# Using an Apple II+ Computer as a Flash Intervalometer

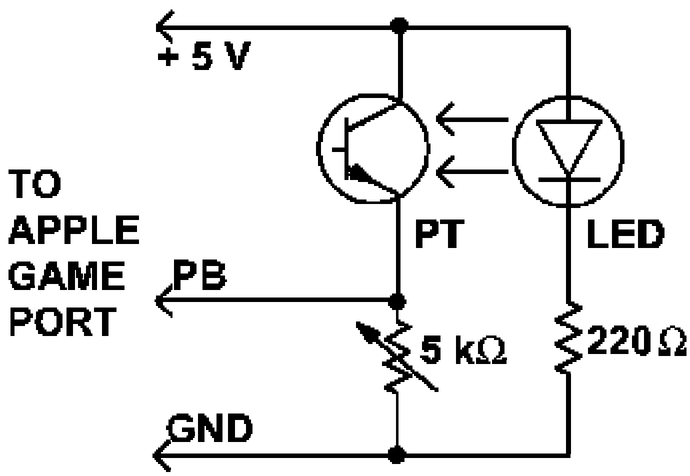
Much of the information contained herein was originally published as "High-Speed Photography with Computer Control", L.M. Winters, *The Physics Teacher 29*, 356 (1991).



*Note*: While the information in this paper is written for Apple II computers, much of it is applicable to IBM-compatible platforms. The input and output circuits, for example, could be connected to pins on a parallel port.[1] The structure of the timing and control program is applicable to computers in general, but the details of the program statements and speed of execution depends on the platform.

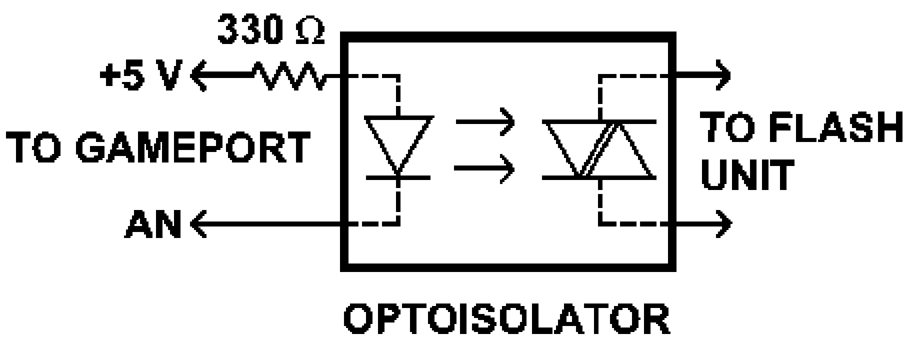
## A. Input/output circuits for Apple computers

As an intervalometer, a computer has three functions. It receives a trigger signal from a transducer, generates time intervals, and sends output signals to discharge the flash units. The interfacing hardware described below has been used with Apple II+, IIe (original version), and IIGS computers. For background information on interfacing for Apple II computers, see footnote 2.




A useful transducer for high-speed photographic projects is a phototransistor, illuminated by a narrow beam of light. Interruption of the beam provides the trigger signal for the computer. The connection of such a photogate to the game port is shown to the right. In this circuit an infrared LED shines on an infrared phototransistor.[3] The voltage at the digital input (denoted PB for pushbutton) is high as long as the infrared beam is unobstructed. When the beam is blocked by a moving object, the resistance of the phototransistor rises, and the voltage at PB falls to its logic zero value, providing a trigger signal for the computer. The variable resistor provides sensitivity control. In order to achieve greatest sensitivity, this resistance is adjusted as small as possible without producing spontaneous triggering.

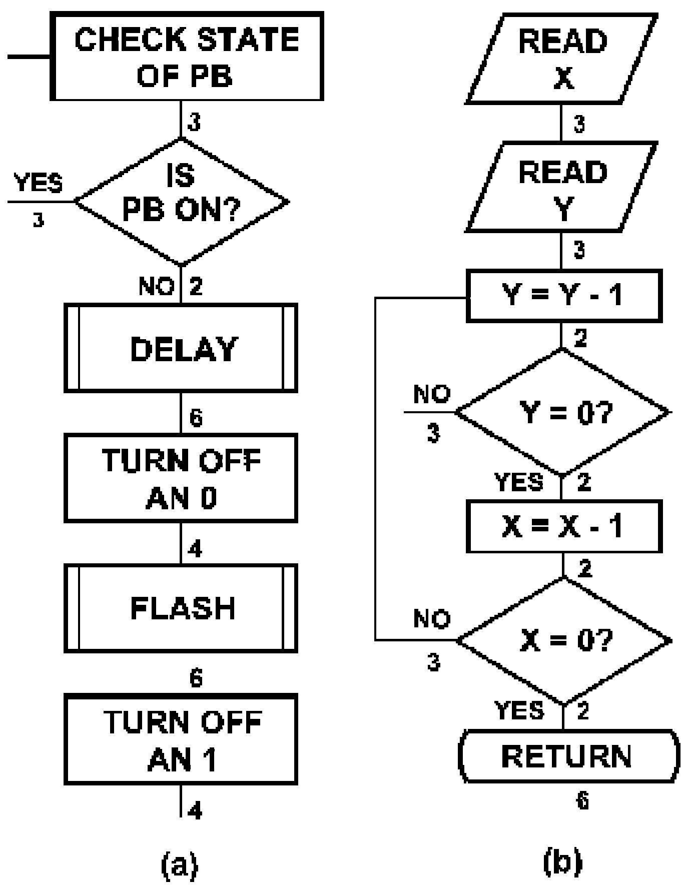
The connection of a flash unit to the game port is shown below. A buffer circuit is required to isolate the computer circuitry from the voltage across the flash terminals. This can be as high as 300 V for some units. An optoisolator with a 400-V SCR or triac output[4] provides sufficient isolation. The LED of the optoisolator is connected in series with a 330-Ω resistor between a digital output (denoted AN for annunciator) and +5 V. The output, which is initially in its high state, is switched low by a program statement in order to allow current in the LED. The SCR or triac switches on when it detects light from the LED, thereby closing the flash unit's internal trigger circuit and discharging the unit. The annunciator must then be switched high again in readiness for the next discharge.




## B. Timing with the computer

The timing and control program is written in assembly language to achieve the speed necessary for generating short time intervals and for detecting rapid signal transients from the transducer. The program monitors the photogate input, generates a delay interval between interruption of the photogate and triggering of the first flash unit, and triggers the remaining flash units at equal time intervals.

Figure (a) to the right shows a flow chart of the control program. The value given after each statement indicates the number of cycles of the system clock required to execute the statement. The state of the pushbutton input, assumed high initially, is checked repeatedly in a loop. Once the input switches low, execution passes to the DELAY subroutine, at the end of which annunciator 0 is turned off to discharge the first flash unit. The FLASH subroutine then generates a time interval before the next flash discharge, which is triggered when



annunciator 1 is turned off. If more flash units were being used, FLASH would be repeated between consecutive discharges.

The flow chart for a time delay subroutine (DELAY or FLASH) is shown in Figure (b). The initial values of the loop indices are first read into the X and Y registers. (These values are the only differences between DELAY and FLASH.) The inner Y loop counts down to 0 for each pass through the outer X loop. On each pass after the first one, the initial value in Y is 0 (equivalent to 256), so that the Y loop will be executed 256 times for each X. This continues until X has reached 0 and execution returns to the control program.

Details of the assembly-language code for the control program and timing subroutines are given in Tables 1 and 2. For more information on writing assembly-language programs and time delay routines, see reference 5.

**Table 1. Control Program**

| Description | Line No. | Op Code | Mne-monic | Address | No. Clock Cycles |
|---|---|---|---|---|---|
| Check PB1 | $0320 | 2C 62 C0 | BIT | $C062 | 4 |
| Branch if high | $0323 | 30 FB | BMI | $0320 | 3 |
| Jump to DELAY | $0325 | 20 30 03 | JSR | $0330 | 6 |
| Switch AN0 low | $0328 | AD 58 C0 | LDA | $C058 | 4 |
| Jump to FLASH | $032B | 20 40 03 | JSR | $0340 | 6 |
| Switch AN1 low | $032E | AD 5A C0 | LDA | $C05A | 4 |

**Table 2. Delay Subroutine**

| Description | Line No. | Op Code | Mne-monic | Address | No. Clock Cycles |
|---|---|---|---|---|---|
| Load X from $08 | $0330 | A6 08 | LDX | $08 | 3 |
| Load Y from $09 | $0332 | A4 09 | LDY | $09 | 3 |
| Decrement Y | $0334 | 88 | DEY | | 2 |
| Branch if not 0 | $0335 | D0 FD | BNE | $0334 | 3* |
| Decrement X | $0337 | CA | DEX | | 2 |
| Branch if not 0 | $0338 | D0 FA | BNE | $0334 | 3 |
| Return | $033A | 60 | RTS | | 6 |

*Reduce by 1 when branching does not occur.

The time intervals generated by the program depend on the initial values in X and Y, the number of clock cycles for each instruction, and the period of the system clock. If X and Y denote the initial values, it can be shown that the number, N, of clock cycles required to jump to the DELAY or FLASH subroutines, execute them, jump back, and switch an annunciator is:

$$N = 1284 \cdot X + 5 \cdot Y - 1259. \quad (1)$$

The time interval is then the product of N and the period of the clock, the latter being nearly one microsecond.

The values of X and Y needed to generate a given time interval are determined in advance in a BASIC subroutine and poked into computer memory. The algorithm for finding the values that give the closest match to the desired interval is described next.

The number of clock cycles needed to produce time interval, t, is found by dividing t by the period, T, of the system clock. Substituting this result for N into equation (1), setting Y equal to 0, and solving for X gives:

$$X = (t/T + 1259)/1284.$$

The integer value of X is taken before substituting back into equation (1). Solving for Y in that equation gives:

$$Y = (t/T - 1284 \cdot INT(X) + 1259) \div 5.$$

Y can be rounded either up or down, depending on which direction gives a closer match to the desired time interval.

X and Y can take on values from 1 to 256. Therefore, time intervals from 22 μs to a third of a second can be generated. The lower limit is smaller than the duration of the flash. In practice, flash intervals less than 100 μs are rarely, if ever, needed.

The system clock is calibrated by generating very long time delays that are compared to measurements made with a stopwatch. The DELAY subroutine is inserted within a third loop, and all the loop indices are set to 256 to give a delay of about 82 s. This entire routine is then executed 12 times to generate one billion clock cycles. When checked against the stopwatch, the period of the system clock can be determined to within about 0.01%. A value of 0.9800 ± 0.0001 μs is typical.

## References


1. For information on interfacing to IBM-compatible computers, see "IBM Adapter Interfacing," D.Synder, *Phys.Teach.,* 5/87.
2. David L. Vernier, How to Build a Better Mousetrap, (Vernier Software, Portland, 1986), pp.xxvii-xxxii.
3. Two possibilities are XC-880-A for the infrared LED and TIL414 for the phototransistor.

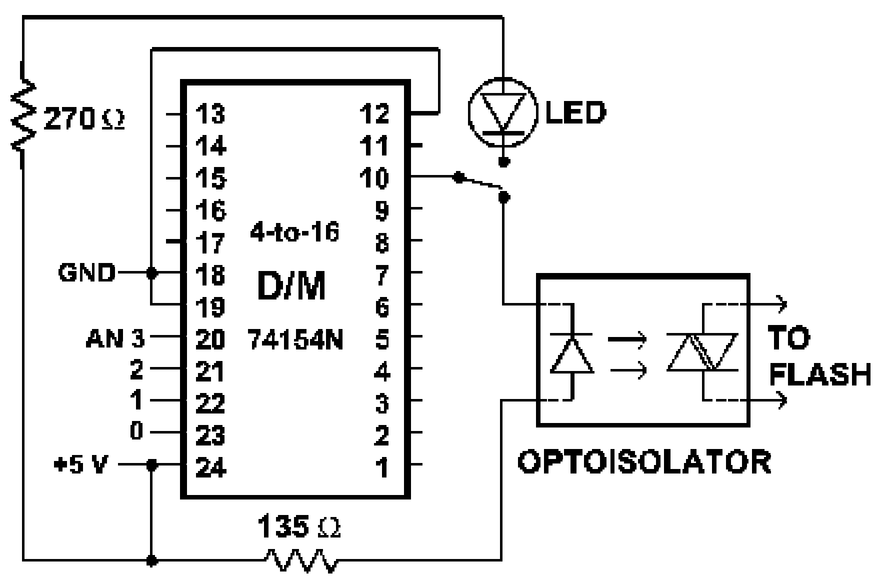
4. One possibility is the optoisolator with triac output (MCP3022GI) from Digi-Key Corporation, P.O. Box 677, Thief River Falls, MN 56701-0677.
5. Leo J. Scanlon, 6502 Software Design, (Howard W. Sams, Indianapolis, 1980). See chapter 3 for time delay programs.

# Appendix: Advanced Methods in Multiple-Flash Photography

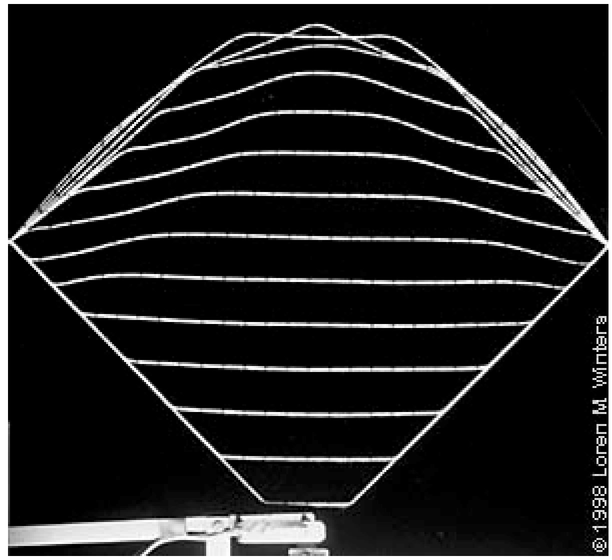


## Controlling 16 flash units with an Apple II game port

This section describes a method of using the 4 digital outputs of the game port to control as many as 16 flash units. The 4 outputs serve as inputs to a 4-to-16 decoder-demultiplexer chip.[1] A diagram of the circuit is shown below. The 16 outputs (1-11,13-17) of the chip are normally high. Each of the 16 possible combinations of the states of the 4 annunciators switches one of the outputs low. These outputs, in turn, are used either to light LEDs (for diagnostic purposes) or to control optoisolators that discharge the flash units. Such a circuit is shown connected to pin 10 as an example. In order to prevent damage to the chip from excessive current, the outputs are used as current sinks, much as the annunciators are used in the game port.




The photograph on the next page gives an example of the information that can be provided in a single frame using this interface. The photograph shows 16 successive images of a plucked elastic cord at one millisecond time intervals, spanning the first half cycle of the motion. The ends of the cord were fixed to a rigid, aluminum frame (not shown), and the center of the cord was held initially in the jaws of a metal clamp at bottom center. The trigger for the computer was an infrared photogate mounted just above the metal clamp. Marks divided the cord into 32 equal intervals so that changes in tension in different parts of the cord could be investigated. While the trajectories of some of the marks are easily traced, others are obscured by the overlap of the images. Changes from the initial trapezoidal waveform are probably due to changes in the speed of wave propagation due to changes in tension in different parts of the cord.



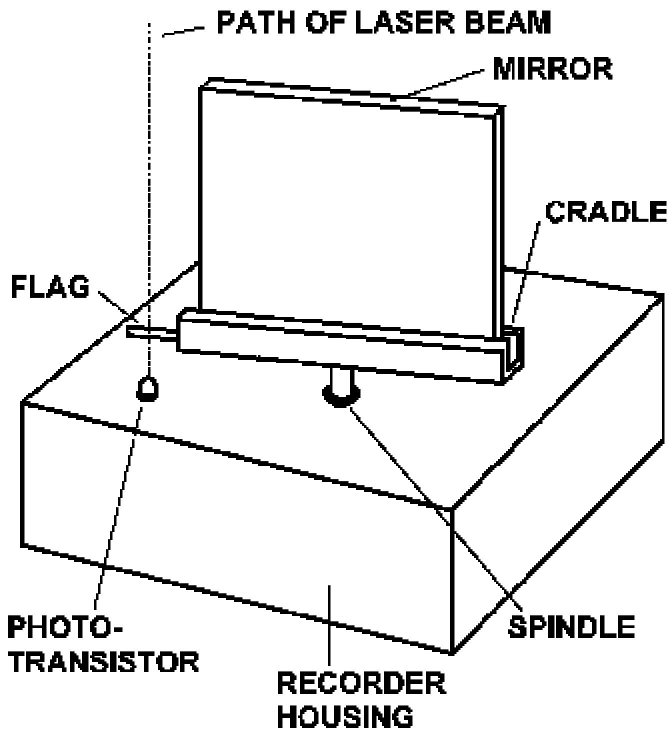

## Sweep photography

1. *The rotating mirror*

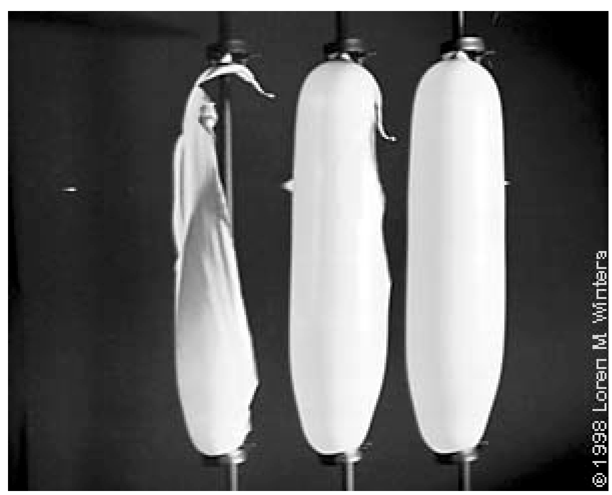
One of the difficulties encountered in extracting information from multiple-image photographs is the overlap of the images. This can be overcome by spatially separating the images on the film. A high-speed motion picture camera does this by moving the film during the exposure. Another method is to reflect the images onto the film from a mirror that rotates during the discharges of the flash units. While the first method is costly, the second can be coordinated inexpensively with a microcomputer.

The use of rotating mirrors to study time-dependent phenomena is not new. A discussion of 19th century applications is given in reference 2. In such applications, the mirror serves a purpose analogous to the horizontal sweep of an oscilloscope, sweeping time across one axis. A complication that arises for the photography of high-speed transient events is the need to synchronize the mirror's rotation with both the start of the event and the discharge of the first flash unit. A microcomputer makes this coordination possible.

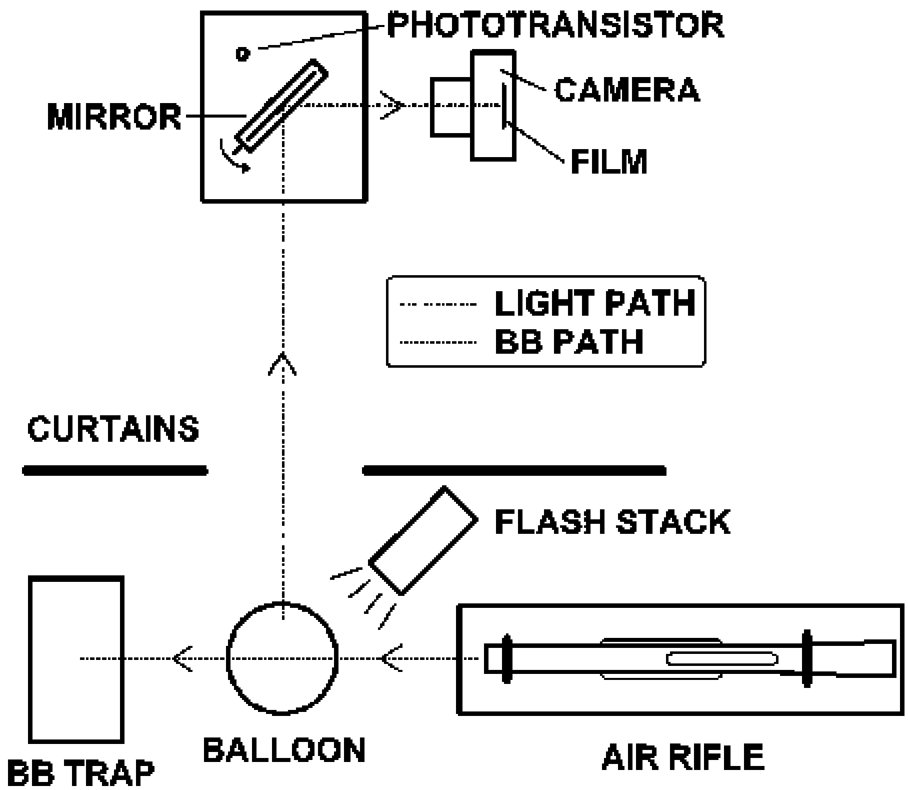
A diagram of a simple rotating mirror apparatus is on the next page. The optical-quality, front surface mirror is held upright in a wooden cradle, mounted on the spindle of a reel-to-reel tape recorder. The spindle protrudes from the center of a large belt-driven flywheel (not shown) which helps to maintain a uniform frequency of rotation. Two pulley sizes provide for frequencies of 4.8 and 9.6 rotations per second. The trigger input, connected to the computer gameport, is a phototransistor mounted in a hole drilled in the recorder platform. A laser (not shown) is directed downward onto the phototransistor to complete the photogate. A flag extending from the mirror cradle breaks the photogate once per rotation. When the computer is enabled, the first passage of the flag through the photogate starts a control and timing sequence. The frequency of the mirror is determined by using the computer to measure the time between successive passes of the flag through the photogate.




The photograph to the right was taken by student, Mitchell Bloom, who did much of the development work for this specialized rotating mirror technique. Three consecutive images, 0.80 ms apart in time, are shown of a bursting balloon being shot with a BB. The BB, which is traveling from right-to-left at 160 m/s, is just entering the balloon in the image on the right and just exiting in the center image.




The figure on the next page shows an overhead view of Bloom's experimental setup. The mirror was positioned 2.5 m from the balloon. The camera was mounted close enough to the mirror to allow the latter to fill the viewfinder. There was a narrow range of angles for which the mirror would be in position to reflect light from the balloon onto the film in the camera. Three flash units were discharged as the mirror rotated through this range. Of course, the gun had to be fired prior to this in order to allow the BB time to reach the balloon. This was achieved by using the computer to actuate, at a predetermined instant of time, a solenoid attached to the gun's trigger. The signal was provided by AN0, which was optically coupled to the solenoid. For safety purposes, a pushbutton switch was part of the output circuit. In order to fire the gun, the switch had to be held down before the computer could be enabled.




2. *Timing*

The function of the computer was to synchronize and time a chain of several events. The times of these events are specified below:

> $t_0$, when the photogate was broken by the mirror flag;
> $t_1$, when the solenoid was actuated;
> $t_2$, when the BB reached the balloon;
> $t_3$, when the mirror rotated into position for a photograph, and the first flash unit was discharged.

Letting the symbol, $t_{if}$, represent the time interval, $t_f$ - $t_i$, the following condition had to be met in order for the BB to reach the balloon as the first flash unit discharged and the mirror reached its optimum position:

$$t_{03} = t_{02} = t_{01} + t_{12}. \qquad (2)$$

The time interval, $t_{01}$, was a delay that had to be generated by the computer after the photogate was broken. In practice, the value of $t_{01}$ was found as the difference of $t_{03}$ and $t_{12}$. The interval, $t_{03}$, was calculated using the frequency of the mirror and the angle between the mirror positions at times $t_0$ and $t_3$. The interval, $t_{12}$, was determined by trial and error testing. A value was first estimated and then used in a time delay routine. Upon actuation of the solenoid, the delay would be generated. It would end with the discharge of a flash unit aimed at the BB's path. If the BB was not seen in the desired location, the time delay could be adjusted accordingly.

Condition (2) could not be met with every firing of the gun, probably due to variation in the time taken for the solenoid to pull the trigger and the BB to be discharged. This variation was usually less than half of a millisecond, resulting in a large number of successful photographs.

A second condition, relating to the sweep speed of images across the film, had to be met so that the three images of the balloon would not overlap. In deriving this condition, it is helpful to think of the mirror as stationary and the balloon as revolving around the mirror at angular velocity, $\omega$, in a circle of radius, r. (Refer to the figure of the experimental setup above for spatial relationships.) The angle through which the balloon moves in a given time is half that through which its reflection from the mirror moves. Therefore, the distance, s, through which the reflection of the balloon apparently moves in time, t, at the same radius, r, is given by:

$$s = 2r\omega t. \qquad (3)$$

Next, it is necessary to determine the corresponding distance, s', through which the image of the balloon is swept across the film in the camera. The ratio of image to object size, s'/s, is equal to that of image to object distance, q/p. Assuming the thin lens equation, $1/p + 1/q = 1/f$, one obtains after some algebraic manipulation:

$$s'/s = f/(p-f).$$

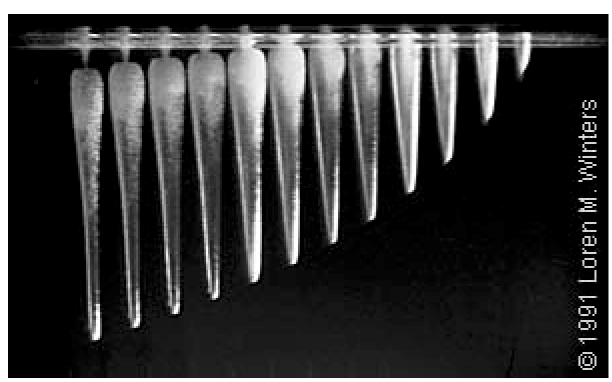
Substituting for s from equation (3) and solving for s' yields:

$$s' = [2r\omega f/(p - f)]t, \qquad (4)$$

where the expression in brackets is the sweep speed of images across the film. Typical numerical values are r = 2.5 m, p = 2.8 m, f = 0.105 m, and $\omega = 9.6\ s^{-1}$. Substitution into (4) then yields s' = (5.9 m/s)t. With a flash interval of 0.80 ms, the calculated image separation is 4.7 mm. This is in good agreement with the measured separation of 5.0 mm on the negative. Note that at a sweep speed of 5.9 m/s each image is smeared horizontally by about 0.2 mm during the 30 µs flash discharge. This accounts for some lack of sharpness in the photographs. The blurring can be reduced by using a lens of shorter focal length; however, this also reduces the image separation for the same flash interval.

3. *Sweep photography with 12 flash units*

When the interface described in Section C is coupled with the rotating mirror, the computer becomes an especially powerful analytical tool. An experiment that employed this apparatus to study the motion of high-speed projectiles in water is described in a paper by M. T. Hinshaw.[3]




The photograph shown to the right is one taken by Hinshaw. Twelve successive images are shown of the cavity created by a BB that was fired downward into water with a muzzle speed of 230 m/s. The flash units were discharged at 300 µs intervals, and a mirror rotating at 4.8 rps separated the images on the film. In order to synchronize the rotation of the mirror and the firing of the gun with the arrival of the BB at the water's surface, it was necessary to measure the speed of the BB. Knowing this, the time for the BB to travel from the end of the gun barrel to the water's surface could be predicted. The BB's speed was measured on each shot by using two infrared photogates[4] positioned 10 cm apart at the end of barrel. The computer measured the time for the BB to travel between the gates.

Single photographs like the one above provide a displacement versus time record of the BB's motion. The relationship between the position, y, below the surface of the water and the time, t, spent in the water, can be shown theoretically to have the form $y = c_1 \ln(c_2 t + 1)$, where $c_1$ and $c_2$ are constants. The derivation assumes that the drag force on the BB is proportional to the square of its speed and that the weight of the BB is neglibible in comparison to the drag force. The experimentally-determined relationship between position and time was found to be in good agreement with the theoretical prediction..

## References


1. The chip was obtained from Digi-Key (address in footnote 5) as a 4-to-16 line decoder (MM74HC154N).
2. Thomas B. Greenslade, Jr., "The rotating mirror", *Phys. Teach.* 19, 253 (1981).
3. M. T. Hinshaw, "Stroboscopic Study of High Speed Projectiles in Water," *Journal of High School Science Research* 2, 1 (1991).
4. L.M. Winters and M.T. Hinshaw, "Measuring High Speeds with Infrared Photogates", *AAPT Announcer* 20, 64 (1990).