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Innovative Uses of Video Analysis

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Abstract: Video analysis is widely used in introductory physics instruction because it helps students make the transition from abstract textbook problems to real-world motions they can observe. In this paper, we report on several new video experiments in mechanics, optics and thermal physics made possible by Tracker, a free, open-source video analysis tool. Experiments include viewing and analyzing 2d collisions in a center of mass reference frame, modeling the air resistance force on falling cupcake cups, measuring thermal expansion using single-slit diffraction, and analyzing the emission spectra of lasers, gases, fluorescent dyes and fluorescent lamps.

Keywords: video analysis, laboratory, instructional technology, center of mass reference frame, air resistance, thermal expansion, emission spectrum.

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Introduction

The value of video analysis in physics education is well established[1,2] and both commercial and free educational video analysis programs are readily available.[3] The video format is familiar to students, contains a wealth of spatial and temporal data, and provides a bridge between direct observations and abstract representations of physical phenomena. This has made video analysis attractive for many 2D (and sometimes 3D) motion experiments including projectiles, oscillations, collisions, rotations and even Brownian motion.[4] This paper describes the use of Tracker[5], a free Java video analysis tool developed by the Open Source Physics Project[6], to extend video analysis beyond these traditional applications. Specifically, we discuss the following introductory physics video experiments, all of which are available for download from the BQ Learning database or ComPADRE[7]:

1. 2D collisions in a center of mass reference frame
2. Modeling the air resistance force on falling cupcake cups
3. Thermal expansion using single-slit diffraction
4. Nonthermal emission spectra of lasers, gases, fluorescent dyes and fluorescent lamps

In a typical experiment, students obtain a live or prerecorded digital video from a camera, local network or the internet, open it in Tracker, and establish a scale and reference frame for position data. They then examine the video frame-by-frame and track objects of interest with a mouse. The time-based position and RGB data generated by these tracks are analyzed by plotting graphs, fitting curves, and observing graphical overlays and transformed views of the video. Data can also be exported to spreadsheets or other programs.

2D collisions in a center of mass reference frame[8]

In this laboratory exercise, students capture videos of 2D collisions between air pucks[9] and then analyze them in two different reference frames: (i) the laboratory frame, in which the camera is at rest and (ii) the center of mass (cm) frame, in which the total momentum of the system is zero. Advantages of transforming to the cm reference frame are (a) visually and graphically, the motions of the particles have a high degree of symmetry, particularly in two-body collisions, and (b) analytically, all translational kinetic energy is "internal" and available for transformation to other forms. Tracker makes it easy to switch reference frames to not only analyze but also "see" the collision from the cm frame.

Compact blowers inside the air pucks allow them to hover just above the floor so that they move with minimal friction (and eliminate the need for a costly air table for two dimensional collisions). To create balanced air pucks of unequal mass, we added to the top of the puck a circular acrylic plate, which was held in place with Velcro for easy removal. Students record the collision between two pucks using a digital video camera connected to a computer to capture an AVI or MOV file.

Students first track the motion of each puck and specify its mass (red and blue dots in Fig. 1). They then create a center of mass track (green dots) that they observe to move with a nearly constant velocity.

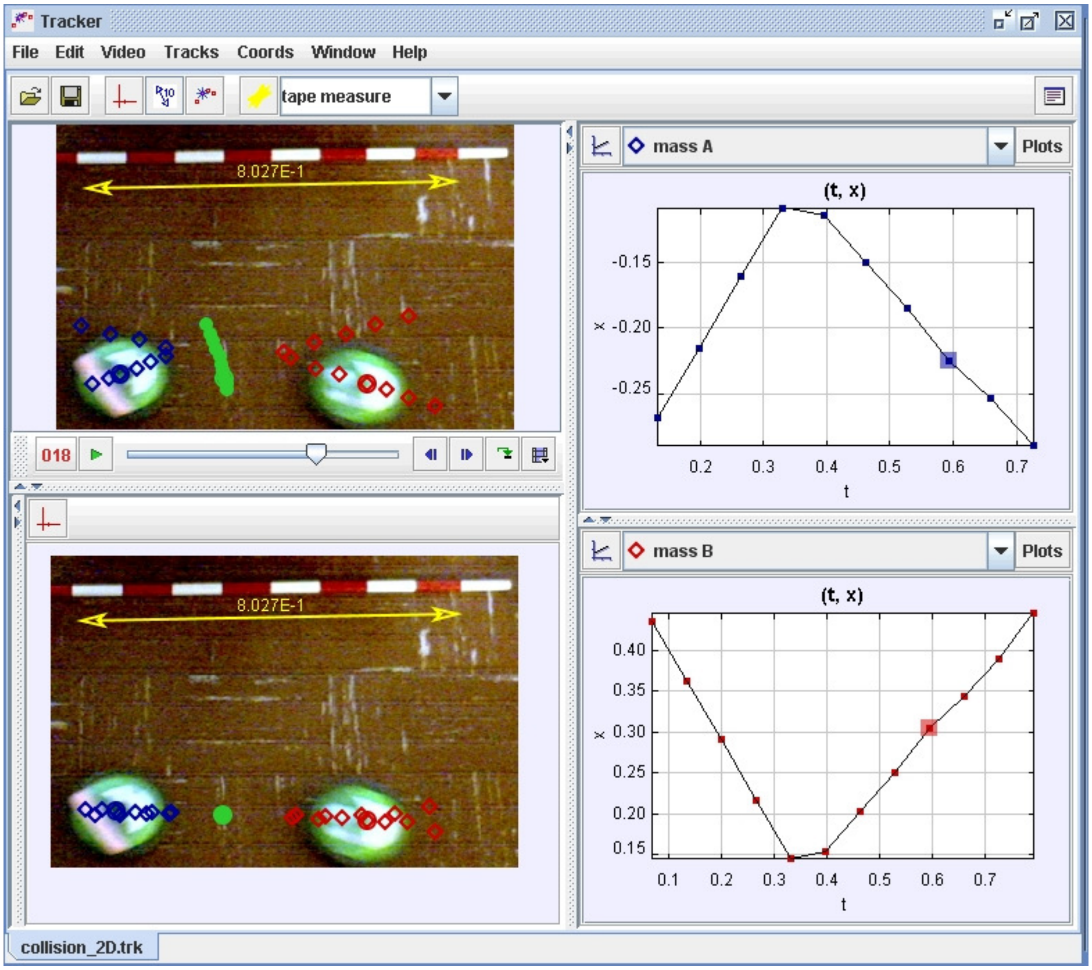


Fig. 1: *Analysis of 2D collision of air pucks. The green points are the center of mass for each frame. The blue-marked puck is 35% more massive than the red-marked puck. The graphs show the x-velocity in the center of mass frame as a function of time for the red and blue pucks. The top view shows the collision from the laboratory frame and the bottom view shows the motion from the center of mass frame.*

Working first in the lab reference frame, students plot the x- and y-momentum of each puck as a function of time and comment on the changes for each. They also plot the kinetic energy and determine whether the collision was elastic. Students are surprised to find that the kinetic energy drops noticeably (generally about in half). However, if they turn a puck on its side and let it fall to the floor and bounce they find the rebound to be noticeably smaller as well (again about half as high). This helps them begin to grapple with the inelasticity of the collision (that they generally expect to be elastic). Finally, they plot the momentum of the center of mass as a function of time. Noting that the momentum of the center of mass is nearly constant over time allows them to begin to discover why the center of mass reference frame is so useful.

Students switch to the cm reference frame by selecting the center of mass track in the reference frame menu. They then open a “world view” of the collision (bottom view in Fig. 1) where they observe that the pucks move in opposite directions at all times, first approaching the cm and then separating. Elastic collisions have separation speeds (radial velocity components) equal to approach speeds while inelastic collisions have slower separation speeds. Completely inelastic collisions have separation speeds of zero. All of this is readily apparent as students view the motion in the cm reference frame.

Students explore angular momentum by analyzing a collision in which one of the pucks is initially at rest and confined to circular motion by being tethered to a post (see the blue-marked puck in Fig. 2 below). Measuring the angular velocity of the tethered puck and comparing the final angular momentum of the system with the initial angular momentum of the blue-marked puck about the same origin leads to conservation of angular momentum.

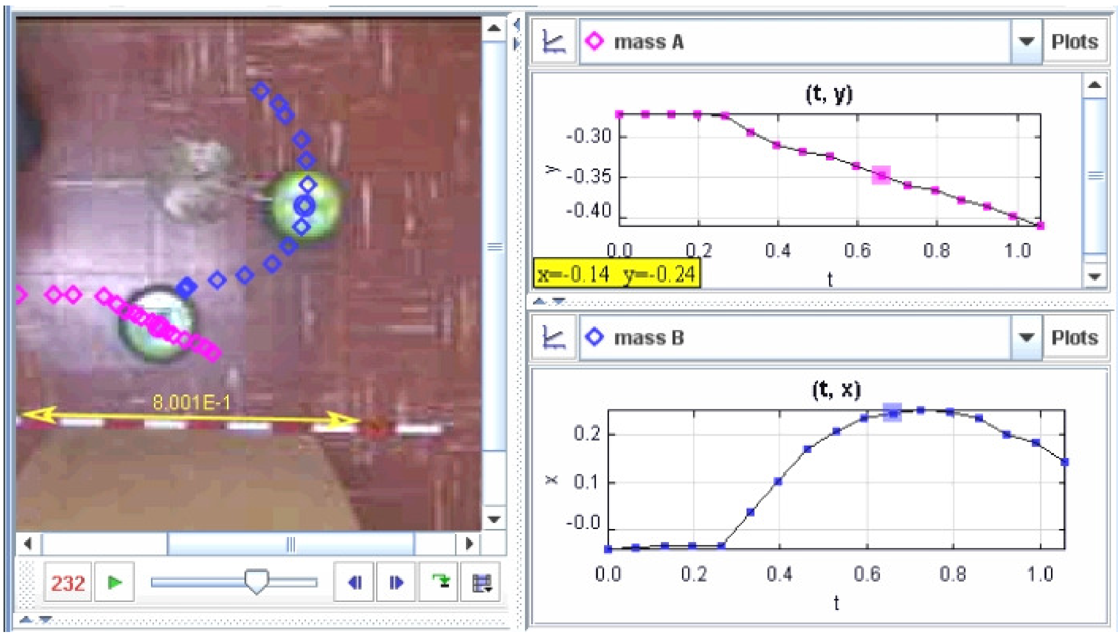


Fig. 2: *The air puck marked by pink points collides into the air puck marked by blue points. The blue-marked puck is constrained to move in a horizontal circle. Students explore the angular momentum of this two puck system.* [10]

Further extensions include considering how the angular momentum of a system during an untethered collision relates to the initial path offsets, the change in path directions during the collision and the spinning of the disc itself. For completely inelastic collisions with angular momentum the discs end up rotating about the cm with purely tangential velocities.

Modeling the air resistance force on falling cupcake cups[11]

In this experiment students use theoretical model overlays to study the motions of falling cupcake cups that approach terminal velocity due to air resistance.[12] The models are tracks that determine their positions from forces and initial conditions using a numerical solver rather than being marked with the mouse. Students define the force functions and parameters for the model (Fig. 3) and then observe how closely its behavior matches the real world. This introduces them to the process of dynamic modeling[13] in an experimental and highly visual context. (The particle models also generate a full set of time-based data, but students did not analyze that data in this experiment.)

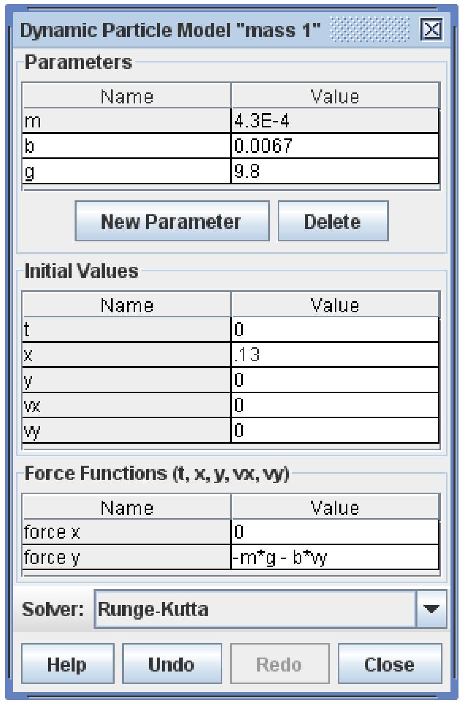
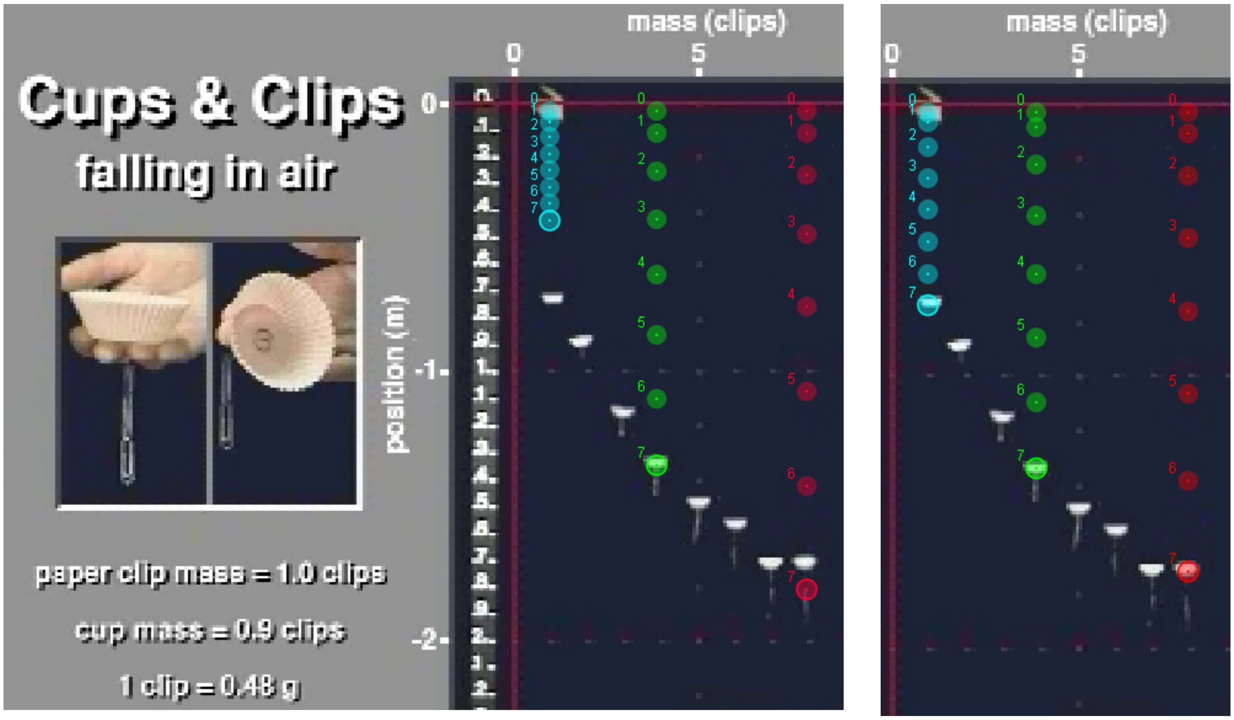


Fig. 3: *Students define the parameters, initial conditions and force functions for a dynamic particle model. The model shown assumes a viscous air resistance force.*

Since this exercise is done in a drop-in learning center rather than a scheduled lab, students observe real cupcake cups but analyze a prerecorded video. The video shows a set of cupcake cups with identical area but varying mass (suspended paper clips) dropped side by side (Fig. 4). A series of guided exercises help the students identify the air resistance force and observe that the cups' terminal velocities increase with mass. They then define two particle models that exhibit this behavior: one experiences a drag force proportional to v^2 and the other a viscous force proportional to v.

Students find that by adjusting the parameters *both* models can be made to reasonably (but not perfectly) match the motion of a single cup (green in Fig. 4)! But only the drag model also matches that of the lighter and heavier cups with fixed parameters. This is strong evidence that the viscous force model is incorrect--a nice example of the scientific method.



(a) **(b)**

Fig. 4: *Particle models overlaid on the video that assume (a) a viscous force proportional to v and (b) a drag force proportional to* v^2*. The drag model fits the motions of all three masses tested while the viscous model does not.*

Thermal expansion using single slit diffraction[14]

Beyond kinematics, Tracker can also measure the brightness along a line in a video image using a "line profile" tool. This allows us to create a more stable version of a thermal expansion experiment published in TPT last year.[15] The experimental set-up consists of a U-shaped aluminum sheet supporting a slit made of two razor blades. A laser projected through the slits produces a diffraction pattern on a screen (Fig. 5). The base of the aluminum sits in a water bath and as the temperature of the bath changes the slit width, and thus the diffraction pattern, changes. An added bonus of this experiment is that students get a preview of diffraction, which they study in detail later in the semester.

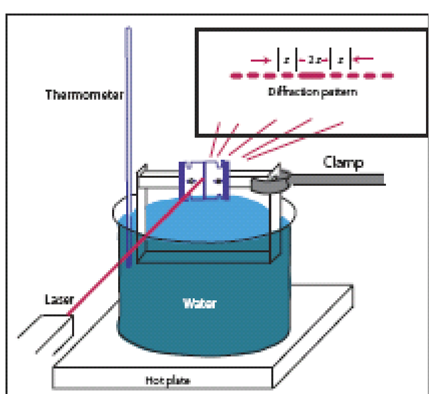


Fig. 5: *Experimental design after Fakhruddin.*[11] *As the laser beam passes through a slit, students see a diffraction pattern. When the water heats up, the aluminum support expands*

increasing the slit width and thus decreasing the spacing between successive minima in the diffraction pattern.

The first time we tried this experiment we had a hard time getting consistent results. It was difficult for students to set the slit width small enough for easily observable changes in the diffraction pattern, and as they waited for the water to heat up tables were bumped and the patterns shifted. Using video analysis and Tracker, however, students see a demonstration of the set-up and then use the video for quantitative measurements. This way, students easily and accurately measure the distance between maxima or minima using the line profile tool (Fig. 6). The mean coefficient of linear expansion obtained in one lab was 18± 2 x 10^{-6}/K compared to accepted values in the range of 20-25 x 10^{-6}/K for typical aluminum alloys.

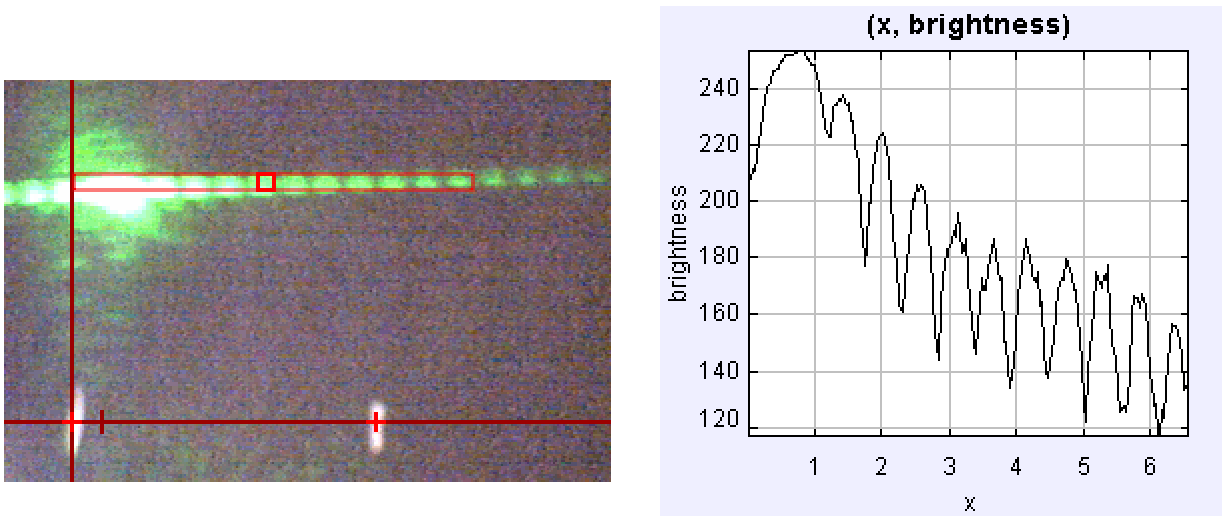


Fig. 6: *Diffraction pattern with line profile tool from Tracker and the associated plot of brightness versus position (in cm). As the temperature increases, the slit spacing increases thereby decreasing the distance between minima in the diffraction pattern.*

Nonthermal emission spectra of lasers, gases, fluorescent dyes and fluorescent lamps[16]

The line profile tool also provides an interactive and highly visual way for students to study visible spectra. In this experiment, students use the line profile to generate spectral intensity plots of nonthermal emission sources. The spectrum images are obtained by placing a diffraction grating directly in front of the video camera lens (a digital still camera could also be used).[17, 18] Red and green HeNe lasers with known wavelengths (633 nm and 543 nm, respectively) are reflected from a small tab protruding below the slit to enable calibration of the spectra (Fig. 7). Students use hand-held gratings to observe all spectra by eye but use prerecorded videos for analysis.

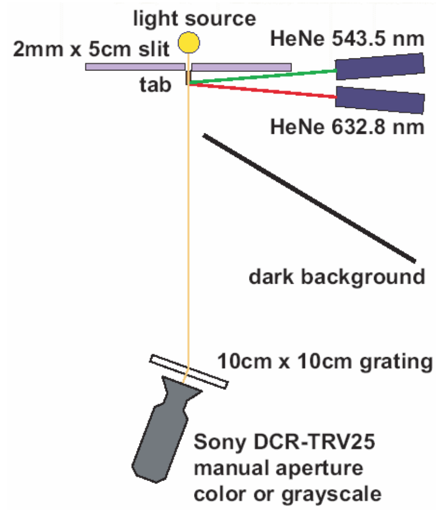


Fig. 7: *Nonthermal emission spectra experimental setup (top view).*

Students start by identifying and measuring typical characteristics (wavelength, relative brightness and width) of laser and gas spectral lines (Fig. 8 left). Typical wavelength results agree with accepted values (theoretical values in the case of hydrogen) to within 2 nm. Questions about relative brightness and comparison of direct observations with captured images lead students to consider how the brightness results are influenced by sensor response curves.

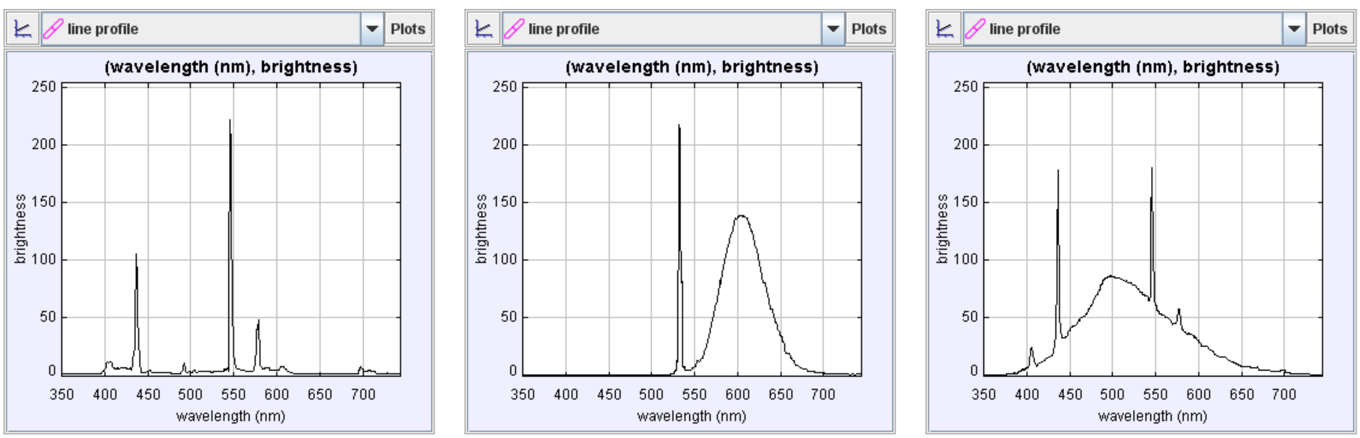


Fig. 8: *(left to right) Spectrum of a mercury gas lamp, a fluorescent dye illuminated by a solid-state laser, and a fluorescent lamp.*

Students then turn their attention to a red fluorescent dye illuminated by a solid-state laser (Fig. 8 center). They are fascinated by the broad fluorescence peak since they have previously observed the same laser illuminating a white non-fluorescent target. The characteristics of the peak are measured and discussed in the context of quantum theory (e.g., why does the dye not fluoresce when illuminated by the red HeNe laser alone?), and the visible color of the illuminated dye (orange) is related to the areas under the laser and fluorescence peaks and the RGB model.

Finally, fluorescent lamp spectra are observed (Fig. 8 right). Students have no problem identifying the mixed emission mechanisms and the gas. Questions about whether there is more than one fluorescent dye and which gas lines should be able to excite the dyes lead to student predictions of additional UV lines not seen. Lamps rated with "color temperatures" of 6300K (shown) and 3000K are then compared to establish the shared and unique characteristics of different lamps.

Summary

Tracker is a free, open-source video analysis tool that has allowed us to introduce new exercises into the introductory physics laboratory: center of mass reference frames, dynamic modeling, thermal expansion and nonthermal emission spectroscopy. Tracker can run directly from a website or the BQ database on both Windows and Mac computers that have current versions of Java and QuickTime installed. Because students can easily (and freely) download Tracker to their own computers, they can use it for independent projects or extended homework assignments as well.

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[6] Open Source Physics: http://www.opensourcephysics.org/
[7] BQ Learning database: http://www.bqlearning.org. See individual exercises for direct links to resources. ComPADRE: http://www.compadre.org/osp/items/detail.cfm?ID=8475.
[8] Lab exercise: http://www.bqlearning.org/ospbd/osp_display.php?phys_text_id=1003
[9] "Kick it Stick it" pucks are available from Educational Innovations, http://www.teachersource.com, AIR-115, $25 each.
[10] Lab exercise: http://www.bqlearning.org/ospdb/osp_display.php?phys_text_id=1004
[11] Lab exercises: http://www.bqlearning.org/ospdb/osp_display.php?phys_text_id=1021
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