

A Tutorial in High-Speed Photography with Electronic Flash

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Notes About the Equipment and Activities

This guide is intended to serve as a tutorial for learning some techniques of high-speed photography using equipment that is readily available to amateur photographers. Knowledge of the basics of handling a camera and selecting exposure is assumed. The use of a 35-mm camera with manual focusing and aperture settings and a B shutter setting is recommended. Two convenient accessories are a tripod and cable release. Film with an ISO rating of 400 is a good choice for most situations.

The activities assume the use of Vivitar 283 flash units.¹ However, the activities could easily be adapted to the use of other automatic flash units. If the unit does not have a PC cord (for connection of triggers), an alternative is the use of a hot shoe adapter which consists of a hot shoe with a PC cord leading from it. This accessory can be found at many photo stores.

The electronic triggers that are used for the flash units can be constructed with common electronic components. A basic knowledge of electricity and electronics will be helpful.²

Access to a darkroom for black-and-white printing and processing is helpful in quickly evaluating the photographs from the activities. Another possibility is the use of a Polaroid camera. This is described in Appendix A.

The activities are divided into four sections. Section I provides an introduction to electronic flash and sound triggers. Section II describes photographic techniques using a single flash unit with a sound or contact trigger. Section III covers the use of photogate triggers and delay circuits, also with a single flash unit. Section IV describes quantitative applications that use two flash units and a high-frequency clock for measuring small time intervals and high speeds. The appendices provide references, circuit diagrams, and practice problems.

Items of equipment that are common to all the activities in a particular section are listed at the beginning of the section. Items that are specific to particular activities are listed at the beginning of the activity.

The activities are only a sampling of what can be done with simple triggers. For inspiration and more ideas, see Refs. 5-7 in Appendix B.

¹ These are available at photo stores and catalog outlets beginning at about \$70. For a better price, look for a used unit.

² *Getting Started In Electronics* by Forrest M. Mims, III, available at Radio Shack stores is a good beginning reference for electronic project work.

SECTION I. Electronic Flash and Sound Triggers

The common items of equipment for the activities in this section are a Vivitar 283 flash unit and instruction booklet, PC cord, SB-4 adapter, extension cord, and flash clamp. Additional items for particular activities are listed at the beginning of the corresponding activity.

Activity 1. Getting acquainted with the Vivitar 283 flash unit

1. While most *electronic flash units* can be used for high-speed photography, we will be using the *Vivitar 283* unit. Refer to the instruction booklet for information on the 283's features. For more general information on how an electronic flash unit works, see Refs. 1-3 in Appendix B.

The 283 is a rugged flash unit, and handling it carefully will help it last a long time. One vulnerable part is the *flash foot*; it tends to break off easily. Another is the *xenon flash tube*. If the unit is dropped, a small crack in the tube would render the unit useless.

Power can be provided to the Vivitar 283 with 4 AA batteries or with an *SB-4 AC adapter*³. Use the AC adapter for now and whenever possible to conserve batteries. Note that the power switch does not function when using the adapter. The flash capacitor should begin to energize as soon as the adapter is plugged in. When the orange light on the back of the flash unit comes on, the capacitor is almost completely charged. Wait several seconds to provide extra time for charging. Now point the flash at a nearby object (preferably not your partner's face) and push on the orange light to discharge the flash.

2. There are other ways to discharge the flash unit. Plug the *PC cord* into the side of the flash unit. Then use something metallic, such as a key or paper clip, to short across the terminals at the end of the cord. This will discharge the flash. Also try shorting across the terminals on the flash foot. One terminal is on the bottom and the other on the side of the foot.

By shorting across the terminals, you are completing a trigger circuit within the flash unit that initiates the discharge of the *main flash capacitor* through the flash tube. Once started, the discharge proceeds to completion unless quenched by a means that will be

³ This accessory is no longer being made by Vivitar.

discussed in the next activity. The voltage across the flash terminals is an important consideration when connecting the flash unit to external trigger circuits. For the 283 that you are using, this voltage is less than 10 V. However, some flash units, including versions of the 283 made before 1984, have 200-300 V across the flash terminals. If you have such a unit, you will be able to identify it by the sting you feel when you short the flash terminals with your finger.

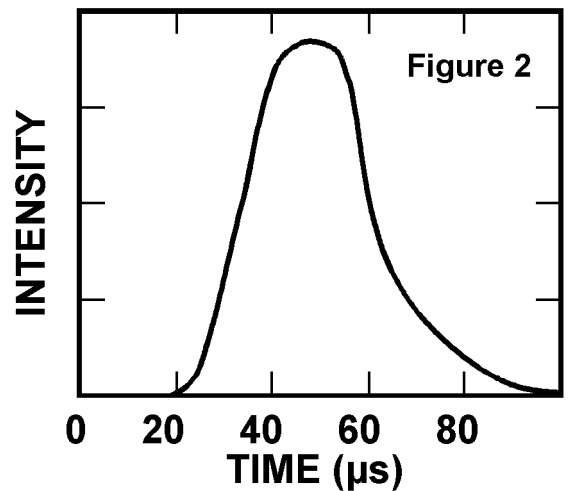
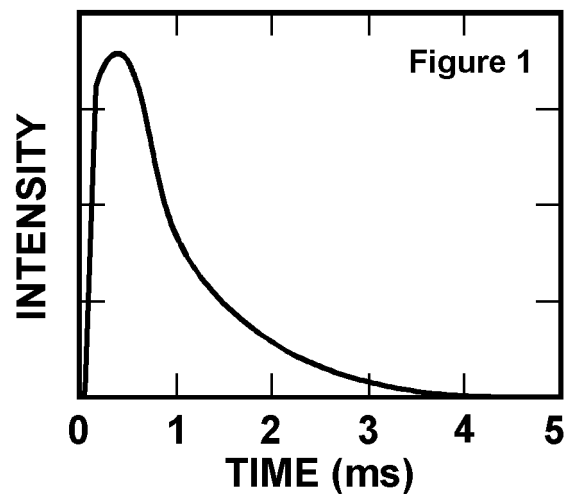
3. Whenever you finish using the flash unit, it is a good idea to discharge the flash capacitor completely after the unit is turned off. To do this, first set the dial on the *sensor module* (labeled *auto-thyristor*) to M (for manual). Then discharge the flash unit.

4. The instructor will show you a disassembled flash unit so that you can see the interior parts for yourself. The largest component is the main flash capacitor, which stores electrical energy for the flash discharge. Other components include the flash tube and the power supply.

Activity 2. Controlling flash duration

Additional equipment: 100-k Ω variable resistor

Background: An important factor to control for high-speed photography is the *flash duration*, that is, the amount of time the flash of light lasts. Typically, one wants the shortest possible burst of light. Fig. 1 shows the intensity of the light vs. time for a full discharge. The intensity is not constant but rather increases from 0 to a maximum in about 0.3 ms⁴. It then decreases more gradually over a period of about a milli-



⁴ The abbreviation, *ms*, stands for millisecond. The prefix, *milli-*, represents thousandths. Thus, 1 ms = 0.001 s (second).

second. This is too long for high-speed photographs. However, if the flash unit is used in the *automatic exposure*⁵ mode, the duration can be decreased to as little as 30 μs ⁶. Such a discharge is represented in Fig. 2. Note that the time scale is expanded by a factor of 50 over that of Fig. 1. The intensity scale is expanded by about a factor of 10, pointing to the fact that decreasing the duration of the flash also decreases the brightness. A 30- μs burst will be quite dim compared to a full discharge. However, there will still be sufficient light for photography.

In order to obtain the briefest flash of light, you will need to arrange for the intensity of the reflected light to be as great as possible⁷. In this activity, you'll find out how to do that.

1. Note the small, circular window on the front of the auto-thyristor module. This window allows light to reach a light detector⁸ inside the module. Light must reach this detector in order for the flash unit to operate in its automatic mode. In the M (manual) setting, the window is completely covered, and the flash unit produces its brightest and longest flash of light. For each of the colored settings--yellow, blue, red, purple--a different *neutral-density filter* is rotated in place over the light detector. These filters reduce the intensity of light reaching the light detector. The darker the filter, the brighter and longer the flash of light will be.⁹ For high-speed photography, the most transparent filter would be used in order to obtain the shortest flash duration.

Which of the colored settings gives the shortest flash duration? Which gives the longest? In order to find out, aim the flash unit at a distant wall, making sure to keep the window over the light detector uncovered. Placing the flash unit in each of the colored automatic modes in turn, discharge the flash unit. Which mode gave the brightest flash? Which gave the dimmest? Remember that the brighter the flash, the longer it lasts.

2. Another way to change the amount of light reflected to the light detector is to change the distance from the flash unit to the subject. Try this by discharging the flash when it is very

⁵ In the automatic mode, the light reflected by the subject is detected by a photoresistor in the auto-thyristor module on the front of the 283. A small capacitor in series with the photoresistor charges through it. When the voltage across the capacitor reaches some predetermined amount, the flash discharge is quenched.

⁶ The abbreviation, μs , stands for microsecond. The prefix, *micro-*, represents millionths. Thus, 1 μs = 0.001 ms = 0.000001 s.

⁷ This results because the resistance of the photoresistor decreases as the light intensity increases. The lower the resistance, the quicker the series capacitor will charge.

⁸ This is the photoresistor referred to in footnote 5.

close to the wall and then again when it is as far away as you can get it. Use the yellow automatic mode. (You should have found that the yellow mode gives the shortest flash of light.) Did you get the brighter flash when the unit was closer or farther from the wall? Can you explain why this result is to be expected?

What does this tell you about where you should place the flash unit for taking high-speed photographs?

3. A third way to change how much light is reflected to the light detector is to change the background. A dark background will obviously reflect much less light than a white one at the same distance. Try this by discharging the flash unit first toward a white wall and then toward a black curtain at the same distance as the wall. What did you find out?

4. Of the second and third factors discussed above, the second is the more important. That's because a black background can still reflect a significant amount of light. It's usually best to set the auto-thyrister module on yellow and place the background as far away as possible from the subject being photographed.

In order to review what you have done so far, what three things can you do in order to obtain the shortest burst of light from the flash unit?

a.

b.

c.

⁹ One would use darker filters in order to use smaller apertures for greater depth-of-field. For high-speed photography, however, the greater flash duration that results is usually undesirable.

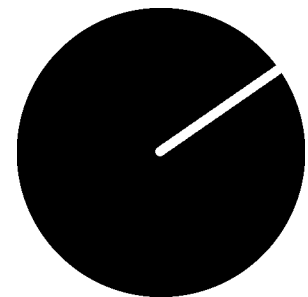
In addition to minimizing flash duration, using the yellow automatic mode will maximize battery life. Therefore, whenever possible when using batteries, be sure the flash unit is placed in the yellow mode and that the flash head is in the 90° position so that the reflected light reaches the light detector. Be sure, of course, that your hand doesn't cover the detector.

5. The Vivitar 283 has a feature that makes it possible to conveniently adjust flash duration. Note that the auto-thyristor module can be removed. Pull it straight out, away from the flash unit. This will expose an arrangement of five holes. The two holes on the right (as seen with the flash unit upright and facing you) are the connections for the light detector. By inserting the leads of a variable resistor into these two holes, you can control the flash duration (and brightness) directly. Try this now with the 100-k Ω variable resistor.

Activity 3. Measuring flash duration

Additional equipment: 100-k Ω variable resistor
AC motor with clock disc
Ring stand and clamp
Electronic stroboscope

Background: The duration of the flash can't be read directly from a dial on the unit, but there are methods of measuring it. The method that will be used in this activity is to set up a motor as a high-frequency clock. A black cardboard disc is centered on the axle of the motor to serve as the clock face. A bright, radial line painted on the disc serves as the hand, as shown in the figure to the right. If the motor rotates fast enough, the hand produces a perceptible blur under the illumination of the electronic flash.



1. Clamp the motor¹⁰ onto a ring stand. Then turn the motor on. If you're using an open-frame AC motor, **don't let it run more than a few minutes at a time**. It heats up quickly and will burn the insulation. Use the *electronic stroboscope* to measure the frequency of the

¹⁰ The motor used for the clock is the type used to operate cooling fans for appliances. The frequency is 50 - 60 rotations per second.

motor. This is done by adjusting the stroboscope frequency until the hand of the clock disc appears stationary. To insure that the clock hand is making only a single rotation between flashes, double the stroboscope frequency. If two equally-bright images of the hand are seen 180° apart, the original frequency was the correct one. Record the clock frequency in flashes per minute. Then calculate the number of flashes per second.

Clock frequency (fpm) =

Clock frequency (fps) =

2. Calculate how long it would take for the hand of the clock to move through an angle of 90° . Repeat for 1° .

3. In order to use the clock to make accurate measurements of flash duration, it's necessary to take photographs of the rotating disc. For this activity, however, you can simply view the disc and make relative judgements about the angle through which the hand moves. Set the flash unit on the purple automatic mode and point it at the rotating disc, about a meter away. Discharge the unit, watching the disc as you do so. Back up to larger and larger distances from the disc, noting the amount of blur each time. Then repeat with the flash unit set on the yellow automatic mode. Also try with the auto-thyristor set on M. Finally, make some tests with the $100\text{-k}\Omega$ resistor replacing the auto-thyristor module. Give the results of the tests.

effect of increasing distance:

effect of yellow compared to purple:

effect of M setting:

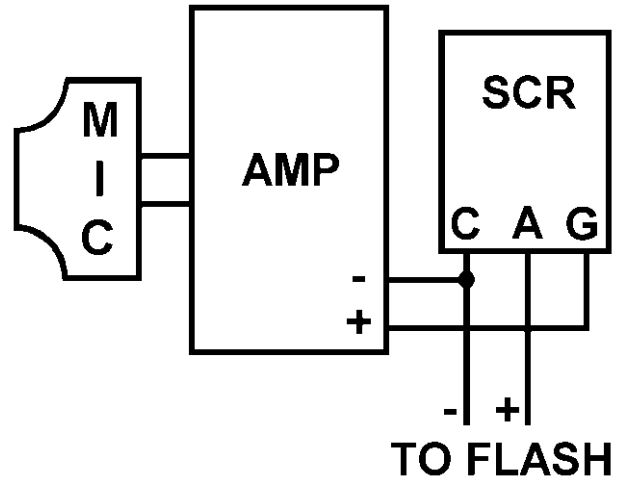
effect of increasing variable resistance:

Activity 4. Triggering the flash unit with sound

Additional equipment: Piezoelectric sound trigger
Balloon and pin

Background: You've already seen how to trigger a flash discharge by shorting across the flash terminals. In this activity, you will use a **sound trigger**, a circuit that shorts the terminals electronically in response to sound.

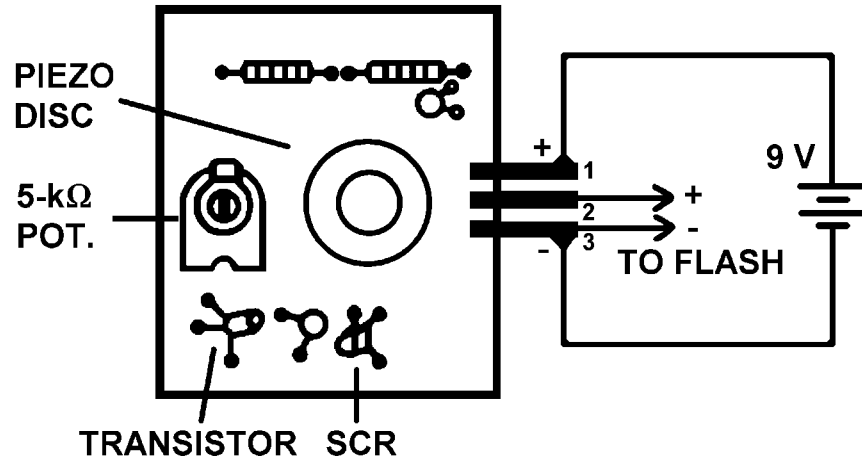
The three parts of a sound trigger are a **microphone**, an **amplifier**, and a **silicon-controlled rectifier (SCR)**. The diagram to the right shows how the components are connected. The microphone picks up the sound of the event to be observed. The amplifier boosts the current from the microphone signal in order to actuate the SCR. The SCR acts as a switch



to short the flash terminals, which are connected to the **cathode (C)** and **anode (A)** of the SCR. The amplifier output is connected to the **gate (G)** and cathode of the SCR. When a sound is picked up by the microphone, the amplified electrical current flows in the gate-cathode circuit of the SCR. That in turn allows current to flow in the anode-cathode circuit, thus discharging the flash unit. Besides acting as a switch, the SCR isolates the amplifier from the voltage across the flash terminals.

The sound trigger for this activity uses a **piezoelectric** film as the microphone. The film is pressure-sensitive, producing a voltage spike in response to the sudden deformation caused by a loud, sharp sound such as a hand clap or balloon burst. A diagram of the internal components of the trigger is shown on the next page.¹¹ The 5-k Ω potentiometer serves as a variable resistor to provide sensitivity control. A 9-V source is connected to pins 1 (+) and 3 (-), and the flash terminals to pins 2 (+) and 3.

¹¹ Kits that include this sound trigger are available from the Edgerton Educational Center, 208 16th St., Aurora, NE.



1. In order to test the trigger, clap your hands or snap your fingers to discharge the flash unit. You can test the sensitivity of the trigger by seeing how far you can stand from it before a clap no longer actuates it. You can also try adjusting the 5-k Ω potentiometer to see how it affects the sensitivity. Turn the dial clockwise to increase the sensitivity. If you have trouble getting the sound trigger to function properly, make sure that all connections are secure and that the sensitivity is not too high or too low. If the sensitivity is turned too high, the flash unit will discharge spontaneously and then will not discharge again. If this happens, turn the sensitivity down just enough to allow the flash unit to be discharged.
2. Set the flash unit in the yellow automatic mode and point it at a nearby object so that the duration will be minimum. Then set off the flash unit repeatedly with successive claps or snaps. This works because each flash uses only a small portion of the stored energy, and it takes a very short time to replenish that energy.
3. Now try observing a balloon burst. Place the microphone of the trigger near the balloon and point the flash unit at the balloon. Turn the room lights down. Pop the balloon with a needle, watching it as you do.

Notes:

- A sound trigger that is much more sensitive than the piezoelectric trigger can be made from a tape recorder with a built-in microphone. See Appendix E for details.
- If you wish to build your own sound trigger from scratch, see Appendix D.

SECTION II. Photographic Techniques

In addition to the flash equipment used in the activities of the last section, those in this section require a camera, film, and background cloth. A Vivitar flash accessory that may be useful is an extender cord for the auto-thyristor module. If you are using a Polaroid camera, see Appendix A.

Activity 5. Photographing bursting balloons and breaking bulbs

Additional equipment: Piezoelectric sound trigger
Balloons, pin, light bulbs, safety glasses

Background: In this activity, you'll learn the basics of taking photographs of high-speed events using a single flash unit, triggered by sound.¹² Before you take a photograph, there are several decisions to be made.

- What camera, lens, and film will be used?

The answer to this question may depend on what you have available. There are only a few requirements. The camera should have a B shutter setting and the lens should have manually-adjustable aperture and focus. The choice of film is not critical. A medium speed film (ISO 400) is sufficient for most purposes. The only advantage of higher film speeds is to make it possible to use smaller lens apertures, thus increasing depth-of-field.

- How far from the subject to be photographed will the camera be?

Usually, one tries to place the camera as close as possible so that the image of the event to be photographed will fill the frame of film. If the subject is small, the minimum focusing distance of the camera may limit the size of the image.

- What background will be used and how far behind the subject will it be?

It is frequently desirable to have a dark, featureless background that will not distract attention from the main subject. A sheet of dark cloth or paper can be placed behind the

¹² If you're not already familiar with the subjects of film exposure and depth-of-field, see Appendix C.

subject. The surface should be rough to minimize glare. The farther behind the subject the background can be, the better. This will decrease the intensity of reflected light.

- Where will the flash unit be placed?

The flash unit is usually placed as close to the subject as possible, while still giving uniform coverage. This increases the concentration of light on the subject, as needed when the flash duration is short. One should also consider the angle at which the light strikes the subject. By choosing the angle correctly, shadows can be produced that help to show structure and texture in the subject. If the flash unit is placed on the hot shoe of the camera, care must be taken that opening the shutter of the camera does not discharge the unit. This can be done simply by putting a piece of tape over the center contact on the flash foot.

- How far from the source of sound will the sound trigger be placed?

The greater the distance of the sound trigger from the source of sound, the longer the delay will be before the flash discharges. If one is not sure how much delay is needed, the trigger can initially be placed very close to the source and then moved farther away if necessary.

- What lens aperture will be used?

If the flash unit is used on an automatic setting, the selection of the lens aperture is easy. Set the calculator dial located on the side of the flash unit to the speed of the film being used. Then read the aperture opposite the color of the automatic setting. This assumes that the flash unit and camera are the same distance from the subject. If this is not the case, the auto-thyristor module can be moved to the location of the camera using an *auto-thyristor extender cord*. Ask the instructor for one.

Note: If you have substituted a variable resistor for the auto-thyristor module, you may need to use trial-and-error in order to determine the correct exposure. Alternatively, you can quickly determine exposure if you have access to a flash exposure meter.

1. Before taking photographs, you'll need to prepare a table to record information about each photograph that you take. With this data and the corresponding set of prints, you'll be able to decide how to make changes in your setup in order to improve the photographs for your next roll of film. In addition, if you happen to discover something interesting, you'll have the record to corroborate your discovery. A table for your first roll of film is given on the next page, and descriptions of the column headings follow that. Additional data pages are included at the end of this manual.

2. Set up to take a photograph of a balloon burst. If you have a tripod, use it to mount your camera. You may also find it convenient to use a flash clamp to clamp the flash to the table. Be careful, though, to place it so that you are not prone to bump into as you move around.

3. Once you are set up, check to make sure that the lens aperture is correct, the camera shutter is placed on B, and the lens is focused on the subject. Then turn out the room lights, hold the shutter open, pop the balloon, close the shutter, and turn on the lights. Try again, using a different sound trigger position to capture the burst in a different stage.

4. You can use the same setup as above to photograph the smash of a light bulb. Simply replace the balloon with a bulb. You could drop the bulb from a height onto the table or hit it with a heavy object. As a safety precaution, wear safety glasses if you are close to the bulb. You may find that the sound trigger has to be placed much further away than for a balloon burst. This is because the bulb breaks much slower than the balloon bursts.

Descriptions of column headings

ROLL DESCRIPTION: Give a descriptive title to identify the roll of film being shot (for example, *Needle bursts of air balloons*)

ROLL ID: Give a shorthand code to identify each roll (for example, *LW-1*)

DATE: Give the date or dates when the photos were taken.

PHOTOGRAPHER: Your own name and any other direct contributors to the photos

CAMERA: Manufacturer and model of the camera used

CAMERA LENS: Manufacturer, model, and focal length of the lens used

FILM USED: Manufacturer and type of film used

FILM SPEED: ISO number of the film

FLASH UNIT USED: Manufacturer and model of the camera used

List data in the table consecutively as you take photographs. Be sure to include a line in the table for each frame advance of the film. If, for example, the flash doesn't fire, indicate that in the appropriate line of the data table.

FRAME COUNT: the number given by the frame counter of your camera.

NEG NO: Fill this in after you get your film developed. It's the number on the film that identifies each frame. This number may differ from the frame counter.

APERTURE: f-stop selected for the photograph

FLASH MODE: exposure mode of the flash unit (for example, *auto yellow*)

For the three distances below, be sure to indicate units of measurement (for example, *feet or meters*)

FLASH DISTANCE: distance from the flash unit to the subject of the photograph

CAMERA DISTANCE: distance from the camera to the subject

TRIGGER DISTANCE: distance from the sound trigger to the subject

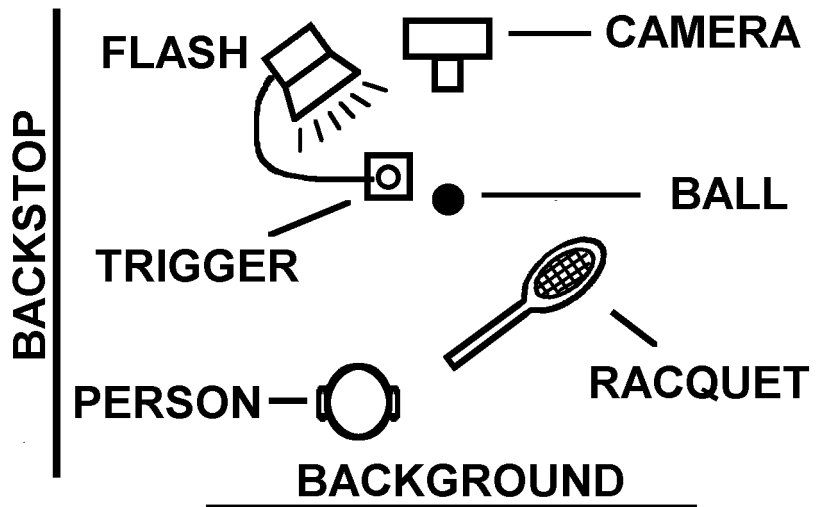
SUBJECT DESCRIPTION: Describe what you photographed. Tell enough to allow you to match the negative with the data (for example: *red air balloon, late rip*)

Activity 6. Photographing the smash of a tennis ball or racquetball

Additional equipment: Piezoelectric sound trigger
Tennis ball or racquetball and racket
Large cloth sheet or blanket

The setup for this photograph is more involved than that of a balloon burst, but it can easily be done in a classroom. A typical arrangement is shown in the overhead on the next page. Place the sound trigger as close as possible to the place where the collision of the ball and racket occurs. If one were doing a forehand shot, for example, the sound trigger could be placed on a stool or box about a foot below the spot where the racket met the ball. Of course, sufficient room would have to be left around the person wielding the racket to allow freedom of movement.

The background can be a problem if you plan to include the person swinging the racket in the photo. You may want to dispense with a hung background and simply make sure the subject is far from a wall and that distracting objects are removed from the background.



The ball can easily be stopped without rebound in a sheet or blanket hung from the ceiling or held at the ends by two people. The position selected for the camera depends on whether one wants a side view, front view, or back view of the ball. The flash position should be selected so as to avoid throwing unwanted shadows across the ball.

Set the sensitivity of the trigger as high as possible. A piezoelectric sound trigger may not work consistently for the thud produced in the collision of the racket and ball.¹³

¹³ For a much more sensitive trigger, try the tape recorder sound trigger described in Appendix E. Take note of the special precaution given in Activity 8.

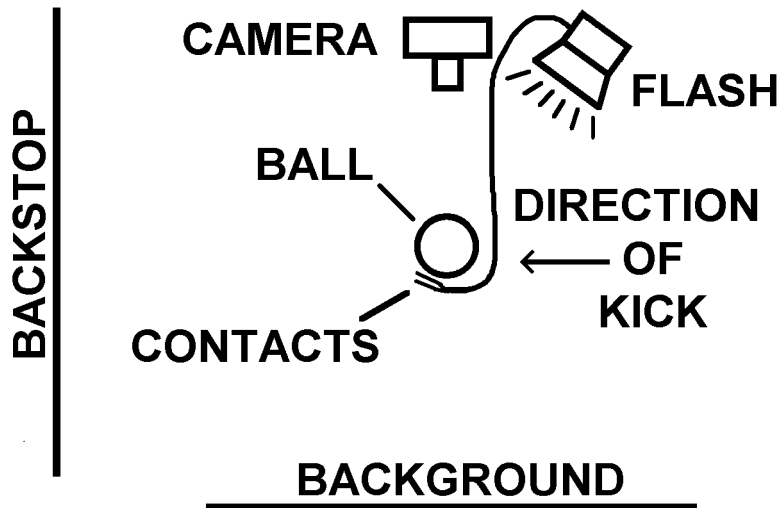
Before attempting photographs, have the person who swings the racket take some practice swings with the room lights on. Then repeat with the lights off. If the room is too dark, a penlight can be used to illuminate the ball during the swing. The flash will probably be bright enough in comparison so that the light from the penlight is not noticeable.

If you wish, try different camera, flash, and sound trigger positions in order to examine how the shape of the ball changes throughout a collision. Also, compare the deformation of a tennis ball to that of a racquetball, which is much softer than a tennis ball.

Activity 7. Using a contact trigger to capture a football kick

Additional equipment: 1-2 m long hookup wires
Aluminum foil
Football and tee
Backstop blanket

This activity uses a very simple trigger, a metallic switch, to photograph a football kick. Two wires are connected to the PC cord¹⁴ and are placed in front of the football so that they are not touching. When the football is kicked, the wires touch and the flash discharges.



The arrangement of equipment is shown in the overhead view to the right. The football rests on a tee. A heavy blanket hanging from the ceiling serves as the backstop. The bottom of the blanket should not be secured tightly; otherwise, the ball will bounce from it. Secure it just enough to prevent the ball from slipping underneath. It will help if the blanket drags the floor. It's also a good idea to place a large foam pad below the blanket to keep the ball from bouncing off the floor.

¹⁴ The wires may be taped to the terminals of the PC cord using the method described in Appendix D.

The camera may rest on the floor or be raised with a stack of books. The flash is placed nearby. The wires from the PC cord should be taped in place in front of the ball (or just to the side if you don't want the wires in the photograph). Small strips of aluminum foil can be taped to the bare ends of the wires to provide greater contact area. When the ball is kicked, it should force the wires into contact and set off the flash unit. You may want to experiment with the positioning of the wires in order to capture the football at different stages during the kick.

Activity 8. Photographing waveforms on an elastic band

Additional equipment: Tape recorder sound trigger
Large rubber band

With a sensitive sound trigger, a snapped elastic band can be observed almost immediately after its release. The tape recorder sound trigger described in Appendix E works particularly well for this.

Use a large rubber band or a length of elastic cord. If you use a rubber band, cut it so that you can stretch it end-to-end. Hold the microphone of the tape recorder near the point where the band will be plucked. Aim the flash unit at the band. When the band is plucked and the flash discharges, the initial waveform can be observed.¹⁵ To observe the waveform at a later time, move the microphone further from the release point of the cord.

If photographs are to be taken, one must be aware that the small size of the subject will fool the flash unit's automatic exposure circuit. The exposure of the film will be determined primarily by the light reflected from the background. This will quench the flash discharge later than needed for correct exposure of the cord. The problem can be minimized by hanging a background (even a dark one) within about a meter of the cord. One could also try photographing a shadow of the cord cast on a white background.

Special precaution: Another problem in taking photographs is that the click of the camera shutter may actuate the sound trigger prematurely, giving unwanted exposures. To avoid this, hold a hand over the camera lens while opening the shutter.

¹⁵ For an explanation of the interesting waveforms produced on the cord, see Refs. 9 and 10 in Appendix B.

SECTION III. Photogate Triggers and Delay Units

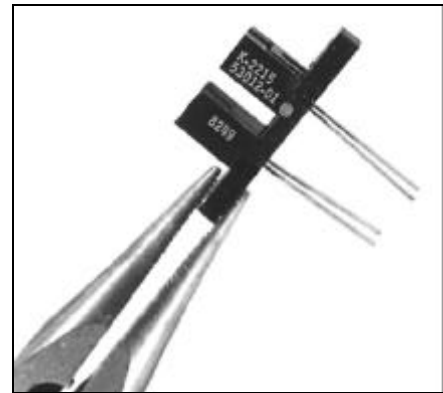
The common items of equipment for the activities in this section are a Vivitar 283 flash unit and instruction booklet, PC cord, SB-4 adapter, extension cord, flash clamp, camera, film, and background cloth. Additional items for particular activities are listed at the beginning of the corresponding activity.

Activity 9. Using an interrupter photogate to observe a plucked cord

Additional equipment: Interrupter photogate trigger
Elastic cord (approx. 1/8" diameter and 0.5 m long)
Two supports for the cord

Background: A **photogate** consists of an **emitter** and **detector** of light aimed at each other. The emitter may produce a beam of visible or infrared light. The interruption of the beam serves as the triggering event. The emitter may be a **light-emitting diode** (LED), a laser, or a beam of white light from, say, a penlight. The detector is a **phototransistor**, serving as a variable resistor whose resistance depends on the intensity of detected light.

Circuit diagrams and parts lists for photogate triggers are given in Appendix F. Two types are described. The one that has a transistor switch will be used in this activity. This trigger has a very rapid response that will be needed for capturing a fast-moving cord. The photogate itself is an interrupter, described in Appendix F. A photograph of an interrupter being held by a pair of needlenose pliers is shown to the right. One

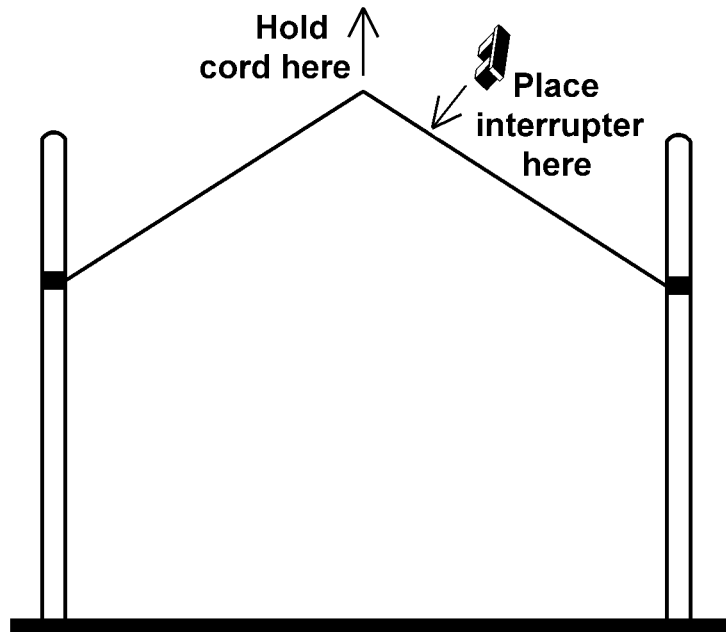


post of the interrupter houses an infrared LED and the other post houses the detector. The two parts face inward across the narrow gap between the posts. When the cord passes between the gap, a flash unit will discharge.

If you did Activity 8, you used a sensitive sound trigger to observe the shape of a plucked, elastic cord. In this activity, the interrupter photogate will be used for observing the shape.¹⁶

1. You'll first need to adjust the photogate trigger for maximum sensitivity. Turn the sensitivity knob (or variable resistance) one way or the other until the flash discharges spontaneously. Then back off slightly to the point where the flash will discharge when something is passed through the gap of the interrupter. What you have done is found the threshold for spontaneous triggering. As long as the resistor is just below the threshold, the trigger will be at its most sensitive. Above the threshold, the trigger will not function.

2. Stretch the elastic cord horizontally between two fixed supports as shown in the diagram. Pull the cord upward at the center and hold it steady. Bring the gap of the interrupter down over the cord on one of the diagonal sides so that when the cord is released, it will pass out of the slot and discharge the flash unit.



3. Try placing the interrupter at different positions. This will change the time delay between the release of the cord and the discharge of the flash unit. The closer the interrupter is placed to one of the fixed ends, the longer the time delay will be, because the wave will have to travel farther before reaching the interrupter.

4. Try releasing the cord from different positions. For example, pluck the cord one-quarter of the way from one end to the other.

5. If you wish to take photographs, review the techniques of Activity 5.

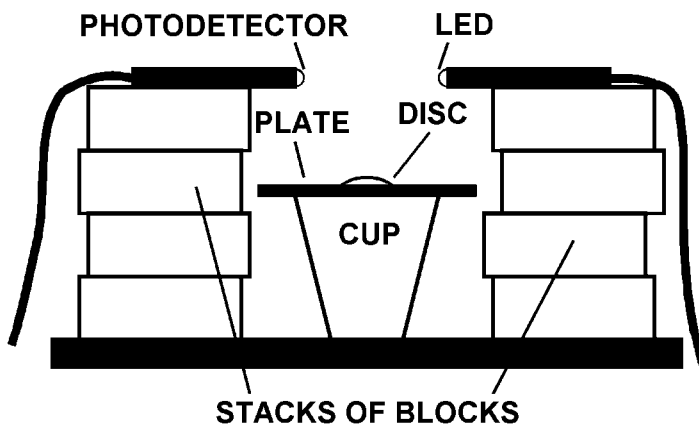
¹⁶ Refs. 9 and 10 of Appendix B provide an explanation of the shapes using the physics of waves.

Activity 10. Capturing vertical jumps with a photogate

Additional equipment: Photogate trigger (transistor type)
Jumping discs

Background: The discs that you will use in this activity are made from bimetallic strips. The top and bottom of each disc are actually made of thin pieces of two different metals such as brass and iron. These metals expand (or contract) at different rates when heated (or cooled). This effect makes it possible for a disc to jump off a table on its own. The disc has two states which can be obtained by snapping the center of the disc in or out. The disc naturally snaps into its low-energy state when left on its own. In order to make the disc work, snap it into its high-energy state and hold it there while heating it in your hand. Then place the disc, convex upward, on a cool surface. As the disc cools, the metal on top contracts faster than the metal on the bottom. This soon causes the disc to snap back to its low-energy state. When it does so, the middle part pushes off of the table, causing the disc to jump. While the disc used in this activity is a novelty, bimetallic strips are extremely important as temperature sensors in heating systems.

1. In the last activity, you used an interrupter as the photogate. In this activity, you'll set up a photogate using a separate LED and photodetector (PD). Put together the equipment shown in the diagram. You'll need a cool surface to make the disc to jump



quickly. One way to cool down a surface rapidly is to fill a cup with ice and then fill it with water to the very top. Then place a metal plate on top of the cup. The plate will cool down very fast. Tape the LED and PD into place a few inches above the center of the plate, using blocks or other risers to position the photogate at the right height. Aim the LED and PD at each other several inches apart. Check to see that the flash discharges when you pass your hand through the photogate. If the flash doesn't discharge, check the alignment of the LED and PD. Also try adjusting the sensitivity control. If this doesn't work, bring the LED and PD

close together, about an inch apart. Once you get the photogate working, then you can move the two parts away from each other gradually, checking to make sure that the photogate continues to work. When you have the LED and PD positioned where you want them, adjust the sensitivity for a maximum as described in Activity 9.

2. Prepare a disc for jumping as described in the *Background*. Then place it in the center of the metal plate. When it jumps and passes through the photogate, the flash unit will discharge and you'll be able to see the disc. Does the disc flip as it jumps? You can try placing the photogate at different heights in order to see the disc in different parts of its jump.¹⁷ You can also try putting several discs on the plate at once. They won't all jump at the same time, so you can see them one after the other.

A related activity--Capturing the burst of a popcorn kernel: If you can capture a jumping disc with a photogate, you can also capture a jumping popcorn kernel as it pops. This is easiest to do by heating one kernel at a time on a hot plate. You'll need to put your LED and PD far apart and just above the surface of the hot plate. This will require some careful adjusting. Do this before turning on the hot plate so that you don't burn yourself.

A good way to heat a single kernel is to place it inside a small iron washer and then put a few drops of cooking oil inside the washer. Position the washer so that the kernel will pass through the photogate as it's jumping off the hot plate. Most kernels open very rapidly, so you'll probably see the kernel bursting open.

You may find that the spray of oil from the burst can break the infrared beam prematurely. If so, decrease the sensitivity of the detector so that tiny oil globules will not trigger the flash unit.

One problem with taking photos of bursting popcorn kernels is that you're never sure when they're going to pop. You may have to hold the shutter of your camera open for a long time in the dark room, waiting for the kernel to pop. After a while, you may learn to anticipate when a kernel is going to pop so that you can open the shutter just before that. Some variables that you'll learn to optimize if you work long enough are the temperature of the griddle and

¹⁷ You'll learn in the next activity how to use an electronic circuit to create a time delay between the interruption of the photogate and the discharge of the flash unit. If you already know how to use this circuit, you could use it with the jumping disc.

the amount of oil that you drop in the washer. You need to be patient and be willing to make many trials. You may want to try placing the photogate at different heights above the hot plate so that you can capture a kernel later in its burst. Be careful not get cooking oil spray on your camera and, more importantly, in your eyes. It may be a good idea to wear glasses or goggles.

Activity 11. Using an electronic delay with a contact trigger

Additional equipment: Electronic delay unit with selection of capacitors
Contact trigger
Rubber ball
Squish ball
Water balloon

Background: When using a photogate trigger, the flash discharges as soon as the beam is broken. For some situations, it may be desirable to have a time delay between the breaking of the beam and the discharge of the flash unit. For example, if a ball were dropped through the photogate, a delay would be necessary in order to capture the ball as it collided with a table or the floor. A delay circuit that can be used with the photogate trigger is described in Appendix G. The purpose of this activity will be to learn how to use the electronic delay with another type of trigger, called a **contact trigger**. A contact trigger is simply composed of two metal strips or plates that are normally held a small distance apart by an insulator. The two plates are connected with wires to the PC cord of a flash unit. When the plates are forced together by, say, a colliding object, the flash unit will discharge. A method of making a contact trigger such as the one that will be used in this activity is described in Appendix H.

1. Connect a flash unit to output 2 of the delay box. Connect the leads of a 1- μf capacitor to the clips on the side of the box. This capacitor and the setting of the variable resistor determine the length of the delay. Turn the resistor to mid range. Then push the test button to trigger the flash unit. You should notice a short delay before the flash unit discharges. Try turning the resistor to different values to see how that affects the delay. What is the maximum value of the delay?¹⁸ the minimum value? You'll probably find that when the resistor is turned

¹⁸ The delay (in seconds) is approximately equal to the product of the capacitance (in μf) and the setting of the variable resistor (in $\text{M}\Omega$). If the maximum value of the variable resistor is 1 $\text{M}\Omega$, as in the circuit of Appendix G, then the maximum time delay with a 1- μf capacitor is 1 second.

too low, the flash will not discharge at all. Now replace the 1- μf capacitor with the 0.1- μf one. Is the delay noticeable? Whenever using the delay box, you'll need to decide what capacitor to use in order to get best results.

2. Place the contact trigger on a table. Connect the wire leads to the input of the delay box. Aim the flash unit so that it will illuminate a ball as it strikes the table. A squish ball (available at some toy stores) works best for short drops. Use the delay box, with an appropriate capacitor selection, to observe the collision of the ball with the trigger at different times after contact. Some trial and error may be necessary to determine which capacitor is best. The best selection will allow you to scan the entire time interval of the collision--but not much more than that--by turning the variable resistor through its entire range. One problem that you may notice in using the contact trigger is that the flash unit discharges on consecutive bounces of the ball. Turn on the reset delay switch to eliminate these unwanted flash discharges.¹⁹

3. Try dropping a water balloon onto the trigger. First, put the contact trigger into a plastic bag with only the wires coming out. Seal the bag well to keep water from leaking into it. Set the trigger on a slightly raised platform in a tray to catch water in case the balloon breaks. You can probably use the same capacitor as for the squish ball. The water balloon takes on an interesting variety of shapes will it is collapsing onto the trigger and also while it is rebounding. Be sure to scan the entire time interval of the collision and a little beyond.

Note: You may wish to calibrate the delay unit so that you know the values of the delays for various resistor settings. This can be done by connecting flash units to both of the outputs and measuring the time interval between flash discharges with a high-speed clock. (See Activity 3.)

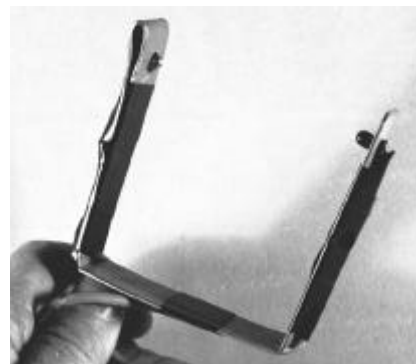
Activity 12. Plucked cords and rubber bands

Additional equipment: Bracket photogate
Photogate trigger (transistor type) and cord to delay unit
Electronic delay unit with selection of capacitors
Elastic cord
Two supports for the cord

¹⁹ See Appendix G for to find out how different reset delay times are achieved.

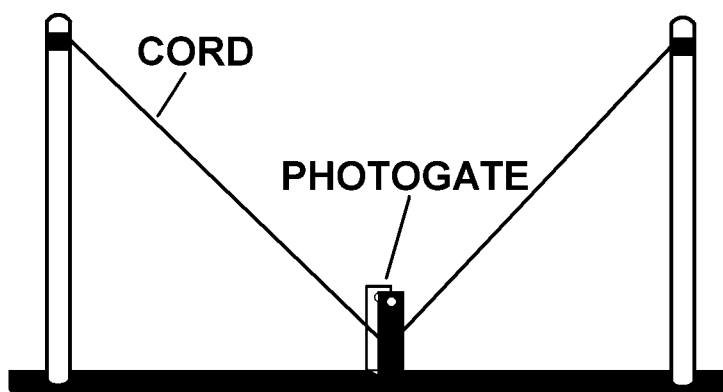
Rubber band gun

Background: In Activity 9, you used an interrupter photogate to observe waveforms on a plucked, elastic cord. You achieved different delays by moving the interrupter to various positions along the cord. In this activity, you'll use a bracket-type photogate in a fixed position in order to obtain a wider range of delays. The



bracket holds the infrared LED and photodetector farther apart than the interrupter, thus allowing larger objects to pass through.

1. In order to observe waveforms on an elastic cord, connect the photogate to the delay unit. Use a 0.01- μf capacitor with the delay unit, and connect the flash unit to output 2. Adjust the photogate to maximum sensitivity as described in Activity 9. Set up the ar-



angement shown to the right. Tape the photogate to the tabletop and stretch the cord between two fixed supports. Pull the cord down into the bracket and release it in order to discharge the flash unit. Adjust the delay in order to show the cord at different times after release. If you need greater delay times, use a larger capacitor. Adding a second 0.01- μf capacitor in parallel with the first will double the maximum delay time.

2. If you have a rubber band gun, hold the end of the barrel near the photogate and fire a rubber band through the photogate. Adjust the delay to show the band at various times after it leaves the gun.

Activity 13. Photographing splashes

Additional equipment: Photogate trigger (Schmitt trigger type) and cord to delay unit
Electronic delay with 0.5- μf capacitor
2 support stands for LED and photodetector

Milk, dropper, ball, bucket of water or aquarium tank

The Schmitt trigger photogate described in Appendix F works best for this activity. Set up a photogate with separate infrared LED and photodetector facing each other about half an inch apart and about a foot above the table top. Connect the output of the photogate to the input of the delay box, and connect output 2 of the delay box to a flash unit. Adjust the photogate for maximum sensitivity. Release a milk drop just above the gate. Adjust the delay so that you can capture the drop as it strikes the table. The 0.5-uf capacitor will provide delays up to about a half second.

Since the milk drop is small, you may not be able to get close enough to produce a large image of the splash on film. In order to produce a bigger splash, drop a ball into a bucket of water. By adjusting the delay, you should be able to see the circular wall of water that forms as the ball is breaking the surface. At slightly later times, you may be able to capture the jet of water that rises vertically as the water rushes inward to close the cavity formed by the ball. If you drop the ball into an aquarium of water and aim the flash unit through the side, you can adjust the delay to see the path of the ball in the water.

Activity 14. Using a light slave

Additional equipment: Electronic delay unit and capacitor selection
NPN phototransistor (e.g. TIL414)
Second flash unit

A light slave is a trigger that sets off one flash unit in response to the flash of light from another. These are often used by photographers to illuminate a subject with more than one flash unit without the need of long cords. The master flash unit may be used on the camera hot shoe and the slave unit positioned to the side.

The delay box can serve as a light slave simply by connecting an NPN phototransistor to the input. Connect the emitter to the positive side of the input and the collector to the negative. In this configuration, a flash of light on the transistor will have the effect of dropping the voltage across it, thus triggering the delay circuit.

Using the delay box as a light slave makes it possible to interject a time delay between the discharge of the master and slave flash units. Use one flash unit directly on your camera so

that it discharges upon pressing the shutter. Use the second flash unit, connected to output 2 of the delay box, off the camera. Of course, you'll have to select a shutter speed long enough so that the slave unit discharges before the shutter closes. And you'll have to pick relatively slow-moving objects since you have to trigger the shutter manually.

If you have a camera with an electronic shutter release, you may want to try connecting a trigger (contact, sound, or photogate) to the input of the shutter release. In that way, the event that you are photographing will trip the camera. This would make it possible to work in a room with subdued lighting, since the shutter would not be open for long. Keep in mind, though, that for most cameras there is a significant delay (hundredths of a second) between the trigger signal and the opening of the shutter.

Note: By using the delay box as a light slave and connecting a single flash unit to output 2, you can cause the flash to trigger repetitively on its own flashes of light. There is, however, a minimum delay which is influenced by the recycling time of the flash unit.

SECTION IV. Measuring Small Time Intervals and High Speeds

In addition to a camera and accessories, the activities in this section require two 283 flash units and accessories. The high-frequency clock described in Activity 3 is needed for timing. While a stroboscope is convenient for frequency measurement, an alternative is described at the end of Activity 15.

Activity 15. Speed of sound

Additional equipment: 2 piezoelectric sound triggers
Meter stick and protractor
2 wooden blocks

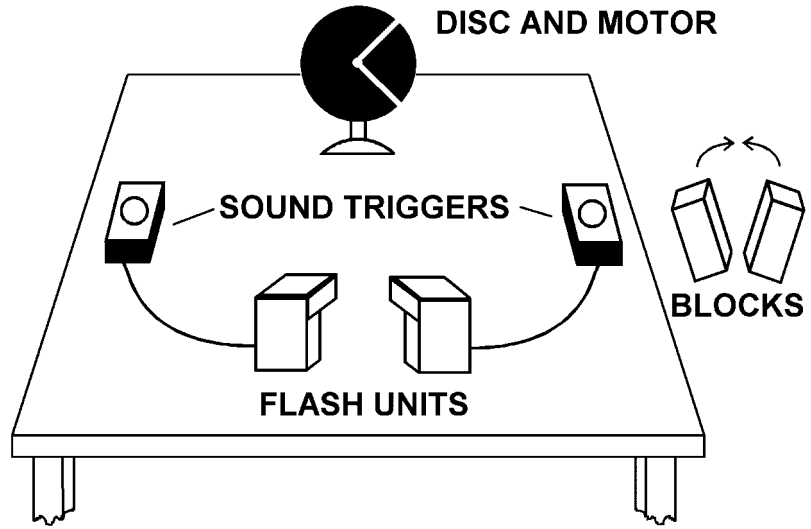
Note: Before doing this activity, try Problem 1 in Appendix I for practice.

1. For this and the next activity, you'll be using two sound triggers and two flash units. Set up the high-speed clock as you did in Activity 3 and measure its frequency. In that activity you were measuring the duration of a single flash. In this activity, you'll measure the time interval between two flash discharges to use in determining the speed of sound.

Frequency of clock =

2. Connect a sound trigger to each flash unit (in yellow automatic mode) and arrange them so that they illuminate the clock disc. Adjust each trigger for maximum sensitivity. (Note that if the sensitivity is too high, the flash will not discharge at all.) Place both triggers next to each other and stand about a meter away. Clap the blocks together, watching the rotating clock disc while you are doing this. If the two triggers have identical sensitivities, the flash units will discharge simultaneously, giving a single image of the radial line on the disc. If you see two images separated by more than a few degrees, adjust the sensitivity of one trigger until it matches that of the other. (In order to determine which flash discharged first, put a piece of colored acetate film--such as a report cover--over one of the flash units.)

3. Now place the sound triggers about a meter apart as shown in the diagram. Clap the wooden blocks next to one of the triggers while watching the clock disc. You should see two images of the hand of the clock. You can either estimate the angle between the images or take a measurement from a



photograph of the clock disc. Once you know the angle, calculate the time between the flash discharges. Dividing that into the distance between the sound triggers will give a value for the speed of sound. (If you're making visual estimates, move the triggers far enough apart to give a 90° angle between the images of the clock hand.)

Angle between images:

Time between flash discharges:

Speed of sound:

4. What are the sources of error in this experiment?

An alternative frequency measurement: Frequency can be measured using an infrared photogate interfaced to a computer. Punch a hole near the edge of the clock disc. Then position the photogate so that the hole passes through the gate once per rotation.

Activity 16. Speed of a balloon rip

Additonal equipment: 2 piezoelectric sound triggers
Meter stick and protractor
Large balloon, preferably cylindrical
Needle or pin

Note: Before doing this activity, try Problem 2 in Appendix I for practice. The photograph for that problem will also help in setting up the experiment.

1. The setup for this activity is similar to that of the previous one. Blow up a large balloon, and place sound triggers at both ends of it. Situate the clock disc above the front edge of the balloon and as nearly parallel to the film plane of the camera as possible. (See the photograph in Appendix I.) Place both flash units next to each other and just to the right out of the picture. The reason for this placement is so that the shadows cast by the rips will contrast with the rips themselves. Use the yellow automatic range, and close the lens aperture 1 stop from that indicated by the calculator dial. This corrects for the fact that the balloon will be illuminated by two flashes of light.
2. Prepare for a photograph and puncture the balloon near the left end. Make an enlargement of the negative and determine the speed of the rip according to the method of Problem 2. (Remember, you will need to know the diameter of the clock disc.)

Note: If you take photographs with a Polaroid camera, see Appendix A for suggestions. In determining exposure, remember that in this experiment each exposure results from two flashes of light.

APPENDICES

Appendix A. Using Polaroid cameras

Two Polaroid cameras that are often used for general recording purposes are the EE Special and the 240 Automatic Land. These cameras can also be used with electronic flash for high-speed photography. One should use type 667 film, an ISO-3000 black-and-white film. Getting good exposures can be tricky, since neither camera has an aperture ring. Also, the cameras cannot be placed closer than 1 m from the subject. On the EE Special, the lens is focused by turning a dial on the lens to the measured camera-to-subject distance. On the 240 Land, a lever near the shutter button is pushed back-and-forth, and a rangefinder is used to determine the best focus.

Both cameras have a photoelectric cell that measures ambient light and automatically adjusts the shutter speed for proper exposure. For high-speed photography, this cell should be covered with something opaque. This will allow the shutter to be held open as long as necessary in readiness for the flash discharge.

Given below are recommendations for obtaining good exposures with these cameras. It is assumed that a Vivitar 283 flash unit is placed half as far from the subject as the camera is and that the unit is set for minimum intensity and duration (see Activity 2). If the camera were placed at its closest focusing distance of 1 m, the flash unit would then be half a meter away. These would be typical conditions for many photographic situations.

Polaroid EE Special Camera

Set the slide bar on top of the camera to the 3000ER setting. If the photograph is overexposed, you can reduce the exposure by holding a neutral density filter over the front of the lens during the exposure. Unfortunately, the only other control over exposure is to change the flash-to-subject distance.

240 Automatic Land Camera

Set the film speed dial under the lens to 3000. Beside this dial is a lever that selects two different lighting situations. The settings are read on a panel above the lens. Set this lever to Outdoors or Flash.

Another possibility is to set the film speed to a much lower value, say, 150. Then, set the lighting selector to Bright Sun. If the photo is over- or under-exposed, the film speed dial may be adjusted either to 300 or 75.

Appendix B. References

1. James Bailey, *How to select and use Electronic Flash* (HP Books, Tucson, AZ, 1983).
2. Lester Lefkowitz, *The Kodak Workshop Series: Electronic Flash*, (Eastman Kodak, Rochester, 1986).
3. Harold E. Edgerton, *Electronic Flash, Strobe* (The MIT Press, Cambridge, MA, 1983), pp. 24-32.
4. M. L. Berry, "Stop Action Photography," *The Physics Teacher* 13, 418 (1975).
5. Harold E. Edgerton and James R. Killian, Jr., *Moments of Vision: The Stroboscopic Revolution in Photography* (The MIT Press, Cambridge, MA, 1985).
6. Estelle Jussim and Gus Kayafas, *Stopping Time*, (Abrams, New York, 1987).
7. Stephen Dalton, *Split Second*, (Salem House, Salem, NH, 1984).
8. Loren M. Winters, "High-Speed Photography with Sound Triggers", *The Physics Teacher* 28, 12 (1990).
9. Philip M. Morse, *Vibration and Sound*, (American Institute of Physics, 1976), pp.71-89.
10. Judith C. Brown, "Time-dependent behavior of strings using Fourier analysis," *American Journal of Physics* 54, 125 (1986).
11. David L. Vernier, *How to Build a Better Mousetrap*, (Vernier Software, Portland, 1986), p. 1-14.
12. Forrest M. Mims III, *555 Timer IC Circuits*, Radio Shack publication, p. 10.

Appendix C. Photographic Basics

Selecting aperture (f-stop)

If you want to take good high-speed photographs consistently, one thing you need to know is how to select the aperture of your camera lens. On most lenses, the aperture dial has a sequence of numbers 22, 16, 11, 8, 5.6, 4, 2.8, 2, 1.4, 1.0. These numbers are called f-stops and are written $f/22$, $f/16$, etc. Some lens won't go as high as 22 and most won't go as low as 1.0. The f-stop is related to the size of the aperture in an inverse way; that is, the larger the f-stop, the smaller the aperture.

It's useful to know how many times more light one aperture lets in than another. For example, $f/4$ lets in twice as much light as $f/5.6$, $f/5.6$ lets in twice as much as $f/8$, and $f/22$ lets in half as much as $f/16$. Here's a problem showing how you might use this knowledge in flash photography.

Problem: Suppose you've determined that $f/5.6$ is the best f-stop to use for taking a high-speed photograph of a bursting balloon using Kodak Gold 400 film. Another person wants to take a photograph of the same subject, but she has Kodak Gold 100 film. What f-stop should she select?

Solution: Each film has an ISO rating which indicates its sensitivity to light. (Gold 400 has ISO 400 while Gold 100 has ISO 100.) ISO 400 film is four times as sensitive to light as ISO 100. This means that the ISO 100 film requires four times as much light to produce the same exposure as the ISO 400 film. The way to get four times the light is to open the aperture wider. $f/4$ would give twice as much light as $f/5.6$. Using $f/2.8$ would give another factor of two more light. Altogether, that would be $2 \times 2 = 4$ times as much light.

Depth-of-field

The aperture that you select for a photograph affects two things: 1) the exposure of the film and 2) the depth-of-field. Depth-of-field refers to the range of distances in front of and behind the subject that will be in acceptable focus in the photograph. There are two ways to increase depth-of-field when using a particular lens:

- a. use a smaller aperture (larger f-stop),
- b. move farther from the subject,

Suppose that you're photographing a balloon burst and you want the balloon to be in focus from front-to-back. You may not want to move too far from the balloon, because you want it to appear large in the photograph. That means you would need to use a smaller aperture. This may require you to use a more sensitive film, that is, one with a larger ISO rating. (See problem above.)

Appendix D. Building your own sound trigger

For those who would like to build their own piezoelectric sound trigger from scratch, a list of parts and a circuit diagram are given below. The circuit is modeled after the one of Activity 4. Most of the parts can be found at local electronics stores. The microphone is a piezoelectric buzzer element.²⁰ The SCR must be sensitive to very small gate currents and must be able to provide up to 400-V isolation.²¹

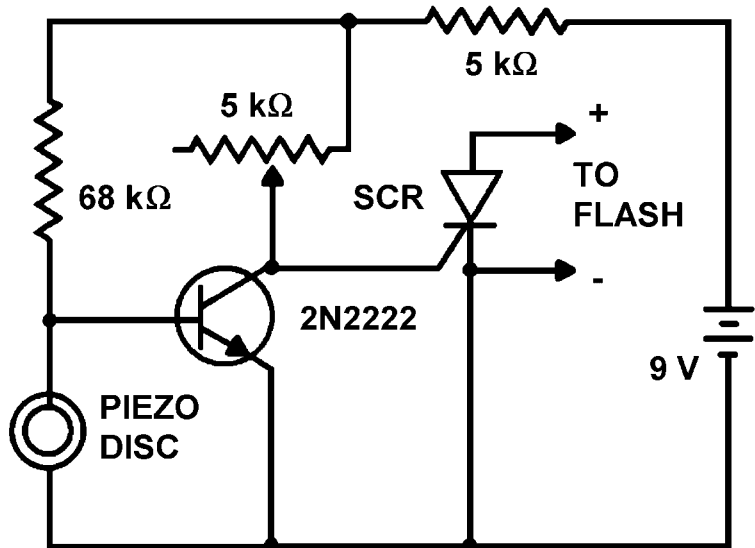
The circuit may function on less than 9 V. This depends on the sensitivity of the SCR. Try 3 V (2 AA batteries) to see if that works.

Try building the circuit on a breadboard first. Later, you may want to transfer it to a circuit board and put it in a project box with an on-off switch and output terminals.

The PC cord of the flash unit can be connected to the sound trigger without having to sever the cord to expose the bare wires. The diameter of a plastic ball-point pen cartridge is about the right size to slip inside the collar of the PC terminal, thus providing insulation between the pin collar. Wire leads can then be taped to the pin and collar.

List of parts

Piezoelectric buzzer element
MPS3904 or 2N2222 transistor
(NPN general purpose)
5-k Ω variable resistor
5-k Ω resistor
68-k Ω resistor
400-V sensitive gate SCR
9-V battery and clip



²⁰ The piezoelectric buzzer element (part no. 273-064) available from Radio Shack is a possibility.

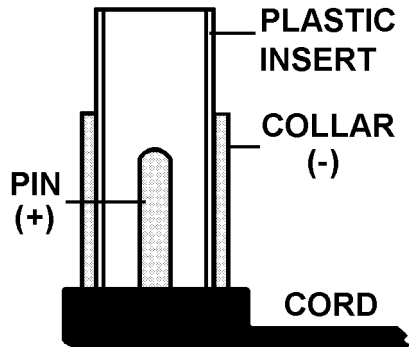
²¹ A 400-V sensitive-gate SCR (part no. EC103D) is available from Digi-Key, 701 Brooks Ave. South, P.O. Box 677, Thief River Falls, MN 56701-0677.

Appendix E. Using a tape recorder as a sound trigger

A very sensitive sound trigger can be made by using a tape recorder for the microphone and amplifier components. It will respond to thuds, such as a tennis ball colliding with a racket, and softer sounds, such as the twang of a snapped cord. The microphone of the tape recorder picks up the sound of the event to be observed. The recorder converts this sound to an electrical signal and amplifies it in order to gate an SCR. Not all tape recorders will work as sound triggers. Check to make sure that yours gives an output to the earphone while recording.

Follow the steps below to connect the tape recorder to the SCR and to the PC cord of the flash. The 400-V SCR used is available from Radio Shack (part no. 276-1020).

1) Cut a 1-cm section from the top of a plastic ballpoint pen cartridge. Insert this inside the collar of the PC cord as shown in the cutaway view to the right. If the plastic doesn't fit, shave or file off a little. The fit has to be snug to prevent the plastic from falling out. It serves as the insulation between the inner positive pin and the outer negative collar.



2) Clip the earphone off the earphone cable of the tape recorder. The leads that come from the recorder are the ones that will be used. They should be several feet long to allow the recorder to be positioned far from the flash. If they're too short, splice extra wire onto them. Strip half a centimeter of insulation from the ends of the leads. Then wrap one lead (either one) around the gate of the SCR and the other around the cathode. Solder or tape them in place.

3) Carefully bend the cathode of the SCR closer to the anode. Bend the gate farther from the anode. Then push the anode into the plastic sleeve inside the collar of the PC terminal. Be sure that the anode is pushed in far enough to make contact with the pin. Also check that the cathode is making contact on the outside of the collar. The completed assembly is shown to the right.



In order to use the sound trigger, turn the tape recorder on to the record function. (It might be necessary to insert a tape first.) A snap of the fingers in front of the microphone should set off the flash. If that doesn't work, check the electrical connections. Also, check that the tape recorder and flash are working properly. When your checks are complete, tape the cathode of the SCR securely to the collar of the PC cord.

Appendix F. Photogate trigger circuits

Two circuits are described. Each uses an infrared emitter and detector. (A penlight can provide a substitute for the infrared emitter, even when using an infrared detector.) The transistor switch has a very rapid response and is good for triggering on fast-moving objects. The Schmitt trigger works better for slow-moving objects such as a milk drop falling through the photogate.

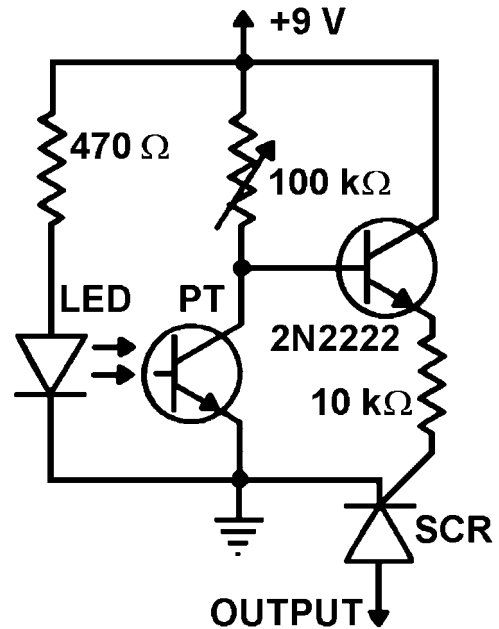
There are many infrared emitters and photodetectors that can be used with these circuits. The ones that are given in the parts lists are usually available from Radio Shack.

An interrupter is a device that includes both an emitter and detector in a single, molded-plastic package. An interrupter is useful when the object that breaks the infrared beam is narrow, since the gap between detector and emitter is only about an eighth of an inch. One possible interrupter that can be used with either circuit is given below.²²

A. Transistor switch

A photogate trigger circuit that uses a transistor is shown to the right. The 2N2222 transistor acts as a switch in the gate-cathode path of an SCR. The SCR is connected either to a flash or delay unit (see Appendix G). As long as the phototransistor is illuminated by the LED, the collector-emitter path of the 2N2222 is open. When the light is blocked, the voltage across the phototransistor rises and the 2N2222 conducts, thereby gating the SCR. (See Appendix D for an appropriate SCR.)

The sensitivity of the photogate is controlled with the 100-k Ω variable resistor.²³ This is an important feature for detecting small, fast objects and allowing large separations between the detector and emitter. For maximum sensitivity, the resistance is adjusted low enough to raise the voltage across the phototransistor to the threshold of triggering. Whenever the detector-emitter separation is increased, the resistance must be increased, since the phototransistor's own resistance rises as the illumination on it decreases.



²² An interrupter available from Digi-Key (see footnote in Appendix D for address) is part no. H21A1QT-ND.

²³ A variable resistor with a smaller range could be used for finer control at high sensitivities.

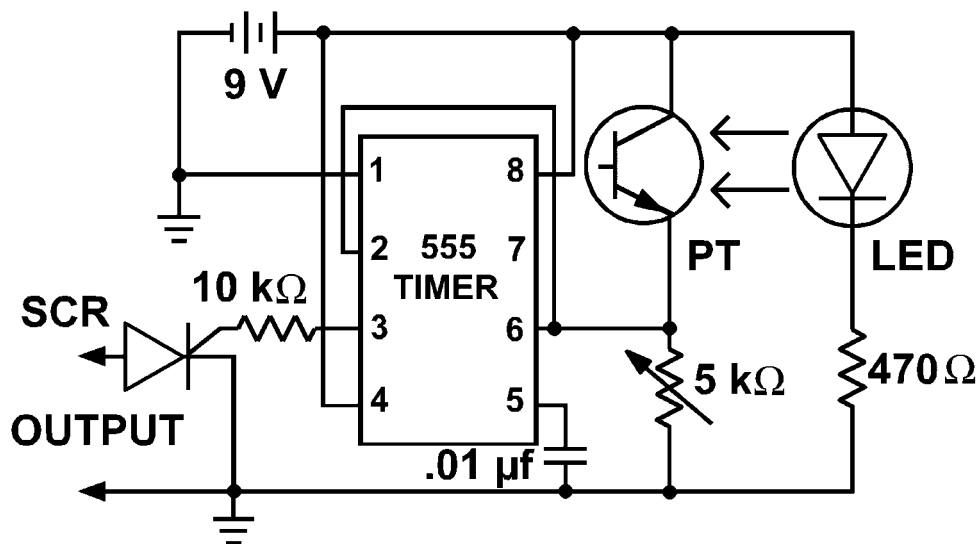
Parts list for transistor switch

Infrared emitter (XC-880-A)	470- Ω resistor
Infrared phototransistor (TIL414)	10-k Ω resistor
2N2222 transistor	400-V sensitive gate SCR
9-V battery and clip	100-k Ω variable resistor

B. Schmitt trigger

The transistor trigger may not respond well to slow-moving objects such as falling liquid drops. A Schmitt trigger provides an alternative.²⁴ The circuit uses a 555 timer IC, shown on the next page. When the light from the emitter to the phototransistor is blocked by a moving object, the voltage across the phototransistor increases. When it reaches a certain level, a square, 9-V output pulse is produced at pin 3, thus gating an SCR. (See Appendix D for an appropriate SCR.)

The sensitivity is adjusted with the 5-k Ω variable resistor.²⁵ For lower values of this resistance, the value of the phototransistor's resistance that results in triggering will also be lower. This means that triggering will occur with less blockage of the light beam. Or, if the emitter-detector separation were greater, giving a lower intensity at the detector, the variable resistance would have to be greater in order to prevent spontaneous triggering.



Parts list for Schmitt trigger

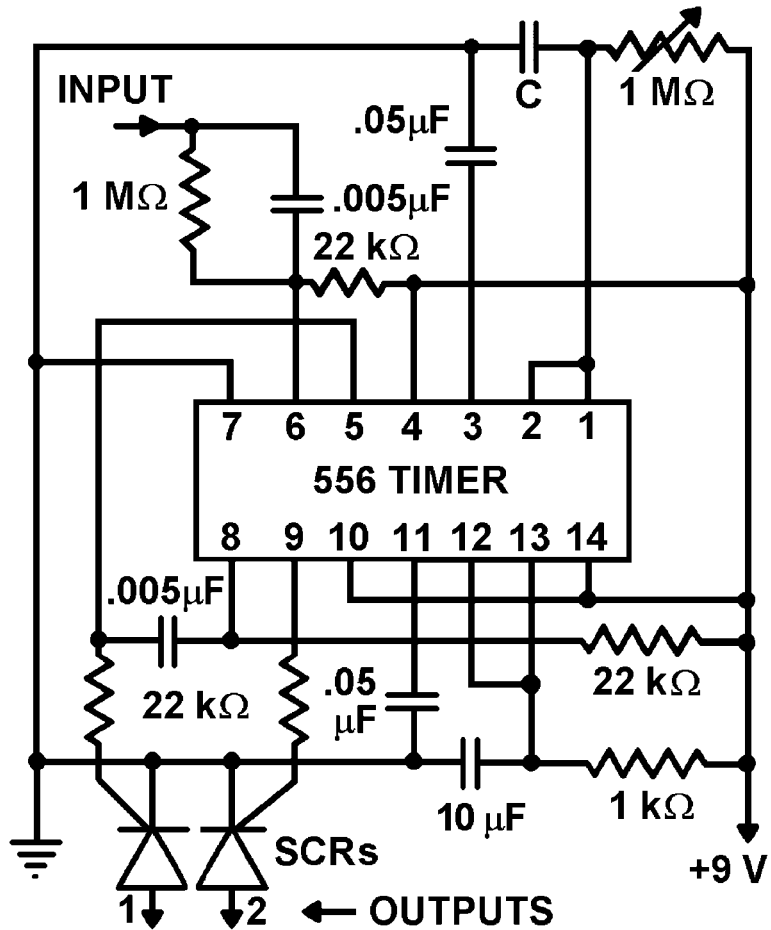
Infrared emitter (XC-880-A)	470- Ω resistor
Infrared phototransistor (TIL414)	10-k Ω resistor
555 timer IC	400-V sensitive gate SCR
0.01- μ f capacitor	5-k Ω variable resistor
9-V battery and battery clip	

²⁴ The circuit is modified from the one given in Ref. 11 of Appendix B.

²⁵ A variable resistor with a larger range may be needed as detector-emitter separation is increased.

Appendix G. Electronic delay circuit

The delay circuit shown to the right is adapted from the cascaded timer circuit described in Ref. 12 of Appendix B. A 556 timer, consisting of two 555 timers, is used. When the input is grounded or a negative input pulse provided, output 1 goes high. It remains high for a length of time that is determined by the setting of the 1-M Ω variable resistor and the value of the capacitance, C. At the end of that time, output 2 goes high, remaining high for about 10 ms. This time, termed the *reset delay*, is determined by the 10- μ f capacitor and 1 k Ω resistor. The reset delay is normally small enough to allow the flash unit to be triggered repeatedly with minimal delay. If a greater delay is desirable, the 1 k Ω -resistor can be replaced with, say, a 100-k Ω resistor.



When used with a photogate or sound trigger to discharge a flash unit, the output of the trigger becomes the input of the delay circuit. Either or both of outputs 1 and 2 can be used to trigger flash units. Output 1 is immediate, and output 2 is delayed.

Try building the circuit on a breadboard first. Later, you may want to transfer it to a circuit board and put it in a project box with an on-off switch, input and output terminals, and a selector for capacitance.

Parts List

In addition to the parts listed below, several capacitors (0.01-1.0 μ f) are needed to provide different time ranges. (This would be the value for C in the circuit diagram.) See Appendix D for appropriate SCRs.

556 timer IC

2 400-V sensitive gate SCRs

9-V battery and clip

1-M Ω variable resistor

Resistors: 1 1-k Ω , 1 100-k Ω , 1 1-M Ω , 4 22-k Ω

Capacitors: 2 0.005- μ f, 2 0.05- μ f, 1 10- μ f

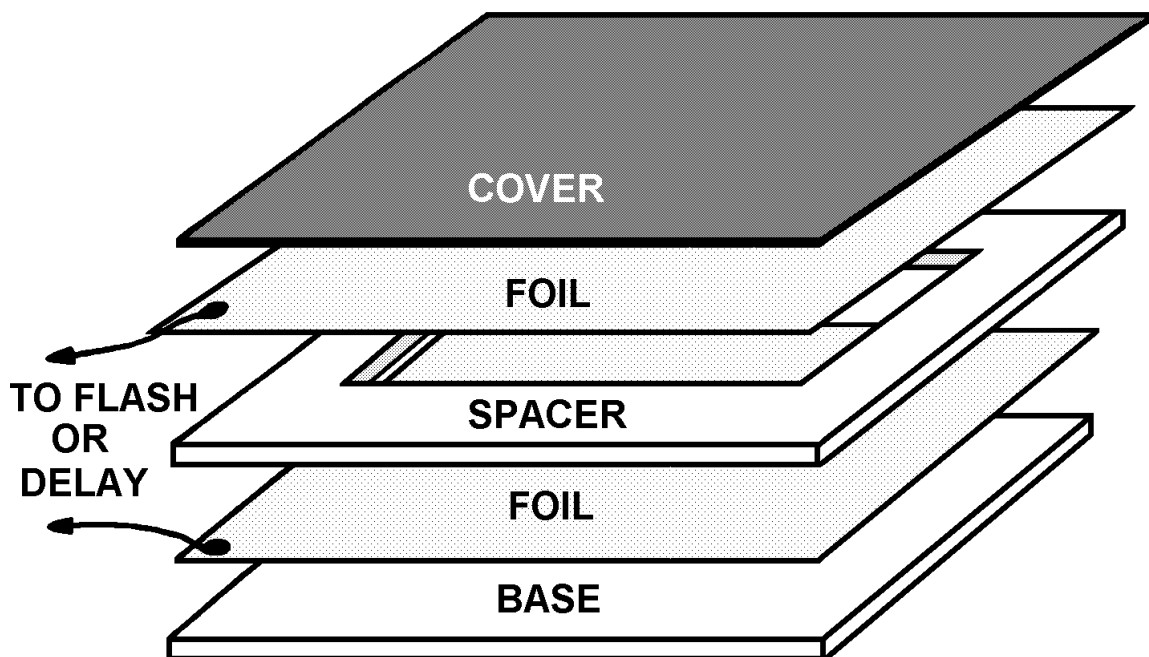
Appendix H. Making a contact trigger

Here is one way to make a contact trigger. Begin by assembling the following supplies:

- 2 20-cm squares of stiff cardboard (1-2 mm thick)
- 2 20-cm squares of aluminum foil
- 1 20-cm square of black construction paper or poster board
- Glue and tape
- 2 1-m wire leads

Now do the following:

- 1) Smooth any wrinkles out of a 20-cm square of aluminum foil. Then glue the foil to the same size stiff cardboard. Tape the bare end of a 1-m wire lead to one corner of the foil.
- 2) Smooth out another 20-cm square of aluminum foil and glue it to black poster board or construction paper of the same size. Tape another 1-m wire lead to a corner of this foil.
- 3) From a second 20-cm square of stiff cardboard, cut out a 15-cm square hole, leaving a square frame of 2.5 cm width. Glue this frame onto the foil prepared in step 2).
- 4) Arrange the various pieces as shown in the diagram below. Notice that the cardboard frame acts as a spacer to separate the pieces of foil. If an object is dropped onto the upper piece, it will be forced into contact with the lower.

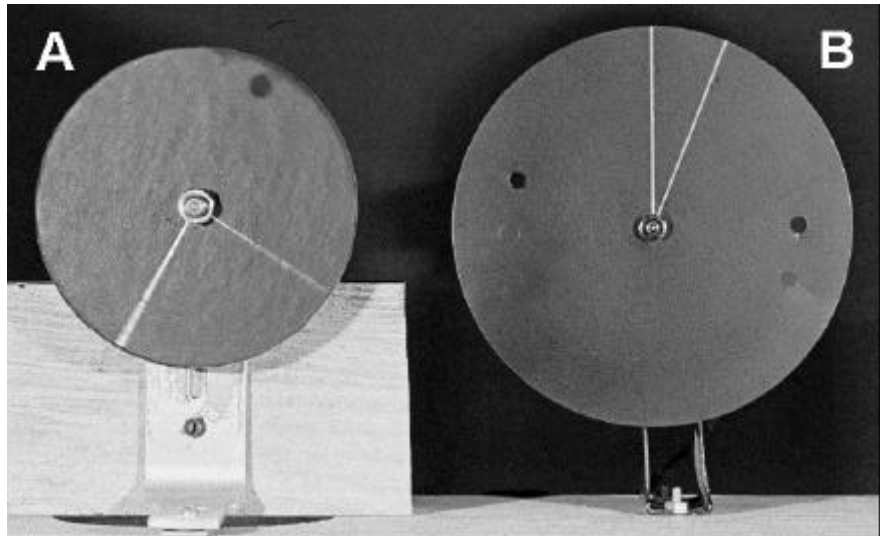


Appendix I. Problems in high-speed measurement

Problem 1. High-speed clocks

a. Clocks with rotating hands measure time in terms of the angle swept out by the hand during the time interval. Representing the angle as θ and the period of the hand as T , write an equation for the time interval, Δt , in terms of θ and T .

The photograph to the right shows two rotating discs, A and B. Although each disc has a single hand, two images of the hand are seen because the discs were lit by sequential bursts of light from two flash units. The frequency of disc B was measured with a stroboscope and found to be 50.5 rotations per second.

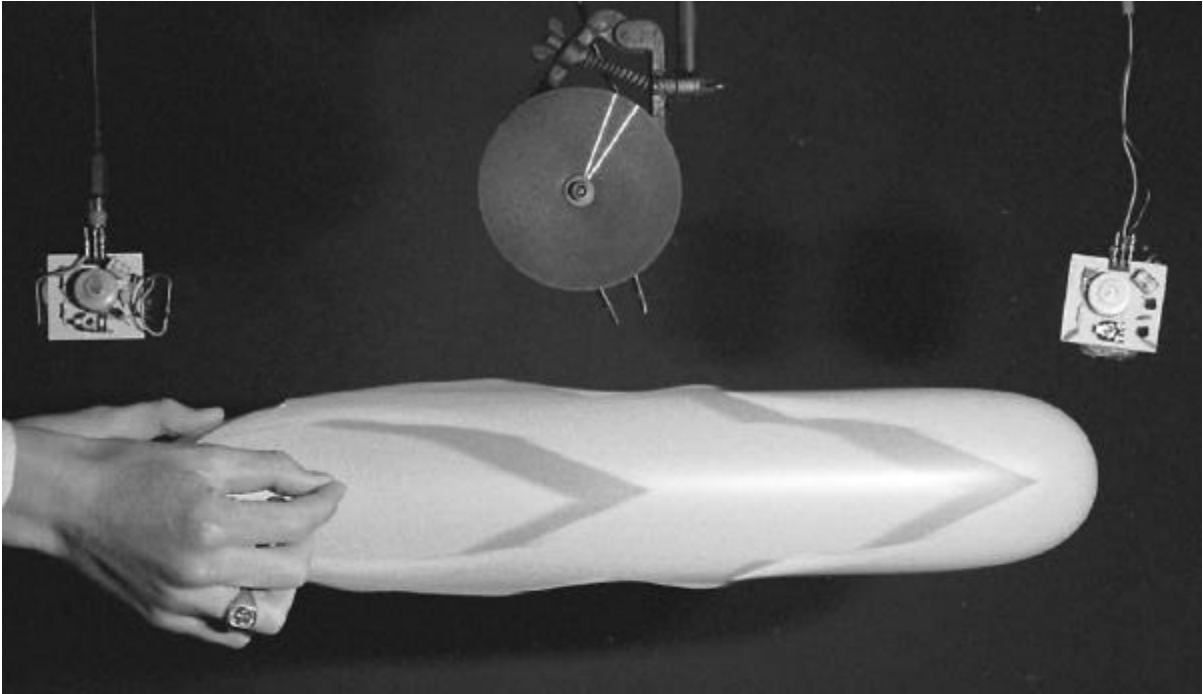


b. Determine the time interval between the bursts of light. Also estimate the uncertainty in your result, based on the accuracy and precision of your measurement of angle.

c. Determine the period of disc A.

Problem 2. Speed of a balloon rip

The figure below shows a double-exposure of a balloon rip taken according to the method of Activity 17. The frequency of the clock was 51.7 rotations per second, and the diameter of the disc was 0.105 m.



a. Measure the angle swept out by the clock hand and calculate the time interval between the flashes of light.

b. Measure the diameter of the clock disc on the photograph and calculate a scale factor to be used in converting distances measured on the photograph to actual size.

c. Measure the distance between the two images of the rip vertex. Then use the scale factor to convert to actual size.

d. Calculate the speed of the rip.

e. Estimate the uncertainties in your measurements of distance and time. Use them to estimate the uncertainty in the measurement of speed.