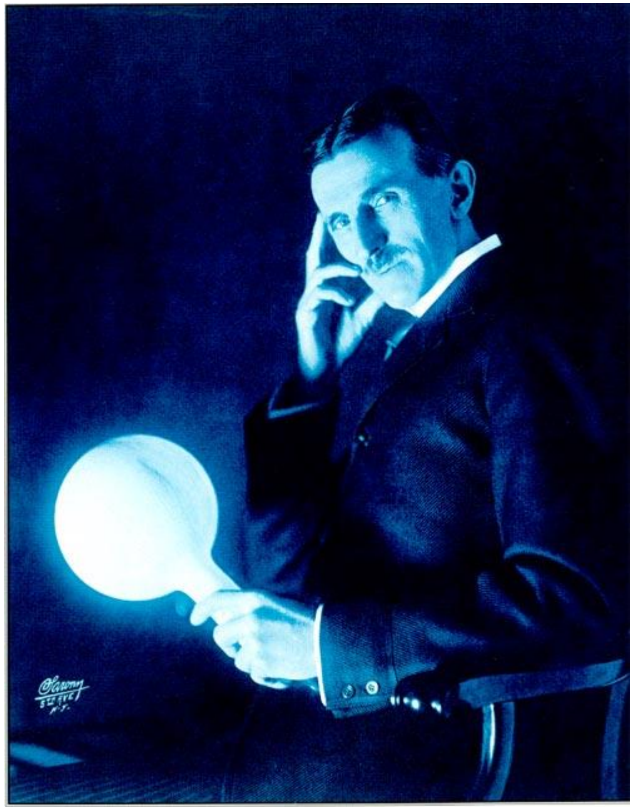


- Q: What happens if somebody accidentally hooks up power backwards?
  - A (w/ no protection): Bzzzzzzt! *Smoke* Noooooooooo!
  - A (w/ protection): Nothing.
- Other techniques include polarized or reversible connectors (only one way to connect or connector orientation doesn't matter)

OTHER POWER CONSIDERATIONS

Wireless Transmission of Power

- Transfer power from one location to another without the use of dedicated wires
- Popular for charging, situations where wires could twist or get tangled, etc.
- Inductive coupling: A magnetic field is induced by a transmitter and received by a separate device (RFID tags, etc.)
  - Air core: Lossy, easy alignment
  - Magnetic core: Similar to a transformer; method used by electric toothbrushes



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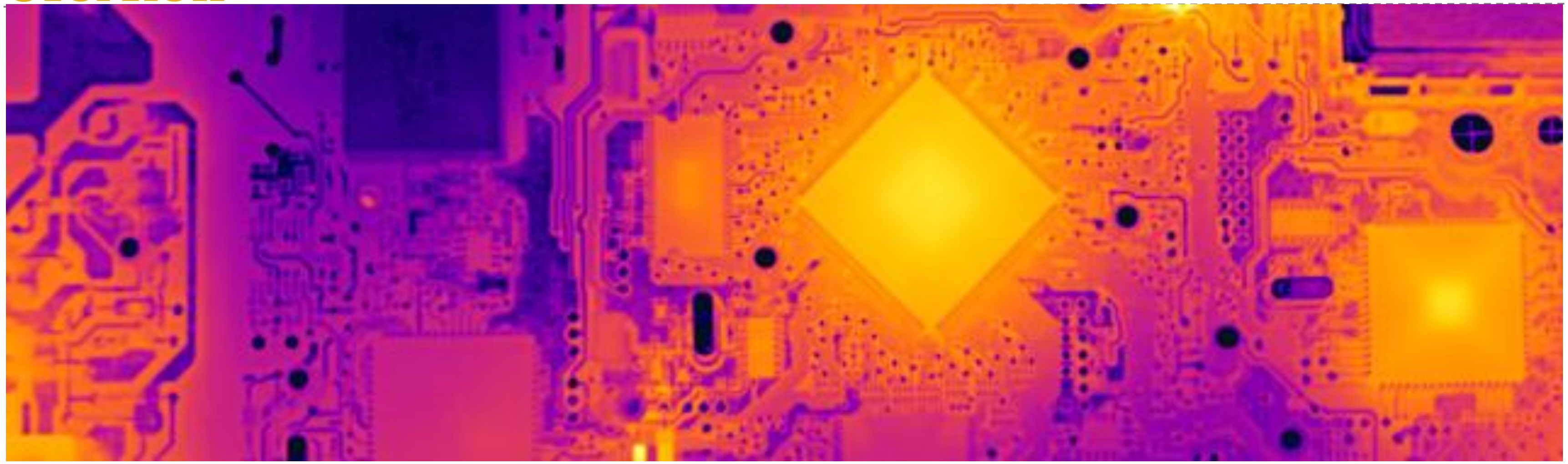
THERMAL CONSIDERATIONS

Overview



- Power electronics can be a significant source of HEAT
- Electrical performance of most components degrades as temperature increases
- User safety concerns (don't want end users to be burnt)
- Need design techniques to safely dissipate heat (heat sinking, thermal paste, ventilation and fans)

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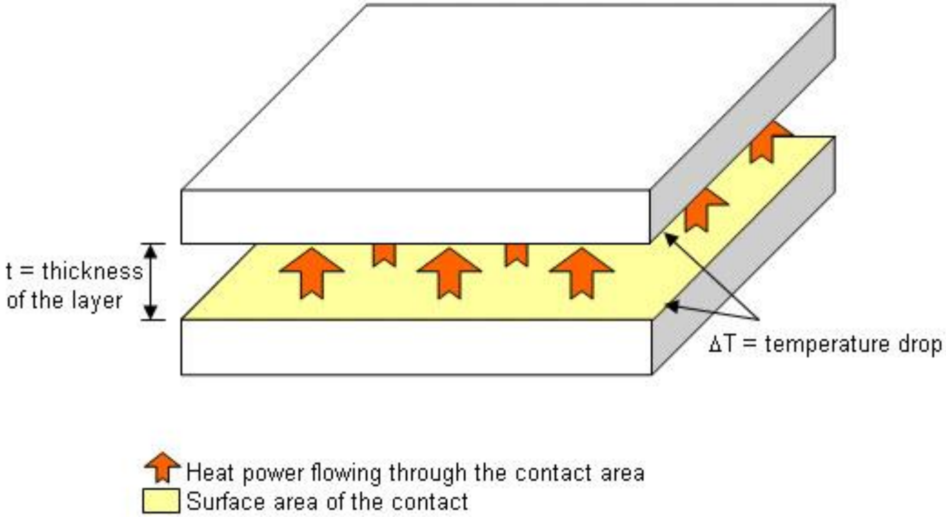
THERMAL CONSIDERATIONS

Temperature, Power, and Thermal Resistance

- Power: P = IV (measured in W)
- Temperature: Maximum temperature is generally a design constraint (recall lecture 2)
- Thermal Resistance: A value given to heatsinks and components, details a junction's resistance to heat flow (ºC/W) (↓Resistance → ↑Performance)

$$\Delta T = Q \cdot R_\theta$$

ΔT: Temperature change
Q: Heat flow
R_θ: Thermal resistance



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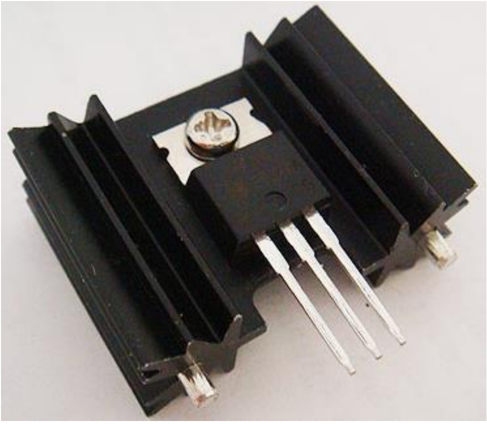
THERMAL CONSIDERATIONS

Heat Sinks

- Heat Sinks: Passive devices used to transfer heat away from a location and dissipate it into the environment
- Many varieties, depending on form factor, thermal resistance, size, etc.
- Better thermal performance generally requires:
  - Size: Larger heat sink = more thermal mass AND/OR
  - Cost: More exotic and expensive materials



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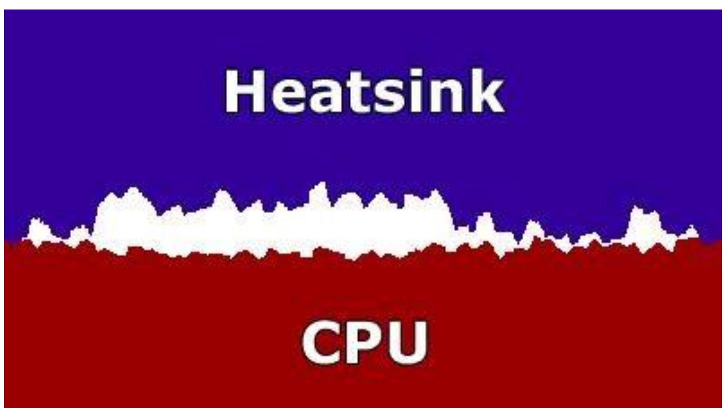
THERMAL CONSIDERATIONS

Thermal Paste

- While heat sinks are excellent conductors of heat, the physical junction between it and a component of interest is not
- <u>Thermal Paste:</u> Specialized compound designed to provide adhesion and improve heat transfer at component/heatsink junction
- Apply with care; some thermal pastes are conductive



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THERMAL CONSIDERATIONS

Fans and Ventilation

- Heat sinks/thermal paste can effectively dissipate heat from the immediate electrical junction, but sometimes this heat must be further dissipated
- Adding ventilation for airflow may be an option for your design (can allow outside contaminants and dust in)
- Fans can further increase airflow and heat dissipation in your designs

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THERMAL CONSIDERATIONS

Thermal Design Example

- Example: Suppose we have a linear voltage regulator designed to regulate 6-10V input down to 5V while passing up to 1A. For safety and performance purposes this regulator should not exceed 122ºF (50ºC) (assume room temperature operation of 25ºC)

- Questions: How much power can the regulator dissipate? What temperature will the regulator reach without a heatsink? What thermal resistance will be necessary to meet the performance/safety spec.? What parts might we use, and what might they cost (passive and forced air cases)?

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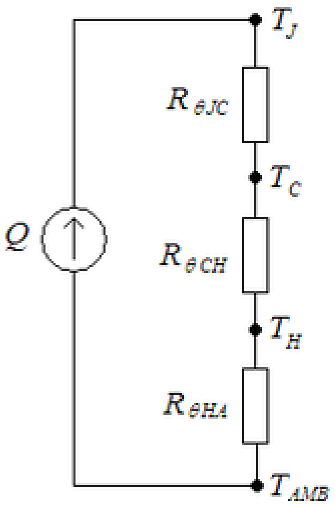
THERMAL CONSIDERATIONS

Thermal Design Example 2



- Dissipated Power:

  $P_{max} = V_{max} * I_{max} = 5V * 1A =$?????

- Estimated Temperature Change (no Heatsink):

  R_θ(junction to case): 1.5ºC/W

  R_θ(junction to air) : 65ºC/W

  $\Delta T = Q*R_\theta = 5W*(65ºC/W) =$?????

  $T = T_{ambient} + \Delta T = 25ºC +$?????

  = ?????

- Thermal Resistance Needed to Meet Spec:

  $R_\theta = \Delta T/Q = 25ºC/5W \approx$?????

  Assuming thermal grease resistance of 0.1ºC/W (typical), need heatsink with $R_\theta = (5 – 1.5 – 0.1)ºC/W =$?????

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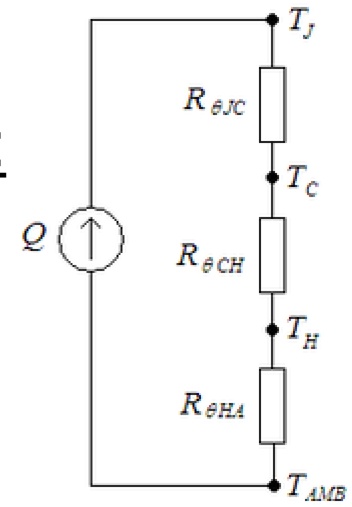
THERMAL CONSIDERATIONS

Thermal Design Example 3

- Dissipated Power:
  $P_{max} = V_{max} * I_{max} = 5V * 1A = 5W$
- Estimated Temperature Change (no Heatsink):
  R_θ(junction to case): 1.5ºC/W
  R_θ(junction to air) : 65ºC/W
  $\Delta T = Q*R_\theta = 5W*(65ºC/W) = 325ºC$
  $T = T_{ambient} + \Delta T = 25ºC + 325ºC$
  $= 350ºC$ (662ºF)



- Thermal Resistance Needed to Meet Spec:
  $R_\theta = \Delta T/Q = 25ºC/5W \approx 5ºC/W$
  Assuming thermal grease resistance of 0.1ºC/W (typical), need heatsink with $R_\theta = (5 – 1.5 – 0.1)ºC/W = 3.4ºC/W$

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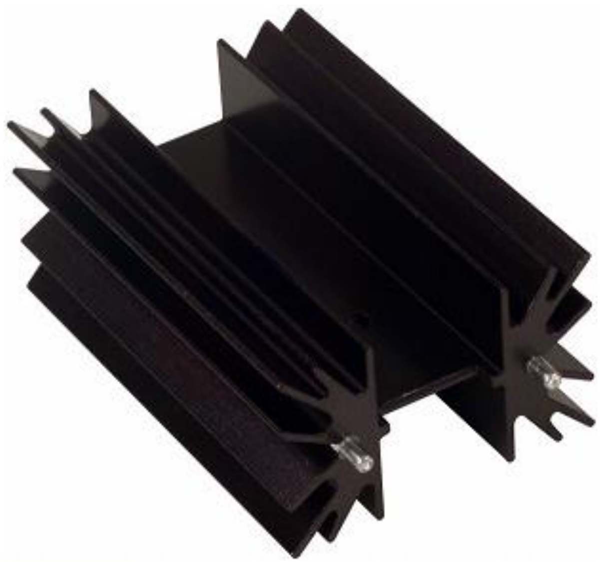
THERMAL CONSIDERATIONS

Thermal Design Example 4

- Heat sink parts meeting R_θ = 3.4ºC/W (without fan):
  - Dimensions: 63.5mm (height) x 41.91mm (width)
  - Minimum cost: $1.63/unit
- Reliability can be further improved using fans, ventilation, and other techniques



Questions?