Polarization
of Light

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1.0 Introduction

Although most of man's information about his environment normally comes to him through his sense of vision, the study of light is often neglected in basic science courses. This situation is perhaps due to the lack of suitable equipment and text material. The Leica Table Top Polarization Demonstrator and this companion booklet are designed to introduce teachers and students to a special, but extremely interesting, aspect of light — that of polarization.

A knowledge of polarization contributes to a fuller understanding of the theory of light in general. It helps to correct overemphasis on the geometrical treatment of light and is thus useful in educational science programs. The phenomena associated with polarization are both easy to demonstrate and beautiful to observe. In addition to its academic value, a study of polarization explains many practical applications which are being developed to use polarized light.

This booklet consists of three parts: 1) a brief review of the major theories of light; 2) a discussion of the basic phenomena of polarized light, with suggestions for class demonstrations; 3) further experiments for individual pupil use. The demonstrations and experiments are based on the equipment found in the Polarization Demonstrator.

2.0 Theories of Light

One of the earliest attempts to account for the process of vision involved the supposition that one's eyes emit invisible streamers. When these streamers reached an object, they transmitted the sensation back to the viewer who then "saw" the object. This naive explanation has been replaced by several concepts which are still current.

2.1 The Corpuscular Theory

Whenever we conceive of light as traveling in a straight-line motion, we are supposing that it behaves like a stream of small particles moving in straight lines as do the balls on a billiard table. The old name given to these supposed particles was "corpuscles." Now we speak of the assumed light particles as "photons."

This concept is useful describing many optical phenomena. We use it in showing the reflection of light from a mirror (figure 1), or in the focusing of light by lenses, for example. The light is represented by rays, which are ideal straight lines. It should be emphasized that this treatment is purely descriptive, not explanatory. Geometrical constructions show only what happens, not why the event occurs.

The corpuscular theory is inapplicable to the processes involved in the polarization of light. In its modern or
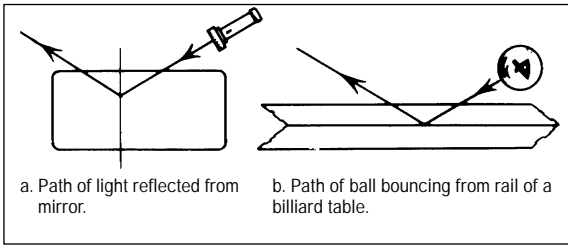
a. Path of light reflected from mirror.   b. Path of ball bouncing from rail of a billiard table.

Figure 1. Corpuscular Theory. List may behave as if it consisted of particles.

"photon" form, it does, however, provide an explanation for the events that occur when energy changes are produced as the result of light absorption by some object. For example, photoelectricity such as that in the exposure meters used by photographers can be explained only by assuming that a beam of light consists of indivisible particles. These bombard the sensitive surface of the meter, causing it to eject electrons which comprise a weak, but measurable, electrical current. The changes which occur when a photographic film is exposed in a camera are also best explained by the corpuscular theory.

2.2 Huygens' Wave Hypothesis

This concept, evolved by the 17th Century Dutch scientist Christian Huygens, supposes that light behaves as sound does — that it is a wave motion carried by some medium. We think of a sounding object, a bell for example, as producing spherical shells of disturbance in the surrounding air. These shells rapidly expand and are

succeeded by further spheres of disturbance as the sound continues. Using this analogy, we may think of a light source as producing similar swelling spherical waves (figure 2).

Huygens' theory is useful in explaining the refraction which occurs whenever light passes from one medium to another. The observed change in the direction of light beam, which is associated with refraction in general, is best understood by explaining it as a change in the speed of the wave. That part of the front of the wave shell, which enters the new medium, is the first to change in velocity. Hence, the whole front takes up a new direction. In this situation, Huygens' wave hypothesis is superior to the corpuscular theory.

The wave hypothesis is, however, inadequate as an explanation for many of the facts of light behavior, including

a. Longitudinal waves produced by a sounding bell. Arrows indicate motion of the medium carrying the waves.

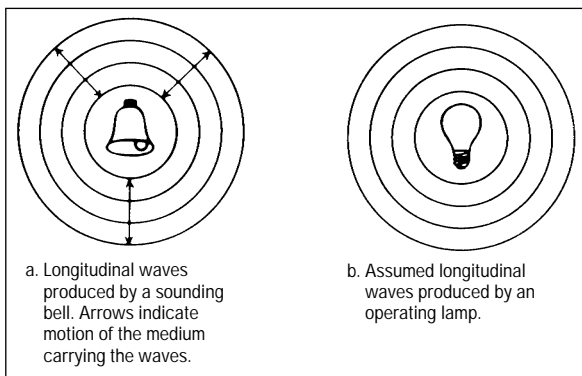b. Assumed longitudinal waves produced by an operating lamp.

Figure 2. Huygens' Wave Hypothesis. Light may behave as if it consisted of spherical longitudinal waves.

those of polarization. This inadequacy is associated with the behavior of the medium carrying the wave-like disturbances. In sound waves, the air particles vibrate in a direction parallel with the direction in which the wave is moving. Such waves are called "longitudinal." Polarization of light, we shall see, can be explained only by supposing that light waves behave differently from those of sound in this respect.

2.3 Transverse Wave Theory

This theory likens light to water ripples. Seen from above, they are spreading, circular disturbances of the water surface, from the side, they are seen as waves in which the water moves in a direction approximately at right angles to the direction of the wave movement. The transverse wave theory conceives of light was similar to such ripples, with the added notion that for an ordinary horizontal light beam, the motion of the (hypothetical) medium may be vertical, horizontal or at any angle to these, as long as the motion crosses the direction of the light path perpendicular to it (figure 3).

A mechanical analogy to this theory may be found (demonstration 1) in the waves produced when a 6-8 foot length of laboratory rubber tubing is laid in approximately a straight line on the floor. When one end of the tubing is grasped and shaken in a random fashion — horizontally, vertically, and at other angles in between, a complex wave

motion can be seen to travel from the hand along the tubing until it disappears at the free end. If the far end of the tubing is fastened, reflected waves occur at that point, and return to the hand. This increases the complexity of the wave pattern.

Such complex waves are not to be found in water ripples. There the motion of the water is nearly always substantially vertical. It is difficult to visualize the behavior of the "medium" carrying the transverse waves of light. The phenomena of polarization strongly indicate that light waves must nevertheless have a transverse motion.

There was a period during which the nature of the medium carrying light waves was seriously considered. The

a. Water ripples from above.

b. Water ripples from side. Arrows show water motion.

c. Perspective view of light waves. Three of the infinitely large number of transverse motions are shown.
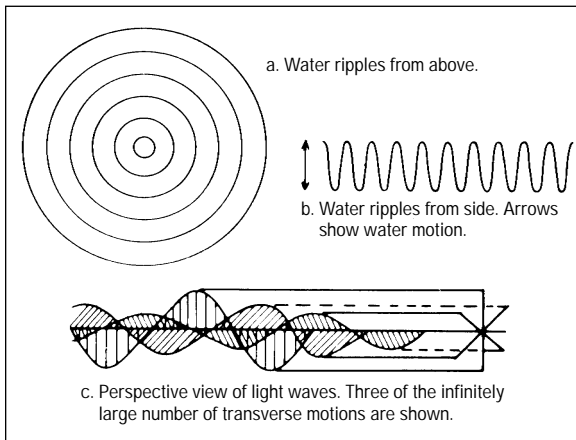
Figure 3. Transverse Wave Theory. Light may behave as if it consisted of a mixture of transverse waves similar to water ripples.

medium was first postulated and named the "aether." More recently, the conclusions of the famous Michelson-Morley experiment were taken as evidence that the postulated aether was non-existent. It was concluded that no medium was necessary to carry light waves. For a time, this seemed to contradict the wave theory of light. More recently still, Einstein's Theory of Relativity is held to indicate that there is no method by which we can determine the absolute velocity of the aether. Most physicists now believe that there is no possible way to test experimentally the existence or the non-existence of the aether. The questions has, in effect, been set aside until more fruitful questions are answered.

Light is now considered to have aspects similar to the electrical and magnetic "fields" in the space near a wire carrying an alternating electrical current. Hence light is grouped with other similar kinds of radiant energy in the "electro-magnetic spectrum." The reader is referred to any reasonably advanced text book in physics for a discussion of these matters.*

The transverse wave theory of light is particularly useful whenever questions of color arise. One may associate different hues with different lengths of the assumed waves. The hue "red" is associated with the longest visible waves, the hue "green" with the medium-sized waves, and the hue "blue" with the shortest waves. Because of a quirk of color vision, the hue "yellow" may be observed either for waves

just longer than those which elicit the perceived hue "green," or for a mixture of the waves associated separately with the hues "green" and "red." Reference will be made to these relationships in the following discussion.

2.4 Summary

For purposes of "explaining" the behavior of light, several different and, in a sense, contradictory concepts are useful. For some purposes it is sufficient, and sometimes it is necessary, to think of light as a stream of particles; for other purposes, it is useful to liken light to the waves of sound. Probably the most sophisticated and generally most applicable theory requires that light be treated as if it were a complex transverse wave motion. The polarization of light can be understood only by the application of the last theory.

* *Fundamentals of Optics* by FRANCIS A. JENKINS and HARVEY E. WHITE. McGraw-Hill.

*Introduction to Modern Physic*s by F.K. RICHTMYER. McGraw-Hill.

Principals of Physics, Vol. III, Optics, by FRANCIS WESTON SEARS. Addison-Wesley Press.

The Principals of Optics by ARTHUR C. HARDY and FRED H. PERRIN. McGraw-Hill.

3.0 Demonstration Methods

Projection is the most convenient and effective way of showing a group the demonstrations which follow. Here are a few different techniques that may be used.

Many old style 3 1/4″ x 4 1/4″ slide projectors have easily-removable bellows. Often the bellows may be slipped out if the projection lens is racked outward from the lamphouse. The resulting space between the light source and the projection lens is large enough to insert the specimens to be shown. The specimens should be supported by clamps held by a ringstand or other similar device. The items could be held manually, but the resulting image motion would be distracting. The 2″ specimens may be conveniently held in a simple lens holder. The 4-cm size (manufactured by various companies) works well if the prongs of the holder are spread apart a little. The specimens should be placed as close to the light source as possible. The illumination is better here and it is easier to focus the images on the screen. If the projector has no cooling fan, the specimens may become quite warm. They are not likely to be damaged, however. Warping does not destroy the effectiveness of the sheet polarizers. The images of the specimens will be inverted on the screen, but this is of little consequence, since they are usually symmetrical.

Vertical projectors are equally useful. The specimens may be placed on the stage, which should be masked down with a piece of opaque card having a central aperture of appropriate size.

The screen illumination level possible with these two projection methods is usually great enough so that the classroom need only partially be darkened. A reduction in stray light, however, enhances the effects. The less "uninvited" light, the clearer your image will be. Placing the projector close to the screen is helpful in the presence of high general illumination, but the images will then be small.

A third method involves the use of a lens bench and easily obtainable optical devices, as shown in figure 4. If the lens has a focal length of 6″, it will give a magnification of about three times when placed 8″ from the specimen. The image quality and light level will be poor as compared with the preceding suggested methods, but will be adequate for small groups.

If equipment is available for none of the preceding methods, many of the demonstrations can be performed merely by holding the specimens in front of a suitable light source. A student's desk lamp, for instance, is satisfactory if it is masked to avoid glare.

4.0 Natural Polarizers

The effects on light produced by certain crystals offer a logical starting point for the study of polarization.

4.1 DEMONSTRATION II

Place on opaque card in the projector slide holder. This card should have a small pin hole (approximately 1 mm in diameter) near its center. Focus the image of the hole on the screen, or hold a similar card over a light source.

a. Place a piece of glass over the hole. Observe that the **single** image is slightly reduced in brightness because of light lost by reflection from the glass surfaces. Notice how the image is shifted slightly in position when the glass is held so that the light falls on it at angles other than the perpendicular.
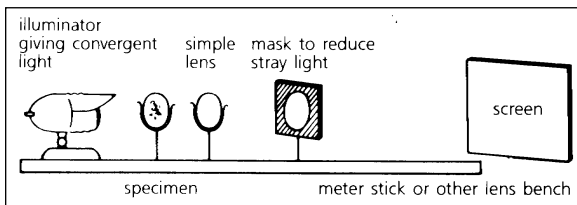

Figure 4. Projection method using optical bench apparatus.

b. Place the calcite crystal over the hole. Calcite is a naturally-occurring form of calcium carbonate, allied to

limestone. The flat surfaces are not artificial, but are formed during the process of crystallization. Observe the **double** image, each part of which is about half as bright as the original spot. The images may be slightly fuzzy, due to small defects in the crystal. This fuzziness is inconsequential. Observe that the two spots appear with any orientation of the crystal. Observe, when the crystal is rotated about an axis parallel to the light beam, that one of the spots remains relatively still, and that the second spot rotates about the first.

These observations lead to the following conclusions:

1. When a beam of light is refracted by glass, only a single path is followed by the light.

2. When a beam of light is refracted by a calcite crystal, the light is somehow divided into two parts, each part containing substantially half the energy of the original beam. That part of the light forming the nearly stationary spot is the "ordinary" ray; the rest is the "extra-ordinary" ray.

Figure 5 shows by ray diagram what must be occurring in these two different situations. We explain the refraction of light on the basis of a change in velocity of the light on entering a new medium. That there is only a single path for the light in glass implies that the light, ignoring wavelength considerations, has only a single velocity in the glass.

Glass, therefore has a single index of refraction. The fact that there are two paths for the light in calcite implies that calcite must have two different velocities for light, and, therefore, two **different** indexes of refraction. We use the term "double refraction" to describe this behavior of calcite and similar crystals.

The difference between glass and calcite just demonstrated is associated with the different arrangements of molecules composing the substances. Glass is believed to consist of molecules randomly positioned. Calcite, on the other hand, has a precise molecular orientation in which the molecules and atoms are arranged in a strict pattern. This is indicated by the flat cleavage which bound the crystal and form definite angles which are characteristic of this substance. One may think of the crystal as having a "grain." Just as wood splits easily with the grain, but not against it, so light

a. Refraction of light by glass at two different angles of incidence. A single path.

a. Refraction of light by calcite at two different angles of incidence. Two light paths. "a" represents the ordinary ray; "b" represents the extra-ordinary ray.
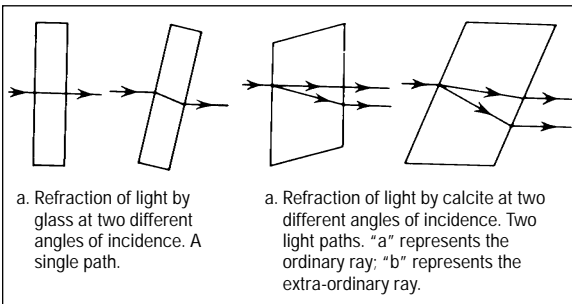
Figure 5. Single Refraction of Light by Glass; Double Refraction of Light by Calcite.

travels more easily "with the grain" of the crystal, than against it.

Although the two beams of light produced by double refraction show no visible difference other than position, it can be shown (Demonstration III below) that they are fundamentally unlike in one significant respect. The beam of light which enters the crystal contains traverse waves whose vibrations lie in many different directions, as in figure 3c. Each of the two emergent beams, however, contains light vibrating only in a single direction. Those waves of the original beam vibrating only vertically or horizontally appear in the correct emergent beam. Waves vibrating at other angles have both vertical and horizontal components. The crystal separates each component into its appropriate beam. Each of the waves is a part of the initial beam containing random vibrations and will have a vertical and a horizontal component. Each of these components appears in the appropriate beam. Hence, there is practically no loss of energy. Thus, we speak of both beams as consisting of plane polarized light, with the two vibration directions at right angles to each other. See figure 6.

Plane polarized light may be imitated by the tubing used in Demonstration I if the hand is moved only vertically, or only horizontally, or in some other consistent direction. Water waves are polarized: the vibration is always consistently vertical or practically so.

Many crystals other than calcite are doubly refracting. The difference between the two indices of refraction may be small (in ice the indices are 1.309 and 1.313) or quite large (in calcite they are 1.486 and 1.658).
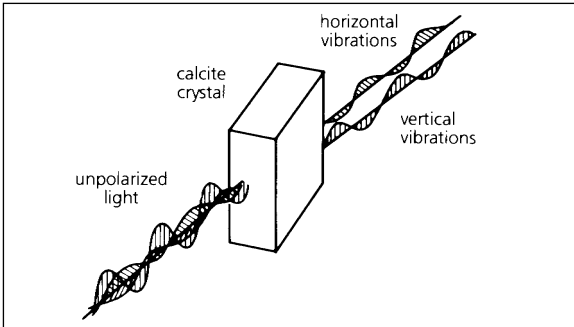

Figure 6. Double Refraction (Schematic). Unpolarized light is converted into two beams of polarized light, with mutually perpendicular vibration directions.

For experiments with polarized light, it is necessary to separate the two beams of polarized light. One difficult technique, used in the Nicol prism, is to saw through a calcite crystal at a precise angle, and then to reassemble the two pieces with a special cement. When this is done correctly, the ordinary ray is reflected to one side at the cement layer, and only the extra-ordinary ray emerges from the front of the crystal. Light which is totally polarized in one plane is thus obtained. Nicol prisms are very expensive and usually of comparatively small aperture, since it is difficult to find large calcite crystals of sufficiently good quality.

Other naturally-occurring crystals, such as tourmaline,

have been discovered which are not only doubly refracting, but also have the property (unlike calcite) of absorbing strongly only one of the two rays. The light which emerges from such a crystal is, therefore, plane polarized. Tourmaline crystals sufficiently clear and free from color are, however, difficult to obtain.

5.0 Synthetic Polarizers

Artificial crystals that would serve as polarizers have been known for over a century. Only recently, however, has it been possible to use such crystals, and other materials as well, to make polarizers of high quality and very large aperture.

The first polarizing sheet film was made of a multitude of very small synthetic crystals, all lying in the same orientation in a sheet of plastic. They were sub-microscopic needles, about a micron (a millionth of a meter) long. There were about $10''$ crystals in a square centimeter of film. Each crystal acted as the tourmaline: it caused the incident light to be doubly refracted, but permitted only one of the two beams of light to emerge.

The sheet polarizers in your Leica Table Top Polarization Demonstrator consist of a special plastic (polyvinyl alcohol) chemically treated with iodine. The long molecules of the plastic are aligned by stretching the material during

manufacture, and serve as the polarizing agents. Compared with the previously available polarizers (Nicol prisms and tourmaline crystals), sheet polarizers are less expensive and obtainable in much larger sizes.

5.1 Demonstration III

Use the same arrangement as in Demonstration II. Slip the 5″ diameter sheet polarizer into the slot which held the forward edge of the bellows in the 3 1/4″ x 4 1/4″ slide projector. It may be necessary to cut a narrow piece of stiff cardboard to fit the bottom of the slot so that it holds the polarizer high enough to cover the projection lens.

Hold the calcite crystal over the hole in the card and rotate the polarizer. Observe the images of the spots of light on the screen. As the polarizer is rotated, each spot appears and disappears.

Explanation: The polarizer will transmit only light waves vibrating in a single plane. Since the calcite causes the initial beam of light to be divided into waves having two mutually perpendicular vibration planes, the orientation of the polarizer determines which will pass. At some positions of the polarizer, two images of reduced intensity will appear. In this case, the axis of the polarizer lies in a direction between the vibration planes of the two beams. It permits only a component of each of them to emerge.

Note: *This demonstration is a crucial one. It confirms the validity of the concept of light as a transverse wave motion. It is impossible to conceive of a longitudinal wave motion, like sound, behaving as in the demonstration. Though sound waves may be refracted, they can never be double refracted — they can never be divided into two waves vibrating in different planes. Only under the assumption of transverse vibrations in light waves can this demonstration be explained.*

5.2 Demonstration IV

Remove the card from the slide holder and remove the calcite. Compare the appearance of the unobstructed light on the screen with that which was transmitted by the single polarizer. Observe that the light is about half as bright with the polarizer, and that it is substantially uncolored. There may be a very slight yellowish appearance, indicating that the transmittance of the polarizer is slightly deficient for blue light. The theoretical maximum transmittance of a polarizer is 50%. Sheet polarizers approach 40% over most of the wavelengths in the visible spectrum.

5.3 Demonstration V

Add a second sheet polarizer to the projection system. The 5″ square sheet may be put in the rear bellows slot of the projector. Rotate the 5″ diam. polarizer through a complete circle. Observe that there are two positions for which the light on the screen is substantially as bright as with a single

polarizer, and that there are two other positions for which almost no light reaches the screen.

Explanation: The first polarizer transmits only light vibrating in a single direction. This light will pass through the second polarizer almost undiminished if the second is properly oriented with the first. That is, there is little loss of light if the "axes" of the two polarizers are parallel. As the second polarizer is rotated, the light diminishes since only a portion of the polarized light can now pass. When the two polarizers are "crossed," that is, when their axes are perpendicular, practically none of the light which emerges from the first polarizer can pass through the second. Continued rotation of the second polarizer will cause a bright light on the screen when the relative angle of rotation is 180°, since the axes will again be parallel. Rotating the second polarizer through the remaining 180° will produce one more extinction and reappearance of the light.

Applications: Two polarizers may be used to control the intensity of the light in viewing apparatus, such as telescopes and microscopes. Since there is a strict mathematical relationship between the light intensity and the angle between the axes of the polarizers (the intensity varies directly as the square of the cosine of the angle), the intensity of the light may be controlled accurately.

It has been proposed to equip automobiles with sheet polarizers over headlights and windshield. The polarizers

would have their axes parallel, but at 45° to the vertical. Since the axes are parallel, the driver would be able to see by means of his own headlights. Oncoming cars, similarly equipped, would have the axes of the polarizers over their headlights crossed with respect to the driver of the other car. In this way, the glare from oncoming headlights would practically be eliminated. Such a system would necessitate doubling the candlepower of the bulbs in the headlights. Most automobiles would need to be fitted with polarizers for the method to be generally effective.

Stereoscopic pictures, still or moving, may be seen simultaneously by a large group of persons through the use of polarized light. Two projectors are used, each fitted with a polarizer. The viewers wear polarizing spectacles. The axes of the projection and viewing polarizers are arranged so that each eye of the observers receives only a single image. These images are combined visually and seen as a single relief image.

5.4 Polarization by Reflection.

Many kinds of reflecting surfaces partially polarize the light they reflect.
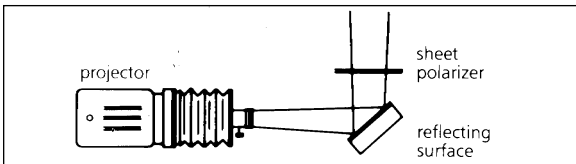

Figure 7. Apparatus for Demonstrating Polarization by Reflection (top view).

5.5 Demonstration VI

Aim the projector (a flashlight, or other source producing a fairly narrow beam of light) across the room. Support the square of black plastic or a piece of plain glass in front of the projector to reflect a path of light to the front wall of the room. Make the angle between the light path and the plastic surface about 40°, (See figure 7.) Rotate a sheet polarizer in the reflected beam. Observe how the intensity of the path of light changes. It becomes nearly zero with some orientations of the polarizer. Change the angle between the plastic surface and the light path from the projector. Observe that the rotation of the polarizer now causes much less change in the intensity of the patch of light on the wall.

Repeat the demonstration with a metallic reflecting surface, such as a small metal mirror or a flat piece of aluminum foil. Observe that there is no angle at which the metallic surface can be held where the polarizer makes a significant change in the intensity of the reflected spot.

Explanation: Non-metallic glossy surfaces polarize light by reflection. The polarization is a maximum at some particular angle. The best angle is that whose tangent is equal to the index of refraction of the material. The angle is measured between the incident light and a perpendicular to the surface. Glossy metallic surfaces do not polarize reflected light to the degree that glass does.

Applications: Polarizing filters used by photographers effectively absorb about half of the light they receive. In addition, polarizing filters suppress much of the glossy reflection from water, store windows, painted or varnished surfaces, or glossy plastics, when they lie at an angle of 30 to 40 degrees to the line of sight. Since this reflection often occurs out of doors, the use of polarizing filters permits seeing "through" the dazzling reflections.

5.6 Polarization by Scattered Reflection

Light which is reflected from very small particles is, in general, partially polarized.

5.7 Demonstration VII

Add two or three drops of milk or a little soap or starch solution to a battery jar of water. A square-sided quart bottle is a good substitute for the battery jar (Figure 8a.) The mixture should have a faint bluish appearance. Shine the light from the projector, or equivalent illuminator, horizontally through the mixture. Observe that the path of the light is seen easily. This is because the small particles
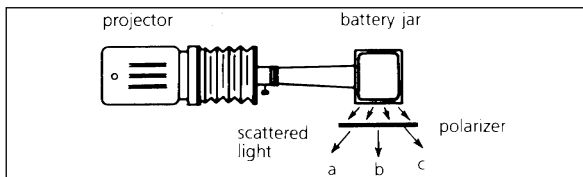

Figure 8a. Polarization by Scattered Reflection.

Top view of apparatus. Polarized light is seen in direction "b." Mostly unpolarized light is seen in the directions "a" and "c."

suspended in the water scatter the entering light. The light is bluish because the particles scatter short wavelengths more effectively than they do long waves. A corresponding effect in the atmosphere makes the sky look blue. Place a sheet polarizer between the jar of water and the observers and rotate the polarizer. Observe a variation in the brightness of the reflected light. The variation is most noticeable when the observer looks in a direction perpendicular to the light beam. Little variation is seen at angles nearly parallel to the beam.

Explanation: A mixture of waves having various vibration directions falls on the particles causing them to move, and to cause secondary waves. Any of the original waves which has a vibration direction parallel to the observer's line of sight would cause a motion of the particle to and fro with reference to the observer. But light is a transverse wave motion. This kind of particle movement would be ineffective in producing secondary waves. Only a crosswise movement of the particle could give rise to transverse waves, and these would vibrate in a vertical direction. Hence, the light which is polarized vertically, is that which is observed. From a direction nearly parallel to the light beam, almost any motion of the particle would be approximately transverse to the line of sight. There is, therefore, no effective polarization in this direction. (See figure 8b.)

Application: Light reflected by scattering from the particles in the atmosphere is partially polarized. The effect is most noticeable when seen from a direction about perpendicular to the direct rays of the sun.
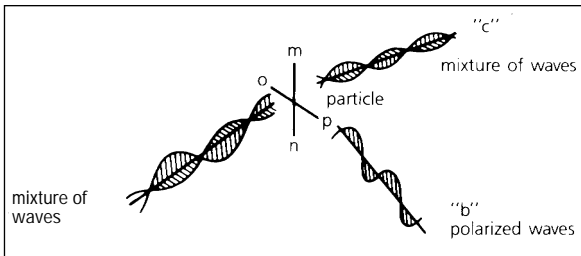

Figure 8b. Polarization by Scattered Reflection

Polarized light reflected to observer "b"; a mixture of waves passes to observer "c." (The lines "m-n" and "o-p" represent two possible vibrations of the particle. Only the "m-n" vibration can produce transverse waves in the direction "b.")

This phenomenon may be used in landscape photography to produce a pictorial effect. A polarizing filter is placed over the camera lens with the filter oriented to produce a subtle variation in the tone of the sky from horizon to zenith. The result is especially pleasing in color photography. Clouds are not affected by a polarizing filter, since the water droplets are too large.

Some scientists believe that birds may be able to find their way on their migrations because they can detect atmospheric polarization, and thus determine their direction by a polarization "compass."

5.8 Retardation Effects

The most beautiful and useful phenomena connected with polarized light are based on the following principle: many doubly refracting substances separate polarized light into two components. The two components have different velocities in the substance. When the two beams of light emerge from the substance, they re-combine. Since, however, one beam has traveled faster than the other, the two are generally "out of step" or out of phase with each other. The extent to which the two components are out of phase depends upon the nature of the doubly refracting substance, its thickness, and the wavelength of the light involved. (See appendix.)

5.9 Demonstration VIII

Superimpose one 1/4 - wave plate on the other so that their axes are parallel. Place them between crossed polarizers. Observe that the screen becomes bright. Also observe that as the pair of wave plates is rotated, the brightness of the screen is modulated. Note that in a complete rotation of $360°$, the screen becomes dark four times and that the brightness is at a maximum four times — this is twice as many cycles as one obtains by rotating one of the polarizers through $360°$.

Explanation: The two superimposed quarter-wave plates constitute a half-wave plate as long as their axes are parallel. The effect of the two quarter-wave plates is to

rotate the plane of polarization of the first polarizer thru an angle which is twice the angle between the first polarizer and the axis of the wave plate. You will note that the screen brightness is at maximum when the angle between the polarizer axis and the wave plate axis is $45°$ (also $135°$, $225°$, $315°$); i.e., when this angle is $45°$, the plane of polarization of the first polarizer is rotated through $2 \times 45° = 90°$, and consequently the light is transmitted by the second polarizer.

5.10 Demonstration IX

Rotate the full wave retarder between crossed polarizers. Observe that this retarder has little effect on the screen brightness, but that distinct colors are seen.

Explanation: A full wave retarder produces a $360°$ out-of-phase relationship between the two retarded beams. A $360°$ shift represents a full cycle and should bring the two beams back together to their original relationship. There is, however, a variation in wavelength for different hues of light. Some wavelengths are shifted by a precise full wave, and other wavelengths are shifted by more or less than a full wave. Different wavelengths therefore have different orientations with respect to the second polarizers and fall on the screen with greater or lesser intensity. Thus we may account for the colors which are seen.

5.11 Demonstration X

Place the sheet of mica in the projector. Focus the image of the mica on the screen, and observe this image. First observe with no polarizer, then with one, then with two. Observe the effect of rotating one polarizer, and of rotating the specimen. Repeat the demonstration with the Benzoic Acid Crystal specimen. If a micro-projector is available, crystals prepared as in Experiment VI may be projected. Beautiful images are produced.

Explanation: Many natural crystals like mica and artificial ones like benzoic acid are double refracting and retarding. Since the crystals vary in thickness, they have different effects on different wavelengths of light.

Application: In the visual examination and photography of crystals, polarized light is frequently used to study their form and structure. Small differences in pattern which are almost impossible to detect with ordinary light are discovered easily with polarized light.

In the microscopic examination of living things, polarized light helps in studying crystalline structures since it is unnecessary to use stains. Standard microscope stains usually kill the specimens.

5.12 Demonstration XI

Form a pattern by sticking various numbers of layers of pressure-sensitive transparent tape (such as "Scotch"

brand tape) on a glass plate. The simplest pattern is a stepped wedge formed of one, two, three, etc., layers. Project this as in Demonstration X. Observe the intense colors. Note that any thickness of tape exhibits two complementary hues. Which hues are seen depends on the setting of the polarizers. The colors seen between crossed and parallel polarizers are complementary. When the specimen is rotated between fixed polarizers, the intensity changes but the hue is constant. For instance, one thickness will show either blue or orange; two layers, either magenta or green. The effective limit is about five layers.

5.13 Demonstration XII

Place the photoelastic specimen in the projector as in Demonstration XI. Observe that the specimen has no effect on the light under any circumstances. Cross the polarizers, and apply pressure to the specimen. Observe the colored patterns at certain spots within the specimen.

Explanation: The material used in making this specimen is not normally doubly refracting. When stress is applied to the specimen, however, its molecular conformation is changed. This specimen, as a result of the applied stress, now exhibits artificial double refraction as do the specimens used in Demonstrations XI and XII.

Application: The patterns seen in the image of the specimen are, in effect, a map of the strains produced. A study of these patterns is exceptionally useful in analyzing expected

performance of machine parts, bridges, and other structures which must resist breaking under stresses. The design of these structures may be improved by examining with polarized light models made of plastic and altering their designs to cause the least strain.

Many manufactured items, particularly those of optical glass, must be strain-free in order to work properly. This is especially true, for instance, of glass lenses. They are inspected with polarized light which clearly shows the strains.

In the photography of rapidly occurring events, like explosions, a very fast shutter is required for the camera. A cylinder of glass or quartz or a selected liquid in a glass cylinder is placed between crossed polarizers. Almost no light passes the system. The glass or liquid is then subjected to a sudden, very intense, electrical or magnetic field. The glass or liquid becomes doubly-refracting almost instantaneously, and thereby permits light to pass to the film. Since the field immediately collapses, the light passes for only a very short time. Pictures may thus be made with exposure times as short as a hundredth of a millionth of a second.

5.14 Summary

The fundamentals of polarized light, which have been discussed and demonstrated, offer confirmation of one of

the theories of light: it must be considered as having the characteristics of a transverse wave motion. Only this theory can explain the phenomena which have been shown.

Polarized light is an effective tool for: (1) the scientist in the fields of light measurement and the study of the structures of crystals; (2) the engineer in the study of mechanical structures and in specialized types of photography; (3) the amateur and professional photographer in the control of reflected light; (4) the theatre-goer or amateur photographer who enjoys viewing 3-Dimensional pictures.

6.0 Experiments

The following experiments are intended for individual work by students who would like to study polarized light more intensively than in the preceding demonstrations. The experiments are especially suitable for the members of a science club. With some modifications, they would serve as interesting exhibits for a science fair.

In addition to the equipment included in the Demonstrators, only materials commonly found in school laboratories (or easily available elsewhere) are required. It is assumed that the students are familiar with the theory and demonstrations in the preceding portions of this booklet. Since the results of these experiments are not given here, students are urged to make a notebook record of their observations.

6.1 Experiment I: Calcite

1. Lay the calcite crystal over a small dot on a piece of white paper. Observe the two images of the dot. Particularly note that one image seems closer to you than the other. Sketch the two light paths from the dot. Observe that one light path is necessarily longer than the other. Relate this fact to the apparent distances of the images from you.

2. Place the crystal so that different faces lie over the dot. Look through the crystal at the dot at angles other than perpendicular. Describe any differences in the images.

3. Use a sheet polarizer having the polarization axis marked on it to determine the plane of vibration of the light forming the two dot images. Place the polarizer over the crystal, and rotate the polarizer. When the image disappears, the axis of the polarizer is at right angles to the direction of the vibration of the light forming the image.

6.2 Experiment II: Sheet Polarizers

1. Look at a bright source of light through two superimposed sheet polarizers. Describe the changes in the transmitted light as one polarizer is rotated through successive small angles.

2. Note the hue seen when the two polarizers are crossed. Determine from this observation for which wavelengths of light the polarizers are most effective. Any light seen

when the polarizers are crossed must be only partially polarized. Recall that short wavelengths of light are blue in hue, middle wavelengths are green, and long wavelengths are red.

3. Obtain a photoelectric "exposure" meter with a linear scale. If the scale is logarithmic, simply paste on a piece of paper with linear markings. Place two sheet polarizers with parallel axes over the sensitive cell. Illuminate the polarizers with the light from a tungsten lamp. Place the lamp so that the meter gives the largest reading possible. Record this reading. Rotate the first polarizer 5° as measured by a protractor. Record the new meter reading. Repeat the rotation of the polarizer and the light measurement, and thus obtain information. Look up in a table the cosines of the angles of rotation. Square these numbers, and plot a new graph showing the relationship between the squares of the cosines of the angles of rotation and the original light measurements.

6.3 Experiment III: Polarization by Reflection

1. Draw a straight line on a sheet of plain white paper. Support the black plastic so that its front surface is vertical, and rests on the line you have drawn. Place a vertical pin 1/2" from the plastic. Examine the reflected image of the pin at various angles through a rotating polarizer. Observe the change in the brightness of the reflected image as you change the angle of view.

2. Find the angle from which the image of the pin appears to dim most as the polarizer is rotated. Place a second pin so that its image lines up with the first (See figure 9.) Remove the plastic, and draw a straight line through the pinholes in the paper to the line marking the position of the reflecting surface. Construct a perpendicular to the reflecting surface at the intersection of the two lines. Measure the angle between the perpendicular and the line through the pinholes. This is the polarizing angle for this material.

3. Repeat the experiment for a piece of glass (backed by black paper) and for a shiny metallic surface.
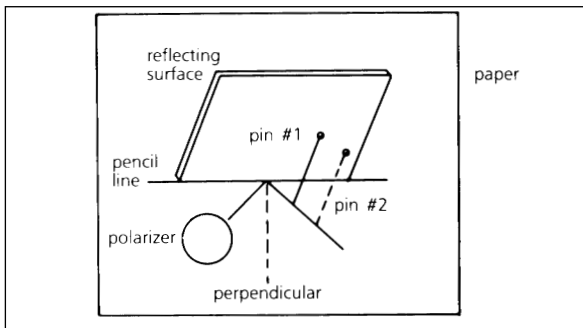

Figure 9. Method of Determining Polarizing Angle for a Reflecting Surface.

6.4 Experiment IV: Polarization by Scattering

1. Look through a polarizer at the blue of the sky and rotate the polarizer. Any change in the brightness of the sky indicates that the light is partially polarized. Try different positions of the sky from the horizon upward and different directions of the compass.

2. Determine by the same method whether light reflected from clouds is polarized.

3. Determine by the same method whether light reflected from a hazy sky is more or less polarized as compared with that from a clear blue sky.

4. Add a very dense photographic negative to protect your eyes. Determine by the same method whether direct light from the sun is polarized.

5. Carefully record your observations.

6.5 Experiment V: Reflection of Polarized Light

1. Provide a narrow beam of light. You may use a card with a small hole in it placed in the slide carrier of a projector or a similar card taped over a flashlight. Shine a light beam through a second polarizer onto the black plastic.

2. Determine whether the light reflected from the plastic is polarized by examining the direct reflected beam through a second polarizer which you rotate.

3. Determine whether a difference in the polarization of the reflected light is caused by a change in the angle which the light makes falling on the plastic.

4. Repeat the experiment with other materials such as glass and metal. Repeat the experiment also with non-glossy reflections like dull white paper, flat painted surfaces, brick, or concrete.

6.6 Experiment VI: Crystals

Note: *For the following experiment you will need a microscope fitted with two polarizers, one under the stage (below the slide) and one in or over the eyepiece. Sets are available especially for this purpose. Polarizing sheets may be fastened temporarily in place with tape. If you have no microscope, a magnifier may be improvised. A 10x magnifier will be reasonably satisfactory, though somewhat higher power is better.*

1. On glass plates (microscope slides or other small, thin pieces of glass), prepare crystals in the following manner: dissolve as much of the substance as possible in one or two milliters (a half-teaspoonful) of warm water. Place a drop of the clear solution on the glass plate. Do not use a cover glass. Observe the growth of the crystals through crossed polarizers, using the low power of the microscope. (Note: since you have no cover glass, be especially careful in the operation of the microscope. The

bottom lens of the microscope must **never** touch the liquid on the slide). Look especially for crystals growing free from interference with other crystals. Suitable substances to use for this experiment are: epsom salts (magnesium sulfate); cream of tartar (sodium potassium tartrate); washing soda (sodium carbonate); baking soda (sodium bicarbonate); aspirin (sodium acetyl salicylate). Some crystals grow rapidly — some slowly. Be patient.

2. Sketch some of the crystal forms, labeling them with the name of the substance.

3. Observe the color changes that occur with some of the crystals. Such changes accompany an increase in the thickness of the crystal. If the color remains constant, you can conclude that the crystal is growing only laterally.

4. Try dissolving mixtures of substances. Observe whether you can distinguish the different substances by their crystal forms.

5. Similarly, grow crystals of common salt (sodium chloride) and table sugar (sucrose). Observe their appearance with polarized light. State the relationship between the shape of the crystal and its effect on polarized light.

6. Examine a few grains of very fine sand in the same manner. No water need be used.

6.7 Experiment VII: Fibers

1. Secure samples of white cotton, wool, rayon, nylon, and other fibers. Fray the end of a thread so that the fibers are separated.

2. Examine the fibers microscopically with crossed polarizers. Make sketches of the appearance of the fibers.

3. From your observations make a key for the identification of fibers by this method. Test your key on an unidentified sample supplied to you by your teacher or a fellow student.

6.8 Experiment VIII: Plastics

1. Use clear plastic tape to make designs by using different numbers of layers of tape pressed to a glass plate. Examine the results with two polarizers, one on each side of the specimen. The tape may be cut with a sharp knife or razor blade to make letters or other simple designs. Try to approximate your school colors. (Hint; changing the direction in which the tape lies produces more colors with a single orientation of the polarizers.)

2. Examine single and double layers of transparent wrapping materials between two polarizers. Observe the effects when the material are crumpled. Similarly, observe the results when the materials are stretched.

3. Secure 1/8″ thick Lucite plastic sheets. Cut (preferably with a fine-toothed saw) the plastic into simple shapes: bars, U-shapes, hooks, hollow triangles. Examine the pieces between two polarizers. Bend, twist, and otherwise apply pressure to the samples. Sketch the patterns that appear.

Appendix

The retardation effects discussed on page 26 can be explained when light is described as "circularly" or "elliptically" polarized. A mechanical analogy may be found in the behavior of the length of rubber tubing used in Demonstration I. The end of the tube is moved rapidly in a circle instead of laterally. The tube forms a wave which moves as a spiral or helix resembling the thread of a screw.

Such a wave may be mathematically described as a rotating vector. A vertical polarized transverse wave may be represented by a double-headed vertical arrow — a line vector. In the same terms, circularly polarized light would be represented by such an arrow which changes direction from vertical to horizontal, then moves back to vertical in the opposite direction. The direction of rotation may be clockwise or counterclockwise. Thus, there are two different kinds of circularly polarized light. Elliptically

polarized light would be represented by a similar vector which not only rotates but changes in length.

Linearly polarized light may be converted to circularly polarized light by passing it through a 1/4-wave retarder. The retarder has two axes along which the light has two different velocities. The light is therefore divided into two parts traveling in the retarder at different speeds. If the two axes are perpendicular to each other, and if the retarder is oriented so that these axes are at $45°$ to the original plane of vibration, the light is split into two equal vibrations at right angles to each other. Since there is a speed difference, there will be a phase difference. In this case, there will be a 1/4-wave difference, which is equivalent to $90°$.

The vector sum of the two beams will no longer be a line, but a **rotating** line, which produces a helical pattern. Since the two beams are equal, the vector sum will always have the same magnitude. Hence, circularly polarized light is formed. By using different materials, or different thicknesses of the same material, any desired phase difference may be produced. Thus, we have 1/2-wave and full-wave retarders, as well as other out-of-phase relationships. The effect of a 1/2-wave retarder is merely to change the direction of the plane of polarization. Color effects are usually observed because the extent of retardation varies with the wavelength of the light involved.

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