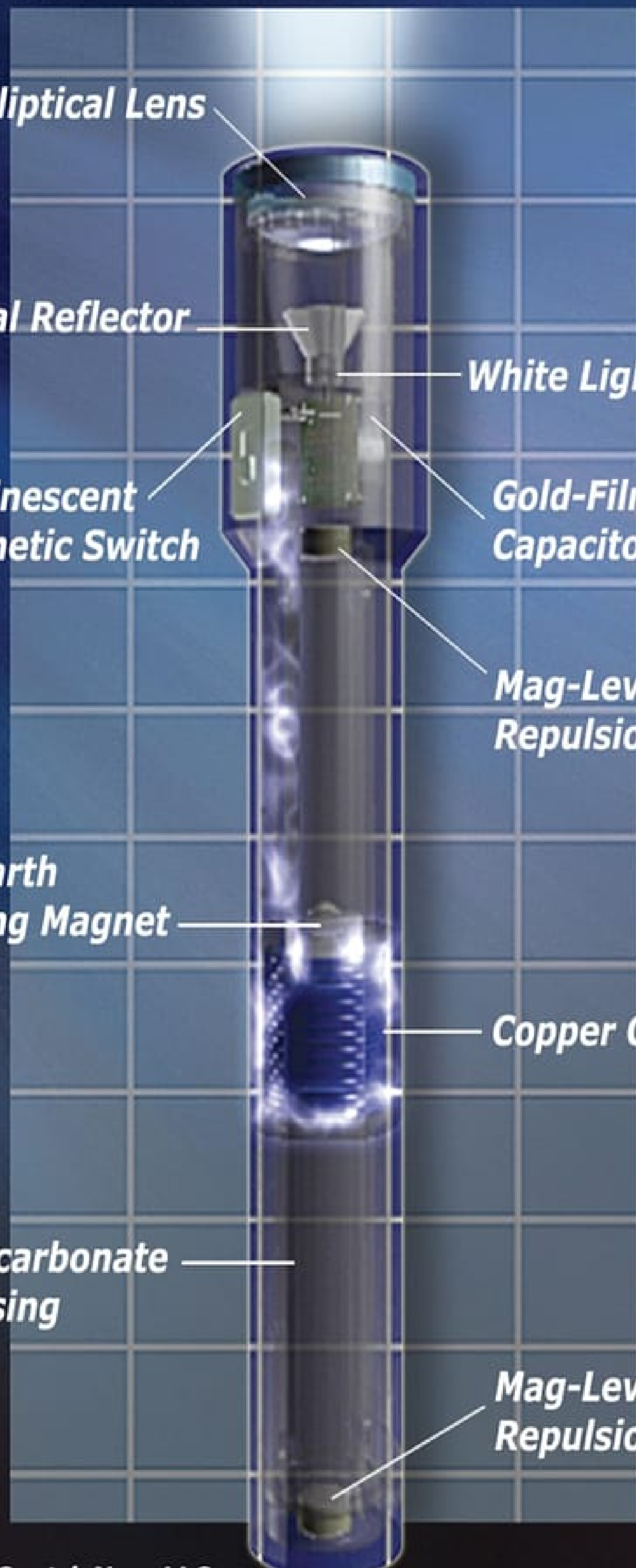
NightStar Shake Flashlight Physics Guide



*S*hake Flashlight Technology – Introduction

NightStar Shake Flashlight was created as a disruptive technology to the battery flashlight market in 1997. Advancements in LED and capacitor capabilities make possible the manufacturing of a zero-maintenance flashlight capable of decades of operation under the harshest environmental conditions.

At the heart of NightStar is the rare earth magnet charging system that utilizes mag-lev repulsion and electricity storage in a gold film capacitor. Building upon the power cell platform are the proprietary optics that maximizes LED collimation. A Reed switch controls LED activation, which is triggered by an external magnet housed in a luminescent slider.

Internal electronics are protected by a clear, crush resistant, impermeable polycarbonate housing, waterproof to 200m depth and buoyant. An added benefit, holding the flashlight horizontally orients the light as a compass in a north-south direction.

A variety of customers benefit from a NightStar shake flashlight including emergency preparedness, recreation, and education market participants. The versatile capabilities are self-explanatory for emergency preparedness and recreation including camping, watersports, and hunting.

Educational benefactors such as STEAM students and teachers use the flashlight to teach an assortment of physics concepts including renewable energy generation and optics, which are explained at length in this publication.

A scaled down version of the NightStar shake flashlight is available in the shake-to-charge flashlight ShakeLight 40B, used by thousands of STEM students around the globe.

NightStar Physics Guide

The NightStar Shake Flashlight Physics Guide presents engineering considerations integrated into the NightStar induction flashlight. This publication provides STEAM education students and teachers with a tool to understand and apply numerous physics concepts.

Learn how the principles of Newtonian Relativity, Faraday's Law of Electromagnetic Induction, Snell's Law of Refraction and Fermat's Principle of Least Time are incorporated into the flashlight design. Develop an understanding about the nature of magnetism, electrodynamics, renewable energy, light and optics.

Shake Flashlight Technology – Topics

Combining Innovative Technologies

Combining Innovative Technologies

With the development of rare-earth magnets towards the end of the 20th century, generators capable of converting mechanical energy to electrical energy reached astounding efficiencies of 85% and higher. In addition, advancements in high energy capacitors, significantly driven by personal computer memory requirements, and solid-state Light Emitting Diodes (LEDs) were simultaneously occurring.

Applied Innovative Technologies, Inc. (EcoCentricNow LLC) recognized combining these technologies would result in a portable lighting device unique to the market. The crowning result is the world’s best capacitor shake flashlight. A self-charging flashlight not dependent upon batteries or incandescent bulbs and contained within an impact resistant waterproof housing. Even when subjected to abuse and neglect NightStar operates for decades with zero maintenance.

The Science of Shake Flashlight Technology

Many of the components and mechanisms of the NightStar flashlight aptly exhibit important physics principles. The repulsion of the mobile magnet by the two fixed end magnets illustrates ***ferromagnetism***. The generation of alternating electric current in the coil by the moving magnet demonstrates ***magnetomotive induction***.

Converting the alternating electric current to direct, or unidirectional, current reflects ***diode rectification.*** The energy conveniently saved for later use shows ***capacitive energy storage.*** Energy carried in the electric current that is converted to blue light demonstrates ***radiative recombination*** in the light-emitting diode.

The phosphor converts some of the blue into other colors, illustrating ***fluorescence.*** Finally, the white light streaming in all directions is collected and projected forward into a useful beam by the reflector and lens demonstrating ***reflection*** **and** ***refraction***, respectively.

Ferromagnetism

In its broadest definition magnetism is the force exerted between moving charges due to their motion. This is distinct from the *electrostatic force*, which exists between charges regardless of their motion. Magnetic force can be demonstrated by passing electrical current through neighboring coils of wire and observing their mutual attraction or repulsion.

Unlike coils the permanent magnets in the shake flashlight need no added source of current. Current is produced by the electrons orbiting around the nucleus of each atom in the magnet. These tiny electrical currents occur in all matter and yet most materials are not magnetic. Why not?

In most molecules the currents generated by electron pairs oppose each other and their magnetism cancels out. In rare cases not all the electron currents within a molecule cancel and a weak magnetic effect called *paramagnetism* is observed. A well-known example of a paramagnetic material is molecular oxygen, which is demonstrated by the attraction of liquid oxygen to a permanent magnet.

In some materials individual molecules are magnetic, but the molecules are oriented in different directions, which tend to cancel each other. The molecules can be temporarily aligned by placing them near a strong magnet but when the magnet is removed the alignment decays and the magnetism is lost.

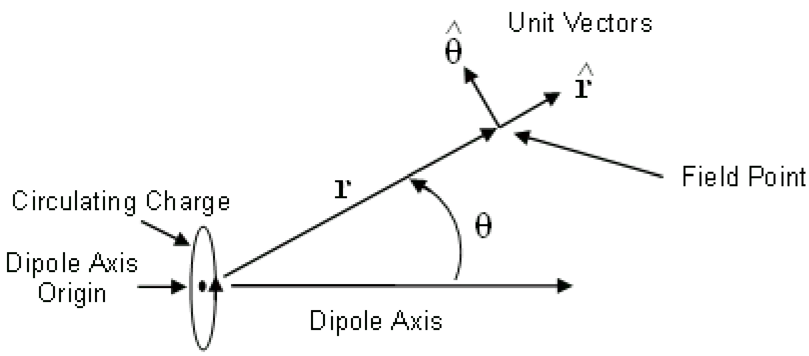
Less commonly, the induced order will persist after removal of the strong magnet, this behavior is called *ferromagnetism.* In a ferromagnet the uncancelled electron currents are aligned and work together to produce a strong magnetic force.

Ferromagnets are directional. If two ferromagnets are placed end to end, oriented so their electron orbits are in the same direction, they will attract each other. This attraction can be quite strong and sudden. If the magnets are oriented so their electron orbits oppose, they will repel each other. Attraction and repulsion both weaken with decreasing distance between the magnets. For any ferromagnetic material, the field strength drops off as the inverse cube of the distance r. The fie strength for a single dipole is given by:

$$B = \frac{\mu_0 m}{4\pi r^3}(2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta})$$

Equation 1

Figure 1 shows the physical arrangement of the dipole.



In the equation for the dipole, m_o is a constant (called the magnetic permeability of free space), m is the magnetic dipole moment, r is the distance from the origin of the dipole axis to the field point, θ is the angle between the dipole axis and a vector from the dipole axis origin to the field point, and **r** and **θ** are polar coordinate unit vectors. (Note that for any field point the unit vectors are oriented so that **r** points away from the dipole axis origin and **θ** is perpendicular to **r** and pointing in the counterclockwise direction). At a point lying on the axis where θ = 0°, Equation 1 reduces to:

$$B = \frac{\mu_0 m}{4\pi r^3}(2\hat{r}) = \frac{\mu_0 m}{2\pi r^3}\hat{r}$$

Equation 2

At a point on the magnetic field line where θ = 90°, Equation 2 reduces to:

$$B = \frac{\mu_0 m}{4\pi r^3}\hat{\theta}$$

Equation 3

At any distance r from the dipole a point on the axis is twice as strong as a point orthogonal to the axis. To calculate the approximate field strength of a magnet the combined effect of all dipoles must be summed together. The math required for this is beyond this tutorial and is left to the reader to investigate further.

NightStar shake flashlight, sometimes referred to as a Faraday Flashlight, contains four ferromagnets, one that is free to travel within a tube that runs the length of the flashlight power cell, one fixed at each end of the power cell tube, and one that activates the internal Reed switch. The fixed magnets are oriented in the same direction while the mobile magnet is oriented in the opposite direction. This creates a repulsion that traps the mobile magnet (hereafter referred to as the charging magnet) part way between the fixed magnets.

When NightStar is shaken the magnetic repulsion recoil system smoothly rebounds the charging magnet with marginal loss in energy. The energy loss that does exist is due to friction of the cylindrically shaped nickel-plated charging magnet sliding along polished rails of the plastic tube. Kinetic energy is therefore efficiently coupled into electrical energy with almost no degradation to the system.

One way to measure the repulsion force between two magnets is to balance it against gravity. By holding NightStar vertically the charging magnet will settle to some height above the fixed magnet. This is the height where the upward magnetic repulsive force exactly balances the downward gravitational force.

The magnets used in NightStar shake flashlight are made from an anisotropic sintered ceramic material containing neodymium, iron, and boron (NdFeB). The anisotropic nature of the material (meaning that it has properties that differ according to the direction of the measurement) is due to the tetragonal crystalline structure of the NdFeB molecule.

The magnetic dipole associated with each crystal lattice site aligns itself along a well-defined axis within the bulk material. Because of its molecular magnetic structure, the material is remarkable in two ways. First, it possesses a high-density magnetic field because of the alignment uniformity of the magnetic dipoles. Second, it will hold this field for an extremely long time even when orientated for repulsion with another magnet or subjected to elevated temperatures, and shock.

All the magnets in NightStar were initially slugs or disks of ceramic NdFeB. After plating they are placed in a toroid chamber that converts electricity into an extremely high strength magnetic field. The ceramic pieces become magnetized within a few seconds and will remain so for thousands of years. Remarkably, the field strength at the core of the charging magnet is approximately 45 million gauss. Along the surface of the magnet the field is approximately 8,000 gauss and at 1 foot the field is still an astounding 300 gauss.

Magnetomotive Induction

NightStar induction flashlight exploits the magnetic force between moving electrons in yet another way, it converts the mechanical energy of the moving magnet into electrical energy. A coil of copper wire wound about the midpoint of the tube performs this transformation.

To understand how this happens imagine the magnet as fixed, as shown in Figure 2, and the coil moving past it. Newtonian Relativity, one of the most useful concepts in physics, says that either the magnet or the coil is equally legitimate to consider as “fixed”, since motion is relative.

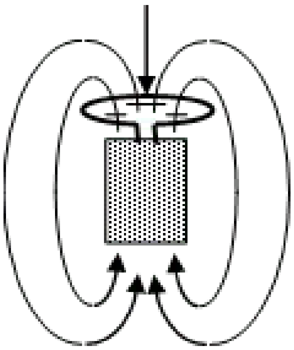


Figure 2

The moving charged particles of each copper atom in the coil all respond as they pass the magnet. However, all but one of the charges is embedded in the material and strains against the bond but cannot break free. This exception is the single free electron per copper atom, which can move about in the material.

Let’s assume it is initially stationary within the wire, which means it is moving parallel, but displaced to the side of the magnet axis. As the free electron approaches the magnet it experiences a force that is perpendicular both to its direction of motion and to a line drawn through and perpendicular to both the direction of motion and magnetic axis. This force happens to be along the direction of the coil wire and the free electron begins moving along the wire accompanied by a vast number of free electrons from other atoms.

This mass motion peaks as the coil passes the end of the magnet where the magnetic field is most perpendicular to the coil. As the coil passes the center of the magnet the motion slows to a halt and then reverses direction, peaks in the opposite direction, and then slows to a halt again as the coil recedes. This action typifies why NightStar is sometimes referred to as a shake to charge flashlight.

This microscopic picture of magnetomotive induction had to wait for the discovery of sub-atomic particles. Historically, magnetomotive induction was first described in macroscopic terms, following the experiments of Faraday and others in the early nineteenth century.

When a single loop of wire is passed over a magnet the induced voltage V is proportional to how fast the number of field lines (arrows going from the top to the bottom magnet pole) surrounded by the loop changes in time.

Mathematically, this is:

$$V = -\frac{d\Phi}{dt} \text{ where } \Phi \equiv \oint dS\, \hat{n} \cdot \vec{B}$$

Equation 4

where F is the “flux”, or number of field lines going through the coil, B is the magnetic field vector, and S is the surface through which the field is passing. As the coil moves down over the magnet, the flux increases until the coil reaches the midpoint and then begins to decrease. The time derivative of the flux and therefore the voltage is at a maximum when the coil is near either end of the magnet and zero at the midpoint.

Of course, a single loop of wire produces a feeble voltage and standard practice is to loop many winds into a coil. A central problem in magnetic design is how many winds are needed in the coil. There are two issues requiring attention, how long to make the coil, and how thick the coil wire should be.

If we imagine starting with one wind and adding another wind, one at a time, along the axis we find that each additional wind adds an increment of voltage equal to that of the original wind. So long as the coil is short compared to the magnet length each wind sees the same change in flux at the same time, the induced voltages add, and the total voltage is proportional to the number of loops.

Eventually when the coil becomes longer than the magnet length the winds on one end see a decrease in flux at the same time winds at the other end see an increase in flux as the coil passes the magnet voltage cancellation results. Lengthening the coil by adding more winds eventually becomes ineffective and then detrimental.

A great deal of experimentation went into the design of NightStar’s coil geometry. Analysis revealed the optimum coupling of mechanical energy to electrical energy resulted when the coil length was equal to the length of the magnet. In addition, the travel distance of the magnet should be 5 times the length of the magnet for the field lines to effectively clear the coil. This geometry produces a single bipolar pulse of energy (Figure 3), which is the next stage in the chain of energy conversions that transmutes the muscular effort of shaking into light.

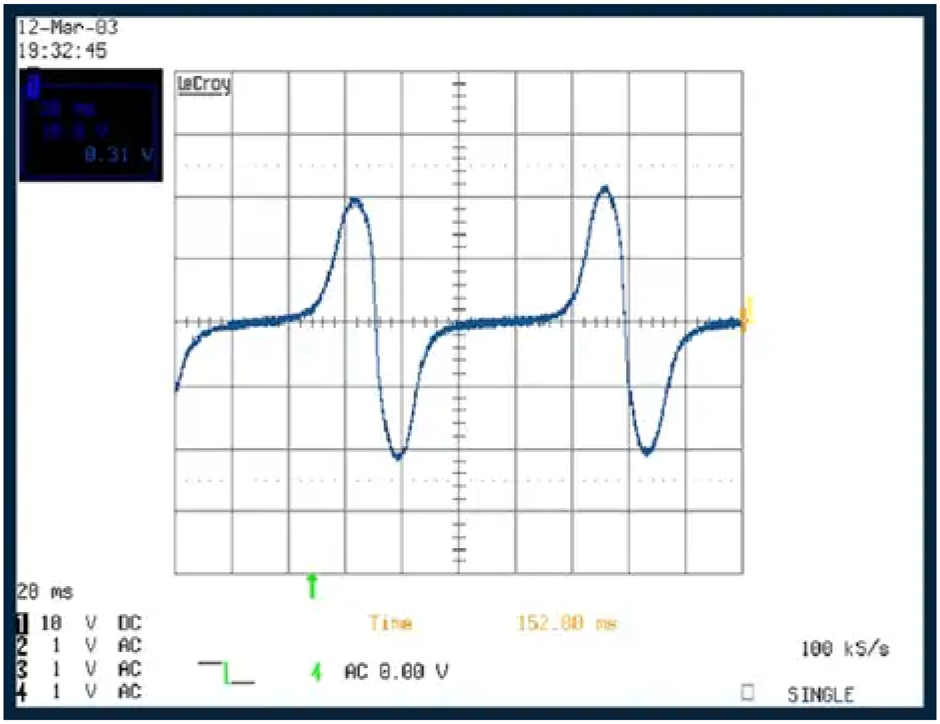


Figure 3

With regards to the wire diameter, large diameter wire allows for higher current with less resistance. However, it decreases the total number of winds in the allowed coil volume reducing peak voltage. Small diameter wire has lower current and higher resistance but allows for more winds and higher peak voltage. The optimum wire size is 30-gauge magnet wire, which effectively couples kinetic to electrical energy, minimizing the effort needed to recharge the capacitor.

An important and yet subtle feature of NightStar's design is its plastic housing. Plastic is necessary for several reasons. Most importantly, metallic housings such as aluminum or copper prevent the charging magnet from moving effectively through the coil. This is due to free electron eddy currents that are set up in the metal housing when the charging magnet travels through the barrel.

Consequently, magnetic fields generated by the eddy currents in the housing oppose the magnetic field of the charging magnet. The faster the charging magnet tries to move the stronger the opposing fields present in the housing, effectively "braking" the magnets motion. Therefore, the charging magnet never passes through the coil with enough speed to charge the capacitor.

Plastic housing is superior to metal housing in several other ways. The material and manufacturing costs of plastic are less expensive than aluminum (aluminum is a choice for metal housing). Additionally, NightStar's plastic housing will never rust, is highly corrosion resistant, and weighs less than aluminum housing with the same crush resistance.

Shake Flashlight Diode Rectification

The electrical current produced by the ferromagnet moving through the coil goes in one direction as the magnet approaches the coil and the other direction as the magnet recedes from the coil. This so-called alternating current is not the most useful form of producing electricity for energy storage or conversion to light. NightStar flashlight uses four diodes as a full-wave bridge rectifier to convert alternating current to the more useful (for our purposes) direct current.

For electrons to flow there must be a continuous path or "circuit" from their point of origin through some number of "components" and back to the point of origin. A component is something with an entrance and an exit, which acts upon or reacts to the current in some way.

Usually, the entrance and exit of a component are interchangeable. Diodes are an exception to this rule. Diodes are the one-way streets of electrical circuits. Suppose we connect each end of the coil to a pair of diodes where one diode allows electrons to flow out of the coil end and the other diode allows electrons to enter. Next, we connect the far end of one exit diode to the far end of the other exit diode and do the same for the entrance diodes. Finally, we connect the direct-current electrical device we wish to power to the junctions we just made. The device we wish to power is called the load.

Referring to Figure 4, when the magnet approaches the coil electrons flow out of end "A" of the coil, through the exit diode for coil end A, through the load, through the entrance diode for coil end "B", back into coil end B, and through the coil back to their point of origin. The current path is shown in blue.

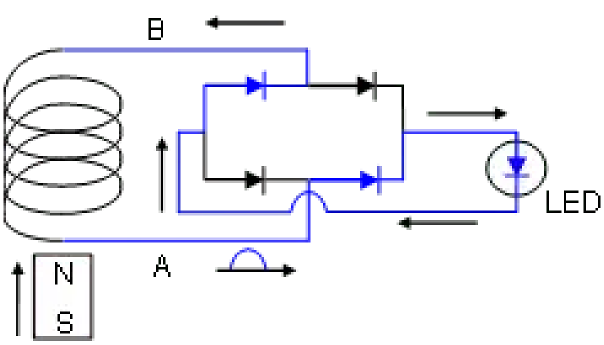


Figure 4

When the magnet passes the coil and recedes, electrons flow from B through its exit diode (the load is *in the same direction as before),* into and through diode A then through the coil back to B making a circuit as shown by the blue lines in Figure 5. Therefore, no matter which direction the current flows in the coil, it flows in one direction in the load. This is called rectification.

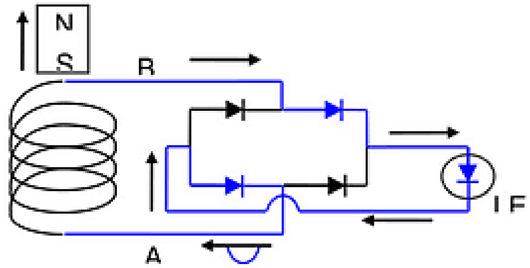


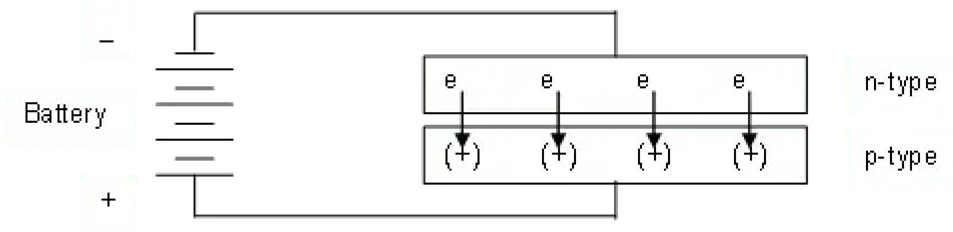
Figure 5

The diodes in the NightStar shake flashlight are made of materials known as semiconductors. Semiconductors come in two varieties, n-type, and p-type. An n-type semiconductor is like copper in that some (not all) atoms have one loosely bound electron that can easily be freed to flow through the material and thus contribute to an electrical current. P-type semiconductors are more difficult to understand. In a p-type semiconductor some atoms have one too few tightly bound electrons, which causes them to steal an electron from one of their neighbors. The atom that lost an electron is now incomplete, so it steals an electron from a third atom and so on.

This moving electron vacancy is often depicted as the current of a fictitious positive charge called a “hole” through the p-type semiconductor.

A diode is formed when an n-type and a p-type semiconductor are brought into contact to form a “junction”. Atoms on the p-type side pull electrons from the n-type side across the junction to fill their vacancies. Another way to view this is electrons jumping across the junction to fill holes in a mutual annihilation. Regardless of the mental model used, the effect of this transfer of electrons is the n-type material loses electrons and becomes positively charged making it increasingly difficult for more electrons to leave. The tendency of electrons to stay quickly balances the tendency to leave and the exodus ceases.

Suppose we want the electrons to continue to cross the junction from the n-type to the p-type side, how could we make that happen? To do this we must replenish the dwindling supply of electrons of the n-type material thereby reducing its positive charge. We must simultaneously drain excess electrons from the p-type material thereby reducing its negative charge. We can accomplish both objectives by connecting a battery to the diode, negative terminal to n-type and positive terminal to p-type. A current of electrons will then flow indefinitely in the circuit in the direction of n-type to p-type as shown in Figure 6.



Assume that we mistakenly connect the battery backwards. Now, the n-type material becomes even more positively charged so that it pulls back some of the electrons that formerly crossed the junction to fill vacancies in the p-type material. This retraction of electrons is quickly balanced by the increasing demand to fill p-type vacancies and the brief flow of electrons stops. If we increase the reverse voltage another brief increment of charge is transferred but no permanent current is established. In this way the diode acts as a one-way street for electrons like a check valve operates in a plumbing system.

Capacitive Energy Storage

The rectified current could be immediately directed into the light-emitting diode, but this would be useless as the flashlight would cease producing light as soon as shaking stops. Therefore, NightStar shake flashlight is equipped with an energy storage device so it can be charged and then used in the future.

Most flashlights are powered by one or more batteries, which even if rechargeable eventually wear out and must be replaced, often at the worst time. NightStar uses a much simpler and more robust energy storage device called a capacitor. This energy storage cell is a principal reason the NightStar Shake Flashlight is the ultimate emergency flashlight.

Previously, it was asserted that an unbroken path must exist for electrons to flow. This is strictly true only for continuous currents. A capacitor allows a temporary current to flow through it while blocking the individual electrons constituting the current from crossing. How is this possible?

A capacitor consists of two flat metal plates with a thin layer of insulator between them. When connected to a battery or other charging source electrons leave the negative terminal and pile onto one of the capacitor plates. As they build up charge, they repel electrons on the other plate. The electrons on the far plate travel to the positive terminal of the battery. No single electron travels through the entire circuit.

This situation is temporary because the growing imbalance of electrons between the plates increasingly inhibits further current until eventually the current dwindles to nothing. At this point the capacitor is said to be charged. Its plates have a voltage difference that opposes the battery and prevents further charging. The ratio of the stored charge Q to the voltage V is the capacitance C given by:

$$C = Q / V$$

Equation 5

If a load suddenly replaces the battery, electrons will take advantage of the newly available current path by flowing from the crowded plate through the load and onto the depleted plate. This current will continue until the electrons are equally distributed on the two plates and the voltage difference is zero. This temporary current dissipates an amount of energy that turns out to be independent of the nature of the load and given by the equation.

$$E = 1/2\,CV^2$$

Equation 6

Since energy is neither created nor destroyed and the capacitor has zero energy when discharged it follows that the stored energy is $\frac{1}{2}CV^2$ for a charged capacitor. To maximize energy storage, C should be as large as possible. NightStar shake flashlight has a 1.5-Farad capacitor, an amount that was science fiction in the early 1980's. Even so, NightStar capacitor can only store about 23 Joules of energy. In contrast, a lead-acid battery used in an automobile stores several million Joules.

Faraday Flashlight Radiative Recombination

An important function of the versatile semiconductor diode is to radiate light. While all diodes rectify current not all radiate. A small bundle of light, called a photon, may be generated when an electron and a hole collide and annihilate each other. Whether or not this happens depends on the details of the collision.

Prior to their collision the electron and hole each has an energy and a momentum associated with their motion. Momentum is a measure of how much effort it takes to stop a moving object, which is proportional to both the mass and the speed of the object.

Momentum has a second equally important aspect, directionality. It points along the direction of motion. Indeed, momentum is usefully represented by an arrow pointing in the direction of motion, whose length is given by mass times speed. Energy is the other quantity associated with the motion of an object. It has no directionality and is proportional both to the mass and to the speed times itself, or the speed squared.

Electron and hole annihilation typically produce either a photon or a small bundle of sound called a phonon. In either case the product must have the same total momentum and the same total ene the free electron and hole. In the annihilation the free electron is now bound and so it no longer exists as a free electron and the hole is filled by the bound electron and so it too no longer exists.

Both the free electron and hole give up their momentum and energy in the process. Whereas a phonon (sound) has quite a bit of both energy and momentum a photon (light) has considerable energy but almost no momentum. Therefore, a collision between an electron and hole that doesn't have equal and opposite momenta always produces a phonon to carry the net momentum away.

A photon can result only when the electron and hole have equal and opposite momenta. It happens that in semiconductors used in common diode rectifiers such as silicon and germanium, electron and hole momenta have differing magnitudes (mass times speed) that cannot cancel each other and so their collisions do not produce light.

Such collisions are called nonradiative recombination's. In semiconductors such as gallium arsenide, electron and hole momenta can cancel so that a photon may be emitted. This event is called a radiative recombination.

Light Emitting Diodes (LEDs) are based on radiative recombination. The first LEDs were made of gallium arsenide, a material that emits invisible light called infrared. Gallium arsenide is an example of a III-V (three-five) compound semiconductor, gallium is a member of the III family of chemical elements and arsenic is a member of the V family.

Investigators realized that other members of the III family could be substituted for gallium and others of the V family for arsenic allowing different visible colors to be radiated. Specifically, adding lighter elements of each group (aluminum for group III and phosphorus or nitrogen for group V) gives shorter wavelengths. First, red LEDs were achieved by replacing some gallium with aluminum. Later, yellow, and green LEDs were made by replacing some arsenic with phosphorus.

Blue LEDs have long been eagerly sought. They are the crucial third component of RGB (red-green-blue) LED displays. Blue LEDs can catalyze chemical reactions in printing and photolithography that longer wavelengths cannot, can achieve greater densities in optical data storage such as the DVD-ROM format, and can excite red and green fluorescence in special phosphors to mix with remaining blue to create white light, as described in the next section.

However, they defied the efforts of many researchers until a group at Nichia Corporation in Japan began to succeed with gallium nitride LEDs in the mid 1990's. Now, numerous companies are producing hyper bright blue LEDs. NightStar uses an exceptionally bright diode, which converts 110 mW of electrical power (at maximum charge) into 77 mW of blue light, which is then converted mW of white light by means of an internal fluorescence phosphor. The efficiency, brightness, an uniform white light spectrum of the NightStar shake flashlight LED would have been considered miraculous pre-1990.

Fluorescence

Fluorescence is a common physical phenomenon in which short-wavelength light is converted to longer wavelengths by interacting with certain materials. Fluorescent materials may be minerals (*e.g.* willemite), organic molecules (*e.g.* rhodamine dye) or biological molecules (*e.g.* the green fluorescent protein in some jellyfish). In principle, fluorescence may occur between any wavelength in the electromagnetic spectrum but in practice few materials fluoresce when excited by visible wavelengths (longer than 400 nm).

Fluorescence is almost instantaneous, appearing as soon as the exciting light is turned on and vanishing as soon as it is turned off. Phosphorescence is a related phenomenon in which the material may glow for hours or even days after being excited as demonstrated by the NightStar's glow-in-the-dark switch and its luminescent wall holster.

In NightStar shake flashlight, 440 nanometer wavelength blue photons generated at the P-N junction strike a fluorescent material called a "phosphor", which is deposited onto the diode junction. The phosphor is excited by the high-energy blue light and emits longer wavelength green, yellow, and red light that combine with leftover blue light to give natural looking white light.

Specifically, the broadband emission generated has a peak at 440 nm and 540 nm and spans from 400 to 700 nm. At this point one might ask why use an LED instead of the standard incandescent filament light bulb?

An incandescent bulb is highly inefficient and requires significantly more energy than an LED. The capacitor in NightStar shake flashlight can only power a filament light bulb for several seconds but can power an LED for several minutes. An incandescent bulb has a lifetime of approximately 500 hours and is extremely fragile. Quite frequently a bulb will break before it burns out.

By comparison, the LED used in NightStar Faraday flashlight will operate for more than 50,000 hours and is resistant to breaking. Therefore, for reasons of energy efficiency and reliability a LED is the logical choice for the NightStar shake flashlight.

Shake Flashlight Reflection and Refraction

NightStar shake flashlight generates light output but not just any light will do. We discussed ho light is transformed into a more natural white light, which the eye is more sensitive to, and whic renders objects in their true colors.

It is equally important to direct the light into a bright and uniform beam so objects of interest can be strongly illuminated without stray light interfering with the user's vision. Radiative recombination and fluorescence are omni-directional light sources, and it is the job of NightStar's reflector and lens to project this light forward in a useful form. The reflector directs sideways emitted light forward into the lens which concentrates the light (collimates) into a tight bright beam.

The actions of the mirror (reflector) and lens are based on the principles of reflection and refraction, respectively. To be reflected or refracted light must interact with matter. Neither effect happens in empty space, *e.g.,* between stars. Both effects are caused by the light exciting motion of the electrons in the material.

As the original light excites the motion of charges, so moving charges can produce new light. The new light that bounces off the surface of the material object is the reflected portion while the light that continues into the interior is the refracted portion.

Reflection is both the more conspicuous and easily understood phenomenon. Flat mirrors are quite common both in the man-made and natural world (as still water). Long ago, it was noticed that light reflects from a flat surface with the same angle from which it impinged, like a billiard ball bouncing off a cushion. The statement of the equality of the incident and reflected angles is called Snell's Law of Refraction and given by Equation 7.

$$\theta_{inc} = \theta_{ref}$$

Equation 7

The angles are defined relative to a line perpendicular to the mirror surface, as illustrated in Figure 7.

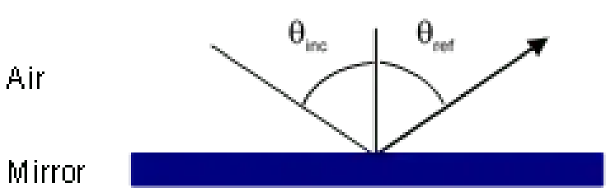


Figure 7

While flat mirrors are quite useful, they do nothing to channel light streaming in all directions into a useful beam. The optimized designed conical reflector in NightStar shake flashlight when placed over the LED redirects side band light in a forward direction. A bright shaped oval of light at the apex of an LED's plastic housing is produced by total internal reflection inside the plastic.

The light emitted from this bright spot exits the LED perpendicular to the normal forward going light. The side band light has between 10 and 20% of the light output power of the forward going light. If no reflector is used, this light is wasted. A reflector with a 70-degree cone angle redirects the side band light forward through the lens. The axial position of the diode inside the reflector determines how much light is collected and where it will overlap the forward moving light.

Experimentally it was found that the conical reflecting surface should intersect the LED 0.04 inches below the center of the hemispherical dome of the LED housing to optimize light gathering and beam overlap. The reflector, as described above, will place side band light on top of the forward projecting light approximately ten feet in front of the lens.

The forward-traveling light, which at this point is rapidly spreading, is then focused into a collimated beam by the refractive action of the lens. The more complicated Snell's Law of Refraction, as expressed by Equation 8 and shown in Figure 8 governs refraction at a large planar interface, such as that between air and a plastic lens.

$$n_{air} \sin\theta_{air} = n_{plastic} \sin\theta_{plastic}$$

Equation 8

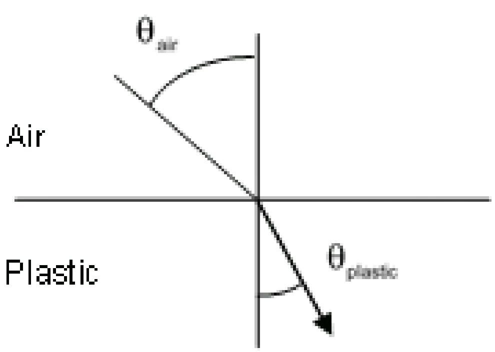


Figure 8

The angles are defined relative to the surface perpendicular as before and "n" is a property of the material called the index of refraction. The index of refraction is inversely proportional to the speed of light in the material. The larger "n" is the slower light moves through the material.

This leads to another way of looking at refraction, called Fermat's Principle of Least Time. Fermat says that out of all possible paths between points in two dissimilar materials light will take the path that takes the least time. How does light "know" which path is fastest? This question crosses the boundary from science into philosophy and will be left for the reader to contemplate. However, if it helps, imagine a lifeguard standing on a long, straight beach about to rush to the rescue of a drowning swimmer, as shown in Figure 9. Which path will minimize the time to reach the swimmer?

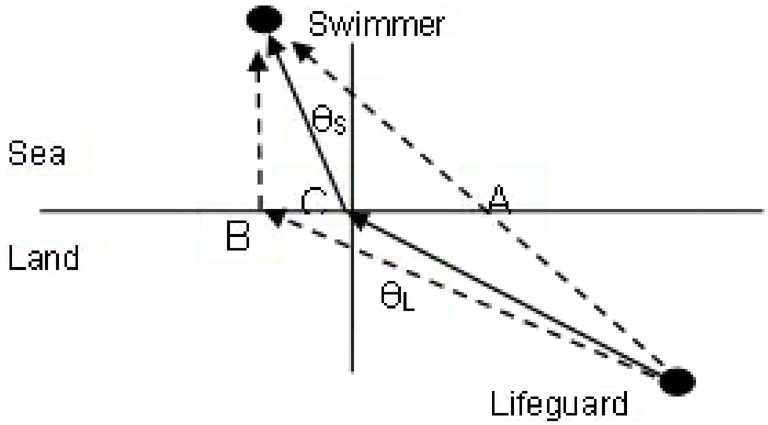


Figure 9

The shortest distance is a direct line (path A). However, the lifeguard can run faster than he can swim so perhaps it's better to run to the point on the shore that is closest to the swimmer (B) to minimize the rescue distance swam. It turns out the best thing to do is to split the difference called point C and then run to C and begin swimming. How does the lifeguard determine C? The lifeguard determines C by finding the point which causes q_L and q_S to obey Snell's Law of Refraction, given the lifeguard "indices of refraction" on land and in the sea.

Snell's Law can be extended to curved surfaces by realizing that any curved surface can be approximated as a quilt work of tiny flat pieces so that the portion of light striking any flat area refracts as if the entire interface were flat with the same position and orientation.

The lifeguard analogy can be extended by imagining the race shown in Figure 10.

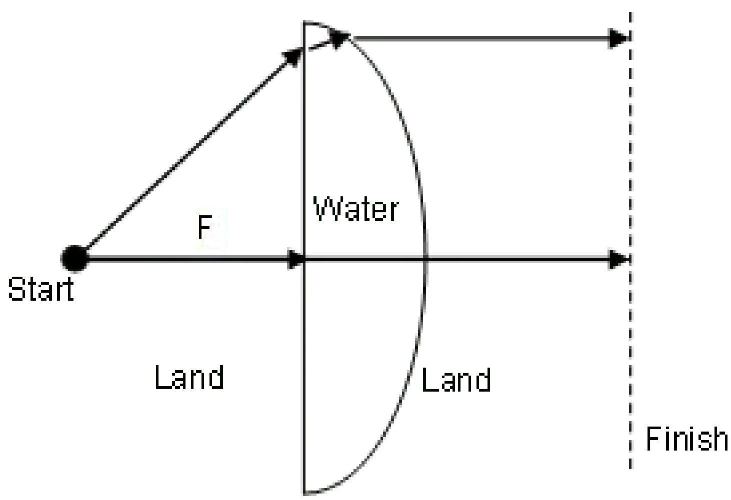


Figure 10

Identical lifeguards race from the start point to the finish line. Each wonder should I take the shortest route even though it goes through the most water or try to save time by running to the edge wh water is narrow, even though the total distance is greater?

Suppose that as a joke the lens designers adjusted the distance from the start point to the water (F) and the radius (R) of the curved shore so that any path takes the same amount of time! Although a race with no winners or losers is hardly very satisfying this is exactly the goal in designing NightStar's lens.

The design equation is:

$$\frac{1}{F} = \frac{n-1}{R}$$

Equation 9

Where n is the ratio of the lifeguard's running speed to swimming speed.

NightStar's lens is designed using this equation along with conical geometry. As a result, the light from the LED is effectively projected into a uniform, collimated beam of illumination.

The Sum of All the Parts … System Integration

The circuit diagram in Figure 11 shows the key electronic and magnetic components discussed thus far. To study the interplay of all the components and the flow of energy through the system we will begin with the coil and magnet. Referring to Equation 4

$$V = -\frac{d\Phi}{dt} \text{ where } \Phi \equiv \oint dS\, \hat{n} \cdot \vec{B}$$

Equation 4

and the discussion regarding the numerous coil windings, the voltage generated by the magnet moving through the coil can be calculated by the equation:

$$V = V_{Peak}(\sin(\omega t)) \text{ where } V_{Peak} = (N)(B)(A)(\omega) \text{ and } \omega = {}^{\pi}\!/_{T}$$

Equation 10

In this equation, V_{Peak} is the maximum peak voltage of the sine wave pulse. The number of coil windings is N, B is the magnetic field strength of the magnet (measured in Tesla), A is the cross-sectional area of the coil (measured in meters squared) and T is the pulse duration (measured in seconds). For NightStar, N = 1472, B = 0.54, A = 0.0006 at 3 shakes per second, T = 0.06 seconds. The theoretical peak voltage is 25 volts. Experimentally the peak voltage was measured to be approximately 22 volts, as shown in Figure 11.

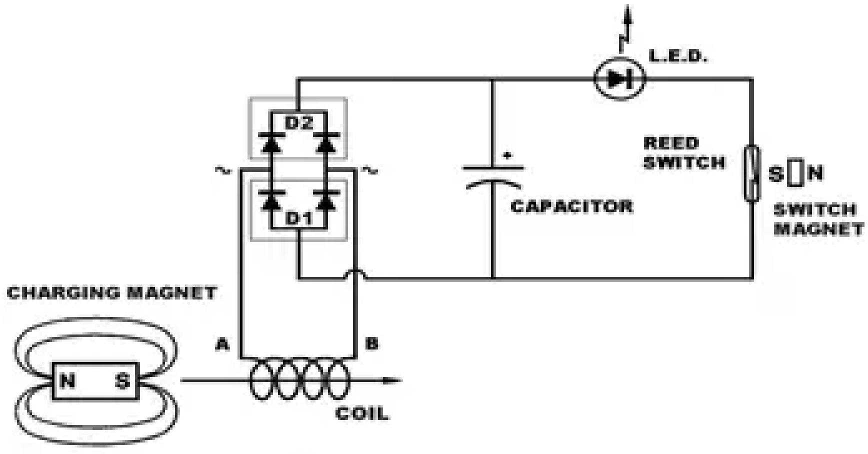


Figure 11

The resistance of the coil is given by the equation:

$$R = \frac{(z)(\rho)}{a}$$

Equation 11

where z is the total length of wire in the coil, ρ is the resistivity of the wire (measured in ohms * meters) and a is the cross-sectional area of the wire. For the 30-gauge copper wire used in NightStar, z = 137 meters, $\rho = 1.7 \times 10^{-8}$, and $a = 5 \times 10^{-8}\ m^2$, which gives a total coil resistance of about 45 ohms. Experimentally the coil resistance was found to be 43 ohms.

Once the voltage and resistance of the circuit are known an equation for the power as a function of time can be derived:

$$P = \frac{V^2}{R} = 21^2 \frac{(\sin^2(\omega t))}{R_{inductor}}$$

$$= 441 \frac{(\sin^2(\pi/T)t)}{43} = 10.25\,(\sin^2(\pi/T)t) = 10.52\,(\sin^2 52t)$$

The energy per sine wave pulse is then the integral of the power from 0 to 0.06 seconds:

$$E = \int_0^{.06} P\,dt = \int_0^{.06} 10.25\,(\sin^2 52t)\,dt$$

$$= 10.25\left[\frac{t}{2} - \frac{\sin(2)(52t)}{(4)(52)}\right]_0^{.06} = 10.25\left[\frac{.06}{2} - \frac{\sin(104)(.06)}{208} - \frac{\sin(104)(0)}{208}\right]$$

$$= 10.25[.03 - .0005] = 0.30 \text{ joules}$$

By assuming that the circuit is about 70% efficient (a reasonable value for electrical circuits of this kind), then approximately 0.21 joules are dumped or stored into the capacitor with each shake.

To calculate the coupling efficiency from kinetic to electrical energy we must determine the speed of the magnet as it moves through the coil. The magnet travels a distance equal to 4 times its length in 0.06 seconds. This corresponds to a maximum speed of approximately 4 meters per second when you consider acceleration at the end of travel. The total kinetic energy of the magnet is given by the expression:

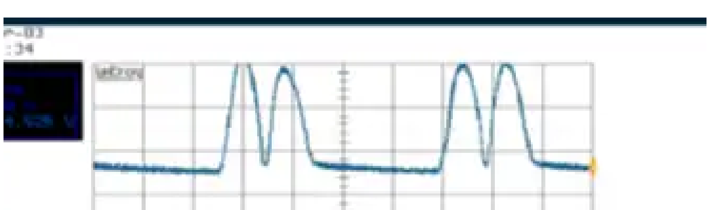
$$E_t = \tfrac{1}{2} mv^2$$

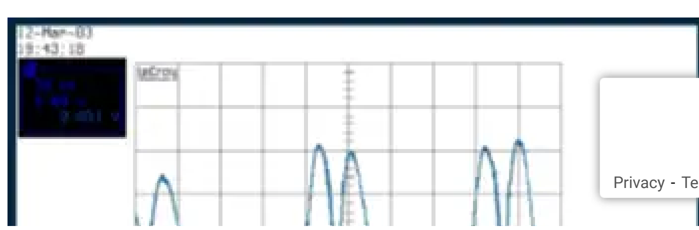
where E_t is the total kinetic energy of the magnet, m is the mass of the magnet (0.06 kg) and v is its velocity. Replacing m and v with their appropriate values gives a kinetic energy of 0.48 joules. This is the total kinetic energy of the magnet. Only part of this kinetic energy is extracted since the magnet does not slow to zero velocity as it passes through the coil.

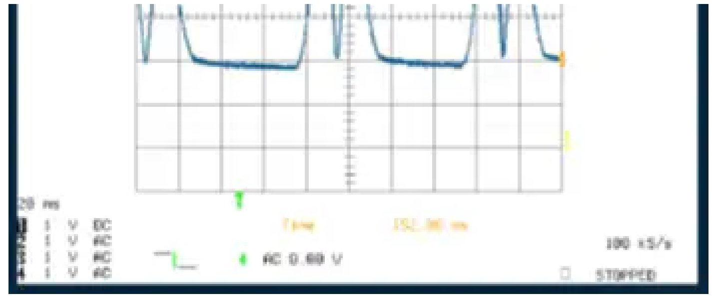
The coupling efficiency from kinetic to electric energy is therefore 62% (0.30 / 0.48). This conversion efficiency corresponds to the magnet slowing by about 39% as it passes through the coils (% slowing = $1 - \{[(2(E_t - E)/m)^{1/2}] / v\} = 1 - \{[(2(.48 - .30)/.06)]^{1/2} / 4\} = 1 - \{2.45 / 4\} = 1 - .61 = .39$). It should also be noted that the coupling ratio changes as a function of the charge in the capacitor. When the capacitor is drained of energy the conversion from kinetic to electric energy is higher.

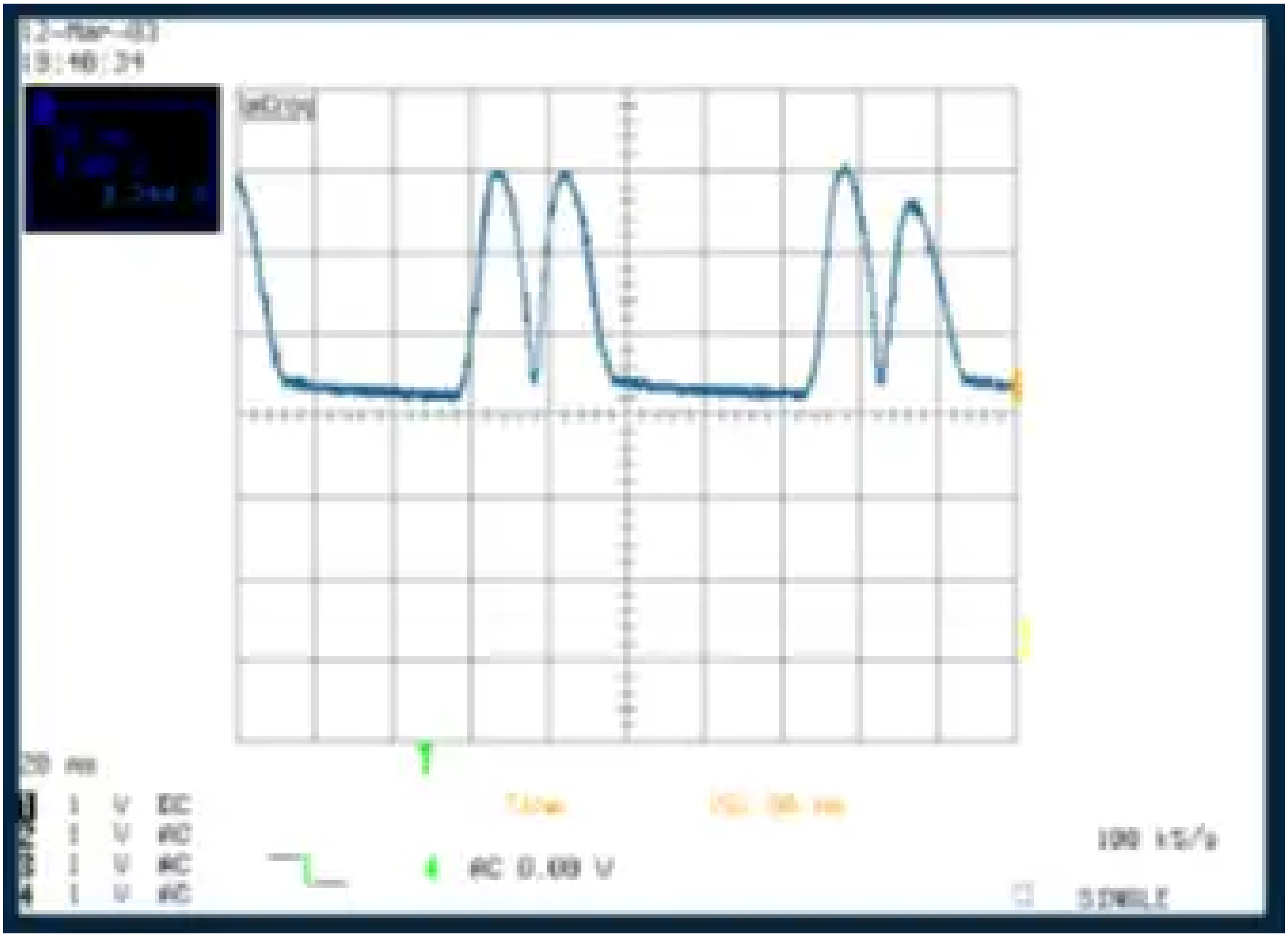
The slowing down of the magnet as it passes through the coil is evidence of this. As the capacitor becomes fully charged, less and less energy is extracted with each pass of the magnet through the coil. As a result, NightStar becomes easier to shake.

The two high-speed switching diodes (designated D1 and D2) act as a full-wave bridge rectifier. Figures 12 through 14 show the voltage measured across the capacitor terminals on the circuit board. After rectification, energy generated by the magnet passing through the coil appears as positive going pulses. With each shake the DC voltage level of the capacitor increases.





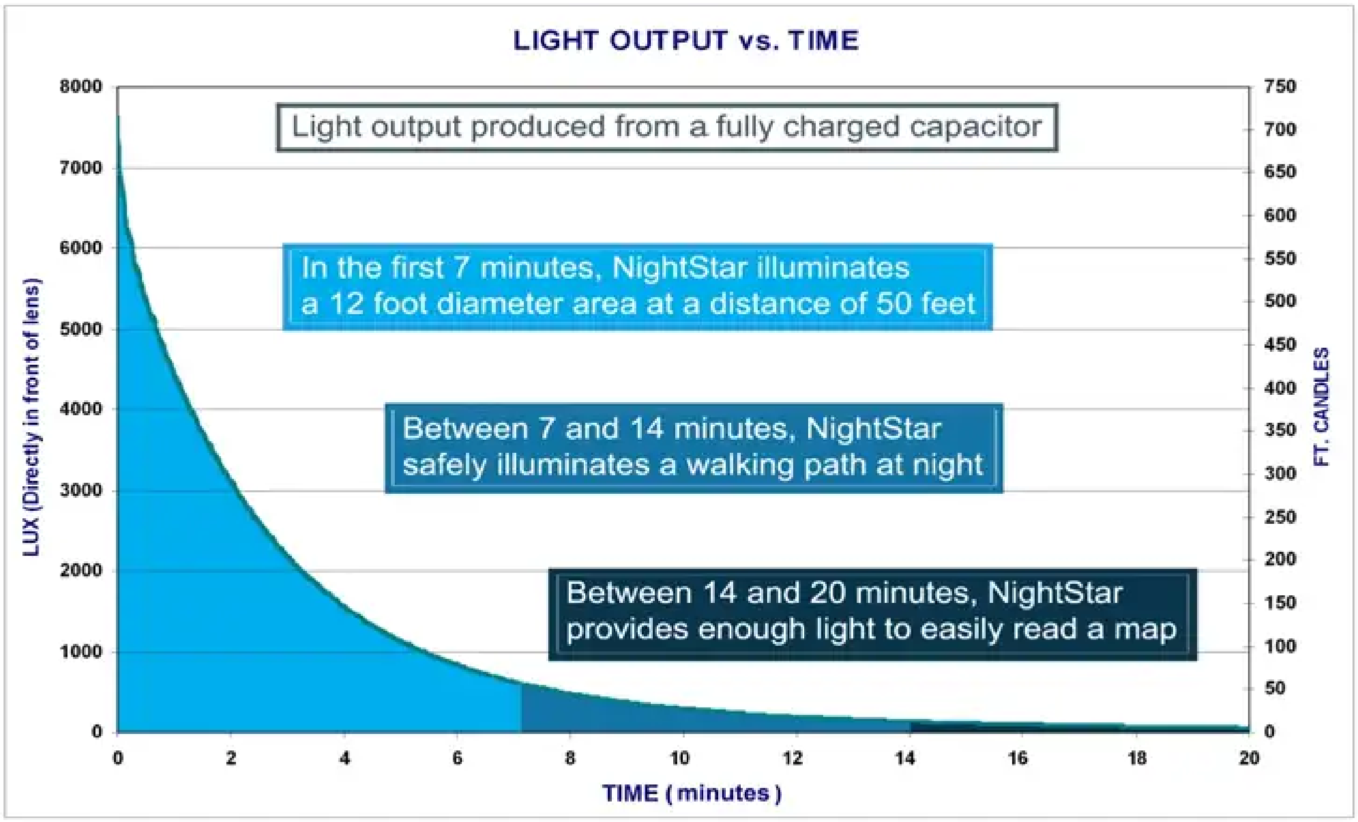




The 5.5-volt, 1.5-farad capacitor (designated C1) stores the electrical energy generated as the magnet passes through the coil. When the Reed switch is closed the energy in the capacitor powers the LED. The total energy that can be stored in the capacitor is about 22.7 joules ($E = ½CV^2$). In NightStar the LED operates from 5.5 volts, the maximum voltage across the capacitor, to approximately 2.5 volts, which is the minimum turn on voltage for the LED.

Consequently, the energy extracted from the capacitor by the LED is approximately 18 joules ($½C \times [(5.5)^2 – (2.5)^2]$). It will therefore take about 87 shakes to recharge the capacitor (18 joules / 0.21 joules/shake). Note, the capacitor leaks off energy at a rate of approximately 0.13 joules per day, which means it takes approximately 3 months to completely discharge. The result, if NightStar shake flashlight is left unused for an extended period it takes approximately 108 shakes to fully re-energize the capacitor (22.7 joules / 0.21 joules/shake).

The LED used in NightStar shake flashlight is a 20 to 30 mA solid-state device with an electrical to light output efficiency of 35%. Initially, and on a full capacitor charge, NightStar shake flashlight produces 0.04 watts of visible light (5.5V x 20mA x .35) with a corresponding luminous flux and intensity of 7600 Lux and 720 ft-candles, respectively. Due to the discharge characteristic of the capacitor this drops off and reaches a stable state after 7 minutes, as shown in Figure 15.



White light diodes are less efficient than green and red diodes because of an internal conversion loss. As stated earlier, white light diodes initially emit high-energy blue photons. As these high-energy photons pass through a phosphor layer, they generate photons of all colors.

As the color of each photon blends together with all the others a white light field of illumination is created. The conversion efficiency of blue photons into other colors is however only 50%. The product of the initial blue photon generation efficiency (about 70%) and the white light conversion efficiency gives an overall device efficiency of 35% (70% x 50%).

The final electrical component that needs to be addressed is the switch. The energy stored in th capacitor is allowed to flow through the load, in our case the LED, when the Reed switch (desigr

S1) is closed. The switch is closed when a small magnet mounted inside the plastic slider is pushed forward to the activation point of the switch.

This design feature has several advantages over conventional mechanical switches used in other flashlights. The most significant advantage is reliability; the simple sliding plastic switch cannot corrode or wear out and the Reed switch is rated at 700,000 cycles. In comparison, mechanical push button or toggle switches have components that corrode and springs that fatigue after a much smaller number of on/off cycles.

Another key advantage to NightStar's switch design is that it does not require a watertight seal since the magnet on the outside is able to activate the Reed switch through the plastic housing. Finally, because the electrical circuit is not exposed to the outside world (as with a typical mechanical switch) there is no possibility of creating a spark and igniting combustible materials.

The End Result – Decades of Maintenance Free Illumination

No other flashlight can be relied upon like NightStar shake flashlight to provide light whenever and wherever needed. This is due to NightStar's simple, optimized design coupled with state-of-the-art materials and electronic components.

With only two moving parts, the charging magnet and the switch, there is almost no component fatigue. This translates into energy efficiency and product reliability. We are confident that you will find NightStar shake flashlight to be the most useful, dependable, economically practical, and educational flashlight you will ever own. It is our hope that this guide inspires you to learn more about the physics and mysteries of the world around you.

NightStar engineering served as the foundation for the creation of our rechargeable NiMH battery powered flashlight Shake Light 40B. Many of the physics principles presented in this publication are incorporated into Shake Light 40B engineering. Both shake flashlights demonstrate numerous physics principles for STEAM education students and instructors.

Shake Flashlight Technology – NightStar JP

NightStar Shake Flashlight Physics Guide

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