COMPUTER-VIDEO METHOD EVALUATES REAL MOTION DATA IN REAL TIME FOR STUDENTS

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Many mechanics experiments in class or laboratory employ complicated gadgets to collect and represent motion data. These devices include photocells, various types of switch, and "smart" pulleys. Sometimes these gadgets distract the student's attention away from the behavior of the moving body, which should be the primary focus of attention. Microcomputer-based methods offer a considerable advantage, and can be used in many experiments. For example, the sonic ranger allows students to record the motion of a body in one dimension. The sonic ranger, smart pulley, and other similar devices have proven successful in teaching kinematics and dynamics in one dimension. These devices, however, are normally limited to one dimension.

The video camera, on the other hand, is inherently a two-dimensional data-recording device. The difficulty lies in the conversion of information recorded by the video camera into useable, digital information. For this purpose, we devised a computer-based system that derives all relevant information from the video signal, and properly processes and displays this information.

The name of this system is Orvico (for Object Recording by Video and Computer). This system, and others that were developed independently, were first described several years ago.[1–5] Since then, we have continued to explore methods of using this approach in a variety of pedagogical experiments. We have used Orvico with PAL video (25 frames per second with 625 lines per frame), which is used in Europe, and NTSC video (30 frames per second with 525 lines per frame), which is used in the USA, Canada, and Japan. In the following we show a selection of examples for various levels of physics teaching.

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Description of Orvico

A video camera delivers electrical signals, which contain the information necessary to reconstruct the pictures (frames). For a normal scene, this information consists of a great number of single dots of various brightness (including color) within each frame. A typical color picture will contain several megabytes of information. While methods of handling this level of video data are becoming available, they require high-level computers with many megabytes of RAM and large hard drives. When we began this project, such machines were not available, and they are not yet common in school or undergraduate laboratories. Thus, we took a different approach.

Frequently, in kinematics and dynamics, students can learn much by studying the motion of a single point on an object. By limiting our analysis to that point, we reduce significantly the amount of information to be handled. In principle, the task is to observe only one single point, and nothing else. This leads to the idea that the "point mass" (the puck, the glider, the pendulum body, etc.) be marked by a bright spot and observed in front of a dark background. With only two coordinate values to be established and processed for each frame, this arrangement reduces the amount of data considerably, so that a computer can handle the task quickly and easily.

To detect and store the coordinates of a bright point in a video scene, a special interface card was created. This 62-contact plug-in card can be used with any MS-DOS computer—8088 level or higher. The card is commercially available, as is the appropriate software.[6]

In general, one may extract only information about one bright point for each frame. This limitation exists for any video camera that has as output a monochrome or composite color signal. However, if a color camera with red, green, and blue outputs and a more sophisticated card are used, one may observe and record up to three points per frame. These points would need to be marked so that only one was the brightest point on the screen with each of the above-mentioned colors. An example for this extended facility is the motion of two bodies before and after a collision, as well as the motion of two bodies in a coupled oscillation. Furthermore, by marking one extended body with spots of different color, a motion composed of translation and rotation may be recorded.

Observations with one camera are bound to the focal plane. The prospect also exists of analyzing motion in three dimensions by simultaneously using two cameras and properly processing their data. This technique will not be described further in this paper.

The educational advantages of Orvico are:

• There are no data-taking gadgets, which might deflect attention from the point of the experiment. The video camera does not directly interfere with the experiment. In its function, together with the computer, it resembles the human observer's eye and brain.

• Because the on-line recorded data (time, position) are stored in the computer, they may be processed and displayed in many different ways, such as trace, stroboscopic illumination, time function, various coordinates, time derivatives by numerical calculation, integral, distribution function, and Fourier analysis. Using a computer in addition to the traditional paper and pencil, teachers and students learn to handle data and means of representation. In this way, they are able to come to conclusions more directly. In addition, students may feel motivated to produce short sequences of software to process and display the data according to their own ideas.

• The use of Orvico is not restricted to indoor or classroom activities. With a video camera and recorder, outdoor activities such as motion in sports and traffic may be recorded and later fed into the computer for processing and display. This possibility clearly matches a demand for more connections between physics instruction and everyday experiences.

Technical details of Orvico and software

Video is composed of 25 or 30 frames/s. However, to decrease noticeable flicker, each frame consists of two separate fields. The odd-numbered lines are placed on the screen (field 1); then the electron beam returns to place an even-numbered line (field 2) in between each odd-numbered pair. Commonly called interlaced video, this technique results in 50 fields/s in PAL and 60 fields/s in NTSC.

In a monochromatic picture, the brightness of each pixel is represented by a voltage. Higher voltage corresponds to a brighter point. The task of Orvico is to detect the brightest point in the picture. A brightness threshold setting, controlled with software, enables the student to suppress relatively bright objects and concentrate on the single brightest point.

The coordinates of the spot are easily derived from the video signal. By counting the lines from top to bottom, the y coordinate of the spot is defined by the number of the line that carries the signal; the x coordinate is defined by the time elapsed between the beginning of this line and the appearance of the signal. In this way the coordinates of the spot are recorded once every 1/50 or 1/60 s.

The video signal is fed directly to an electronic circuit, which is inserted into the computer and processes the data appropriately for the computer. Transition from PAL to NTSC only requires small software adjustments for scaling. The setting of the threshold to discriminate the spot against the background is done via the keyboard and may be displayed on the screen. All consecutive steps of calculation or display are achieved by the software.

In creating software to process these data, we have prepared materials that have the widest instructional applicability. Possibilities include the following:

• Recorded motion can be represented in true coordinates. The proper calibration is accomplished by recording two special positions of the point object, and entering their real distance via the keyboard. The coordinates established in this way are available for any further calculated displays. The location of the object can be displayed in real-time, i.e., as the signal enters the computer.

• Various types of screen representation (graphs) are possible in real-time as well. The (x, y) trace of the moving body within the focal plane can be shown by leaving each plotted point on the screen. Because the display flickers, this trace comes out as if the moving object were illuminated by a stroboscopic flash at the frame frequency. Representations of x vs. t or y vs. t are possible. In all cases, the "stroboscopic" points may be connected by short straight lines, which leads to an almost "continuous" trace.

• These data can be processed to obtain and represent diagrams of functions such as $x(t)$, $y(t)$, and $(x^2+y^2)^{1/2}$. As a nontrivial application, for a motion with change of direction the local acceleration may be calculated from the recorded data, and the corresponding vectors may be shown overlaid on the trace picture.

• More sophisticated graphs are also possible, such as polar representations of the coordinates $r(t)$ and

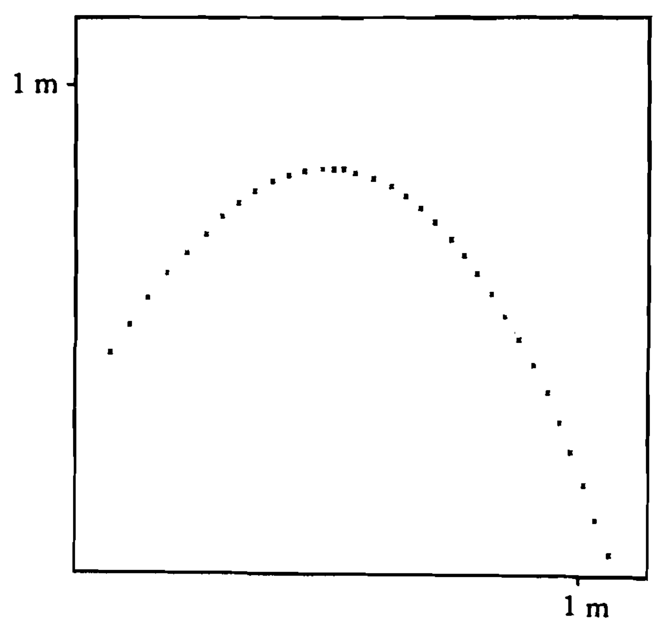


Fig. 1: Stroboscopic picture records ballistic curve of a snowball.

$\phi(t)$ with respect to an arbitrary center, and the Fourier spectrum (for a given time basis) of any periodic process, and the distribution function of statistical events.

- The software contains additional facilities for the evaluation, handling, and representation of data. These facilities include: enlarging details, simultaneous imaging of different sections, labeling of coordinates, and help.

In summary, users have some control over the manner in which the data are collected, and much control over the representation of those data. Control of the threshold of brightness provides a means by which users can select the object of interest within the scene and correct for less-than-ideal lighting situations. In addition, the users control the method of representing the data graphically on the screen. They can display a variety of graphs—such as *x-y, x-t, y-t, v-t, v-x*—in real-time, so that the graph appears as the data are being collected. For periodic data, the users may also display Fourier components, but this analysis cannot be displayed as the data are being collected.

All of these processing, analysis, and display functions are accessible through the menu structure, which guides the user to manage these possibilities and leads to various submenus. It is also possibile to insert additional program parts (written in Turbo Pascal) according to individual ideas or needs.

Examples

The following examples are selected to show typical applications for various teaching levels. They are described only to the extent necessary to make the possibilities clear. Complete details on teaching the physics related to these subjects are omitted here.

Ballistic curve. Figure 1 shows a stroboscopic picture of a ballistic curve; it was obtained by throwing a small snowball within the focal plane of the camera. (Although this was done outdoors, a classroom production would also be possible.) The time spacing between the points here is 1/50 s (with the NTSC system, other points, spaced by 1/60 s, would be obtained). In teaching this subject, one could ask the students to try to obtain a detailed description of the curve, including the extraction of $x(t)$, $y(t)$ and their time derivatives. Later, the computer may carry out this task by using the data already stored. The software to do this is, of course, available, but the teacher should also consider the advantages of letting the students try to produce the steps of the computer program for the intended evaluation. Other examples of outdoor observations are: acceleration of a vehicle, acceleration of a pedestrian's leg, movement of various parts of a gymnast performing a somersault, etc.

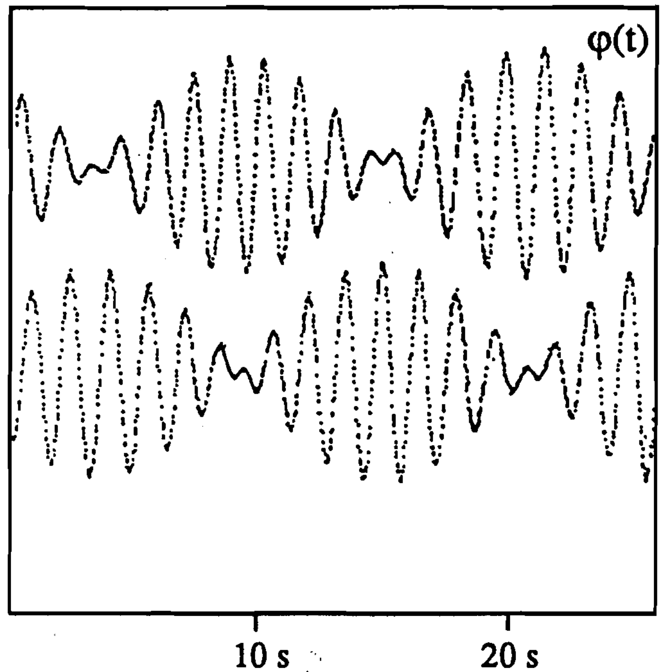


Fig. 2: Coupled pendula oscillate simultaneously while exchanging kinetic energy. Two data points were recorded for each frame by using red and green outputs from a color video camera.

Motion of pendula. Various types of pendula provide instructive subjects for investigation. We illustrate Orvico's performance with results obtained for coupled, stiff, and spherical pendula.

Figure 2 shows the well-known case of two coupled pendula; one pendulum was marked by a green spot, the other by a red spot. The "green" and "red" channels have been recorded simultaneously.

The next example is a little more unusual: A stiff pendulum (solid stick instead of a string) is observed in its circular motion around its point of suspension. Fig. 3(a) shows a stroboscopic recording when the motion is started with $v \approx 0$ at position S (point of unstable equilibrium). From the spacing of the points the varying speed is seen. As a further evaluation, the direction and magnitude of acceleration, yielding the total acting force, may be obtained from the stroboscopic points. Again, this evaluation may be done "by hand," or by software; the arrows in Fig. 3(a) are obtained in the latter way, showing the total force $\mathbf{F}_t$. This force has two components: the gravity force (weight) $\mathbf{G}$ of the body attached to the stick, and the constraining force $\mathbf{F}_c$ exerted by the solid stick. If $\mathbf{G}$ is subtracted from $\mathbf{F}_t$, then $\mathbf{F}_c$ is isolated, as shown in Fig. 3(b). Several interesting values have been labeled for $\mathbf{F}_c$. At point S, the stick has to push upwards to compensate for $\mathbf{G}$. At points A and B, $\mathbf{F}_c$ disappears; these are the points where a body rolling within a vertical circular track would jump off. Finally, at point C, the weight and the centrifugal force have the same direction.

Another interesting experiment is the spherical pendulum (a simple pendulum with two directions of free

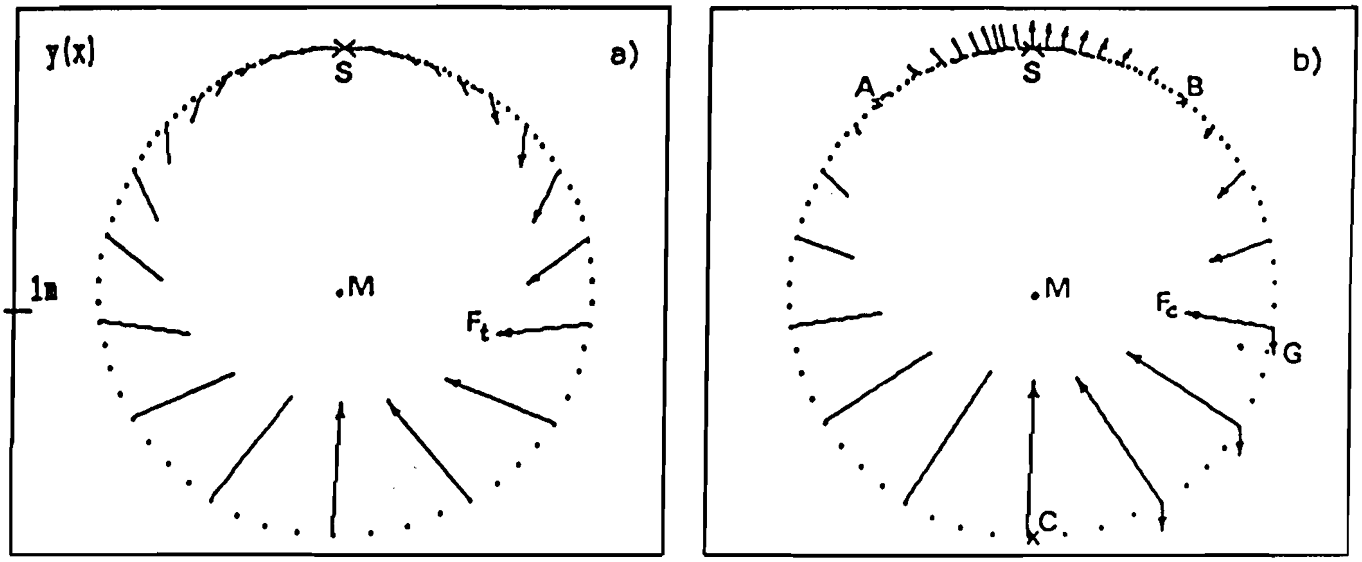


Fig. 3: (a) Stiff pendulum (solid stick) rotates in vertical plane. M = point of suspension, S = starting point. The arrows show the total force $\mathbf{F}_t$. (b) Solid stick exerts a constraining force $\mathbf{F}_c$ such that $\mathbf{F}_c + \mathbf{G} = \mathbf{F}_t$.

motion). A bright spot marks the lowest point of the pendulum body, and the camera is placed underneath the pendulum, looking upwards so as to record its motion. Fig. 4(a) gives one example, showing the precession of the motion (arising from different periods of oscillation in the two perpendicular directions, due to different amplitudes in the two directions).

A chaotic pendular motion is shown in Figs. 4(b) and 4(c). The setup is the same as for Fig. 4(a), with additional nonlinear forces introduced. (The pendulum body is a permanent magnet and below it four other repelling magnets are fixed to a horizontal glass plate. The camera is looking through the glass plate from underneath.) You can see one characteristic of chaotic motion (long-time divergence in spite of very similar initial conditions).

Collisions on air track. Two bodies marked by two different colors may move toward each other on the air track and collide. We show the Orvico recording of the position/time function of two colliding bodies for two cases [see Figs. 5(a) and 5(b)]. As one possibility for evaluation, the position of the center of gravity C is

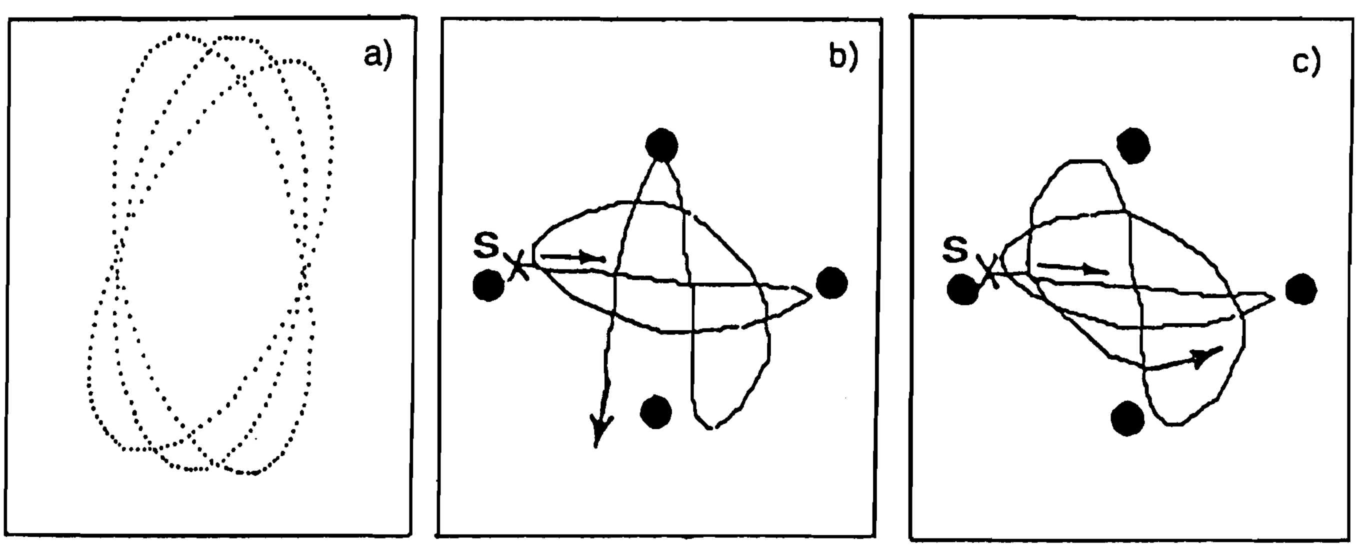


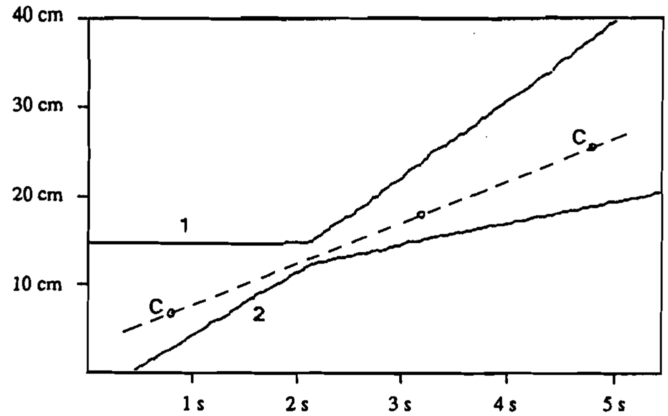
Fig. 4: (a) Spherical pendulum precesses as it traverses a curve in a horizontal plane. Because the precession is very slow, we show only three full periods, which are separated by longer periods without recording. (b) Nonlinear forces induce chaotic behavior in spherical pendulum. The black dots represent four magnets that repel the pendulum bob. S = starting point. (c) Experiment illustrates the nonreproducibility of chaotic motion. At the start of the experiment, the traces are very similar to those in part (b), but later they deviate strongly from the previous situation.

inserted into the graphs following the experiment. The speed of C comes out to be the same before and after the collision.

Statistical motion on air table. One puck is marked with a white dot, and its movement among 10 other pucks on an air table of area 1 m^2 is recorded by Orvico in the stroboscopic mode [see Fig. 6(a)]. One can see various characteristics of this situation. Because there are no long-distance interactions, the motion of these hard spheres proceeds in a straight line between collisions. Various spacings of points indicate various speeds, and various distances between collisions indicate various lengths of free path. Distribution functions may be established by a tedious evaluation of this picture, but this job may also be done by the computer [see Fig. 6(b)].

An interesting variation of this setup is shown in Fig. 7(a). Here, a small air table 0.1 m^2 in area is filled with small pucks that are repelling magnets. Because of the magnetic field, the trace of the observed puck no longer follows a straight line between the hard collisions. Still more interesting is an effect that shows up as the number of pucks is increased [see Fig. 7(b)]. The observed puck, then, is mainly found at distinct places, suggesting that a "solid" begins to develop with a higher density of particles.

Moving frames of reference. The frame of reference in all Orvico recordings rests within the camera (in the examples described above, the camera was at rest in the laboratory). Consequences concerning moving frames of reference may be drawn from data delivered by a moving camera. As an example, we show the



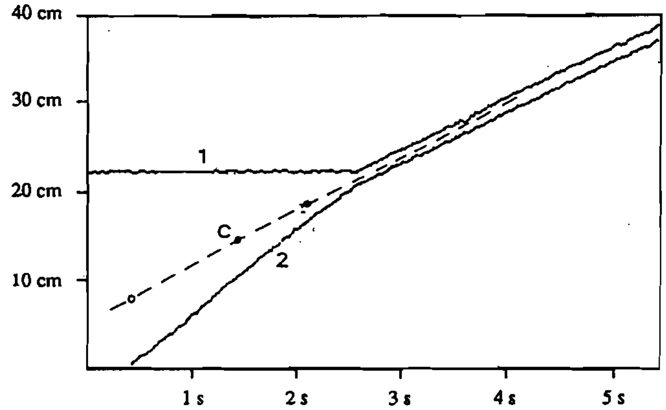
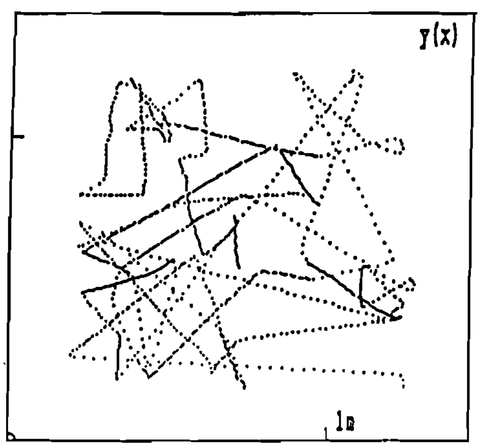


Fig. 5: (a) Two bodies collide elastically on an air track. Body 1 has a mass of 100 g; body 2, 200 g. The dotted line, which represents the position of the center of mass C, was inserted after the display was created. (b) This inelastic collision is otherwise the same as Fig. 5(a).



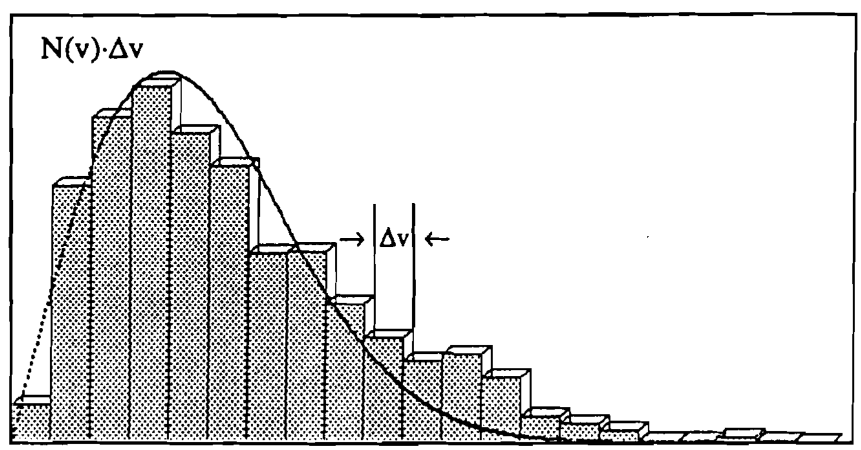


Fig. 6: (a) Stroboscopic recording captures the motion of one puck moving among 10 others on an air table. The type of interaction is a hard-sphere elastic collision. (b) Computer-generated display illustrates the velocity distribution derived from Fig. 6(a). The solid line represents a Maxwell distribution for a two-dimensional case. The small deviation at high speed is the result of nonthermalized excitation caused by shaking from outside.

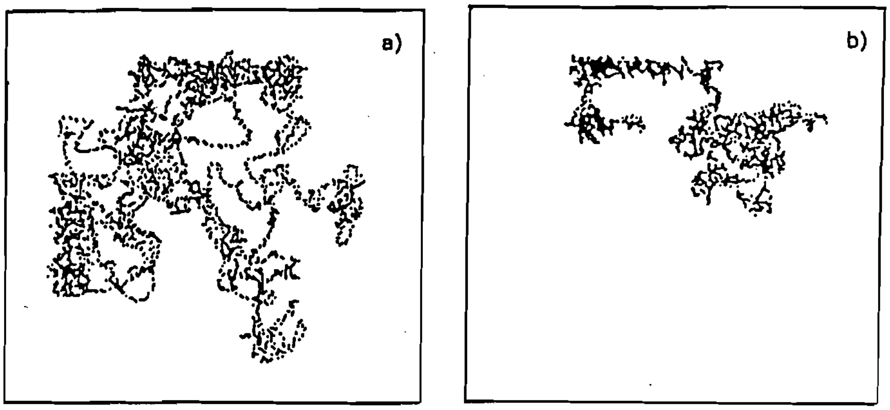


Fig. 7: (a) This trace records the motion of one puck moving among many others on an air table when the interaction is via repelling magnets. (b) An increase in the number of particles, in comparison with Fig. 7(a), leads to coalescence.

fictitious forces derived from the data.

The camera is fixed to a horizontal table that rotates at angular velocity ω, and it is looking vertically upward. A horizontal air track is mounted above the camera. The slider on it is marked with a bright spot visible for the camera from below, and it moves with constant speed along the air track. Fig. 8 shows this motion as seen by the rotating camera. With this stroboscopic picture an interpretation of the appearance of fictitious forces may be performed, either point by point, by evaluating the apparent velocity ($\mathbf{v}' = d\mathbf{r}/dt$) and force ($\mathbf{F}_{tot} \sim d^2\mathbf{r}/dt^2$), or directly, by using the stored data and software. The result of the latter evaluation is displayed by the inserted arrows. The total force, $\mathbf{F}_{tot}$ (heavy arrows) in each instant can be represented by two components: a force $\mathbf{F}_{cf}$, which always points outward from the center of rotation M, and a force $\mathbf{F}_{co}$, which is always perpendicular to the apparent velocity $\mathbf{v}'$. $\mathbf{F}_{cf}$ is the centrifugal force (note that its magnitude comes out to be proportional to the distance r between the slider and M. The dependence on angular speed ω can only be shown with another recording, employing another ω for the table; the total outcome is $\mathbf{F}_{cf} \sim r\omega^2$. $\mathbf{F}_{co}$ is the Coriolis force; note that its magnitude comes out to be proportional to v'. To show the dependence of $\mathbf{F}_{co}$ on ω requires another recording; the total outcome is $\mathbf{F}_{co} \sim v'\omega$). This inductive treatment cannot replace the usual theoretical considerations, but it may help to instill physics intuition, the cultivation of which, unfortunately, is sometimes overlooked.

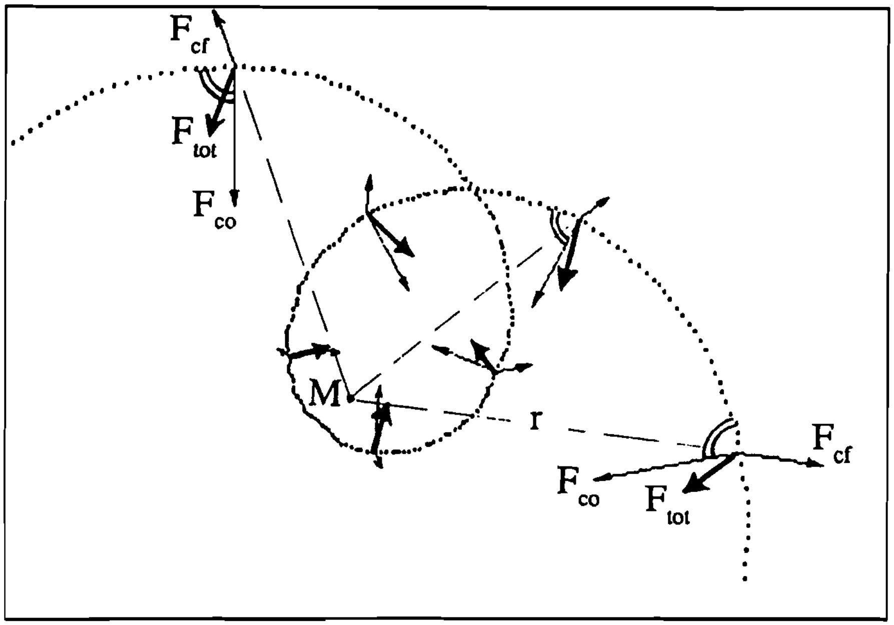


Fig. 8: Rotating camera records the motion of a body moving with constant velocity in an inertial system. The arrows are calculated by computer, but enhanced by hand. (The screen display does this by using different colors.) The forces $\mathbf{F}_{tot}$, as derived from $d^2\mathbf{r}/dt^2$, $\mathbf{F}_{cf}$ (pointing outward from center of rotation M), and $\mathbf{F}_{co}$ (perpendicular to trace) are defined such that $\mathbf{F}_{cf} + \mathbf{F}_{co} = \mathbf{F}_{tot}$. The result is $F_{cf} \sim r\omega^2$; $F_{co} \sim v'\omega$.

Conclusion

The use of Orvico enables students to build intuition about two-dimensional motion. The real-time nature of the analysis enables students to watch the motion and a variety of representations. Thus, it provides an effective way for students to learn and understand the physics of motion.

Several of the examples have shown how these analyses can be extended to rather sophisticated situations. Because all results can be presented visually, they can be understood by students who do not have the background to work with the mathematics of chaos, statistical mechanics, or relative motion. As a result, these sophisticated topics can be taught to students at introductory levels.

Finally, and most importantly, none of the analyses or visual representations arises from computer simulations. All of the results come from processing of data from video of experiments completed by the students. The students themselves complete the experiment for which they see the representations.

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References

1. R. Dengler, K. Luchner, and R. Worg, Physik und Didaktik **2**, 128 (1987).
2. R. Dengler and K. Luchner, Eur. J. Phys. **10**, 106 (1989).
3. R. Dengler, Ph.D. thesis, University of Munich, physics faculty (1989).
4. E. Keshishoglow and P. Seligmann, Am. J. Phys. **57**, 179 (1989).
5. E. Huggins (private communication).
6. Contact Dr. Dengler for more information.