The Joule Thief

An exploration project by Jeff Pennoyer and Ralph Iden

Introduction

If you have toys or flashlights that use single-use batteries, you know that the batteries often need to be replaced after a short time of use. Fresh batteries start out at their rated output voltage, a nominal 1.5 volts for alkaline batteries, but their output decreases with time until there isn't enough energy to properly power the toy, flashlight, or other device. When that occurs, the batteries need to be replaced.

However, unless the device was left on and has drained all of the power out of the battery, it is possible for that battery to provide power for other devices even when it appears to be mostly depleted. This project explores one method to extend the useful life of a battery: a device nicknamed the Joule Thief.

A Joule Thief is a clever circuit that helps squeeze the last bit of energy out a battery, even when it seems too weak to power anything. It is estimated that 2.11 billion single-use batteries, including the popular AA and AAA batteires, are discarded annually or an average of 8 batteries per year, per person. Batteries that are not recycled end up in a landfill. Eventually these batteries will be completely drained, but let's explore one way to extend their useful life.

Introducing the Joule Thief

Let's say that you have a flashlight that needs 1.5 volts to turn on. When the battery has only 0.7 volts left, the flashlight won't stay on, right? Well, what if there was a way to take that remaining 0.7 volt and boost it to 1.5 volts or even higher? Wouldn't that be useful? That is exactly what a Joule Thief does.

The concept of a Joule Thief goes back to the 1930's and has been refined over the years. In fact, many cellphone power banks use the same principle to charge phones and tablets from batteries having a lower voltage.

A Joule Thief is a type of self-oscillating voltage booster. It takes some of the battery energy and stores it a little at a time, like winding up a spring. Then, that energy is released all at once, making the voltage higher for a short period of time. This happens very quickly, over and over again, giving the impression that the light is continuously lit.

Later in this guide, Jeff will share his journey with the Joule Thief and the different configurations that he explored. His experiments revealed some surprises and sparked additional ideas, so be sure to look his notes over.

What’s cool about a Joule Thief?

1) It uses “dead” batteries that would normally be thrown away.
2) It teaches you how a simple circuit can boost voltage.
3) It is easy to build and experiment with.
4) It makes a fun school science project.

The Joule Thief that you will be buiding consists of just a few parts:

1) A transistor, which is an electronic switch that can turn itself on and off.
2) A resistor the controls the flow of electricity to the transistor.
3) Two inductors (coils of wire) that store the boosted energy.
4) A light emitting diode (LED) which will use the boosted energy.
5) AA or AAA battery that has at least 0.5 volts remaining. Rechargable batteries also work, but are not recommended because that can be overdischarged which will harm them.

Getting started

Before starting to assemble your Joule Thief, carefully open the envelope and make sure you have all of the parts on the following list. If you are building the no-solder kit at the presentation, the componets marked “(pre-installed)” will have been already placed on the printed circuit board.

Qty	Part	Notes
1	1000 ohm resistor (R1)	brown, black, red bands
2	220 uH inductors (L1, L2)	red, red, black bands
1	2N3904 transistor (Q1)	TO-92 case
1	SPDT slide switch	(pre-installed)
1	500 ohm variable resistor	(pre-installed)
1	Printed Circuit Board	PCB
3	LED	bright white
1	AA battery holder (AAA fits too)	(pre-installed)
1	4-40 5/16” screw	(pre-installed)
1	4-40 nut	(pre-installed)
1	Six pin female header	(pre-installed)
1	Three pin female header	(pre-installed)
2	Two pin female header	(pre-installed)
2	One pin female header	(pre-installed)

Solder the componets on the PCB

If you are constructing the no-solder version, jump to “Insert components” as your kit has this step already done for you.

CAUTION: When soldering the parts, especially the single-pin headers, do not hold the headers in place with your finger. You can be burned. Use a tweezer, needle-nose plier, or insulated gloves.

NOTE: If you rather not use the female headers provided, you can solder the componets directly to the board. However, it is prefered to install all the headers (or at least the six-pin and three-pin headers) as they provide a means to experiment with other componets.

Step 1: Insert the six-pin header on the top side of the PCB (the side with the printing). Making sure that all the header pins are flat against the PCB, solder one of the end pins. Confirm that the header is vertical, reheating the pin and adjusting the position, if necessary, and then solder the remaining five pins.

Step 2: Insert the three-pin header in a similar manner as the six-pin header.

Step 3: Insert the two two-pin headers following the same procedure as the other headers.

Step 4: Insert the two single-pin headers. Be very careful and DO NOT use your finger to hold the pin in place when soldering it the the PCB.

Step 5: Insert the slide switch on the top of the board and solder the three pins checking that it is flat and vertical. Slide the switch to the “off’ position. Trim leads to the same height as the other componet leads.

Step 6: Insert the 500 ohm variable resistor and solder to the PCB. Please note that an error was made when ordering this part and that the adjustment screw is on the opposite side. The design called for the adjustment to be made from the end of the PCB. This will be corrected in the next version of the board. Turning the control fully counter-clockwise will result in the brightest output.

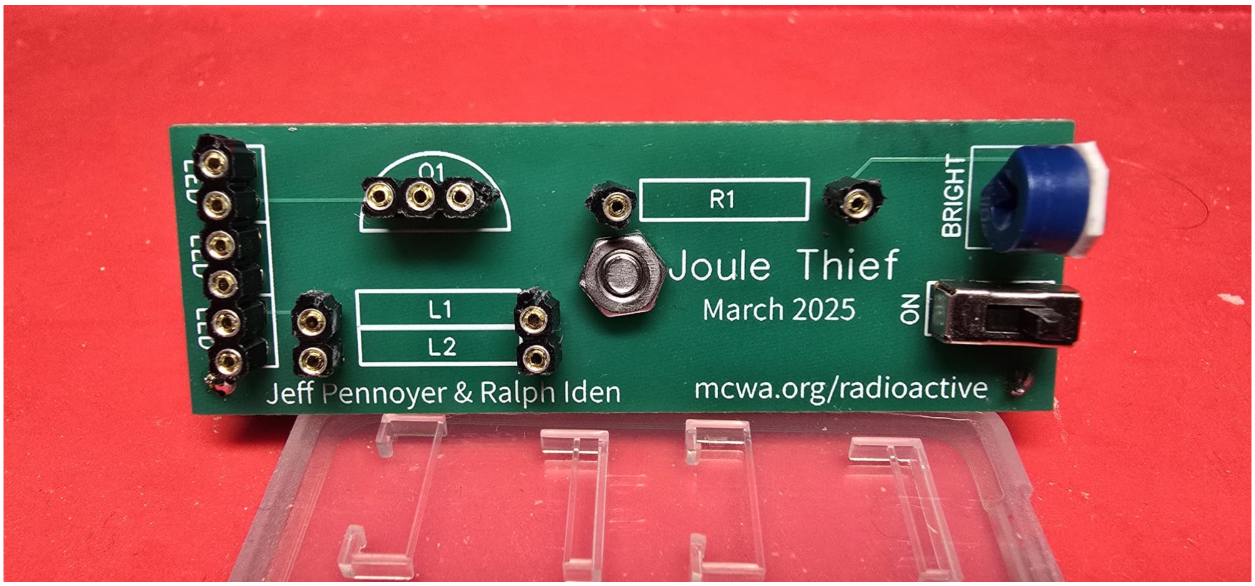
Step 7: Attach the battery holder to the back of the PCB using the 4-40 screw and nut. The red (positive) wire should be facing the side of the PCB where the switch is mounted. Do not overtighten.

Step 8: Rotate the battery holder so that the hole near the switch on the bottom of the board is exposd. Insert the red wire through the hole and solder it to the PCB.

Step 9: Rotate the battery holder in the opposite direction so the hole on the bottom of the board on the opposite end is exposed. Insert the black wire through the hole and solder it to the PCB.

Step 10: Rotate the battery holder so that it is aligned with the PCB and tighten the screw to hold the battery holder in place. Do not over tighten.

This is what your Joule Thief should look like at this stage:



Insert components

The leads of the transistor, resistor, inductors, and LED have been bent and cut to size. When inserting the leads into the headers on the PCB, be gentle and press straight downward and not on an angle. Using a tweezer or needle-nose pliers will make this easier. The two single-pin headers are particularly fragile and can snap off if you are too rough. If the happens, you will have to solder the component directly on the board.

Step 1: Insert the transistor (Q1) into the three-pin connector. Ensure that the flat side of the transistor aligns with the printing on the PCB. Make sure all three pins are in the holes and then gently press the transistor into the socket.

Step 2: Insert the two inductors (L1 and L2) into their sockets.

Step 3: Carefully insert the resistor (R1) into the two single-pin headers. Insert the leads into the holes and press directly downward. Do not use excessive force.

Step 4: Insert the LED into one of the three pairs of connectors in the six-pin female header. The LED must be inserted properly in the header. There is a black marking on one side of the LED. This side should be inserted into the header pin with the little dot on the PCB and the other lead to the adjacent pin. The LED should be pointing outwards from the board. If the LED is not inserted properly, it will not light, but it won't be damaged.

The leads of the LED are thinner than the resistors and inductors and can be easily bent. They can be installed if you are careful. Partially straightening the leads when inserted using a tweezer or needle nose pliers can make insertion easier. Once installed, you can bend the leads back to the right-angle position.

Although the Joule Thief only requires one LED, the board has space for up to three LEDs for further experimentation. Your kit comes with three bright-wide LEDs for this purpose.

Step 5: Insert a used AA or AAA battery into the holder. Make sure the battery is positioned correctly in the holder. Any battery having 0.5 volt or more of voltage left will work.

Step 6: Slide the switch to the “on” position and let there be light!

If you see light coming from the white LED, you will know that the Joule Thief has boosted the battery voltage. A white LED requires between 3.0 to 3.5 volts (its forward voltage) in order to turn on.

It is magical. Well, actually science.

Ideas for your own explorations

Now that you've built a working Joule Thief, it's time to run some fun experiments of your own! If you're testing how long the LED stays lit, try using a voltmeter or battery tester to choose batteries with similar remaining power, which will help make your results more accurate.

Here are some ideas to get you started. Jot down your discoveries below or start your own experiment journal to track your investigations like a real scientist!

1) Does adjusting the brightness control affect how long the battery lasts? Try turning the brightness up or down. What happens? Does the battery last longer or shorter? Can you explain why?

2) At home, if you plug multiple electrical appliances into wall outlets, they end up using more electricity. What happens when you add more LEDs? If you add one or two more LEDs to the six-pin connector, how does it affect brightness? Do they shine as brightly as a single LED, or are they dimmer, or do they stay off completely?

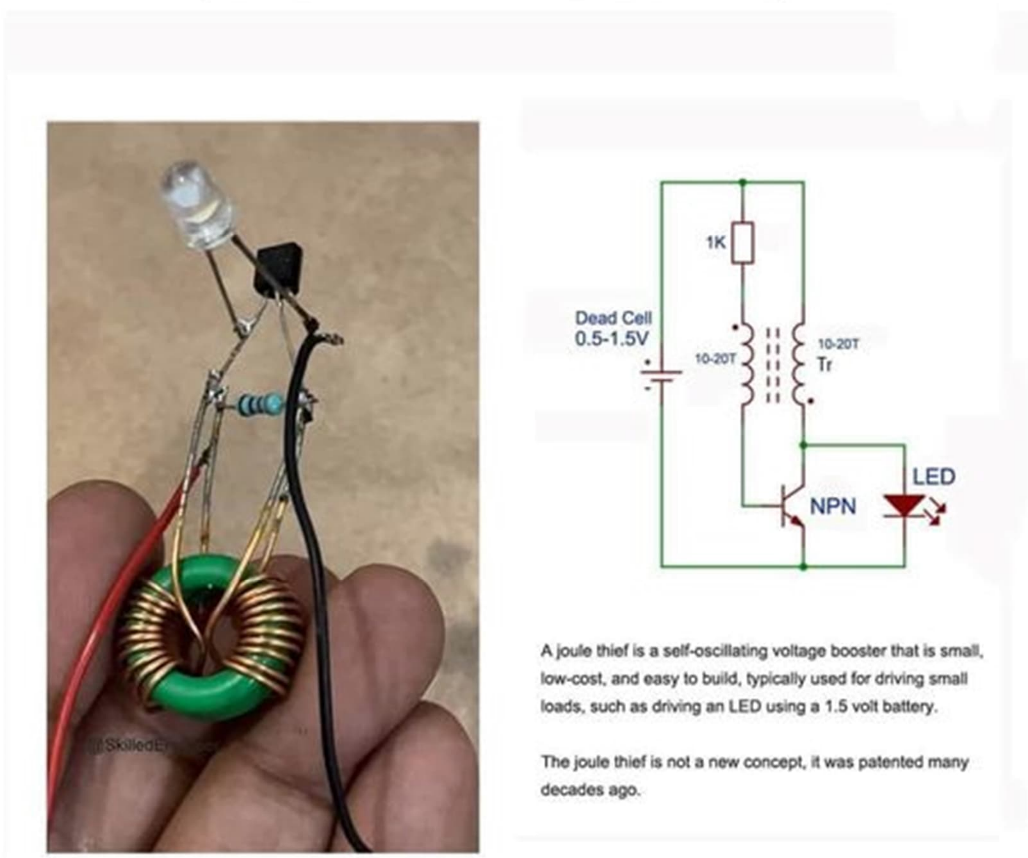
3) How do different colored LEDs behave? Different colors of LEDs require different voltages to turn on. If you have other colored LEDs, swap the white LED for a red, green, or blue one. Do they light up the same way? Try adding more colored LEDs. Are the results similar to when you tested multiple white LEDs?

Jeff's Journey

The Joule Thief intrigued Jeff and he began experimenting with different designs and using different values for the components to see which resulted in the best performance. The Joule Thief you are building was a direct result of his studies. Along the way, Jeff was surprised by some of the results of his experiments and perhaps you find that to be true for you as well. We will leave those discoveries to you.

Below is the schematic of the basic design of Jeff's Joule Thief. Your Joule Thief is identical with the addition of an on/off switch for the battery and a variable resistor between the battery and the switch that controls brightness. In his initial design, he constructed a transformer using powered iron toroid (the green "donut").

Basic Self-Oscillating Voltage Booster



In your Joule Thief, this transformer was replaced by the two inductors placed very close to each other.

Here are various variations of his Joule Thief that incorporate different components and features. His prototypes were hot glued together for testing. If you compare your Joule Thief with these early versions, can you spot the version that uses the two inductors (the green parts) instead of the toroid used in the far right of the photo? The board second from the left introduced the variable resistor to control the brightness.

This photo shows a Joule Thief prototype with a brightness control mounted in a medicine container for use as a nightlight.

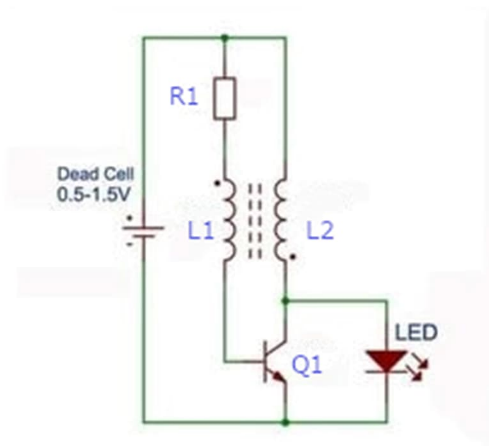
Ralph’s Technical Notes

This section is more technical in nature and explains in greater detail how the Joule Thief works and its limitations.

The Joule Thief is a type of circuit called an oscillator. An oscillator generates a repeating signal once power is applied to it. It can do this by feeding back part of the output of the oscillator to the input generating a loop.

In the schemattic below, inductors L1 and L2 are magnetically coupled to form an air core transformer. When the voltage from the battery is applied to resistor R1, it also flows through L1 and finally through the base-emitter junction of transistor Q1. With the type of transistor being used (2N3904), it takes 0.5 volt for the transistor to begin to turn on or conduct. Thus the battery powering the circuit must have at least an output of 0.5 volts.

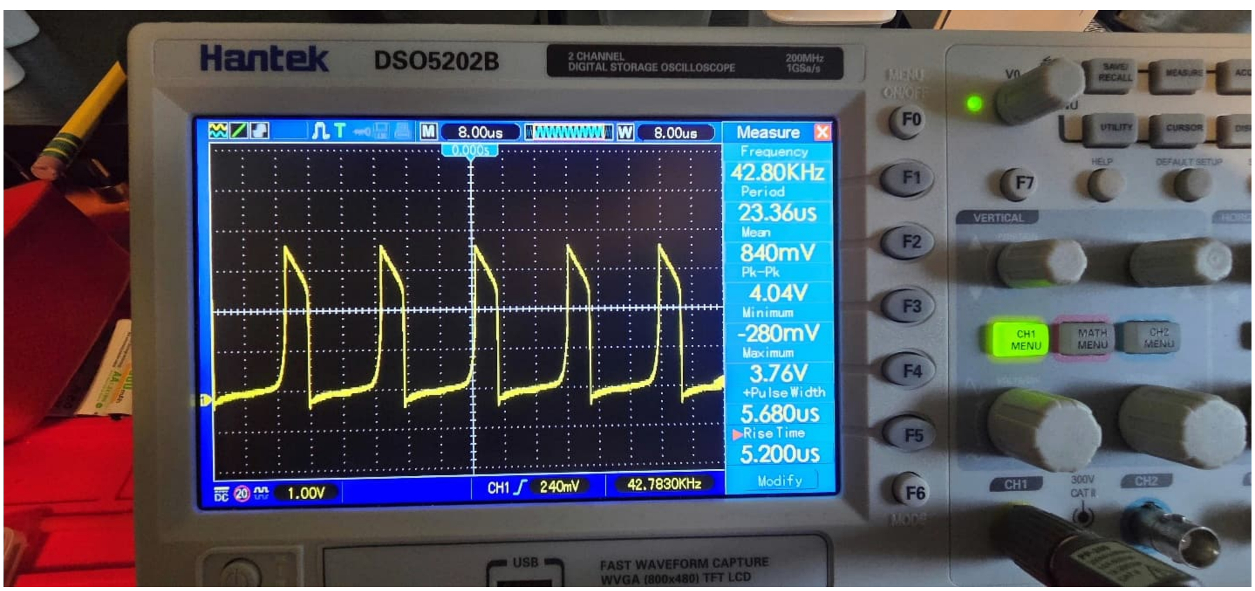
When Q1 begins to conduct, it causes electricity to flow through inductor L2 generating a magnetic field (just like an electromagnet). Some of this magnetic field is picked up by L1 causing the transistor to turn on even more increasing the magnetic field.



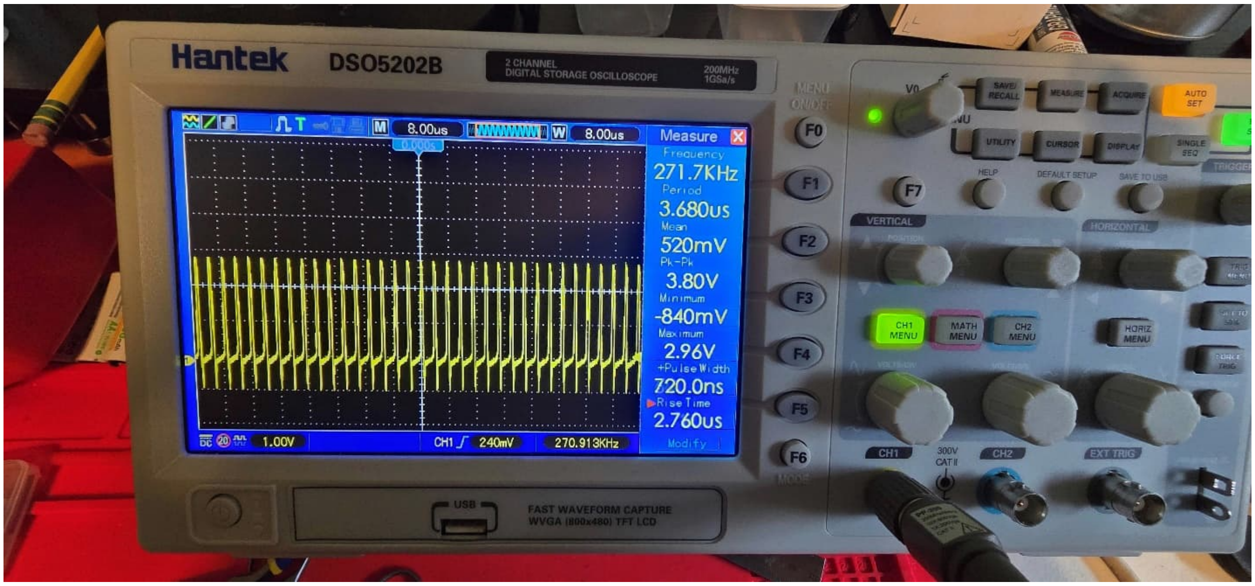
Eventually, the magnetic field can increase no further and the current flow stops and the transistor turns off. The collapsing magnetic field causes a large but brief voltage spike to be applied to the LED. This voltage causes the LED to light up briefly.

The cycle starts over again with resistor R1 turning on the transistor. This gives the appearance that the LED is continously on.

The number of times per second the cycle repeats, its frequency, will change depending upon the battery voltage. The lower the battery voltage, the higher the number of cycles as shown in the images below.



With 1.0 volt applied to the Joule Thief, the frequency is 42,800 cycles per second, which produces an output voltage of 4.04 volts. One volt in, yields four volts out.



With 0.5 volt applied to the Joule Thief, the frequency is 271,700 cycles per secoond producing an output voltage of 3.8 volts. One half volt in, 3.8 volts out.

However, there is no such thing as a free lunch. Although the voltage is boosted, the amount of electrical current it can produce is limited. It takes energy to power the oscillator which takes away from the available output. Typical efficiency is in the 40% - 90% range, depending mostly on the quality of the transformer and the magnetic field level it can take before saturating to the point where the magnetic field cannot be increased further.

In Concluision

We hope you enjoy experimenting with your Joule Thief and feel inspired to try your own ideas. Keep a notebook and don't be afraid to innovate!

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PCB soldering and final assembly: Bill Wacaser (AF9I)
PCB design, kitting, and documentation: Ralph Iden (WB9ICF)