3: Oscillations and Waves

3A: Oscillations
3B: Wave Motion
3C: Acoustics
3D: Instruments
3E: Sound Reproduction

3A: Oscillations
3A10. Pendula
See also Bowling Ball Pendulum (1M40.10).

Simple Pendula with Different Lengths and Masses (3A10.10) -- single bob on a string one meter long, or choose from the following for comparisons:

- Equal length with bobs of different mass (wood and lead)
- Equal length with different mass bobs of the same material
- Bobs of equal mass with pendulum lengths in a ratio of 1:4,

Weight on a Flexible Bar (Inverted Pendulum) (3A10.20) -- a vertical bar with a sliding weight is clamped at the bottom and free to oscillate at the top. The period of oscillation depends upon the position of the weight.

Metronome as a Pendulum (3A10.21) -- A metronome is used as an adjustable pendulum.

Torsion Pendulum (3A10.30) -- a heavy disc at the end of a limber vertical rod can be set into torsional oscillation. Mass can be added to the disc to show the effect on the period of oscillation.

Variable Angle (Variable g) Pendulum (3A10.40) -- A physical pendulum is mounted on a bearing so the angle of the plane of oscillation can be changed.

Conical Pendulum -- A ball on string suspended from a tall ring stand.

3A15. Physical Pendula

Physical Pendulum (3A15.20) -- Compare the period of a bar supported at the end with a simple pendulum that is 2/3 the length of
the bar.

**Hoops and Arcs (3A15.40)** -- a full circular hoop and portions of a hoop of the same diameter pivot from a hole at the center of the periphery of each. Though they vary greatly in size, each will swing on the pivot with the same frequency of oscillation.

**Kater Pendulum (3A15.70)** -- device used for a highly precise measurement of g. Analysis requires moments of inertia, for which we have no precise data.

### 3A20. Springs and Oscillators

**Oscillating Mass on a Spring (3A20.10)** -- a large mass is hung on a spring mounted in front of the blackboard, then pulled down and released to show simple harmonic motion.

**Oscillating Glider on an Air Track (3A20.35)** -- an air track glider of variable mass oscillates between two springs.

**Water in U-tube (3A20.55)** -- colored water oscillates between two legs of a glass U-tube. Motion can be frozen at any point by corking one leg of the tube.

**Ball in Plastic Bowl (3A20.60)** -- a rubber ball rolls in a large hemispherical plastic bowl.

See also Inertial Balance (1F10.11).

### 3A40. Simple Harmonic Motion

**Circular vs. Simple Harmonic Motion (Spring) (3A40.10)** -- the shadow of a pin moving uniformly around a circle in the vertical plane is superimposed over that of an oscillating spring and weight. The shadows of the pin and the weight are synchronized so that the shadows move in unison on the screen.

**Circular vs. Simple Harmonic Motion (Pendulum) (3A40.20)** -- the shadow of a pin moving uniformly around a circle in the horizontal plane is superimposed over that of a swinging pendulum. The shadows of the rotating pin and pendulum are synchronized so that the shadows move in unison on the screen.

**Tuning Fork with Light (3A40.41)** -- a large tuning fork with a low frequency has a small light bulb on one tine. The tuning fork is set into vertical oscillation and then moved horizontally in a dark room. The light bulb traces out a sine curve.

**Lights on a Circle (Θ Device)** -- lights on a large board are arranged in the shape of the Greek letter theta. Turn a crank slowly and pairs of bulbs light sequentially, one moving around the outer circle and the other moving back and forth across the horizontal crossbar; these two bulbs are aligned vertically to show the connection between circular motion and SHM.

**Phase Shift (3A40.65)** -- a vertical disc has two balls mounted at its edge which may be moved to different angular positions. As the disc is rotated, the balls are shadow projected so that their circular motion appears as SHM. By moving the balls to different relative positions on the disc (in multiples of 45 degrees), their motion on the screen will be 90 degrees out of phase, 135 degrees out of phase, etc.

### 3A50. Damped Oscillators

**Water Damped Spring and Weight (3A50.10)** -- a weight on the end of a hand-held spring is set oscillating in a large jar of water and quickly damps out.
3A60. Driven Mechanical Resonance

**Tacoma Narrows Bridge Collapse (3A60.10)** -- A film showing the collapse of the original Tacoma Narrows Bridge due to resonance.

**Resonant Driven Pendula (3A60.31)** -- Three simple pendula of different lengths are hung from a horizontal bar with an attached driver pendulum. The driver pendulum is a stiff rod with an adjustable bob so that its frequency can be changed. The driver pendulum is set to the natural frequency of each pendulum in turn, and only that one pendulum oscillates.

**Bowling Ball Pendulum and Hammer (3A60.35)** -- A bowling ball hangs from the ceiling on a long cord. A rubber mallet is used to strike the ball and build up oscillations. If the striking frequency equals the natural frequency of the ball, the oscillations build up to large amplitudes, otherwise not.

**Driven Spring and Weight (3A60.43)** -- Mass on spring is motor driven at an adjustable frequency; damping the motion in a cylinder of water shows a small shift in the resonant frequency of the oscillator.

**Driven Oscillator with Display (3A60.43)** -- A newer version of the above demo (Driven Spring and Weight). A spring with a weight on the bottom hangs from a driver made from an audio speaker. It is driven by a signal generator with a digital display, and exhibits a sharp resonance at approximately 0.9 Hz. The up-and-down motion of the driver is amplified by a simple lever mechanism for visibility so that the phase relationship of mass and driver can be studied below, at, and above the resonant frequency. A cylinder of water can be used to provide (a lot of) damping, or a piece of cardboard stuck to the bottom can be used for lighter damping.

**Reed Tachometer (3A60.50)** -- A set of metal reeds of descending natural frequencies is attached to a gyroscope. The gyroscope is slightly off-balance so that it vibrates as it spins, and as its rotational frequency passes through the frequencies of the reeds each reed vibrates in turn.

3A70. Coupled Oscillations

**Wilberforce Pendulum (3A70.10)** -- Spring with weight which has a natural rotational frequency equal to its up-and-down frequency. Start the weight oscillating, and energy will transfer back and forth between the rotational and translational modes. Large bright dots on the weight improve visibility.

**Coupled Pendula (3A70.25)** -- Two identical massive bobs at the ends of two pendulum rods are coupled by a spring and set swinging. Alternately each one stops oscillating as its energy is transferred to the other, then begins swinging again as the energy is transferred back. Different springs change the amount of coupling and the time required for total energy transfer.

**Metronome Synchronization (Spontaneous Synchronization)** -- Five small metronomes on a lightweight plank are set to the same frequency and started oscillating out of phase. At first the plank sits on the table and the metronomes' tick-tocks will be independent. The plank is then set on two empty soda cans (on their sides) to provide some light coupling between the metronomes. The metronomes will phase lock with each other within a minute or two and the tick-tocks will all be in unison.

3A75. Normal Modes

**2 or 3 Glider Air Track Resonance (3A75.10)** -- Either two or three gliders are hooked together with springs to form a coupled oscillator system. Different modes of oscillation may be set up easily by hand, or driven (more finicky) at the resonant frequencies of the modes by a push-pull driver of variable frequency.

**Air Track Gliders with Spring Steel** -- Two gliders are attached with a long piece of spring steel. With the air track turned off,
gliders are brought close together (compressing the spring) and the gliders are tied with a loop of string. When the string is burned, the gliders oscillate about the midpoint of the spring steel. Can also be set in motion before burning the string.

3A80. Lissajous Figures

Lissajous Patterns (3A80.20) -- two audio oscillators, one connected to the vertical input of a large oscilloscope and the other to the horizontal input. A change of pattern is observed with a change in amplitude, frequency ratio, or phase.

3A95. Non-Linear Systems

Lockable Double Pendulum -- a (chaotic) double pendulum that has a locking bolt to turn it into a simple (non-chaotic) physical pendulum.

Periodic, Non-Harmonic Device (3A95.38) -- a pendulum bar with a massive bob at the end has a long limber wire projecting out of the top. The pendulum exhibits simple harmonic motion, but the wire is constrained by a loop encircling it and exhibits periodic but non-simple harmonic motion.

Pump Pendulum (3A95.70) -- a weight swings on the end of a string which passes over a pulley and is tied to a rod. If the string is tugged to lift the weight at the right frequency and phase the amplitude of the pendulum’s swing increases gradually.

3B: Wave Motion

3B10. Transverse Pulses and Waves

Wave on a Rope (3B10.10) -- a long rope is attached to one wall, prof holds other end and shakes a wave along the rope to show a travelling transverse wave.

Tension Dependence of Wave Speed (3B10.15) -- waves plucked on a length of stretched rubber tubing shows a strong dependence on tubing tension.

Spring on Table (3B10.20) -- a long brass spring is stretched out on the lecture table and shaken at one end. Transverse waves of large amplitude and low velocity will propagate along the spring. The far end can be fixed or free.

Pulse on a Moving Chain (3B10.26) -- a loop of chain is hung loosely across two wheels at the same level, one free and one motor driven. Motor speed and chain tension can be adjusted so that a pulse wave produced by a sharp blow from a stick will propagate at the same speed as the chain motion and thus appear motionless. Practice to avoid knocking the chain off with too heavy a blow.

Transverse Waves (Bell Labs Wave Machine) (3B10.30) -- In these three machines, rods are arranged like ribs along a square wire "spine." A torsional wave can be sent down the spine by sharply displacing the tip of the first rod. As the wave propagates along the spine, each rod is tipped in turn by the passage of the wave, and the displacement of the ends of the rods is visible to the class, appearing as a transverse wave (visibility can be increased by illuminating the fluorescent tips of the rods with UV). The spines are identical in each machine, but the lengths of the rods differ (46 cm in one, 23 cm in another, and lengths increasing regularly from 23 to 46 cm in the third), causing different propagation speeds. The 23 and 46 cm machines can be hooked directly together or through the "coupling" section, showing the advantages of coupling. The end rod of the machines can be free, fixed, or damped to show the effects on reflection from the end. Note: This is on the same setup as Longitudinal Waves (Hanging Slinky) (3B20.10).

3B20. Longitudinal Pulses and Waves
Longitudinal Waves (Hanging Slinky) (3B20.10) -- longitudinal waves propagate slowly on a large plastic slinky suspended horizontally on strings. The slinky is hand-driven and can be used to show single pulses or standing waves. Paper markers hang on the coils to increase visibility of compression and rarefaction. The far end can be free or fixed. Note: This is on the same setup as Transverse Waves (Bell Labs Wave Machine) (3B10.30).

Longitudinal Wave Model -- a model of travelling longitudinal waves. 21 vertical rods are attached to a horizontal shaft. Turning a crank turns the shaft, moving the vertical rods back and forth in place in such a way that a longitudinal “wave” passes along the rods, with a compression followed by a rarefaction for as long as you want to turn the crank. Reversing the cranking direction reverses the direction of the wave. In reality each rod moves back and forth sinusoidally in a groove on the shaft, with the motion of each rod progressively 30° ahead of its neighbor, creating the illusion of a wave.

3B22. Standing Waves

Standing Waves in Rubber Tubing (Varying Frequency) (3B22.10) -- a long piece of rubber tubing is stretched out horizontally and run over a pulley at one end, then tensioned with a hanging weight. At the other end a revolving beater bar strikes the tubing at a frequency which can be adjusted with a motor speed control. Transverse waves of any frequency can thus be sent along the tubing, and when the right frequencies are reached the tubing vibrates in various standing wave modes.

Three Strings (Varying Tension) (3B22.15) -- three strings of approximately the same length but under different tensions are driven at the same frequency. With the help of a stroboscope, the envelopes of the wave forms (fundamental, 1st and 2nd harmonics) can be observed in slow motion.

Standing Waves in Hanging Slinky (3B22.50) -- drive a hanging slinky by hand to produce standing longitudinal waves.

Standing Wave Model (3B22.90) -- a simple model that shows how standing waves form. A sine wave is drawn on a loop of acetate that moves between two rollers. The students see two sine waves, one moving to the left and one to the right at the same velocity. At some points (nodes) the amplitudes of the two waves will always be equal and opposite, so they cancel. At points in between (antinodes), the two waves will always be moving together, so they will reinforce at those points to create greater amplitudes. A grid can be inserted that marks the nodes and antinodes for easy viewing.

See also Vibrating Circular Wire (7A50.40).

3B25. Impedance and Dispersion

Impedance Matching (Bell Labs Wave Machine) (3B25.10) -- The long and short rods sections of the wave machine can either be connected abruptly (unmatched coupling) or with a section of gradually lengthening rods (matched coupling).

Wave Reflection (3B25.20) -- the Bell Labs Wave Machine described above can be used with the end fixed, damped, or free to show the effect on the reflected wave.

Spring Wave Reflection (3B25.25) -- reflections from a long horizontal brass spring (3B10.20) with fixed and free ends.

Acoustic Coupling (3B25.35) -- a small speaker has a coupling horn which may be removed. With the horn on, the sound is much louder than with the horn off.

Space Phone (Spring and Horn Toy) (3B25.55) -- two plastic earpieces connected by a long light spring. If you put an ear to the earphone and twang the spring, a very spacey science-fiction sound is heard. There is some disagreement as to the cause, with some
crediting dispersion of the wave in the spring, others saying that isn't possible. Your call. A microphone can be placed at the earphone for class enjoyment.

3B27. Compound Waves

Wave Superposition (3B27.15) -- Start positive pulses from each end of the Bell Labs Wave Machine.

3B30. Wave Properties of Sound

See also Light and Siren in Vacuum (6A02.10) in Section 6: Optics.

Phonodeik -- shows the y vs. t deflection of a scanning light beam which is reflected from a delicate mirror on the diaphragm of a mechanical microphone during oscillation. An "oscilloscope" from the pre-electronic era of candle flames, levers, and ingenuity. Note: This demonstration is currently missing.

Sound in Helium (3B30.50) -- helium can be blown through a variety of resonant music makers to demonstrate the higher notes that are created with a lower density gas. Choices include organ pipes, a jug or ocarina instrument, and (most popular) an inhaled lungful by the lecturer.

3B33. Phase and Group Velocity

3B35. Reflection and Refraction (Sound)

Refraction of Water Waves (3B35.60) -- Plane waves refract in a tank with deep and shallow sections.

3B39. Transfer of Energy in Waves

3B40. Doppler Effect

Doppler Effect (3B40.10) -- a siren at the end of a string emits sound as it is swung around and class hears the pitch rise and fall as the siren moves toward or away from them.

3B45. Shock Waves

3B50. Interference and Diffraction

Ripple Tank - Single Slit Diffraction (3B50.10) -- diffraction from a plane wave passing through a single slit on the ripple tank.

Ripple Tank - Double Source Interference(3B50.20) -- two point sources in phase show interference.

Ripple Tank - Double Slit Interference (3B50.25) -- interference from a plane wave passing through two slits.

Ripple Tank - Multiple Slits -- plane waves pass through multiple slits.

Moiré Pattern (3B50.40) -- two patterns of concentric circles are laid atop one another on the overhead, and the separation between their centers changed by sliding one across the other. An interference pattern whose number of nodal lines depends on source separation appears on the screen.

Please see section 6: Optics for more interference and diffraction demonstrations using lasers or microwaves.

3B55. Interference and Diffraction of Sound
Two Speaker Interference (3B55.10) -- two small speakers driven in phase are attached to a long bar which can be rotated to sweep the minima and maxima points past the students (have them plug one ear). Frequency can be varied.

3B60. Beats

Beats from Tuning Forks (3B60.11) -- two matched tuning forks are used, one of which has an adjustable weight on one tine. By adjusting the weight the forks can be set to equal frequencies to show resonance, or set slightly apart to demonstrate beats.

Beats on Oscilloscope (3B60.20) -- the outputs of two audio oscillators are mixed and fed into an amplifier, then the amplifier output is fed into an oscilloscope and an audio speaker to produce visible and auditory indications of beats.

Beats (Two Speakers) -- two speakers powered by separate audio oscillators produce beats.

Also see Singing Glass Tubes (Beats) (3D30.70) and Organ Pipes (Beats).

3B70. Coupled Resonators

Coupled Tuning Forks (Sympathetic Vibrations) (3B70.10) -- Two matched tuning forks are mounted on resonance boxes. Hit one and the other vibrates too.

3C: Acoustics

3C10. The Ear

Model of the Ear (3C10.10) -- shows anatomical structure of the human hearing mechanism.

3C20. Pitch

Oscillator with Speaker and Oscilloscope (Range of Hearing) (3C20.10) -- run the frequency up and down, announcing the value as class gets a feel for the audio range and the relationship between frequency and pitch. Can also display on the scope subsonics and ultrasonics that cannot be heard.

Galton Whistle (3C20.15) -- this small ultrasonic whistle produces high intensity sounds at frequencies that are essentially inaudible to humans.

Siren Disk (3C20.30) -- a disk with four circular rows of holes uniformly spaced and another circular row of randomly spaced holes. The disk is rotated by a motor and a jet of air is directed at the holes. Puffs of air through the disk as a hole passes the air jet produce pressure variations, and thus sound. Different musical notes are heard from different circles of regularly-spaced holes but noise is heard from the circle of randomly-spaced holes.

Gear with Vibrating Card (3C20.40) -- similar to a card in the spokes of a bike wheel. Rotation of the gear can be varied to produce everything from a rapid clicking (under 20 Hz) to full-fledged sounds.

3C30. Intensity and Attenuation

Decibel Meter (3C30.22) -- a modern meter using a microphone and electronic amplification, with calibrated output in decibels. Try it with various sounds or have your class yell.
3C40. Architectural Acoustics
3C50. Wave Analysis and Synthesis

**Fourier Synthesizer (3C50.10)** -- a commercial Fourier synthesizer is connected to a speaker and an oscilloscope. The synthesizer can generate two fundamentals of 500 Hz and eight higher harmonics, each with amplitude and phase control. The synthesizer can produce either sine, square or triangular wave forms.

**Audio Filter** -- electronic filter can operate as a high or low pass filter with selectable frequency.

3C55. Music Perception and the Voice

**Tuning Forks on Resonant Boxes (3C55.55)** -- Two tuning fork and two resonant boxes. Shows that the box needs to be matched to the fork.

**Microphone and Oscilloscope (3C55.70)** -- Show the output of a microphone on the oscilloscope. Observe patterns of voices, speech, tuning forks, and musical instruments.

3D: Instruments

3D20. Resonance in Strings

**Sonometer (3D20.10)** -- the two ends of a stretched steel wire are hooked to an audio amplifier and a small horseshoe magnet is placed over the wire, so that transverse vibrations of the wire are transformed into currents along the wire. The currents are amplified and fed into an oscilloscope and/or speaker. Thus the waveform can be seen, and heard if desired. The wire is finger-plucked, and both tension and length are adjustable. Harmonics can be either ignored or intensified by changing placement of the magnet, and can also be damped out selectively with a small paintbrush.

3D22. Stringed Instruments

**Guitar** -- an acoustic guitar provides a good example of standing wave dependence upon string length and tension.

**Piano** -- a small upright piano is available in or from room A114 by arrangement.

**Piano Key Action** -- cutaway of actual key and hammer mechanism to show complicated nature of the system used to properly strike piano strings in order to excite a note and avoid damping.

3D30. Resonance Cavities

**Vertical Resonance Tube (256/512 Hz) (3D30.10)** -- a glass cylinder is filled with water to one of two preset levels and the tuning fork with a frequency equal to the resonant frequency for that level is held over the opening. It is noted that the sound is much louder than when the tube is filled to any other level.

**Open and Closed Resonance Tube (256/512 Hz) (3D30.20)** -- A metal tube is cut to length to resonate at 256 Hz when closed and 512 Hz when open.

The previous two demonstrations are most often used together.

**Resonance Tube with Piston (3D30.15)** -- a long glass tube with a moveable piston inside has a speaker at one end. Using a sound
wave of known frequency, move the piston while listening for changes in sound intensity. Different points of maximum intensity will be found at regular spacing, which can be marked with stick-on dots on the side of the tube. The distance between the dots (½ λ) and the known frequency can be used to calculate the speed of sound in air.

**Helmholtz Resonators (3D30.40)** -- classic spherical resonators can be made to resonate loudly by a tuning fork of the corresponding frequency.

**Kundt’s Tube (3D30.60)** -- Air column resonance in a horizontal glass tube is shown by adding cork dust to the tube and driving the air column with a speaker inserted in one end of the tube. Accumulation of cork dust shows nodes (displayed on overhead projector). Tube length may be varied with a sliding stop at the far end.

**Rijke Tube (3D30.70)** -- a 6 cm diameter 62 cm long glass tube has a piece of wire mesh across the tube about 1/4 up from the bottom. The tube is held over a burner until the wire mesh glows red-hot, then removed and held vertically. A loud pure tone is produced as a result of a standing sound wave in the tube. Turn the tube horizontally and the tone stops, then starts again when the tube is held upright. The mesh is at the velocity antinode for the standing wave, and the moving air reinforces the standing wave by removing energy from the mesh at the frequency of oscillation.

**Organ Pipes (Beats)** -- 2 large (10 cm diameter, 140 cm and 122 cm long) metal pipes mounted vertically on lecture table will resonate at low frequencies when a source of “white noise” (Fisher burner) is placed at the bottom end. If both pipes are excited at once they produce beats.

**Singing Glass Tubes (Beats) (3D30.70)** -- two small glass Rijke tubes have electrically-heated wire grids and moveable tubes. Move a tube so that the grid is at the 1/4 point and the tube will "sing." Put it anywhere else, and no song. Since the tubes are slightly different lengths, running them both together produces beats.

### 3D32. Air Column Instruments

**Slide Whistle (3D32.15)** -- toy whistle has a slide arrangement to vary column length and thus pitch.

**Open and Closed End Pipes (Various) (3D32.25)** -- a variety of mouth blown organ pipes with different lengths and removable end pieces to show the effects of pipe length and the difference between open and closed end resonators.

**Cardboard Tube** -- a long cardboard mailing tube with a cap at one end produces a “thunk” sound at the resonant frequency of the tube when the cap is removed. Note: Another variation uses small metal tubes and stoppers.

**Recorder** -- a clarinet-like instrument used to discuss the effect of hole openings in effectively shortening the resonance length.

**Ocarina** -- a toy musical instrument (resonant cavity with finger holes).

### 3D40. Resonance in Plates, Bars, Solids

**Xylophone (3D40.10)** -- small xylophone covering two octaves, including sharps and flats.

**Xylophone Bars** -- produce xylophone sounds by striking centers of bars mounted on individual sounding boards.

**Wooden Xylophone** -- a set of tuned wood bars on a rope support cover one octave of frequency when struck.
Rectangular Bar Oscillations (3D40.11) -- a long hand-held metal bar has a rectangular cross-section. A high-pitch longitudinal oscillation frequency is excited by hammering the end. Two lower transverse frequencies are excited by striking one side or the other of the bar, with the wider side having the lower frequency.

High Frequency Metal Bars (3D40.12) -- three finger-held resonant metal bars are struck on the ends to produce frequencies of 5, 10, and 15,000 Hz.

Singing Rods (3D40.21) -- an aluminum rod (approximately 1.3 cm diameter by two meters long) is held at the center with one hand. The other hand strokes the rod between a rosined thumb and forefinger to induce longitudinal oscillations. The support point may be changed to produce harmonics of the fundamental tone, and two other rods of shorter lengths produce higher frequencies. Note: This demo requires some practice.

Chladni Plates (3D40.31) -- Classic demonstration of nodal patterns in vibrating metal plates as seen by heaping lines of white sand which build up at the nodes as the plates are excited by the driver section of a speaker. Many different patterns can be seen at different frequencies. Nodal patterns can also be varied by pressing a finger to the edge of the plates at various points.

Drumhead (3D40.40) -- a large rubber sheet stretched over a circular frame is driven by a speaker from below and develops standing waves at certain frequencies. Black grid lines on the sheet emphasize the displacement patterns (fundamental and 1st and 2nd overtones, which are not in harmonic multiples). Off-center placement of the speaker produces other patterns. Sheet tension can be adjusted to alter the fundamental frequency and overtones. Motion can be frozen using a strobe.

Wine Glass Resonance (3D40.50) -- Dip your finger in water and run it around the rim of a wine glass.

Chinese Spouting Bowl (3D40.51) -- A 15” diameter decorative bowl with handles is partially filled with water. Wet your hands and then rub the handles to create resonance. The standing wave will cause the water to jump up several inches or more. Note: Make sure your hands are clean first.

3D42. Percussion Instruments
3D46. Tuning Forks

Tuning Forks (3D46.15) -- various tuning forks for show and tell.

3D50. Electronic Instruments

3E: Sound Reproduction
3E20. Loudspeakers

Cutaway Speaker (3E20.10) -- a speaker that has been sliced to allow a side view of the cone motion when the speaker is speaking. Works best on the overhead projector.

Simple Speaker -- Daryl's favorite.

3E30. Microphones
3E40. Amplifiers