The one-year flashlight

Russell Gurrin describes his design for a night light/flashlight that runs continuously for one year on three AA rechargeable batteries.

Over the last 20 years or so, LEDs have become much more efficient at producing light, so much so that they're now one of the most efficient light sources known. Back then, a "superbright" LED had a peak brightness of around 200mcd to 600mcd. With modern superbright LEDs, the peak brightness has increased to more than 20,000mcd, two orders of magnitude brighter, using the same amount of power. That got me thinking: instead of using the same amount of power to produce dazzlingly-bright light, could these modern superbright LEDs produce a moderate amount of light with a hugely reduced power consumption?

A bit of experimentation provided the answer: Yes, but not by using the usual single-resistor circuit to reduce the current flowing into the LED. I tried increasing the resistance by a factor of 100, to reduce the typical LED current of 20mA down to 0.2mA. I found at 0.2mA, some superbright LEDs won't light up at all, and others light poorly. On reading the datasheets of some of the LEDs, the reason became apparent: modern superbright LEDs are designed for peak efficiency at their typical operating current of 20mA. The efficiency curves showed that they are less efficient at lower current, and my experimentation showed that they just don't operate dependably at extremely low current.

So a different approach was needed. Instead of operating the LED at extremely low current, operate the LED at its rated current, achieving maximum efficiency from the LED, but pulse the current going into the LED so it's only receiving that current for 1% of the time. Each pulse of current will produce a flash of light.

The circuit board takes the place of one of the batteries in the AA battery holder.

As long as you flash the LED fast enough, the flashing won't be detectable by the human eye. This effect is used in everyday lighting, for example a fluorescent light actually flashes 100 or 120 times a second, depending on whether your mains runs at 50Hz frequency (as in Australia) or 60Hz (as in many other countries). The fluorescent light does not look like it's flashing, because your eyes average out the flashing, so it appears as continuous light.

So I tried to make such a circuit, and it does work. It produces a moderate amount of light with a very low current draw. For fun, I worked out how long I could keep the LED lit when running from three AA rechargeable batteries, and it was a little over one year!

That got me thinking: this could be a useful device. Imagine how useful a one-year light could be in areas where mains power is intermittent, unreliable, or unavailable. Or if you are going caving or into a mine, it will be useful as a personal emergency light that will just keep on working for a very long time. Or even use it as a night light when camping, or for other uses. I keep one on my bedside table, shining at the white ceiling, and the reflected light from the ceiling is enough that I can dimly see everything in the room. I can also grab it and use it as a torch for a midnight trip to the toilet, where it provides enough light that I don't have to turn on any house lights.

You're probably wondering "how bright is it?". I don't have technical details, but I can say that if you position it so it produces

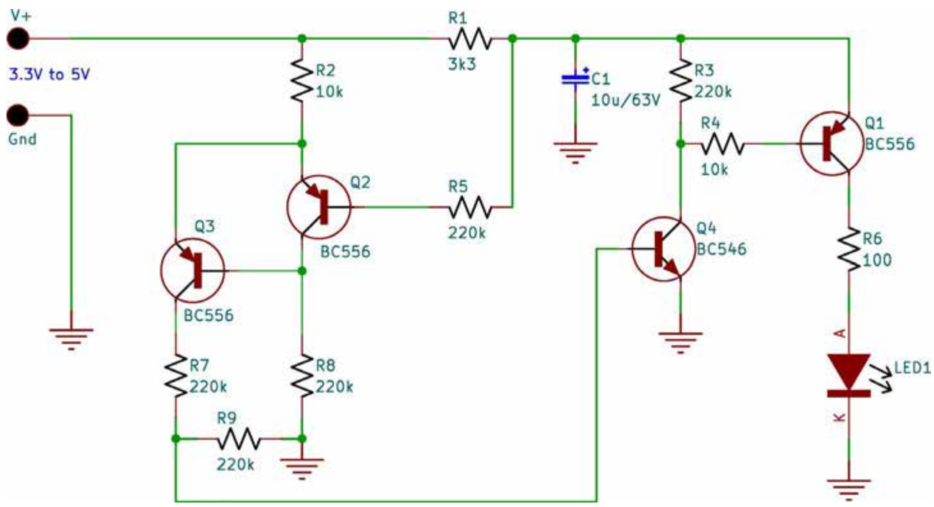


Figure 1. The circuit schematic for the one year flashlight.

The battery holder has to be slightly modified by removing one terminal and feeding the black wire through an enlarged hole and soldering it to the circuit board's negative terminal.

a disk of light about 30cm across, it appears to be the same brightness as the full moon directly above. If you shine it at a typical-size novel so it illuminates a whole page, you can read the novel, but you can't read quickly as you'll frequently mis-read some letters—for example, the letters "c", "o" and "e" can be difficult to distinguish in the dim light. But if you shine the light from the side, so it illuminates one-quarter to one-third of the page, it's brighter, and it's easy to read the novel.

When using the torch as a night light, I position it so it shines up at the white ceiling in the room. To dark-adjusted eyes, the reflected light gives enough illumination to see all the furniture in the room, but it's quite dim, so you only see in monochrome. It lights up the room about as much as someone reading their mobile phone while in bed. I have tried using this light reflected from the ceiling to read the writing on boxes, and if the letters are the same size as on car number plates, the writing can be read.

How it works

The circuit regulates electrical current, but instead of regulating the current going into the LED, it regulates the current coming out of the battery. This current from the battery charges up a capacitor, storing energy, and then the capacitor is rapidly discharged into the LED, releasing that energy. Roughly 99% of the time this circuit is in "charging capacitor" mode, and the other 1% of the time the capacitor is discharging into the LED.

Looking at the circuit in Figure 1, the 3k3 (3.3k) resistor at the top is supplying the current to charge the 10uF capacitor. The two transistors on the left monitor the voltage across the 3k3 resistor, and when that voltage drops to roughly 0.7V, they signal the other two transistors to turn on, allowing the capacitor to discharge into the LED. During this discharge, the voltage across the capacitor is dropping, so the voltage across the 3k3 resistor is increasing. When the voltage across the resistor has increased to about 0.8V, the two transistors on the left of the circuit send a "turn off" signal to the other two transistors. The 10uF capacitor then starts charging again, and the cycle repeats.

For the technically-minded, the two transistors on the left are configured as a Schmitt Trigger circuit. The signal out of the Schmitt Trigger circuit is only a fraction of a milliamp, so the other two transistors amplify that signal to a level suitable to power the LED.

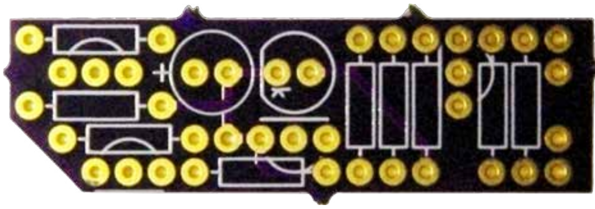
This circuit works best with rechargeable low-self-discharge (LSD) AA NiMh (nickel metal hydride) batteries. It will also work with AA alkaline batteries, but they will only last about half as long. The reason for this is that although both types of battery have about the same capacity, the voltage they output is different. NiMh batteries start at about 1.4V straight off the charger, and they drop to 1.1V by the time they are flat. Alkaline batteries start about 1.6V, and are considered flat at 0.8V, which is lower than the NiMh batteries. This circuit needs a minimum of 3.3V, and we are using three batteries, so the three NiMh batteries will be completely flat by the time their combined voltage drops to 3.3V. The alkaline batteries, on the other hand, are only a little over half-way through their discharge before their combined voltage drops below 3.3V, so although there is still power left in the alkaline batteries, the circuit can't use it.

Choosing an LED

To get the best out of this circuit, you need to choose a high efficiency LED—that is, one that produces the most light for the energy consumed. There are two numbers that you need to consider when choosing an LED for illumination: brightness and beam angle.

Brightness is the easiest to understand, it's how bright the LED is when you are looking directly on-axis, straight into the LED. To achieve a fair comparison between different LEDs, you want to compare the brightness with the same level of power being put into each LED. The datasheets for most small LEDs give their brightness figure when being supplied with 20mA of forward current, which lets you easily compare. Brightness is measured in millicandela, abbreviated mcd, or sometimes in candela (1000 millicandela = 1 candela).

The other number you need to compare is the beam width—how much "spread" the light has. For example, a laser pointer has an extremely narrow beam width, and a household light bulb has an extremely wide beam width. You don't want the LED's beam width to be too narrow, or that LED won't make a very useful torch, as you'll have to scan it across items to identify what the items are. For example, it would be very tiresome to read a book if you could only illuminate one word at a time. But if the beam width is too wide, then the LED is unlikely to have a high millicandela figure, as



This is what the final PCBs look like, as delivered from OSH Park. A little trimming is required.

it's spreading a fixed quantity of light over a larger area.

I tried two white superbright LEDs: a 45000mcd LED rated at 30mA, and a 28000mcd LED rated at 20mA. When both are run at 20mA, and positioned so they both make a 30cm-wide disc of light on the wall, they appear to be the same brightness. But the 45000mcd LED was about twice as far away from the wall as the 28000mcd LED, proving that it has a much narrower beam angle. I tried using them both as a torch, and found the 28000mcd one more natural to use, because of its wider beam angle. Jaycar sell this LED as part number ZD0196, but don't identify the manufacturer nor the LED's part number.

Choosing batteries for the light

The most important thing is to choose low-self-discharge NiMh batteries with a capacity of at least 2000mAh. See the section 'About NiMh batteries' for information on how to identify such batteries. This torch consumes an average current of 0.25mA, so a 2500mAh battery will last (2500/0.25=) 10,000 hours. One year is 8760 hours, so a 2500mAh battery will last about a year, allowing a small derating due to the self-discharge of the battery.

Lower-capacity 2000mAh batteries will typically last about 11 months. Their capacity is lower, but their self-discharge is also lower, so you get a better result than you would expect from the capacity figure alone. If you want to use 2000mAh batteries and still get one year, change the 3k3 resistor to 3k9, which will lower the current consumption. A little less light will be produced.

Another possibility for powering this circuit is to use supercapacitors. You'll get a much shorter "battery life", as supercapacitors store energy in a different way to batteries, and can provide far less power. I calculate that two 35-Farad 2.7V supercapacitors, connected in series, can power this circuit for approximately 18 hours. During this time the voltage across the supercapacitors will drop from 5V to about 3.5V. So with a little extra circuitry, you could have a solar panel charge the supercapacitors during daytime, and have them produce light all night long. Garden pathway lights already do this, using batteries, but the batteries wear out quickly. Supercapacitors have a theoretically infinite life, and good-quality solar panels have a 20+ year life.

If you want to make this flashlight yourself, the printed circuit board (PCB) can be ordered from OSH Park, a PCB manufacturer in the USA. They are very inexpensive, and delivery is free for the slowest option (4-6 weeks), but their pricing is in US dollars, and they charge in US dollars. Unless you're familiar with how your bank charges fees for foreign currency purchases, it's safest to purchase using PayPal, letting Paypal do the conversion to Australian dollars.

The address of the ordering page is oshpark.com/profiles/Renew-Magazine-1-year-flashlight. There is also a link to assembly instructions on that page.

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For thirty years Russell has been running a company that designs electronic circuits. Russell enjoys stretching the boundaries of what is possible with electronics, and lately has been gaining experience in micropower design.

About NiMH batteries

NiMh (Nickel-Metal Hydride) batteries are the commonest AA and AAA rechargeable battery available, and they come in two types. The "ordinary" type suffers from self-discharge, which means that the batteries lose about 1% of their stored energy per day, so after three months they only have about 40% of their energy left (maths: three months = 91 days, 0.99^91 = 0.40). This self-discharge is inconvenient—it means you can't charge the batteries and leave them stored as 'ready to go', as a significant amount of their energy will have dissipated by the time you want to use them. The much older NiCad (Nickel-Cadmium) batteries also suffered from this problem.

There is a newer type of NiMH with drastically lower self-discharge. These are known as "Low Self-Discharge" (LSD) NiMH batteries, and they ARE suitable for charging and storing away until you want to use them. One of the best-known brands is Panasonic eneloop, and their current batteries claim "Holds 70% charge up to 10 years". Different brands and models of these batteries make varying claims about how long they store their charge for.

Unfortunately, LSD NiMH batteries are not easy to identify from what is written on their packaging. Eneloop batteries tell you clearly on their package how long they will store charge, but other brands are less clear about this. Many simply say "pre-charged" or "ready to use", but don't give information on how long they will hold their charge. And some battery manufacturers are deceptive—one claims "partially pre-charged" on a packet of ordinary NiMH batteries.

It's worth noting that the NiMH AA batteries with 2400mAh capacity or higher have roughly the same amount of energy as the best alkaline batteries, and alkaline batteries aren't rechargeable. However, NiMH batteries start at a lower voltage than alkaline batteries, and some devices can't tolerate the lower voltage. NiMH batteries measure 1.4V straight off the charger, dropping rapidly to about 1.25V as they are used, and finally drop to 1.1V when they have expended most of their energy. Alkaline batteries start at 1.65V and drop to 0.8V when they are considered flat.

To charge NiMH batteries (including LSD NiMH batteries), you'll need a battery charger, and if you want your batteries to last a long time, you need to get a good one. There are two main types of battery charger, and only one of them can be considered good.

The commonest type of battery charger is known as a timer charger, also known as a "dumb" charger, although it won't tell you that on the packaging. This type of charger forces a fixed amount of energy into the batteries, irrespective

Nickel metal hydride batteries come in all common sizes, including the AA size seen here. There are many brands, but some of the cheaper ones lose chargeable capacity quite quickly over time. The "low self discharge" aspect of cells varies greatly as well, with some holding more charge for longer compared to others. In the background is the flashlight inside a square jar, to stop dust from collecting when used as a night light. This jar was sold with basil pesto inside. Some rectangles of soft foam secure the flashlight in the desired orientation.

of how flat the batteries are. Usually the charge cycle is 10 to 14 hours. Unfortunately, when a battery receives more energy than it needs, that excess energy turns into heat, and heat is the commonest way of damaging rechargeable batteries. If you've ever taken batteries out of a charger and they were so hot you couldn't hold them, the batteries were almost certainly damaged by the charger.

NiMh batteries are damaged by heat because they contain a liquid electrolyte, which is water with some chemicals dissolved in it. There isn't much of this liquid in an AA battery, but when the battery gets hot, the liquid builds up pressure inside the battery. The battery has a tiny plastic pressure-relief seal, almost always located near the positive pip of the battery. If the battery gets too hot, the pressure seal will rupture, and then the electrolyte can leak out, or evaporate over time. There's no way to repair the pressure seal once it has ruptured—the capacity of the battery will continuously drop over time. On some batteries, you can tell that the seal has ruptured: it looks like there is a water stain around the positive end of the battery, under the clear plastic sleeve. This is due to the electrolyte that has leaked out.

The better type of charger is known as a smart charger, and usually such chargers WILL proclaim this on their packaging. Unfortunately some smart chargers are better than others—more on that later.

A smart charger can detect when the battery reaches full charge, and stop charging, so the battery doesn't get excessively hot. With such chargers, you can hold a finger against the battery at any time during the charging, and while it may feel uncomfortably warm, you won't feel the unconscious reaction to pull your finger away. Humans are pretty good at detecting temperatures like this: first degree-burns can start at 55°C, and most people will pull away or drop anything hotter than 50°C, and feel uncomfortable holding things above 45°C.

There are two ways that a smart charger can detect the battery has reached full charge: by monitoring the temperatures of the batteries (uncommon), or by measuring a thing called the "-dV/dT" or "delta V" effect. This effect means that the battery voltage stops rising, or may even drop a tiny amount, during the charge cycle. This effect is most strongly seen when the charging current is chosen so the charge cycle takes one to two hours. At three hours, the effect is getting smaller, and with a four-hour charging cycle the effect will be difficult to detect, so the charger may not stop at the correct point, and may overcharge your batteries. While there are a few chargers that have longer charging cycles and won't mistreat your batteries, the majority that take longer than three hours are just poorly-designed chargers that will probably damage your batteries. If the charger doesn't mention its charging time on the packaging, or says something vague like "overnight", that's usually a warning sign it's a bad charger.

Another thing you should look for when selecting a charger is individual charging channels. So, for example, a charger with four battery slots can charge one, two, three or four batteries at a time. Some chargers can't charge odd numbers of batteries, they require you to charge the batteries in pairs. So if you were to insert two batteries, one of which was completely flat and the other partially flat, the partially-flat battery will reach full charge before the fully-flat battery does. The charger will inevitably overcharge the battery that was initially partially flat, with the resulting heat and potential damage.

There is a third type of battery charging that is perhaps the safest for preserving battery life, and that is known as trickle charging. Such chargers are extremely uncommon, and charge your battery over 20 hours or longer. As they put energy into the battery so slowly, the battery may become warm, but won't overheat. Trickle chargers have a disadvantage—you must not leave the batteries continuously on the charger, or they will eventually develop an internal short, which kills the battery. If you take the batteries off after 24 or 48 hours, trickle charging is a reliable and safe way to charge NiMH batteries.

Apart from overcharging, the second most common way of damaging NiMH batteries is over-discharging the batteries. This sounds odd, how can you over-discharge a battery? Well, most devices use several batteries, and they are connected in series, so the same current flows through each battery. When using the device, invariably one battery will go flat a little earlier than the others, but the device will continue to operate. So now the current is still flowing in the battery pack in the direction that makes the batteries discharge, but one battery is already flat, so that battery becomes over-discharged. This harms the battery, so next time it will go flat even faster, and the remaining batteries will over-discharge it for even longer. So if you notice that your device has a drop in performance, indicating one battery has gone flat, the best advice is to take the batteries out so they can't over-discharge, and charge them when you have time. NiMH batteries are not harmed by being left in a discharged state.

Brand	Rated capacity	Self-discharge rate	Comments
eneloop	2000mAh	Holds 70% charge up to 10 years	
eneloop pro	2550mAh	Holds up to 85% charge after 1 year	
GP ReCyko+ Pro	2000mAh	Holds up to 70% charge after 5 years	
Turnigy NiMh	2550mAh	Holds up to 70% charge after 1 year	Only available from Hobbyking.com
LADDA	2450mAh	Unknown	Only available from IKEA

Table 1. Commonly available LSD NiMH AA batteries.