Tu. 1/29: Ch 4 *Sound Propagation* **Th. 1/31:** Ch 4 *Sound Propagation*	HW4: Ch 4: 1,3,4, Project… Ch 4: 8^w,10^w,11^w, 13	**Mon. 1/28** or **Tues. 1/29:** Lab 4 *Wind Instruments: Vibrating Air* (11.3, 12.1)

Materials

- function generator
- ball
- Speaker with tweeter disconnected (to get more beaming)
- Log on and go to http://www.falstad.com/circosc/
- Log on and go to PhET – waves on a string
- Laptop with Odeon
- Laser, diffraction single slit slide (and holder) hair slide, and lab jack
    - Aim above the door (gets far enough, everyone can see, and no one looks into the laser)

Last Time

So, we spent last week thinking about how a musical sound is produced. We spent much to the time focusing on how string and wind instruments take a non-musical impetus (some push, pull, pluck, blow,… that imparts motion) and tunes it to vibrate only at specific frequencies. That happens because whatever medium is doing the vibrating – a string on a guitar or air in an organ pipe – must obey certain ‘boundary conditions.’ The string simply cannot move at the two ends where it’s anchored, so only vibrations with specific wavelengths will fit, those with nodes (points of no displacement) at the ends:

$\lambda_n = \frac{2L}{n}$ where n = 1,2,3,4,…

So, given a particular wave speed, only a family of frequencies will be produced $f_n = \frac{n}{2L}v$.

You explored this in last week’s lab.

Similarly, though not as intuitively, air in a tube that’s open at both ends is *extra free* to displace and so the ‘boundary condition’ is that those two ends must be *antinodes (places of maximal displacement),* again

$\lambda_n = \frac{2L}{n}$ where n = 1,2,3,4,… and thus $f_n = \frac{n}{2L}v$

Then again, if the tube has one closed end then *that* end would be a place where the air *wasn’t* free to move (while the open end would be a place where it was extra free to move) so one end would be an node while the other would be an anti-node, and the wavelengths that ‘fit’ those conditions would be

$\lambda_n = \frac{4L}{n}$ where n = 1,3,5,7,… and thus $f_n = \frac{n}{4L}v$

You have (or are about to have) explored resonance in these two kinds of air columns in this week’s lab.

I'll draw your attention to two important differences between the two kinds of tubes – ones open at both ends (like a flute or some organ pipes) and ones open at just one end (like most wind instruments)

Say you want an organ pipe to play a 344 Hz (around F_4), that has a wavelength of $\lambda = \frac{v}{f} = \frac{344\,m/s}{344\,Hz} = 1m$. Now, if you use a pipe that's open at both ends, it will resonate at this frequency if its length is ½ the wavelength: 0.5 m. Then again, if you use a pipe that's open at just one end, then it will resonate at this frequency if its length is ¼ the wavelength: 0.25 m.

So the one type of pipe can be half as long and play the same note as the other. But there's another difference that comes with the difference in types of pipes: the one that's open at both ends is capable of playing *all* the harmonics of its fundamental (n = 1,2,3,,..) while the one that's open at just one end can play only the *odd* harmonics (n=1,3,5,…); as we'll understand later, that makes for very distinctive sounds for the two different kinds of pipes.

Now, regardless of which type of pipe, or if we're talking about a string, one thing is universal – the frequency that's played is inversely proportional to the length of whatever's vibrating (be it air or string). For example:

Clicker Question: Say you have a guitar and one of the strings is tuned so that when it's 'open' (no fingers pressing down on it) it plays G (392 Hz), then pressing down on the neck ¾ of the way up from the bridge would allow you to play

a) 98Ha
b) 130.7Hz
c) 294 Hz
d) 522.7 Hz
e) 1,176 Hz
f) 1,568 Hz

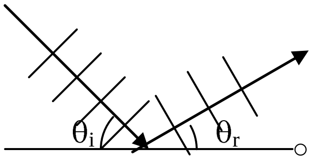
This Time

Ch. 4 Sound Propagation

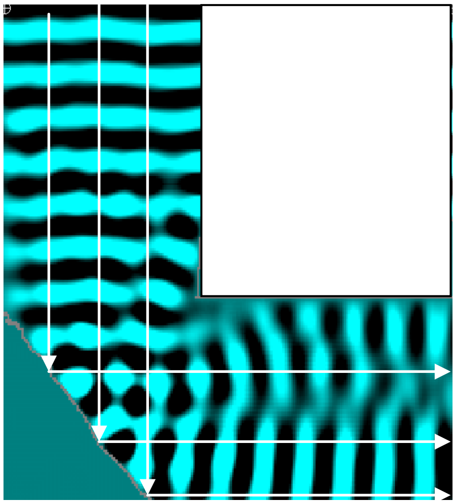
- **Introduction:** Now that we understand (in very broad terms) how instruments produce pleasing sound waves (music), we return to the topic of how sound propagates. A few weeks ago we developed the basic picture of sound propagation as compression waves traveling through the air, this time we'll focus more on the ***direction*** of its propagation. Left alone, in a wide-open space, of uniform air, sound radiates out pretty uniformly. A visual might be a firework exploding – just as the sparkle expands out like the surface of a sphere, so does the boom – you hear the explosion when that invisible sphere of sound expands out to wash over you.
- Things get interesting when the sound ***reflects*** off of surfaces (4.1), ***refracts*** through air at different temperatures (4.1), ***diffracts*** through openings (4.2), gets stretched out or compressed by a moving source or observer (4.4), or ***interferes*** with sound from another source(4.5).

4.1 Reflection and Refraction

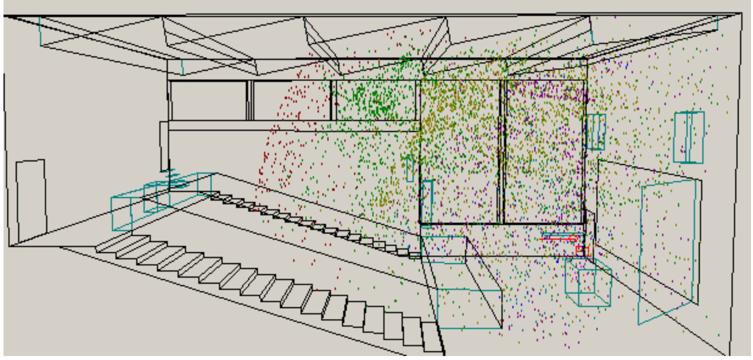
- **Sound reflection**
  - Sound front is a front of air molecules pushing.
  - Consider the individual air molecules, how about the ones right up against a wall
  - **Demo:** Ball to throw against a surface
  - **Q:** If I throw this ball at the table at an angle, how will it come off? Back at me, or off continuing at the angle?
  - **A:** Equal angles of incidence and reflection.
    - The reason has to do with Physics' Law of Inertia. *A body in motion tends to remain in motion unless acted upon by an external force*. The wall provides the external force, but it just reverses the component of the motion perpendicular to the wall, the component parallel remains unchanged.

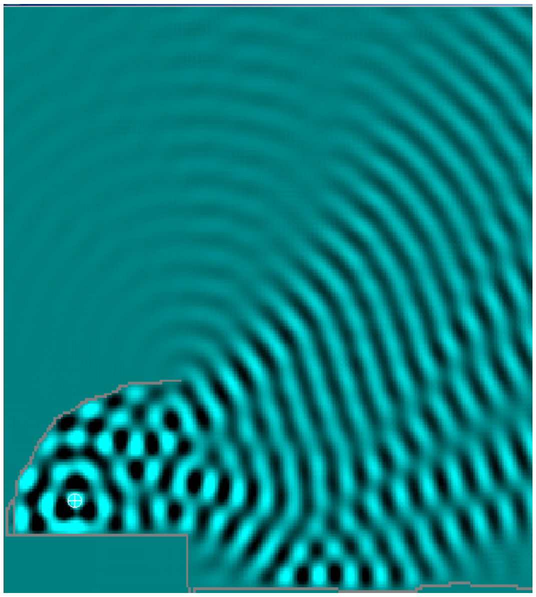


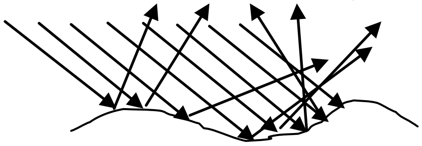
  - So when the push of a sound wave makes it to a wall, that push bounces back, at an equal angle to that of incidence.
  - **Demo: applet** (http://www.falstad.com/ripple/) set "plane source" and switch mouse to draw walls, then draw one wall to allow only a narrow beam from the source, and another to reflect the beam smoothly.



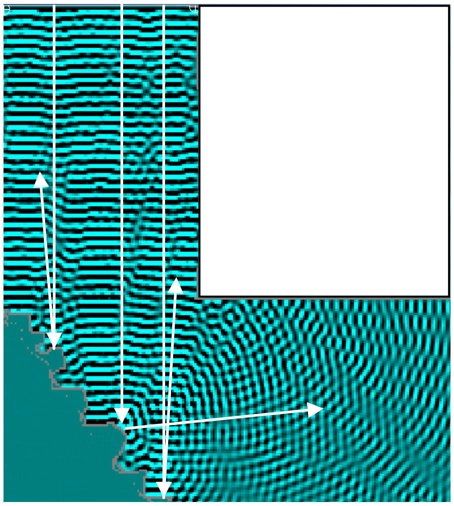
  - **Demo:** Speaker playing a high (beaming) frequency. Reflect off the black board back to the class – pan through angles and let them hear the reflected beam come back.
  - **Differnet representations:** wave fronts and rays of propagation
  - **Application:** This simple idea is very important in the design of listening spaces – lecture halls or concert halls – walls or reflectors get placed to redirect sound.







- **Reflection from a bumpy surface**
  - Each piece of the wave front reflects from the piece of wall it hits with an angle of reflection equal to the angle of impact; however, the wall itself is at different angles. So the wave reflected from the different parts of the wall go in different directions.
  - Draw bumpy wall with parallel lines of impact, and scattered lines of reflections.
  - “Bumpy” and “smooth” are relative terms. Relative to what?
  - **Demo: applet.** Now draw in a jagged wall.

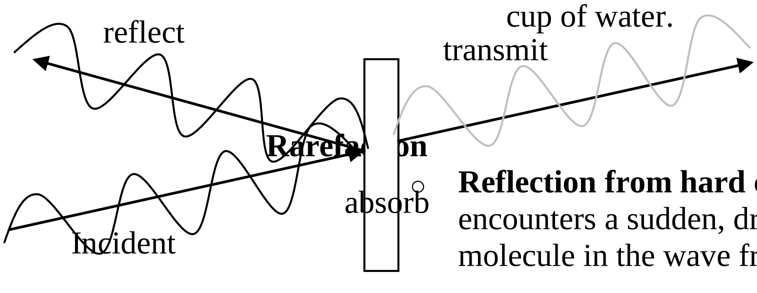


  - **wave table**. Vary the wavelength relative to the bumps in the Styrofoam reflecting block. See the qualitative difference between wavelength smaller and larger than bumps.
  - Relative to the sound’s wavelength. If the surface bumps are as big or bigger than the wavelength, then the wave reflects every which way. If the bumps are small compared to the wavelength, then the waves reflect smoothly.

        - That’s why you’ll see huge baffled panels at a recording studio – to diffuse reflections and avoid setting up standing waves.

- **Adsorption and Transmittance**
    - When a sound wave hits a surface, it doesn’t *just* reflect, it can get transmitted through or adsorbed by the material.
    - **Transmittance**
        - **Q:** How many of you sometimes hear, the phone ring in the other room, or someone speaking loudly out in the hall? Even when your door is closed?
        - The sound is transmitted through your wall or door.
        - With instruments, drums and such, we considered solid surfaces as being acoustically active. The wall is only made of molecules, just like the air, but more closely packed. When the air pushes on the wall, the wall pushes back, but also the push gets transferred into the wall, and on through it. The person speaks, displaces air, the air fronts bombard the wall, the wall deforms in response, the molecules of it that are pushed by the air, push their neighbors, who push their neighbors, pretty soon the push is at the other side of the wall, and being transmitted to the air in your room, which pushes on your eardrum.
        - **Reflected weaker than incident.** So, the wall is not perfectly rigid, some of the push gets transmitted. Back on the source side of the wall, this means that the strength of the incident wave was split between transmitted and reflected – the reflected is weaker than the incident.

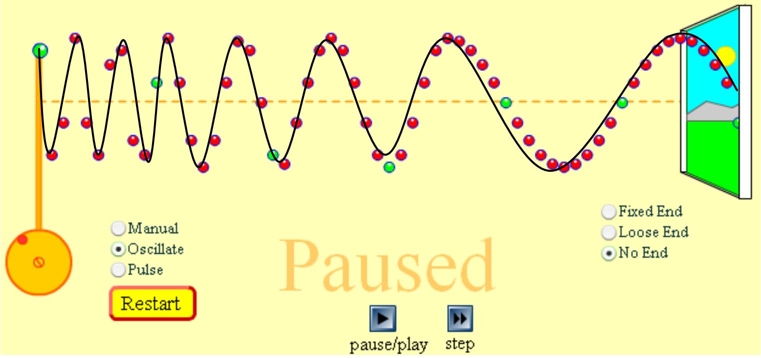
    - **Adsorption**
            - Something else can happen to the sound when it hits a surface. That nice, ordered motion of pushing in and out, that characterizes a sound wave, can get translated into random moving here, there, left, right… in the wall. The motion of a sound wave can degenerate into random motion – heating the wall. No sound re-emits on the other side of the wall; it’s been absorbed, never to be recovered. We will look more closely at adsorption when we get to Chapter 15 – Room Acoustics. It’s just worth noting for now that sound can get adsorbed by a surface and thus the reflected sound can be less than the incident sound.
        - How much sound is transmitted, reflected, adsorbed depends on the material, it’s stiffness & its sluggishness, and how similar this is to air determine how easily it adsorbs the sound. This is similar to the reflection of waves off the end of the torsion wave demo anchored vs. cup of water.



Rarefac on

    - **Reflection from hard change in medium.** In striking a wall, a wave encounters a sudden, drastic change in media. It was fairly easy for each air molecule in the wave front to transfer the push forward to the next air molecule, without much of a return push, not much of a restoring force. But then the air pushes on the wall, and it is denser, it is stiffer, it pushes back more quickly and allows less deformation. This drastically changes the propagation of the wave. Much of it is reflected.

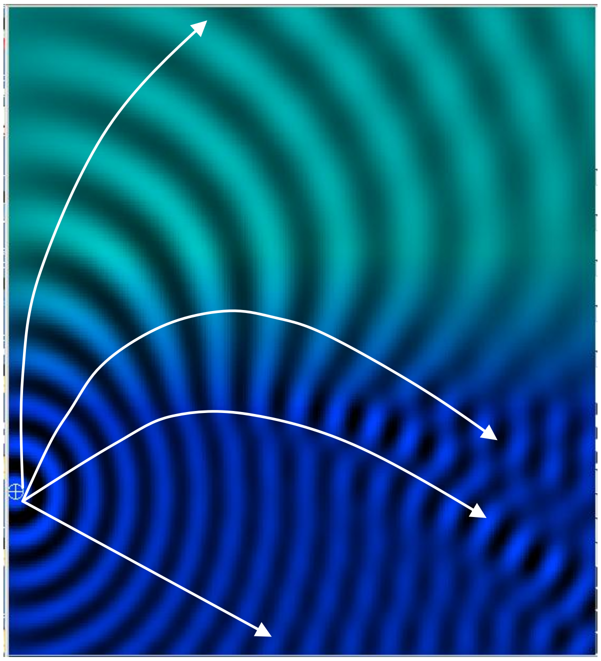
- **Rarefaction from gradual change in medium.**
  - Remember when you varied the tension in the simulation of waves on a string, the wave sped up or slowed down, and along with that the wavelength spread out or shrank.



○ Manual
● Oscillate
○ Pulse

○ Fixed End
○ Loose End
● No End

- While it's hard to *actually* have a string's tension, and thus wave speed, vary along its length, it's not uncommon for the air's temperature to vary from one location to another, and thus for the speed of sound to vary.
- **Temperature Inversion and Rarefaction.** In fact, ever notice that some mornings sounds outside just seem a little crisper, clearer? Maybe, you can hear the distant highway noise more easily than normal? It's not the radioactive spider bite giving you superhuman hearing, it's because of rarefaction.
  - On a cold morning, while the air high above quickly warms up with the rising sun, the surface of the earth is cold and keeps the air down near it cold. So, sound that travels through the cold air moves slowly and with short wavelength while sound that moves through the warmer higher air moves faster and has a longer wavelength. You might not guess it, but that makes the sound waves *bend.*

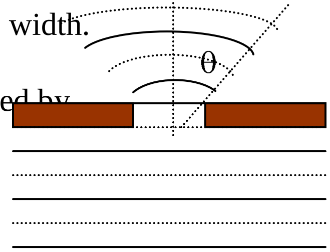


(temperature gradient 2)

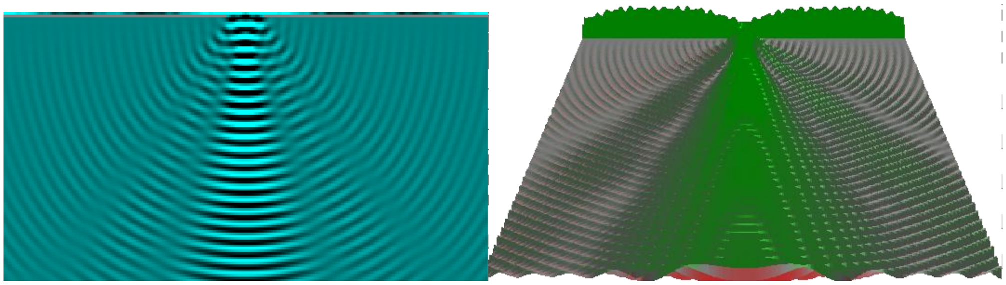
So much of the sound that was bound for the air bends back down to the ground.
The book points out that this doesn't have so much of an effect in musical contexts (it's not like a concert hall will be so much cooler in one area than another that sound gets redirected because of it), but it is something that we all experience – particularly on cold winter mornings.

4.2 Diffraction

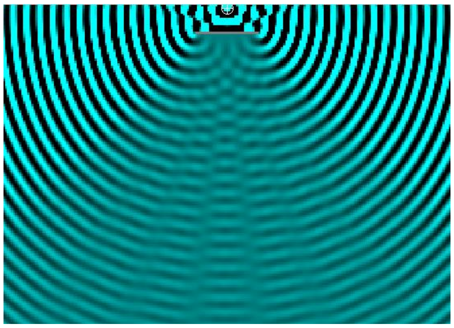
- Ever wonder *why* a speaker has a big woofer and a little tweeter? If you really want to make the loudest sound, you want a big speaker since it will push the most air, yet we use a little tweeter to produce the high pitches. Why? Because of diffraction – the way sound bends around an opening or obstacle.
- You can hear someone talking outside your open door, even if you can't see them. While you need 'line of sight' to see, you don't need it to hear, the sound must be able to bend around to you. Let's see how waves get around obstructions and through openings.
- **Demo: Obstruction.**
  - **Applet** – vary the wavelength and the width of the obstruction, probably crank up the contrast; see how the shadow depend on the ratio of the wavelength to the width – bigger wavelength, smaller shadow.
  - **Wave table**, vary the wavelength and the width of an obstruction.
    - **HW:** In the homework, you're asked to discuss how water waves of different sizes would diffract around an island.
- **Demo: Gap.**
  - **Applet -** vary the wavelength and the width of a gap, see how the width of the beam of waves transmitted depends on the ratio of wavelength to width.
  - **Wave table**
- Specifically, the ½ angle of the beam's cone for a 2-D window is related by



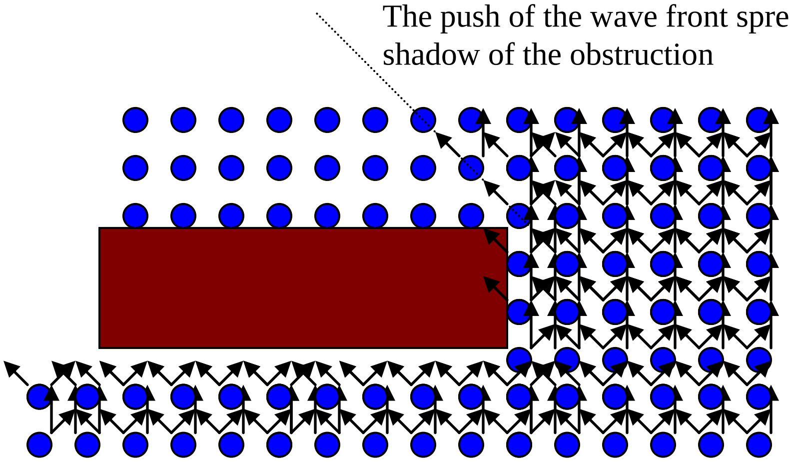
  - $\sin\theta = \dfrac{\lambda}{D}$
- Specifically, the ½ angle of the beam's cone for a 3-D circular window is related by
  - $\sin\theta = 1.22\dfrac{\lambda}{D}$
- You'll get some experience with this in *next* week's lab.
- **High-frequency / short-wavelength components don't bend as well.** Not only does this tell us that waves can bend around corners, it also tells us that, relative to the gaps, long wavelengths (low frequencies) do it better than short wavelengths (high frequencies). Say you hear a bird or a siren outside an open window, or door, or you're at a concert surrounded by tall people. You can still hear the music, but the high frequency sound is weak – it can't bend around the people, the door way, the window, so easily. Things sound better if you get above the tall people, go to the window or door. Then you get both the high and low frequencies.
- **Example: Speaker beaming** I have a 6 inch diameter woofer
  - through which I'll play a high frequency, say 8 kHz. What will be the angle of diffraction?
    - $\sin\theta = 1.22\dfrac{\lambda}{D}$ so, $\theta = \arcsin\left(1.22\dfrac{\lambda}{D}\right)$
    - Given the frequency, we can find the corresponding wavelength, assuming a wave speed of roughly v = 344m/s
    - $v = f\lambda \Rightarrow$ $\lambda = v/f = 344\,{}^{m}\!/_{s}/8kHz = 344\,{}^{m}\!/_{s}/8000\,{}^{1}\!/_{s} = 0.043m(39.37\,inch/m) = 1.69\,inch$
    - $\theta = \arcsin\left(1.22\dfrac{1.69inch}{6inch}\right) = 20°$
  - **Clicker Question.** What frequency would produce a 30° diffraction angle for the woofer (diameter of ____) for the tweeter (diameter of ___)?

  - **Demo**, that has a wavelength of 1.7 inches. Pointing the speaker around, you can really hear that it is strongly *beaming* straight out the speaker mouth, not diffracting much.
  - Then I play a 200 Hz tone, 68 inch wavelength. It doesn't much matter whether I have the speaker pointing at you or not. This is why you don't want your woofer to handle the high notes – you send those to the tweeter, with its small radius, it allows sound to diffract strongly.
  - **In general,** the threshold between beaming and not beaming is $\lambda \approx D$. We'll be able to better understand why this is next time.
  - **Universal wave phenomenon.** This effect can be seen for any kind of wave – sound as we've just heard with the speaker
  - – water as is simulated here
  - 

  - – light **Demo:** laser and diffraction pattern
    - The pattern we see is like the cross-section of the water waves washing up against the tank's end – where the waves are strongest and weakest is where the light is ultimately strongest and weakest on the wall.
    - Vary width of slit and see that width of pattern varies inversely.
  - **Obstruction.** A very similar pattern gets produced when a wave washes over an obstacle.



- **Explanation:** Without getting into a fairly mathematical description, I can't give a good explanation for the wavelength/width dependence, but I can at least describe what how sound waves can expand around corners. In the particle picture of sound, with air atoms pushing into their neighbors, say the wave front moves up the page, particle pushes the particle up the page from it. But it also pushes forward on the particles up and to the right and up and to the left. They do the same…So this push fans out.



The push of the wave front spreads into the shadow of the obstruction

4.3 Outdoor Music

- A performer, floating out in space would produce sound, roughly radially – that is, the sound wave fronts would travel out like expanding balloons.
- **Demo: applet** (single point source, drag it down left, a little away from the wall. Then an audience member would hear just the sound that happened to be directed in his/her direction. The shame of it is that a lot of the sound would be sent of in directions where there were no audience members – completely wasted.
  - **Wave tank -** tapper in the wave tank
- Of course, the performer doesn't just float out in space, he or she stands on a platform, so let's see what effect that has.

- **Demo: applet** – draw floor.
- Now the sound that was heading down, hits the stage floor and (partially) reflects back up. But that still doesn't help the audience, this redirected sound still misses them. But it gives us an idea, how about putting walls up behind the performer to reflect the sound forward, and putting a ceiling over the performer to reflect the sound back down.
- put a block of wood by the tapper in the wave tank.
- **Demo: applet** – draw back wall and floor.
- This is getting better, but still, much of the sound is headed the wrong way. Now, the angle of sound's reflection equals the angle of its incidence, so what we really want is a surface that bends around to catch the sound as it radiates radially out from the source, and redirect it toward the audience.
- **Demo: applet -** draw semicircle behind sound source. Play with different distances from the source. See how the sound from a well positioned source radiates straight out.
- By properly angling the surfaces and placing the performers, sound can be redirected so the performers can hear each other and so the audience gets more of the sound.
- **Time lag** I should note that the reflected waves go a greater distance before arriving at your ear, so there is a slight time lag between the direct and reflected sound. If the time lag is small, this is tolerable, and you hear a louder combined sound, but a large time lag produces an echo. In Chapter 15, we'll get into that and other topics to do with Room Acoustics.