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Teaching Mechanics Using Kinesthetic Learning Activities

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As students learn physics, they are often required to reason about the behavior of macroscopic and microscopic phenomena, and to synthesize prior knowledge from several different areas of physics to construct understanding of new ideas. This can be a tremendously difficult cognitive task for novice students, especially when the unfamiliar phenomena described are potentially microscopic or abstract. Therefore, it can be very helpful for physics instructors to develop and employ pedagogical techniques that help students to visualize and to reason productively about these concepts. A particularly effective strategy uses Kinesthetic Learning Activities (KLAs).

Introduction and motivation

KLAs are classroom activities in which students physically act out the behavior of physical objects to be studied. To do this, learners must think in real time about how the objects would respond in the scenario. A classic example comes from the study of one-dimensional motion: A student is asked to move back and forth in front of a motion detector to reproduce a position-vs.-time graph or velocity-vs.- time graph provided by the instructor. Or in a lesson about electrical conductors and insulators, students can act out how ions and electrons behave in these materials both in and out of an applied electric field.[1] In each of these examples, students must reason productively about what the particles in question would be doing from one moment to the next in order to agree with physical laws. While KLAs in general can refer to any pedagogical activity in which students are kinesthetically engaged in some way (for examples, see Refs. 2 and 3), I will use the term specifically to refer to activities in which students actually assume the role of a physical object and must act accordingly (as in the conductors and insulators example above); this subset of KLAs sometimes goes by other names in the literature, such as simulation role play[4] or analogical modeling role play.[5]

Why use KLAs?

Many undergraduate and high school physics courses follow a traditional, lecture-based format. Research has shown that this format suffers from many shortcomings, most notably "decreased student engagement, frequent student inattention, and the exclusion of nonverbal learning modalities."[6,7] KLAs can address many of these shortcomings by raising the level of engagement during instruction, and can reenergize a class during periods of lecture.[6] These activities also engage learning preferences that may be neglected by traditional instruction, improving learning outcomes for all students.[8] Additionally, KLAs can positively affect the culture of interaction in the classroom, encouraging student participation and collaboration.[6,9] There is evidence to suggest kinesthetic learning may prove especially beneficial to at-risk students.[10] Finally (anecdotally), these activities are fun and memorable and they inject a great deal of excitement and enthusiasm into the classroom!

In my own experience, KLAs provide two main advantages: They help to crystallize new ideas in the minds of the students, and they serve as useful formative assessment tools for instructors, allowing them to monitor the learning process. In light of this, I find these activities to be especially effective later in the instructional sequence, after students have some familiarity with the concepts. Thus, students are better equipped to reason productively about the behavior of the system and assume the role appropriately. The instructor can observe how the students behave as they attempt to represent their own understanding of the physics phenomena in real time. How they portray their role yields a great deal of information about their level of comprehension.

While there have been a handful of reports detailing KLAs used in computer science courses,[6,11,12] there seem to be very few examples of these activities in the literature that are appropriate for an introductory physics course. Certainly, individual instructors may well be using activities of this nature already, but they have not been broadly disseminated. In this article, I present three KLAs I have devised to use while teaching mechanics or physical science at the introductory college or high school level.

Phases of matter

This activity allows students to visualize what makes the three familiar states of matter different from each other and gives them each their unique properties, by examining their behavior at a microscopic level using kinetic molecular theory (KMT).

- ***Materials:*** None
- ***Time:*** ~5 minutes (may be longer depending on discussion afterwards)
- ***Learning goals:*** Students will recognize the differences in microscopic behavior between the three basic phases of matter.

Students gather in a cluster in an open space in the classroom (almost any number of learners can participate, either the entire class or a subset). Each student represents a molecule in the substance to be examined (I consider water since its states are very familiar to the learners). We begin by modeling a solid such as ice. The instructor asks the students to arrange themselves in an appropriate way, based on what they know about solids. They should move themselves into some sort of lattice or regular grid; sometimes I see students extend their arms and grab onto their neighbors, showing that they recognize the strong intermolecular forces that characterize a solid. It's important to note that in these activities the instructor is not telling the students how to act. Rather, she is telling the students what they are supposed to be representing, and it's up to the learners to figure out how they need to behave. For example, if the students do not array themselves in a lattice, she can prompt them with, "How do molecules in an ice crystal line themselves up?" or something similar; the students must then communicate amongst themselves and reason about how to act. When everyone is ready, the instructor "presses play" (usually by a voice command to begin acting) and the students must move appropriately. Using their understanding of KMT, the students don't travel anywhere through the bulk of the material, but they do vibrate and jitter slowly in place. This represents the behavior of molecules at low temperature in the solid phase.

Next a liquid is modeled. The students array themselves, this time not in a regular lattice but in a disordered cluster. Some students may lightly drape a hand over a neighbor's shoulder, but it is not held tightly; this represents the weaker (but still present!) intermolecular forces in a liquid. When the instructor verbally presses "play," the students begin acting, vibrating moderately vigorously and/or moving around past each other to move through the material. In my lectures, I often describe the motion of liquid molecules as "sliding past one another," so students may try to represent this type of motion by slipping past a neighbor with back-to-back contact (like two strangers might do when squeezing through a narrow doorway in opposite directions). In this way, learners are representing the behavior of molecules in a material in the liquid state.

Finally, the students are asked to model a gas such as steam. The students arrange themselves in an extremely disordered way, with large spacing and no real contact between neighbors. When the instructor presses "play," the students move very quickly and chaotically, occasionally bouncing off of each other or the walls of the classroom in a frenetic way, using what they know about KMT to represent the behavior of gaseous molecules.

I concede this activity is a little silly; however, it *is* quite memorable for the students. Herein lies one of the major benefits of KLAs. This sort of activity is so different from most learners' expectations of what a science lecture will be that it really distinguishes itself in the minds of the students. The opportunity to bounce off of your classmates in a crazy way for several seconds further augments the memorable nature of the KLA. Students always laugh during this activity, and I consider the fact that they're having fun while reinforcing their understanding of KMT to be a very powerful learning experience.

Depending on the level of the students, it may be wise to engage in a short discussion about the limitations of the simulation. As with any representation of a physical phenomenon, some aspects of the reality are not simulated authentically. For example, in this activity the students are not representing the polar nature of water molecules, nor the anomalous expansion of water. Furthermore, differences in viscosity, density, or various crystalline structures are being neglected. As we instructors know, when trying to describe any real phenomenon, we must make decisions about which complicating factors must be included and which can be glossed over. A teacher who believes her students could benefit from the discussion is encouraged to touch briefly on these additional aspects of KMT and how substances behave on microscopic scales. As the appropriate scope of these discussions depends greatly on the ability, preparation, and interest of the students, I leave it up to the discretion of the individual instructor whether and how deeply to engage in them.

To obtain formative assessment from this activity, the teacher should observe closely the behavior of the students as they attempt to represent the physics phenomena at work here. The mental image the learners have of the phenomena will be borne out in how they act, and this allows instructors the opportunity to notice any gaps. For instance, if none or very few students dramatically increase their chaotic motion when the liquid and gas phases are modeled, this can indicate that the class does not yet understand the relationship between phase, temperature, and thermal velocity. If many students reach out to grab hold of their neighbor when modeling a solid, it can be concluded that they understand there are strong intermolecular forces in that state of matter. In this way, the activity can provide useful feedback for the teacher while also serving as a reinforcing demonstration for the learners.

Transverse and longitudinal wave propagation

This activity helps students to visualize how individual particles move during the propagation of different wave types. It is especially helpful in illustrating why longitudinal waves can propagate easily in all materials, but transverse waves really only travel through solids and cannot easily move through liquids or gases (this is a slight oversimplification of course, but it generally holds true), which many of my students struggled with previously.

- ***Materials:*** None
- ***Time:*** ~5 minutes
- ***Learning goals:*** Students will understand the mechanism by which mechanical waves are transmitted through a solid or fluid medium.

A group of 7-10 students forms a line in front of the classroom parallel to the front wall of the room (along the blackboard, for instance). The students should all face the same direction—as if they were queuing for something—with perhaps a foot separating each student. First, they will simulate molecules in a solid material, so each student firmly grasps the shoulders or upper arms of the student in front of him to represent the strong intermolecular bonds. The instructor takes her place at the very back of the line and grasps the arms of the student in front of her; she will be the initiator of the wave disturbance, and she tells the class that first she will create a longitudinal wave. She pushes firmly on the student's shoulders, pushing him forward slightly, and then pulling him back to his original position. Because the students are holding each other's shoulders rigidly, the next student in line will also be pushed forwards and back, and so on; thus, the class sees a longitudinal disturbance propagate down the line to the last student.

Next the instructor demonstrates a transverse wave in a solid. The students still grasp each other's shoulders (since they're still modeling a solid), but this time the instructor pushes transversely (e.g., towards the class) on the rearmost student and then immediately returns him to his original orientation. I find it more effective to try to "rotate" the torso of the student—causing him to bend at the waist towards the class—rather than simply pushing to the side, which would force the student to take a step towards the class; it's best if the student's feet remain planted. When the student bends, he causes the next student in line to bend, and so on. The class sees each student displacing transversely and then returning to the original position, and the disturbance travels down the line of students.

Third, the students will model a gas, so they do not firmly grasp each other, as the intermolecular bonds between gas molecules are negligible. Instead, they place their hands near the shoulders of the student in front of them with their palms facing out, as if they were about to give the student a shove (the reason for this will become clear momentarily). As before, the instructor stands at the rear of the line and initiates a longitudinal wave by pushing (gently!) on the student in front of her. This sends him forward, and his hands make contact with the next student in line, pushing him forward slightly, and so on. The wave will propagate, although probably a bit more slowly than in the solid case, because the transmission from one student to the next is slightly delayed since they are not holding each other tightly. This shows why longitudinal waves (I use sound as the most relevant example) often travel more slowly in fluids than in solids.

Finally, the students will model a transverse wave in a gas; again, the students do not grasp each other. The instructor initiates a transverse disturbance, pulling the rearmost student to the side as before. However, since that student is not holding on to the student in front of him, nothing else happens. The rearmost student displaces transversely and returns to his original position as a result of the instructor's pushes, but there is no transmission of this disturbance to the next student in line. This kind of wave cannot propagate in the medium.

It is important to consider student safety with respect to this activity. Students should stand with feet about shoulder width apart for stability; it may be useful to tell them in advance that they will feel some pushes or shoves coming from the student behind them, so they can brace themselves a bit. Also, in part 3 (longitudinal wave in gas), be sure the students put their arms up in front of them, as if ready to shove the next student. Otherwise, when pushed from behind, their torso and face will simply crash into the next student, which is obviously far less safe. The idea is that the hands should be the only body part that ever makes contact with the next student in line. Finally, it is not necessary to create waves with large amplitude for the activity to succeed. You only need to displace the rearmost student a small amount to begin the wave; it should propagate on its own quite well and be visually apparent to the class even if the amplitude is small.

As before, it is left to the discretion of the instructor to discuss the limitations of the representation. Notably, when acting out the role of solid vs. gas particles, the students are only representing the intermolecular forces (by gripping or releasing their neighbors) and not the thermal motions these particles exhibit (by, for instance, bouncing or moving around). In reality, the thermal velocity of a typical molecule in a gas is faster than the speed of sound in that medium, and that fact is not well represented here. However, a brief explanation of this fact by the instructor should alleviate any confusion students may have.

Vector addition

This activity helps students visualize how to add vectors. It uses both "tip-to-tail" methods and addition by components, as students act out two successive displacements of a particle in order to find the resultant.

- ***Materials:*** Large protractors (such as the type used when drawing figures on a blackboard), measuring tapes
- ***Time:*** 20-30 minutes (can vary depending on students' facility with trigonometry)
- ***Learning goals:*** Students will be able to better decompose vectors into components and apply vector addition techniques to find vector sums.

It is useful to have a large space for this activity; an athletic field or gymnasium would be excellent (as the boundaries and other field lines can be helpful landmarks). The instructor gives each group of students two 2D displacement vectors in magnitude-angle form (e.g., "6.5 m at 35° East of North and 3.2 m at 20° South of West") and the students must find the resultant vector from adding these two displacements. This is accomplished by students walking out the displacement vectors in succession, then measuring their final position relative to their initial position to find the total displacement. I recommend using obvious landmarks to define the coordinate system for the class (say, the center spot on a soccer field is the origin and the halfway line forms the y-axis). This way, students can put their protractor on the ground (lining it up with the coordinate system) and then pace off the correct distance using the tape measure, then repeat for the second displacement vector. They can mark their final position and measure the distance and angle of that position from their origin to find the overall displacement (the vector sum).

Displacement vectors seem to be the most obviously tangible for the students, and they seem much easier to visualize (especially in a vector addition context), than some of the less tangible vectors encountered in introductory mechanics (e.g., velocity, acceleration, force). Furthermore, the "sequential" nature of adding displacement vectors ("displace this way, then displace this way")—as opposed to, for example, net force, which is more simultaneous ("these forces both act at the same time and the resultant points like this")—appears to reinforce the "tip-to-tail" or graphical method of vector addition, since in this method learners draw each vector in turn.

From a differentiation perspective, the instructor may wish to prepare vector pairs of various levels of complexity, distributing more difficult pairs to the more advanced groups. Ideally, students who have mastered the concept can be recruited to assist those groups who are struggling. Advanced groups can also be challenged with finding the sum of three or four vectors instead of two.

It can be instructive to have students break each of their displacement vectors they received into components and add them that way, then convert their resultant back to magnitude-angle form to see how well it compares to what they found using the original method; this part can potentially be done when back inside the classroom. An alternative is to give two different groups the same vector pair—with one group's pair in magnitude-angle form and the other's in component form—and see how closely they end up. This can be a nice verification of the equivalence of the two vector addition approaches (graphical and by components).

Summary

KLAs represent an excellent way to invigorate a period of lecture and to encourage students to reason productively about physical phenomena that are often difficult to visualize, due to their abstract or microscopic nature. These activities can be a wonderful addition to any introductory physics or physical science course.

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