NEWSLETTER

ONTARIO ASSOCIATION OF PHYSICS TEACHERS
(An Affiliate of the A.A.P.T., and a charitable organization)
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Editor's note: The following article was written in response to Rolly Meisel's article in our November newsletter . Responses are encouraged and can be sent to james.ball@ugdsb.on.ca

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Pianos and Inharmonicity

The amusing article "Lies My Physics Text Told Me" by Rolly Meisel in the November 2006 OAPT Newsletter points out important differences between idealized systems discussed in school texts and real applications. Rolly's experience revisited the famous contest in 1706 between Johann Nickolas Bach (an organist in Jena, Germany, and a cousin of Johann Sebastian Bach) who used only his ear to tune an organ and Johann Georg Neidhardt, who used a monochord with carefully worked out mathematical ratios. Bach won hands down, both on speed and on musical results. Reality does tend to complicate simplified scientific analyses, but details can illuminate subtleties of deeper physical principles. This is especially true in music, where I've had an enduring interest, and I felt some further discussion of tuning was appropriate.

It is important to distinguish between harmonics and natural modes of resonance. Not all texts or websites do this well. Any steady periodic tone can be analyzed into Fourier components at integer multiples of the fundamental frequency. The inverse of the fundamental frequency is the period at which the wave form repeats. The fundamental frequency is also known as the first harmonic, and the nth harmonic refers to the component at exactly n times the fundamental frequency.

Every physical object (string, drum head, xylophone bar, air cavity, block of wood, ...) has natural (or normal) modes of resonance, in which all parts of the object vibrate sinusoidally and in phase when appropriately excited. In melodic instruments, selected modes of resonance are usually aligned closely with some of the lower harmonics of a fundamental, but frequently some harmonics are not supported by resonant modes. In the clarinet family, for example, there are no resonances to support the lower even harmonics. When excitation stops, vibrating modes decay, as energy is radiated away as sound and lost as heat. The decay of isolated modes is typically exponential decay, but different modes have different decay times. Since decaying modes are not steady and thus not exactly periodic, their frequencies--as displayed in a Fourier or spectral analysis--are not precisely defined but have some spread or width.

The vibrating strings treated in high-school or first-year university texts are idealizations, like frictionless motion and massless pulleys. They are approximated not only as frictionless, having lossless vibrations, but also as being completely flexible, that is, having zero stiffness. One also approximates the both ends of the string as perfectly rigid whereas the bridge must move to transfer energy to the sound board, whose vibrations produce most of the audible sound. As Rolly points out, true strings all have some stiffness, and piano strings are much stiffer than violin or harpsichord strings. Stiffness is bad because it adds a restoring force that increases with frequency and raises the natural resonances above the corresponding harmonics, making them inharmonic. Thick strings are stiffer than thin ones, and in order to have sufficient mass without excessive stiffness, low strings on pianos are overwound with copper.

When a single note is played on a piano or practically any musical instrument, several modes are excited together. The strengths of the contributing modes depends on details of the excitation and damping conditions. To the extent that the excitation is steady, as can be approximated in a bowed string or a held tone on a wind instrument, the frequency components are harmonic, that is at integer multiples of a fundamental. Any harmonic whose frequency lies outside the natural width of any natural mode will not contribute appreciably to the sound. On a percussively excited instrument such as a piano or church bell, the several modes can contribute and their resonant frequencies are not restricted to a harmonic series.

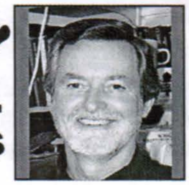
When two or more notes are played together, components with similar frequencies can interfere and produce beats that musicians use in tuning. Rapid beats are perceived as harshness and dissonance. As the frequencies of the principal beating components are brought together, the primary beat rate decreases to zero and the notes are perceived as being tuned to each other. However, softer beats between nearly matching frequencies of higher modes can often still be heard. When two notes an octave apart are tuned on a piano, the first (fundamental) mode of the upper note is tuned to match the second mode of the lower note. Because of stiffness in the string, the second-mode frequency is slightly higher than the second harmonic, and the best-sounding tuning occurs when the beats vanish and the octaves are slightly "stretched" relative to the harmonic frequencies. The resulting inharmonicity on a good piano is not great, usually only a fraction of a per cent on octaves near middle C, but it is more extreme near the ends of the keyboard and can add up to half a semitone (about

There are many other details of piano tuning that reflect subtleties in the physical phenomena and in our perception of sounds. These include the prompt and aftersound arising from degenerate modes with different polarizations, the effects of multiple stringing and the possibility of tuning them so well that the sound is dead, and the necessity of choosing a temperament. An introduction to these can be found in a couple of my favourite references:

Donald E. Hall, Musical Acoustics, 3rd edition, Brooks/Cole 2002; and

Arthur H. Benade, Fundamentals of Musical Acoustics, Oxford Univ Press, 1976.

The Demonstration Corner



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Physics and Music: Harmonics

Diane Nalini de Kerckhove

Diane Nalini de Kerckhove is an Assistant Professor in the University of Guelph's Department of Physics. She is also a singer/songwriter and recently launched her third CD, "Songs of Sweet Fire", a collection of Shakespeare songs and sonnets set to her original jazz and blues music.

I have never met anyone who doesn't like music. After teaching the physics of waves at various levels over the years, I've come to realize that demos involving music have a wide appeal with students, especially since most of them have studied an instrument at some point or another. Here are two options for exploring harmonics of standing waves. When first introducing the idea of a standing wave, I like to dig out a long spring (at least 2 metres long) and ask a student to hold one end
steady. By moving the other end in simple harmonic motion, it is a simple matter to set the spring moving in the fundamental mode (and visually, it looks very much like a giant guitar string). Using a stopwatch, students can then find the average frequency. Finding the second harmonic (shown in Figure 1) is easy enough, and it is useful to slowly increase the oscillating frequency. The erratic movement of the spring as you ramp up from f_1 to $f_2 = 2f_1$ is helpful in demonstrating that a string of a given length will not sustain waves at frequencies other than multiples of the fundamental. The appearance of the first node between two antinodes always elicits an 'a-ha!' reaction. And, with a bit of practice, the third and fourth harmonics can be achieved, demonstrating very readily how nodes are evenly spaced, and added one at a time as one moves through the harmonic series. At this point I like to remind students that real strings on instruments oscillate in all modes simultaneously, with varying amplitudes. As a jazz singer myself, I first noticed this fifteen years ago when a bassist I was working with plucked an open G string and quickly 'tapped' the octave above the note as he slid through an intricate solo sequence.

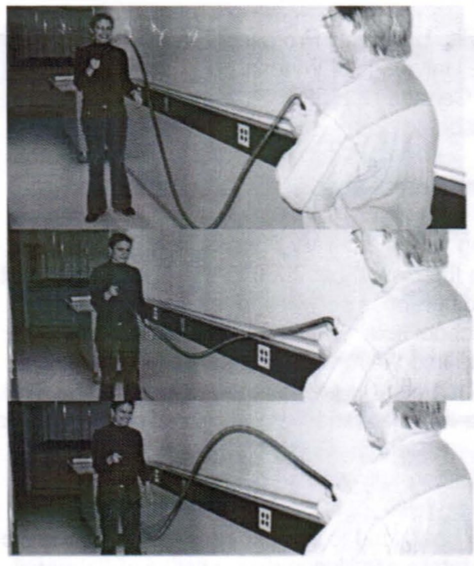

Figure 1 *Demonstrating the second harmonic on a long spring.*

Afterwards, I asked him to show me again how he did it: he simply touched the string (which was still sounding low G) at its midpoint. This damped out the fundamental in the exact position of the node for the second harmonic, which continued to sound, thus producing the octave above the low G.

Using a microphone connected to an oscilloscope with a Fast Fourier Transform setting (for example, the Tektronix TDS 1002), one can monitor sound waves in both the time and frequency domains. If you do not have access to such a scope, there is some simple Freeware software (such as "Frequency Analyzer" available for free download at: http://www.relisoft.com/Freeware/freq.html). This will produce a frequency spectrum for either a microphone input to your computer or pre-recorded sounds (they must be .WAV files). Shown in Figure 2 is a spectrum of a soprano sliding up a scale, using one of the files available from the website for the University of New South Wales's Acoustics Lab. See: http://www.phys.unsw.edu.au/music/ for more details. Standing waves and Fourier series can be dry and abstract for many students, but applying them to the acoustics of voices and instruments can help make the subject come alive.

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Submissions describing demonstrations will be gladly received by the column editor.

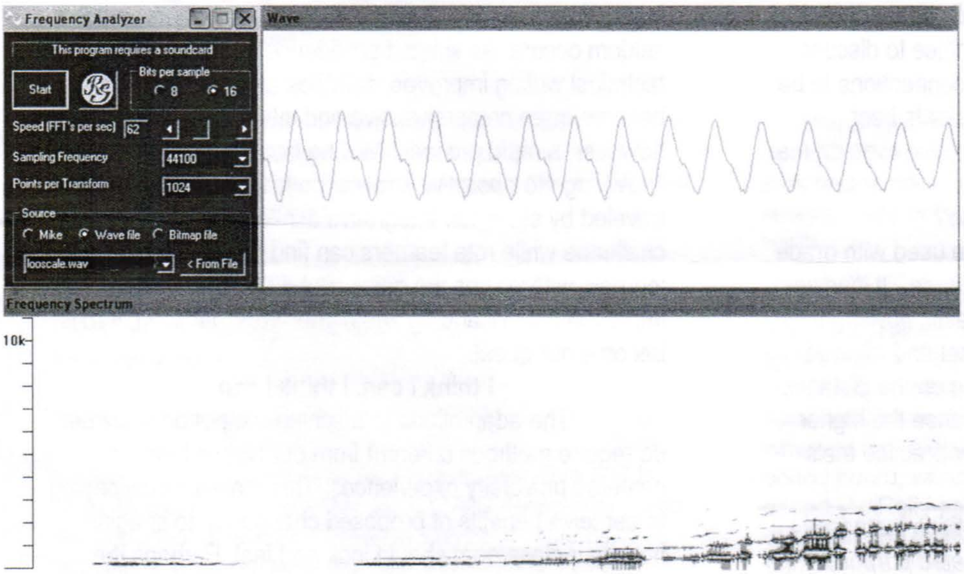

Figure 2 *A screen capture of the wave form above) and the frequency spectrum (below) for a soprano sliding up a scale, using the software "Frequency Analyzer." Time is on the horizontal axis in both displays, and the vertical axis in the lower display is frequency in hertz. Note the significant presence of higher harmonics.*

Dave Doucettes PER Corner

An Introduction To P.E.R.

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Hot off the press is 'America's Lab Report, 2006', an insightful look at the current state of science literacy in North America. The chair of the committee is 2001 physics Nobel prize winner Carl Weiman(previously University of Colorado, now at U.B.C.), The report cites primary reasons for failure to achieve improved literacy and points to current research for promising steps forward.

Carl Weiman's presence on this committee is not coincidental. Obviously an outstanding researcher and thinker, he is also a committed PER supporter. Under his auspices the University of Colorado physics education group has developed a public domain site offering research papers and excellent java applets to aid with physics instruction internationally. I urge all physics teachers to check out this marvelous teaching aid. Go to http://phet.colorado.edu/web-pages/index.html .I have summarized some key points on the report recommendations in the following concept map:

Integrated Learning of Science Concepts and Processes *content and process are seamlessly woven in learning activities*

Clearly Communicated Purposes: *transparent learning goals for laboratory experiences maximize student engagement and learning*

Principles for Design of Highly Effective Laboratory Experiences

Ongoing Discussion and Reflection: *students need opportunity to discuss and reflect, make sense of data, refine and clarify mental models*

Sequenced into the Flow of Instruction: *laboratory activities are explicitly linked to prior and subsequent learning experiences*

At first blush, teachers may feel they are doing all of this. In fact, they often are. That is the problem – teacher centered learning! Instructors are often the only ones in the classroom connecting the distinct modes of thought required in a physics classroom: algorithms, terms and concepts, graphical analysis, free body diagrams. These *habits of mind* are processed in separate areas of the brain and do not easily cross-connect. Students must be given multiple opportunities to make the linkages themselves, through carefully sequenced activities and guided inquiry worksheets, in sequentially richer contexts. These need to be coupled with opportunities to discuss and reflect . It is not sufficient for these connections to be lucidly explained by a passionate instructor.is best achieved by being 'a guide on the side, not a sage on the stage.'

What Does it Look Like?

Below is an example of an activity I have used with grade 11 students near the beginning of the course. It involves 1.5 V, DC 'constant motion' cars and plastic bowling pins (dollar store). Each team is provided a set and allowed five 'shots'. They score points depending on the distance from the car to pin – the greater the distance the higher the point value. I provide five minutes for practice trials before the competition gets underway.

Pitching it as a friendly competition increases student engagement (*clearly communicated purposes*). They pay careful attention to the actual path taken, as this is crucial to scoring well. It is also crucial to distinguish *distance* from *displacement* – the actual agenda *(integrated learning of science concepts and processes)*. The activity is followed with a guided-inquiry worksheet [below].

Activity: Car Bowling
Literacy 1 2 3 4 Understanding 1 2 3 4
Overall Level ___ Score __/10

1. How did today's activity differentiate between the terms *distance* and *displacement*?
2. Would the term *uniform velocity* (aka *uniform motion*) be appropriate to describe your car's motion across the table? Explain.
3. How does the term average velocity, v_{av} defined as d / t, apply to the motion of your car across the tabletop? Do you think it is an accurate representation of the entire trip?
4. How was the motion of your car different at the moment you released your car from rest? Or the moment it struck the bowling pin? Speculate as to the causes of the change in motion.
5. Speculate as to how the motion of the car striking the pin might change if the plastic bowling pin was made of solid wood instead of hollow plastic. Explain your reasoning.

Coaching students to produce a detailed, grammatically correct report requires persistence and patience. To this end, they must be guided specifically as to what to write about, evidenced in questions 1-3 of the worksheet. Questions 4-5 allow for speculation and serve as a diagnostic about forces before this topic is introduced. These questions serve to link previous (gr 10) learning and foreshadow future topics (*sequenced into the flow of instruction*). A quick perusal of student reports informs instructors of the extent to which deep understanding of basic concepts has occurred.

Students are encouraged to discuss in groups as they prepare their worksheets (*ongoing discussion and reflection*). If activities are sequenced in the flow of instruction, there is little need to copy from others and this seldom occurs. As subject confidence and the level of technical writing improves, activities and questions can become more comprehensive and integrative. It is not, however, a rapid process. Moving from *declarative* knowledge to *operative* knowledge is a route seldom traveled by students. Integrative thinkers enjoy the challenge while rote learners can find it stressful. It is a journey, with you as the guide. But if the grail we seek is improved understanding and higher-order-thinking, it must become our quest.

I think I can, I think I can

The adaptations to teaching are not onerous but do require methods different from our typical teacher-centered university experiences. This makes it challenging to perceive benefits of proposed changes or to imagine how your classroom should look and feel. Perhaps the easiest way to get a sense is to attend a workshop where these techniques are incorporated. Incorporated, not merely discussed or explained! Participation is key, as the comments of a leading PER researcher attest, "Teachers should be given the opportunity to learn the content they will be expected to teach in the manner they will be expected to teach." [2] Look for opportunities in STAO, OAPT and other conferences. Scan the wealth of literature on the internet (start with the PhET site mentioned earlier, then check out some of the links).

In a future article, we will examine results of a culminating egg launch activity, and the misconceptions revealed in student reports.

1. America's Lab Report: Investigations in High School Science The National
Academies Press, 500 Fifth Street, N.W., Washington, D.C. 20001, ISBN: 0309096715
2. **Lillian C. McDermott** *Department of Physics, University of Washington, Seattle, Washington, U.S..A. Connecting Research in Physics Education with Teacher Education. An I.C.P.E. Book © International Commission on Physics Education 1997,1998*

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http://www.oapt.ca/index.html

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- Hold an in-school contest and make participation a mandatory part of the course. Evaluate under either "Making Connections" or "Communications".
- Have students vote for favourite entries to send in to the provincial contest.
- Run a separate contest in each semester and compile entries in January and April.
- Set a deadline that is well in advance of April 1 in order to leave time to compile materials and meet the deadline of May 1, 2007.
- Don't hesitate to contact me *(Diana Hall, Contest Coordinator)* with questions or ideas.

*Please visit **www.OAPT.ca** and read complete contest details, see past winners and sample photos*

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