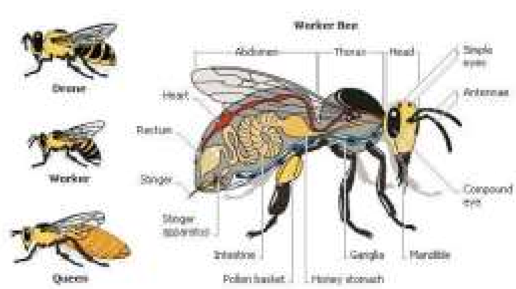
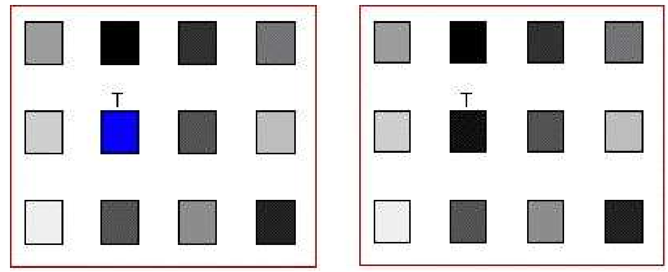
Polarized Light and Bee Vision: Sweetness and Light

Karl von Frisch (1914) knew that the bright colors of bee-pollinated flowers would only make sense if the bees had color vision. That is, he realized that the flowers were communicating with the bees. From this initial insight, von Frisch elucidated the **language of bees** and found that the bees were also communicating with each other. When a worker honey bee finds flowers that contain nectar, she (all worker bees are female) returns to the hive to give the nectar to the young worker bees. The young worker bees suck the nectar from the forager and then convert it to honey in a process that involves regurgitation and dehydration. Then the foraging worker bee performs a special dance that enlightens the worker bees as to where the nectar is. It turns out that the original forager is able to communicate the direction of the food source in relation to the sun by means of **analyzing polarized ultraviolet light** from the sky. Generally, humans cannot perceive ultraviolet wavelengths or the polarization of the waves. The bees however can see what is invisible to us.

The initial experiments that were aimed at testing whether or not bees had **color vision** were done by von Frisch who put a dish of sugar solution over a piece of blue paper. The bees would drink the sugar solution until their **crops** or **honey-stomachs** were full and then they would fly back to the hive. After the bees repeated this behavior a few times, von Frisch put out two pieces of paper—a red one and a blue one but neither of them had a sugar solution on them. The bees paid no attention to the red paper and flew to the blue paper even though it had no



sugar on it. From these kinds of experiments, von Frisch concluded that **bees have color vision and can distinguish blue from red**.



In order to make sure that the bees were not sensing blue as being brighter than red, von Frisch placed a blue square without sugar water in the midst of many shades of gray guessing that if the bees that were **previously fed on blue paper** did not really have color vision but were only sensing the brightness monochromatically, then the bees would go to the blue card and a shade of gray that matched the brightness of the blue. Since the bees always fly towards the blue and never go to any shades of gray, the bees must be able to distinguish blue from every possible shade of gray.

Von Frisch (1915) trained the bees to **recognize blue** by putting sugar water, which has no scent, on a dish over the blue square and putting dishes without sugar over the gray squares. When he moved around the position of the blue square, the bees would always fly directly towards the blue square. In the same manner, von Frisch could also train the bees to **recognize an orange square, a yellow square, a green square, a violet or a purple square**, but he **could *not* train them to go exclusively to the red square**. When he tried to train bees to go to the red square, they would also go to the black square, indicating that they could not see red as a color. In order to test all the colors, including ultraviolet, Alfred Kühn (1927) extended von Frisch's experiments by irradiating the squares with various colors split by a prism and assayed which ones the bees would fly towards. Below is von Frisch's summary of the **comparison between bee and human vision**:

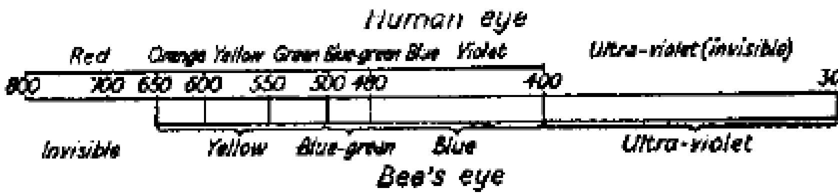


Fig. 19. The colours of the spectrum. Above: as they appear to the human eye; below: to the bee's eye. The numbers indicate the wave lengths of the beams of light (in thousandths of a thousandth millimetre) at given points of the spectrum.

Note that just because a flower looks red to us does not mean that bees see it as red and do not pollinate it. Bees will pollinate red flowers such as poppies or *Silene dioica*, but ***only*** if they also have ultraviolet reflectance that the bees can see. We see the flowers as being red or reddish while the bees see them as being ultraviolet (http://www.naturfotograf.com/UV_flowers_list.html).

Von Frisch (1915) also found that bees could be taught to **distinguish** drawings of shapes with different **forms**, and they do it best when the forms look like the flowers that they would likely visit.

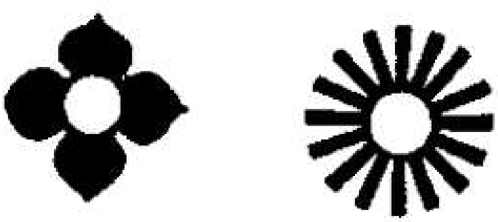


Fig. 24. Shapes that can be distinguished easily and certainly by bees.

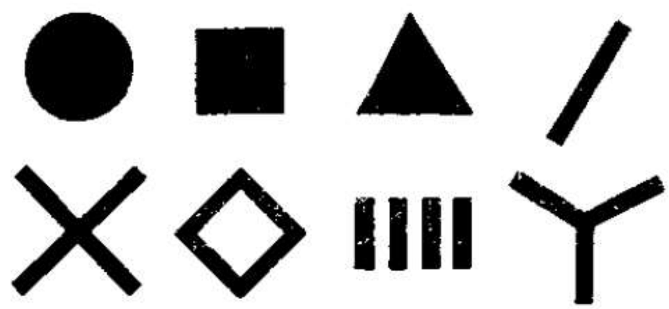


Fig. 25. Bees cannot distinguish between the shapes in the top row, nor between those in the bottom row. But they can distinguish those in the top from those in the bottom.

The ability to distinguish shapes depends on the **visual acuity** of the bee's eyes. Insects have compound eyes and the acuity depends on the size and number of wedge-shaped **ommatidia**. The acuity of a worker honey bee is about one degree of arc. This is because a worker honey bee has about 5,500 ommatidia in each eye where the diameter of the lens of each ommatidium is about 20 μm.

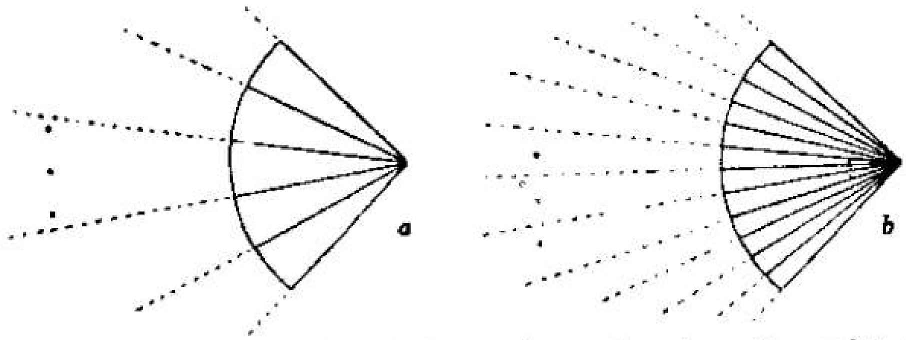
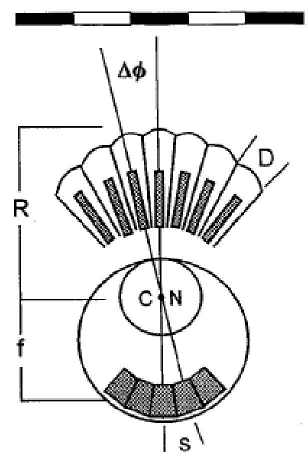


Fig. 23. Sharpness of vision of the insect's eye depends on the number of wedge-shaped sections.

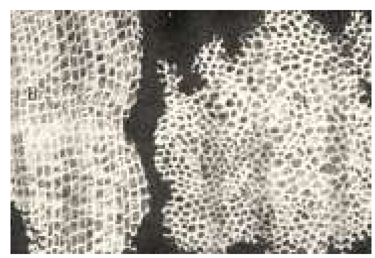
By contrast, the human eye is able to resolve two separate points that are greater than **70 μm** or 0.07 mm from each other, which is equivalent to one minute of arc. The **acuity** of the human eye is limited by the diameters of the **cones**, which are about 2 μm, in the **fovea** of the **retina**. The acuity of the human eye is sixty times better (60' = 1°) than that of the honey bee eye, indicating that things look a little fuzzier to the bee than they do to us.



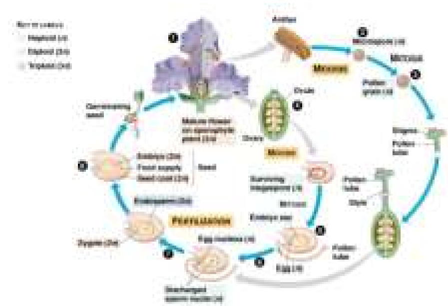
(a)

The nectar and pollen produced by the flowers will serve as a make-your-own room and board for the honey bees. The foraging worker honey bees leave the hive to look for flowers that contain pollen and nectar. Once they frenetically fill their pollen sacs and honey-stomachs with pollen and nectar, respectively, they fly back to the hive with a mass of pollen and nectar that is equivalent to their own

mass. The young worker bees in the hive use the nectar to make honey to feed the young, and they also use the honey to make scales of wax that are used to build the honeycomb. **A worker bee forages for about ten hours a day for nectar and pollen. It takes nectar from about 5 million flowers to make one pound of honey and one pound of honey to make about two ounces of wax**. Two ounces of wax consist of about 100,000 scales. Now you know what it means to be as busy as a bee!!

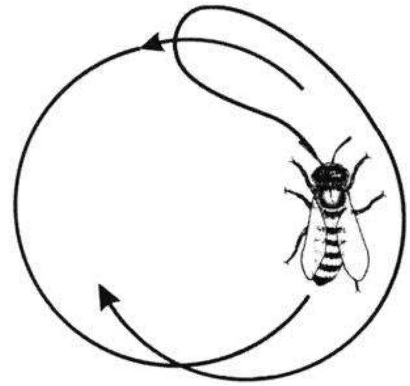


Each unit of the honeycomb is known as a **cell**, which inspired **Robert Hooke** (1665) to call the component parts of cork—cells. The cork, according to Hooke, was "*all perforated and porous, much like a honey-comb….walls (as I may so call them) or partitions of those pores were neer as thin in proportion to their pores, as those thin films of wax in a honey-comb (which enclose and constitute the hexangular* ***cells****) are to theirs*." The hexagonal shape of honeycomb cells is the most efficient design for filling a given volume with the least amount of material. It is known as **hexagonal close packing**.



The **angiosperms** or flowering plants gain from attracting the bees by becoming **cross pollinated** so that the next generation enjoys **hybrid vigor** and avoids **inbreeding depression**. The bees also gain from this **symbiotic relationship** by collecting nectar and pollen. When foragers return to the hive, they communicate to the worker bees the type of flower the nectar came from, the amount of nectar, its distance, and direction.

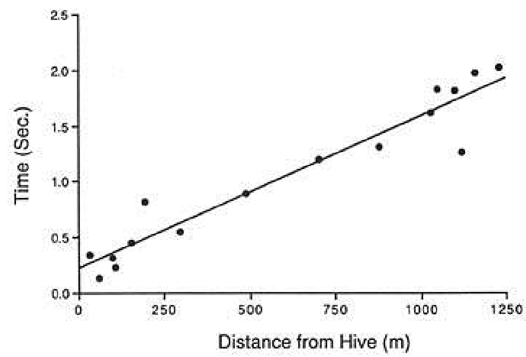
If the nectar-containing flowers are **nearby** to the hive, say **ten to fifteen meters** away—the definition of nearby depending on species, the forager will perform a **round dance** on the vertical side of the honeycomb when she returns to the hive. She will run in circles for several seconds to minutes around a single cell on the comb—reversing direction every one or two laps. If the scent on the pioneering foraging bee is the same as what some bees have collected before, they will follow the foraging bee in her dance with their antennae close to her body and then follow her out of the hive to the flowers. But if her scent is different from that that the bees collected before they will stay in the hive. It seems like there are groups in the hive that become flower-specific **loyalists** or specialists. This loyalty ensures that the bees will **cross pollinate** flowers of the same species. The strength of the scent of the foraging bee alerts the worker bees in the hive as to the amount of nectar at the foraging site about which the foraging bee is communicating. As the sugar content of the nectar decreases, the bees dance less enthusiastically—that is for shorter times and less vigorously and they attract or enlist fewer bees to go to that foraging site. At this point, the worker bees change their flower scent loyalty and are attracted to the scent—for example *Phlox* v. *Cyclamen*—that is associated with more sugar and longer and more vigorous dancing.



Von Frisch found that when the nectar-containing flowers are **50 -100 meters** away from the hive, the round dance begins to morph into another dance, known as the **waggle dance**. When the food is still farther from the hive, even as far as 15 km, the

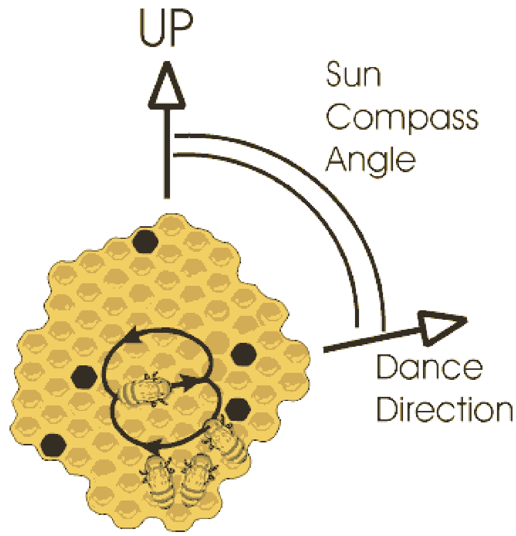
forager performs a **waggle dance** upon returning to the hive. The forager dances in figure eights on a vertical surface of the comb. In moving through the figure eight, the bee moves straight ahead for a short distance while waggling her body and then returns to the starting point by way of a semicircle. Then the bee again moves the same distance along the straight path while waggling her body and returns again to the starting point along a semicircle—but this time moving in the opposite sense as she did in the prior semicircle.

The waggle dance communicates both the **distance** to and the **direction** of the flower. By moving a feeding site to greater and greater distances from the hive, von Frisch found that the **distance** from the nectar-containing flowers to the hive is communicated by the **duration of the wagging part of the dance**. Although the actual relationship between dance duration and distance to the nectar-containing flowers depends on the species of honey bee, in general, the wagging lasts for about one second for every 500 meters between the hive and the nectar-containing flowers.



Want to hear something amazing? If the bee is subjected to a **headwind** or has to fly uphill, her dance overestimates the distance to the nectar-containing flowers. This is because she measures distance by how much **fuel** she uses to fly between the nectar-containing flowers and the hive. Scholze et al. (1964) found that the fuel the foraging worker bee is measuring is her **blood sugar**. The lower her blood sugar when she returns to the hive, the longer she estimates the distance to be.

Von Frisch noticed that the straight part of the waggle dance performed by bees that returned from a food source 200 meters **south** of the hive was always **tilted left** and that the straight part of the waggle dance performed by bees that returned from a food source 200 meters **north** of the hive was always **tilted right**. Von Frisch concluded that the **direction of the straight part of the waggle dance was somehow correlated with the direction of the nectar-containing flowers**.



Then von Frisch noticed that even if the position of the nectar-containing flowers remained constant and the duration of the waggle dance was constant, **the direction of the straight part of the dance shifted during the day**. Von Frisch guessed that the direction of the straight part of the dance was correlated with both the constant position of the nectar-containing flowers and the diurnally-varying position of the sun. The **direction** of the nectar-containing flowers is communicated by the angle from the vertical of the straight path along which the bee waggles. That is, the bee can sense both light and gravity and she converts the angle with respect to the sun to an angle with respect to the gravitational field of the earth. This conversion is

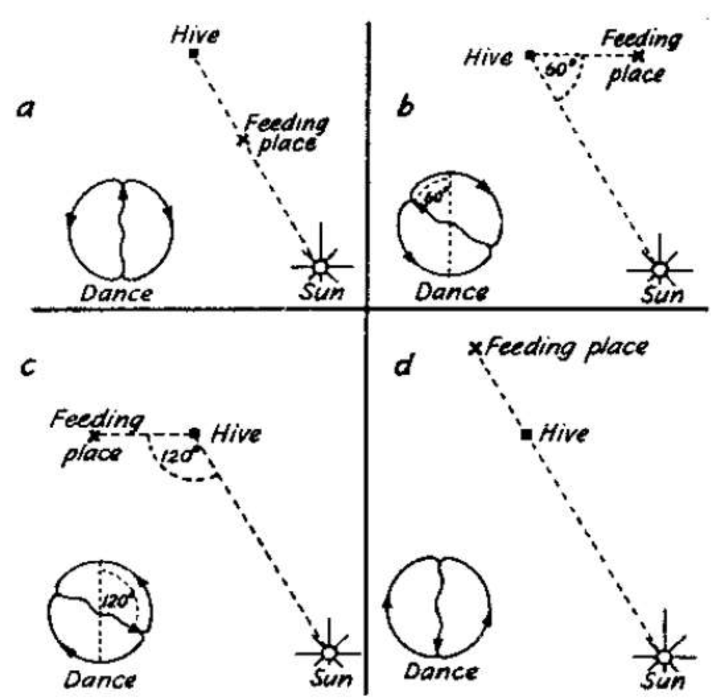
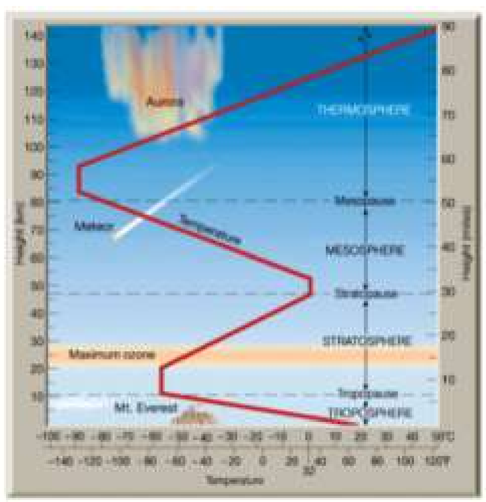


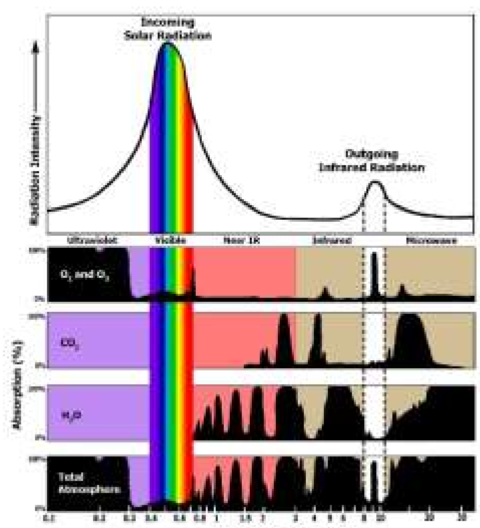
Fig. 44. Giving the sun's bearing in a dance on a vertical comb surface. The little diagrams on the left of each drawing show the dance as it appears on the vertical comb.

important since the inside of the hive is dark and the sun is not visible. Waggling while moving upward communicates "fly towards the sun" and waggling while moving downward communicates "head away from the sun."
https://www.youtube.com/watch?v=bFDGPgXtK-U

If the nectar-containing flowers are sixty degrees anticlockwise relative to the direction of the sun, then the direction of the straight part of the waggle dance will be sixty degrees anticlockwise relative to up. If the nectar-containing flowers are one hundred twenty degrees clockwise relative to the direction of the sun, then the direction of the straight part of the waggle dance will be one hundred twenty degrees clockwise relative to up. By performing the waggle dance, the position of nectar-containing flowers within 360° degrees and 15 km can be communicated from the forager to the rest of the worker bees in the hive. The bees communicate a **vector quantity** that has both magnitude (distance) and direction.

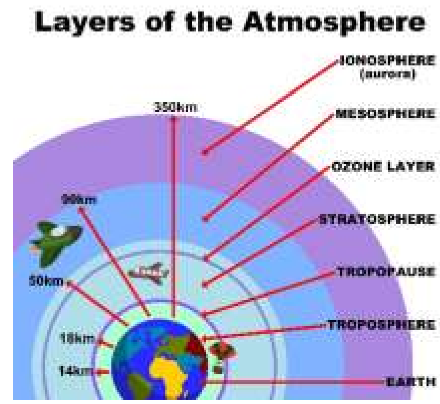
Von Frisch showed that even on a **cloudy day**, the dancing bees can still communicate the direction of the nectar-containing flowers. How do they (have sunshine on a cloudy day) and know where the sun is?

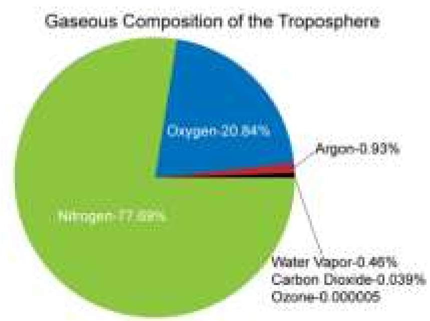




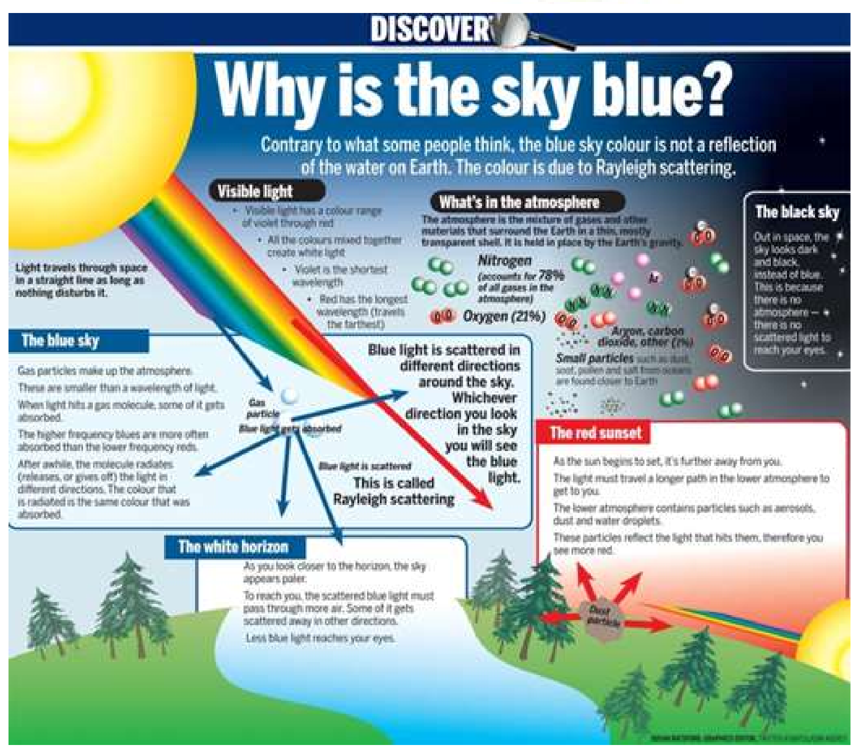
To answer this question, we will begin by reviewing what we know about **sunlight and the atmosphere**. The sunlight has a **blackbody distribution** or **color**

temperature that is a function of the temperature of the surface of the sun. As the sunlight enters the earth's atmosphere, the **ultraviolet** (all UVC and some UVB) rays are absorbed in the ozone layer by O_2 and O_3 and converted to heat (IR) that warms up the **stratosphere** where the **ozone layer** occurs.



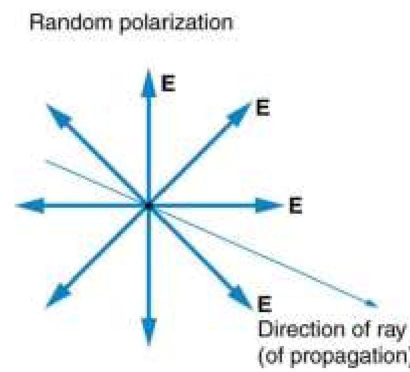


Below the stratosphere layer is the **troposphere** layer. The troposphere contains N_2, O_2, Ar, H_2O, CO_2 and O_3, **colorless** molecules that **scatter** the sunlight in a manner that is inversely proportional to the fourth power of the wavelength. The CO_2 and H_2O in the troposphere also absorb and scatter the incoming infrared radiation of the sun and the outgoing radiation from the earth (Tyndall, 1861; Arrhenius, 1896). Johann Lambert's (1760) law states that absorption is proportional to the thickness and August Beer's (1852) law states that the absorption is proportional to the concentration. The Beer-Lambert law states that the absorbance is proportional to both the thickness and concentration and the proportionality constant is called the extinction coefficient.

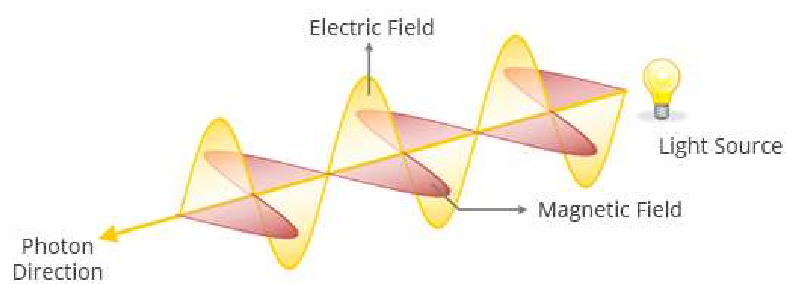


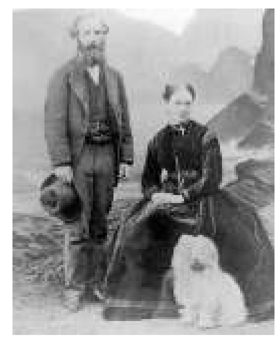
This **Rayleigh scattering** is why the sky is blue. It is also why blue eyes and the blue-eared glossy starling are blue.

What I have not told you is that the scattered light is **polarized** (Arago, 1809, Tyndall, 1869). What is polarized light? The amplitudes of the wave in natural light vibrate in all azimuths (angles) around the axis of propagation of the light. Linearly polarized light is when light vibrates in one azimuth (angle) relative to the axis of propagation.

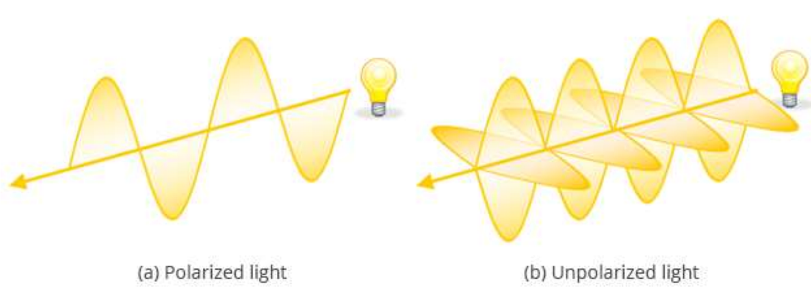


I also did not tell you that thanks to the theoretical treatment of many experiments done in the study of electricity and magnetism, **James Clerk Maxwell** (1865) determined that the light wave can be considered as an electromagnetic light wave with **vibrating electric and magnetic fields**.

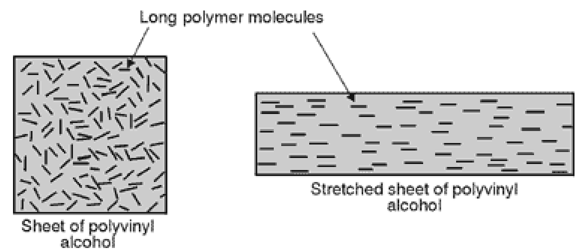




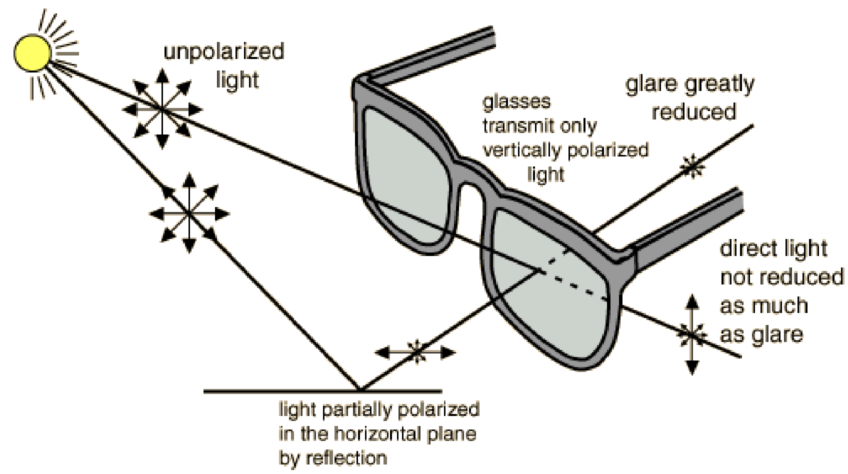
With linearly polarized light, the electric field of all the waves vibrate in one azimuth (angle) relative to the axis of propagation and with natural or unpolarized light, all the electric fields vibrate in each and every azimuth (angle).



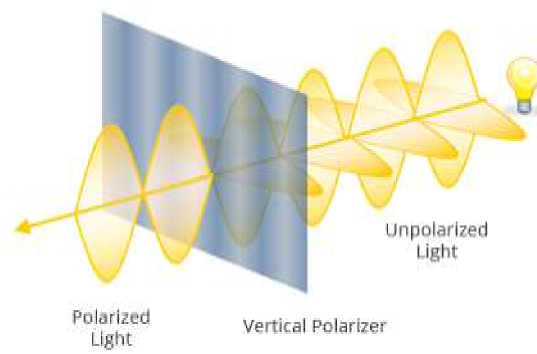
Whether or not light is linearly polarized can be determined with an **analyzer**. A **Polaroid** is an **analyzer** that **absorbs** all the light that is linearly polarized parallel to the long axis of the aligned bonds of the molecules of **polyvinyl alcohol impregnated with iodine** that make up the Polaroid. A Polaroid **transmits** all the light or the components of the light that is not linearly polarized parallel to the **aligned bonds** of **polyvinyl alcohol impregnated with iodine**.



When direct sunlight passes through Polaroid sunglasses, only light whose electric field is **perpendicular** to the aligned bonds of **polyvinyl alcohol impregnated with iodine** is transmitted through the glasses. Thus when natural sunlight reaches Polaroid sunglasses, the light that is transmitted is linearly polarized light. On the other hand, glare which is caused by the **reflection of sunlight** from a surface is not transmitted at all. This is because **reflected light is linearly polarized with an azimuth parallel to the surface producing the glare**. Polaroid sunglasses work because glare is linearly polarized **parallel** to the surface causing the glare and the molecules in the Polaroid are aligned horizontally which is parallel to most glaring surfaces. This is how Polaroid sunglasses work.

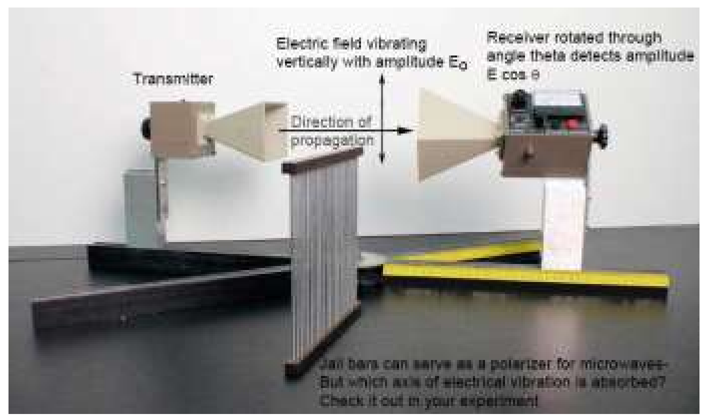


A Polaroid is similar to a prism in **that a prism resolves natural light into each wavelength while a Polaroid resolves natural light into each azimuth of polarization**.

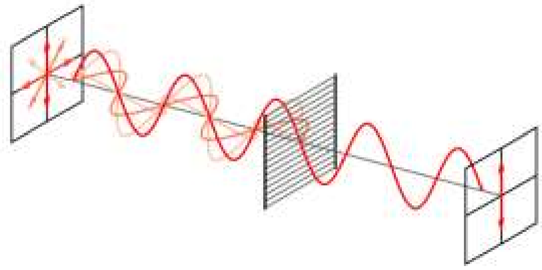


Demonstration: Observe glare through a Polaroid. Rotate the Polaroid to find the position of maximal and minimal transmission of glare. At the position of minimal transmission, the aligned molecules of **polyvinyl alcohol impregnated with iodine** will be **parallel** to the surface producing the glare**.**

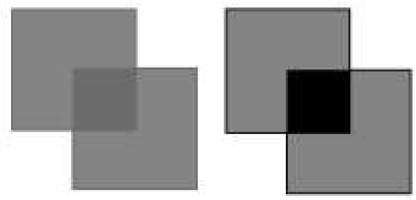
Demonstration: We can use **microwaves** that have a **wavelength of three centimeters** to understand polarization of waves. The transmitter is an antenna that transmits microwaves that are linearly polarized in the **vertical direction** (0°). The antenna of the transmitter uses electrical energy to move electrons up and down and the moving electrons emit electromagnetic waves with vertical polarization. The antenna of the receiver uses the electromagnetic wave to move electrons up and down and the moving electrons create an electric field in the antenna which is given by the meter. The receiver maximally absorbs the microwaves if its antenna is oriented in the **vertical direction**. It does ***not*** absorb any microwaves if the azimuth of the antenna is **perpendicular** to the azimuth of polarization. We can put an analyzer between the transmitting antenna and the receiving antenna. When the wire grid is oriented with the bars **horizontally**, the microwaves are transmitted through it, as measured by the meter. When the wire grid is oriented with the bars **vertically**, the microwaves are not transmitted to the receiver as measured by the meter. This is because the **microwaves interact with the free electrons in the bar** and are in part reflected



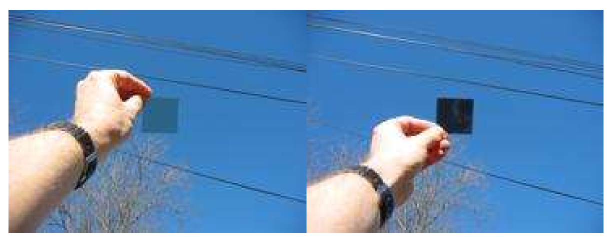
back to the transmitter. In addition, the energy of the microwaves is absorbed as it is converted into the kinetic energy of the electrons and is thus dissipated. The wire polarizer is used for centimeter long microwaves just as a Polaroid is used for 400-700 nm visible light waves. The polarizer in the figure on the right can represent the orientation of wire bars or the alignment of iodine in a polyvinyl alcohol sheet.



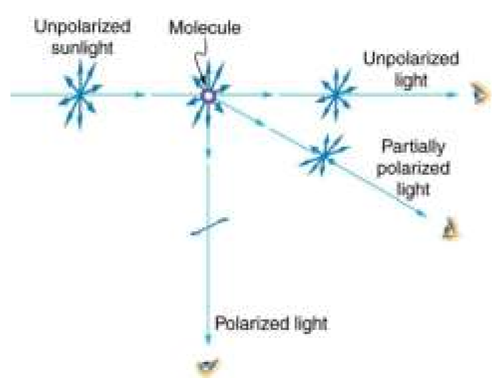
Demonstration: Each Polaroid filter transmits linearly polarized light. Use the overhead projector to see what is transmitted through two Polaroid filters when their axes of transmission are parallel and when their axes of transmission are perpendicular.



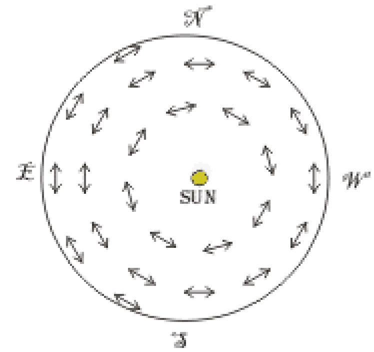
Demonstration: Look though a Polaroid at the skylight through the window. Rotate the Polaroid. What happens to the brightness of the skylight?

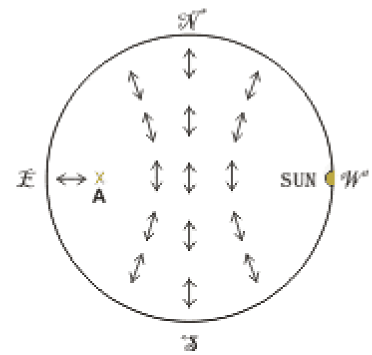


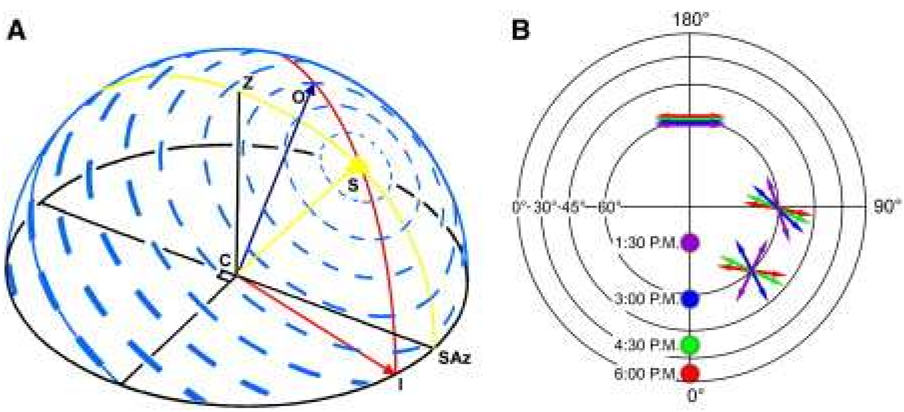
Now that we know how to analyze polarized light, let's turn our Polaroids towards the sky. A Polaroid, turned to a certain azimuth, reduces the amount of skylight. Photographers use a Polaroid filter (right) in front of the lens to increase the contrast of pictures that have a lot of sky.



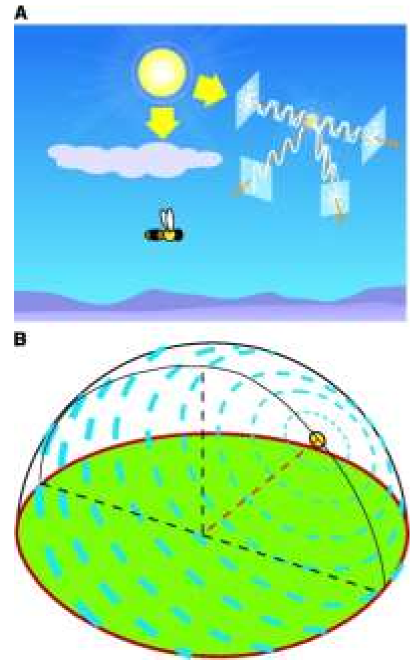
The above photographs demonstrate that the blue skylight is linearly polarized as a result of scattering by atmospheric molecules. **The azimuth of polarization of sunlight is a function of the position of the sun**. The degree of polarization increases as the angle made with the observer at the vertex by the sun and the position of the sky increases up until 90° from the sun. When the sun is at its **zenith** (maximal height), light at the horizon is maximally polarized and the azimuth of polarization is parallel to the horizon. When the sun is either rising or **setting**, the light along the **meridian** (the circular path along which the sun appears to travel) is maximally polarized and the azimuth of polarization is perpendicular to the meridian.







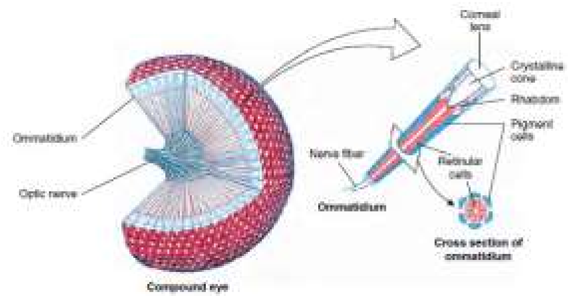
The pattern of polarization not only changes throughout the day but also throughout the year since the meridian is higher in the summer and lower in the winter. The amount of polarization at any point in the sky can be estimated by looking at the sky at that point through a linear polarizer. If there is a large intensity change when rotating the polarizer 90°, then there is a substantial amount of polarization. If the intensity change is small, then the amount of polarization is small too. It is generally true that where the skylight is polarized, the azimuth of polarization is perpendicular to the plane made up of three points—the position of the sky, the position of the sun and the position of the observer.



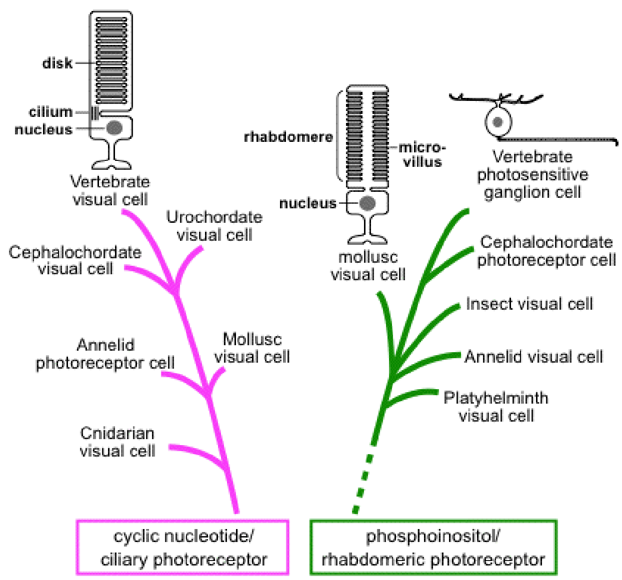
Von Frisch showed that the honey bees were able to tell the direction of nectar-containing flowers relative to the sun by analyzing the azimuth of polarization of light waves scattered by the gas molecules in the atmosphere. He did this first by determining the **action spectrum** of light that would cause the bees to perform the correct **waggle dance**. He put filters that transmitted a small part of the skylight spectrum around an enclosure. He found that the bees could communicate the correct position of the nectar-containing flowers relative to the sun only when the filter passed **ultraviolet light**. Therefore the bees were using **ultraviolet wavelengths** (300-400 nm) to determine the position of the nectar-containing flowers relative to the sun. This action spectrum correlated with the ability of the bees to see in the ultraviolet.

Next, von Frisch put a large Polaroid filter over the bees so that he could arbitrarily introduce polarized light with a given azimuth from the blue sky to the bees in a hive that was exposed to sunlight. Von Frisch rotated the polarizer to the right or to the left. Von Frisch (1971) wrote "*Never shall I forget the joy with which I saw the dancers react to it at once and shift the line of their wagging runs in the direction of rotation. Without exception the dances pointed farther toward the right after a rotation to the right, and farther toward the left after a rotation to the left. This of itself demonstrated that they orient with reference to the polarization of the blue sky….But they did not always shift their indication of direction by precisely the angle through which I had rotated the polaroid sheet. For example, it sometimes happened that after a rotation of 30 degrees the line of* *dancing was shifted in the same direction, but by 35 degrees. In order to comprehend this we need more intimate knowledge about the polarized light in the blue vault of heaven and about its analysis by the eye of the bee.*"

The polarized light ultraviolet is sensed by the two large compound eyes of a honey bee.

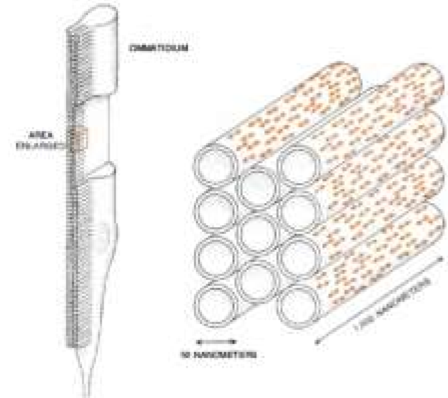


The honey bee eye must have an analyzer composed of a pigment that will absorb polarized ultraviolet light as a function of its azimuth. **Is there anything in the insect eye that looks like an analyzer**?

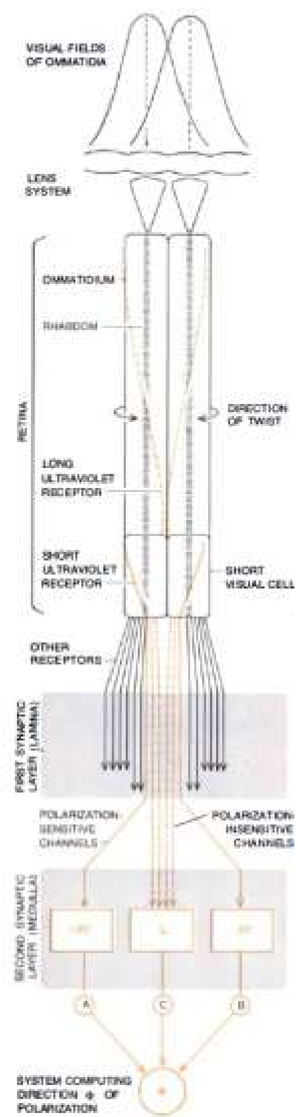


The structure of the visual cells in the retina of insects differ in the structure visual cells in the retina of humans and are similar to the melanopsin-containing intrinsically photosensitive retinal ganglion cells. The visual cells of insects have parallel microvilli that contain the photoreceptor pigment. The 11-cis retinal of the photoreceptor pigment is a dipolar molecule that maximally absorbs polarized light whose azimuth is oriented parallel to the molecule and does not absorb polarized light whose azimuth is perpendicular to the molecule.

Rüdiger Wehner and Timothy Goldsmith measured the absorption of ultraviolet light with varying azimuths. If the photoreceptor molecules were randomly oriented in the visual cells, the amount of absorption would be independent of the azimuth of the ultraviolet light. If the photoreceptor molecules were not randomly oriented, the amount of absorption would depend on the azimuth of ultraviolet light. They found that the amount of absorption was maximal when the azimuth of polarized ultraviolet light was parallel to the microvilli, indicating that the **photoreceptor pigments are oriented parallel to the microvilli**. In humans, the photoreceptor molecules are randomly arranged in the visual cells, which is why we cannot detect the azimuth of polarization with our naked eyes.



There are about 5,500 **ommatia** in each eye of a honey bee and each ommatium contains nine visual cells. **Three of the visual cells have UV-absorbing photoreceptor pigments.** Two of the UV-absorbing ommatidia are long and are twisted 180° throughout their length, meaning that they will absorb any and all azimuths of UV light equally. However, the third UV-absorbing visual cell, which is a **short cell**, is only twisted 40° and thus retains its sensitivity to polarized light. In each eye, half of the UV-absorbing visual cells are twisted **clockwise** and half are twisted **anticlockwise**. Rüdiger Wehner (1976) has suggested "*a simple model explaining how the insect analyzes the direction of skylight polarization. In brief, the model indicates that if two polarization analyzers of opposite twist work together with at least one long ultraviolet-sensitive cell that is insensitive to the*



polarization of the skylight polarization anywhere overhead can be determined unambiguously. Hence any two adjacent ommatidia of opposite twist are equipped with all three of the necessary cells and will provide the analyzing system with all three of the necessary signals: two independent signals that are modulated by polarized skylight and one signal that is not."

Polarized light whose azimuth is the same as the azimuth of maximal absorption of the pigment will be maximally absorbed and a message will be sent to the brain. Polarized light whose azimuth is perpendicular to the azimuth of maximal absorption of the pigment will not be absorbed and no message will be sent to the brain. The brain is necessary to decode the polarization of skylight to use the sun as a compass.

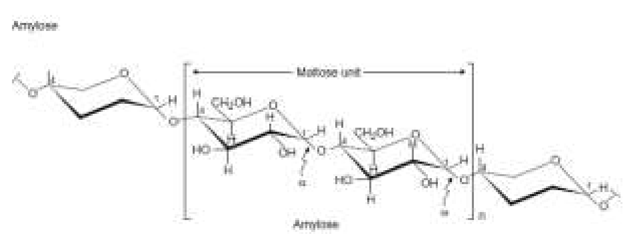
Since the pattern of polarization of skylight varies during the day and the season, bees must be able to **keep track of time** in order to use the sun as a compass. Von Frisch (1971) that bees "*have an excellent memory for time*" after all their foraging has to be **synchronized** with the **flower clock** that controls the blooming of as well as the opening and closing of flowers. "***Only connect***."

When Therese von Oettingen-Spielberg (1949) put a beehive containing bees that had never visited flowers in a screened-in courtyard that contained colored paper without scent and scented flowers that could not be seen she was surprised to find that only one or two bees visited the color displays or the scented but covered flowers. Von Frisch, who won the Nobel Prize for his work, described her findings like so: "*As with human beings, pioneers seem to be rare in the beehive. Most individuals prefer to wait for the discoveries of a few scouts in order to find food by following their instructions*." See the waggle dance (http://video.nationalgeographic.com/video/weirdest-bees-dance and http://www.pbs.org/wgbh/nova/nature/waggle-dance.html).

In order for a material to respond to be sensitive to the polarization of light, it has to have some kind of **asymmetry**—such as an asymmetry in absorption or an asymmetry in refraction. The refractive index (n_i) of a material is a measure of the speed of light through the material. The refractive index is the ratio of the speed of light in a vacuum (c) to the speed of light in the material (v_i) according to the following equation.

$$n_i = \frac{c}{v_i}$$

It is the **electrons in the bonds** that interact with and that slow down the light. If the bonds are randomly arranged, then linearly polarized light of any azimuth will be slowed down equally. However, if the bonds are not randomly arranged, then polarized light with an azimuth that is parallel to the bonds will be slowed down more than polarized light with an azimuth perpendicular to the bonds. Such material will have two refractive indices, one for light that is parallel to the bonds and one for light that is perpendicular to the bonds. The refractive index parallel to the bonds will be greater than the refractive index perpendicular to the bonds. Substances with two refractive indices are **birefringent**. Amylose is birefringent having two indices of refraction. The index of refraction parallel to the long axis of the molecule is greater than the refractive index perpendicular to the long axis of the molecule. **Refractive index is all about the interaction of electromagnetic waves in the visible light range with electrons in the bonds of molecules**.

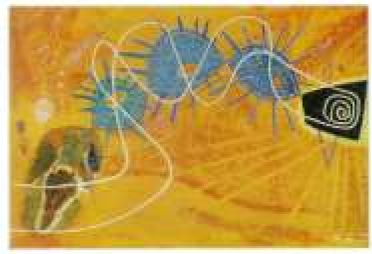


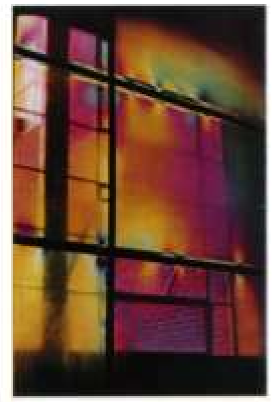
Birefringent substances will become colored when put between two Polaroids whose axes of transmission are perpendicular to each other. These **crossed polars** normally pass no light through them. They pass no light when a substance with one refractive index such as glass is put between them. They pass light when a birefringent substance is put between them. They also pass light when a substance with one refractive index that has been subjected to **stress** which **aligned the bonds** is put between them. This technique, known as **photoelastic stress analysis**, can be used by architects and engineers to visualize and measure the effect of stress in materials (http://flickrhivemind.net/Tags/birefringence/Interesting).

When molecules are not randomly arranged or symmetrical, then the electrons in the bonds interact with polarized light in a way that depends on the azimuth of polarization of the light. If the azimuth of polarization is parallel to the bonds the light will interact longer with the bonds than if the azimuth of polarization is perpendicular to the bonds. If the azimuth of polarization is at a forty five degree angle to the bonds, half of the light will interact parallel to the bond and half of the light will interact perpendicular to the bond. The way the two components recombine in the analyzer will result in the generation of colors.

Demonstration: Observe crossed polarizers. What happens when you put thin sheets of mica or cellophane (plant cell walls) between them? You can arrange the pieces in more or fewer layers and with different orientations to get the desired color.

The principles of polarized light can be applied to art. **Joe Burns** (Cornell) **and his wife Judith** have done art using polarized light and **photoelastic stress**.





Top: *Louis Cork Marcheschi. 'For Marcel', 1972. The 500 watt incandescent lamp is activated by electricity provided by a high-voltage high-frequency generator.* (Photo: W. Young, Minneapolis, Minn., U.S.A.) (Fig. 7, cf. page 298.)

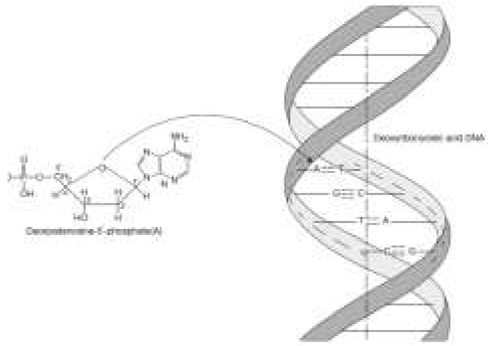
Bottom left: *Richard Bowman. 'Kinetograph, 6', oil on canvas, 40 × 60 in.*, 1950. (Collection of Mr. and Mrs. D. Hart, Mountain View, California, U.S.A.) (Fig. 1, cf. page 291.)

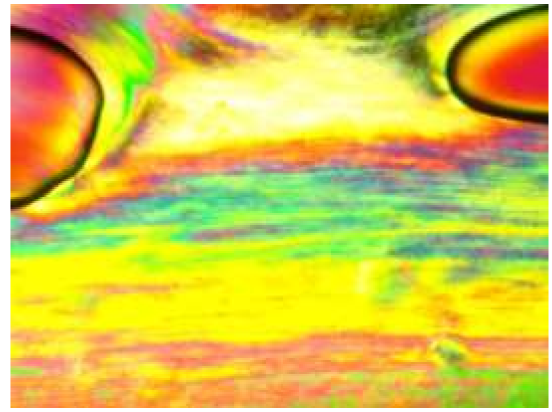
Bottom right: *Joseph A. Burns and Judith Klein Burns. View of a portion of the kinetic mural of stressed photoelastic material and light polarizers.* (Fig. 3, cf. page 325).

Chrono Art is the transformation of time into art. They make clock faces that get their colors based on polarized light.

http://www.chronoart.com/index.html

Demonstration: Polaroids can be used with a microscope to do **polarized light microscopy**. Since the bonds in DNA are nonrandom and linearly polarized light with its azimuth perpendicular to the long axis of the is slowed down more than linearly polarized light with its azimuth parallel to the long axis of the molecule, DNA is birefringent. DNA, the chemical basis of heredity, is beautiful when visualized in a polarizing light microscope.





Demonstration: **Calcite or Icelandic spar** is birefringent and it resolves one beam of natural light into two beams of polarized light, each one with a polarization perpendicular to the other.

Lars Chittka, a behavioral ecologist, and Julian Walker (2006), an installation artist, wanted to show people, who were obviously attracted to flowers, that they should think about the "*fundamental philosophical issue of whether perception reflects reality, about the nature of the image as object, and about the biological meaning of colour for different receivers*." Lars Chittka and Julian Walker presented paintings to bumble (humble) bees that had never seen flowers before. The paintings included Vincent van Gogh's *Sunflowers*, Paul Gauguin's *A Vase of Flowers*, Patrick Caulfield's *Pottery*, and Fernand Léger's *Still Life with Beer Mug.*

Fig. 2. Paintings used: (a) Vincent Van Gogh (1853–1890) *Sunflowers* (1888). The original is in the National Gallery, London. The copy was painted by J. Walker (acrylic on canvas-board; 45.5 × 35.5 cm). (b) Poster of Paul Gauguin (1848–1903) *A Vase of Flowers* 1896; oil on canvas 64 × 74 cm (copyright: The National Gallery, London). (c) Poster of Patrick Caulfield (b. 1936) *Pottery* 1969; oil on canvas 213.4 × 152.4 cm. Presented by Mrs. H. K. Morton through the Contemporary Art Society; Tate Gallery, London (copyright: Patrick Caulfield 2004. All rights reserved, DACS, London). (d) Fernand Léger (1881–1955) *Still Life with Beer Mug* 1921–1922, oil on canvas 92.1 × 60 cm; purchased with assistance from the Friends of the Tate gallery 1976; Tate Gallery, London. Copyright: ADAGP, Paris and DACS, London 2004. Posters of (a) and (b) are available in The National Gallery shop, posters of (c) and (d) are available in Tate Modern's shop.

Fig. 3. Bees exploring paintings: (a) *Bombus terrestris* worker exploring Van Gogh's "Sunflowers". Some bees bear number plates on their backs to allow for individual recognition, (b) a *Bombus terrestris* male is landing on the edge of a blue flower of Gauguin's "A Vase of Flowers" (the most attractive portion of the painting for bees), (c) a worker bee hovering over Caulfield's "Pottery", and (d) another worker landing on a high contrast edge in Léger's "Still Life with Beer Mug".

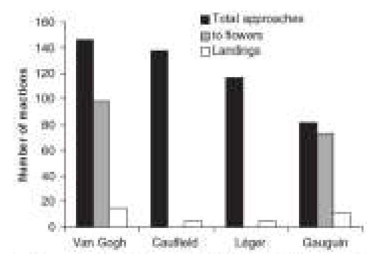
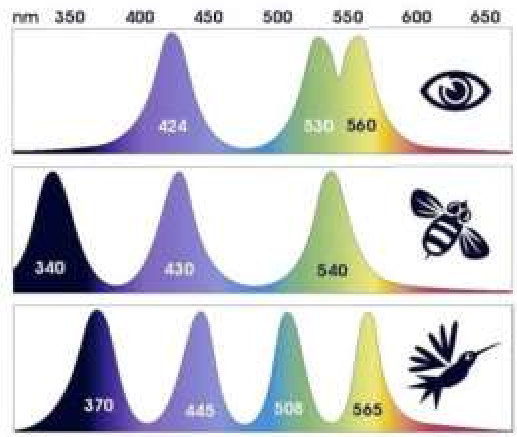


Fig. 4. Bees' reactions to the four paintings (arranged from left to right in decreasing order of popularity). Twelve minutes of observation time were evaluated for each painting.

They found that the bees were most attracted to Van Gogh's painting and the flowers on the paintings were the most common target where they landed. It was not just the flowers that attracted the bees since two other paintings—Caulfield's *Pottery* and Léger's *Still Life with Beer Mug*, which do not have flowers attracted more bees than *A Vase of Flowers*. Chittka and Walker want us to know that the colors we see, although related to what is really there, also depends on the biology of our species. That is, "***colour is neither firmly physics nor a domain of the arts: it is, to a large extent, biology***."

This is something we all know from studying the diversity of photoreceptors in various organisms and the diversity of colors outside the visible spectrum!

Fig. 1. A flower of *Iris pseudacorus* photographed in the visible (left) and in the ultraviolet (centre panel). The centre of the flower is strongly UV absorbing and appears as black, whereas the periphery reflects UV light. Right panel: a bumblebee worker probes the boundary between the two areas with her antennae. Photos by Prof. K. Lunau, with permission.

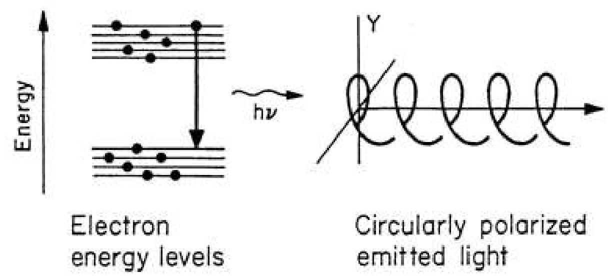


We began this semester looking at the real and virtual images of beeswax candles from Monticello, the home of Thomas Jefferson. On October 21, 1822, Thomas Jefferson wrote in a letter to Cornelius Camden Blatchly: *"I look to the diffusion of light and education as the resource to be relied on for ameliorating the condition, promoting the virtue, and advancing the happiness of man."*

All types of candles were burned at Monticello, including **beeswax**, bayberry and tallow. We now have a great store of knowledge about how the candles come about. We know about how the colorful flowers on photosynthesizing plants attract the bees that carry the nectar, a product of photosynthesis and of sunlight, back to the hive where it is turned into honey and then beeswax. We know a lot about how the candle converts the chemical energy of wax into the radiant energy of the flame—sweetness and light!

Actually, Thomas Jefferson preferred to use expensive spermaceti candles, because they burned so cleanly. According to one of Jefferson's granddaughters, "*When the candles were brought, all was quiet immediately, for he took up his book to read, and we would not speak out of a whisper lest we should disturb him, and generally we followed his example and took (up) a book…*"

Each **photon** emitted by the candle is **polarized**. I believe that the electric field is linearly polarized and the magnetic field is circularly polarized. However, the standard interpretation of quantum mechanics says that each photon is circularly polarized, half are polarized clockwise and half are polarized anticlockwise.



We can learn a lot about light and life from watching the honey bees and follow all the **connections**. It is as true today as it was in 1792, when **Johann Wolfgang von Goethe** wrote in an essay entitled, *The Experiment as Mediator of Object and Subject* "*In living nature nothing happens that is not **in connection with a whole**….Since everything in nature, especially the more common forces and elements, is in eternal action and reaction, we can say of every phenomenon that it is connected to countless others, just as a radiant point of light sends out its rays in all directions.*"

First issue of Nature

Nov 4, 1869

Goethe: Aphorisms on Nature

T. H. Huxley

NATURE! We are surrounded and embraced by her: powerless to separate ourselves from her, and powerless to penetrate beyond her.

Without asking, or warning, she snatches us up into her circling dance, and whirls us on until we are tired, and drop from her arms.

She is ever shaping new forms: what is, has never yet been; what has been, comes not again. Everything is new, and yet nought but the old.

We live in her midst and know her not. She is incessantly speaking to us, but betrays not her secret. We constantly act upon her, and yet have no power over her.

The one thing she seems to aim at is Individuality; yet she cares nothing for individuals. She is always building up and destroying; but her workshop is inaccessible.

Her life is in her children; but where is the mother? She is the only artist; working-up the most uniform material into utter opposites; arriving, without a trace of effort, at perfection, at the most exact precision, though always veiled under a certain softness.

Each of her works has an essence of its own; each of her phenomena a special characterisation: and yet their diversity is in unity.

She performs a play; we know not whether she sees it herself, and yet she acts for us, the lookers-on.

Incessant life, development, and movement are in her, but she advances not. She changes for ever and ever, and rests not a moment. Quietude is inconceivable to her, and she has laid her curse upon rest. She is firm. Her steps are measured, her exceptions rare, her laws unchangeable.

She has always thought and always thinks; though not as a man, but as Nature. She broods over an all-comprehending idea, which no searching can find out.

Mankind dwell in her and she in them. With all men she plays a game for love, and rejoices the more they win. With many, her moves are so hidden, that the game is over before they know it.

That which is most unnatural is still Nature; the stupidest philistinism has a touch of her genius. Whoso cannot see her everywhere, sees her nowhere rightly.

She loves herself, and her innumberable eyes and affections are fixed upon herself. She has divided herself that she may be her own delight. She causes an endless succession of new capacities for enjoyment to spring up, that her insatiable sympathy may be assuaged.

She rejoices in illusion. Whoso destroys it in himself and others, him she punishes with the sternest tyranny. Whoso follows her in faith, him she takes as a child to her bosom.

Her children are numberless. To none is she altogether miserly; but she has her favourites, on whom she squanders much, and for whom she makes great sacrifices. Over greatness she spreads her shield.

She tosses her creatures out of nothingness, and tells them not whence they came, nor whither they go. It is their business to run, she knows the road.

Her mechanism has few springs — but they never wear out, are always active and manifold.

The spectacle of Nature is always new, for she is always renewing the spectators. Life is her most exquisite invention; and death is her expert contrivance to get plenty of life.

She wraps man in darkness, and makes him for ever long for light. She creates him dependent upon the earth, dull and heavy; and yet is always shaking him until he attempts to soar above it.

She creates needs because she loves action. Wondrous! that she produces all this action so easily. Every need is a benefit, swiftly satisfied, swiftly renewed.— Every fresh want is a new source of pleasure, but she soon reaches an equilibrium.

Every instant she commences an immense journey, and every instant she has reached her goal.

She is vanity of vanities; but not to us, to whom she has made herself of the greatest importance. She allows every child to play tricks with her; every fool to have judgment upon her; thousands to walk stupidly over her and see nothing; and takes her pleasure and finds her account in them all.

We obey her laws even when we rebel against them; we work with her even when we desire to work against her.

She makes every gift a benefit by causing us to want it. She delays, that we may desire her; she hastens, that we may not weary of her.

She has neither language nor discourse; but she creates tongues and hearts, by which she feels and speaks.

Her crown is love. Through love alone dare we come near her. She separates all existences, and all tend to intermingle. She has isolated all things in order that all may approach one another. She holds a couple of draughts from the cup of love to be fair payment for the pains of a lifetime.

She is all things. She rewards herself and punishes herself; is her own joy and her own misery. She is rough and tender, lovely and hateful, powerless and omnipotent. She is an eternal present. Past and future are unknown to her. The present is her eternity. She is beneficient. I praise her and all her works. She is silent and wise.

No explanation is wrung from her; no present won from her, which she does not give freely. She is cunning, but for good ends; and it is best not to notice her tricks.

She is complete, but never finished. As she works now, so can she always work. Everyone sees her in his own fashion. She hides under a thousand names and phrases, and is always the same. She has brought me here and will also lead me away. I trust her. She may scold me, but she will not hate her work. It was not I who spoke of her. No! What is false and what is true, she has spoken it all. The fault, the merit, is all hers.

So far Goethe.

When my friend, the Editor of NATURE, asked me to write an opening article for his first number, there came into my mind this wonderful rhapsody on "Nature," which has been a delight to me from my youth up. It seemed to me that no more fitting preface could be put before a Journal, which aims to mirror the progress of that fashioning by Nature of a picture of herself, in the mind of man, which we call the progress of science.

A translation, to be worth anything, should reproduce the words, the sense, and the form of the original. But when that original is Goethe's, it is hard indeed to obtain this ideal; harder still, perhaps, to know whether one has reached it, or only added another to the long list of those who have tried to put the great German poet into English, and failed.

Supposing, however, that critical judges are satisfied with the translation as such, there lies beyond them the chance of another reckoning with the British public, who dislike what they call "Pantheism" almost as much as I do, and who will certainly find this essay of the poet's terribly Pantheistic. In fact, Goethe himself almost admits that it is so. In a curious explanatory letter, addressed to Chancellor von Muller, under date May 26th, 1828, he writes:

"This essay was sent to me a short time ago from amongst the papers of the ever-honoured Duchess Anna Amelia; it is written by a well-known hand, of which I was accustomed to avail myself in my affairs, in the year 1780, or thereabouts.

"I do not exactly remember having written these reflections, but they very well agree with the ideas which had at that time become developed in my mind. I might term the degree of insight which I had then attained, a comparative one, which was trying to express its tendency towards a not yet attained superlative.

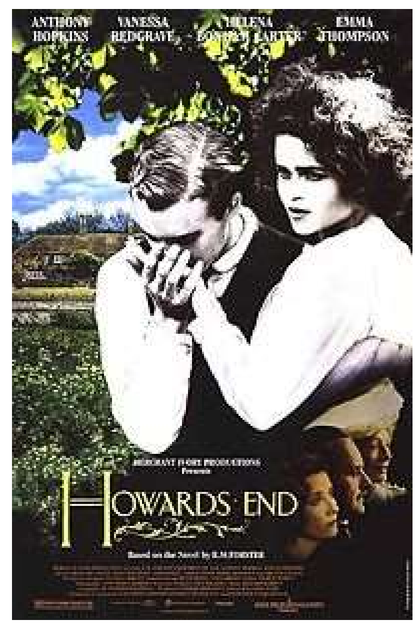
"There is an obvious inclination to a sort of Pantheism, to the conception of an unfathomable, unconditional, humorously self-contradictory Being, underlying the phenomena of Nature; and it may pass as a jest, with a bitter truth in it."

Goethe says, that about the date of this composition of "Nature" he was chiefly occupied with comparative anatomy; and, in 1786, gave himself incredible trouble to get other people to take an interest in his discovery, that man has a intermaxillary bone. After that he went on to the metamorphosis of plants, and to the theory of the skull; and, at length, had the pleasure of seeing his work taken up by German naturalists. The letter ends thus:—

"If we consider the high achievements by which all the phenomena of Nature have been gradually linked together in the human mind; and then, once more, thoughtfully peruse the above essay, from which we started, we shall, not without a smile, compare that comparative, as I called it, with the superlative which we have now reached, and rejoice in the progress of fifty years."

Forty years have passed since these words were written, and we look again, "not without a smile," on Goethe's superlative. But the road which led from his comparative to his superlative, has been diligently followed, until the notions which represented Goethe's superlative are now the commonplaces of science — and we have super-superlative of our own.

When another half-century has passed, curious readers of the back numbers of NATURE will probably look on our best, "not without a smile;" and**, it may be, that long after the theories of the philosophers whose achievements are recorded in these pages, are obsolete, the vision of the poet will remain as a truthful and efficient symbol of the wonder and the mystery of Nature.**



E. M Forster also emphasized the **importance of connections** in seeing the relationships of the parts to the whole in *Howard's End* (1910) "*Margaret greeted her lord with peculiar tenderness on the morrow. Mature as he was, she might yet be able to help him* ***to the building of the rainbow bridge that should connect the prose in us with the passion*.** ***Without it we are meaningless fragments, half monks, half beasts, unconnected arches that have never joined into a man*.** *With it love is born, and alights on the highest curve, glowing against the grey, sober against the fire. Happy the man who sees from either aspect the glory of these outspread wings. The roads of his soul lie clear, and he and his friends shall find easy-going…. It did not seem so difficult. She need trouble him with no gift of her own. She would only point out the salvation that was latent in his own soul, and in the soul of every man.* ***Only connect! That was the whole of her sermon. Only connect the prose and the passion, and both will be exalted, and human love will be seen at its height. Live in fragments no longer. Only connect, and the beast and the monk, robbed of the isolation that is life to either, will die*.**"

Look at all the connections between light and life in ***The Birds and the Bees*** by Herbert Newman:

Let me tell ya 'bout the birds and the bees
And the flowers and the trees
And the moon up above
And a thing called 'Love'

Let me tell ya 'bout the stars in the sky
And a girl and a guy
And the way they could kiss
On a night like this

When I look into your big brown eyes
It's so very plain to see
That it's time you learned about the facts of life
Starting from A to Z

https://www.youtube.com/watch?v=umyl-wWRkJ4

You can buy polarizers for your smartphones.

https://www.youtube.com/watch?v=VFLLP9gnZlg

Important Dates

Prelim 2 will be available online 8 AM, May 10 and Due 9AM, May 12 in my lab. It is closed book and you must work alone.

Calendars are due with the Prelim on May 12.

Final Project Due: Tuesday May 17, at 9 AM. We will meet in Trillium for breakfast and to share our creative writing projects.