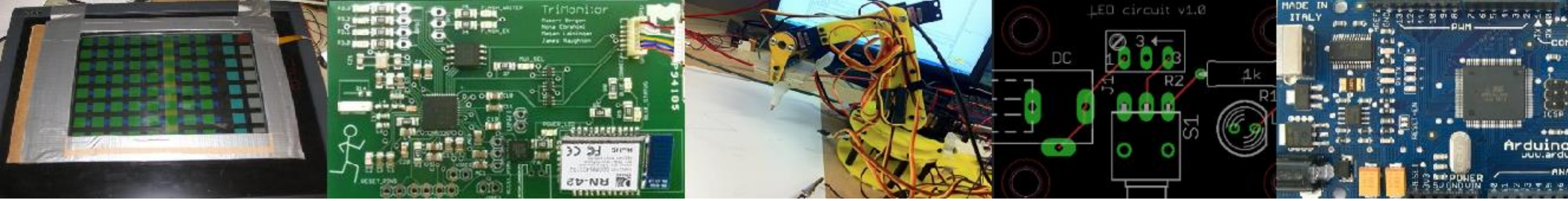
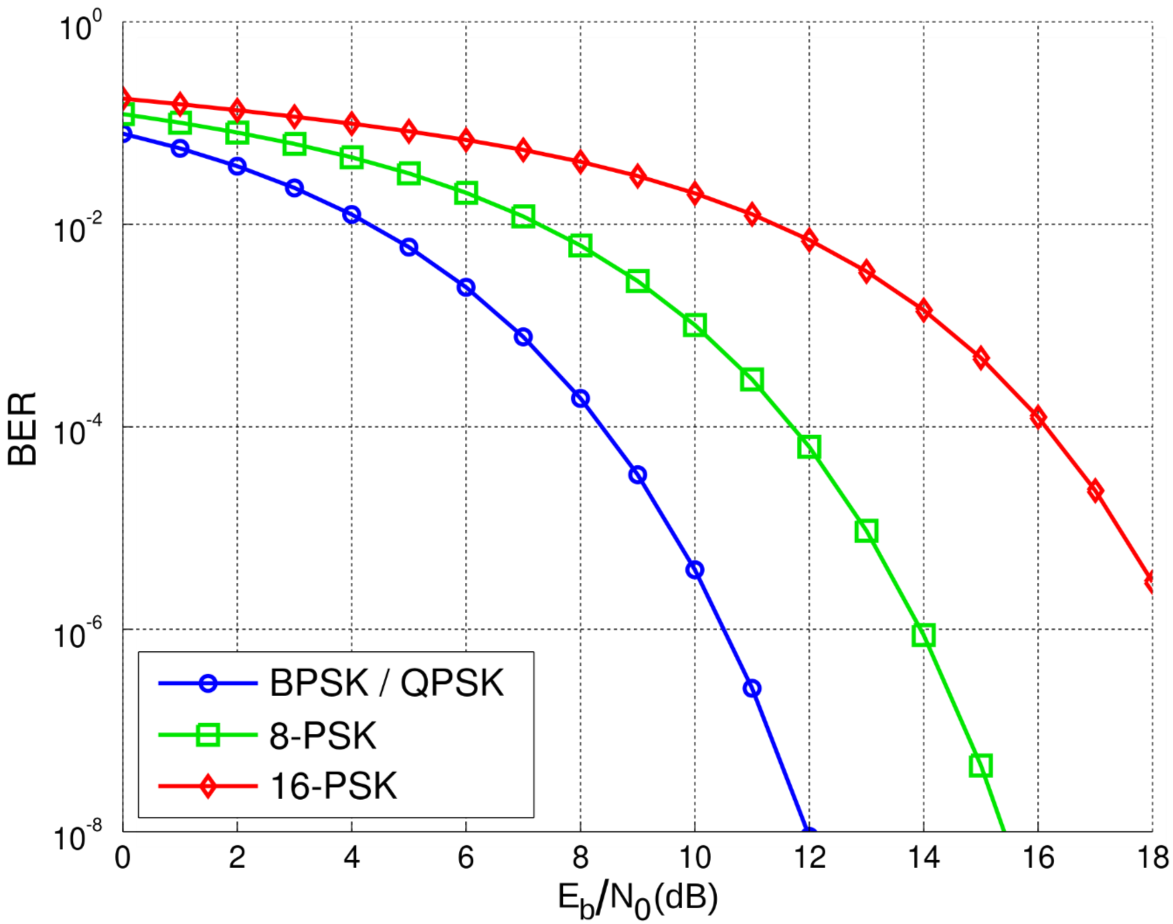


EECS 473
Advanced Embedded Systems

Lecture 15:
Antennas and switching regulators

A number of slides taken from UT-Austin's EE462L power electronics class.
http://users.ece.utexas.edu/~kwasinski/EE462LS14.html -- very useful!

So, who cares?
Noise immunity



https://en.wikipedia.org/wiki/Eb/N0

- Looking at signal-to-noise ratio needed to maintain a low bit error rate.
  - Notice BPSK and QPSK have lower error rates.
  - And as "M" goes up, we get higher error rates.
    - Easier to confuse symbols!

Project updates

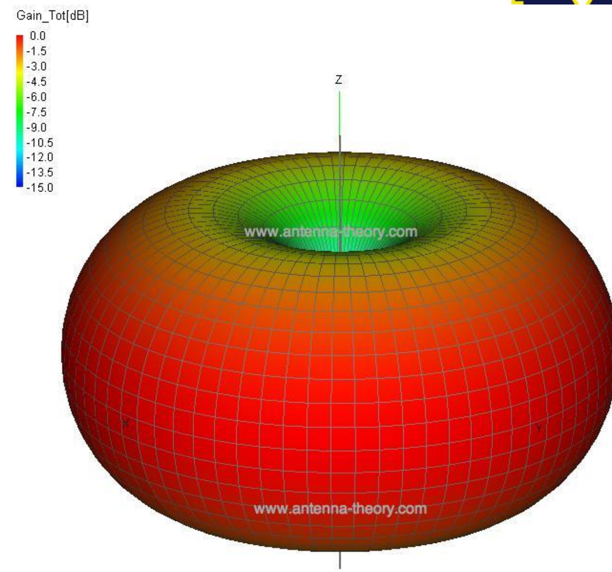
- **Largest roadblock**; Thing you are most pleased with wrt your project.
  - Robot Arm
  - FLEX Lift
  - Key Oracle
  - Canbats
  - Transcriber Glasses
  - Chess
  - Solar Cell

On to…
Antennas and transmission power

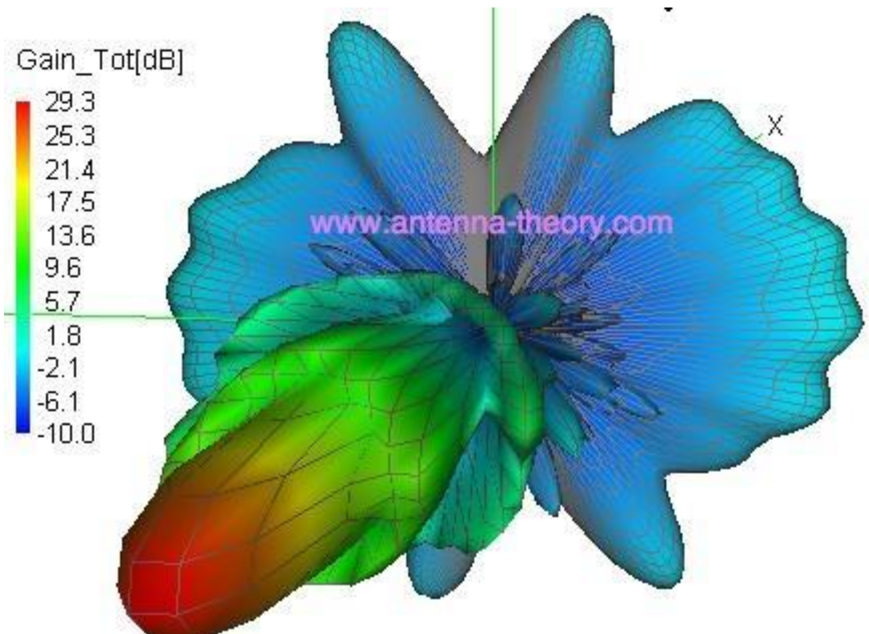
- Antennas receive power differently depending on where the power is coming from.
  - An isotropic antenna is one that receives power equally well from all directions.
    - These don't exist.
- Real antennas focus their "effort" more in some directions than others.
  - A narrow antenna, like a dish, will be focused in a very narrow range (radiation angle)
  - Others, like a traditional dipole (the most common antenna) tend to have less narrow of a range.

Antennas

- Nothing is free here.
  - If you have a narrow beam, you get some great gain in that beam but get loss in the other directions.
    - This can be good.
    - Think about body-area networks or Bluetooth headphones



Toroidal radiation pattern



Dish antenna radiation pattern

Figures from antenna-theory.com (if you couldn't tell…)

Radio power

- Radio signals are generally measured in Watts
  - However embedded systems generally measure power in mW
    - Typically 30-100mW for WiFi
  - It is often easiest to deal with power on a log scale.
    - So we use “dBm” where

$$P_{dBm} = 10 \log P_{mW}$$

$$P_{mW} = 10^{\left(\frac{P_{dBm}}{10}\right)}$$

dBm	mW	dBm	mW	dBm	mW
-3	0.5	9	8	21	126
-2	0.6	10	10	22	158
-1	0.8	11	13	23	200
0	1.0	12	16	24	250
1	1.3	13	20	25	316
2	1.6	14	25	26	398
3	2.0	15	32	27	500
4	2.5	16	40	28	630
5	3.2	17	50	29	800
6	4	18	63	30	1000
7	5	19	79	33	2000
8	6	20	100	36	4000

dBm is basically just dB but scaled to mW.

Much of this (including graphics) from https://www.allied-automation.com/wp-content/uploads/2019/03/industrial-wireless-guidebook.pdf

Aside: dB, dBm, dBi

- dB itself is a unit-less value
  - Generally a ratio between two things
  - On a log scale.
- dBm a single value where the "ratio" is to 1mW.
  - So 20dB means a 100 to 1 ratio
  - 20dBm means 100mW (100 times 1mW)

- We'll also see dBi when looking at antennas.
  - That's the power ratio of an antenna to an isotropic antenna (that completely non-directional antenna)
  - You might see dBd, which is compared to a lossless dipole antenna. It's 2.15dB lower than dBi.
    - Vendors generally use dBi ('cause it's bigger) and thus so will we.

Power received vs. power sent.

- The Friis Transmission Formula tells us how much power we'll receive. It is:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

Where:

- **P_t** is the radiated power
- **P_r** is the received power
- **G_t** is the gain of the transmitting antenna
- **G_r** is the gain of the receiving antenna
- **λ** is the wavelength
- **R** is the distance between antennas

- However, many of those terms aren't easily available from real spec. sheets.
- Instead we do some algebra and unit changes and get the following equation for range in km:

$$r = \frac{10^{(p_t + g_t + g_r - p_r)/20}}{41.88 \times f}$$

- Where f is the frequency in MHz, p_t and p_r are in dBm and g_t and g_r are in dBi.

Example

- You are running an IEEE 802.11b network and you are currently using wireless devices with the following specifications:
  - Tx power: 18 dBm @ 11 Mbps
  - Rx sensitivity: -81dBm @ 11 Mbps
  - Antenna gain: 2 dBi (both)
  - 802.11b is at 2.4GHz.

$$r = \frac{10^{[18+2+2-(-81)]/20}}{41.88 \times 2442} \text{ km} = 1.38 \text{ km}$$

- Notes:
  - We are looking at 63mW of broadcast power.
  - If we had dish antennas pointed at each other with a gain of 25dBi, we'd have (18+50+81)/20=275km!
  - Note that this assumes an unobstructed line-of-sight signal with no significant interference.
    - Sometimes realistic, often not.

50kW@720KHz

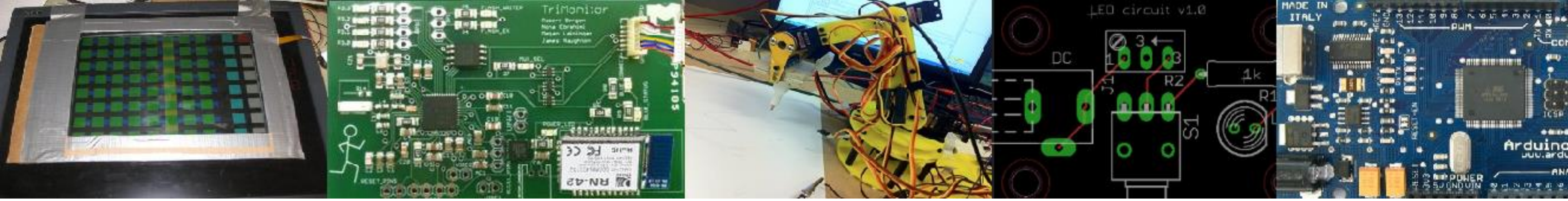
Looking at a real antenna (ANT-WSB-ANF-09)

Antenna Characteristics

Frequency: 2.4 to 2.5 GHz
Antenna Type: Omni-directional
Typical Antenna Gain: 9 dBi
Connector: N-type (female)
Impedance: 50±5 ohms
Polarization: Linear
HPBW/horizontal: 360°
HPBW/vertical: 10°
V.S.W.R.: 1:1.3 max.
Power Handling: 15 W max.

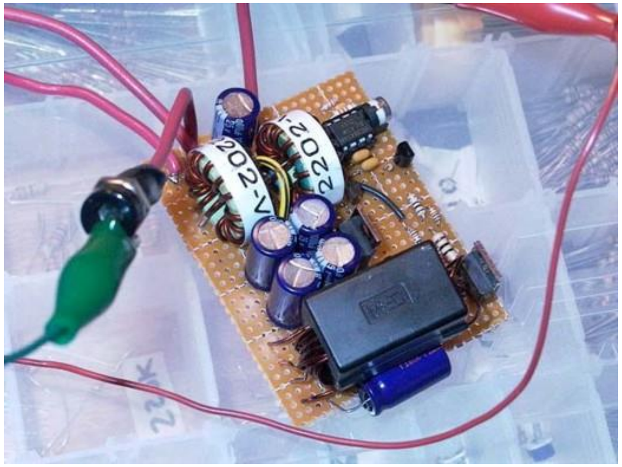
- 9dBi
  - Gets there by radiating in a toroid
    - Spread evenly along the ground (half power beam width is 360°)
    - Doesn't go up or down at all.
      - Half power beam width is at 10°

HPBW: Half power beam width—where you get ½ power.
VSWR (viz-wer): impedance matching stuff, not covered by us.

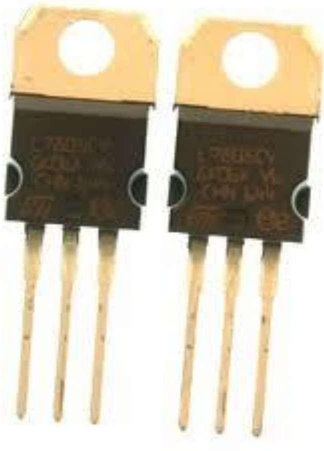


Switching regulators

What are DC converters?



- DC converters convert one DC voltage level to another.
  - Very commonly on PCBs
    - Often have USB or battery power
    - But might need 1.8V, 3.3V, 5V, 12V and -12V all on the same board.
  - On-PCB converters allow us to do that



Images from http://itpedia.nyu.edu/wiki/File:V_reg_7805.jpg, http://www.electronics-lab.com/blog/wp-content/uploads/2007/10/p1000255.JPG both now dead links...

Different types of DC converters

Linear converters

- Simpler to design
- Low-noise output for noise-sensitive applications
- Can only drop voltage
  - And in fact ***must*** drop it by some minimum amount
  - The larger the voltage drop the less power efficient the converter is

Switching converters

- Can be significantly more complex to design
  - Worth avoiding for this class unless you have to do it.
- Can drop voltage or increase voltage
  - "buck" and "boost" respectively
- Generally very power efficient
  - 75% to 98% is normal

Characteristics of DC Converters

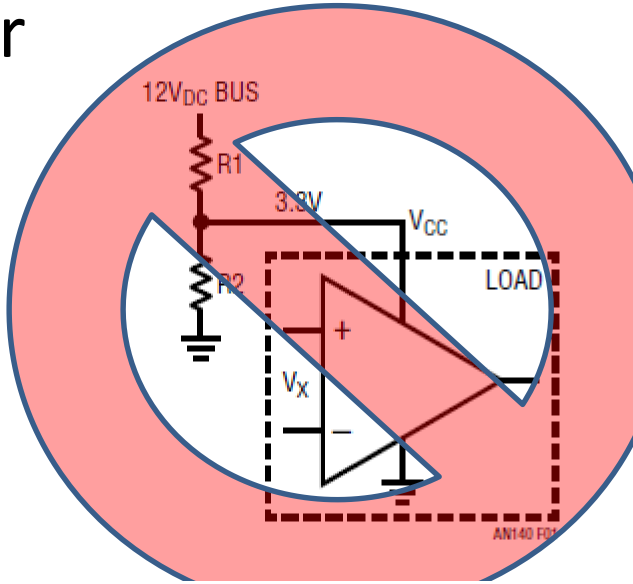
- To better understand how to pick a converter we will go over the following characteristics seen in all DC converters
  - Power wasted (as heat)
  - Quiescent current, I_Q
    - The leakage current that occurs regardless of operation.
  - Power supply rejection ratio (PSRR)
    - The ability to reject output noise at different frequency
  - External capacitors and equivalent series resistance(ESR)
    - Output noise filter that helps keeping the signal clean
- These characteristics are what people generally look for when selecting converters, but they're not by any means the only characteristics that matter.

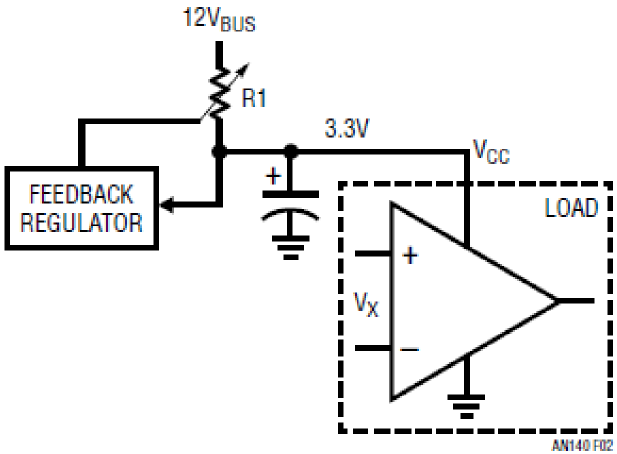
Quick look at the options

- Linear converter
  - LDO
- Switching converter
  - Buck
  - Boost
  - Buck-Boost

Linear converter

- One can think of a linear converter as a “smart” voltage divider.
  - If we were using a very small amount of current, that would work.
  - But hugely wasteful.
- Instead, we want the top resistor to vary with the load.
  - As load draws more current, R1 drops resistance to keep voltage constant.





Figures on this slide and the next taken from https://www.analog.com/media/en/technical-documentation/application-notes/an170f.pdf, which is a great app-note.

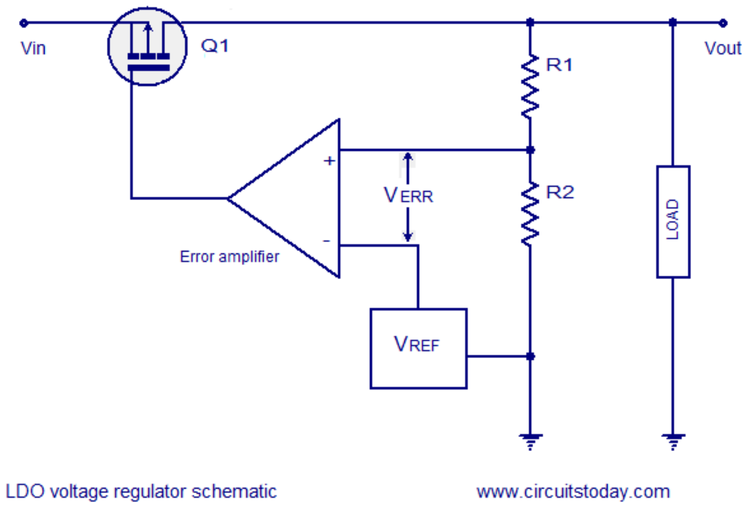
Voltage converters/regulators: Review Linear

- Drops voltage
  - Heat waste > (Vin-Vout)/Vin
    - That's a lot if we are dropping much voltage
  - Has minimum drop
  - Uses current even if no load (quiescent current)
  - Often needs an output (and maybe input) cap.

- LDO – low dropout is main variation.
  - Minimum drop is often very small (though can vary by current draw…)
  - Generally needs larger caps.
  - Can have larger quiescent current
    - Depends on if "resistor" is BJT or FET, FET more common these days.

Stability

An MOSFET LDO.



- The opamp adjusts the effective resistance of the transistor to control the voltage.
  - Clearly we've got a control loop and there is delay in that loop.
    - That means that if the load (or source…) is varying at a certain frequencies, we could get positive feedback.
    - The output (and sometimes input) cap can filter out those frequencies.

http://www.ti.com/lit/an/snva020b/snva020b.pdf provides a very nice, detailed overview with Bode plots etc., though it is a bit dated.

Is stability a real issue for linear regulators?

- Well yes.
  - But these days, the requirements are pretty lax.
    - The LT3007 wants a 2.2μF ceramic cap at the output and maybe a ~1 μF input cap.
      - Needs moderately low ESR.
      - Data sheet expresses concerns about cheap ceramic caps.
  - Older linear regulators had a lot more restrictions
    - Often required some additional ESR, but not too much.
- Older and cheaper devices might have some pretty significant (and sometimes costly) needs.
  - Just be aware that in the early 2000s this was a pretty big issue.

Switching Converters

- Once you leave the realms of linear converters it gets more complex.
  - Introducing common switching converters!
    - All include a diode, transistor, inductor and a capacitor

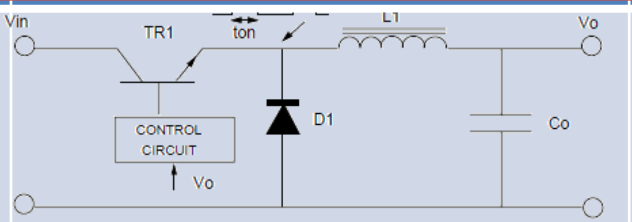
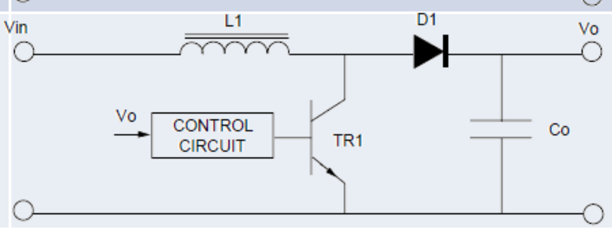
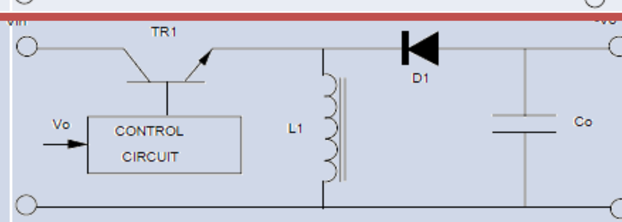
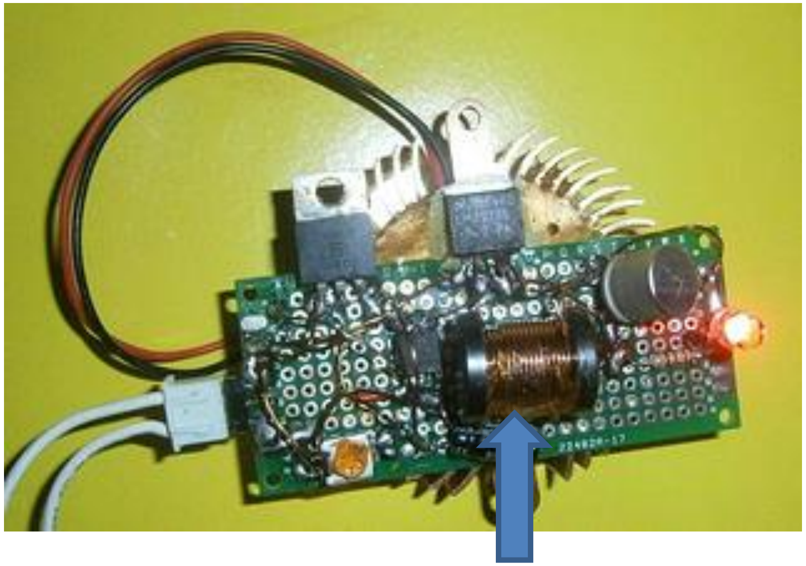
Converters	General Topology	Application
Buck		Drop voltage
Boost		Increase voltage
Buck-boost(inverting)		Increase or decrease voltage and inverse polarity

Table from http://www.nxp.com/documents/application_note/APPCHP2.pdf

Functionality – Switching Converters

- Common switching converters
  - Converters now include a transistor and diode used for switching and an inductor as energy storage.
    - In general, a switching converters works by controlling the frequency and duty cycle that the transistor is operating at
  - Similar to linear converters, most of the work is already done.
  - Only have to pick IC with the right parameter and follow the datasheets given for appropriate inductors and capacitors.



Size of inductor in relation to the rest of the component

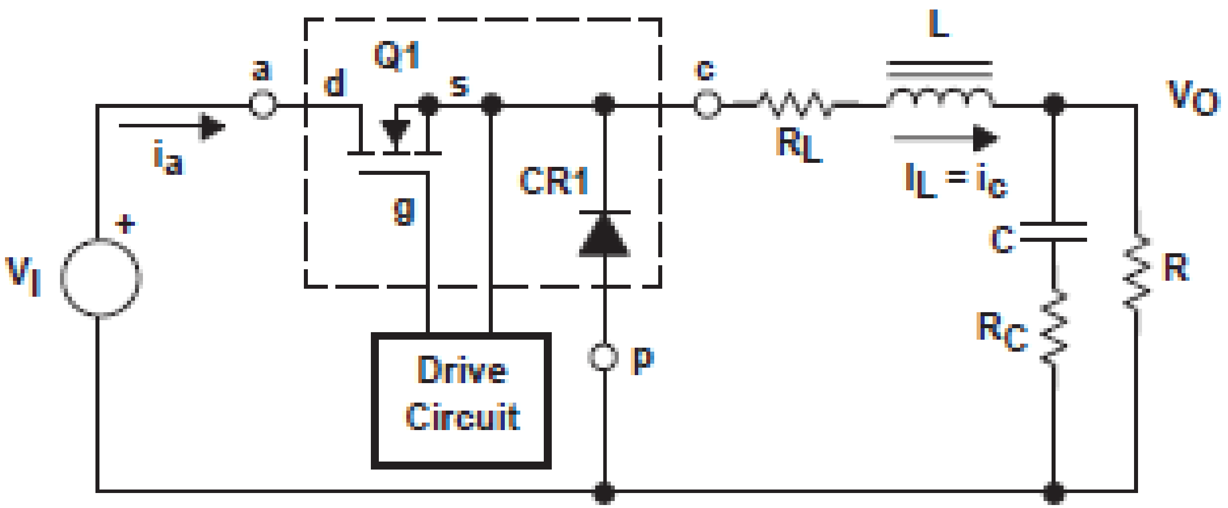
Example switching regulator from http://ycprojects.wordpress.com/

Functionality – Switching Converters

- Common switching converters
  - Aside from the noble goal of making circuit analysis more complex (☺) both the inductor and capacitor play important roles in switching converters.
    - Capacitor
      - Used to store energy due to the voltage applied thus maintaining a constant voltage
      - Generally selected to limit V_o ripple to the correct specification
    - Inductors
      - Similar to the capacitor, but an inductor is used to store energy due to current flow. This in turn maintains a constant current or is used to limit the rate of change of current flow.
      - This will also determine the peak to peak current in the circuit which affects the transistor, diode and the "mode" the converter will operate at.

Functionality – Buck

- Common switching converters
  - Let's start with the buck converter



- Note the drive circuit, this is what the IC is
- For simplicity's sake let's disregard R_L and R_C, the internal resistance of the inductor and capacitor
- It looks pretty complex, so let's try to understand why we need each component!

Capacitors and Inductors

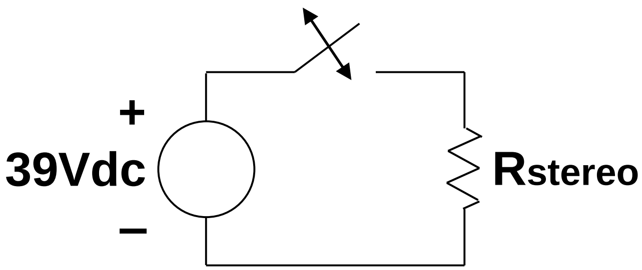
In capacitors: $i(t) = C\frac{dv(t)}{dt}$ **The voltage cannot change instantaneously**

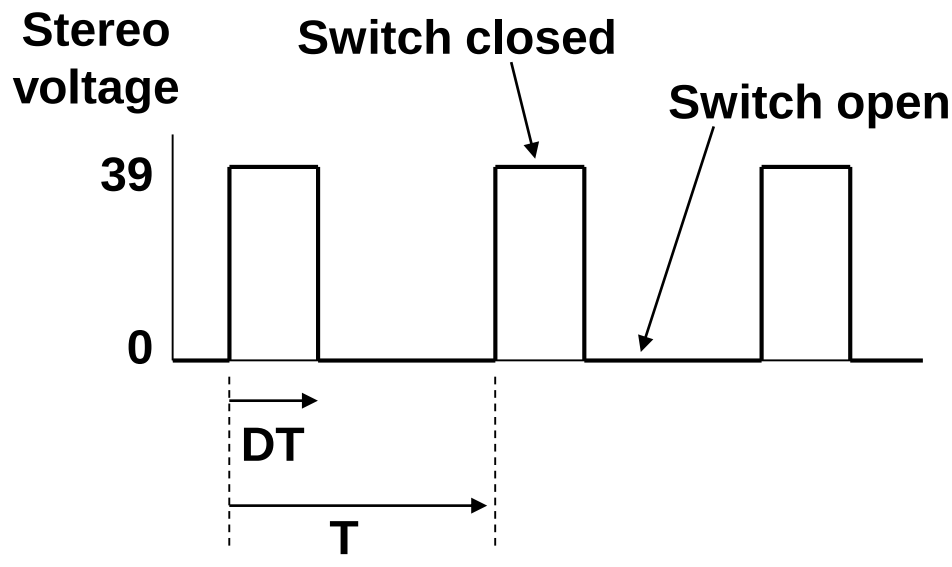
Capacitors tend to keep the voltage constant (voltage "inertia"). An ideal capacitor with infinite capacitance acts as a constant voltage source. Thus, a capacitor cannot be connected in parallel with a voltage source or a switch (otherwise KVL would be violated, i.e. there will be a short-circuit)

In inductors: $v(t) = L\frac{di(t)}{dt}$ **The current cannot change instantaneously**

Inductors tend to keep the current constant (current "inertia"). An ideal inductor with infinite inductance acts as a constant current source. Thus, an inductor cannot be connected in series with a current source or a switch (otherwise KCL would be violated)

Switching – ***lossless*** conversion of 39V to average 13V

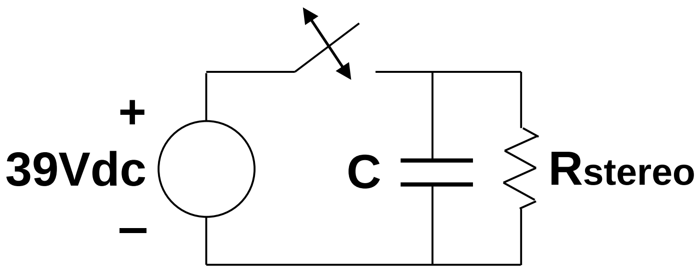




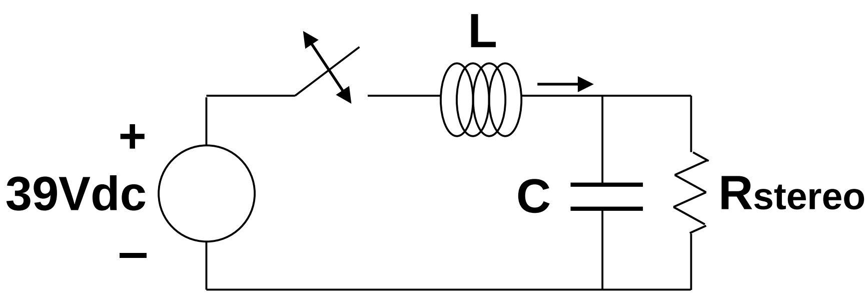
Switch state, Stereo voltage
Closed, 39Vdc
Open, 0Vdc

If the duty cycle D of the switch is 0.33, then the average voltage to the expensive car stereo is 39 • 0.33 = 13Vdc. This is *lossless* conversion, but will it work?

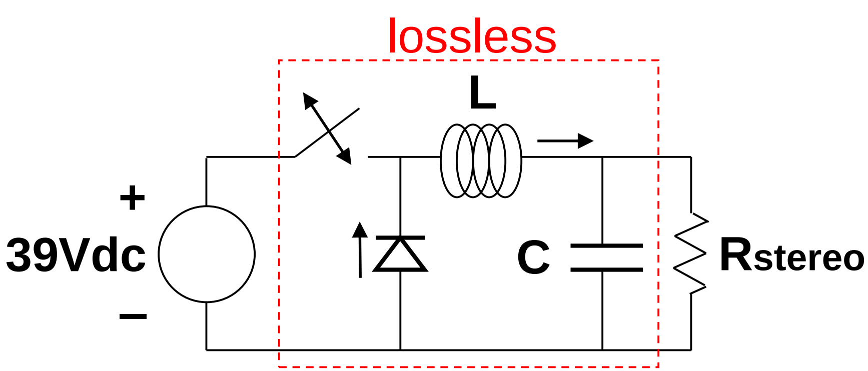
Convert 39Vdc to 13Vdc, cont.



Try adding a large C in parallel with the load to control ripple. But if the C has 13Vdc, then when the switch closes, the source current spikes to a huge value and burns out the switch.



Try adding an L to prevent the huge current spike. But now, if the L has current when the switch attempts to open, the inductor's current momentum and resulting Ldi/dt burns out the switch.

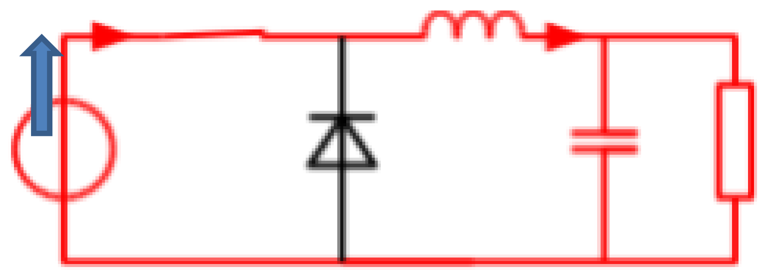


A DC-DC Buck Converter

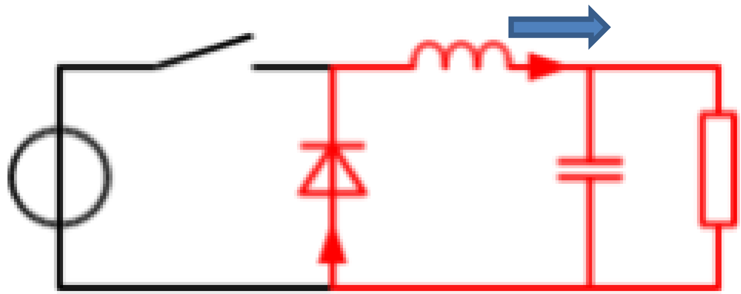
By adding a "free wheeling" diode, the switch can open and the inductor current can continue to flow. With high-frequency switching, the load voltage ripple can be reduced to a small value.

Functionality – Buck

- Common switching converters - buck
  - During operation, the buck converter functions differently depending on the switch
    - On state
      - Current flows through the transistor but reverse bias prevents current flow through the diode
      - Inductor begins to charge and a smaller current becomes I_{load}
    - Off state
      - Switch opens and the inductor starts discharging as the only power source
    - This on-off state will determine the “mode” the converter operate in



Buck: switch on



Buck: switch off

Figures from Wikipedia

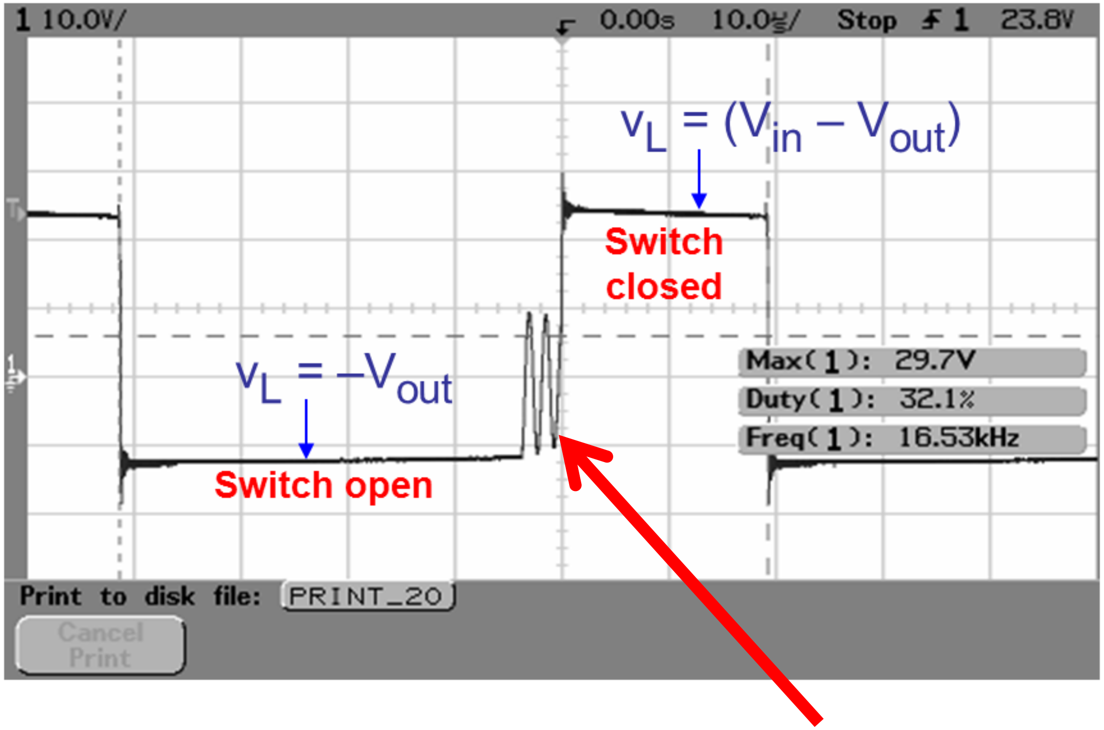
Functionality – Switching Converters

- The duty cycle of the switching will determine the mode each converter operate at various loads
  - Continuous Mode
    - The inductor current will never fall to zero when the switch is off
  - Discontinuous Mode
    - Inductor current will reach zero before the end of the full duty cycle
  - Each mode has its advantages and disadvantages depending on the switching converters.
    - In generally it's how they change the frequency response.

Net effect—avoiding discontinuous mode

- Lower load current, lower inductance and lower switching frequency move us toward discontinuous mode.

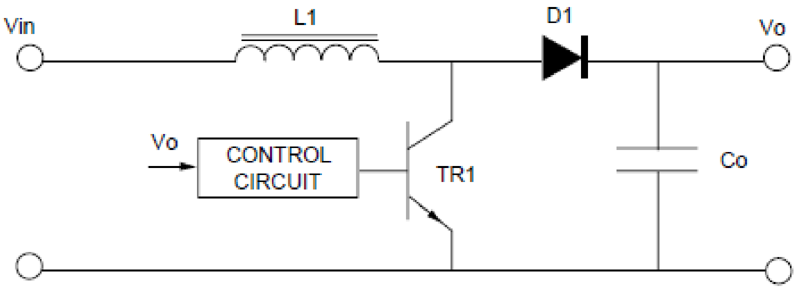
There are pros and cons to both modes, but one real issue is that switching between them can cause ringing on the inductor's output.
(See UT slides for why, has to do with parasitic cap in transistor and diode.)



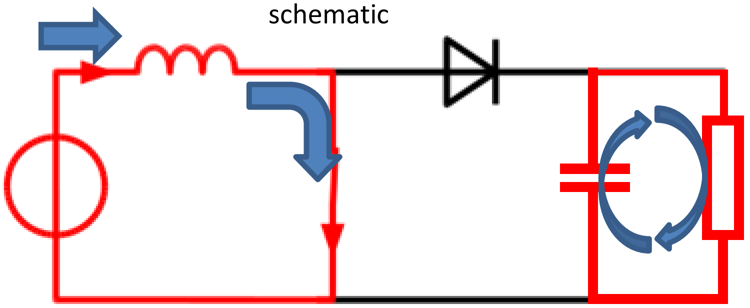
Functionality – Boost (Doing this much more quickly)

- On state
  - Current flows through the transistor(least resistance) making the diode reverse bias and no I_D
  - Inductor is charged in the process
- Off state
  - The energy discharged by the inductor is superimposed to the input, generating a higher output

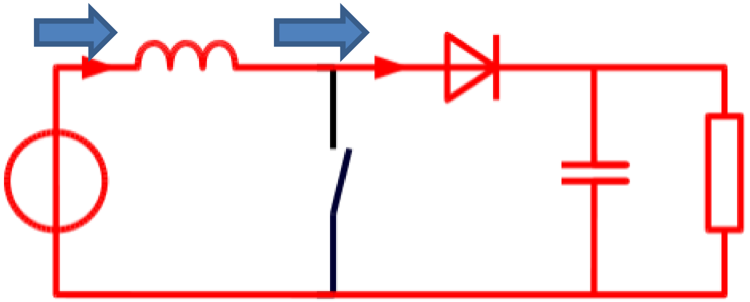
$$V_{out} = \frac{V_{in}}{1-D}$$



Generic boost schematic



Boost: on state

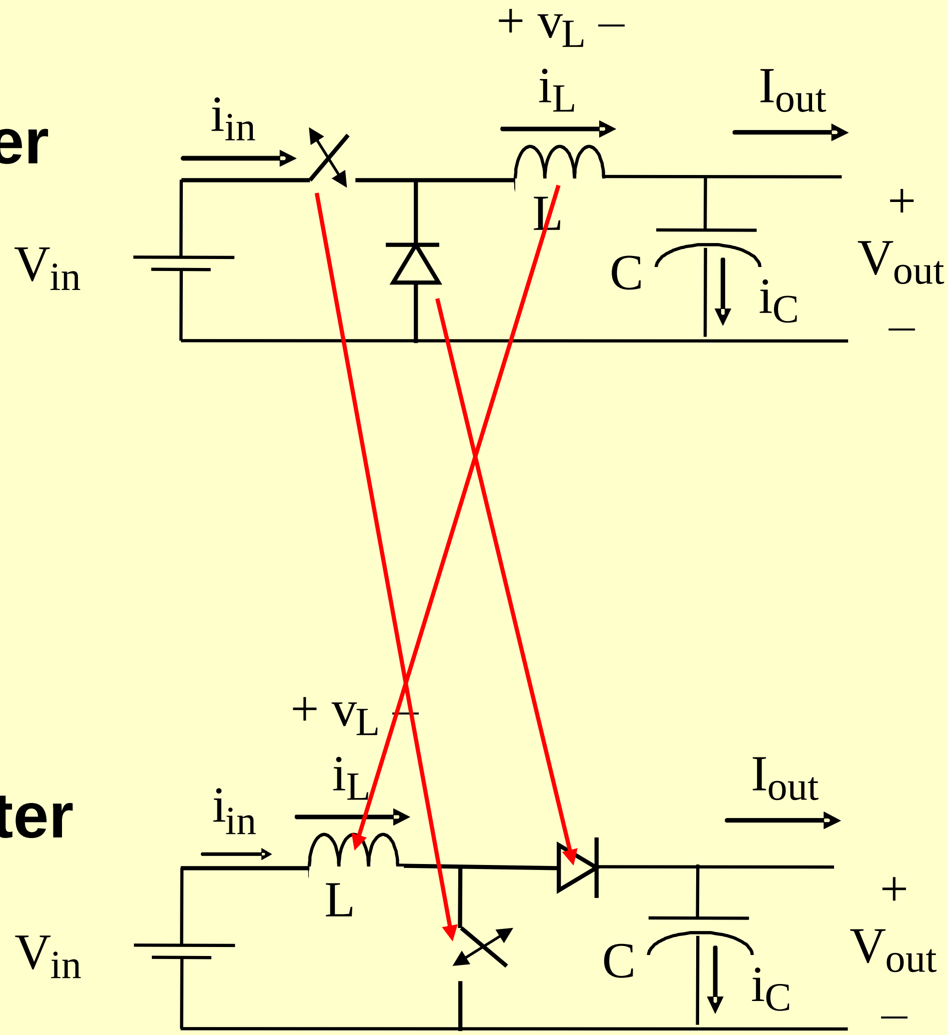


Schematics from http://en.wikipedia.org/wiki/Boost_converter

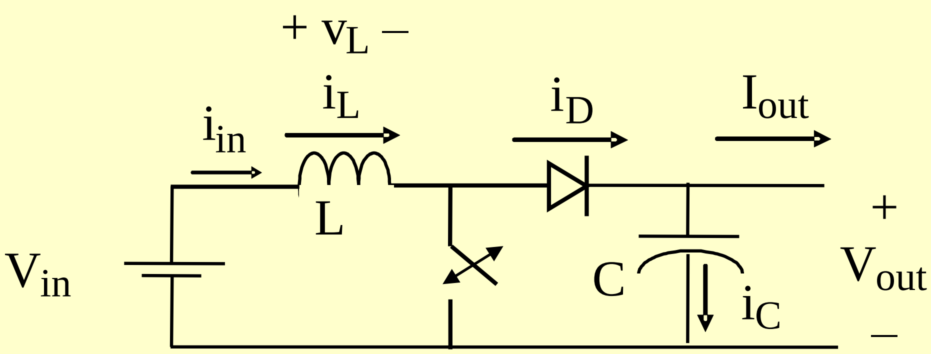
Boost: off state

Buck converter

Boost converter



Boost converter

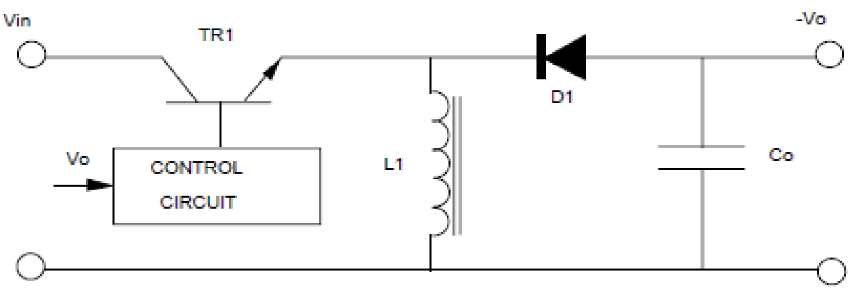


This is a much more unforgiving circuit than the buck converter

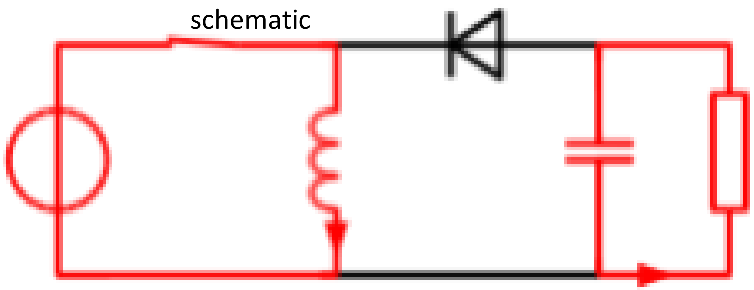
- If the MOSFET gate driver sticks in the “on” position, then there is a short circuit through the MOSFET – blow MOSFET!
- If the load is disconnected during operation, so that I_{out} = 0, then L continues to push power to the right and very quickly charges C up to a high value (≈250V) – blow diode and MOSFET!
- Before applying power be sure that a load is solidly connected

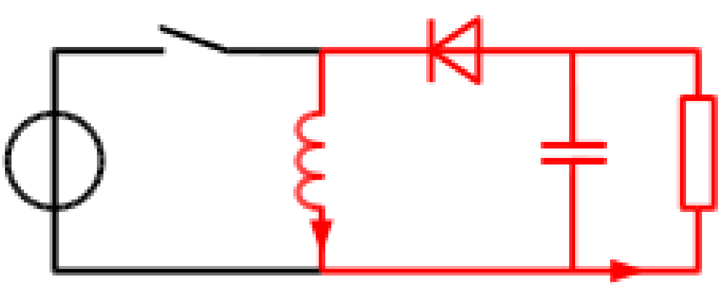
Functionality – Switching Converters

- Common switching converters
  - Buck-boost(inverting)
    - The baby of buck and boost…
    - On state
      - Diode is reverse biased and the inductor is charged but input and output is isolated from each other
        - » Creates more stress on the diode!
      - V_o is now the charged V_c from off state but different polarity
    - Off state
      - Inductor voltage reverses, passing energy to the capacitor and load through forward biased diode
    - Due to the characteristics of boost, buck-boost suffers the same problem. Therefore a discontinuous mode is favored



Generic buck- boost schematic


Buck-boost: on state


Buck-boost: off state

Schematics from http://en.wikipedia.org/wiki/Buck%E2%80%93boost_converter

Functionality – Switching Converters

- To give you a better idea of how duty cycle affect the output of each converter in continuous mode refer to the table below

Converters	Duty cycle impact on output Voltage
Buck	Vout=Vin*D
Boost	Vout=$\frac{Vin}{1-D}$
Buck-boost(inverting)	Vout=$\frac{Vin*D}{D-1}$

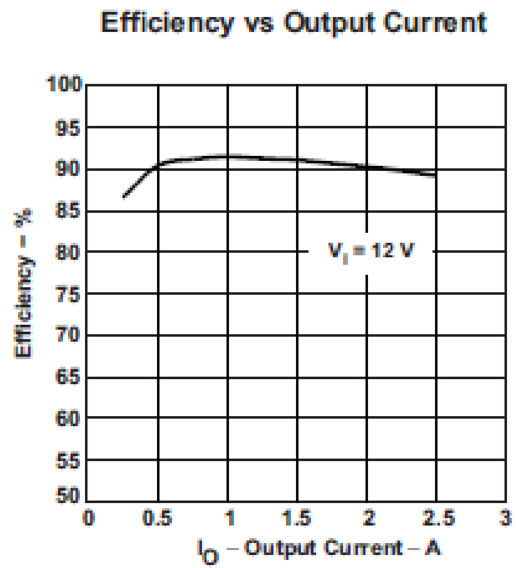
  - In discontinuous mode these equations are no longer true, but we will not discuss them here and they can also be found online
  - More information on switching converters can be found at
    http://educypedia.karadimov.info/library/APPCHP2.pdf
    https://web.archive.org/web/20120306171808/http://ecee.colorado.edu/copec/book/slides/Ch5slide.pdf
    http://www.ti.com/lit/an/slva057/slva057.pdf

Picking converters

- Hopefully at this point you can start to see how much more complicated a switching converter is relative to a linear converter
  - Every change made to the capacitor, inductor, transistor or diode will have an significant effect in not only the efficiency of each converter but also the life and way they operate
  - Fortunately it won't be the end of the world if you decide to use switching converters
    - Using mic2168a, a controller for buck converter, as example. We can see not only do they provide information on the controller but also the external components needed for proper functionality (9pages!).
  - ON semiconductor also provide a detailed, though dated, published paper on both linear and switching regulator, covering the theory and design consideration needed.

Efficiency of switchers

- It's going to vary a lot.
  - Depends on the converter, the output current, etc.
  - Graph on the right is of a TPS5420 under reasonable conditions.
    - Typically has only 18µA current when you shut it down (needs a control pin)



TPS5420