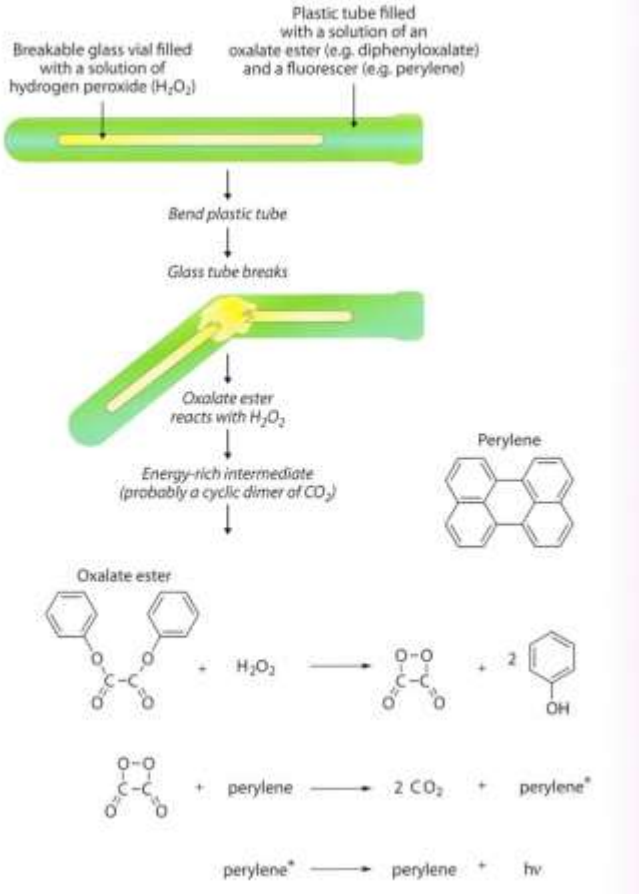
Luminescence and the Production of Light by Living Organisms

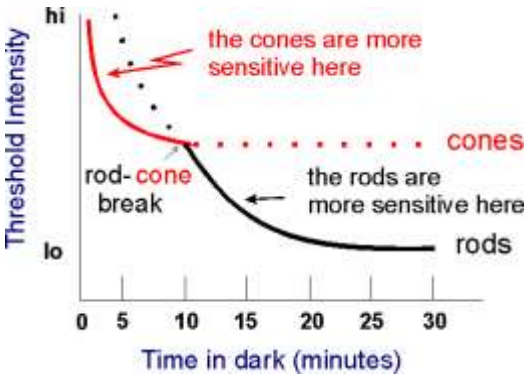
The term **luminescence** was coined by **Eilhard Wiedemann** (1888) to distinguish the **cold light** produced by x-rays, radioactivity and "*all those phenomena of light which are not solely conditioned by the rise in temperature*" from **incandescence** or **hot light** that comes from **incandescent** sources such as the sun, an oil lamp, a candle, a gas lamp and an electric lamp with a carbon or tungsten filament.

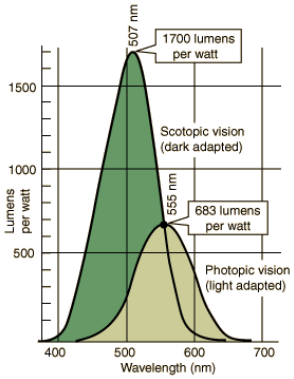
Wiedemann defined many kinds of luminescence, based upon the **type of energy transformed into light**. We have talked about **chemiluminescence**, in which light emission is the result of a chemical reaction (e.g. white phosphorous). We have talked about **photoluminescence**, in which light emission is a result of the absorption of light. When the emission is somewhat immediate and transient (10^{-8} s), photoluminescence is known as **fluorescence** (e.g. chlorophyll) and when the emission is delayed (1 millisecond) and long lasting (milliseconds to hours), photoluminescence is known as **phosphorescence** (e.g. Bologna stone). **Radioluminescence** is when light emission is a result of a material being bombarded by ionizing radiation (e.g. the purple glow of the ^{22}Na that caused a huge change in Martin Kamen's life). **Triboluminescence** is when light is emitted as a result of the mechanical breakage of bonds (e.g. flash rocks made of quartz, **Uncompahgre Ute Indian rattles**, and **Wint-O-Green life savers**), **electroluminescence** is when light is emitted as a result of an electric field or the passage of an electric current through a gas (e.g. neon lights) or semiconductor (e.g. light emitting diode; **LED**), and **bioluminescence** is the emission of light by living organisms.

Demonstration of luminescence or cold light: Bioluminescent bacteria: *Vibrio*; bioluminescent fungi: (*Armarillia*, *Panellus*); photoluminescent Krypton (Europium) sheets and pellets; chemiluminescent glow sticks; and triboluminescent quartz "flash rocks."

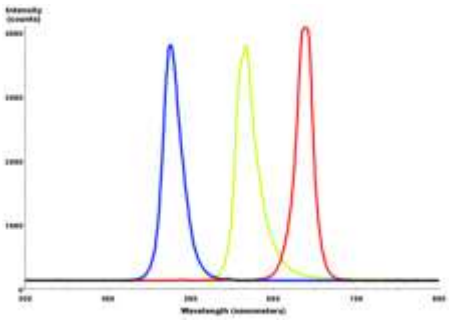


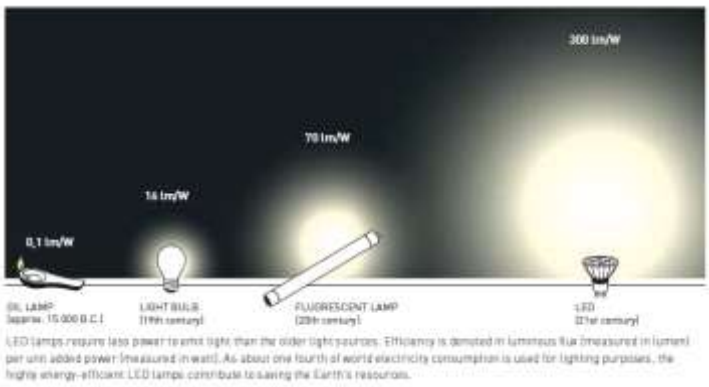
Luminescence is typically a very low light phenomenon that requires our dark-adapted, wide-open, dilated pupil, **rod-dominated**, **scotopic vision** to see. **Robert Boyle** had to do his experiments on luminescence at night and it is quaint how he described each experiment he did **yester-night**.





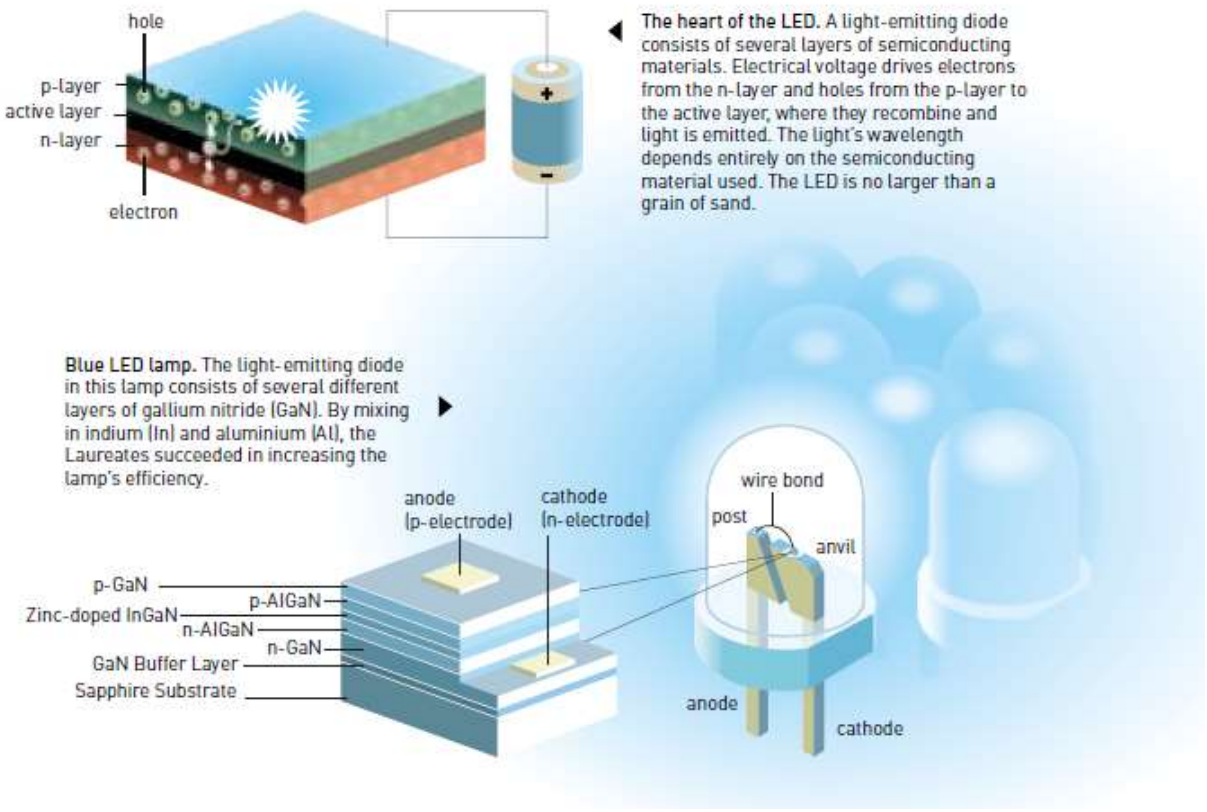
Currently work is being done which would allow the replacement of **incandescent light** with **electroluminescent light** produced by red-green-blue (RGB) light emitting diodes (LEDs) that minimize the amount of energy transformed into thermal energy but maximize the amount of energy transformed into white visible light that is seen by our **cone-dominated, photopic visual system**. The ratio of the energy output (luminous flux in lumens) to the energy input (in Watts) is spectacular for LEDs. LEDs produce approximately 300





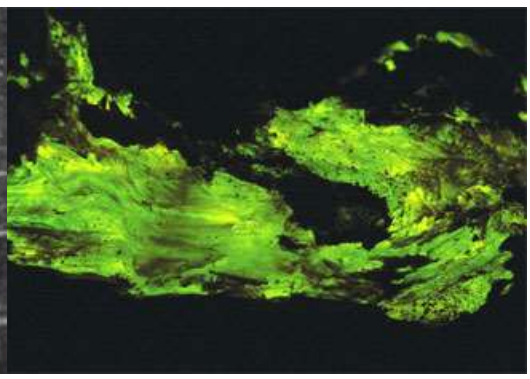
lumens/watt while tungsten lightbulbs produce about 16 lumens/watt. The 2014 Nobel Prize in Physics was awarded to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura "*for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources.*" "*The Laureates challenged established truths; they worked hard and took considerable risks. They built their equipment themselves, learnt the technology, and carried out thousands of experiments. Most of the time they failed, but they did not despair; this was laboratory artistry at the highest level.*"

http://www.nobelprize.org/nobel_prizes/physics/laureates/2014/presentation-speech.html



Since ancient times, Aristotle, Pliny the Elder, and others have noticed that rotten wood, fish and meat emitted light. Using his vacuum pump, **Robert Boyle** (1667,1672) showed that the luminous emission of greenish-blue light from stinking fish, a rotting neck of veal and rotten wood required **air** (which later was shown to contain **oxygen**). Clever people have used the luminescent light of rotting fish and wood and tiny crustaceans to see at times and in spaces that that are not reached by sunlight or moonlight.

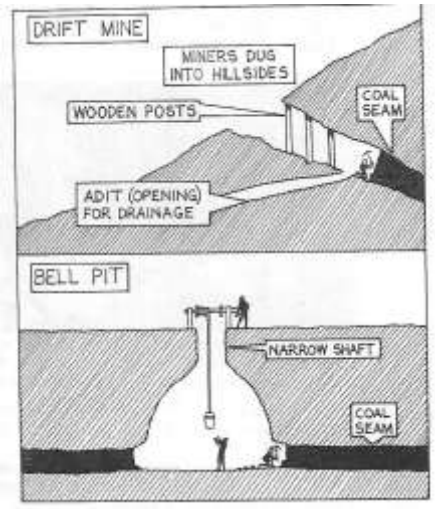
During the Revolutionary War, **David Bushnell**, while an undergraduate at Yale, designed the **Turtle**, so called because it resembled "*two upper tortoise shells of equal size, joined together*." The Turtle was about six feet high, three feet wide and four feet long with just enough space for one person. It could hold enough air for one person for about 30 minutes. The operator drove the Turtle about 3 mph by turning a propeller with a hand crank. On the top of the Turtle, a second propeller, also turned by a hand crank, moved the Turtle up and down. The Turtle had a rudder to steer it and a foot valve to let water into a ballast tank at the bottom to submerge the Turtle. The Turtle carried a **time bomb** also designed by David Bushnell that he made from a hollow log containing 150 pounds of gunpowder and a clock to ignite it. A



barometer and the needles of the compass in the Turtle were illuminated with "***fox-fire, i.e. wood that gives light in the dark***."

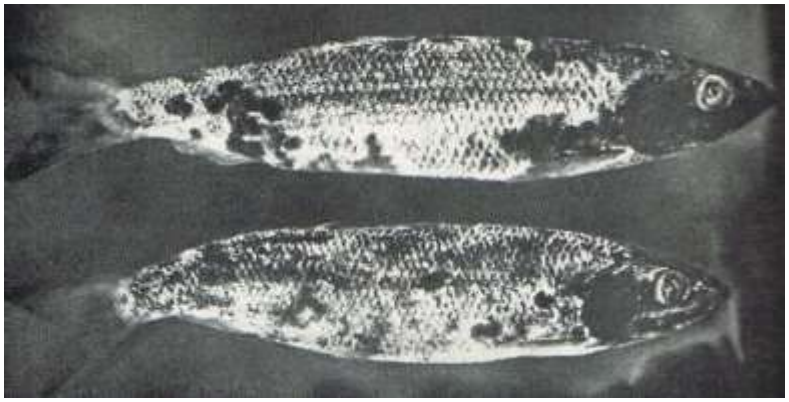
David Bushnell had built the Turtle to break the British blockade of Boston harbor. However, throughout the winter, it was so cold that the fox fire was not able to glow. He sent word to Benjamin Franklin asking "*whether he knows of any kind of phosphorus which* ***will give light in the dark and not consume the air***," noting that "*he has tried a candle, but that destroys the air so fast he cannot remain under water long enough to effect the thing*." On March 17, 1776, the British forces commanded by William Howe evacuated Boston and the Turtle had lost its chance for action in Boston. Not wanting to miss his chance to fight in warmer weather, when the fox fire would glow, David Bushnell offered the Turtle to help George Washington defend New York City from the British. The Turtle, commanded this time by Ezra Lee, was transported to New York Harbor where the HMS Eagle, commanded by William Howe's brother, Richard Howe was moored. Unfortunately, the Turtle did not contain enough air to securely fasten the time bomb to the Eagle and move away safely. Thus the Turtle never succeeded in helping win the Revolutionary War against the British. In this class however the Turtle is famous for its clever use of **bioluminescence**!

http://156.112.98.23/library/online/sub_turtle.htm



Coal weaves a thread through many aspects of light and life. With the development of the **external combustion engines** that used coal to heat water to **steam** in the late 18th century, water powered factories were replaced by steam-

powered factories. This **industrial revolution** resulted in an increased demand for



coal that was greater than that that could be extracted from **drift mines** and **bell pits**. Consequently, **deep mines** were dug. The deep mines were not only dark but contained flammable gas and explosive coal dust. For this reason, miners would bring **bioluminescent rotting fish** to see in the mine. Miners stopped using rotting fish to illuminate the mines after Humphry Davy discovered that flame cannot pass through a screen mesh and invented the vegetable oil burning **Davy safety lamp** in 1815. Since the flame could not pass through the **screen mesh** but gases could, the lamp could also be used as a gas detector. The presence of **methane (firedamp)** in the mine would cause the flame to burn **higher and bluer**. The presence of **carbon dioxide gas (chokedamp)** and not enough oxygen in the mine would cause the flame to **burn low**. The metal gauge along the side of the lamp was used to measure the height of the flame and thus the amount of methane or carbon dioxide in the mine.

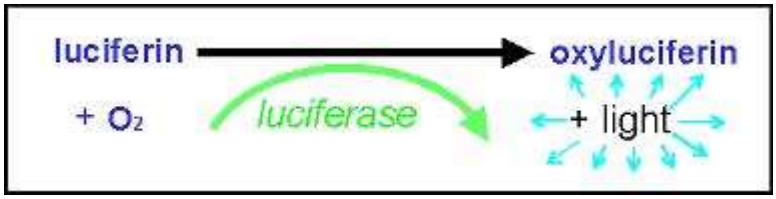
Eugene Petrov (1941), a Soviet writer, dramatist, and war correspondent wrote in his Front Diary, "*I observe many small and large **luminous blue grains** under foot. It is as though someone has trod ahead with magic **perpetual fire** trickling from his knapsack. It takes some time to realize that it is simply bits of **rotten wood** which a*

*fatigue party has carefully collected in the forest and used to lay **luminous tracks** between the tents. Here such tracks are known as the 'Milky Way'.*"

During World War II Japanese soldiers fighting in the Pacific theatre used dried ground *Cypridina* (= *Vargula*), a tiny **crustacean** mixed with water to produce weak but sufficient luminescent light to see on moonless nights. The soldiers would then rub small amounts of the solution on each other's back so that they could follow the soldier who was 15-20 feet in front of them. The soldiers may have also rubbed their hands with *Cypridina* to illuminate and read maps.

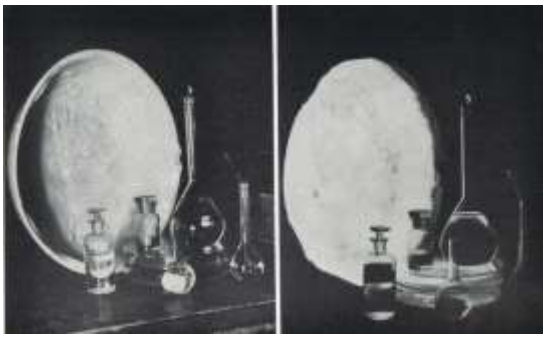
Raphaël Dubois (1885) performed experiments with many bioluminescent taxa and discovered that the production of living light required **two separate water-soluble components**. The first one, which he extracted with hot water, was a heat-stable component that he called **luciferin**, after **Lucifer**, the Latin word for light-bearer. It may have come from the Hebrew word הֵילֵל (*heilel*) for morning star that appears in Isaiah 14:12 "*How you have fallen from heaven, morning star, son of the dawn! You have been cast down to the earth, you who once laid low the nations!"*

The second component, which Dubois extracted with cold water, was heat-labile and therefore an enzyme. He called the enzyme **luciferase**. The two components were **necessary and sufficient** to produce light in a test tube.



In 1866, Raphaël Dubois "*opened a new and promising field for future progress by showing the inferiority of these means [of artificial lighting] when compared with those of nature and by placing the question upon the ground of producing illumination by a new method*." In the **Paris International Exposition of 1900,** Raphaël Dubois showed the world that six one-gallon flasks of bioluminescent bacteria could light a room sufficiently for the visitors to read newspapers without any danger of fire or explosion.

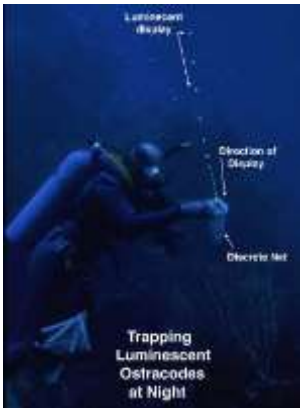
Human beings had made use of bioluminescence for light outside the home. Putting his research to practical use, Raphaël Dubois built a **bioluminescent lamp** for inside the home and created a photograph of paper lace using bioluminescent bacteria to expose the paper. E. Newton Harvey used bioluminescent bacteria to illuminate a still life.



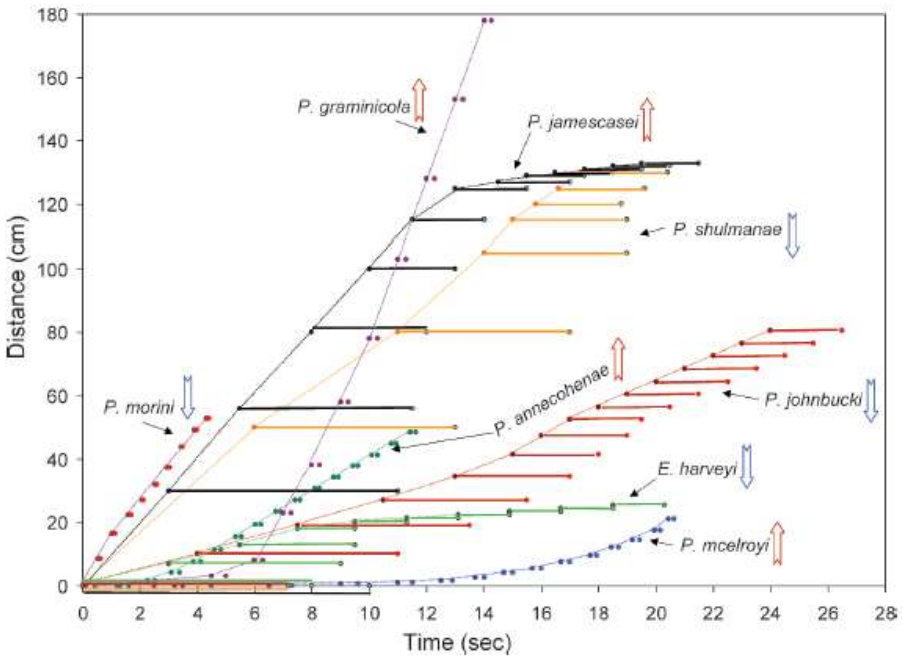
Like the 19th century naturalists, such as Charles Darwin and T. H. Huxley, at the beginning of the 20th century **E. Newton Harvey** made expeditions all over the world making observations and collecting animals. While on his honeymoon in 1916 and while he was swimming at night in the waters near the Misaki Laboratory Biological Station south of Tokyo, he became enamored by the blue bioluminescence of *Cypridina hilgendorfii*, known as the sea firefly or **Umihotaru** (海ほたる) in Japanese. *Cypridina* are scavengers that live on the ocean bottom waiting for fish to die and sink—at which time they rapidly consume the fish.

As **Jim Morin** (Cornell) observed, when the Caribbean Ostracodes like *Cypridina* are pursued by a predator, they emit clouds of blue bioluminescence as a means to escape the predator.

In their **courtship behavior**, which occurs on moonless nights, the males synchronously release pulses of blue bioluminescence in a species-specific manner to attract the females, who use the displays to orient and intercept the male producing it. The bioluminescence of Ostracodes is always extracellular. The courtship displays may be at risk as a result of



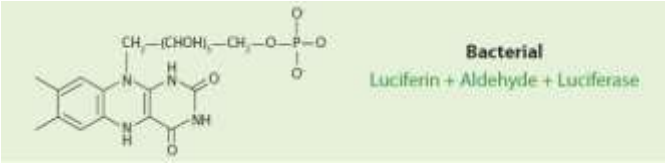
light pollution coming from resorts built on the seashores where cypridinid Ostracodes live.

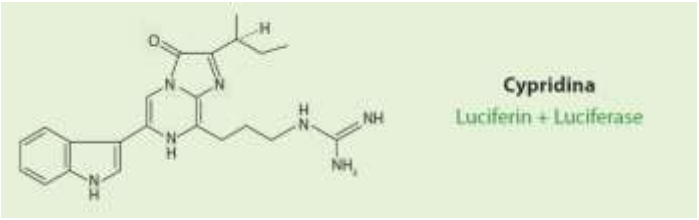


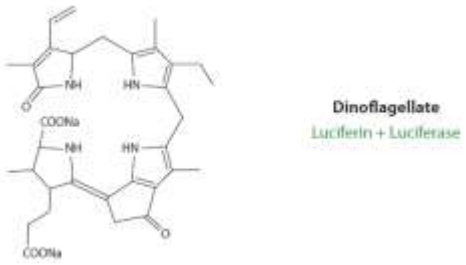
E. Newton Harvey caught *Cypridina* by suspending a large fish head by a string in shallow sandy water and waiting for swarms of *Cypridina* to eat it. After two hours, he lifted the fish head out of the water and picked off the *Cypridina*. E. Newton Harvey had a passion for bioluminescence and studied its physics, chemistry and biology. E. Newton Harvey showed that the bioluminescent organisms all had the two components that Raphaël Dubois had discovered: a **luciferin** and a **luciferase**. However, the luciferin of one taxon would not necessarily interact with the luciferase of another. By discovering that the luciferins and luciferases from different taxa were ***not*** interchangeable, E. Newton Harvey learned that there was not just one kind of luciferin and just one kind of luciferase, but ***many*** kinds of luciferins and ***many*** kinds of luciferases. He found the **diversity in the apparent unity**.

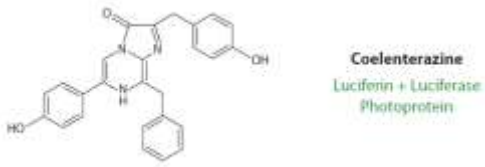
E. Newton Harvey found that **Charles Darwin's** idea that unity of function results is a consequence of **common descent** does ***not*** apply to bioluminescence. According to **J. Woodland (Woody) Hastings** (1996), a graduate student of E.

Newton Harvey, *"Many different organisms, ranging from bacteria and fungi to fireflies and fish, are endowed with the ability to emit light, but the bioluminescent systems are not evolutionarily conserved: genes coding for the luciferase proteins (Lase) are* ***not homologous****, and the luciferins are also different, falling into many unrelated chemical classes."*





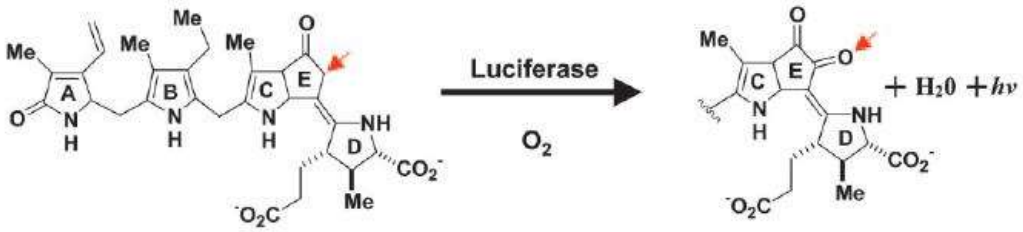




While the **specific** chemical natures of luciferin and luciferase differ, the bioluminescence they generate all follow a **general rule**: A **high-energy molecule** containing a number of **conjugated double bonds** is converted to a **low-energy molecule** in an **oxygen-requiring enzymatic process** and in the process the

energy difference is released as visible light energy. The oxygen is usually consumed in the form of **molecular oxygen** although some systems use the peroxide anion (O_2^{2-}).

For example, the **mechanically-induced bioluminescence of dinoflagellates**, which has been shown by Esaias and Curl (1972) to function as a burglar alarm to scare away predators, is described by the following reaction:

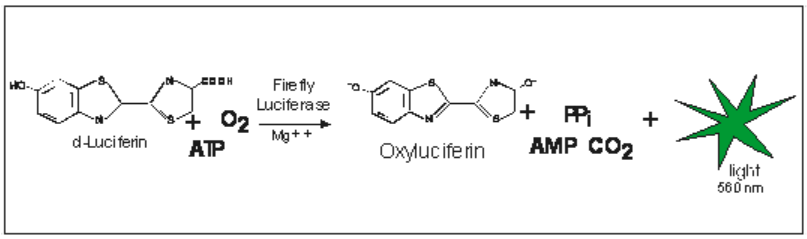


Luciferase binds **oxygen** and a reduced or high-energy form of luciferin. The luciferase functions as an **electron and proton pipe** that passes **two electrons** and **two protons** from the high-energy form of **luciferin to oxygen**. This transfer results in the formation of **oxyluciferin**, a low-energy form of luciferin and water. In the process, the difference in the redox energy of the reduced luciferin and the oxyluciferin is transformed into visible light. In some respects, bioluminescence, where the **luciferase enzyme** acts as an **electron pipe**, is the **reverse of photosynthesis** where **chlorophyll** acts as an **electron pump**.

The mechanisms of bioluminescence in *Cypridina*, bacteria (*Vibrio*) and fungi (*Armillaria*, the honey fungus) share some similarities with dinoflagellates, although their luciferins and luciferases differ. While the function of bioluminescence in all fungi is not known, some suggest that bioluminescence in some fungi is a strategy to attract arthropods and insects that will disperse the spores. This may be true for fungi with bioluminescent fruiting bodies (e.g. *Omphalotus*, *Mycena*, *Panellus*; https://blog.mycology.cornell.edu/2010/04/12/this-bark-glows-in-the-dark-bioluminescence-in-mushrooms/), but cannot explain bioluminescence in *Armillaria*, whose underground mycelia are bioluminescent but its fruiting body (mushroom) is not.

In the case of **firefly bioluminescence**, like bioluminescence in dinoflagellates, a high-energy molecule that contains many conjugated double bonds is converted to a low-energy molecule in an oxygen-requiring enzymatic process and in the process the energy difference in released as visible light energy. In the case of fireflies, however, the high-energy form of luciferin requires supplementation by **ATP** which is converted to AMP and pyrophosphate (P_iP_i).

The redox energy is the primary source of energy as the energy of ATP (8×10^{-20} J) is too little to produce a photon itself ($E = \frac{hc}{\lambda} \approx 4 \times 10^{-19}$ J).



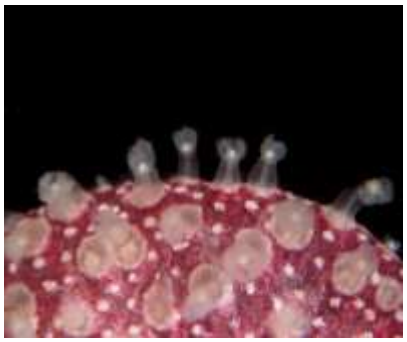
In fireflies, bioluminescence is used in **courtship behavior.** In some taxa, the male fireflies (or beetles to an entomologist) produce a sequence of light flashes in a species-specific manner. The females recognize the flash sequence and flash back once. The males recognize the single flash by the amount of time elapsed between the end of the male's sequence of flashes and the female's single flash. Then the male flies to the female and mates with her.

Now, there is a complication involved in the courtship behavior. The females of one genus of fireflies (*Photurus*) are ***femme fatales*** and prey on the male fireflies of another genus (*Photinus*). The females of *Photurus* have two different light delays that that can use: one that matches their own genus and effects mating and

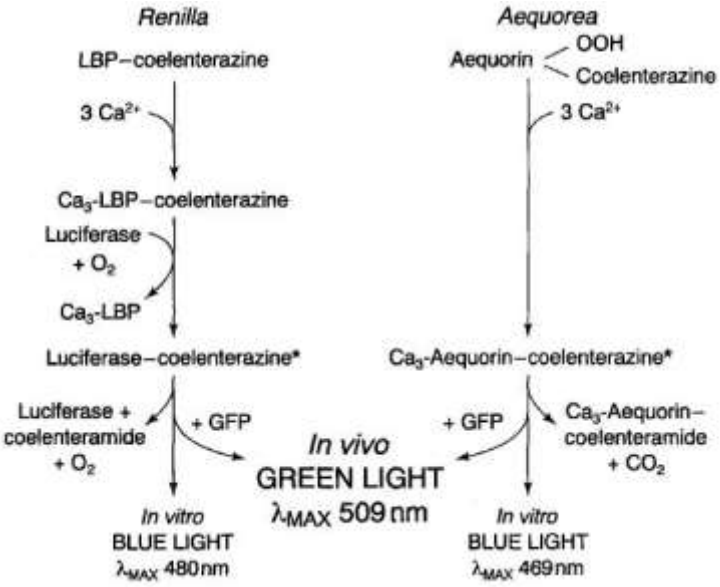
one that matches the other genus and effects eating. **Tom Eisner** (Cornell), author of *For Love of Insects*, showed that the females of *Photurus* incorporate a chemical known as **lucibufagin** (*luci* from the Latin for light, *bu* from the genus of toad *Bufo* that produces a similar chemical named bufalin) when they eat the lucibufagin-producing males of *Photinus*.

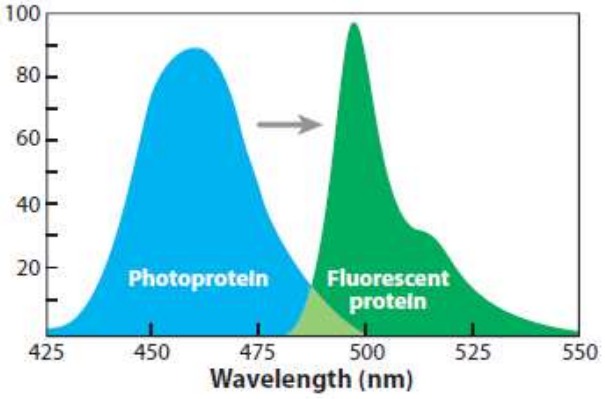
Lucibufagin makes the *Photurus* females and their eggs **unpalatable** to predatory **jumping spiders**. When the female *Photurus* have not eaten *Photinus* males, they do not acquire the lucibufagins and are eaten by predatory spiders. The more *Photinus* males that the *Photurus* females eat, the more lucibufagins they acquire and the better the protection they have from predators.

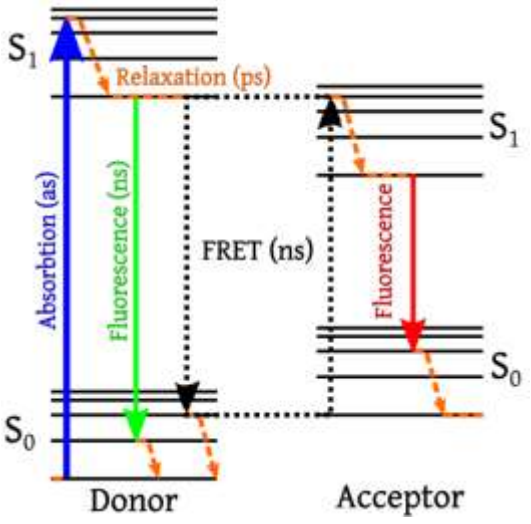
Another variation in the production of bioluminescence is found in jellyfish (*Aequorea*) and related hydroids (*Obelia* and *Renilla*) where the luciferin is a **coelenterazine** (that they probably ingest as part of their diet).



The green bioluminescence in these organisms is stimulated only when they are disturbed and perhaps it may have a defensive function. The luciferase of *Aequorea* is a protein called **aequorin**. The aequorin binds the luciferin, known as **coelenterazine** in an oxygen-dependent manner. The luciferin-luciferase complex does not emit light until it binds **calcium ions**. *Aequorea* emits blue light *in vitro*, but it emits green light *in vivo*. It emits green light *in vivo* because *Aequorea* contains a protein that fluoresces green after it absorbs blue light. When the aequorin and **green fluorescent protein** molecules are close enough (i.e. 5-10 nm) to each other, as they are in the living cell, the energy that would be emitted by aequorin after it binds calcium ions is transferred to the green fluorescent protein by a process known as **resonance energy transfer** (RET) and the green fluorescent protein emits green light. I will talk about fluorescent proteins again when I discuss fluorescence microscopy.



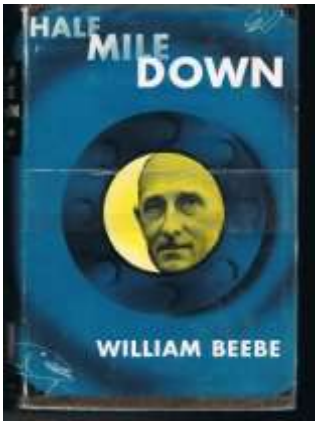




Genetically-engineered bacteria can produce the aequorin protein. This aequorin is sold as Prevagen.

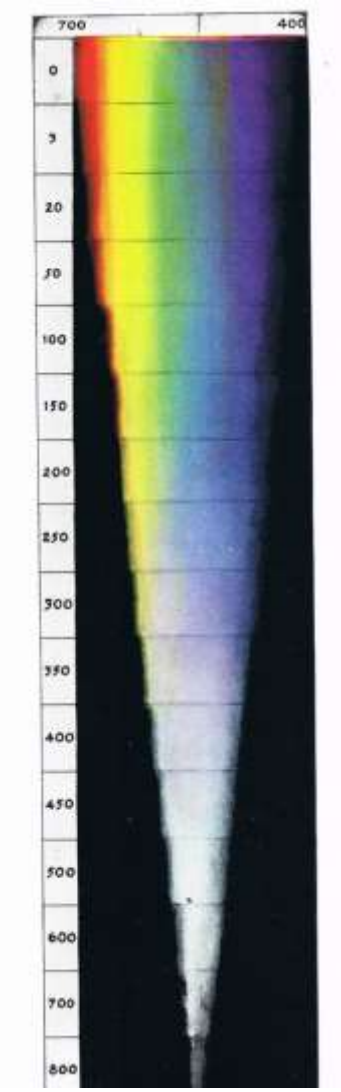
Prevagen™ (aequorin)

Bioluminescence is ***rare*** in **terrestrial habitats** and nonexistent in fresh water. However, deep down in the ocean, deeper than where sunlight can reach, there is a world of **marine creatures** that **turn life into light** in order to create their own light **to see**, to **catch prey**, **to mate**, and to **confound predators**. **William Beebe** was a seasoned **explorer and a naturalist** who turned his attention from the jungles to the sea. He and **Otis Barton** built the **bathysphere** that allowed them to go into the depths and darkness in August 1934 where no living person had gone before, and to **discover a world of living light**.



William Beebe wrote in ***Half Mile Down***, "*Ever since the beginnings of human history, when first the Phoenicians dared to sail the open sea, thousands upon thousands of human beings had reached the depth at which we were now suspended, and had passed on to lower levels. But all of these were dead, drowned victims of war, tempest, or other acts of God. We were the first living men to look out at strange illumination: And it was stranger than any imagination could have conceived. It was an* ***indefinable translucent blue*** *quite*

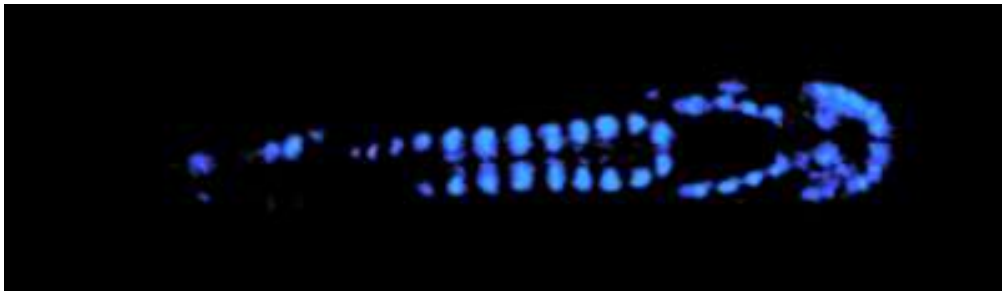
unlike anything I have ever seen in the upper world, and it excited our optic nerves in a most confusing manner. We kept thinking and calling it brilliant, and again and again I picked up a book to read the type, only to find that I could not tell the difference between a blank page and a colored plate. I brought all my logic to bear, I put out of mind the excitement of our position in watery space and tried to think sanely of comparative color, and I failed utterly. I flashed on the searchlight, which seemed the yellowest thing I have even seen, and let it soak into my eyes, yet the moment it was switched off, it was like the long vanished sunlight—it was as though it never had been—and ***the blueness of the blue****, both outside and inside our sphere, seemed to pass materially through the eye into our very beings. This is all very unscientific; quite worthy of being jeered at by optician or physicist, but there it was."*



"*Here and at 800 feet a human being was permitted for the first time the sight of living, silver hatchet-fish,* ***heliographing****, their silver sides. I made Barton look quickly out so he could verify the unexpected sight.*"

The **hatchet-fish** produce bioluminescence on their undersides as **counter illumination** to confound predators by eliminating their silhouettes that would be recognized by predators swimming beneath them.

Because of the **counter illumination**, the hatchet-fish confound their predators by becoming **invisible from below**.



"*Life again became evident around 1300 feet and mostly luminous. After watching a dozen or more firefly-like flashes I turned on the searchlight and saw nothing whatsoever. These sparks, brilliant though they were, were kindled into conflagration and quenched in the same instant upon* ***invisible bodies***."

"*After these dives were past…, I would feel like an astronomer might who looks through his telescope after having rocketed to Mars and back, or like* ***a paleontologist who could suddenly annihilate time*** *and see his fossils alive.*" On the right is a picture of the luminous stars in the heavens and on the left is a picture of the luminous fish in the sea.

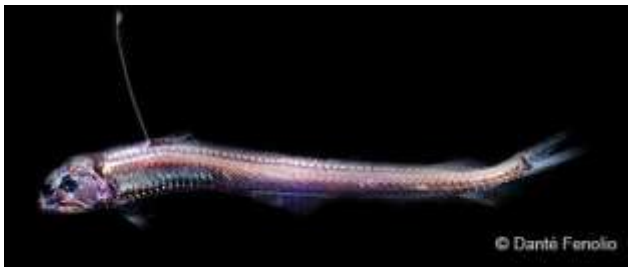
William Beebe estimated that at depths greater than 400 meters, ninety five percent of fish are bioluminescent.

Flashlight fish (*Kryptophanaron alfredi*; *Photoblepharon palpebratum; P. steinitzi* and *Anomalops katoptron*) and the giant squid farm bioluminescent bacteria in pockets near their eyes that act as **headlights** so that the hosts can see deep beneath the sea.

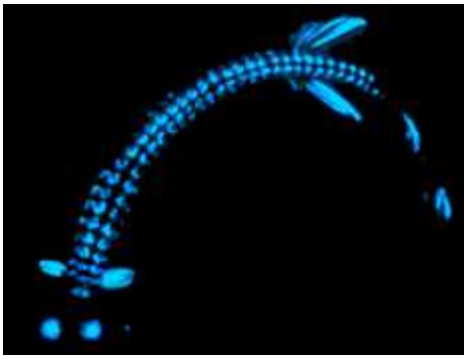
Dragonfish have **blue bioluminescent headlights** and **red bioluminescent headlights** that act as a **sniper scope**. The blue bioluminescent light can be seen with the **scotopic rod-dominated visual system of most deep-sea fishes**, but among the deep-sea fish, **only the dragonfish has the long wave photoreceptors** to see the red light that the photophores produce.

Like the Ostracodes discussed above, some deep-sea fish, crustaceans, and the **vampire squid** emit clouds of bioluminescent materials into the water to escape from predation.

Anglerfish, **viperfish** (*Chauliodus*) and **dragonfish** use **blue bioluminescent "lures"** to attract prey. Blue light travels in water farther than others colors that are absorbed more readily. The fish produce blue bioluminescent light in two different ways. The viperfish and dragonfish produce bioluminescence themselves while the anglerfish farms bioluminescent bacteria.

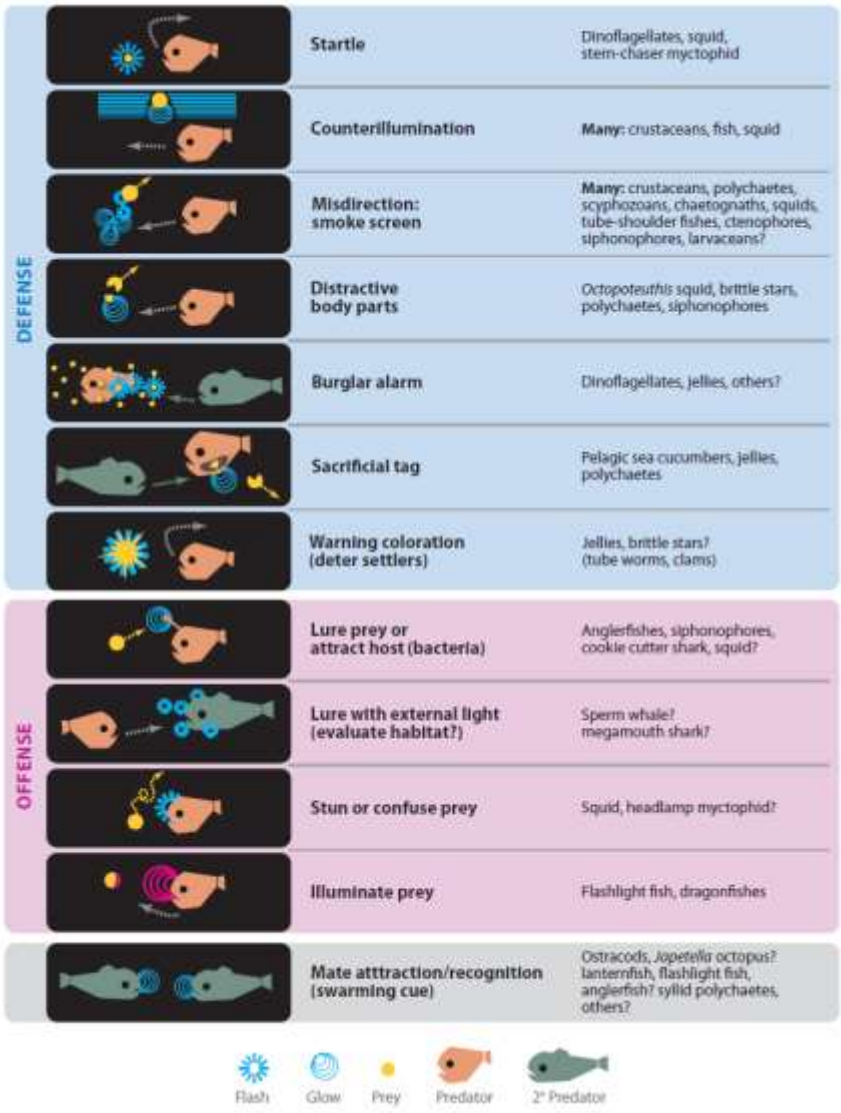


The **lanternfish** are undersea bioluminescent artists. They use bioluminescence for **vision**, **courtship** and **counter-illumination**. Let's now watch these deep sea marvels in the video entitled, "*Marine Bioluminescence: Secret Lights in the Sea*."

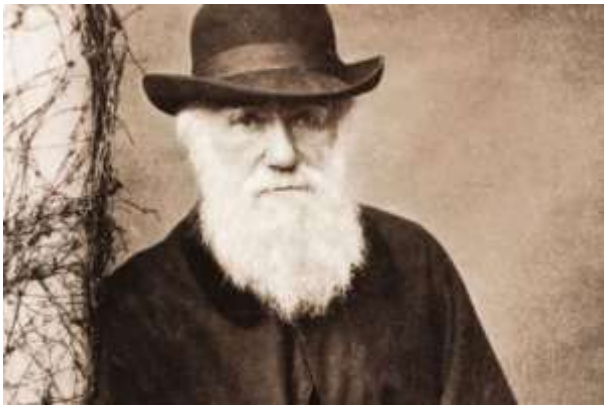


William Beebe wrote, "*In this kingdom most of the plants are animals, the fish are friends, colors are unearthly in their shift and delicacy; here miracles become marvels, and marvels recurring wonders. There may be a host of terrible dangers, but in hundreds of dives we have never encountered them. One thing we cannot escape—forever afterward, throughout all our life, the memory of the magic of water and its life, of the home which was once our own—this will never leave us.*"

Here is a chart that summarizes marine organisms that are bioluminescent and the likely functions of the bioluminescence. But what are the functions of bioluminescence of the symbiotic bacterium *Vibrio* or the fungus, *Armillaria*?



Lars Olof Björn (1976) wrote in his book entitled, *Light and Life*, "*Even for a person with a vivid imagination there are many cases of bioluminescence left for which* ***no sensible purpose*** *can be invented. What use do bacteria and protozoans have for their light emission? To explain the many cases of seemingly useless bioluminescence, some scientists have assumed that the light is a by-product of biochemical processes serving a different purpose. But this does not seem very reasonable either. The emission of a photon requires the collection of a large amount of energy in a single molecule and this must be regarded as a remarkable biochemical feat which hardly occurs by accident.*" What is the **Law of Nature** that describes and explains the occurrence of bioluminescence?



Can you explain the bioluminescence of the bacterium *Vibrio* or the fungus *Armillaria* in terms of the **Laws of Nature**? Charles Darwin (1859) had a hard time. He wrote, "*The electric organs offer another and even more serious difficulty; for they occur in only about a dozen fishes, of which several are widely remote in their affinities. Generally when the same organ appears in several members of the same class, especially if in members having very different habits of life, we may attribute its presence to* ***inheritance from a common ancestor****; and its absence in some of the members to its loss through disuse or natural selection. But if the electric organs had been inherited from one ancient progenitor thus provided, we might have expected that all electric fishes would have been specially related to each other. Nor does geology at all lead to the belief that formerly most fishes had electric organs, which most of their modified descendants have lost.* ***The presence of luminous organs in a few insects, belonging to different families and orders, offers a parallel case of difficulty****....In all these cases of two very distinct species furnished with apparently the same anomalous organ, it should be observed that, although* ***the general appearance and function of the organ may be the same****, yet some fundamental difference can generally be detected. I am inclined to believe that in nearly the same way as two men have sometimes independently hit on the very same invention, so* ***natural selection****, working for the good of each being* ***and taking advantage of analogous variations****, has sometimes modified in very nearly the same manner two parts in two organic beings,* ***which owe but little of their structure in common to inheritance from the same ancestor****.*

Although in many cases it is most difficult to conjecture by what transitions an organ could have arrived at its present state; yet, considering that the proportion of living and known forms to the extinct and unknown is very small, I have been astonished how rarely an organ can be named, towards which no transitional grade is known to lead. The truth of this remark is indeed shown by that old canon in natural history of 'Natura non facit saltum.' [Nature does nothing in jumps]. *We meet with this admission in the writings of almost every experienced naturalist; or, as Milne Edwards has well expressed it, nature is prodigal in variety, but niggard in innovation.* ***Why, on the theory of Creation, should this be so? Why should all the parts and organs of many independent beings, each supposed to have been separately created for its proper place in nature, be so invariably linked together by graduated steps? Why should not Nature have taken a leap from structure to structure? On the theory of natural selection, we can clearly understand why she should not; for natural selection can act only by taking advantage of slight successive variations; she can never take a leap, but must advance by the shortest and slowest steps***."

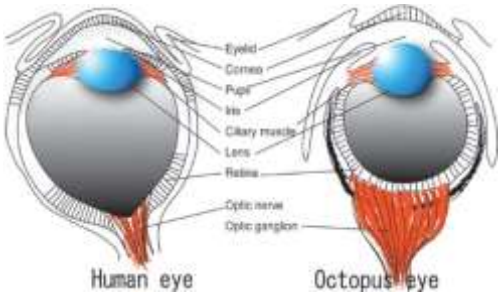
Is bioluminescence in these taxa better described and explained by Charles Darwin's theory of **natural selection** or by **congenital changes, mutations** or **jumps**. Such jumps might give the appearance of **design** exhibiting "*the Power, Wisdom, and Goodness of God, as manifested in the Creation*." **Francis Henry Egerton**, the 8th Earl of Bridgewater who loved to give dinner parties for dogs commissioned the **Bridgewater Treatises** to present design in nature. As it says in Job 12:7-9, "*But ask the animals, and they will teach you, or the birds in the sky, and they will tell*

you; or speak to the earth, and it will teach you, or let the fish in the sea inform you. Which of all these does not know that the hand of the LORD has done this."

Back to natural selection. Is bioluminescence in *Vibrio* or the fungus *Armillaria* a **random variation** upon which **natural selection** could capitalize on if its **selective value** were greater than its **cost**, or eliminate if its cost were greater than its selective value? Could bioluminescence be a result of an ancient process that has been **lost** in most organisms but **repressed** and later **revived** in other unrelated taxa where it proved useful? What are the meanings of homologous processes derived by **evolution from common descent** and analogous processes derived by **convergent evolution**? How do you distinguish convergent evolution from design? While I only pose these questions here, I want to mention **Richard Owen**, who coined the word **dinosaur** and was the scientific consultant to the sculptor Benjamin Waterhouse Hawkins, who produced the life-sized models of the dinosaurs for the **Crystal Palace** after it was moved to Sydenham. Richard Owen is the 19th century scientist who introduced the terms **homology** and **analogy** in terms of **progressive evolution.**

After finishing grammar school, **Richard Owen** became an apprentice to Leonard Dickson, a local surgeon who performed post-mortems at a local prison. This led to a lifelong interest in anatomy, **comparative anatomy** and fossil anatomy. Richard Owen studied hard tissue such as **teeth and bones** as well as soft tissue such as the brain.

In order to make sense of the basic **unity** (**archetype**) and **diversity** of organs, Richard Owen (1848) distinguished **homology** from **analogy**. If two or more parts are related by **common descent**, they are considered to be **homologous**. The wing of a bat and the forearm of a rat is an example of a homology. If two or more parts have some similarities in terms of **form or function**, but are not related by common descent, they are considered to be **analogous**. The wings of butterflies, birds and bats or the **camera-like eyes** of cephalopods and vertebrates are examples of analogy. Analogous parts of organisms that are not related by common descent can be considered to be analogies that are the result of **convergent evolution** and/or **design**.



Using evidence of comparative anatomy, Richard Owen saw the **succession** of fossil organisms from the lower strata to the upper strata and the **progression** of simpler vertebrates such as fish to more advanced mammals to be a result of a "*continuous operation of the ordained becoming of living things*"—God was the **first cause** and a **number of possible second causes**, including **natural selection** and more importantly **congenital changes** (e.g. mutations or jumps) resulted in the transformation of species. Owen did ***not*** believe in the immutability of species.

Based on his **personal philosophy** and his **scientific observations**, Richard Owen (1859) saw anatomical as well as spiritual distinctions between human(ity) and apes. At the **1860 meeting of the British Association for the Advancement of Science at Oxford**, Richard Owen proposed that there are sufficient differences in the brains of apes and human beings to set humans apart. Humans had a seahorse-shaped region of the brain known as the **hippocampus minor** and apes lacked a hippocampus minor. Could his **personal philosophy** have prejudiced his ability to objectively observe and interpret anatomical observations?

Thomas H. Huxley, on the other hand, made more accurate observations on the brains and did not see anatomical or any other differences to be significant enough to separate human beings struggling for existence from apes and monkeys. Then again, such a separation also went against Huxley's **personal philosophy**. Could Huxley's personal philosophy have prejudiced his ability to acknowledge the possibility that there may be more to being human than that which can be weighed, measured and counted? Any challenge to Huxley's personal philosophy brought out the **firebrand** and **provocateur** in him.

T. H. Huxley wrote to Frederick Dyster on January 30, 1859, "*both [Theology and Parsondom] are in my mind the natural and irreconcilable enemies of Science. ... If I have a wish to live thirty years, it is that* ***I may see the foot of Science on the necks of her enemie****s*." In a review of *Origin of Species*, T. H. Huxley (1860) wrote, "*Extinguished theologians lie about the cradle of every science as the strangled snakes beside that of Hercules; and history records that whenever science and orthodoxy have been fairly opposed, the latter has been forced to retire from the lists,* ***bleeding and crushed if not annihilated; scotched, if not slain***." On October 11, 1862, T. H. Huxley wrote to Frederick Dyster, about Richard Owen, "*Before I have done with that mendacious humbug I will nail him out, like a kite to a barn door, an example to all evil doers….*"

According to Huxley (1863), "*As if to demonstrate, by a striking example, the impossibility of erecting any cerebral barrier between man and the apes, Nature has provided us, in the later animals, with an* ***almost complete series of gradations*** *from brains little higher than that of a Rodent, to brains little lower than that of Man. And it is a remarkable circumstance, that though so far as our present knowledge extends, there is one true structural break in the series of forms of the Simian brains,* ***this hiatus does not lie between Man and the man-like apes,***

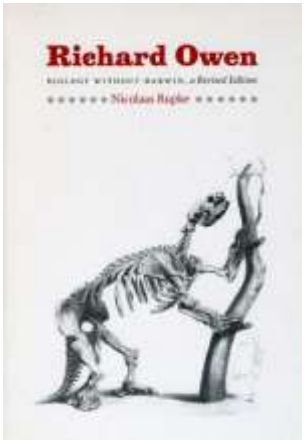
but between the lower and the lowest Simians*; or, in other words, between the old and new world apes and monkeys, and the Lemurs…. So far as cerebral structure goes, therefore, it is clear that Man differs less from the Chimpanzee or the Orang, than these do even from the Monkeys, and that the difference between the brains of the Chimpanzee and of Man is almost insignificant when compared with that between the Chimpanzee brain and that of a Lemur*."

T. H. Huxley (1861) had previously expanded on the series between humans of various races and apes, "*...the cerebral hemispheres of the Bosjesman (and to a certain extent of the negro), so far as the evidence before us goes, are different from those of the white man…the same nature as most of those which distinguish the ape's brain from that of man. In other words, if we place A, the European brain, B, the Bosjesman brain, and C, the orang brain, in a series, the differences between A and B, so far as they have been ascertained, are of the same nature as the chief of those between B and C….The brains of the lowest races of mankind have been hardly at all examined; and it would be a matter of great interest….Medical men living at the Cape of Good Hope, in Australia, and within reach of the Hill-men of India, will, it is to be hoped, some day solve these problems for the zoologist."*

Realizing that brain size was a function of body size, but intelligence was not, Richard Owen (1862) wrote, "Al*though in most cases the Negro's brain is less than that of the European, Tiedemann and the author* [Richard Owen] *of the present paper had observed individuals of the Negro race in whom the brain was as large as the average one of the Caucasian; and the author concurred with the great physiologist of Heidelberg in connecting with such cerebral development the fact that there had been no province of intellectual activity in which individuals of the pure Negro race had not distinguished themselves. The contrast between the*

brains of the Negro and Gorilla, in regard to size, was still greater in respect of the proportional size of the brain to the body —the weight of a full-grown male Gorilla being one-third more than that of an average-sized Negro."

T. H. Huxley embraced **August Comte's materialist and positivist philosophy**. Huxley (1861) wrote, "***Theologians and moralists****, historians and poets, impressed by a sense of the infinite responsibilities of mankind, awed by a just prevision of the great destinies in store for the only earthly being of practically unlimited powers, or touched by the tragic dignity of the ever-recurring struggle of human will with circumstance, have always tended to conceive of their kind as something apart, separated by a great and impassible barrier, from the rest of the natural world. On the other hand, the* ***students of physical science****, discovering as complete a system of law and order in the microcosm as in the macrocosm, incessantly lighting upon new analogies and new identities between life manifested by man, and life in other shapes,--have no less steadily gravitated towards the opposite opinion, and, as knowledge has advanced, have more and more distinctly admitted the closeness of the bond which unites man with his humbler fellows. A controversy has raged between these opposed schools…."*



There are significant **similarities** and **differences** between humans and apes and there is no reason for a thinking person to deny either the similarities or the differences. Moreover, there are also significant differences between individuals and one must make sure that sufficient evidence has been collected and covariant causes eliminated before making extrapolations from limited facts that may later be proven to be unjustified. I think Nicolaas Rupke (2009) gives a fair analysis of Owen and Huxley in *Richard Owen: Biology without Darwin*. The actual two year-long

scientific rivalry between T. H. Huxley and Richard Owen (as opposed to the science versus religion rivalry between Huxley and Wilberforce fabricated in the histories told by Francis Darwin and Leonard Huxley and propagated to this day) became famous and was treated with humor in its time.

Punch published ***Monkeyana*** in May, 1861.

Monkeyana

Am I satyr or man?
Pray tell me who can,
And settle my place in the scale.
A man in ape's shape,
An anthropoid ape,
Or monkey deprived of his tail?

The Vestiges taught,
That all came from naught
By "development," so called, "progressive;"
That insects and worms
Assume higher forms
By modification excessive.

Then Darwin set forth
In a book of much worth,
The importance of "nature's selection;"
How the struggle for life
Is a laudable strife,
And results in "specific distinction."

Let pigeons and doves
Select their own loves,
And grant them a million of ages,
Then doubtless you'll find
They've altered their kind,
And changed into prophets and sages.

Leonard Horner relates,

That Biblical dates
The age of the world cannot trace;
That Bible tradition,
By Nile's deposition,
Is put to the right about face.

Then there's Pengelly
Who next will tell ye
That he and his colleagues of late
Find celts and shaped stones
Mixed up with cave bones
Of contemporaneous date.

Then Prestwich, he pelts
With hammers and celts
All who do not believe his relation,
That the tools he exhumes
From gravelly tombs
Date before the Mosaic creation.

Then Huxley and Owen,
With rivalry glowing,
With pen and ink rush to the scratch;
'Tis Brain versus Brain,
Till one of them's slain,
By JOVE! it will be a good match!

Says Owen, you can see
The brain of Chimpanzee
Is always exceedingly small,
With the hindermost "horn"
Of extremity shorn,
And no "Hippocampus" at all.

The Professor then tells 'em,
That man's "cerebellum,"
From a vertical point you can't see;
That each "convolution"
Contains a solution
Of "Archencephalic" degree.

That apes have no nose,
And thumbs for great toes,
And a pelvis both narrow and slight;
They can't stand upright,
Unless to show fight,
With 'Du Chaillu,' that chivalrous knight!

Next Huxley replies,
That Owen he lies,
And garbles his Latin quotation;
That his facts are not new,
His mistakes not a few,
Detrimental to his reputation.

"To twice slay the slain,
By dint of the Brain,
(Thus Huxley concludes his review)
Is but labour in vain,
Unproductive of gain,
And so I shall bid you 'Adieu'!"

Punch also published ***The Gorilla's Dilemma*** in October, 1862:

The Gorilla's Dilemma (Excerpt)

(To Professor Owen & Huxley)

SAY am I a man and a brother,
Of only an anthropoid ape?
Your judgment, be 't one way or 'tother,
Do *put into positive shape.*

Must I humbly take rank as quadruman
As OWEN maintains that I ought:
Or rise into brotherhood human,
As HUXLEY has flatt'ringly taught?

For though you may deem a Gorilla
Don't think much of his rank in creation,
If of feeling one have a scintilla,
It glows to know "who's one's relation"—

Charles Kingsley (1863) wrote about the rivalry in his book, ***Water Babies***:

"*You may think that there are other more important differences between you and an ape, such as being able to speak, and make machines, and know right from wrong, and say your prayers, and other little matters of that kind; but that is a child's fancy, my dear. Nothing is to be depended on but* ***the great hippopotamus test****. If you have a hippopotamus major in your brain, you are no ape, though you had four hands, no feet, and were more apish than the apes of all aperies. But if a hippopotamus major is ever discovered in one single ape's brain, nothing will save your great- great- great- great- great- great- great- great- great- great- great- greater- greatest- grandmother from having been an ape too. No, my dear little man; always remember that the one, true, certain, final and all-important difference between you and an ape is, that you have a hippopotamus major in your brain, and it has none; and that to discover one in its brain will be a very wrong and dangerous thing, at which every one will be very much shocked.*"

What happened to T. H. Huxley and Richard Owen? They both became grandfathers. T. H. Huxley's grandchildren include Julian Huxley, **Aldous Huxley** and Andrew Fielding Huxley.

Richard Owen became the prime mover in establishing the **British Museum of Natural History** in 1881 in South Kensington, the former site of the **Crystal Palace** and Great Exposition of 1851. It was a museum for both the specialists and for the general population. The building, which was a **cathedral to nature** was designed by Alfred Waterhouse. It was a Romanesque **terracotta** building that produced a **romantic skyline**. It is an example of a work of art in the service of science. In contrast to the limestone that was typically used for buildings, the terracotta was resistant to acid and washable, two desirable characteristics in coal burning-Victorian London. The terracotta could also be inexpensively made and molded into decorative plants, animals and gargoyles. http://nhm.ac.uk/visit-us/history-architecture/index.html










The **British Museum of Natural History** houses collections of butterflies, beetles, fossils, plants and animals. http://www.nhm.ac.uk/nature-online/collections-at-the-museum/museum-treasures/charles-darwin-pigeons/index.html

The **British Museum of Natural History** houses Charles Darwin's pigeon collection. http://www.nhm.ac.uk/nature-online/collections-at-the-museum/museum-treasures/charles-darwin-pigeons/index.html

The **British Museum of Natural History** houses Alfred Russel Wallace's insect collection: : http://www.nhm.ac.uk/nature-online/collections-at-the-museum/museum-treasures/alfred-russel-wallace-insects/index.html

The **British Museum of Natural History** has also created an excellent and free online book about ***Slavery and the Natural World***

http://www.nhm.ac.uk/nature-online/collections-at-the-museum/slavery/index.html

You can see that the world was in need of **William Wilberforce's** and his son **Samuel Wilberforce's** vision for the right to liberty for all people no matter what their color. Oddly enough, William Wilberforce is mentioned only in terms of having a correspondence with **Joseph Banks** and Samuel Wilberforce and the **slave-making instinct of ants** is not mentioned at all.

Joseph Banks was a botanist, who sailed with Captain James Cook, and gave advice to King George III on how to make plants profitable. Banks initially accepted slavery as necessary part of the global economy and suggested that William Bligh, Captain of the **HMS Bounty**, collect breadfruit plants from Tahiti and transport it to the Caribbean, where the trees would be a ready source of the carbohydrate-rich fruits that could be used to feed the slaves.

In 1868, in a letter to Charles Darwin, T. H. Huxley drew this sketch **elevating Darwin to Pope**. Since then, a part of biology could be looked at as **hagiology**, the study of the life of the saints. T. H. Huxley's son, Leonard Huxley (1903), a writer, wrote ***Life and Letters of Thomas Henry Huxley***. This book, along with ***The Life and Letters of Charles Darwin***, written by Francis Darwin (1887), Charles' son, became the official history. The Darwin-Huxley story is basically the only story that is told. The Owen-Wilberforce story has been so marginalized as to be nearly forgotten.

The hegemony of Darwin-Huxley versus Owen continues in terms of statuary. When the **British Museum of Natural History** opened, a statue of Richard Owen was placed below a stained glass window in the Central Hall. When Charles Darwin died in 1882, his statue was also placed in the Central Hall. When T. H. Huxley died in 1899, his statue was placed near Owen's. In 1927, Darwin's statue was moved to the North Hall. In 2009, Owen's statue in the Central Hall was replaced by Darwin's.

There were many reasons behind the Darwin-Huxley and Owen-Wilberforce polarity. But I think **materialism or naturalism versus spiritualism** was a part of it. Richard Owen did not eliminate God from the evolutionary process, Darwin and Huxley did. As scientists, we (including or perhaps especially me) bring our **personal philosophy** to bear on our science. For example, I see both the value and limitations of Charles Darwin's theory of natural selection. As someone that sees the limitations more so than most scientists, I have no problem in accepting the **existence of free will** and the **meaningfulness of life** and the observational evidence that they both exist.

Others disagree. For example, in response to an essay written by Phillip E. Johnson[1], **Will Provine** (1990; Cornell) wrote, "*Evolution produces two results that cry out for explanation adaptation and diversity. Sonar in bats,* ***eyesight in eagles, sunlight energy capture in plants****, and adaptations in general had only one kind of explanation before Darwin; the argument from design. The same argument explained the vast diversity of kinds of animals and plants. The greatest minds in*

[1] http://www.firstthings.com/article/1990/10/002-evolution-as-dogma-the-establishment-of-naturalism

the history of Western Civilization, from Plato and Aristotle to Augustine, St. Thomas Aquinas, Kepler, Galileo, Newton, and Boyle, all believed that the argument from design was the only reasonable explanation for adaptations in animals and plants. When they were alive, they were right.

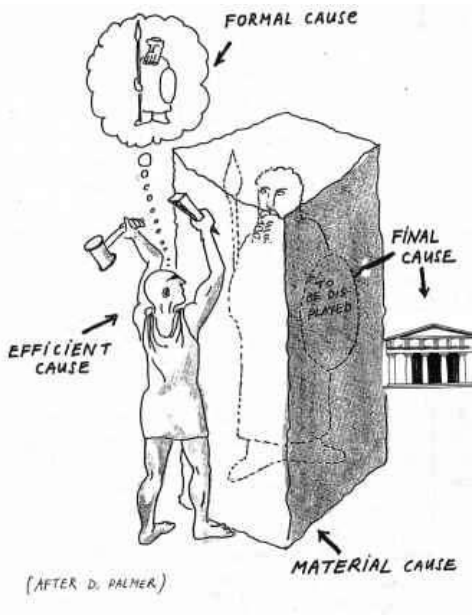
As a young man, Charles Darwin was a creationist deeply impressed with William Paley's version of the argument from design. But after returning from the voyage of H.M.S. Beagle, reconsideration of what he had seen on the voyage convinced him that evolution had occurred. A short time later, when he deduced the theory of natural selection to explain the adaptations in which he had previously seen the handiwork of God, ***Darwin knew that he was committing cultural murder****. He understood immediately that if natural selection explained adaptations, and evolution by descent were true, then the argument from design was dead and all that went with it,* ***namely the existence of a personal god, free will, life after death, immutable moral laws, and ultimate meaning in life****. The immediate reactions to Darwin's On the Origins of Species exhibit, in addition to favorable and admiring responses from a relatively few scientists, an understandable fear and disgust that has never disappeared from Western culture.*

Johnson [author of *Evolution as Dogma: The Establishment of Naturalism*] *has excellent reasons for fearing and despising modern scientific conceptions of the evolutionary* ***process. He clearly wants animals and plants (humans in particular-he says nothing about disgusting parasites) to have been designed by divine purpose.*** *He wants to have free will and divinely inspired moral laws that last forever unchanged, and I suspect that he wants to have some kind of ultimate meaning in life coupled with life after death****.*** *If modern evolutionary biology is true, then all these lofty desires are hopeless*."
http://www.arn.org/docs/johnson/pjdogma2.htm

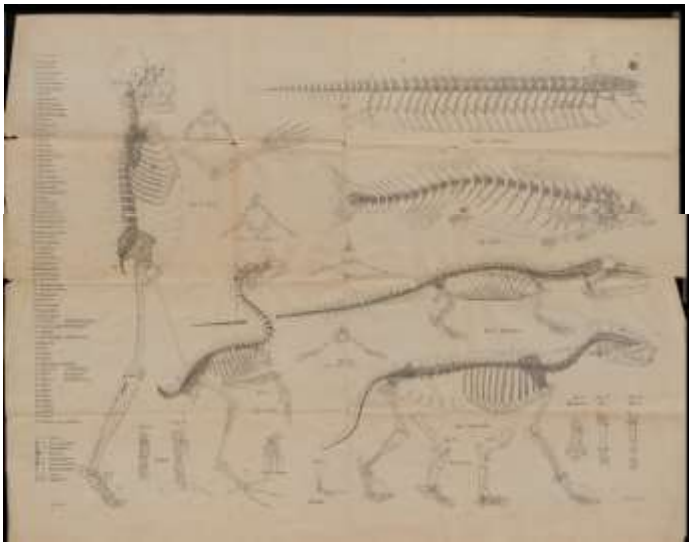
The movie "*Creation*" is a superbly done movie on Charles Darwin's personal struggles based on the book *Annie's Box: Darwin, His Daughter, and Human Evolution*, by Darwin's great, great grandson, Randal Keynes.
https://vimeo.com/8921583

Is there room for more than one cause in science? Must we accept unconditionally that the materialist theory of natural selection will describe and explain all aspects of life? Let's consider the story of **Theseus's Paradox**. According to Plutarch, "*The ship wherein Theseus and the youth of Athens returned from Crete had thirty oars, and was preserved by the Athenians down even to the time of Demetrius Phalereus, for they took away the old planks as they decayed, putting in new and stronger timber in their place, in so much that this ship became a standing example among the philosophers, for the logical question of things that grow; one side holding that the ship remained the same, and the other contending that it was not the same*." Thomas Hobbes wondered: What would happen if each of the original planks were collected after they were replaced and used to build a second ship? Which ship, if either, is the original Ship of Theseus? I want to say, a reasonable person can hold more than one explanation for the same object or process. **Dualism** or even **quadrupleism** is not a bad thing.

Aristotle proposed **four causes** (or explanations) that are needed to describe an object such as Theseus's ship. The **formal cause** is the form of the object; the **material cause** is the matter that makes up the object; the **efficient cause** is the mechanism of how or by whom the object is made; and the **final cause**, is the intended purpose of the object. Taking the four causes into consideration, there is no single answer to Hobbes' question about which is the original ship. By reducing the question to a single cause, we can only get a partial answer. Is it possible that Thomas H. Huxley dismissed any potential causes too quickly?

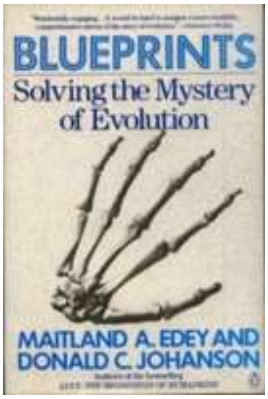


While Richard Owen's name has been lost, his theory of **analogy** and **homology**, which was presented in a lecture entitled *On the Nature of Limbs*, given at the Royal Institution in 1849, has become a cornerstone in all levels of biology. Although he was a comparative anatomist, Richard Owen realized that every grade of organization can be considered to have at least **two meaningful causes**: **form** that arises from an evolutionary and developmental plan, and **function** that facilitates the processes, such as movement that are necessary for life.



The concepts of **analogy** and **homology** can be applied to genes as well as limbs. If two or more objects are related by **common descent**, they are considered to be **homologous**. If two or more objects have some similarities in terms of form or function, but are not related by common descent, they are considered to be **analogous**. Without sufficient experimental evidence to support convergent evolution or design, gradual or salutatory change, the **bioluminescent production of light** by organisms that are not related by common descent can be considered by reasonable people to be analogies that are the result of **convergent evolution** that results from **gradual natural selection**, **large congenital changes (e.g. genetic mutations or jumps) that have no selective advantage**, and/or **design**.

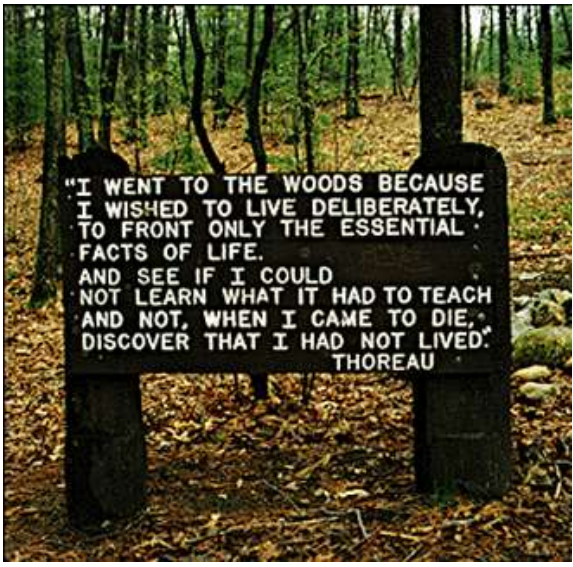
The **National Center for Science Education** defines anti-evolutionism in the classroom as teaching the strengths and weaknesses of evolution and teaching how to critically analyze evolution (http://ncse.com/evolution/education/anti-evolutionism-classroom). I obviously disagree and would not call myself an anti-evolutionist. I am just a strong believer that a healthy science demands questioning and believe that any consensus on any issue does not eliminate the possibility of questioning. **Henrik Ibsen** wrote in "*An Enemy of the People*," "*The majority is never right. Never, I tell you! That's one of these lies in society that no free and intelligent man can help rebelling against*." There is a trend however that treats **science as a package deal** that has been packaged by the consensus. The trend suggests that you cannot choose for yourself those parts of science that you think have strong support and reject the other parts. In their book *Blueprints: Solving the Mystery of Evolution*, Maitland A. Edey and Donald C. Johanson (1989) write, "*You can`t accept one part of science because it brings you good things like electricity and penicillin, and throw*



away another part because it brings some ideas you don`t like about the origin of life."

Science does not have to be **monolithic**. Use your own mind! Think for yourself! Make your own decisions! In *The Everlasting Gospel*, William Blake wrote about the importance of the mind/soul in seeing:

This life's five windows of the soul
Distorts the heavens from pole to pole
And leads you to believe a lie
When you see with, not through, the eye.



"*I know of no more encouraging fact than the unquestionable ability of man to elevate his life by a conscious endeavor. It is something to be able to paint a particular picture, or to carve a statue, and so to make a few objects beautiful; but it is far more glorious to carve and paint the very atmosphere and medium through which we look, which morally we can do. To affect the quality of the day, that is the highest of arts.*" -- Henry David Thoreau, "Where I Lived and What I Lived For"

Some picture windows in the city are truly beautiful! Here's a ***trompe l'oeil*** **stained glass window** designed by Richard Morris Hunt for Henry Gurdon Marquand's New York City home.