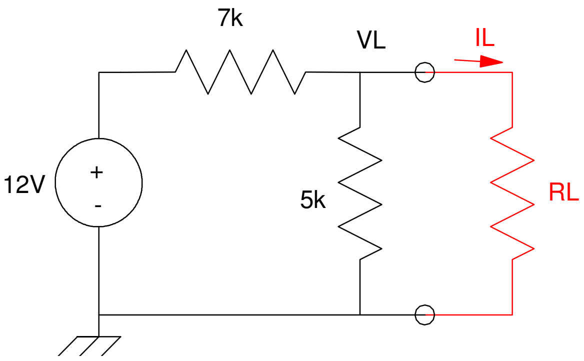
DC to DC Converters

Objective:

- Convert a DC voltage to some other voltage.
- 13.2V is the power to a car. 5V DC is the power for a USB port.
- Going the other way, 5VDC is a common voltage for digital logic. The serial port on a PC needs +/-12V, however.

DC to DC Converter Capable of 0mA

At first glance, you might want to use a voltage divider. This doesn't work very well, however. Consider the problem of dropping 12V down to 5V, capable of driving a 100mA load. If you ignore the load, you can use a 7k and 5k resistor:



If there is no load (IL = 0), the load voltage is 5V

$$V_L = \left(\frac{5k}{5k+7k}\right)12V = 5.00V$$

If you try to add a load which requires 100mA, however

$$R_L = \frac{5V}{100mA} = 50\Omega$$

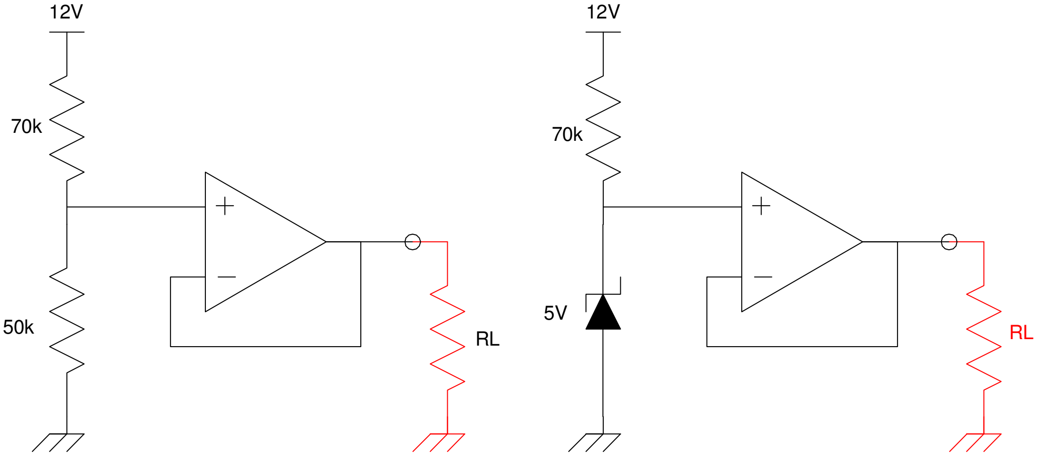
the voltage drops

$$V_L = \left(\frac{5k||50}{5k||50+7k}\right)12V = 0.08V$$

A voltage divider works as long as you don't use it.

DC to DC Converter Capable of 20mA: (take 2)

If you can find an op-amp capable of driving your load, a op-amp buffer fixes this problem



The circuit to the left is less expensive - but the output voltage will vary if the 12V supply varies.

The circuit to the right requires a 5V Zener diode - but it holds the output voltage at 5V even if the 12V supply varies.

The efficiency is about the same for both - still not great. Op-amps work by dumping voltage. If the load draws 100mA, the op-amp draws 100mA from the source to supply the load current. In terms of power, this means

$$P_{out} = 100mA \cdot 5V$$

$$P_{in} \approx 100mA \cdot 12V$$ (plus the power dissipated in the 50k and 70k resistors)

$$\eta = \frac{P_{out}}{P_{in}} = \frac{5}{12} = 41.7\%$$

The problem with these circuits is they require an op-amp capable of driving the load. That can be an expensive op-amp.

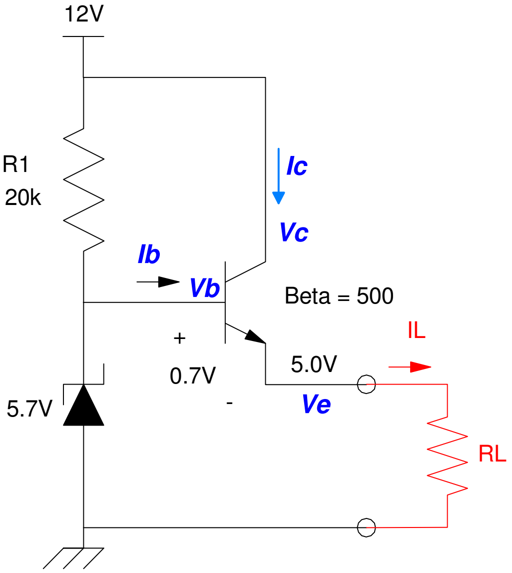
DC to DC Converter Capable of 3A: (7805 Voltage Regulator)

A third solution uses a zener diode and a transistor. Transistors are current amplifiers where

$$I_c = \beta I_b$$

where β is the current gain. If you use a transistor with a gain of 500 (a typical gain), the following circuit will have

- A zener diode holding the voltage Vb at 5.7V
- The arrow in the transistor indicated a diode with a 0.7V drop. This results in Ve = 5.0V (as desired)
- The transistor amplifies the current: Most of the current to the load (500 parts) come from the power supply (Ic). Only 0.2% come from Ib, preventing loading of the 20k resistor / zener diode.



The advantage of this circuit is it works for a wide range of power supplies: +6V to +36V for a 7805 regulator.

- The lower limit (6.0V) is the minimum voltage you need to drive the zener diode and 20k resistor.
- The upper limit (36V) just relates to the need to cool the regulator.

The disadvantage of a 7805 regulator is its efficiency.

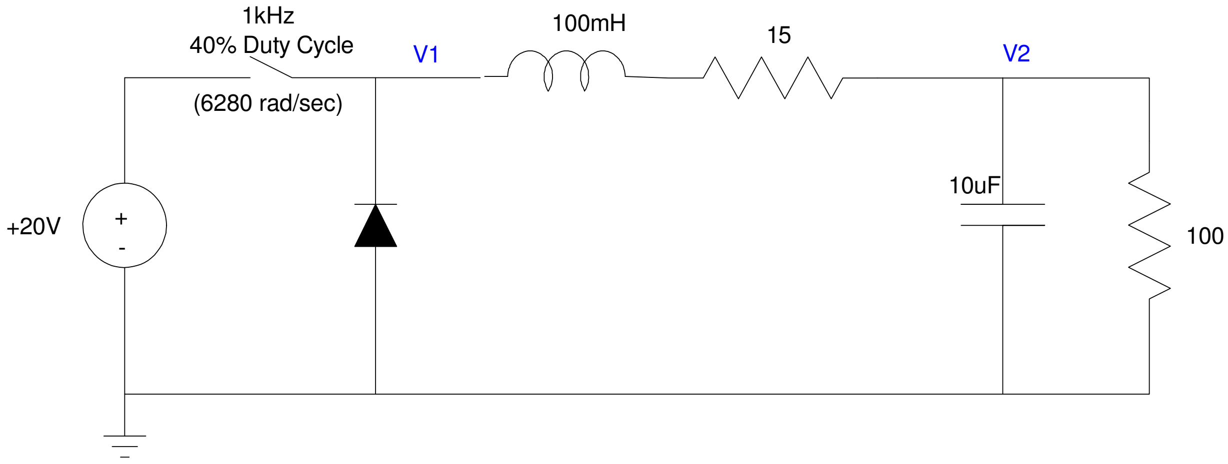
- If the load draws 1A @ 5V, you are delivering 5W to the load.
- Assuming a 12V power supply, 1A @ 12V means you are using 12W

The efficiency is thus:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{5W}{12W} = 41\%$$

Buck Converters: Analysis

A way to get higher efficiency is to use a Buck converter:



Buck Converter

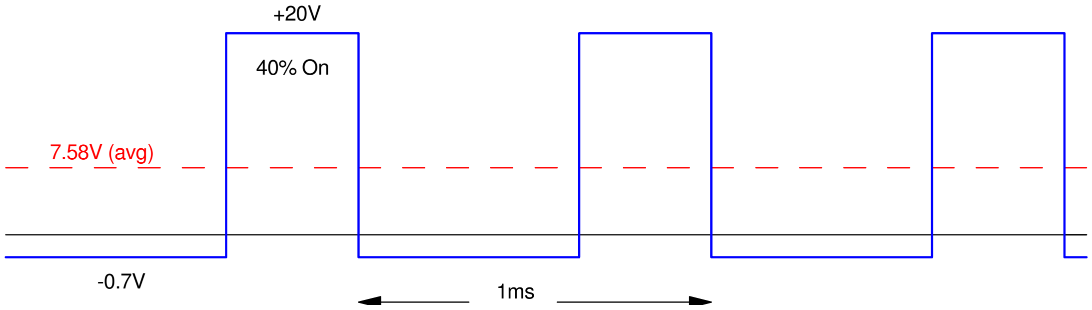
Buck Converter Analysis: Assume the switch closes at 1kHz with a duty cycle of 40%, meaning

- The switch chatters on and off every 1.0ms (1kHz),
- With an on-time of 0.4ms (40% on)

What happens is

- When the switch is closed, V1 = +20V
- When the switch is open, the inductor maintains current flow - sourced by the diode. This diode results in V1 = -0.7V.

This makes V1 a fairly complicated waveform, chattering from 0.7V to +20.0V.



Voltage at V1: When the switch closes, V1 = +20V (40% of the time).
When the switch opens, V1 = -0.7V due to the diode (60% of the time), for an average voltage of 7.58V

Given this waveform at V1, the voltage at V2 is not easilly found. One way to solve this problem is to change the problem so that

- It can be solved (a big plus), but
- It keeps the flavor of the problem at hand.

Assume instead that V1 has just two terms: DC term and an AC term:

- DC: V1 = 7.58V
- AC: V1 = 20.7Vpp @ 1kHz

This approximation isn't exactly correct, but it keeps the flavor of V1:

- The DC level is the same (7.58V)
- The ripple is the same (20.7Vpp), and
- The frequency of the ripple is the same (6280 rad/sec or 1kHz)

But, with this V1 you can now solve for V2 using superposition. That's a big plus.

Using circuits techniques, the voltage at V2 is from voltage division:

$$V_2 = \left(\frac{Z_c || R}{Z_c || R + Z_L}\right) V_1$$

Using superposition, since V1 has two parts, solve for V2 in two parts.

DC Analysis: V1 = 7.58

Inductors and capacitors don't matter at DC. By voltage division

$$V_2 = \left(\frac{100}{100+15}\right) 7.58V$$

$$V_2 = 6.5913V$$

AC Analysis: V1 = 20.7Vpp @ 1kHz

$$\omega = 6280$$

$$Z_L = j\omega L = j628\Omega$$

$$Z_c = \frac{1}{j\omega C} = -j15.9\Omega$$

$$R || Z_c = (2.46 - j15.51)\Omega$$

$$V_2 = \left(\frac{(2.46-j15.51)}{(2.46-j15.51)+(15+j628)}\right) 20.7V_{pp}$$

$$V_2 = 0.5305V_{pp}$$

Note: Take the magnitude of V2. There is also a phase shift (this tells you that V2 is delayed from V1) which we don't really care about.

Add the DC and AC terms together to get V2

- V2(DC) = 6.5913V
- V2(AC) = 0.5305Vpp @ 1kHz

You can verify this in Circuitlab. The trick in CircutiLab is how to build

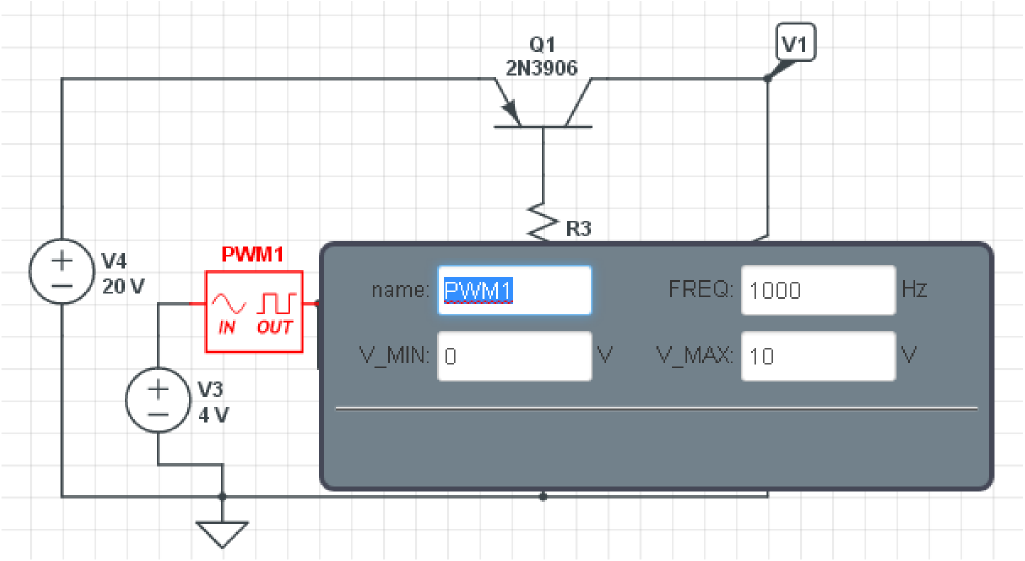
- A switch
- Which is closed 40% of the time

There are a couple of ways to do it. The following follows how you would build this circuit in lab.

First, add a PWM output. This actually would be a microcontroller (like a PIC processor) which outputs

- A 0V / 5V TTL signal
- At 1kHz, with
- 40% duty cycle (on for 400us, off for 600us)

If you set the limits to 0V & 10V, the 4V in sets the duty cycle to 40%.

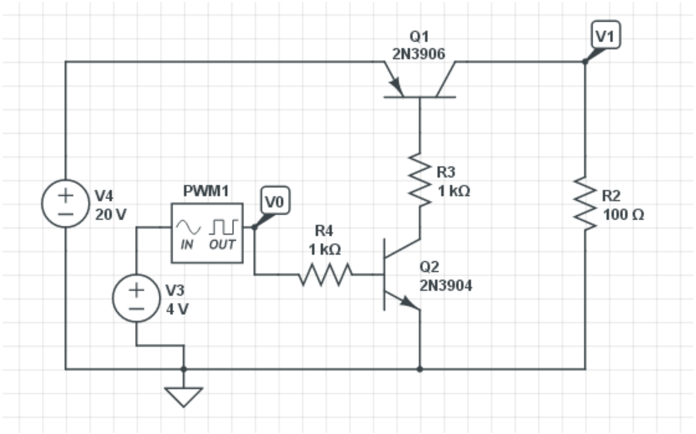


name: PWM1
FREQ: 1000 Hz
V_MIN: 0 V
V_MAX: 10 V

CircuitLab: Use a PWM block to generate the 40% duty cycle square wave

Next, to create the switch, use a PNP transistor as a switch.

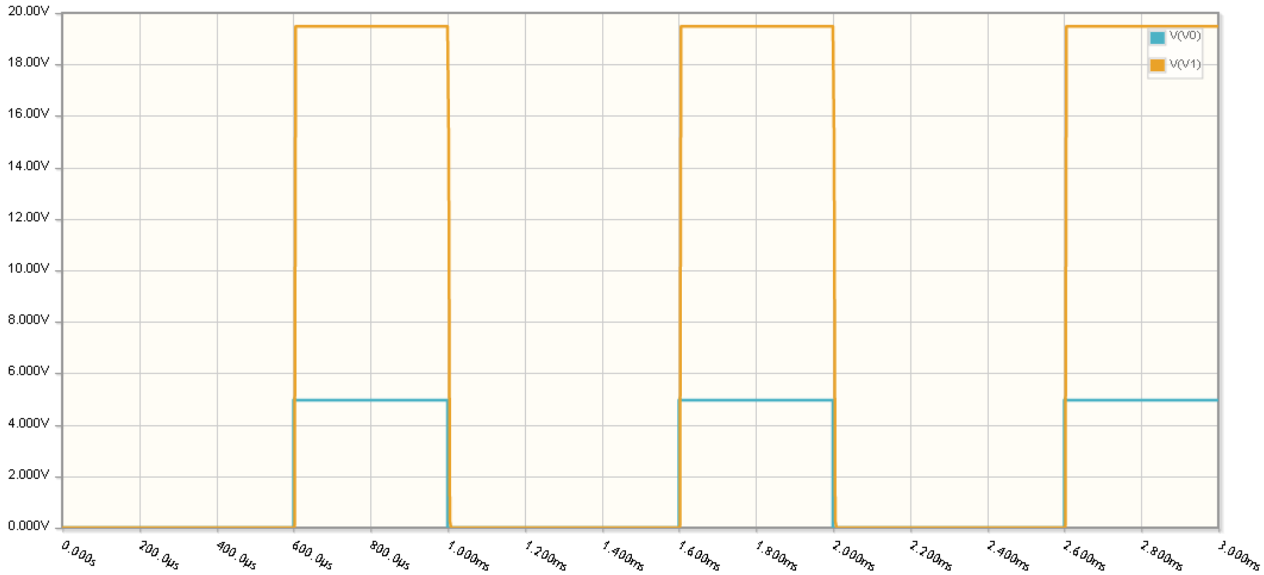
- When V0 = 5V, Q2 saturates which in turn saturates Q1 (switch closed)
- When V0 = 0V, both Q1 and Q2 are off (switch open)



A time-domain simulation checks that this circuit is working

- When V0 = 0V, the switch is open (V1 = 0V)
- When V0 = 5V, the switch is closed (V1 = 19.48V)

Vce for Q2 is 0.52V - it's saturated with 198mA flowing (about the maximum a 3904 can take)

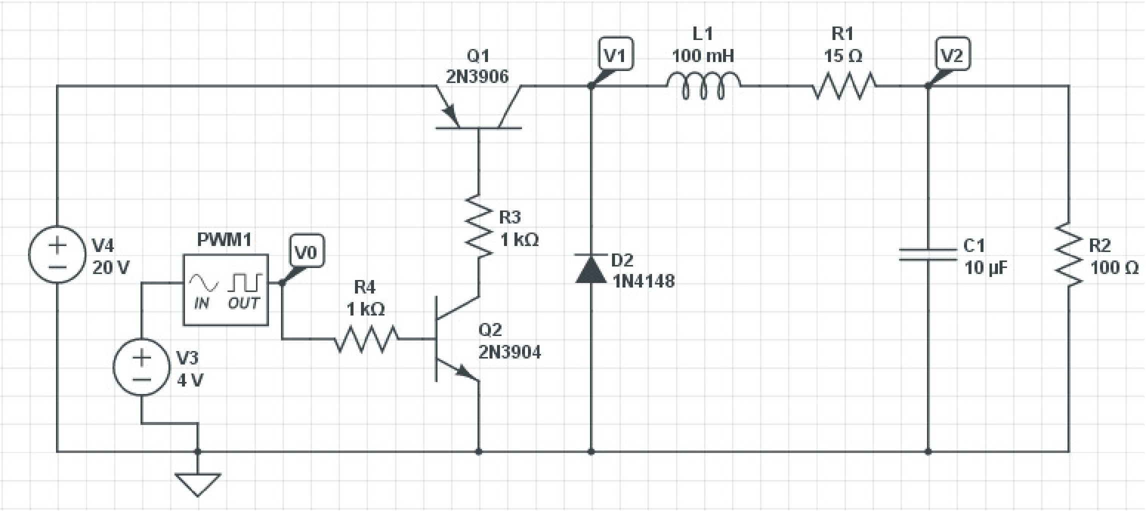


Test to see that the switch is working: When V0 = 5V (blue), the switch is closed (V1 = 19.48V, orange)

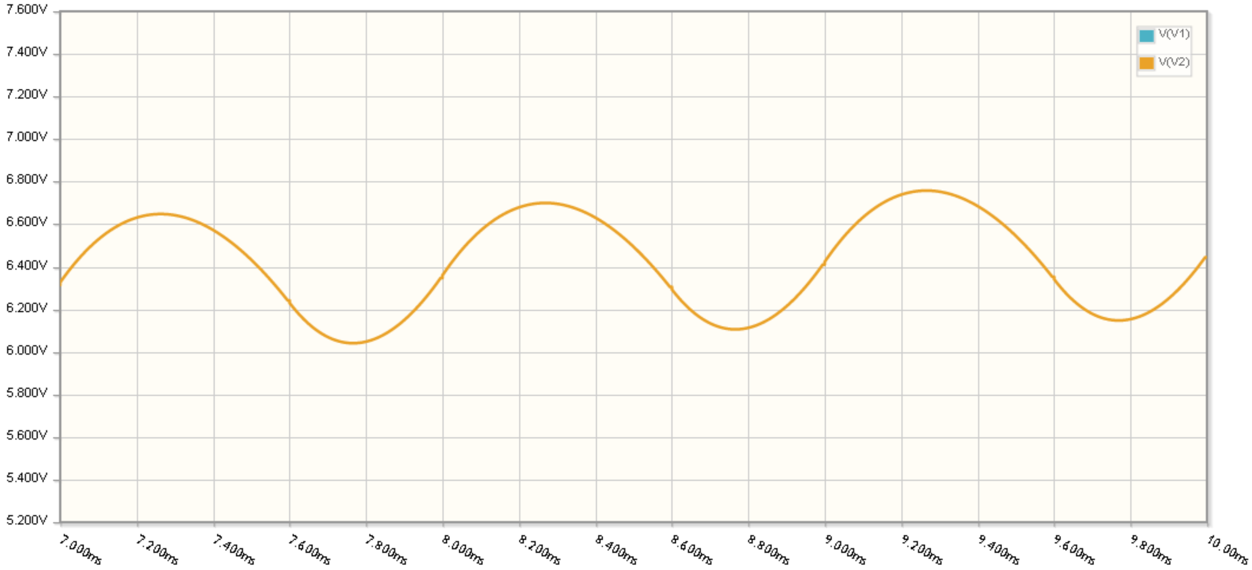
The rest of the circuit serves as a filter to

- Pass the DC signal (the average of V1), and
- Block the AC signal (the 20Vpp ripple on V1)

Checking in CircuitLab to make sure this works,



Buck converter: Q1 acts as a switch. L1 and C1 serve as filters to reduce the AC ripple at V2.



Voltage at V2 when C2 = 10uF. Adding C2 reduces the ripple another 6x (j15.9 Ohms vs. 100 Ohms)

	V2(DC)	V2(AC)
Calculated	6.5913 V	530.5 mVpp
Simulated	6.404 V	592 mVpp

Note that our calculations are slightly off. This is due to making several approximations with the circuit analysis. You can get more accurate answers using Fourier Transforms (coming up), but this is a LOT more work for slightly improved results.

If you want more accurate answers, use CircuitLab.

Buck Converters and Efficiency

The big advantage of a Buck converter is its efficiency. An 7806 voltage regulator is 305% efficient (6V / 20V).

When the switch is closed (40% of the time here), the efficiency is 84.7%.

- Current = 65.9mA (on average)
- Power to the 100 Ohm load = 434.5mW
- Power to the 15 Ohm resistor (part of the inductor) = 65.2mW
- Power to the 0.2V drop across Q1 = 13.2mW

$$\eta = \frac{\text{power to load}}{\text{total power}} = \frac{434.5mW}{434.5mW+65.2mW+13.2mW} = 0.8473$$

When the switch is open (60% of the time), the efficiency is 79.6%

- Current = 65.9mA (on average)
- Power to the 100 Ohm load = 434.5mW
- Power to the 15 Ohm resistor (part of the inductor) = 65.2mW
- Power to the 0.7V drop across the diode = 46.1mW

$$\eta = \frac{\text{power to load}}{\text{total power}} = \frac{434.5mW}{434.5mW+65.2mW+46.1mW} = 0.7961$$

The net efficiency is

$$\eta = 0.4 \cdot (84.7\%) + 0.6 \cdot (79.6\%)$$

$$\eta = 81.6\%$$

Buck Converter Design

Design a Buck converter to convert

- +20VDC to +5VDC,
- With a ripple of 500mVpp,
- A switching frequency of 1kHz, and
- A 100 Ohm load (50mA).

Solution: First, determine the DC voltage at V1 and the duty cycle. If V2 has a DC value of 5.00V, then by voltage division

$$V_2 = \left(\frac{100}{100+15}\right) V_1$$

$$V_1 = \left(\frac{100+15}{100}\right) V_2 = 5.75V$$

The duty cycle is then

$$5.75V = \alpha \cdot 20V + (1-\alpha) \cdot (-0.7V)$$

$$\alpha = \left(\frac{5.75+0.7}{20+0.7}\right) = 0.3116$$

The duty cycle should be 31.16%.

Second, add L (assume C = 0). Assume L reduces the ripple at V2 by 10x is to be 2.07Vpp (somewhat arbitrary). To reduce the ripple 10x, make the impedance of L 10x that of R:

$$|j\omega L| = 10R$$

$$L = \left(\frac{10R}{\omega}\right) = 159.2mH$$

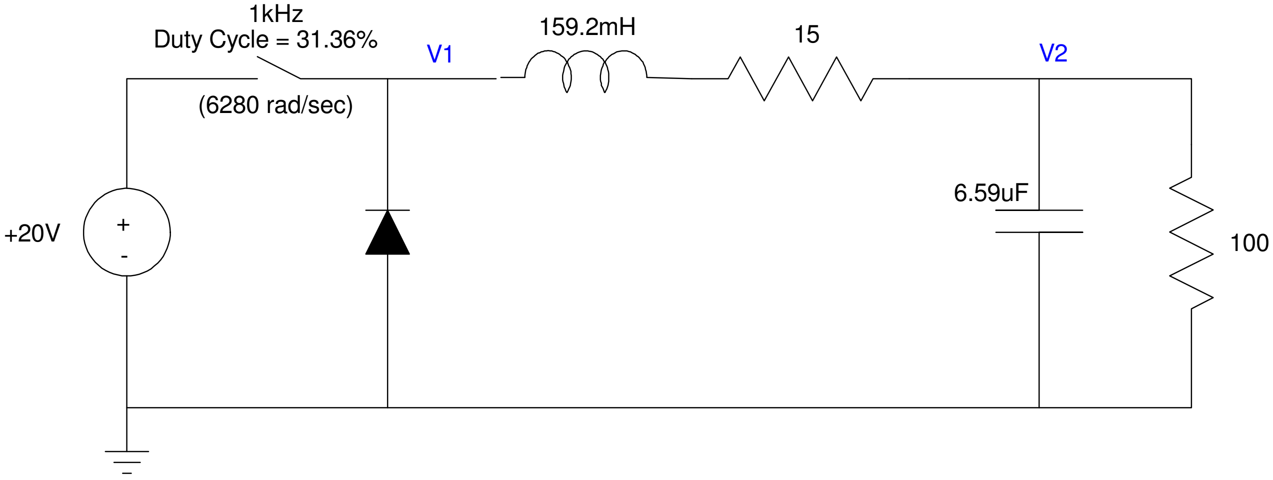
This should reduce the ripple at V2 to 2.07Vpp.

Finally, add C. C reduces the ripple from 2.07Vpp to 0.5Vpp, a reduction of 4.14x. To do this, pick C so that its impedance is 4.14x smaller than R

$$\left|\frac{1}{j\omega C}\right| = \frac{1}{4.14} \cdot R$$

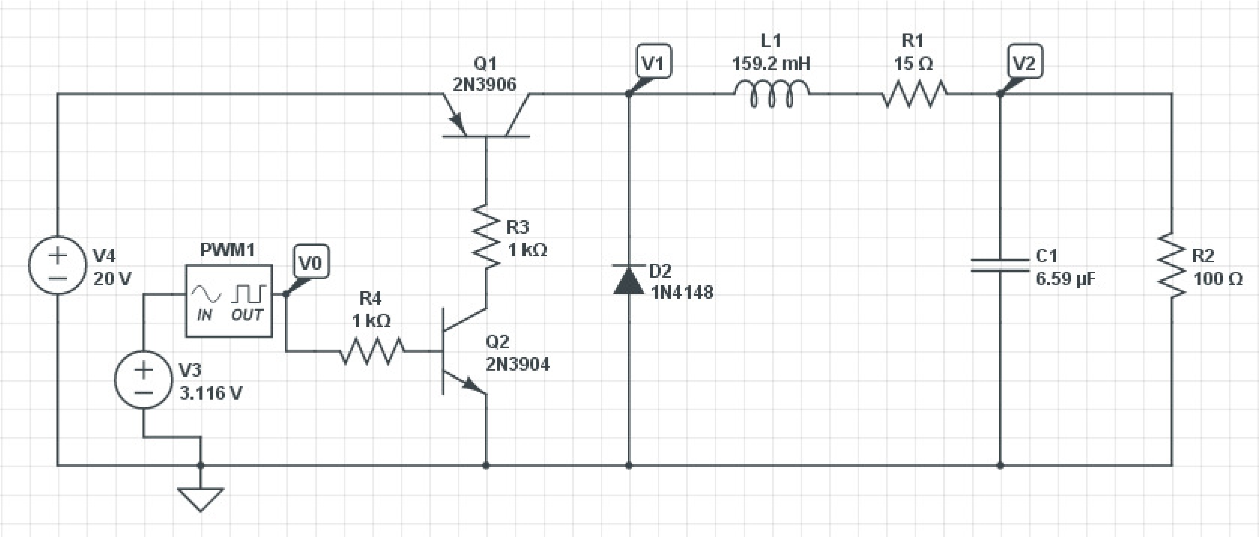
$$\frac{1}{\omega C} = 24.15\Omega$$

$$C = 6.59\mu F$$

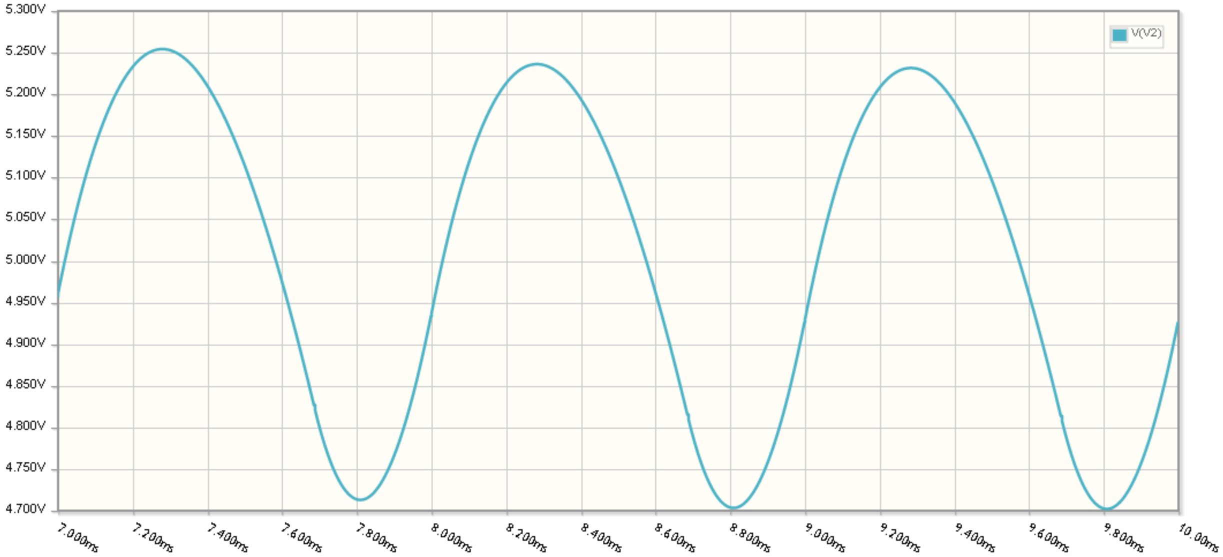


Resulting Buck converter: V2 should be 5.00V DC with 500mVpp ripple

Checking in CircuitLab



Schematic for CircuitLab implementation of a Buck Converter



V2 vs. Time for the Buck Converter

The CircuitLab results match up with our calculations:

	V2(DC)	V2(AC)
Calculated	5.00 V	500.0 mVpp
Simulated	4.97 V	532 mVpp

Note that the ripple at V2 is 6% too large. If you make C2 6% larger (7.01uF), the ripple becomes the 500mVpp as desired.