Interactive Instruction on Ideal and "Real" Gases

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This article explores efforts to use simulation software in conjunction with peer instruction techniques toward improving student comprehension of particle interactions in ideal and "real" gases. A series of Interactive Physics™ simulations builds group student inquiry from small-scale ideal gas cases through larger, more realistic particle simulations. The mathematics associated with the simulations is intentionally minimized in order to focus student attention on conceptual understanding. References are made to other efforts in this educational direction, both in terms of rationale and applications. A website is cited in the Notes section containing both movie versions of the simulations, and includes the files available for download by IP users.

Background

My first inclination toward a particle interaction perspective on mechanics came from the Winter 2000 Concord Consortium newsletter.[1] Bob Tinker's opening article advocated an emphasis on improving students' understanding of particle interactions as a fundamental goal of physics education. He made the point that an emphasis on particle interactions is crucial to the success of the "physics first" movement in high schools across the country. Only when physics truly lays the groundwork for chemistry and biology will we reap the maximum benefits from this change. Uri Wilensky followed up Tinker's message in this same newsletter with practical applications of StarLogoT programming toward this end. Among other areas, he uses it to teach particle interactions in an ideal gas.[2]

The inspiration of this newsletter started me thinking that a true grasp of these phenomena had to begin with really understanding the interactions of the particles on a very small scale. I chose a pattern of instruction that involved building up from small-scale ideal gas type interactions, to larger ideal gas interactions, to "real" gas behavior on a small scale, and then progressing to "real" gas behavior on a larger scale. Treating these ideas visually and conceptually using an interactive lecture/discussion format and computer simulations was my goal.

I am a subscriber to the peer instruction technique of encouraging student interaction during lectures by periodically focusing student-to-student discussion on well-conceived questions that bring out the heart of important physics concepts.[3] The verbal exchange between students on these questions really adds to their understanding and enjoyment of the class. I use this approach to fully engage the students in discussing the simulations.

The Simulations

Simulation #1—Two Ideal Gas Particles

At the point where students have completed a traditional lab on conservation of momentum in collisions and explosions (I use the qualitative PASCO dynamics cart experiments), I introduce the first of the simulations meant to connect discrete particle behavior to gases. It is simply two spheres in a two-dimensional box, both having the same initial velocities and constrained to bounce off the walls. The

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only force of interaction between particles or walls occurs during the collisions. All collisions are perfectly elastic.

Before the simulation is run in its initial state, the question asked is:

If both particles start with the same speed, will the total kinetic energy of all the particles remain the same? Will the speed of each particle remain the same as the simulation runs?

After allowing time for students to formulate their thoughts and share their ideas with each other, we run the simulation with the values of both total kinetic energy and individual particle speed being displayed. Our hope is that they realize that making all collisions elastic will yield conservation of kinetic energy in the system as a whole, but that the speed and energy of individual particles will vary over time.

Simulation #2—Multiple Ideal Gas Particles

The second simulation I used was a large number of similar particles in a two-dimensional box, each with the same initial speed, and interacting with each other only during the impacts.

My question here is:

How will increasing the number of particles in the box affect the results of the simulation in terms of energy conservation and the speeds of the particles?

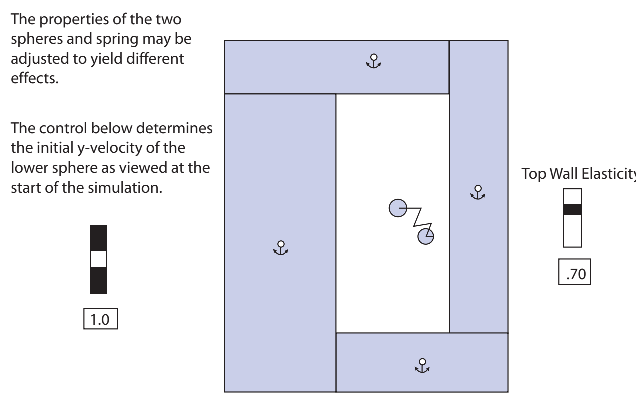
Of course, I hope they conclude that the total kinetic energy of the system will remain constant, despite the wide variations in speed observed between the individual spheres. Depending on the level of the students addressed and their background in chemistry, they may already be familiar with the Maxwell distribution of speeds in an ideal gas. If a visual and qualitative sense of this distribution pattern leads students to analyze the results in more depth, Interactive Physics data can be transferred to a spreadsheet for more quantitative discussions.

From a concept-building perspective we may ask:

How would the range of speeds of the particles change if, say, all were doubled in initial speed? How about if the initial speed were decreased by half?

What we are really getting at here is an intuitive sense of the Maxwell distribution. Higher temperatures (initial speeds) should lead to a broader distribution of velocities, and lower temperatures should lead to a narrower range of velocities. This concept can be verified with more experienced students by studying the Maxwell distribution in its mathematical form and using calculus (see Notes at the end of this paper).

Simulation #3—Two Particles Held by Springs While Electrostatically Repelled from Each Other



The third simulation I use is that of two spheres connected by springs and having the same electrostatic charge. I do this next because students already have an intuitive sense of these two forces in action. Of course, our ultimate goal is to model a system similar to that of a "real" (van der Waals) gas, where there is a strong short-range repulsive interaction and a relatively weak long-range attraction. The definition of a "real" gas in these systems is based on the Lennard-Jones potential, and we will eventually model a system having this interaction between all of its particles. Starting with springs and electrostatic repulsion, however, makes the simulation less foreign. Any collisions with walls or between balls are again perfectly elastic. The first question related to this simulation is simply:

If the spheres start at rest, how will they move over time?

We hope this generates discussions about the stiffness of the spring, the masses of the spheres, the quantity of charge on each, and the frequency of the vibration. Even though I would not normally have covered Coulomb's law at this point in the course, students still have an intuitive sense that "more charge means a greater force." Again, it is very simple to both display and change any of these variables as the students request more information. In addition to requiring the students to discuss their ideas at this point, I also asked them to write a brief statement describing their ideas of how the different variables affect the motion of the connected spheres. They share these written statements with each other as well. I am interested in helping the students get an intuitive "feel" for this physical situation, not in burdening them with mathematical complexity.

The second question explores the effect of initial velocities on the motion of the particles:

If we vary the particles' initial velocities, what effect will this have on their motion over time?

We want to compare the results of the simulation beginning at rest to this one. Hopefully, students will see that the translational motion of the two spheres depends on their initial velocities, but that they are still influenced by the attractive force of the spring and the repulsion of the like charges.

The last effect explored in this simulation is changing the elasticity of the collisions with one of the walls. We are, in effect, changing the coefficient of restitution between the top wall and the spheres. Again, we ask the students to

Predict the effect of taking energy out of this system by gradual cooling (making collisions with the top wall no longer perfectly elastic).

Having the particles slow down because of energy loss in collisions with the walls is our analogy to removing heat by conduction to the walls of a container. *The difference between this means of removing kinetic energy from the gas particles and what happens in reality must be clearly explained to the students.* There are only elastic collisions taking place between atoms/molecules in reality. The energy loss occurs for a real gas because of interactions with slow, relatively fixed wall atoms.

Simulation #4—Two Particles with an Attractive and Repulsive Force Field Between Them

The next simulation involves introducing the Lennard-Jones interaction, an idea that would not typically be presented in high school but is crucial to this presentation of the change of state in a "real" gas as it condenses and eventually freezes.

The standard form of the Lennard-Jones potential is given as

$$V = 4\epsilon\ \{(r_0/r)^{12} - (r_0/r)^6\},$$

where r_0 is the separation at which $V = 0$, and ϵ is the minimum value of potential energy. [6]

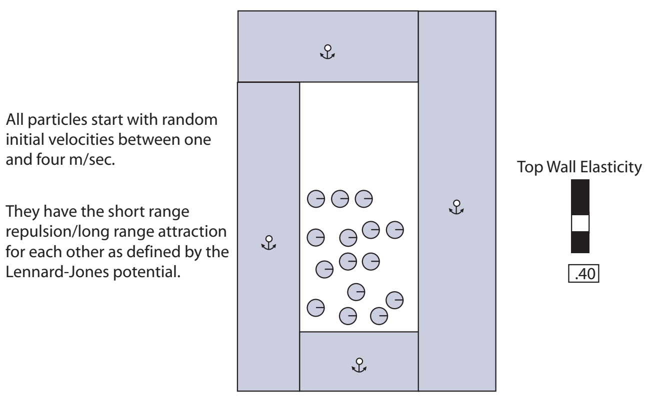
With my high school students I do not explore the mathematics of this formula at all. I simply tell them that the force field we defined would act in a similar fashion to the prior simulation, but without visible springs or charges. I suppose with some particularly capable students a teacher could do some useful spreadsheet modeling or numerical calculation exercises, but I have not as yet.

The concept is really the same as the previous model, in that there exists an electrostatic repulsion when the particles are very close together, and a restoring force (van der Waals attraction) similar to the spring tension when the particles move apart beyond equilibrium. So, instead of using springs and charges to create this effect, we now define the interaction using a formula in Interactive Physics. (Please note: more information on using Interactive Physics to create this force field can be found in the Notes at the end of this paper.) When the two-particles-in-a-box simulation runs, I ask the students to simply watch the simulation run first, then to

Predict the effect of reducing the elasticity (coefficient of restitution) of one of the walls.

Hopefully, they conclude that the particles will tend to slow down and reach a stable equilibrium with each other after most of their translational kinetic energy is removed due to collision with the top wall. The effect is like the previous simulation in the sense that the particles are electrostatically repelled from each other, held by a relatively weak spring, and allowed to lose energy by inelastic collisions with a wall. It bears repeating that real atoms do not have this type of inelastic interaction; it is only a trick we use in the simulation to cause a reduction in the kinetic energy of the gas atoms after colliding with a wall. As far as the gas atoms are concerned, the net result is the same as if they collided with a cool wall.

Simulation #5 — Multiple "Real" Gas Particles



The final simulation in this series is the one that has the most dramatic effect. Up to this point in their high school careers, most students are familiar with ideal gases and the formulas for heat exchange and changes of state. But they have not seen a simulation that connects these ideas in a meaningful way. The simulation of a large number of Lennard-Jones particles in a box seeks to help make this conceptual connection.

Once the students see the array of particles in the box, they are asked to describe the motion they will see in the box if the particles have random initial velocities and all interactions are defined by the force field they have seen previously, with all collisions being elastic. This is, of course, very similar to an ideal gas condition with the elasticity of all the walls set to the maximum. The important conceptual point here is that "real" gases will behave much like ideal gases when their temperature is high enough to prevent the attractive forces from really taking effect.

However, as one wall is set to a lower elasticity, heat is removed from the system and cooling occurs. Students are again asked:

Predict the effect on the system of allowing heat removal to occur by introducing a lower coefficient of restitution for the top wall.

When the simulation runs, the system cools rapidly, transitioning between the ideal gas to formation of droplets in a primarily liquid system, to a crystalline solid. The students have seen a phase transition simulated before their eyes!

I have used this sequence of simulations over several class periods with my physics students, and it served as a culminating activity to a study of situations involving conservation of momentum and energy. It also serves as a supplement to the knowledge of ideal gases gained previously in chemistry.

Notes

• Video for Windows movies of these simulations in action can be seen on my webpage at: http://www.e-lcds.org/fac/ringlein/sims. Anyone using Internet Explorer as their browser should be able to view these. On the same page are the actual Interactive Physics files available for download and use by users of IP.

• The expression for the Maxwell distribution of molecular speeds in an ideal gas is given by

$$f(v) = 4\pi\, [M/(2\pi RT)]^{3/2}\, v^2\, e^{-Mv^2/2RT},$$

where v is speed, M is molecular mass, T is Kelvin temperature, and R is the gas constant.[5]

• Recent physics education research has confirmed the difficulties many students experience in fully comprehending the ideal gas law, and the microscopic interactions at the heart of it. See "Research on Student Understanding of the Ideal Gas Law" by Kautz, Loverude, Heron and McDermott at http://www.ipn.uni-kiel.de/projekte/esera/book/b027-kau.pdf and their listed references.

• Other researchers have developed laboratory/demonstration apparatus for teaching about molecular interactions in a macroscopic and dramatic fashion. See "Motorized Molecules: From Molecular Chaos to Thermal Order" by Prentis and Yuhasz in *Phys. Teach.* **39**, 242–248 (April 2001).

• A significant number of ideal gas computer simulations can be seen online, allowing for a variety of simulated experiments to be done. See http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html by physicist Fu-Kwun Hwang and http://jersey.uoregon.edu/vlab/Piston/index.html at the University of Oregon.

• Information on Interactive Physics software in general can be found at http://www.interactivephysics.com.

• Information on the Materials Research Science and Engineering Center at Johns Hopkins is available online at http://pha.jhu.edu/groups/mrsec.

• Feedback on this article is requested to be sent to ringleij@e-lcds.org.

Special Notes for IP users

• As noted above, the website http://www.e-lcds.org/fac/ringlein/sims contains both the movies of the simulations and the files available for download.

• These are instructions on creating the Lennard-Jones interaction between particles for the van der Waals fluid:

With the box and spheres already created in the simulation, we find under the "World" menu "Force Field" and a "Pair-Wise" field. In the top slot we write:

```
48 *((sqr( self.p – other.p )) ^ -6.5) – 24 * ((sqr
  ( self.p – other.p )) ^ -3.5)
```

This defines the interaction forces between all the particles in the simulation. In this code the term (self.p – other.p) is the displacement between the centers of mass of any two particles in the simulation. The constants are essentially based on the size of the particles involved.[4]

• See a group of Interactive Physics simulations (available for download by IP users) dealing with change of state in a fluid at http://www.interactivephysics.com/simulationlibrary/evaporation.html by Raymond Nackoney of Loyola University of Chicago.

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References

1. Bob Tinker, "Atomic scale models — The key to science education reform," *@CONCORD* 4, No. 1 (Winter 2000).
2. Uri Wilensky, "Monday's lesson using StarLogoT, *@CONCORD* 4, No. 1 (Winter 2000).
3. Eric Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, Upper Saddle River, NJ, 1997).
4. Thanks to Mark Robbins of the Physics and Astronomy Department at Johns Hopkins University for help in deriving and applying this formula.
5. Peter Atkins, *Physical Chemistry,* 6th ed. (W.H. Freeman, New York, 1998), p. 26.
6 Ibid., p. 667.

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What Do You Do After Majoring in Physics?[1]

etcetera... Editor
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"Since finishing my residency in 1988, I have been practicing Emergency Medicine.... My background in physics comes in handy in understanding medical technologies such as ultrasound, MRI, CT scan, radiation therapy, PET scans, and digital signal processing."[2]

"Much of my job (systems engineer) is sorting out complex problems with many interrelated issues – physics provides a great foundation for this kind of problem solving."[3]

"I manage product liability and commercial litigation.... Training in physics and chemistry...has been extremely helpful in dealing with fascinating issues in litigation involving accident reconstruction, mechanics, biomechanics, occupant kinematics, metallurgy, electricity, electronics, chemistry, etc." [4]

1. These are from the *Physics & Astronomy Alumni Newsletter,* Colgate University, Spring 2000.
2. Jonathan Rill ('80)
3. Russ Sharpless ('82)
4. David R. Williams ('63)