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Velocity measurements of humans by computers

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Distance and time, two fundamental quantities, are discussed early in most introductory physics courses. By dividing a change in distance by time to get velocity, and by dividing a change in velocity by time to get acceleration, two more important quantities result. With these the real world of automobiles and jet planes and applications of Newton's second law is available for interpretation from an analytical point of view. In order to get students thinking reliably about these important ideas it seems important to have direct measurements of distance and time over short enough intervals to talk sensibly about "instantaneous" velocities.

To do this we use eight phototransistors, eight flashlights and a PET Personal Computer as the main instrumentation for three experiments:

1. Human velocity measurements
2. Human power measurements
3. Free fall and inclined-plane acceleration measurements

The apparatus is simple, inexpensive, easy to set up, easy to use, reliable, and gives results good to within 1%. The apparatus may be constructed from materials readily available at any lumber and hardware store. The experiments are appropriate for high school and introductory college physics courses and, with enhancements, may be adapted for a higher level course as well. In about 20 minutes, each student in a lab section of 25 to 30 gets unique data. The analysis is straightforward and teaches basic physics – just as it is described in any text.

Funding from a NSF CAUSE Grant[1] has given us the time to develop these and other applications of personal computers as smart instruments in physics and astronomy laboratory experiments for introductory and advanced students.

James Rafert *received his Doctoral degree in Astronomy from the University of Florida in 1977. At Appalachian State University he constructed the 18" telescope at the Dark Sky Observatory and served as its first Director. At this time he also worked with Dr. Nicklin on the computer project. Presently, Dr. Rafert serves as the Astronomy Coordinator at Stephen F. Austin State University and is building a 41" telescope. (Stephen F. Austin State University, Nacogdoches, Texas 75962)*

Robert Nicklin *received his Ph.D. in Physics from Iowa State University in 1967. During 1976 he sat in on a course on microcomputers and completely failed to understand how they work. He fought back, learned the basics, and finally developed general purpose data collection interfaces for PET and APPLE computers. This led to an NSF CAUSE Grant to develop undergraduate experiments using computers as smart instruments. (Appalachian State University, Boone, North Carolina 28608)*

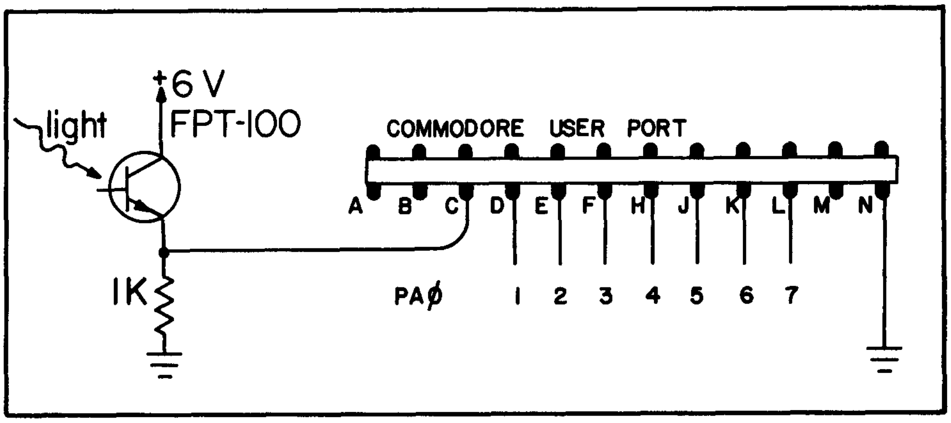


Fig. 1. The FPT-100 phototransistor interface wiring diagram. A single phototransistor is shown connected to pin C of the Commodore user port (Port A, bit 0). Seven other phototransistors are similarly connected to user port pins D, E, F, H, J, K and L. (Port A, bits 1-7).

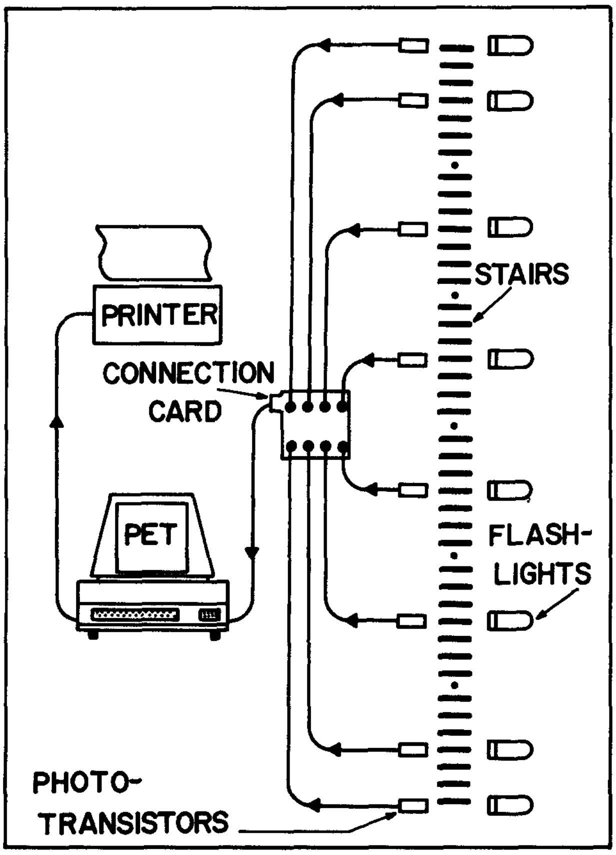


Fig. 2. Block diagram of the human-velocity or human-power apparatus. All of the detectors are connected to a single interface card, which is connected to the Commodore user port.

Basic apparatus

A. Computers and detectors

As most of the inexpensive microcomputers which are available today for use in the physics laboratory are eight-bit machines, we designed the basic apparatus to consist of eight identical flashlight/detector pairs, each of which is connected to one bit of a Commodore 4016 User Port via the circuit shown in Fig. 1. We also use Commodore disk drives and printers, although the basic apparatus is easily attached to any of the commonly used microcomputers, such as the Apple, TRS-80, or Atari.

Each of the eight detector pairs consists of a regular size hand-held flashlight as the light source, and an FPT-100 phototransistor.[2] The phototransistors are mounted in one end of a 6-in. cardboard or metal tube, and are held in place with a single-hole rubber stopper. The stopper provides a convenient mounting device for the phototransistor if the two active leads of the phototransistor are insulated with short lengths of heat-shrink tubing.

All of the detectors are powered by a 6-V lantern battery, and are energized by the flashlight beams. Even in a brightly lit hallway, the cardboard or metal tubes provide sufficient light immunity so that the phototransistors are only activated when the flashlight beam is aimed directly down the tube. After 6-10 hours of use, the flashlights still provide enough intensity to maintain a flashlight-detector spacing of 4-5 ft.

The detectors are wired to the user port consecutively: detector number one to bit 0, detector number 2 to bit 1, etc., so that as a student or object advances through the eight beams of light, the resulting interruption of each of the light beams will drive a specific bit of the user port low (to a logic 0) state. Each of the eight detectors is cabled to a single interface card[2] on which are mounted eight 1-K resistors, RCA phono jacks and some interconnecting wires.

Since we don't have enough space available to set up the apparatus used for the determination of human velocity or human power permanently, the detectors and flashlights are mounted knee-high with standard laboratory stands and three finger clamps. Total set up time for the apparatus is usually about an hour (the time it takes to scrounge up all the parts and apparatus you used and put away last time), including the collimation of the flashlights and detectors. Figure 2 shows a block diagram of the apparatus. Figure 3 shows a student sprinting through the actual apparatus.

The total cost of the apparatus is surprisingly low – even if you include a disk drive and a printer in your shopping list. Table I contains a minimum list for getting this project started. Some further economy is possible if you already own a microcomputer and some peripherals.

B. Inclined plane

For about $60, we have constructed a mobile inclined-plane apparatus which serves well for several experiments: free fall with any object such as a ball (diameter up to 9 cm); sliding friction at angles of 30 and 40 degrees; rolling objects, such as balls and soup cans. We dedicated

Fig. 3. A student can be seen running through the detector array, which has been set up in the handball court gallery of our gymnasium. Note the relatively narrow beam width of the flashlights which we used.

Table I
Apparatus required for human-velocity or power experiments

Item	Quantity	Unit cost	Cost
Flashlight (2)	8	$1.29	$10.32
Battery 1.5-V (2)	16	2/2.50	20.00
Battery 6-V (2)	1	3.20	3.20
FPT-100 (2)	8	0.90	7.20
Resistors (2)	8	5/0.40	0.64
Microcomputer (3)	1	139.00	139.00
Printer (4)	1	335.00	335.00
Wire (2)	400 ft	4.60/100 ft	18.40
Edgecard (2)	1	1.95	1.95
User port connector (5)	1	2.25	2.25

eight photodetectors and eight flashlights (in addition to the eight used for human velocity and power) to make a permanent setup. The detectors, flashlights, and cables cost an additional $120. The same interface card described in A above is used. The apparatus is hung from wall supports for storage or for the free-fall experiments. A simple platform with casters supports it when used as an inclined plane.

The inclined plane is constructed from 5/8-in. particle board and is 28 in. wide and 10 ft long. Four 2 x 4's 10 ft long on edge serve as support rails for the lights and detectors (Fig. 4). The central channel is 11 in. wide and the

Fig. 4. A basketball is shown rolling down the inclined plane, which can also be positioned vertically for free fall experiments. Also shown is our "PET on a cart," which is used with the apparatus.

outer rails are pulled in 1½ in. from the edges to protect the lights and detectors from misalignment during use or moving. The particle board provides a smooth sliding surface and also helps straighten the rails so alignment is easily maintained.

The support platform is also 28 in. x 10 ft and is constructed from 2 x 4's on edge with several flat cross members for stiffening and four small furniture casters for easy rolling. Two more 2 x 4's, 5 ft and 7 ft long and hinged to the rear of the support platform, hold the inclined plane up at either 30 or 40 degrees. The supports fold down flat for storage with the platform. The inclined plane is fastened to the platform with two pieces of 1/2 in x 6 in. threaded rod (about which it rotates when inclined). When used for free fall the plane is pushed up against a wall, the bolts are removed, and the plane is hung on the wall.

The telescopes and flashlights are each held in holes drilled in the support rails. The holes in the inner rails are just slightly larger than the tubes they contain. These holes stop about 1/4 in. short of going all the way through. A 7/8 in. hole for the flashlight beam and a 3/8 in. hole for the photodetector illumination port are then drilled in the inner rails. The holes in the outer rails are 1/2 in. larger in diameter than their respective tubes. Each telescope tube and each flashlight has three adjusting screws, 1/4-20 x 2 1/2 in. long, threaded directly into the 2 x 4 support rails, one screw from the back. The parabolic reflectors in the flashlights and the small holes nicely collimate the beams and only minor adjustments are necessary, after which the adjusting screws clamp the beams in line.

At first we thought the detectors should be spaced to give equal time intervals during free fall. Consideration of the errors involved led us to change the spacing of the top three detectors. We were able to trade off relative errors in the measurement of spacing at the top with relative errors in the time at the bottom, at least approximately.

Three meter sticks are mounted on the top of the inner detector rail. A piece of sheet metal was bent to hook over and slide along the meter sticks. A one line BASIC program:

```
10000 PRINT PEEK(59471):GOTO 10000
```

continuously reads the PET User Port and displays the value on the PET screen. When all the detectors are illuminated the value is 255. Detector spacing is easily measured to within 0.5 mm by sliding the metal sheet along and noting when the value read from the User Port changes from 255.

C. Software

We have designed a generalized program which accepts input information, acquires the data, and produces a variety of output options for each set of basic apparatus which has been discussed. An attempt has been made to make these programs as "foolproof" as is possible, although this requires a substantial investment of time – most of which is spent reducing the options which are available to the relatively unskilled user to the point where it is very difficult to bomb the program. Such an approach is required, however, if you wish to save all of the student data which has been taken on a diskette– as a blown program can lead to disaster with unclosed disk files.

We use only a few BASIC INPUT statements, as an inadvertant pressing of the RETURN key from within an INPUT statement drops the user from the program. Most options, with the exception of the student's name and mass (when appropriate), or the detector spacing (data which are entered by the instructor) are menu driven with GET statements and a few options. Some other features which have proven to be of value include: (1) a detector checking sub-

Fig. 5. Students compare their timing data after running through the human-velocity apparatus.

routine, where prior to each student's run through the apparatus, all of the detectors are polled to be sure that they are properly aligned and working; (2) a video display of each student's data set as soon as that "run" is completed.

At the end of each individual experiment, we print a hard copy of the distance and time data which each student analyzes. We also save the data on a disk file so that the instructor (via an analysis/grading program) may calculate the correct values to check the numbers computed by the students.

Two fundamentally different timing algorithms are used for the two sets of basic apparatus. For the determination of human velocity and power, the time interval between successive "breaking of the beams" is long enough that the PET jiffy clock (which is accurate to about 1/60th s) can be read and stored every time a flashlight beam is interrupted. To obtain acceptable accuracy for a freely falling object with the inclined-plane/free-fall apparatus we use a machine-language loop, which reads the User Port 1666 times/s. Several seconds worth of data can easily be taken and stored in protected memory above the BASIC program.

When the jiffy timer is being used, we have programmed the PET to accept data for students moving "one way" through the apparatus. The machine-language timing routine is capable of detecting motion in either direction, or the motion of multiple objects within the apparatus.

This same technique (and program) of data recording may be used to acquire data from an Analog to Digital Converter.[6]

Fig. 6. Prior to the start of each laboratory period, the instructor enters the distances to each of the flashlight/detector pairs. We also use the PET video output to view student data before it is printed out or stored on diskette.

General experimental method

Our classroom methodology, which is applicable to all of the experiments covered in the following section, uses a single computer and laboratory setup as a data acquisition device. For other uses see Ref. 7. Our method stresses a high level of student activity during the data-taking phases of an experiment. An experiment is chosen in which the student is likely to possess a high intuitive understanding of distance and time (such as running). This is a natural starting place to present the fundamental relations between these and related quantities.

The following procedure is employed: (1) setup and input information (detector spacing, data file name, etc.) is entered by the laboratory instructor before the experiment; (2) the eight detectors are checked via the computer to be sure they are collimated properly (this is also done automatically after acquisition of every additional data set); (3) a single experiment's data is taken – coded by student name, and recorded on both a printer and a diskette; and (4) printouts are given to the students. Typically, a laboratory section of 24 students obtains data in less than 25 minutes.

Once the data is distributed to the class, students begin their analyses. There is a bonus. Since all the data have been recorded on a diskette, and recorded by student name, a relatively simple "grading" program quickly furnishes the laboratory instructor with the correct answers required for much of the classroom analysis. The answers are different for each student. Whether or not these values are used by the instructor only for grading, or for immediate feedback or checking of partially completed laboratory exercises during the laboratory period is a matter of pedagogical choice. Here the microcomputer is being used in a different role – number crunching – than it was used for earlier in the experiment – data acquisition.

Although the natural competitive instincts of the students add a great deal to those experiments which require some physical effort, we're careful that anyone who has a physical impairment doesn't feel compelled to perform the experiment (they can use their laboratory partner's data). It is also a good idea to keep several different sizes of tennis shoes on hand if you have slippery floors.

Applications

A. Human velocity

In this application, we line the eight flashlight-detector pairs up "linear accelerator" fashion along a 15 to 30 m section of hallway. We allow about 10 m of extra space for the students to decelerate. The first three detectors are spaced at 2-m intervals, successive detectors are spread further apart in a quasi-geometrical series spacing up to the total length available. The flashlights are separated from the detectors by about 4 ft – if they are placed any closer together flying coats and feet present a hazard to the collimation of the detectors. Shown in Fig. 5 is a student viewing data from the apparatus, while Fig. 6 shows the format of the video output from the PET screen.

In order to minimize the time error which results from a differential triggering of successive detectors by different parts of the student's bodies, we require all of the

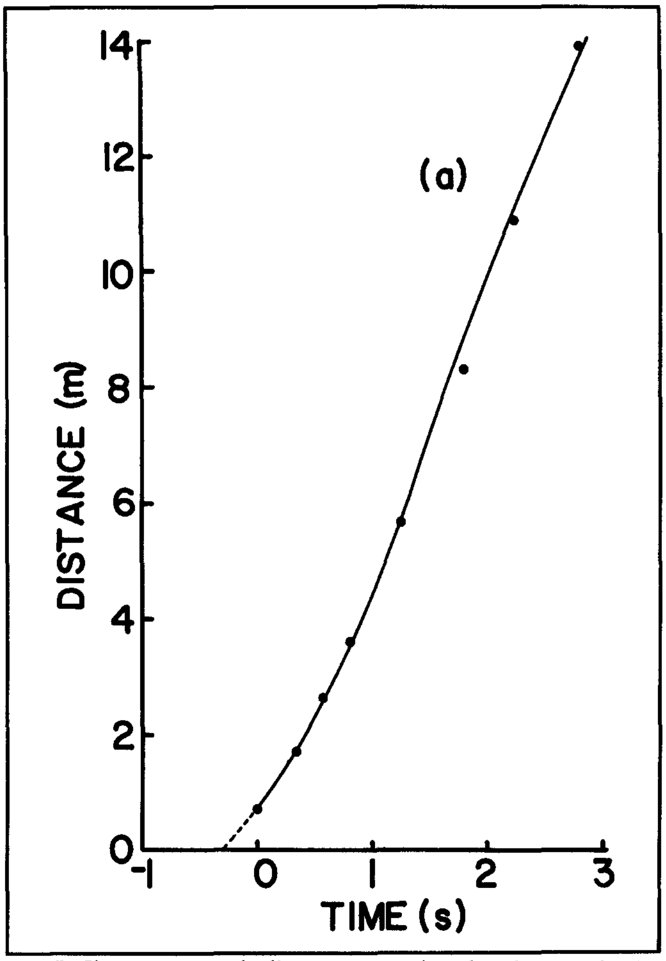


Fig. 7. Shown are sample distance versus time data for a student's efforts with the human-velocity apparatus. This run was made in the Science Building, where we were restricted to a smaller space than was available in the gymnasium.

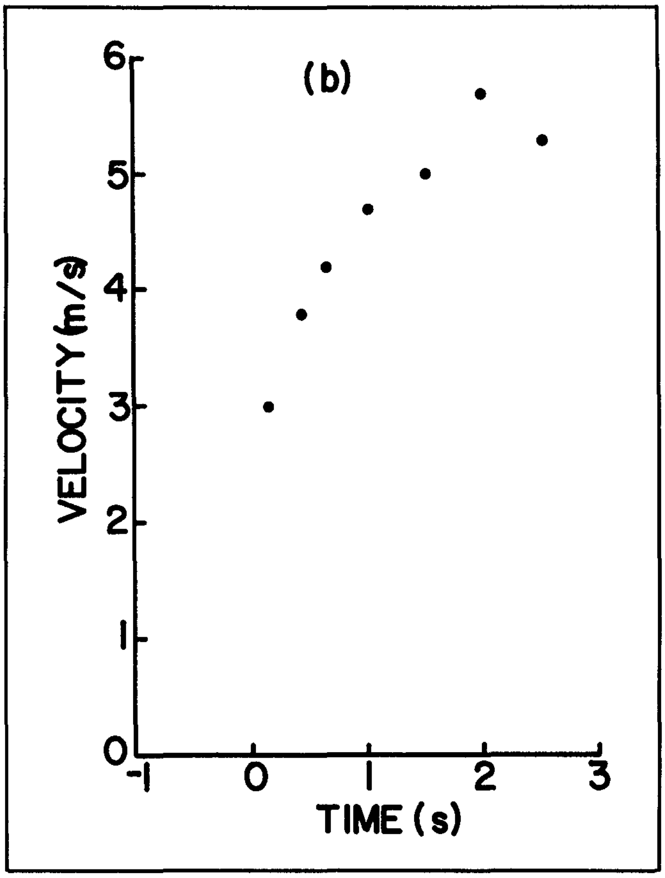


Fig. 8. A velocity versus time graph for a different run.

students to start with their hands on their heads. This greatly reduces the time error at the start where the detectors are closely spaced; further on down the apparatus the detectors are placed far enough apart, and the students are moving rapidly enough that it no longer really matters whether one of the beams is broken a fraction of a second prematurely by an arm or leg extended in front of the body. In fact, it only takes about 0.2 s longer to run 30 m with your hands held on your head than if they are allowed to swing normally. Sample graphs of distance versus time and velocity versus time are shown in Figs. 7 and 8.

B. Human power

The same apparatus can be used to measure human-power output quantitatively, and to give the student a better appreciation of the relationship between force, work, and power. Traditional measurements of human power, such as described by Nelson,[8] use a single time interval for a student to climb a known height. We have used digital stopwatches for a similar experiment for some years. However, if you're interested in an analysis which contains a section requiring a graph, or of using the concept of "instantaneous" power, the eight detectors used in the previous application can be set up on a flight of steps. We use six flights of stairs, with one detector per flight of stairs. The remaining two detectors are located at the extreme bottom and top of the six flights of stairs. A block diagram of the apparatus is shown in Fig. 2.

Locate the detectors on the inside of the stairwell, so that the cables can be draped straight down to the microcomputer. Students won't trip over them, or grab them accidentally as they are running up the stairs. This also minimizes cable length. The stairwell should be wide enough so that only half of the width is required for the flashlight-detector setup, leaving the other half of the stairwell as a return path down. Real sadists can extend this experiment to their football stadium. Shown in Fig. 9 are some sample height versus time plots. The line of lowest slope belongs to one of the authors, the next steepest line to the other author, and the line of steepest slope to a member of the track team. Table II contains some sample questions which we ask for these two applications.

C. Free-fall inclined plane

Originally we planned to build an apparatus large enough to accomodate a basketball but the practical consideration of keeping the plane to a finite weight crept in. We allowed a maximum diameter of about 3 1/2 in. for

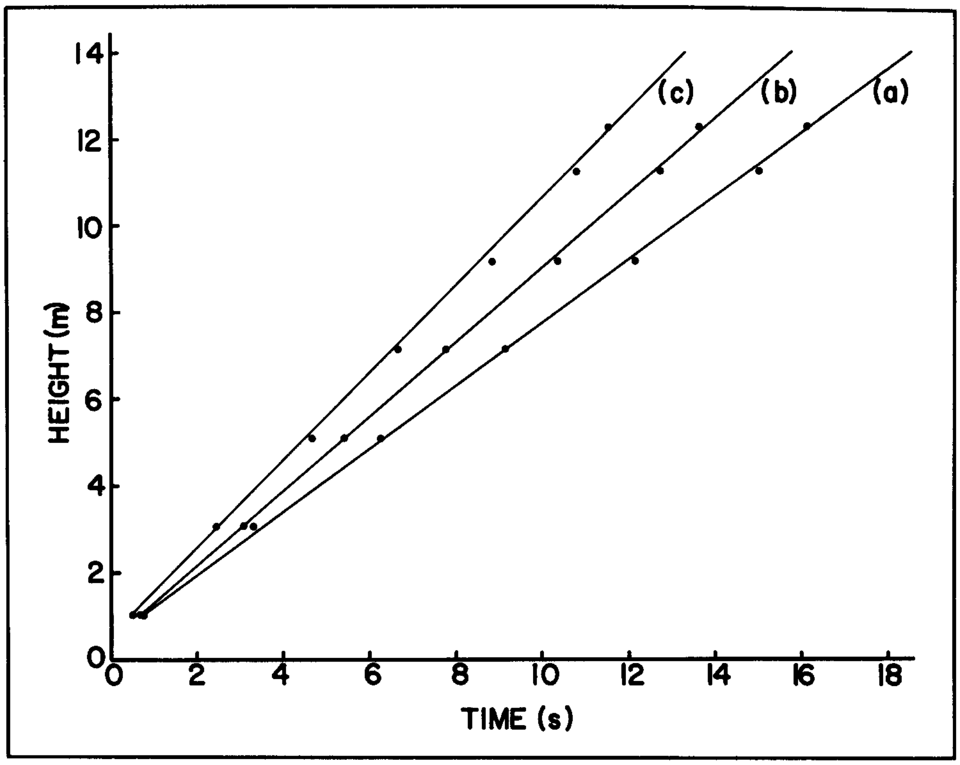


Fig. 9. Three height versus time experimental runs are plotted here. Each run consisted of a sprint up six flights of stairs.

a falling ball, determined by the 2 x 4 support rails. Still, we have a REAL free-fall apparatus. Any ball, super to nerf, makes a good falling body. A plumb bob helps to line up the detectors. At first it seemed we needed a guide tube at the top to line up the ball to hit all the light beams. It turned out that all we needed was a little practice.

Free-fall and inclined-plane experiments require a time resolution of better than 1 ms. We chose to take 1666 readings/s, although the program will run the PET at least 10 times faster. At present, two people are needed to run the experiment. One person gives a countdown and starts the computer. The other releases the falling or sliding object. The PET User Port is read 1666 times/s and the values are stored sequentially in memory. The value stored changes from 255 each time a light beam is interrupted and returns to 255 after the object passes that beam.

A short subroutine scans these memory locations and returns with the eight addresses where transitions from 255 occurred. Time in seconds from the first detector is obtained by subtracting the first transition address from all the others and then by dividing each difference by 1666. We could also retrieve the total time that each beam is interrupted and divide by the ball diameter to get the velocities at the detectors. We chose not to do this because the small diameter balls used would yield too large a relative error from the diameter measurement. This would be a particular problem for a ball falling at a slight angle to the line of the detectors. An offsetting factor is that eight, rather than seven, velocities would result and a least-squares fit might give acceptable results. A summary of timing techniques and instantaneous velocities, as applied to the determination of g is given elsewhere.[9]

When used as an inclined plane, the time resolution is still 1/1666 s and distances along the plane may still be determined to about ±0.5 mm. However, the angle of inclination has an uncertainty of about ± 0.15° at 40° because floor unevenness gives at least a ±5-mm uncertainty

Table II

Some questions for human-velocity and human-power labs:

1. How does your **largest velocity** show up on your **distance** versus **time** graph?
2. How does your **largest acceleration** show up on your **velocity** versus **time** graph?
3. How would a **negative** acceleration appear on your **velocity** versus **time** graph?
4. The world record for 100 m is 9.95 s, by J. R. Hines, and 10.88 s for women, by M. Gohr (as of April 1, 1980). Their respective average velocities are .... and ....
5. Suppose you have 5 kg strapped to each leg. How much more work would you have to do to climb the stairs?
6. Suppose you plotted **work** versus **time** instead of vertical **height** versus **time**. How would the graph look and what would be different from your **height** versus **time** graph?
7. In Boone (Feb. 1983) 1 kWh costs 4.76 cents. Calculate the cost of using electricity to lift your body to the top of the stairs. (Works out to about 0.01 cent.) Can **you** compete profitably against Duke Power by selling your physical labor?

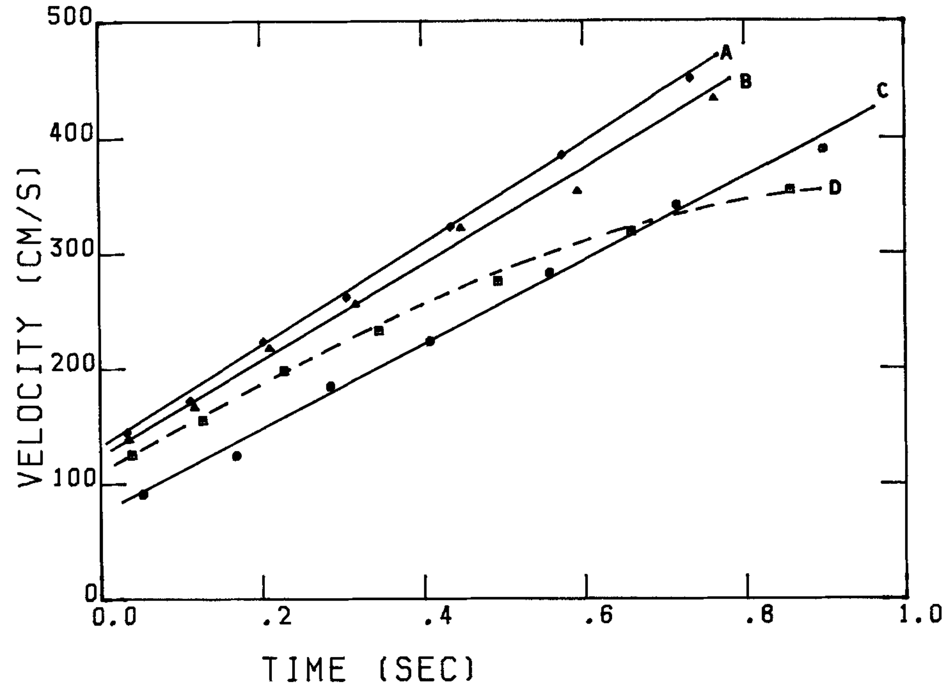


Fig. 10. Velocity versus time plots are shown for various objects which were allowed to roll or slide down the inclined plane. The behavior of a rolling rubber ball (A), a rolling soup can (split pea; solidified by age) (B), a sliding block (C), and a rolling nerf ball (D) may be compared.

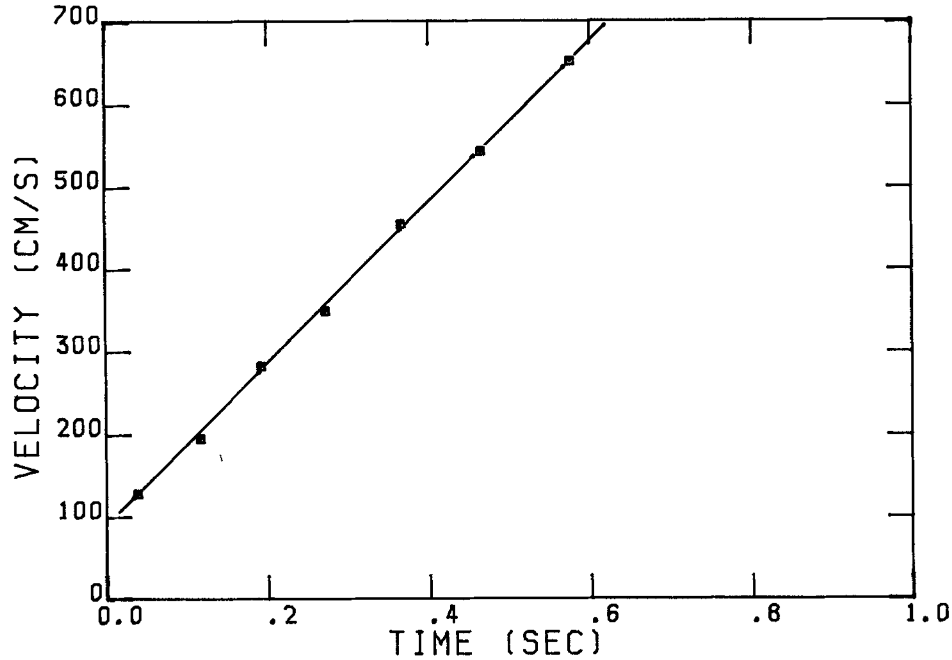


Fig. 11. A velocity versus time plot for a freely falling superball. The slope of the line is 979 cm/s/s, with a standard deviation of 5.8 cm/s/s. At these low velocities, the effect of air resistance is negligible.

in vertical height along the plane. In fact, measuring this angle accurately presents a small challenge to students.

Figure 10 shows the results of a sliding friction measurement, a rolling can of soup (with solid contents), a rolling rubber ball and a rolling nerf ball. All but the nerf exhibit constant acceleration. Figure 11 gives free fall results with a superball. Using rolling objects introduces the possibility of incorporating the moment of inertia and rotational kinetic energy into the calculations. We don't do this in the courses for which this apparatus was designed. Another possible experiment, in the vertical orientation, is measuring the coefficient of restitution of a ball. A superball, for example, will bounce straight up from a level floor. If it goes back up through at least two detectors then the incident and reflected velocities can be calculated.

Analysis and results

A recurrent experiment in introductory physics is the determination of the acceleration of gravity. We have our students use a straightforward analysis using numerical differences. We give it here in some detail as representative of the analysis of all the related experiments described in this article.

Immediately after releasing a falling object each student gets a printout of the distance and time from the first light beam. They can proceed to carry out the analysis of their data according to a plan outlined in laboratory instructions. A sample calculation is presented in Table III for a superball in free fall.

Successive differences in distance are divided by successive differences in time to produce the average velocity for the interval. This velocity is assigned to the midtime in the interval and a graph of velocity versus time is plotted. The slope gives the acceleration due to gravity. For this typical trial, a linear least-squares fit gave $g = 979$ cm/s/s and is given in Fig. 11. We get agreement to better than 1% of the local value of g and plan to make the least squares program available, in a nearly crash-proof form, to our students next year. Even minor variations in placing a transparent straightedge through the points for an eyeball fit result in ± 20 cm/s/s variations in g.

Analysis for the human-velocity and human-power experiments is similar. However, in the human-power experiment we have students find their mass, make a graph of vertical height versus time and then make a table of work versus time for their run up the stairs. Figure 9 shows three cases of vertical height plotted versus time. Interestingly, all are linear. The slopes give the constant vertical velocities. Multiplication by their mass and the acceleration of gravity gives the powers of the runners. We suspect that a run up higher stairs would reveal that this linear relationship is just the early part of a saturating exponential function which would resemble a charging capacitor. This, at least, was how another experiment[10] turned out when the students were directed to ride an exercise bicycle at full effort while their work output was measured.

Conclusion

We have used a PET personal computer as an accurate and programmable timer to support data acquisition from velocity experiments. The experiments cover falling objects, rolling or sliding objects, and human velocity, acceleration, and power measurements. Instrumentation is simple and easy to use and can be made for about $225, exclusive of the computer. A suitable computer and printer may be obtained for $500. The cost and performance compares very favorably to conventional apparatus[11] which sells for $1300 and is only good for one experiment. The experiments are suitable for high school and introductory college physics.

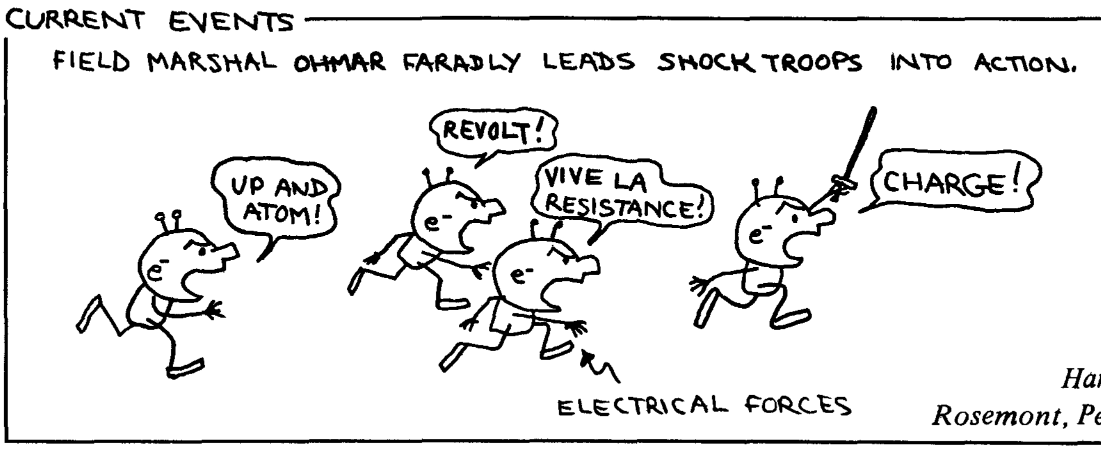
Table III

Freefall Data Analysis

Detector	Distance (cm)	Time (s)	dt (s)	ds/dt (cm/s)	t (s)
1	0	0			
			0.0834	116.9	0.0417
2	9.75	0.0834			
			0.0817	190.9	0.1242
3	25.35	0.1651			
			0.0726	276.9	0.2014
4	45.45	0.2377			
			0.0882	348.6	0.2818
5	76.20	0.3259			
			0.1003	450.6	0.3761
6	121.40	0.4262			
			0.0996	538.7	0.4760
7	175.05	0.5258			
			0.1237	654.8	0.5877
8	256.05	0.6495			

References

1. NSF CAUSE Grant No. SER-8103765.
2. Radio Shack. PC board #276-158, $1.95; flashlight #61-2624, $1.29; 1.5-V batteries #23-550, 2/$2.50; 6-V battery #23-006, $3.20; phototransistor #276-130, $0.90; 1-K resistors #271-1321, 5/$0.40; #22 stranded wire #278-1385, 100 ft/$4.59.
3. K-Mart. Commodore VIC-20, $139.
4. AB Computers, 252 Bethlehem Pike, Colmar, PA 18915. VIC Printer $335.
5. Jade Computer Products, 4091 West Rosecrans Ave., Hawthorne, CA 90250. CNE-1502411 12/24 SE for PET.
6. R. C. Nicklin and J. B. Rafert, Am. J. Phys. 51 (May 1983).
7. B. Rafert and R. C. Nicklin, Am. J. Phys. 50, 108 (1982).
8. J. H. Nelson, Phys. Teach. 10, 529 (1972).
9. J. B. Rafert and R. C. Nicklin, Am. J. Phys., in press.
10. R. C. Nicklin, Am. J. Phys. 51 (May 1983).
11. Central Scientific Co., 11222 Melrose Ave., Franklin Park, IL 60131-1364. Behr free-fall apparatus #74905-000, $752; dc supply #79563-000, $140; spark timer #74912-000, $368; falling body #00067-497, $38.25.



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