EXPLORING THE Nanoworld

Activity Kit

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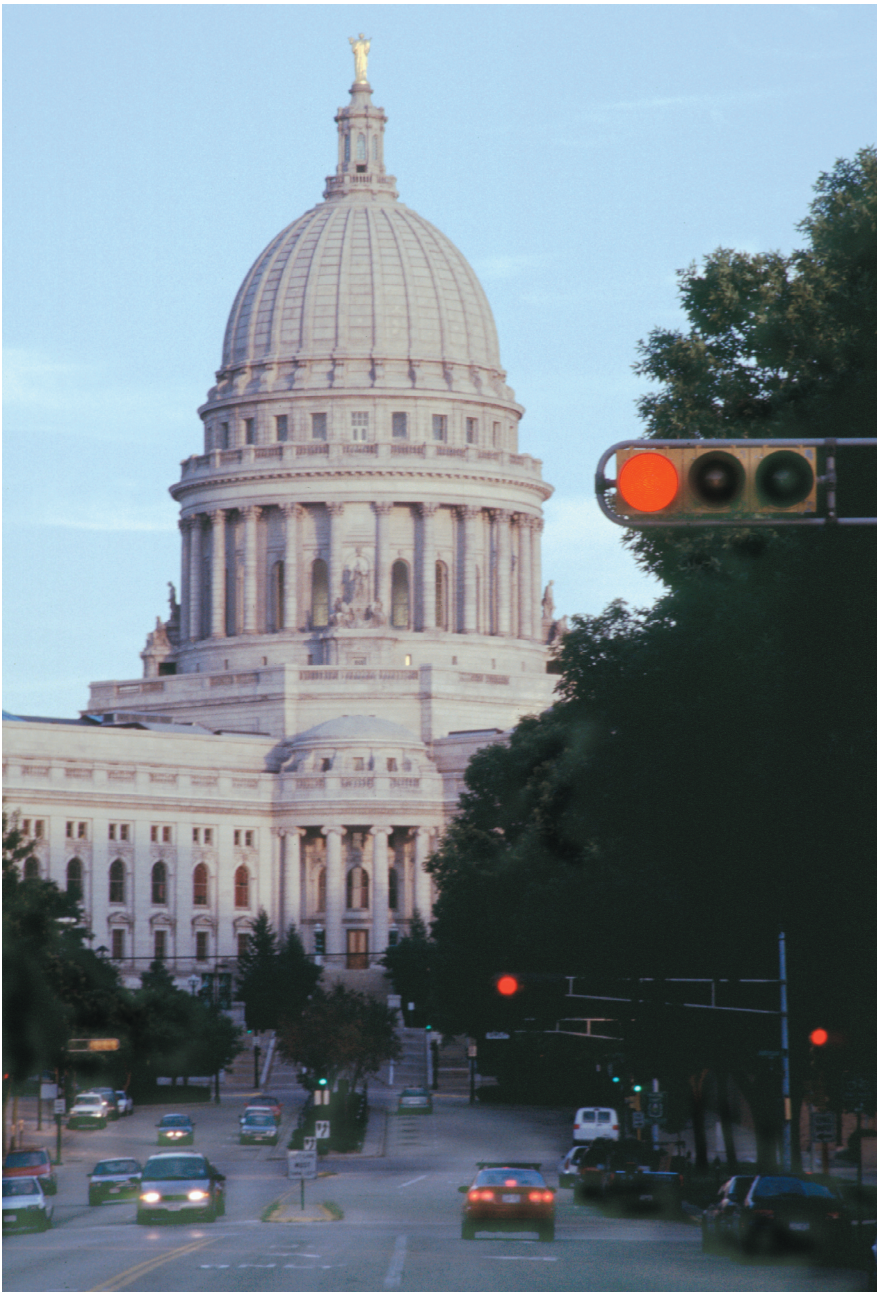
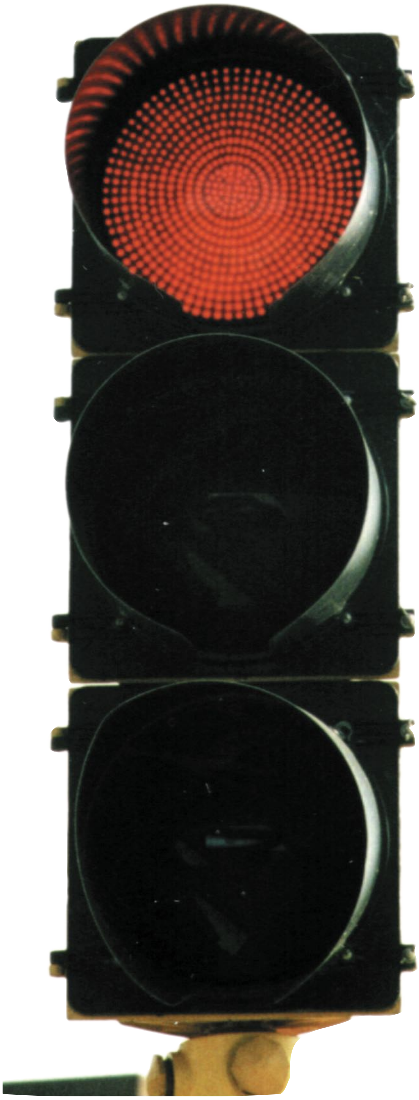
The nanoworld – the scale of atoms – is reached by shrinking to dimensions that are roughly a billion times smaller than the smallest dimensions we typically encounter. To appreciate the notion that one billionth is a thousandth of a thousandth of a thousandth, consider this view of the Wisconsin Capitol building. The distance from the top of the building to the red traffic light shown in the foreground is roughly 1,000 meters or 1 kilometer.

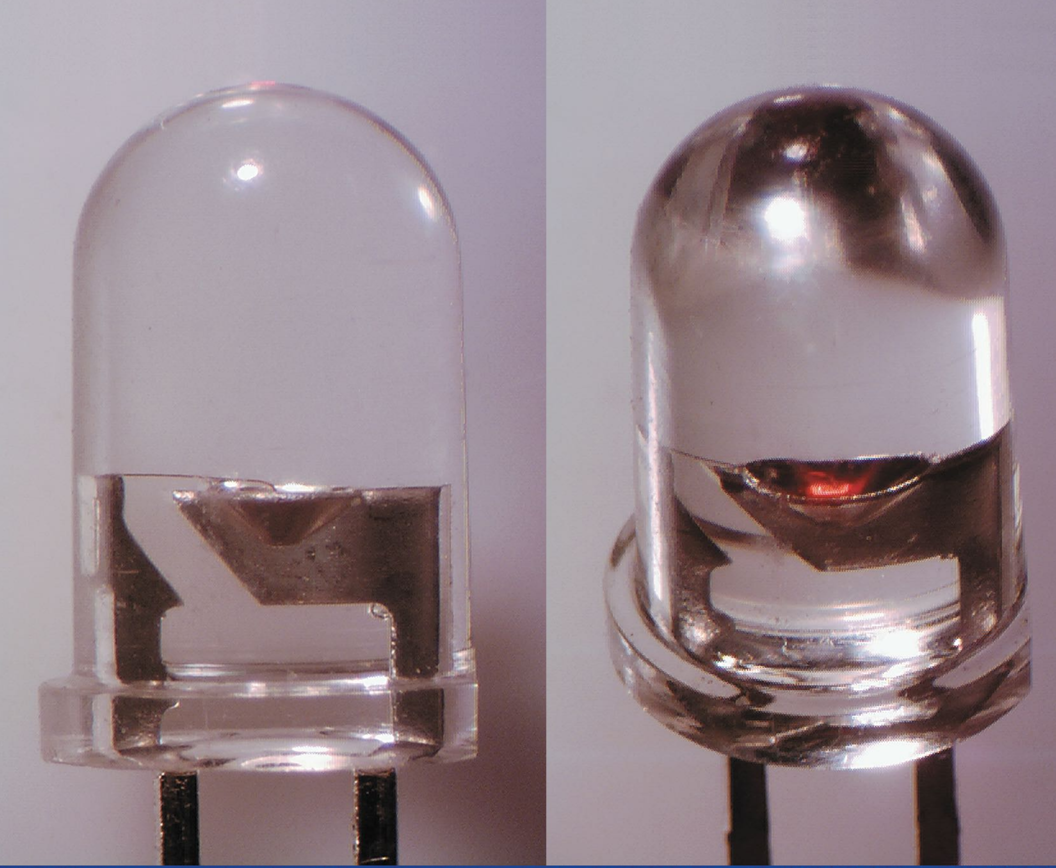


Let's move a thousand times closer to the red traffic light so that we are about one meter from it.



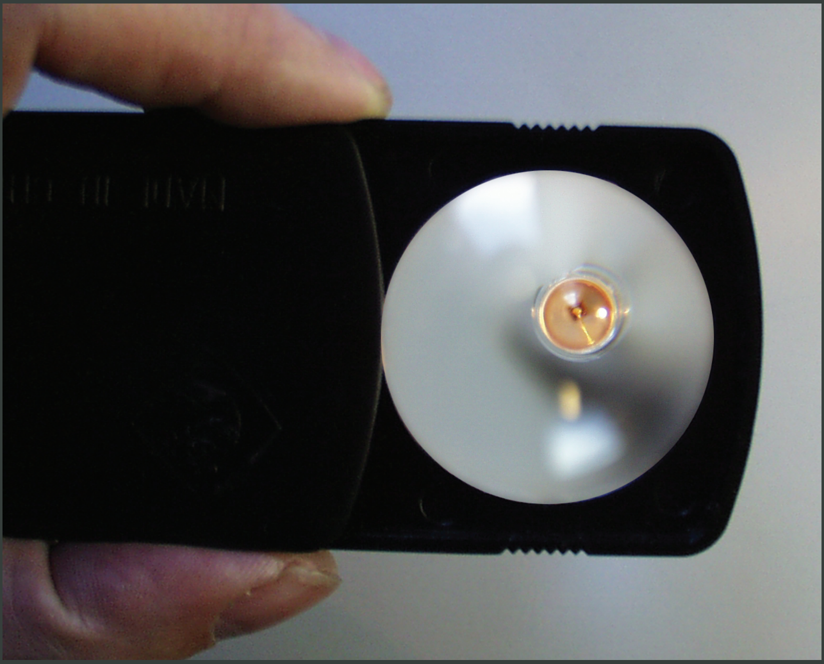
At a distance of 1 meter from the traffic light, we can see that the red light is made from nearly a thousand small sources of light, called light emitting diodes, or LEDs. These tiny light sources are made from semiconductors. They are replacing standard white incandescent lamps that have red filters. LED traffic lights require less energy than incandescent lamps and do not need to be replaced as often. They are also safer, because they can continue to operate even when some of the individual LEDs fail.

Moving yet another thousand times closer to the traffic light, to a distance of 1 millimeter, we can more clearly see an individual LED.

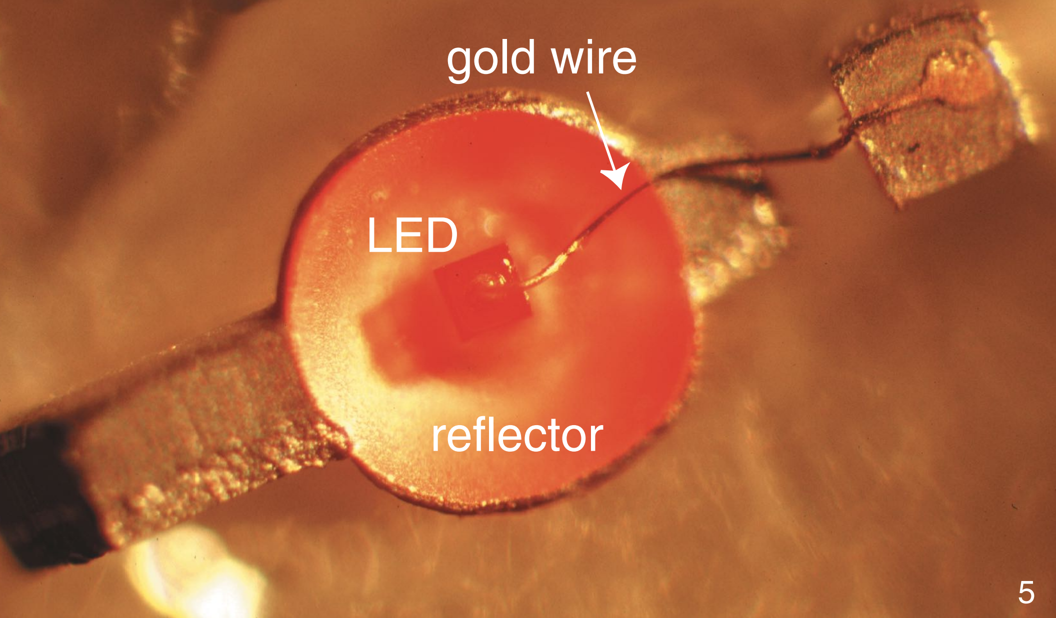


An LED and LED flashlight are included with this booklet. If you slide the switch on the flashlight, its LED will emit red light!

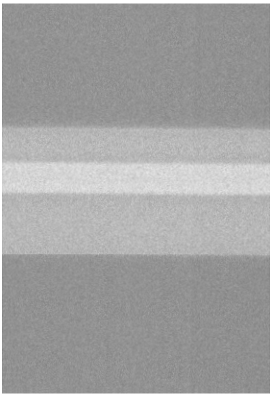
There is also a hand lens enclosed. If you examine the LED or LED flashlight with the hand lens, you should be able to observe a small square chip mounted in a shiny cup.



Viewed through a microscope, the LED is the square chip in the center of the image. It is less than half a millimeter on a side. A gold wire makes the electrical contact to the top of the chip.

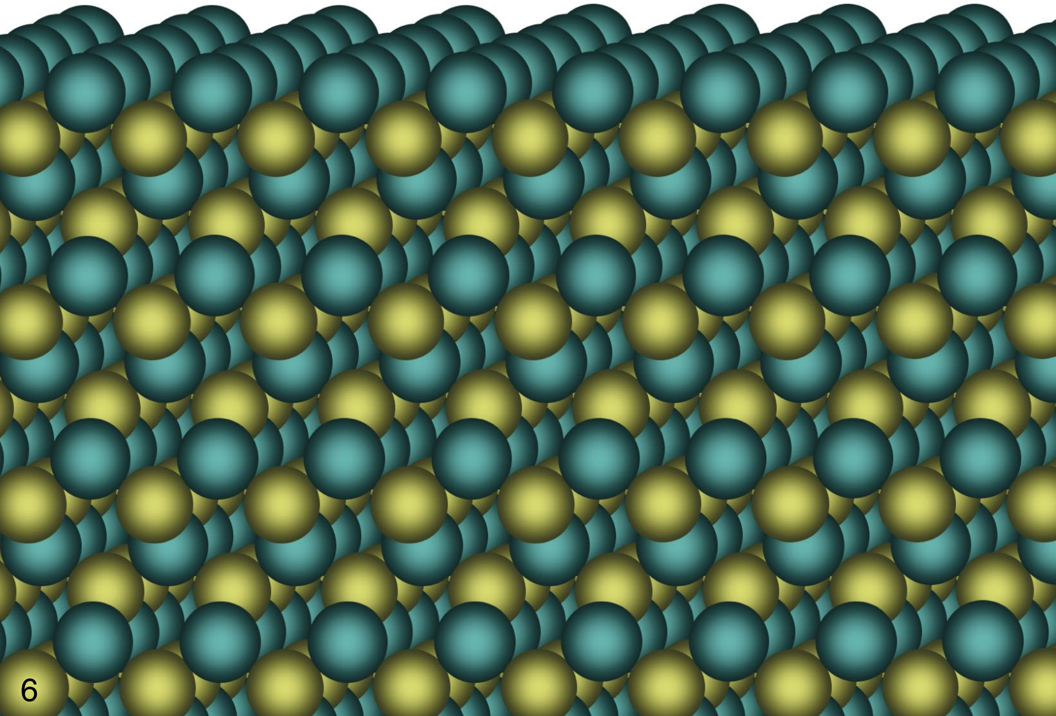


Moving another thousand times closer, to a distance of a one-millionth of a meter - 1 micrometer or 1 micron - allows us to view the construction of the LED chip itself.

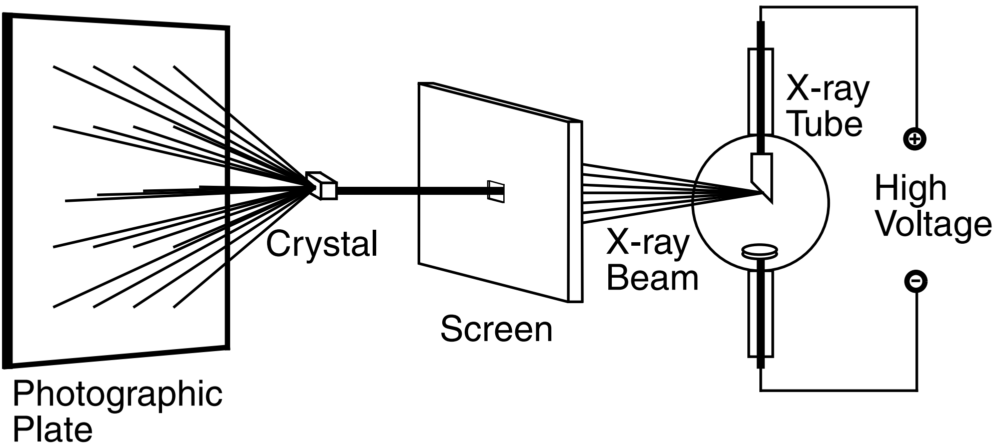


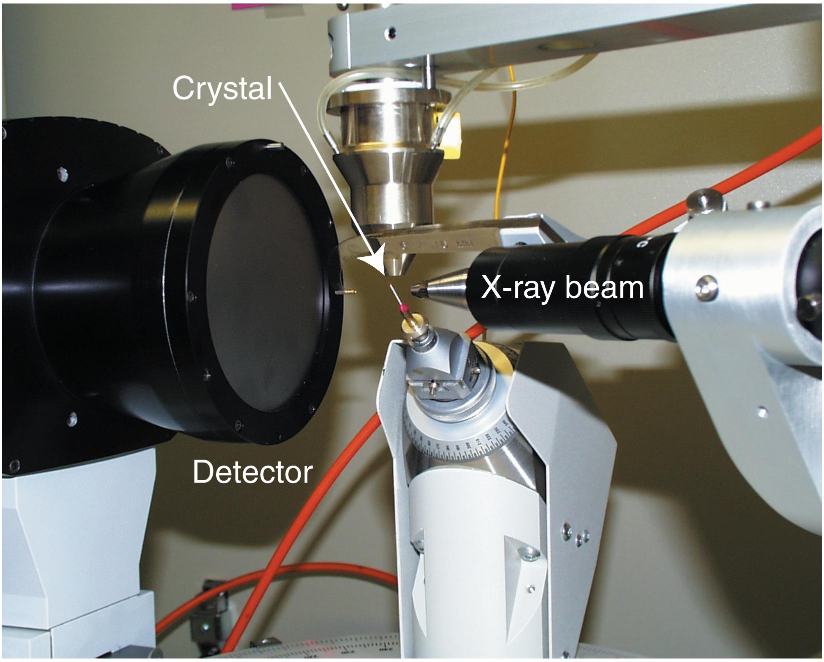
A special kind of microscope that uses electrons for imaging reveals that the chip is made up of layers, much like a sandwich. These layers are built from different combinations of atoms, a reflection of our ability to prepare materials virtually an atomic layer at a time. This exquisite control of the kind and number of atoms used to form the layers of the LED chip allows LEDs of any desired color to be made, like the red color of your LED. The kinds of atoms used to control the color of light emitted by an LED are discussed on page 27.

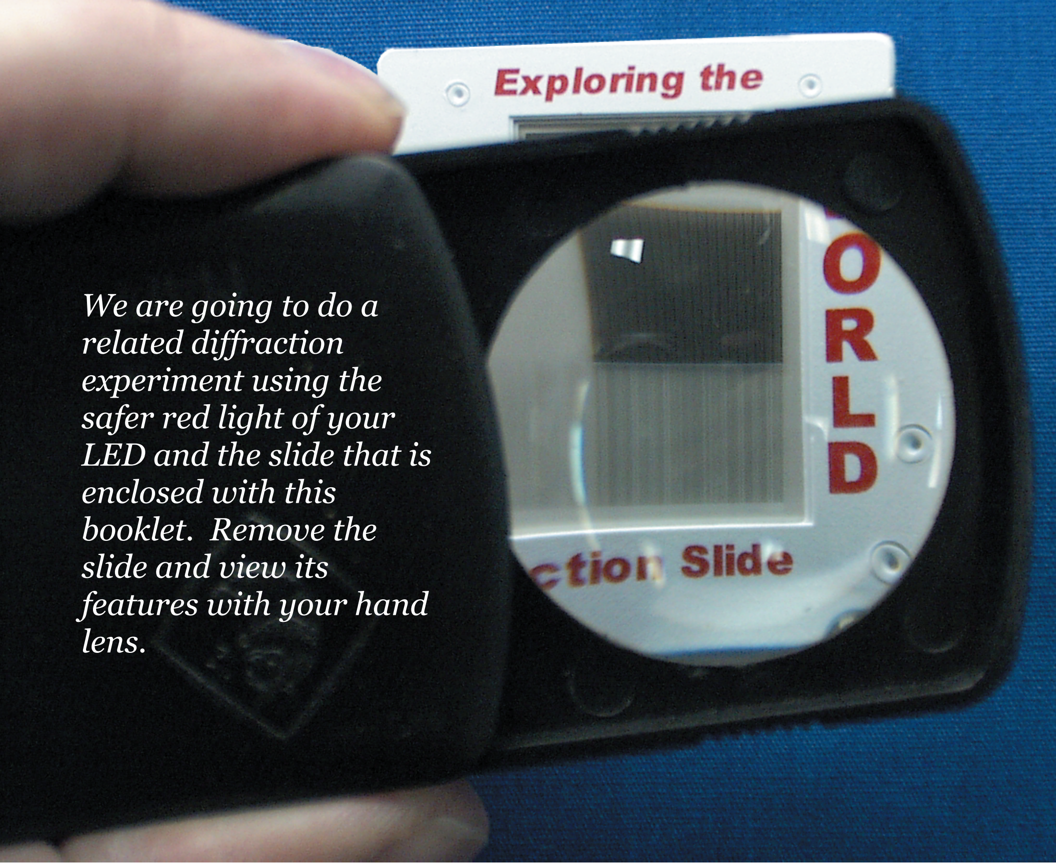
Moving finally a thousand times closer, to a distance of one-billionth of a meter, 1 nanometer, we have reached the nanoworld and a length that is roughly half-a-dozen atoms placed end to end. Each of the colored spheres below represents one of the two kinds of atoms in a common LED material, gallium arsenide (GaAs).



How do we see the arrangement of individual atoms in the nanoworld? Historically, we had only an indirect method for seeing the atoms of a solid like a semiconductor: By shining high energy light called X-rays onto the semiconductor, the light is scattered into diffraction patterns, and from these patterns the arrangement of atoms can be inferred.

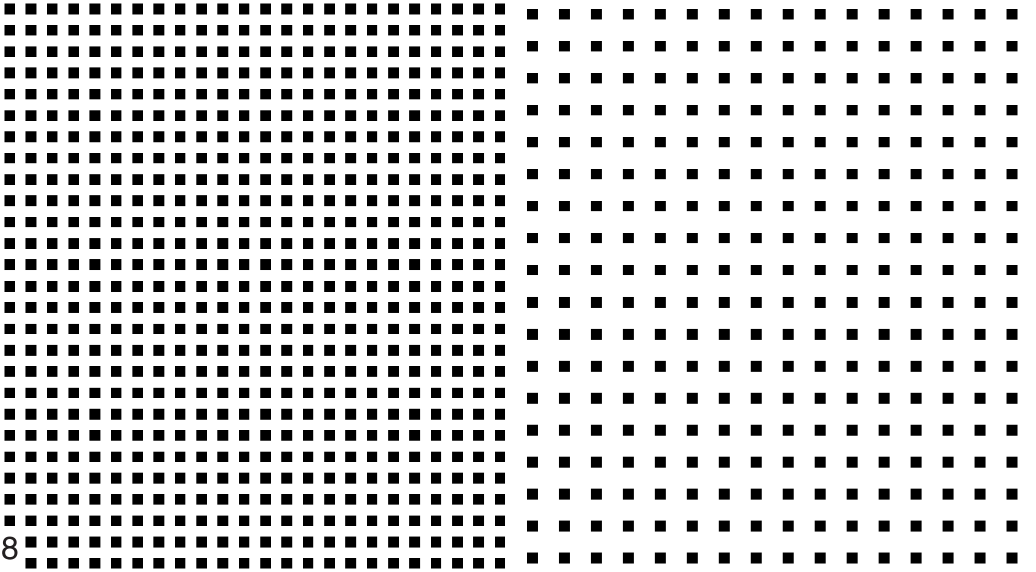




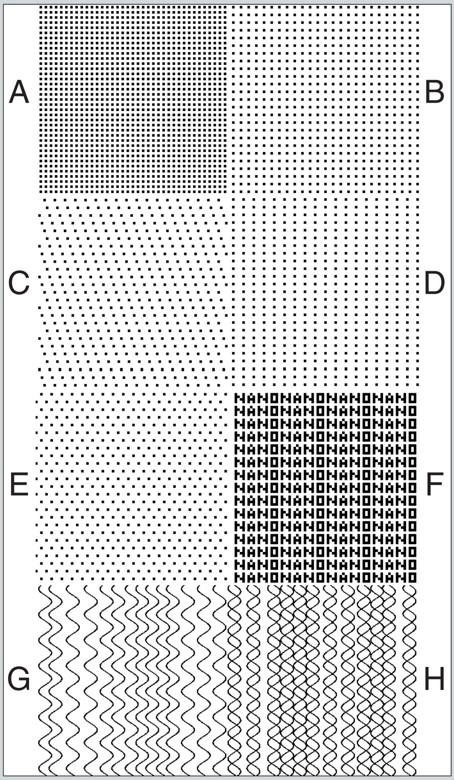


We are going to do a related diffraction experiment using the safer red light of your LED and the slide that is enclosed with this booklet. Remove the slide and view its features with your hand lens.

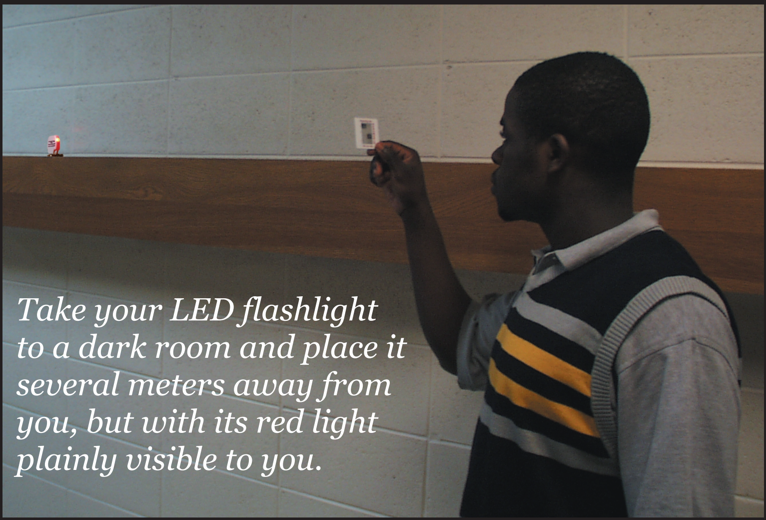
You should be able to recognize the eight arrays on the next page. Let's look first at the top two arrays, A and B, made up of square arrays of dots. In the nanoworld these dots would represent individual atoms.



Exploring the NANOWORLD

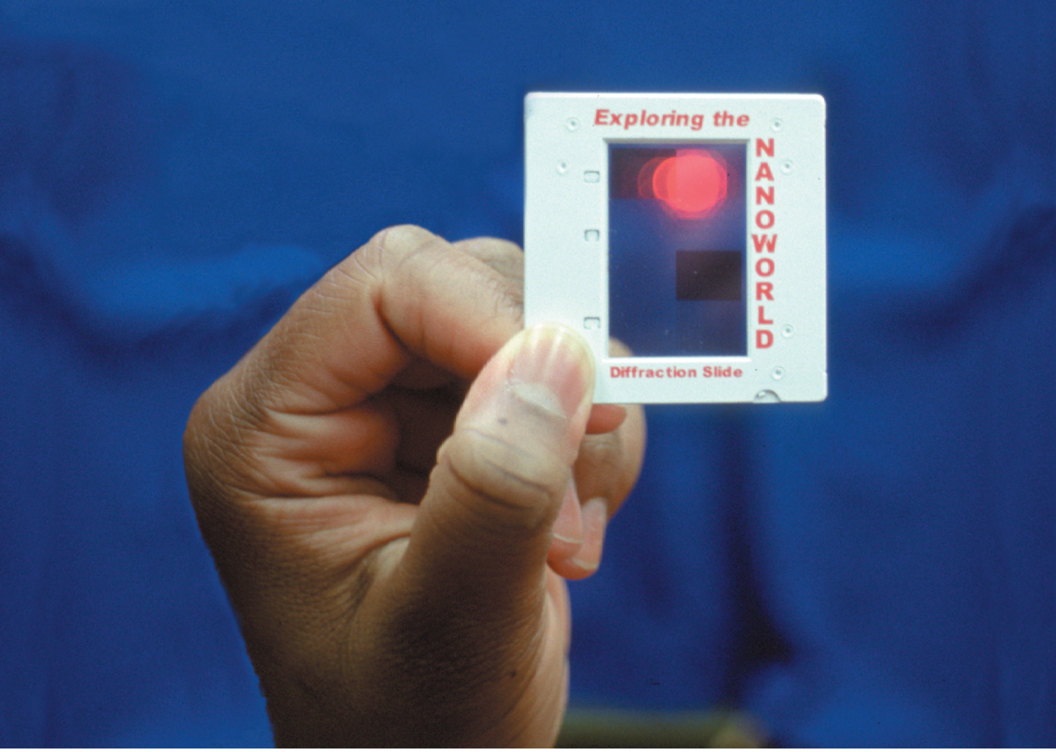


Diffraction Slide

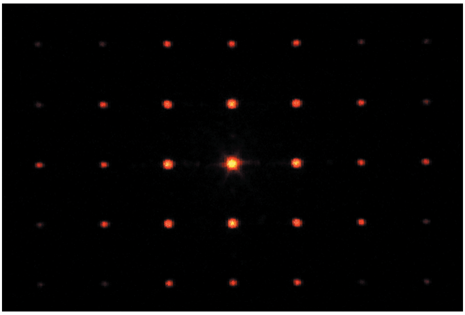


Take your LED flashlight to a dark room and place it several meters away from you, but with its red light plainly visible to you.

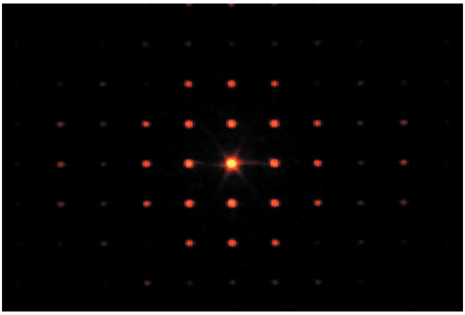
Holding your slide up to your eye, view the red LED from a distance of several meters through each of the top two arrays in turn and observe their diffraction patterns.



Comparing arrays A and B, you should see, surprisingly, that array A, having dots closer together, gives a diffraction pattern where the red diffraction spots are farther apart; and array B, having dots farther apart, gives a diffraction pattern with red spots closer together.

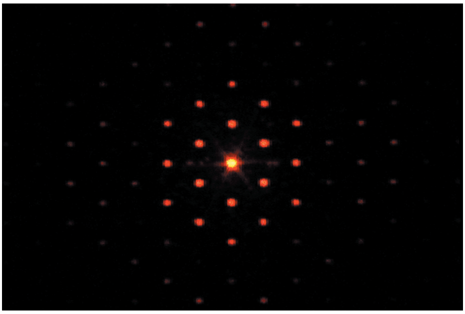


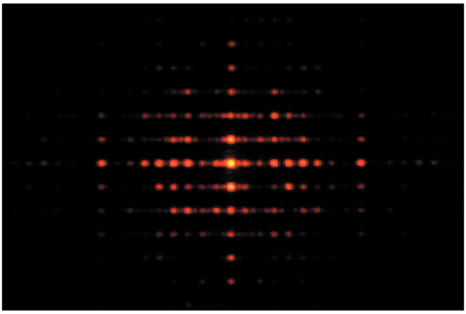
Diffraction from array A



Diffraction from array B

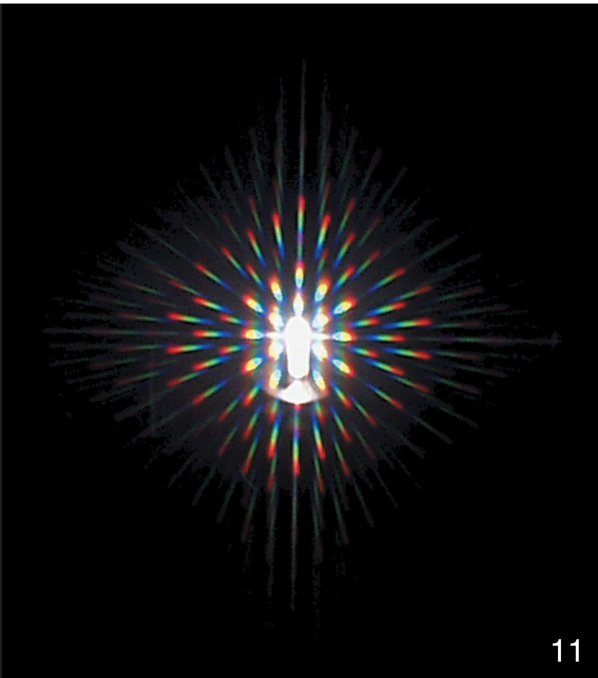
To see just how general this experiment can be, can you match the diffraction patterns below to their arrays on the slide?



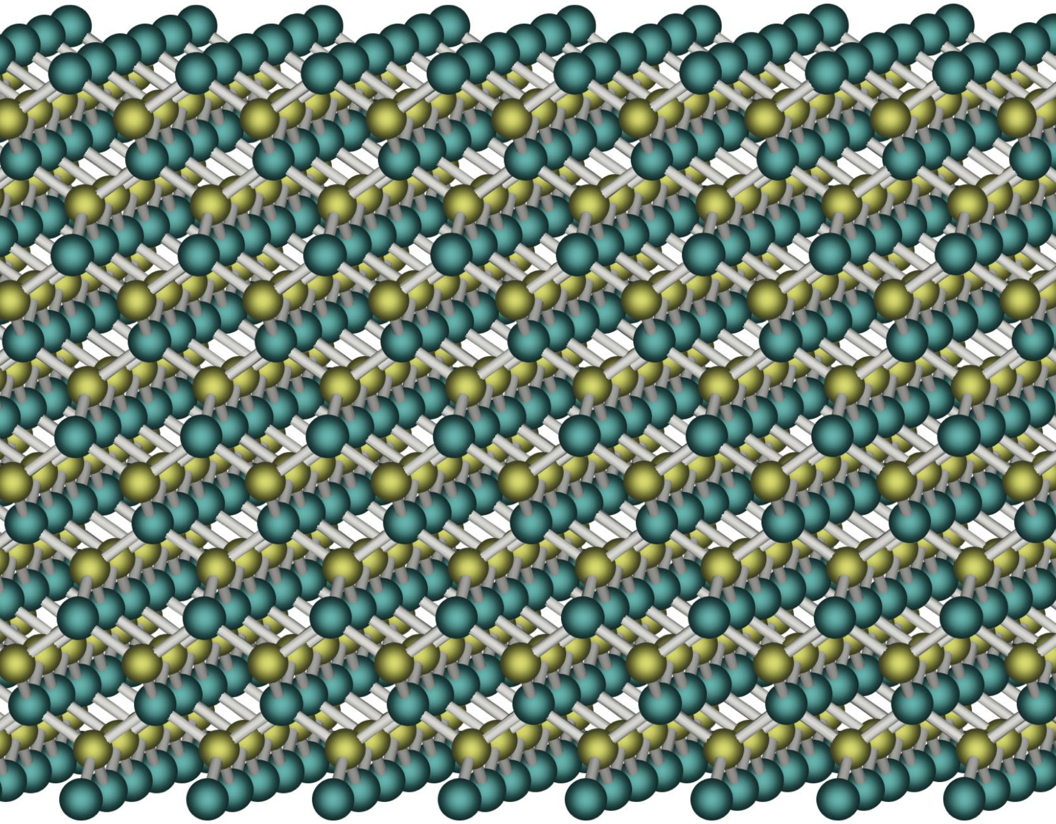


If you said that the diffraction pattern on the left comes from array E and the one on the right from array F, you are correct! *Using your hand lens, you can see that in array E each dot is surrounded by six others in a hexagon.* This is the arrangement of atoms in the gold wire of your LED and in other common metals like copper. *Use your hand lens to see that array F is constructed from the word "NANO" rather than dots*. This shows that any repeating arrangement of features can produce a characteristic diffraction pattern.

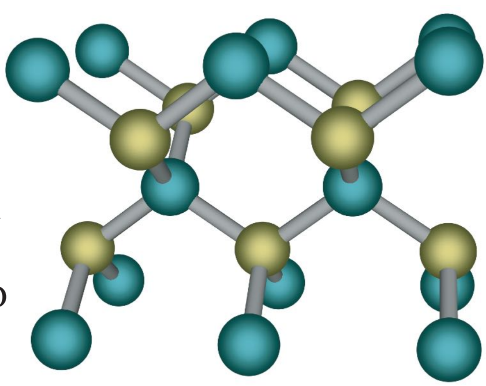
You can try looking through your slide at a distant white streetlight or flashlight to see each diffraction spot break spectacularly into a rainbow of colors, demonstrating that different colors affect the size of the diffraction pattern. Which color spreads out the most?



Diffraction experiments like these, conducted with X-rays, led to a model of how the atoms are arranged in semiconductors used to make LEDs. The model is shown below in an idealized way, with balls representing atoms and sticks representing the electrons that hold the atoms together in the solid.

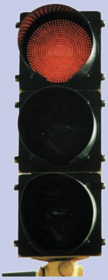


Because atoms are so very small there are a very large number (billions of billions of them) in your LED, and the illustration above shows only a minuscule fraction of them. Just as wallpaper can be represented by a portion of the pattern, the arrangement of atoms in an LED can be represented by a smaller repeating unit as shown at the right.



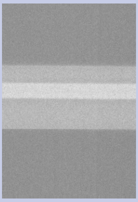
We have now reduced our length scale by a factor of a billion – from the close-up of the traffic light that we could experience on many street corners to the nanoscale that is everywhere!

kilometer
(1,000,000,000,000 nanometers)

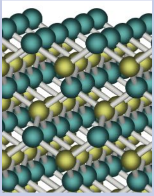


meter
(1,000,000,000 nanometers)

millimeter
(1,000,000 nanometers)



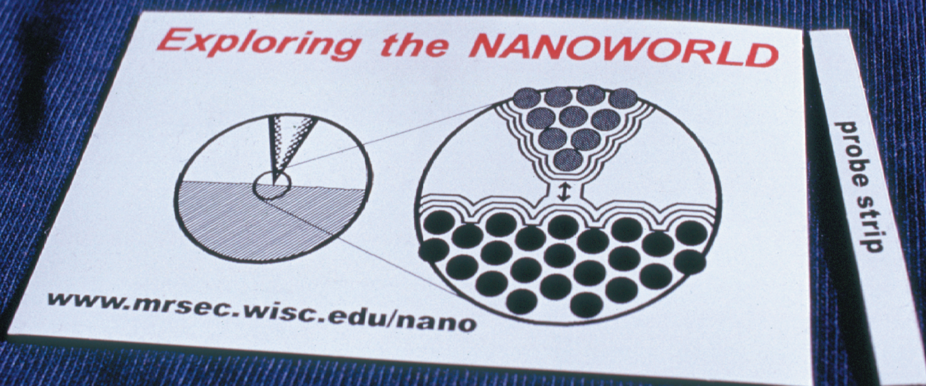
micrometer
(1000 nanometers)



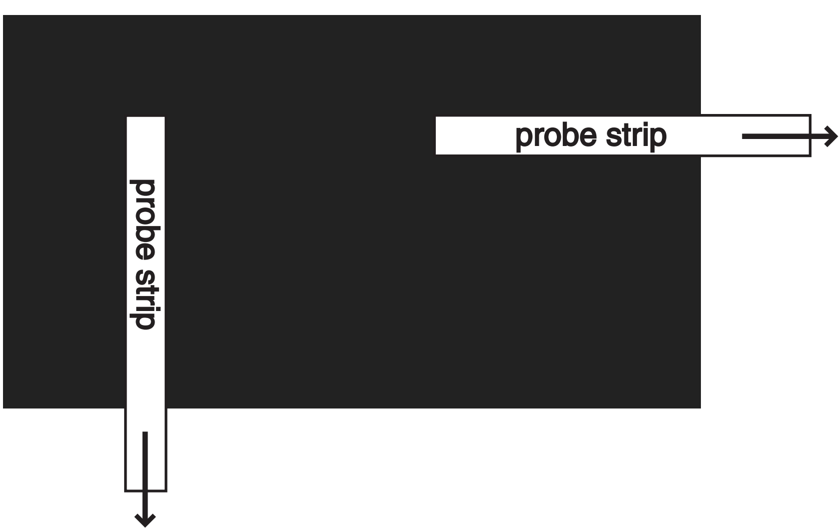
nanometer

Today we can directly "see" the individual atoms that make up the nanoworld using methods called scanning probe microscopies. One common method for "seeing" atoms on a surface is to drag a probe tip carefully across the surface.

To demonstrate how such an experiment works, remove the refrigerator magnet that comes with this booklet. Note that the magnet has been partially cut on its right-hand side, enabling the right-hand strip – labeled the "probe strip" – to be ripped off, as shown. Once the probe strip has been removed, you are ready to conduct the experiment.

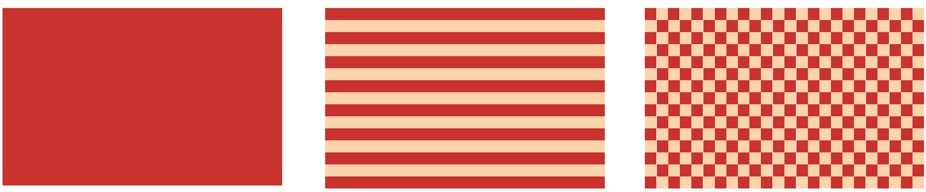


First, turn the refrigerator magnet over so its unprinted, dark side is up. Now try dragging the probe strip (with its unprinted side facing the unprinted side of the refrigerator magnet) in the two perpendicular directions shown and note what you feel and hear.



You may recall that magnets have a north and south pole and that the north pole of one magnet will attract the south pole of another; in contrast, two magnets with either their north poles or their south poles pointed at one another will repel.

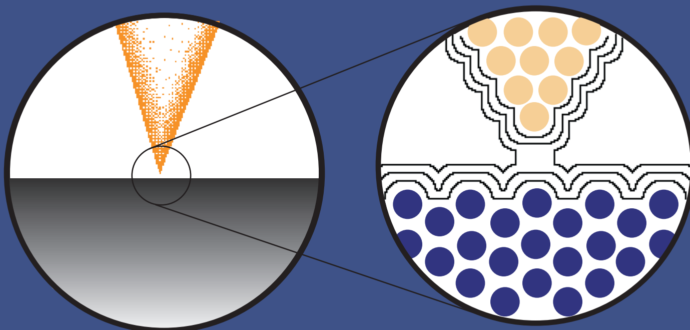
Knowing this characteristic of magnets, can you tell by what you feel and hear which of the three arrangements of magnetic poles below is present on the unprinted side of your refrigerator magnet?



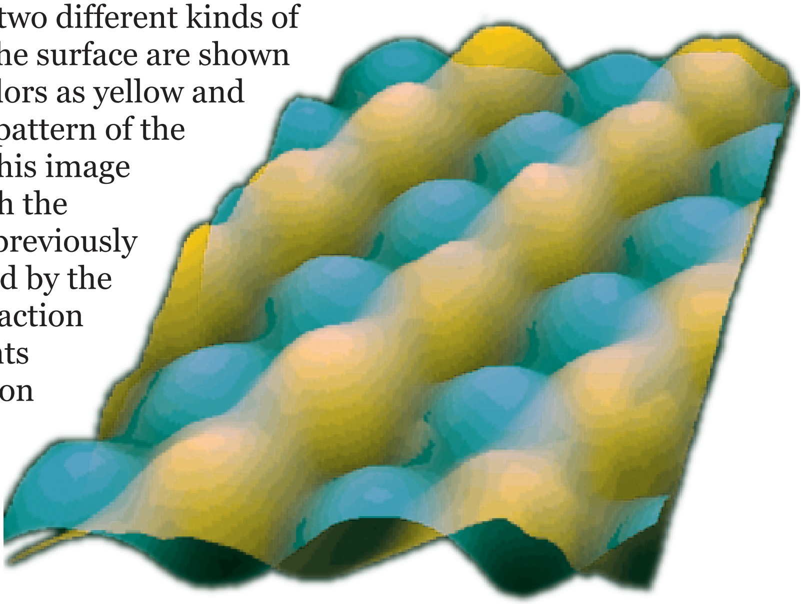
In the left pattern there is only one orientation of the magnetic field, and the probe strip would experience the same force in any of the directions in which it is dragged. In the center pattern the magnetic field is in stripes, with the probe tip experiencing alternating north poles and south poles as it is scanned in one direction but not in the other direction. In the right pattern, the magnetic poles are in a checkerboard arrangement, and the probe strip will experience alternating poles when scanned in either of the directions shown.

If you picked the middle choice, you are correct! You have successfully conducted a force imaging experiment.

Imagine now making a probe tip that is so sharp that it ends in just a single atom. When such a probe tip is scanned across a surface in atom-sized movements, there will be differences in force felt by the probe tip as it is closer to or farther away from surface atoms. In the cartoon below, the left-hand diagram illustrates the probe tip near what looks like a smooth surface. The right-hand diagram expands this tip-to-surface view to highlight the atoms in the tip (pale circles) and the surface (dark circles) and reveals that on the atomic scale, the nanoscale, the surface is bumpy. When the tip moves along the surface, the force it experiences (represented by the wavy lines) will vary and can be used to make a map that identifies the arrangement of the surface atoms.

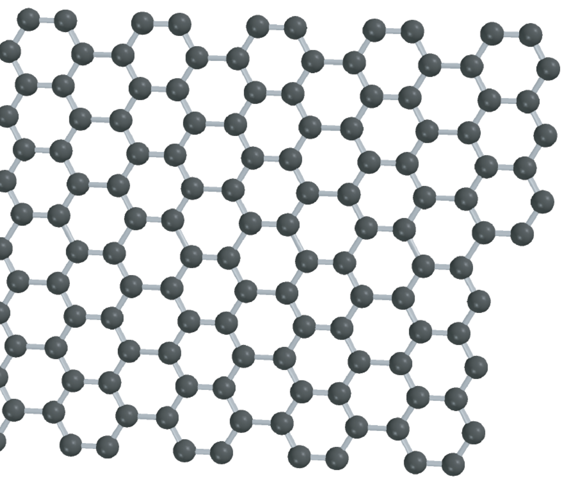


When related experiments were conducted on the surface of a semiconductor used to make LED chips, two types of atoms were seen. The two different kinds of atoms at the surface are shown in false colors as yellow and blue. The pattern of the atoms in this image agrees with the structure previously determined by the x-ray diffraction experiments described on page 12.

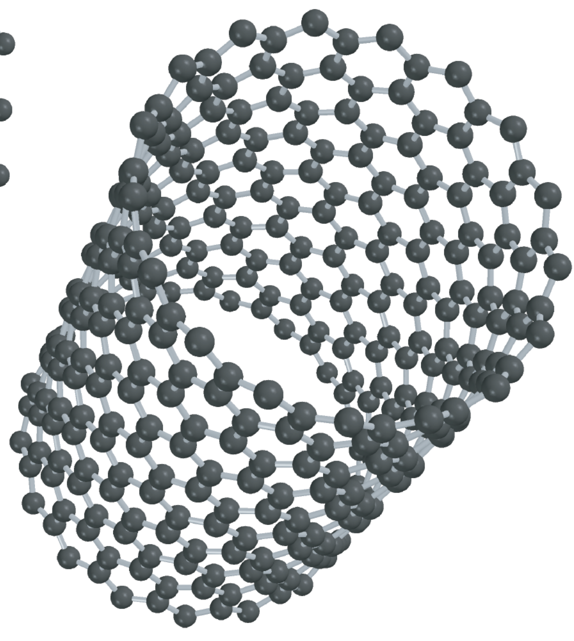


The atom-sized tips used in scanning probe microscopy can not only be used to image atoms, but under certain conditions they even let us pick them up and put them down at desired locations, enabling us to shape the nanoworld!

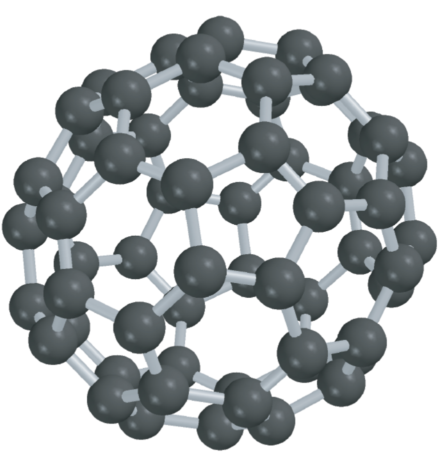
As we enter this era of nano-architecture, probe tips made of carbon atoms are increasingly being used. Carbon has a natural ability to form hexagons, as in sheets of graphite. Another form of carbon uses 60 atoms arranged in hexagons and pentagons to make a soccer ball-shaped molecule called "buckyball" after the architect Buckminster Fuller. It is also possible to make tubes from the carbon atoms, which can be thought of as rolled-up sheets of graphite. These carbon nanotubes can serve as probe tips and as nano-tweezers to position individual atoms or groups of atoms.



A graphite sheet



A carbon nanotube

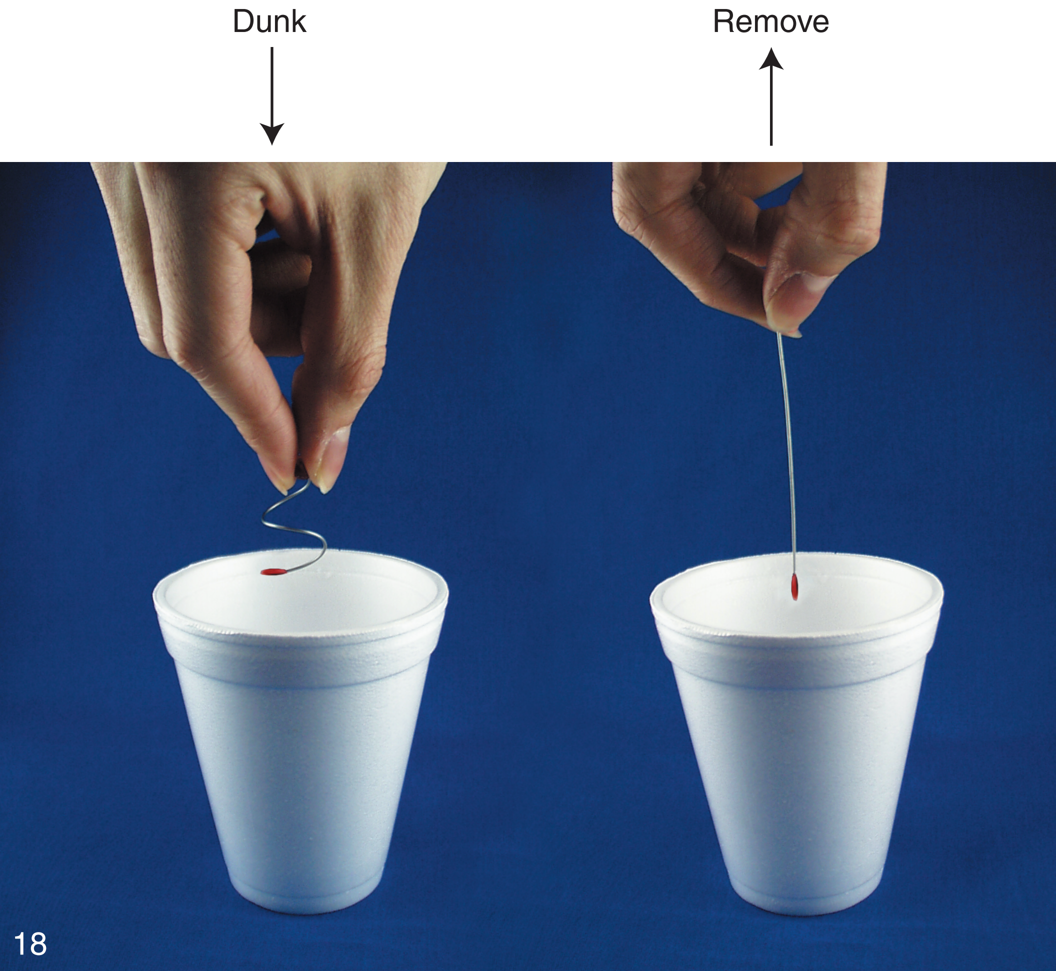


A buckyball with 60 carbon atoms

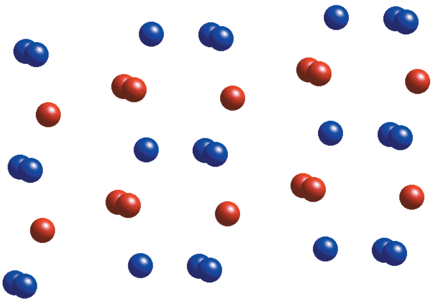
With our emerging ability to assemble atoms, what structures would we want to make for the nanoworld? How about "smart materials," that respond in a predictable way to some change in their environment, like a change in temperature?

An example of such a material is "memory metal," which is a combination of nickel and titanium atoms.

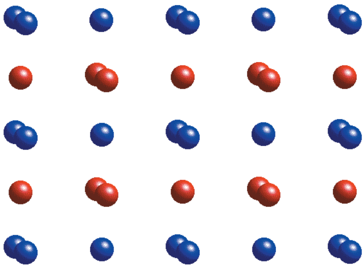
To demonstrate how this smart material works, take the enclosed wire strip and bend it gently. (The plastic at the ends of the wire cover its sharp ends.) Then, holding one end VERY FIRMLY, dip the bent portion of the wire into a cup of very hot water. Watch the wire jump to its original, linear shape and beware of splashing hot water!



The origin of this remarkable effect is a subtle atomic ballet, in which atoms in the metal use the energy from the hot water to change their positions. The subtlety of the shifts is represented below by the different arrangements of the nickel atoms (blue) and titanium atoms (red) that occur when your metal strip is at room temperature (left picture) and heated (right picture).



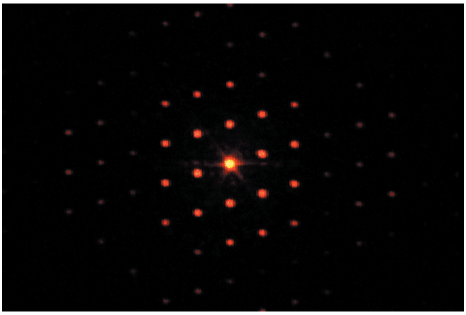
cold



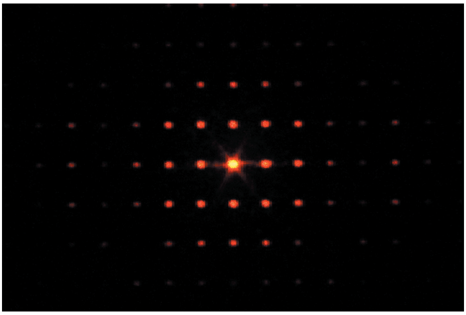
hot

How do we know that the atoms move? Diffraction experiments tell us the atoms move on the nanoscale and that the atomic structure changes.

You can get a feel for how the diffraction patterns differ by examining arrays C and D on the slide, which represent idealized room temperature and heated arrangements of atoms, respectively. If you now look at your red LED alternately through arrays C and D, you can watch the diffraction patterns change back and forth.

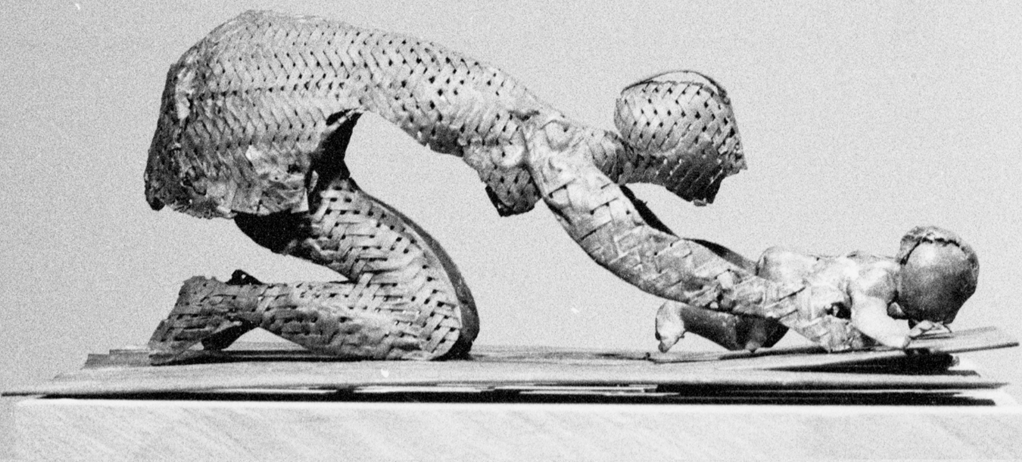


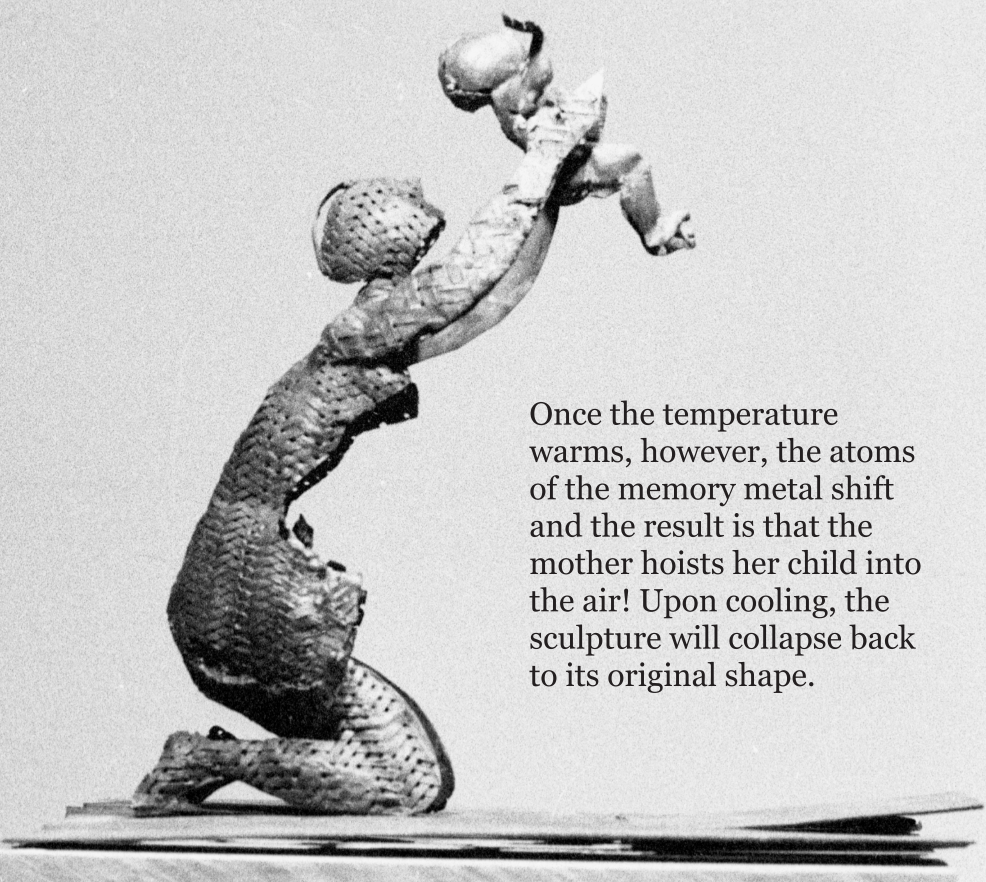
Diffraction from array C



Diffraction from array D

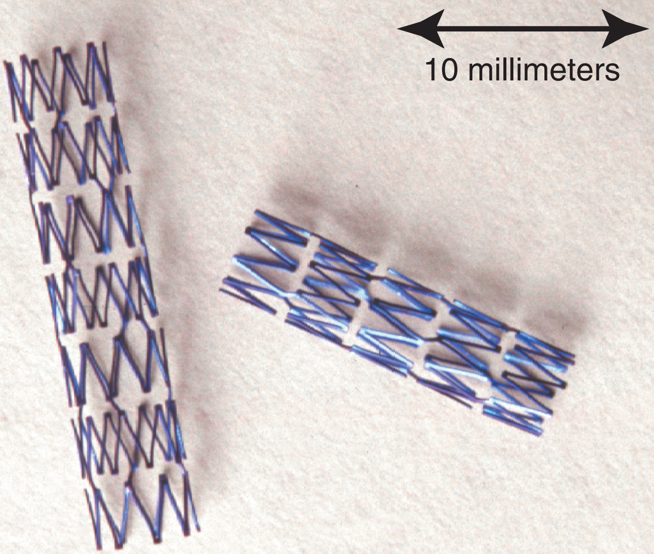
Smart materials are already used in a variety of interesting ways. Sculptures have been made with memory metal, for example. As the illustration shows, in cold temperatures the mother and her child are bent over.





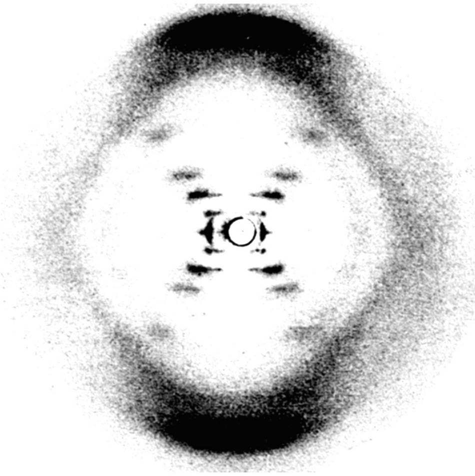
Once the temperature warms, however, the atoms of the memory metal shift and the result is that the mother hoists her child into the air! Upon cooling, the sculpture will collapse back to its original shape.

Because this type of memory metal is biocompatible, it can be used in surgical stents, shown below, to keep blood vessels open. It can also be used in the archwires of orthodontic braces to exert uniform pressure on teeth. Eyeglass frames that spring back to shape are another commercial use of the metal.



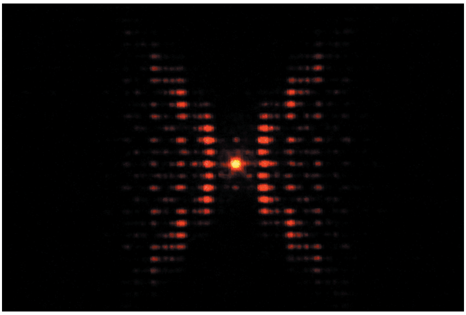
What other uses can you think of for memory metal?
An intriguing idea is to make nanoscale components out of memory metal: damage could be reversed simply by heating!

For nanoworld examples that may lead to breakthroughs in medicine, let's think about DNA, the "stuff of life". DNA is a long stringy molecule. Determination of the architecture of DNA as two intertwined chains of atoms, called a double helix, was accomplished by X-ray diffraction experiments in the 1950s. The original diffraction pattern determined by Rosalind Franklin is shown here.

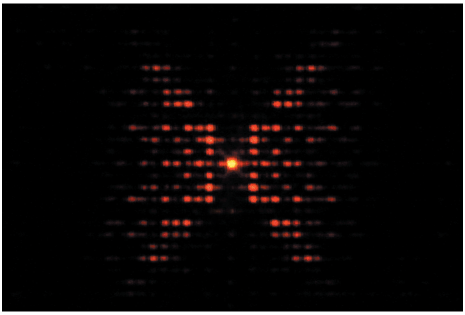


You can see some of the key features of this diffraction pattern using arrays G and H on your slide. Note that array G is a wavy line, representing only one of the chains of atoms of DNA; and that array H is a pair of intertwined wavy lines, representing the double helix.

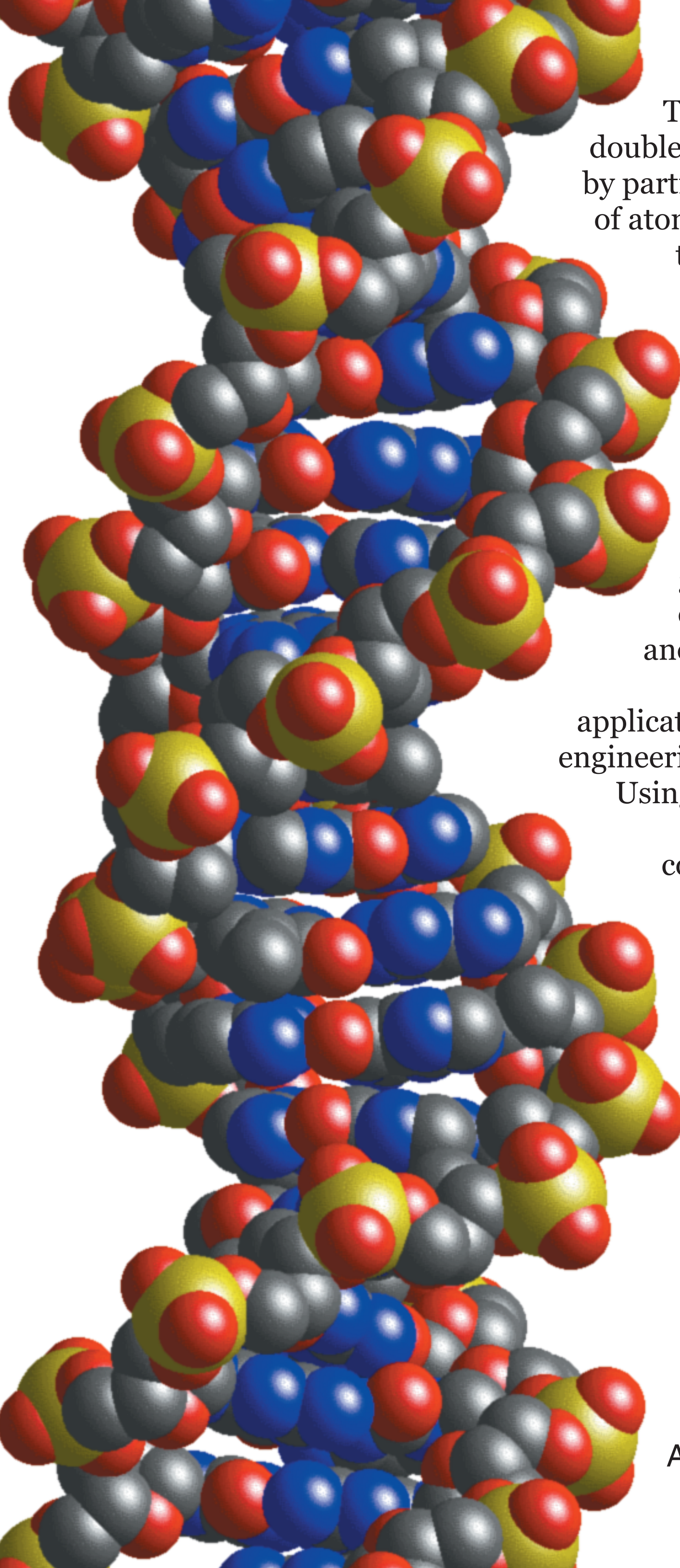
If you view the red LED flashlight, as you have done previously, you can see how the double helix can be identified from the difference in the diffraction patterns of arrays G and H.



Diffraction from array G



Diffraction from array H



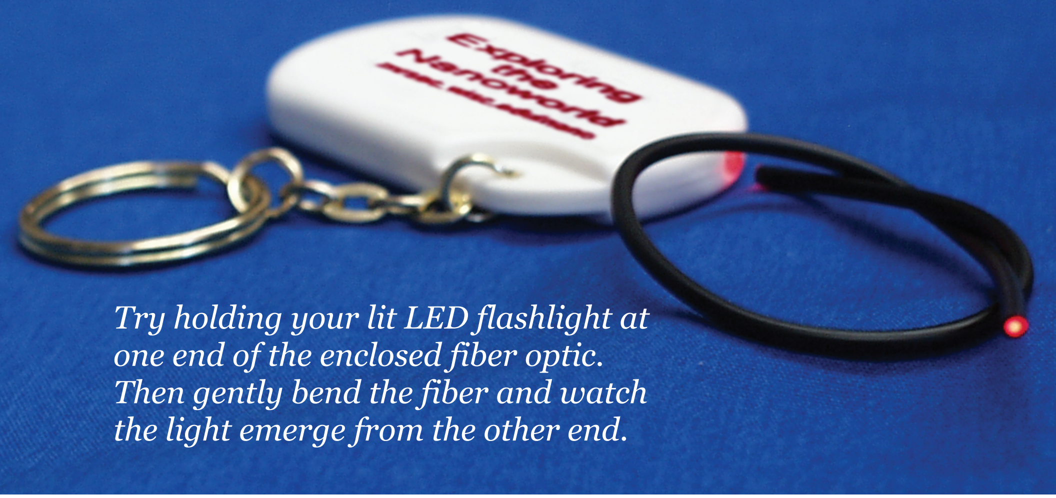
The two chains of the double helix are connected by particular arrangements of atoms. The sequence of these connections in fact is responsible for our individual features and how they are inherited across family generations. Our developing ability to "pick and place" groups of atoms will enable us to prepare and modify nano-sized regions of DNA for applications such as genetic engineering and drug design. Using this technology we may even be able to construct DNA-based computers.

A DNA molecule

To continue our story, let's return to the LEDs. These and related devices have already found applications in transportation, communication, and displays. Some examples from transportation beyond the traffic light include brake lights and turn signals (page 24), car speed indicators (page 25), and warning signs (page 30).


SPEED
LIMIT
35
38
YOUR SPEED

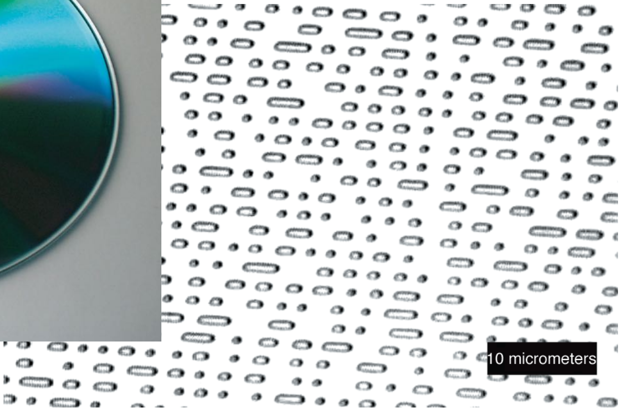
The construction of LEDs can be altered to produce diode lasers. These are commonly used as laser pointers, but they can also be used to transmit information. By combining light from a diode laser with a fiber optic, a kind of pipeline for efficiently transmitting light, information can be sent over long distances.



Try holding your lit LED flashlight at one end of the enclosed fiber optic. Then gently bend the fiber and watch the light emerge from the other end.

Diode lasers are also used to read compact disks for music and computer data storage.

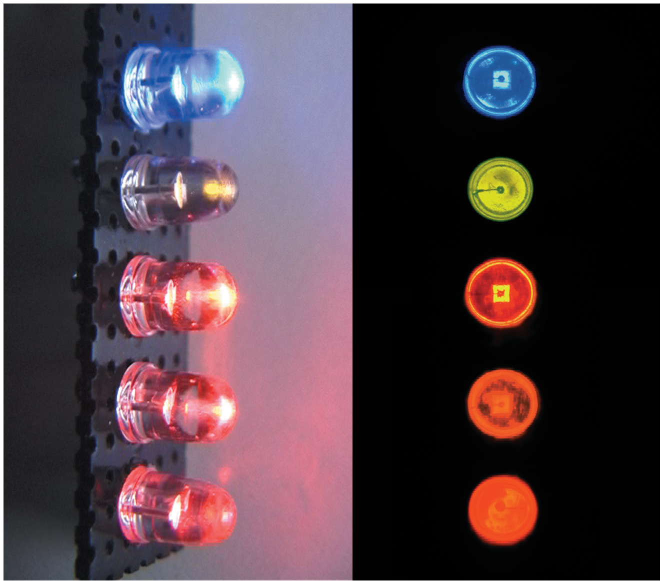
Pits on a CD store data in digital format.



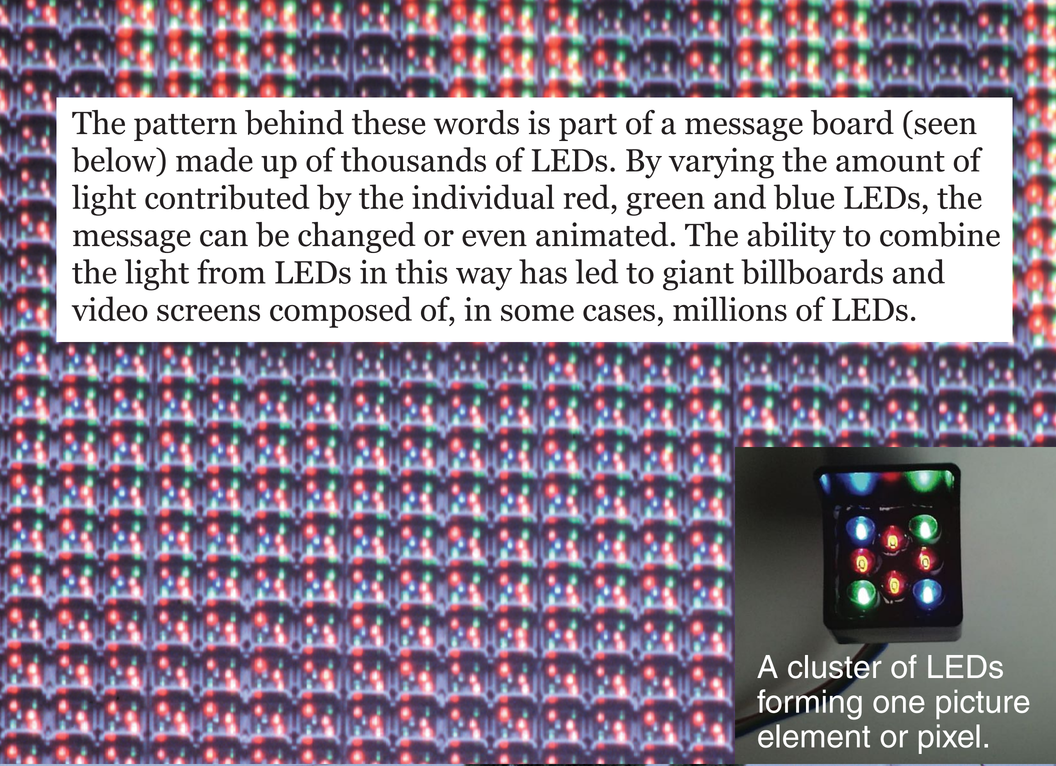
Use the diffraction slide to look at a far-away white light source (as on page 11). Which color spreads out least? Blue laser light will be able to read smaller features than the red laser light used now, so such CDs could contain more data or music.

LEDs made from GaP and GaAs have been available for many years and will produce red, orange, yellow, and green light. The recent invention of GaN LEDs that produce blue light now makes it possible to create a full range of colors.

	C	N
Al	Si	P
Ga	Ge	As
In		



Television and computer monitors combine red, green and blue light to create all of the other colors of visible light. For example, red and green combine to make yellow; and red, green, and blue combine to make white. *Try looking at a TV screen or computer monitor with the enclosed hand lens to see if you can identify these color combinations.*



The pattern behind these words is part of a message board (seen below) made up of thousands of LEDs. By varying the amount of light contributed by the individual red, green and blue LEDs, the message can be changed or even animated. The ability to combine the light from LEDs in this way has led to giant billboards and video screens composed of, in some cases, millions of LEDs.

A cluster of LEDs forming one picture element or pixel.

This arrangement of red LEDs is designed to screw into a standard light bulb socket. White LEDs may lead to partial or complete replacement of traditional incandescent and fluorescent lighting in the workplace and home.

The key to all of these breathtaking technological developments is our ability to image and manipulate the brave new nanoworld. The future looks bright and small!

A Field Guide to the Nanoworld

Can you find these in your neighborhood?

__LED traffic light (red)
__LED traffic light (yellow)
__LED traffic light (green)

__LED indicator light
__LED flashlight
__LED-containing toy
__LED-containing shoes

__Memory metal eyeglass frames
__Memory metal orthodontic braces
__Memory metal shower head

__Graphite
__A sphere made of pentagons and hexagons
__Geodesic dome

__LED taillight (car)
__LED taillight (bus)
__LED taillight (truck)

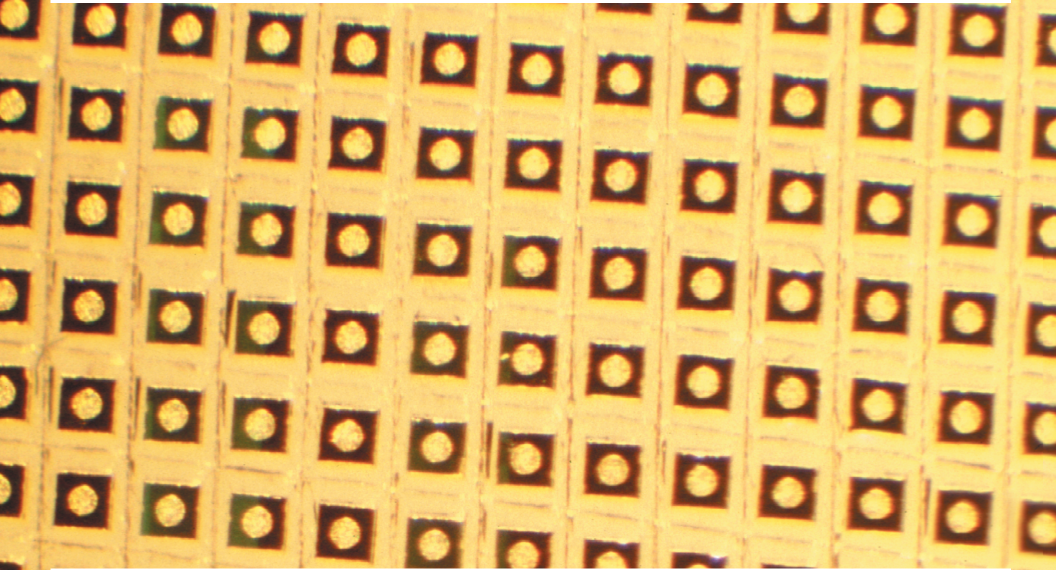
__LED bicycle light
__LED exit sign
__LED message board
__LED large array display

__Solid-state laser pointer
__Compact disk player

__DNA sculpture

__A newspaper or magazine article about the nanoworld

The magnified image in the background shows a manufactured wafer containing thousands of LEDs. An electrical contact will be made to the circle in the center of each LED (see page 5).



Some Additional Resources

- The web address on your refrigerator magnet: http://mrsec.wisc.edu/nano
- *On the Surface of Things: Images of the Extraordinary in Science* by Felice Frankel and George M. Whitesides; San Francisco: Chronicle Books, 1997.
- *From Light to Life* Videotape by Amand Lucas http://www.scf.fundp.ac.be/~alucas/DNA/dna.html
- *A Drop of Water* by Walter Wick; New York: Scholastic Press, 1997.
- *Nanotechnology: Shaping the World Atom by Atom*, by I. Amato; National Science and Technology Council, 1999 http://itri.loyola.edu/nano/IWGN.Public.Brochure

Contact Information

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Nanoworld adventures await inside! Explore how we can accomplish the feats of "seeing" atoms, assembling them into a variety of novel structures, and customizing their properties to develop new technologies.

This activity kit contains a color booklet and the supplies you need to do many experiments:

- **a light emitting diode and flashlight**
- **magnifying glass**
- **diffraction slide**
- **magnet**
- **memory metal**
- **fiber optic**

A product of the Materials Research Science and Engineering Center at the University of Wisconsin-Madison, established by the National Science Foundation to carry out research in the formation, characterization, and exploitation of materials at the nanoscale–the scale of individual atoms. Our goal is the fundamental understanding of topics of substantial technological importance, and the communication of this understanding to the public.