

Physics 310
Lecture 7b – Waveform Generators & Timers

Wed. 3/10	Ch 10: Oscillators & Timers - Beginning	
Thurs. 3/11	Ch 10: Oscillators & Timers – Rest of; Lab 7: Oscillators & Timers	
Fri. 3/12	Lab 7: Oscillators & Timers; Quiz Ch 10	HW 7: Ch10 Pr. 2*, 6,7,8; Lab 7 Notebook

Handout:

- Project Design doc
- Project Proposal Example
- Electronics Magazines

Announcements

- **Office Hour Switch.**
 - The next few weeks of the semester will have labs begin on Thursday and HW due on Thursday. With that in mind, would you rather I move office hours to Thursday morning or keep them Tuesday morning? It doesn't matter to me.
- **Projects.** The last few weeks of this course are dedicated to individual projects. By the end of next week you'll have met most of the basic types of circuit components, so you'll be prepared to contemplate a wide range of projects. In preparation for that,
 - **Monday the 22nd** I ask you to give me a project Proposal – the general idea of / parameters for what you'd like to build.
 - **Monday the 29th** I ask you to give me a project Progress Report – the specific design, etc. of what you'd like to build.
 - **Handouts.** Here are two documents – one that explains what's expected in a Project Proposal and in a Project Progress Report, and the other (stapled to its back) is a sample Project Proposal.
 - **Selecting a Project.** You may already have a project in mind, or you may be completely uncertain about what you'd like to do. You can create a project from scratch, or you can select one from any number of sources – surf around and you'll find a lot of projects, and we've got a lot of magazines with Electronics projects in them I'll bring them into the room when we get going on lab today.

Waveform Shaping

- Comparator (Schmitt Trigger is better version) – sine or triangle to square wave
- Integrator – square to triangle wave
- Differentiator – square wave to “pulses”

Oscillators (just a few examples)

- Crystal oscillators – LC equivalent
- Relaxation oscillators – neon lamp, op-amp square-wave oscillator, Wein bridge

555 Timer

- Basic operation
- Circuit examples – One-shot (monostable operation), astable operation

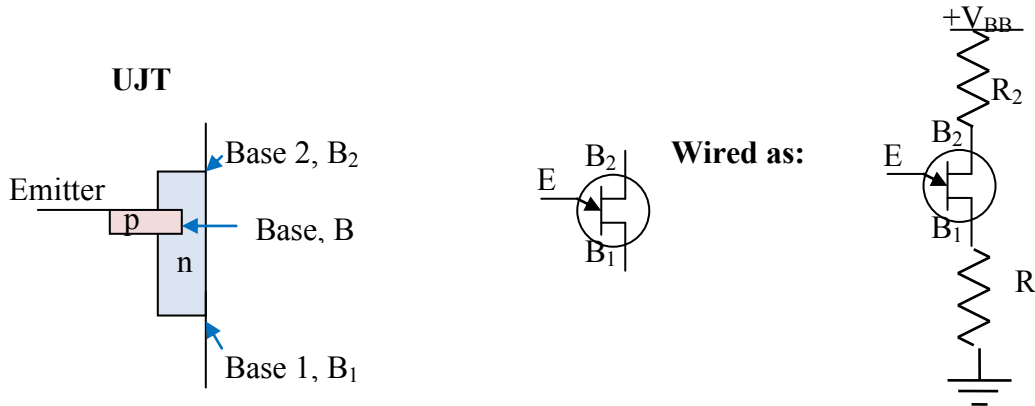
Waveform Generators – ICL8038 is an example, external components determine frequency

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10-1 Intro.

- Often you want a circuit to generate a specific waveform – maybe a sine wave to help smoothly drive a motor, maybe a square wave to blink a light, or maybe a sawtooth wave to drive stick-slip motion of a piezo. Last time, we considered a few circuits that *shaped* periodic input into periodic output of different forms. We also began looking at circuits that actually *generate* periodic wave forms from scratch. We’ll continue with that today. The UJT’s a quirky component and the 555 is a very popular one.

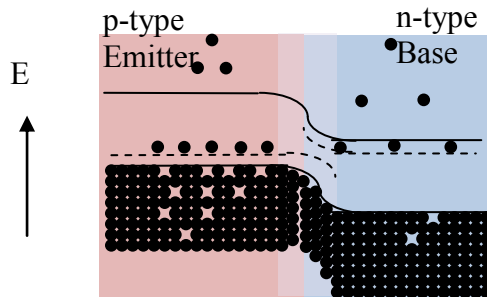
10-1.1 The Unijunction Transistor (UJT)



The Emitter is a p-type blob with a regular level of doping (and thus mobile charge carriers / holes). The Base, on the other hand, is an n-type slab with *very low* doping (and low density of mobile charge carriers / electrons), this means that it has a fairly *high* resistance (important later.)

The Emitter probe contacts into the Base slab at some point, B, a fraction of the distance up from B₁ toward B₂; we’ll call that η_o (between 0 and 1, by design it’s greater than 0.5, i.e., the emitter is closer to B₂ than to B₁). That means that the Base bias *at the point of contact* is $V_B \equiv \eta (V_{B_2} - V_{B_1}) + V_{B_1}$. Similarly, though the B₁ to B₂ resistance of the UJT will vary, the resistance between B and B₁ can be phrased as a fraction of it, $R_{B-B_1} = \eta R_{B_2-B_1}$ (actually, η will be varied, but generally around η_o .)

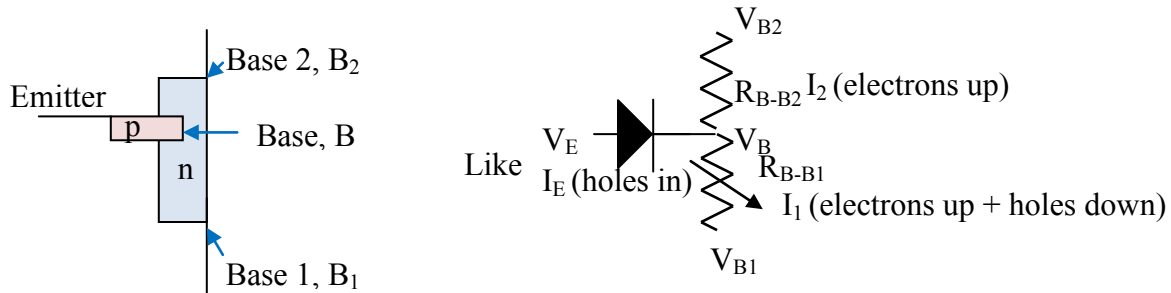
Looking across the I_E axis, we’d get small current *out of* the emitter when heavily reverse biased, i.e., $V_E < V_B$ ($E_E > E_B$). This would die off at $V_E = V_B$.



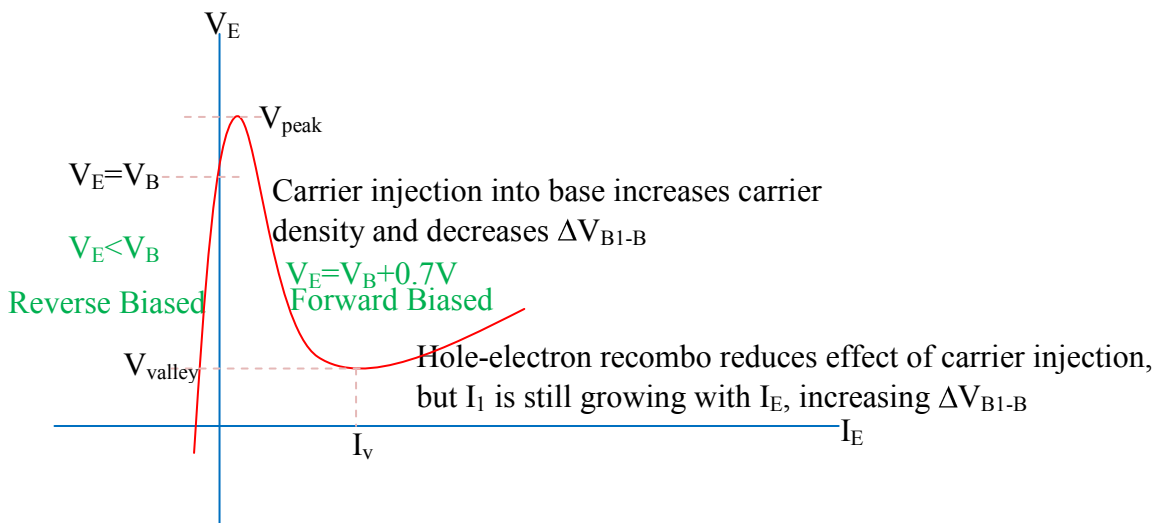
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Then current would start flowing *into* the emitter (and on into the base) for $V_B < V_E < V_B + 0.7V$. Since the Emitter is P-type, the current that it injects would be *holes* into the valance band. There are a few important things about this: first, since the p-type Emitter is more heavily doped than is the n-type Base, more holes flow *in* than electrons flow *out* through the p-n junction. So, it serves to *increase* the net density of charge carriers in the Base. Note that the strength of this current depends directly on just ΔV_{EB} , regardless of ΔV_{B-B1} . However, once the holes *are* injected, they are free to be swept away by ΔV_{B-B1} . The effect is that the Emitter has dumped new charge carriers into the bottom half of the Base and thus *upped* its carrier density and thereby *reduced* its resistance, and thus reduced the fraction, η . Looking at the UJT as a voltage divider, clearly V_B 's value becomes closer to V_{B1} . With $V_E \approx V_B + 0.7V$, V_E comes with it.



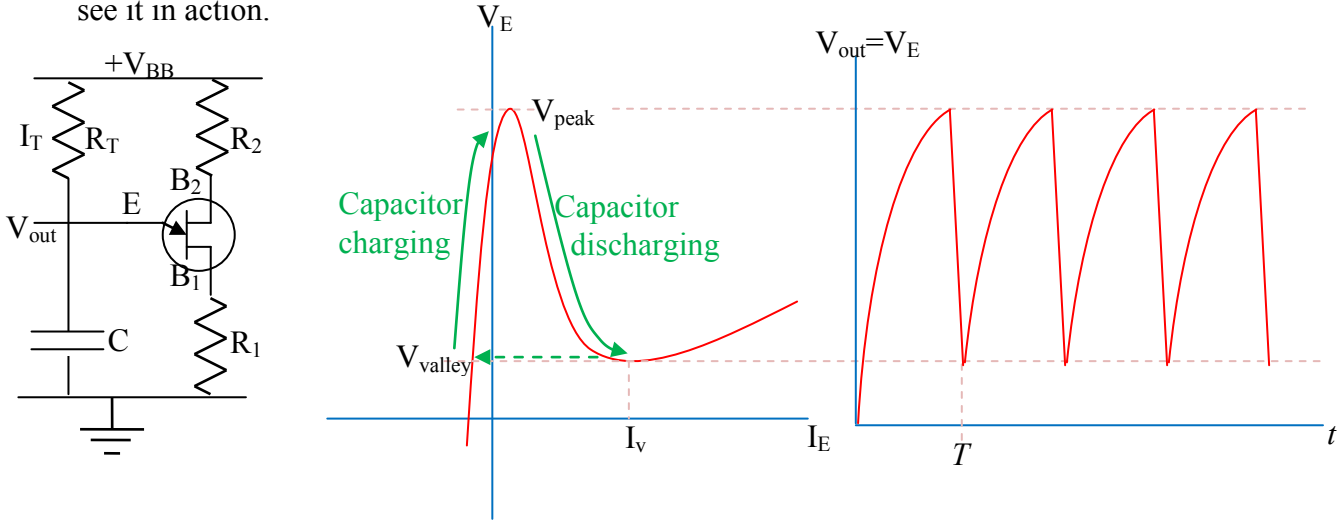
As the current continues to increase though, it does so by drawing more and more current out of the bottom half of the base, so I_1 grows and grows while I_2 does not. For a while, this is more than offset by the decreasing resistance, but eventually that increasing the population of minority carriers significantly increases the rate of minority – majority carrier recombination which eliminates *both* kinds of carriers. Thus the resistance increases again and $\Delta V_{B-B1} = R_{B-B1} I_1$ actually increases again.



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Now that we've got an appreciation of the strange current-voltage relation of this device, let's see it in action.



In this circuit, say the capacitor starts out grounded and so begins charging up. For a while, the UJT is 'off' since the emitter is lower voltage than the base. So the capacitor charges exponentially toward V_{BB} . However, when $V_{out} = V_B$, it's forward biased and so the UJT 'turns on', passes current, and discharges the capacitor through the UJT and R_1 . Once V_p is surpassed, think kind of snowball since passing all that current actually *reduces* the UJT's resistance between E and B_1 , so the current, once begun takes off. This quickly discharges the capacitor and brings $V_{out} = V_E$ down toward V_{valley} . Before it hits there, we want V_E dragged below V_B , and so the UJT is shut off and so charging resumes.

Note: R_T must be chosen so that enough current *can* flow through it when the V_{out} is at its peak (thus ΔV_T its smallest) so that the UJT turns on, yet not so large that it rushes to the sat into saturation and never turn off the transistor, that means that $I_p < \frac{V_{BB} - V_{peak}}{R_T} < I_V$.

Well, in a hand-wavy way, that's how this circuit works. The capacitor charges with time constant $1/(R_T C)$, until it reaches V_{peak} , at which point the UJT rapidly 'turns on' and drains the capacitor (comparatively, instantaneously) until V_E is dragged below V_{valley} , at which point the UJT 'turns off' and the capacitor is free to charge up again.

Oscillation Frequency

What's the frequency / how long does it take to charge up?

In the interest of getting a fairly *simple* expression that gives us the right *ball-park*, we'll make a few approximations, but I'll flag each as we go, so you can imagine how one might make a more exact expression.

Well, if we just wired up the left branch, between ground and the positive rail, V_{BB} , the capacitor's voltage would charge up toward the rail according to $V_{out}(t) = V_{BB}(1 - e^{-\frac{t}{R_T C}})$.

However, when the output voltage, which is the UJT's V_E , reaches the peak, V_p , the charge up ceases and discharge takes comparatively no time at all, so we've executed a full cycle.

$$V_p = V_{BB} \left(1 - e^{-\frac{T}{R_T C}}\right)$$

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Note: in truth, we should analyze this just as we did the Neon lamp oscillator, but if V_v is much less than V_p , we can assume that the difference in time to charge from 0 or from V_v is negligible, so we'll do alright ignoring that slight difference.

Flipping this relationship around to solve for the charge time, we have

$$T = R_T C \ln \left(\frac{1}{1 - \frac{V_P}{V_{BB}}} \right) \quad \text{or} \quad f = \frac{1}{R_T C \ln \left(\frac{1}{1 - \frac{V_P}{V_{BB}}} \right)}$$

Now, we can rephrase this ratio of voltages.

$$V_P \approx V_B + 0.7V = \left(V_{B_2} - V_{B_1} \right) + 0.7V$$

Here's another approximation, let's just drop that pesky 0.7V. If V_p is on the order of even 7V, then we might expect that dropping this introduces only a 10% error in our frequency calculation.

$$V_P \approx \left(V_{B_2} - V_{B_1} \right)$$

Now, to the extent that the internal resistance of the UJT is far greater than R_2 or R_1 at the time V_p is achieved, then most of the voltage drop across the right branch of the circuit occurs across the UJT / negligible drop is across R_2 or R_1 , so $V_{B_2} \approx V_{BB}$ and $V_{B_1} \approx 0$. Thus we have

$$V_P \approx \eta V_{BB} \quad \text{so that} \quad \frac{V_P}{V_{BB}} \approx \eta$$

And we, at long last, get the book's expression

$$f \approx \frac{1}{R_T C \ln \left(\frac{1}{1 - \eta} \right)}$$

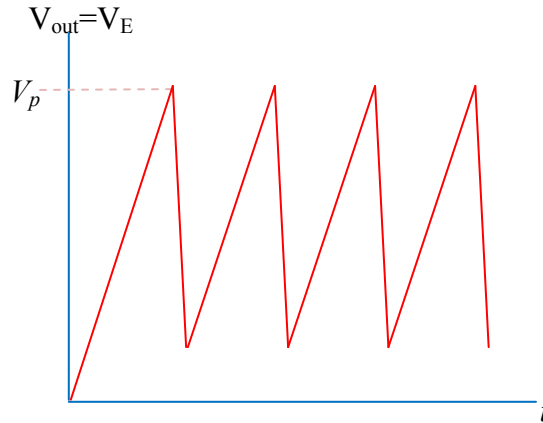
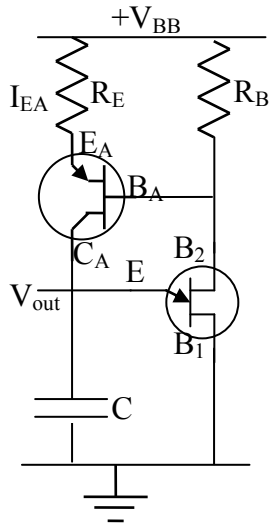
The book notes that, if you'd rather have a wave form that looks more like a series of right triangles than arcs, you can charge the capacitor only a small fraction of the way to its maximum, so you're operating in a more 'linear' region of the exponential curve. The most obvious way would be to use two different upper rails for the left and right branch of the circuit – say 100V on the left and only 10V on the right.

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With Constant Current Source

Better yet, replace R_T with a constant current source. You may recall from Lab 5 that you used a transistor and a couple of resistors to create a “constant current source” which essentially drew a constant current through the transistor regardless of the collector resistor.



Now, looking across the capacitor,

$$V_{out} = Q_{cap} / C = \int I_{cap} dt / C$$

So, *if* the current flowing onto the capacitor is constant, then V_{out} rises linearly with time until V_p is reached and the UJT is ‘turned on’ to discharge the capacitor.

So, let’s find I_{cap} and see how constant it is.

$I_{cap} = I_{CA} - I_E \approx I_{CA}$ while the UJT is *off* it draws negligible current in its emitter

$$I_{CA} = I_{EA} - I_{BA} = I_{EA} - \frac{1}{\beta} I_{CA} = I_{EA} \frac{1}{1 + \frac{1}{\beta}}$$

$$I_{EA} = \frac{V_{BB} - V_{EA}}{R_E}$$

$$V_{EA} = V_{BA} + 0.6V$$

(“+” because it’s a PNP, as arrow indicates, emitter is higher voltage than base)

$$V_{BA} = V_{BB} - R_B (I_{BA} + I_{B2})$$

$$I_{BA} = I_{EA} / (1 + \beta)$$

Substituting these back in, we find that

$$I_{cap} \approx \frac{I_{B2} R_B - 0.6V}{\frac{1}{\beta} (R_E - R_B) + R_E} \approx \frac{I_{B2} R_B - 0.6V}{R_E}$$

So, to the extent that the UJT isn’t varying the current that it draws, the PNP transistor is feeding the capacitor at a constant rate...until it charges to V_p and thus the UJT switches on to discharge it.

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10-2 The 555 Timer (our first Discrete Logic encounter)

All of the preceding oscillators are nice to have met, but here's one that gets a lot of use and has some versatility, so it's *particularly* nice to understand how to use it. The 555 timer, like an Instrumentation Amplifier, is an integrated circuit that itself can be thought of as built of smaller integrated circuits, op-amps and such. With just a few external components, you can wire it up to select the frequency and even shape of the periodic output. Internally, the 555 Timer can be thought of as built of three resistors, two transistors, an inverter, two comparators, and a "flip-flop." We'll walk through the function of each. Before we do, I should prepare you for a significant change in how we look at circuits. Most of the internal components of the 555 have fairly discrete outputs – high voltage (near V+) or low voltage (near 0), and not much in between. So it's useful to think of these as "logic devices" – making "signals" either "Hi" or "Lo." That's actually the next phase of this course – looking at (discrete) logic circuits. Here will be our first dabbling.

Here are the basic rules the 555 lives by:

Left op-amp: acts like a comparator

Hi when $V_{\text{thresh}} > V_{\text{control}}$

V_{control} can be set through pin 5 or, default it's $2/3 V_+$

Lo when $V_{\text{thresh}} < V_{\text{control}}$

Right op-amp: acts like a comparator

Hi when $V_{\text{trig}} < 1/2 V_{\text{control}} = 1/3 V_+$ if pin 5 is connected.

Lo when $V_{\text{thresh}} > 1/2 V_{\text{control}}$

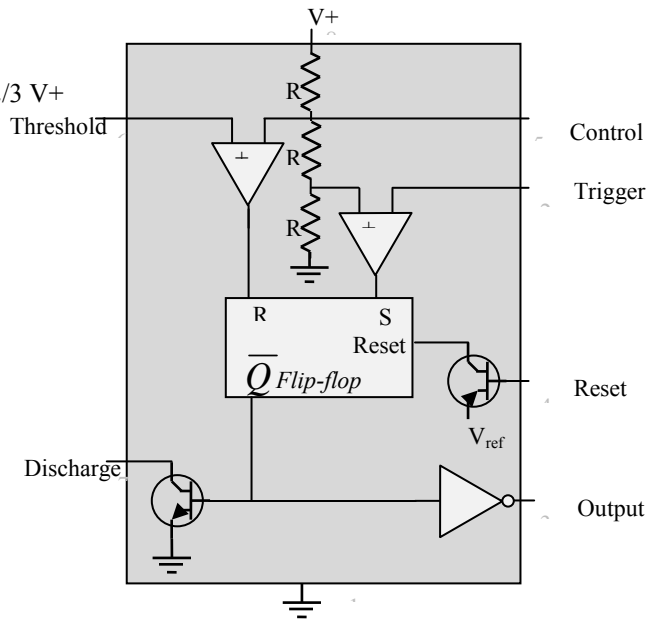
Flip-Flop

\bar{Q} just holds its value unless $V_{\text{reset}} > V_{\text{ref}}$ then

$$\bar{Q} = \begin{cases} \text{Hi} \\ \text{Lo} \\ \text{Holds} \end{cases} \text{ if } R = \begin{cases} \text{Hi regardless of S} \\ \text{Lo and S = Hi} \\ \text{Lo and S = Lo} \end{cases}$$

Left Transistor: When \bar{Q} goes Hi, the transistor is on, so "Discharge" line is connected straight to ground.

Inverter: Makes output equal opposite of \bar{Q} .



Condensing this chain of reasoning as to skip the middle men of Q, S, and R:

555:

$$\text{Output} = \begin{cases} \text{Lo} \\ \text{Hi} \\ \text{Holds} \end{cases} \text{ if } V_{\text{th}} \begin{cases} > V_{\text{control}} \\ < V_{\text{control}} \\ < V_{\text{control}} \end{cases} \begin{cases} \text{regardless of } V_{\text{trig}} \\ \text{and } V_{\text{trig}} < \frac{1}{2} V_{\text{control}} \\ \text{and } V_{\text{trig}} > \frac{1}{2} V_{\text{control}} \end{cases} \text{ where } V_{\text{control}} = 2/3 V_+ \text{ or set through pin 5}$$

When Output = Hi, discharge switch is *off*

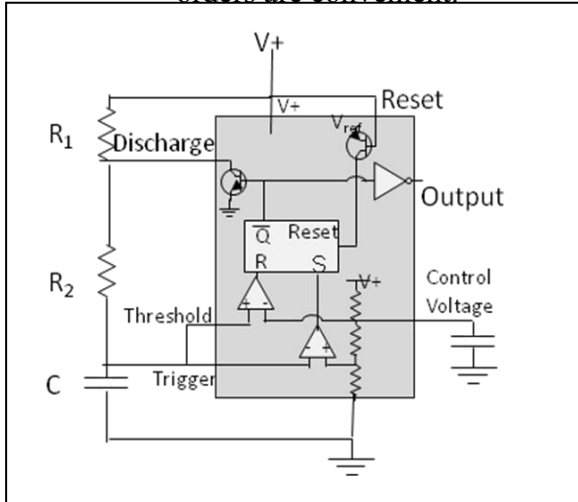
When Output = Lo, discharge switch is *on*

Of course, the proof of this thing's usefulness is in its application.

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10-2.1 Astable Operation

You may have noticed that Figures 10.16 and 10.17 show the different pins geometrically distributed differently, and neither is in the order that the pin's numbers suggest. The numbers do represent the *actual* order in which the pins are arranged around the real chip; however, for the sake of illustrating the *internal logic* and *external logic*, different orders are convenient.



Let's apply the rules of operation above to figure out how this behaves.

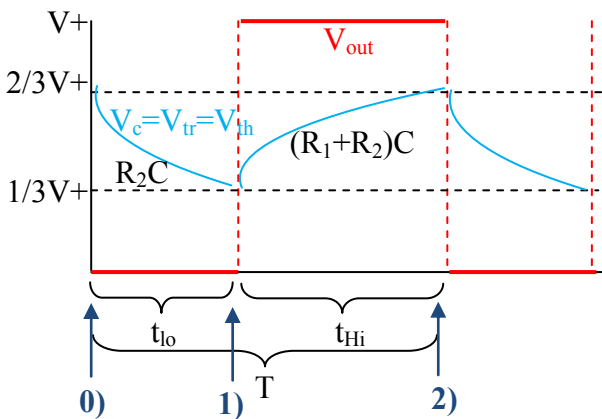
0) Let's start imagining that the external capacitor is charged to $2/3V^+$ (or above) and V_{out} has just become low; of course that only happens if \bar{Q} is Hi which also means that the internal "Discharge" transistor is making good connection between pin 7 and ground, thus discharging the capacitor through R_2 . That allows the Trigger/Threshold voltage to drift down too.

0)->1) In the process, $V_c=V_{th}=V_{tr}$ gets down below $2/3 V^+$ and so the first left internal op-amp sets $R \Rightarrow Lo$; but S must already be Lo for \bar{Q} to have been holding its value.

1) Eventually $V_c=V_{th}=V_{tr}$ gets below even $1/3V^+$; now the right internal op-amp sets $S=Hi$; this, along with $R=Lo$ sets $\bar{Q}=Lo$. That of course shuts off the discharge transistor and sends $V_{out}=Hi$.

1) -> 2) With the discharge transistor off, the capacitor starts charging up through resistors R_1+R_2 toward V^+ . It charges up, bringing $V_{tr} > 1/3 V^+$ therefore S goes Lo. With R already Lo, \bar{Q} holds its value and...

2) eventually brings $V_{th} > 2/3V^+$ so R goes Hi and now \bar{Q} goes Hi, $V_{out}=Lo$ and it starts all over again.



Finding t_{Hi} :

$$V_c(t_{Hi}) = \frac{2}{3}V^+ = V^+ \left(-\frac{2}{3}e^{-t_{Hi}/(R_1+R_2)C} \right)$$

$$t_{Hi} = (R_1 + R_2)C \ln(2)$$

Finding t_{Lo} :

$$V_c(t_{Lo}) = \frac{1}{3}V^+ = \frac{2}{3}V^+ \left(-e^{-t_{Lo}/R_2C} \right)$$

$$t_{Lo} = R_2C \ln(2)$$

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Thus T: $T = t_{Hi} + t_{Lo}$
 $T = t_{Hi} + t_{Lo} = (R_1 + R_2) C \ln(2) + R_2 C \ln(2) = (R_1 + 2R_2) C \ln(2)$

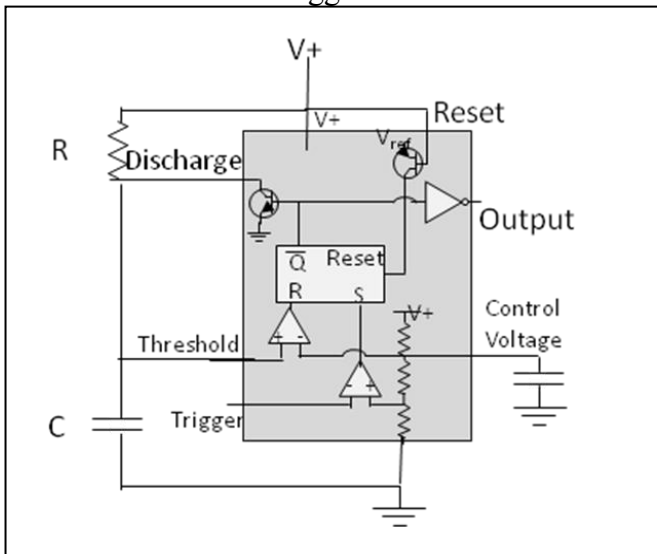
Duty Cycle

To fully characterize this wave's time dependence, since it spends un-equal time "hi" and "lo", you don't just need the period but something that communicates the fraction of the time in one state versus the other. That's often referred to as a device's "duty cycle" (you'll see a "duty cycle" knob on our function generators). For the 555, the common definition is time the output is Lo vs. the total period

$$D.C. = \frac{t_{Lo}}{T} = \frac{R_1 C \ln(2)}{(R_1 + 2R_2) C \ln(2)} = \frac{R_1}{R_1 + 2R_2}$$

10-2.2 Monostable Operation

The 555 Timer is a very versatile chip, wired up in this way, it responds to pulse in the Trigger line.



- 0) Say $V_{trigger} = Hi$, C is initially discharged and $V_{out} = Lo$ (thus $\bar{Q} = Hi$ and the Discharge transistor grounds out pin's 7 & 6.)

a. Note: $V_{tr} = Hi \Rightarrow s = Lo$
 $V_{thr} = Lo \Rightarrow R = Lo$ } \bar{Q} holds

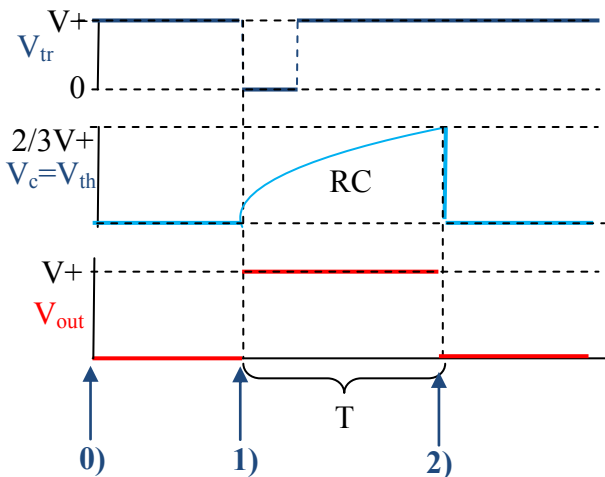
- 1) Pulse V_{tr} from Hi to $< 1/3 V+$ and back. The moment V_{tr} drops below $1/3 V+$, $S \Rightarrow Lo$, but since $R = Lo$, \bar{Q} goes Lo.

- 1)->2) Even after V_{tr} returns high, the new value of $\bar{Q} = Lo$ is held (see a. above). The capacitor charges.
- 2) Along the way, V_{th} crosses $> 2/3 V+$. When that happens, $R \Rightarrow Hi$, sending $\bar{Q} \Rightarrow Hi$ and turning on the discharge transistor and sending $V_{out} \Rightarrow Lo$

Timing: Of course it's pretty easy to determine how long the output remains 'Hi.'

$$V_c(T) = \frac{2}{3} V^+ = V^+ (1 - e^{-T/RC})$$

$$T = RC \ln(3)$$

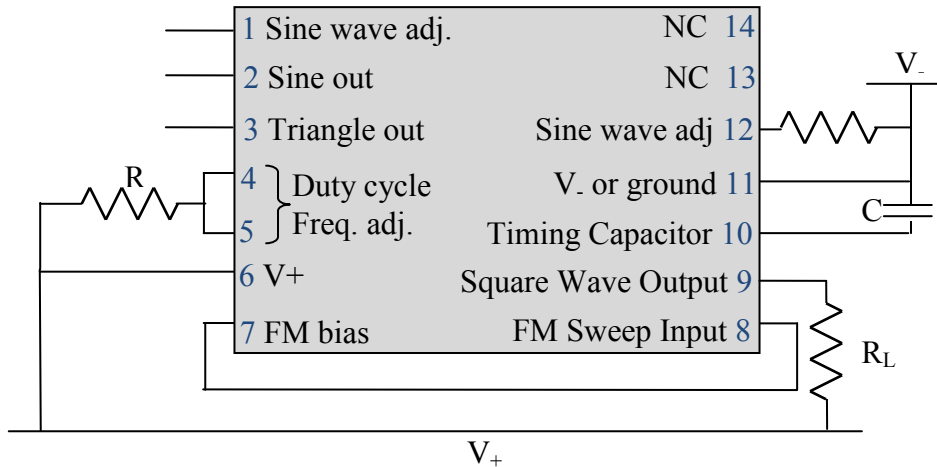


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10-6 Precision Waveform Generator: the ICL8038

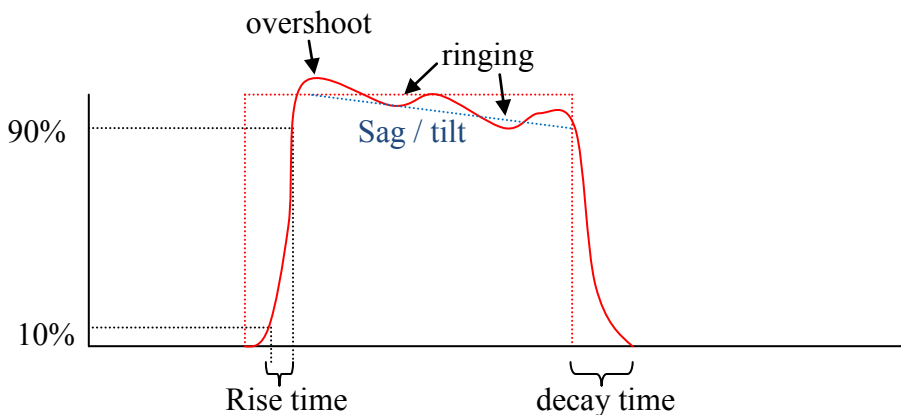
Lucky for us, Intersil has made a chip that makes the standard waves and operates over a range of frequencies 0.001 Hz to 300,000 Hz. We won't even *try* to peek under its hood. In the tradition of numbering the pins according to their actual geometric order around the chip, but displaying them as to minimize the number of crossed wires. In the configuration illustrated, the load is across the square wave output. We are told that the frequency of the signal it generates is

$$f = \frac{0.15}{RC}$$



10-7 Characterization of Wave Forms

A number of the circuits we've looked at generate square waves, but how square are they? If we zoomed in on one of the squares, what might it look like? It clearly can't *instantaneously* jump from one value to another, and it probably can't *perfectly* hold a given value. What imperfections you can't eliminate, you characterize. Here's a zoom-in on a single 'square' of a square wave output with the usual imperfections.



The fact that a real device will have finite rise and decay times (can't instantaneously change values) has the obvious implication that the output signal will be slightly delayed relative to the ideal output. It has a further implication – if the signal is asked to change too frequently, it just doesn't have the *time* to come to full amplitude before it's asked to come back down again. There's a simple quantitative relationship that speaks to this – for a given rise time, there's a

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corresponding ‘cut-off’ frequency, i.e. a frequency of signal for which the output would actually only make it up to $1/\sqrt{2}$ of the intended peak.

The book gives $t_r f_2 = 0.37$.

I don't know about getting exactly 0.37, but we can easily see that the ball-park is right.

Approximate the rise as linear, then the slope is $\frac{(0.9-0.1)V_{\max}}{t_r}$. Now, if we tried to produce a periodic square wave of frequency f_2 but what we got in return was triangle waves (never makes it to the plateau at the top, starts decaying) that only makes it to $(\sqrt{2}/2)V_{\max}$, it takes $1/4$ of the period to get up that high from 0, or $\frac{1}{4f_2}$, then the slope is $\frac{(\sqrt{2}/2)V_{\max}}{1/(4f_2)} = \sqrt{2} f_2 V_{\max}$

Equating the two slopes gives $\frac{(0.9-0.1)V_{\max}}{t_r} = \sqrt{2} f_2 V_{\max} \Rightarrow t_r f_2 = \frac{0.8\sqrt{2}}{4} = 0.28$

