Simple 40106 oscillator with diode-based CV input

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Comments, suggestions and corrections are welcomed & encouraged:
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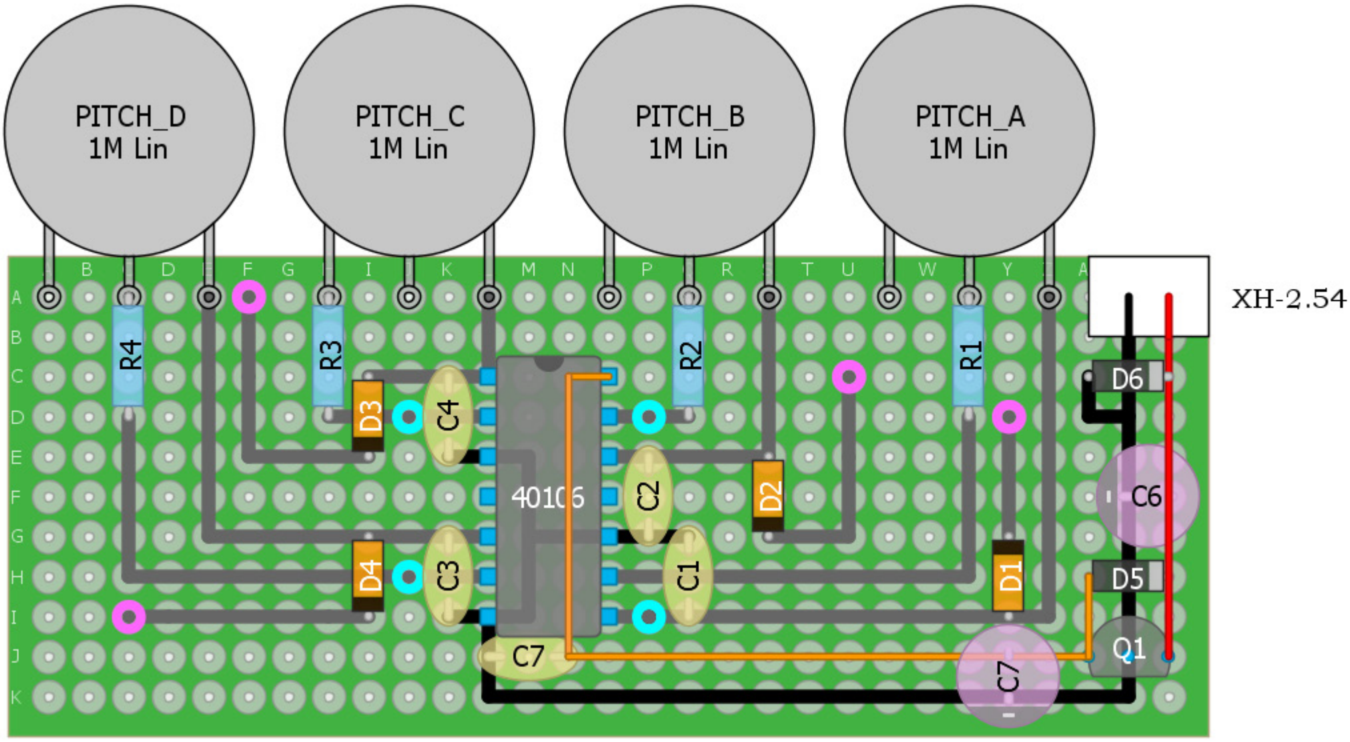
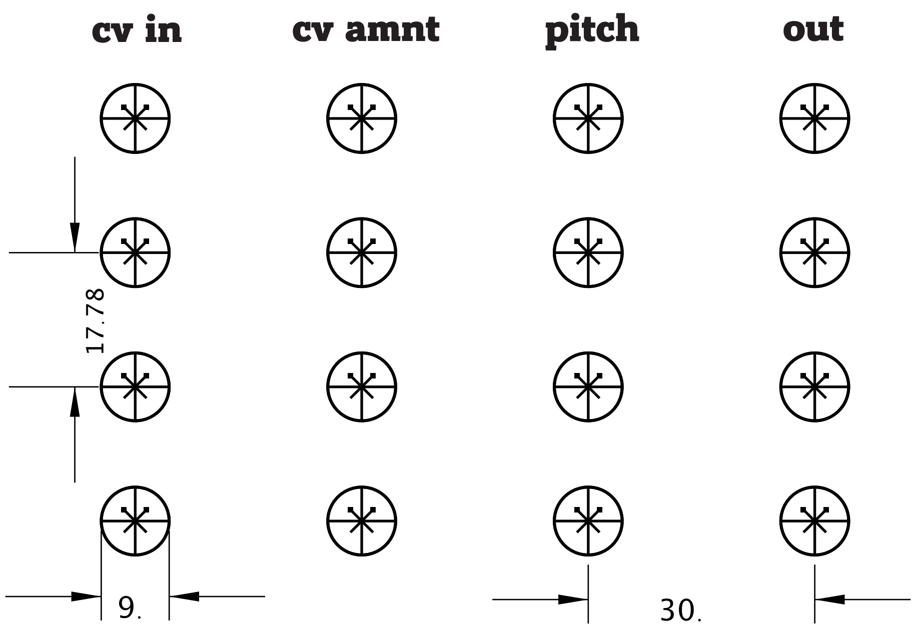
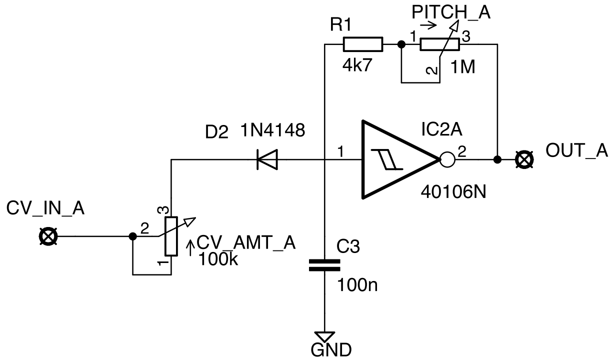


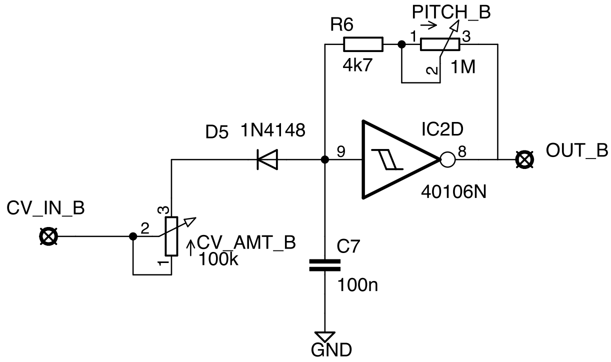
Pink to CV amount pots, Blue to out

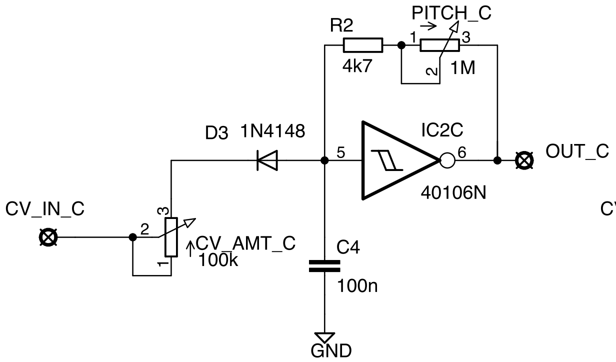


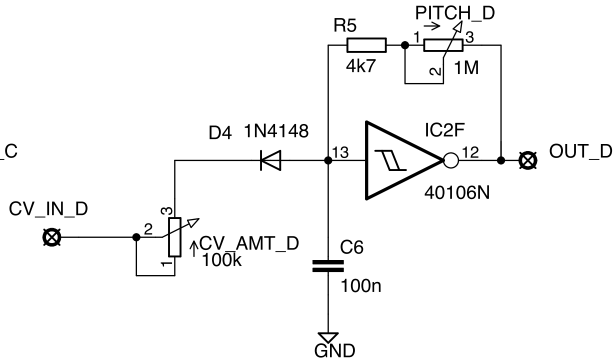
All measurements in milimeters

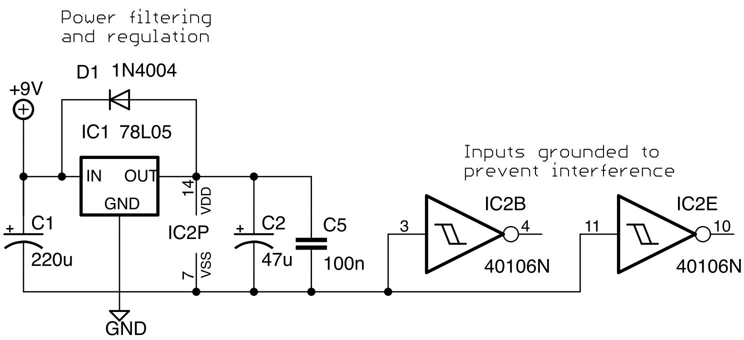
1:1 scale











ICs

78L05	*x1*
40106	*x1*

Pots

B1M	*x4*
B100k	*x4*

Resistors

4.7k	*x4*

Capacitors

220uF	*x1*
47uF	*x1*
100nF	*x5*

Diodes

1N4148	*x4*
1N4004	*x1*

Connectors

Banana Jack	*x8*
XH-2.54	*x1*

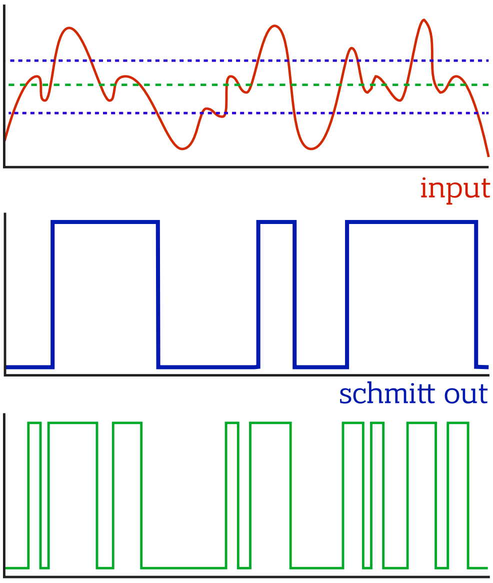
1. Circuit Overview

1.1 The 40106 Hex Inverting Schmitt Trigger

This little oscillator module is based on a combination of the MFOS Weird Noise Generator[1] and a schematic on the dlb electronics website[2]. Both of theses square-wave generators are based around the 40106 Hex Inverting Schmitt trigger chip.

Schmitt triggers are a special type of comparator. Comparators compare their input to some reference and output a high or low voltage depending on if the input is higher or lower than the reference.

The difference between a Schmitt trigger and a normal comparator is that a Schmitt trigger moves its reference voltage. This might be a little tough to understand at first, but try looking at *(fig 1.1a)* which compares a non-inverting Schmitt trigger to a comparator.

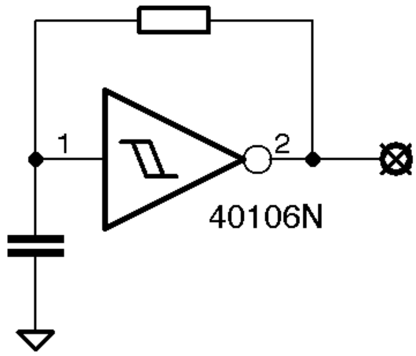


(fig 1.1a)

You'll notice that while the comparator has only one threshold, the Schmitt has two – an upper and a lower. The comparator will change its output no matter how little an amount the input goes over its threshold. The Schmitt trigger needs the input to cross over the its lower threshold after it goes high and its higher threshold when it goes low. This has a lot of practical applications in electronics because it lets us ignore small changes, like noise, and pick out bigger movements – which also removes the noise and interference from our output.

1.2 Getting the 40106 to make noises

To get our Schmitt triggers to start oscillating we only need to add a resistor and a capacitor *(fig 1.2a)*



(fig 1.2a)

Any resistor and any capacitor will do but try out a 100n cap and a 100k resistor first. Put another cap between the output and your amp and then listen to that sweet, sweet square-wave drone. Keep the volume low though! If you are using a 9V battery then that square wave is going to be a full 9 volts peak-to-peak!

What seems at first like witchcraft and mystery is actually fairly simple, and depends on the capacitor changing the voltage at the Schmitt trigger's input to make it switch up and down fast enough to be heard as sound.

When capacitors have current fed into them, they store that current

[1] *http://www.musicfromouterspace.com/*
[2] *http://dlbelectronics.com/lunetta*

as charge. And the more charged up they are, the bigger a voltage difference there is between their two terminals.

Caps don't just charge though, they also discharge and spit current back out when they get the chance to.

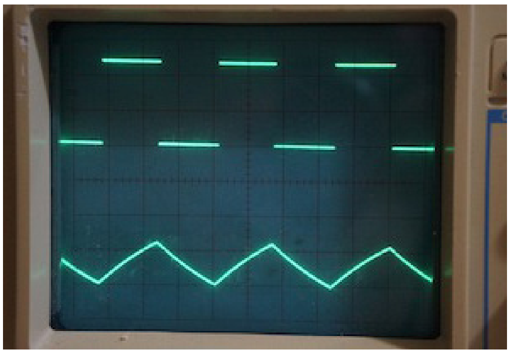
This charging and discharging, along with the Schmitt trigger inverting its output are what make the magic happen.

Lets consider what happens when we first power up the circuit. At t=0 (a.k.a the start), the cap has no charge in it so there is 0V worth of difference between the two sides of it. This means that the input of the Schmitt trigger, which is connected to one side of the cap, sees this 0V. The Schmitt trigger, being an inverting Schmitt trigger goes high in response. This means the output of the Schmitt trigger will jump up to 5V or 9V (or whatever you are powering the chip with – we're going to go with 5V from this point on though to make things simpler.)

However, we've been sneaky and we've hooked up the output of the Schmitt trigger to the cap with a resistor in between. Now, the resistor sees 5V on one side of it and 0V on the other so it allows current to flow through it. This current flows into the capacitor, which reacts to the current by charging up and making a bigger and bigger voltage drop across its two sides. It would keep going too, all the way to 5V if it wasn't for something in its way – the Schmitt trigger.

When the cap has a certain amount of charge stored, the voltage drop across it will reach the upper threshold of the Schmitt trigger. When this happens, the Schmitt trigger jumps down to 0V. Now the resistor sees a 0V at one side and a charged capacitor at the other, so it starts to let the current flow again. This time however, it's flowing the other way. Similarly, the current is coming from our cap, who is spitting its stored charge out through the resistor. As it spits it out, the voltage across it drops lower and lower, and it would make it all the way down to 0V if it wasn't for the same problem it had last time: the Schmitt trigger.

If you guessed that when the cap discharges enough, the Schmitt trigger will go high again, then congratulations! If you take a look at this photo of an oscilloscope trace *(fig 1.2b)* you can see this back and forth charging and discharging in action. The top trace is the output and the bottom is the voltage at the cap and the Schmitt trigger's input.



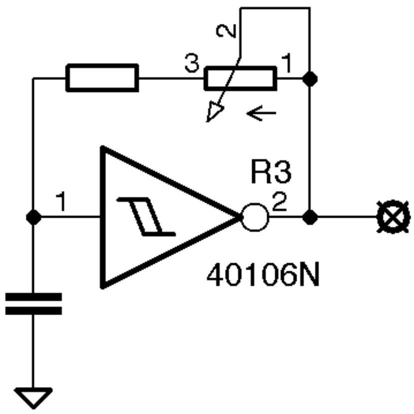
(fig 1.2b)

1.3 Changing the pitch

One of the other things that makes using the 40106 as an oscillator so fun and simple is how easy it is to change the pitch. All you need to do is add a pot wired in series with the resistor *(fig 1.3a - next page)*.

How does changing the resistance change the pitch? Well as we noted before, caps charge when current flows into them. Resistors allow us to set exactly how much current we want flowing thanks to ohm's law.

We're going to go into more detail later about how to calculate the frequency in section 2, but for

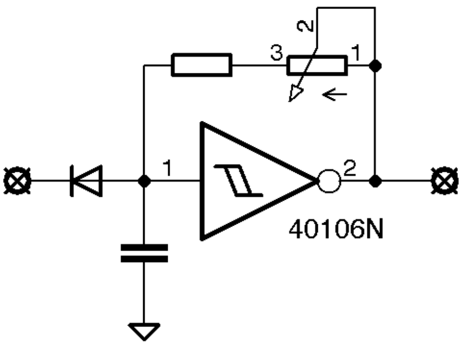


(fig 1.3a)

now all you really need to know is that a bigger resistance means less current. Less current means both slower charging and discharging of the cap - thus, a lower pitch. Conversely, a smaller resistance means more current which in turn allows for faster charging and discharging – resulting in a higher pitch.

1.4 Adding a diode

Here's where the Weird Sound Generator and dlb electronics influence comes in to play. We've added some very simple voltage control by attaching a diode to the input of the Schmitt trigger *(fig 1.4a)*.

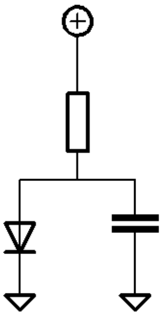


(fig 1.4a)

At first glance it might not be obvious how this diode allows cv control at all. For one, it's facing "outwards" so no current is going to be able to flow from outside the circuit in. In fact, the opposite is going to happen – current is going to flow out!

This might seem like the opposite of what we want to do but lets look at what a 0V CV in at the diode looks like when our capacitor is charging *(fig 1.4b)*.

As you can see, this is the same as tying the cathode (the negative side) of the diode to ground. If you didn't already know, silicon diodes need a voltage drop of ~0.6V to turn on. After they are turned on, they can pretty much allow any amount of current to flow through them. This means that we can be certain that after the voltage drop across the diode reaches 0.6V, it will ultimately pin the voltage at its annode (positive side) to ~0.6V above ground. The input will never be able to get any higher than 0.6V because all the current coming in will end up flowing through the diode to ground and not into the cap. Any that does flow into the cap and does charge it to above 0.6V will get sucked back out by the diode anyway.

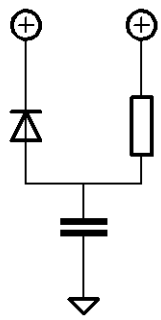


(fig 1.4b)

0.6V sounds pretty low, and that's because it is. If we think back to our Schmitt trigger's upper threshold, it will be around 2/3rds of our power supply. Even at 5V the threshold will be around 3.3V – much higher than 0.6V. This means that our cap is going to be unable to charge itself high enough to make the Schmitt trigger's output change – our oscillation has stopped.

Let's look at what happens when the CV input is at 5V *(fig 1.4c)*.

With the CV up at 5V, the diode is now back biased – no current is able to flow. This is because there is no way for the voltage at the



(fig 1.4c)

annode side to get to 5.6V, the 0.6V higher than the cathode needed to let current flow. This is for two reasons: the circuit only goes up to 5V, so 5.6V is impossible; even if it was, the Schmitt trigger would flip and the cap would start discharging before the voltage got there. This means that with our CV at 5V, our oscillator is oscillating again.

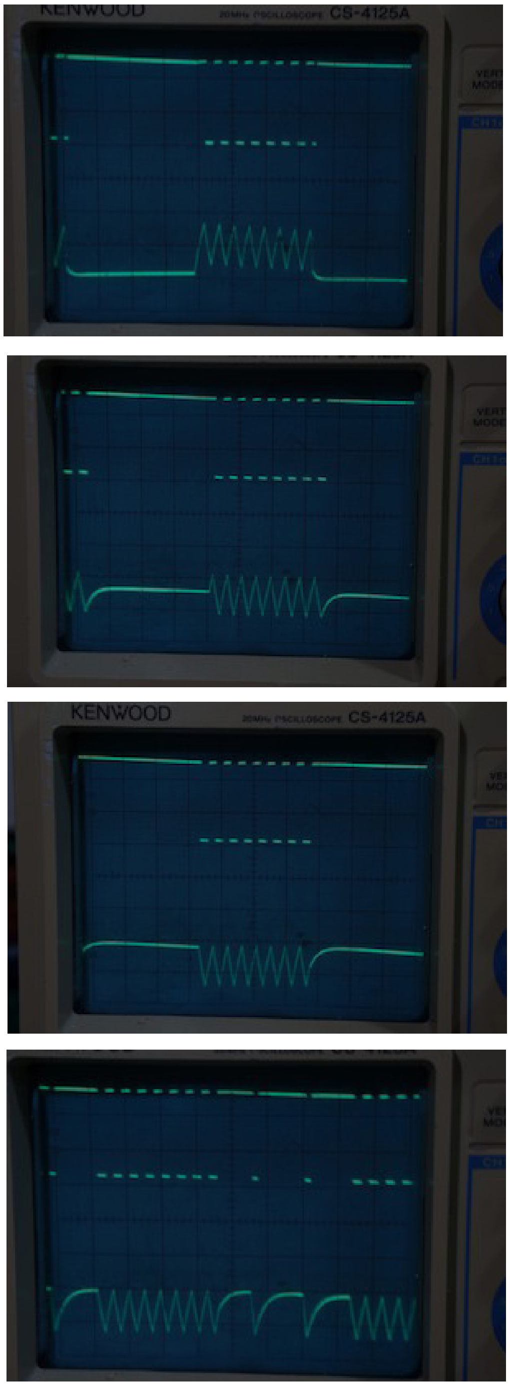
This might seem a little pointless at first, as all we seem to have done is made a switch so far. However, we have made an incredibly fast switch. We have made a switch that can go so fast that it can switch the oscillator on and off at an audio rate. This lets us create some really cool pseudo-sync sounds when we pump in an audio rate CV, or some more traditional on-off-on-off tremolo sounds with an LFO.

1.5 Adding another pot for better CV control

Although this kind of gating & sync sound is really cool and very useful, it's always nice to have even more options and control. Adding a pot between the diode and the the CV input gives us exactly that.

How does it work though? Again, we're going to leave the specifics and maths till the next chapter but for now it will probably help a lot to take a look at this series of oscilloscope traces *(fig 1.5a – d)*. Again top is the output and the bottom is the voltage at cap and the input to the Achmitt trigger.

Turning up the resistance brings the flat sections (where the CV is at 0V) up untill they become high enough to allow oscillation. This happens because for the diode to switch itself on, it needs to source current. When it does this however, the current flows through our CV amount pot, which is being used as a resistor, and the current



(fig 1.4 a – d)

flow causes a voltage drop across the pot. The ~0.6V voltage drop across the diode is then added to this voltage drop, also raising the voltage the cap can charge to.

There is something else at play here too, which is what gives us the actual pitch control. The diode's knee.

You can see this in oscilloscope trace *(fig 1.4d)*. Notice how the cap's charging is not a straight line, but obviously curved. This is because for a small region of the diode's conduction, the current through it increases slowly.

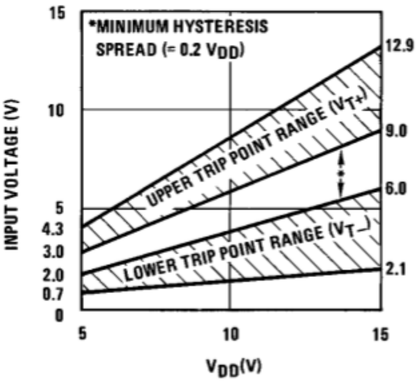
You might also notice that the fact the speed of charging is far more affcted. As a result, when we changge the oscillator's pitch we also change the duty cycle. The output is no longer so close to a 50/50 waveform. Instead, the pitch changes by making the output spend more time high but all of the low parts of the waveform will will be almost the same length as they were before.

2. Analysis

2.1 Calculating the oscillator frequency

Unfortunately, there is one drawback of using a 40106 as an oscillator: its not possible to calculate the frequency exactly for all chips. The reason for this lies in small differences between chips that causes the upper and lower thresholds to be different for every ic. Fortunately, these aren't really different enough to matter too much, especially since we're not trying to build the next great poly synth so accuracy isn't too big a deal.

If we look at the National Semiconductor datasheet we can get an idea of how much variation there can be *(fig 2.1a)*.



(fig 2.1a)

The National Semiconductor datasheet is also nice enough to include the oscillator we are using as an example and provide the following equation for the frequency:

$$f \approx \frac{1}{RC \ln\left(\frac{V_{T+}(V_{DD}-V_{T-})}{V_{T-}(V_{DD}-V_{T+})}\right)}$$

That probably just looks like a scary mess of mathematics right now but fear not, we'll work through it step by step.

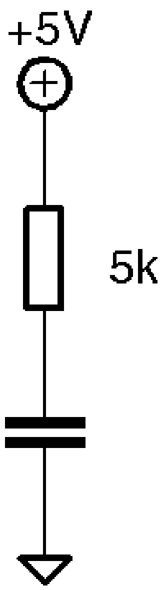
2.1.1 The RC time constant

The first step to calculating the frequency is figuring out how fast our capacitor charges and discharges. We've already established that more resistance means slower and less means faster. Luckily, some smart engineer out there came up with this incredibly important and thankfully simple equation:

$$\tau = RC$$

The Greek letter τ ("tau") represents the time it takes for a capacitor to charge ~63.2% of the difference between its starting point and its target, or to discharge to ~36.8%. ~63.2% and ~36.8% might seem like strange numbers at first, but actually come from the mathematical constant *e*. From this point on, we're going to forgoe using τ and just use RC. This is to avoid confusion when we use *t* to represent time in seconds.

Lets take a few steps back and revisit a simple resistor charging a capacitor circuit *(fig 2.1.1a)*.

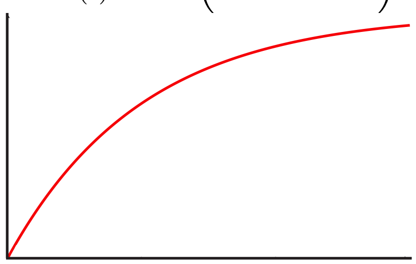


(fig 2.1.1a)

When we switch the power on (*t=0*), the capacitor is completely empty and both of its sides are at 0V. This means that the resistor has a full 5V across it. Thanks to the power given to us by the mighty law of Ohm, we can now easily calculate exactly how much current flows through the resistor. I=V/R so 5V/5kΩ=0.1mA.

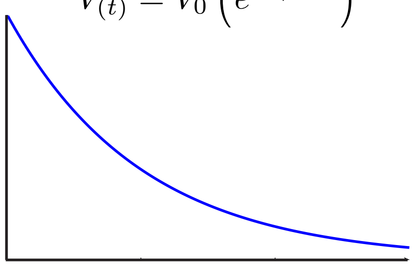
However, with every bit of current that flows into the capacitor, the capacitor will also charge. When it charges, the voltage drop across its terminals increases. This causes the voltage drop across the resistor to shrink, making less current flow, which in turn means the capacitor is charges slower with every bit of current that flows into it. This happens right up until the cap gets to its target of 5V, after which no current flows.

$$V_{(t)} = V_0 \left(1 - e^{-t/RC}\right)$$



(fig 2.1.1b - charging)

$$V_{(t)} = V_0 \left(e^{-t/RC}\right)$$



(fig 2.1.1c - discharging)

Luckily, this is very easy to graph thanks to that nice constant *e* we mentioned earlier.

$V_{(t)}$ represent the voltage at some point after *t* seconds. To find the voltage after 1 second we just replace every *t* on the right hand side with 1, for two seconds in we'd replace them with 2, and so on.

We should make the point here that V_0 is difference between the voltage already across the cap and its target. In our simplified circuit, that means 5V for charging as we are charging from 0V to 5V. For discharging it would mean 5V again, as we're heading from 5V to 0V.

So why ~63.2% and 36.8%? Well, when *t* = RC, then ${}^{-t}/_{RC} = {}^{-RC}/_{RC}$ so ${}^{-t}/_{RC} = -1$ and e^{-1} is ~0.368.

2.1.2 Accounting for the Schmitt trigger output changing

Before we mentioned that our capacitor's target when it charges is 5V. However, it never gets there because the Schmitt trigger with switch to a low output before the capacitor makes it. Similarly, after the output switches, the capacitor wants to start discharging down to 0V, but again never makes it. For our circuit this affects the starting point for its charging and discharging cycles, so we have to adjust V_0 to compensate for this.

This is where our manufacturing inconsistencies stop us from being precise without measuring the exact chip we are going to be using so instead we are going to come up with a generic expression we can use. Let's look at how it affects our discharging half of the cycle first as it's a little simpler.

2.1.3 Calculating time for cap to discharge to the lower threshold

To get the right answer, we are going to need to do a little bit of tweaking to our cap discharge expression. We'll need to figure out V_0 needs to be replaced with. V_0 is always the difference between our starting voltage and our target voltage.

Luckily, in this example our solution is simple. It's the upper threshold of the Schmitt tsrigger V_{T+}. This is because when the input of the Schmitt trigger's input hits this voltage. the output goes low and discharging begins. Remember, as far as the capacitor is concerned, it's trying to discharge all the way to ground, so the difference between the start and the target is just going to be:

$$V_0 = V_{T+} - 0 = V_{T+}$$

We can figure out what that would look like with the following expression

$$V_{(t)} = V_{T+} \left(e^{[-t/RC]}\right)$$

To figure out how long it will take for voltage at the input to reach the lower threshold we need to find the *t* for which $V_{(t)} = V_{T-}$

$$V_{(t_{discharge})} = V_{T-} = V_{T+}\left(e^{-t/RC}\right)$$

$$\frac{V_{T-}}{V_{T+}} = e^{-t/RC}$$ *Divide both sides by V_{T+}*

$$-\frac{t}{RC} = ln\left(\frac{V_{T-}}{V_{T+}}\right)$$ *If $x = a^y$, then $y = log_a(x)$*

$$-t = RC\ln\left(\frac{V_{T-}}{V_{T+}}\right)$$ *Multiply both sides by RC*

$$t_{discharge} = RC\ln\left(\frac{V_{T+}}{V_{T-}}\right)$$ $log_a(x/y) = -log_a(y/x)$

2.1.4 Calculating time for cap to charge to the upper threshold

We're going to do the exact same thing this time, except the cap is trying to get from V_{T-} to whatever our supply voltage is. So we need to adjust Vo appropriately.

$$V_0 = V_{DD} - V_{T-}$$

When dealing with CMOS chips we usually refer to our positive power supply V_{DD}.

We also have to account for the fact that the cap is already partially charged so we're going to add V_{T-} to our result to compenate for this.

$$V_{(t)} = (V_{DD} - V_{T-})(1 - e^{[-t/RC]}) + V_{T-}$$

This time we want to replace $V_{(t)}$ with V_{T+} because we are interested in when the voltage across the cap will reach the upper threshold. Again, we are trying to move everything around till only *t* is on the left hand side:

$$V_{(t_{charge})} = V_{T+} = V_0\left(1 - e^{-t/RC}\right) + V_{T-}$$

$$V_{T+} = V_0 - V_0\left(e^{-t/RC}\right) + V_{T-}$$ *multiply out brackets*

$$-V_0\left(1 - e^{-t/RC}\right) = -V_0 + V_{T+} - V_{T-}$$ *subtact* V_0 *and* V_{T-} *from both sides*

$$V_0\left(e^{-t/RC}\right) = V_0 - V_{T+} + V_{T-}$$ *convert signs*

$$e^{-t/RC} = \frac{V_0 - V_{T+} + V_{T-}}{V_0}$$ *divide both sides by* V_0

$$e^{-t/RC} = \frac{V_{DD} - V_{T-} - V_{T+} + V_{T-}}{V_{DD} - V_{T-}}$$ $V_0 = V_{DD} - V_{T-}$

$$e^{-t/RC} = \frac{V_{DD} - V_{T+}}{V_{DD} - V_{T-}}$$ $(V_{T-} - V_{T-})$ *cancells out*

$$t_{charge} = -RC\ln\left(\frac{V_{DD} - V_{T-}}{V_{DD} - V_{T+}}\right)$$ *If* $x = a^y$*, then* $y = log_a(x)$, $log_a(x/y) = -log_a(y/x)$

2.1.5 Summing the results to get the frequency

Now we expressions for the time it will take for the cap to move from the upper threshold from the lower one and back, figuring out the frequency of the oscillator is simple.

All we need to do is add both results together then take the inverse. Time, measured in seconds, is the inverse of frequency, measured in HZ

$$f = 1/t$$

$$t = 1/f$$

Taking this relation, and the following rules of algebra:

$$a\,log_b(x) + a\,log_b(y) = a\,log_b(xy)$$

$$a/b + x/y = ax/by$$

We get the expression in the datasheet:

$$f \approx \frac{1}{RC\ln\left(\frac{V_{T+}(V_{DD}-V_{T-})}{V_{T-}(V_{DD}-V_{T+})}\right)}$$

2.2 The effect of the diode on the circuit

Unfortunately, when we get to this point it is not possible for us to calculate the effect of the diode on the frequency through algebra. This comes about from the fact that creating a mathematical model of the diode's behavior is considerably more difficult. Diodes, as with all semi-conductors, are affected by changes in the temprature for one. For another, any expression we make for our diode will be TRANCENDENTAL. This fancy expression means that like $x = cos(x)$, there is no algebraic solution. The only way to solve it would be through iteration, which needs either a ton of patience or a computer.

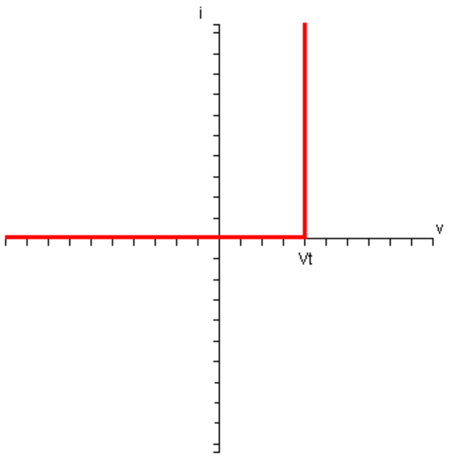
Thankfully, we're also not super fussed about accuracy so we can get away with relying on our ears while using our synth.

However, we can predict with a fairly decent amount of accuracy what the uppermost limit for how much the capacitor can charge will be. This will let us figure out whether or not some CV voltage and resistance at the CV amount pot will stop oscillation or not.

2.2.1 A very simplified diode model

Although there are ways to model a diode very accurately, and even simpler ways to model a diode with gmoderate accuracy[1], we are going to choose an even simpler model. The advantage of this is that our calculations will be much simpler.

So, in the name of simplicity, we are going to pretend that diodes are magical devices that allow absolutely no current to flow until the voltage drop across them reaches 0.6V, at which point they can conduct infinite current. *(fig 2.2.1a)*[2]:

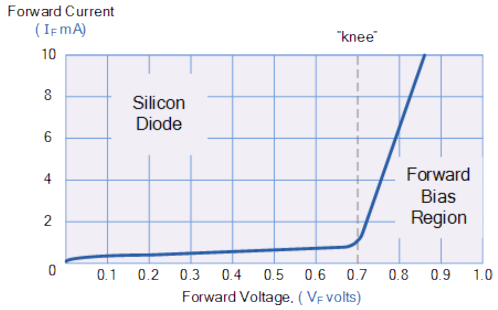


(fig 2.2.1a)

Unfortunately, this model is very different from reality, as we can see from this more accurate diode IV curve*(fig 2.2.1b - next page)*[3]:

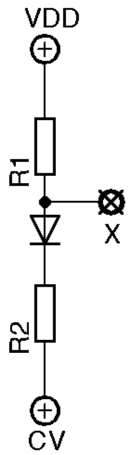
2.2.2 Creating an equivalent circuit

Now that we have a model for our diode, we need to figure out how we



(fig 2.2.1b)

can use it to estimate our circuit's behavior. Since we are only interested in how the diode limits the maximum voltage the capacitor charges to, we can actually leave our capacitor out all together! (Fig 2.2.2a)



(fig 2.2.2a)

This might seem a strange choice, but when the capacitor is charged to the highest voltage it can be, it is no longer drawing any current so it is effectively removed from the circuit until it discharges.

Because of this, all we have to do to find the limit imposed on the capacitor, is figure out what the voltage at point *x* is.

Thanks to ohm's law, this basically boils down to us figuring out the current through the R_1 and then using that to calculate the voltage drop across it.

2.2.3 Calculating the current through the resistors

Since our circuit is just a linear DC affair, we know that the current at every point in the circuit must be the same. Since there are two resistors in series, together with our diode, the current will be directly related to how high their resistance is.

If there were no diode, it would be as simple as summing the two

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[1] If you are interested, read up about the "piecewise linear model" of a diode. Sometimes called the PWL model

[2] Credit: (https://en.wikipedia.org/wiki/File:Diode_Modelling_Image8.png)

[3] Credit: (http://www.electronics-tutorials.ws/diode/diode36.gif)

resistances together and subtracting the CV from V_{DD} then pumping it all into Ohm's law.

However, there is a diode and it makes things a little bit more complicated by adding an extra 0.6V that we need to account for. Thankfully, this is actually very simple. All we need to do is treat the circuit as having 0.6V less across it. We don't need to care about the diode's current draw because it is infinate – in our very simplified model at least.

$$I = \frac{V_{DD} - V_{CV} - 0.6V}{R_1 + R_2}$$

Now we know the current flowing, all we need to do is calculate the voltage drop that puts across R_1 and then subtract that from V_{DD}

$$V_{limit} \approx V_{DD} - R_1 \left(\frac{V_{DD} - V_{CV} - 0.6V}{R_1 + R_2} \right)$$

It should be stated again that this won't be exact. It is however good to around ± 10mV, which is fairly good.

From here all we need to know is whether or not:

$$V_{limit} > V_{T+}$$

2.2.4 Drawback of the diode cv method

As a closing note, it should be mentioned that there is one big drawback to using a diode for CV in this way.

If you look at the expressions, you'll notice that the results are very dependant on R_1, which is our pitch pot. This basically means that at lower pitches, it will be harder to have the CV modulate the frequency or even allow oscillation.

However, considering how low the parts count is and how simple it is to implement simple CV this way, we consider it still very much worth it.

3. Modifications

3.1 Better 'feel' for pitch pots

The pitch pots can either be replaced by C taper (anti-log) potentiometers, or a 4–5MΩ resistor can be put in parralel across the two lugs of the pot that are used.

This allows for some compensation that allows the frequency pot to feel more consistent throughout its rotation and allow something closer to an octave-per-n° responce.

3.2 CV trim pot

A trim pot can easily be added in series with the diode and the CV amount pot to allow for a "set-and-forget" change to adjust where oscillation begins, or even prevent gating at all above certain frequencies.