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Dramatic and unusual physics lecture demonstrations

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WORKSHOP

"Dramatic and Unusual Physics Lecture Demonstrations"

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Friday, 26 October 2001, 3:00 – 5:00 pm,
starting in Spanagel 117

Dramatic and unusual demonstrations will be performed, explained, and discussed. The demonstrations will tentatively include those described below.* The times of each session are approximate.

*Mechanics, fluid mechanics, acoustics, and electromagnetically coupled oscillators Some of these demonstrations are publishable. If you are interested in this, please contact Bruce Denardo (denardo@physics.nps.navy.mil).

Mechanics

3:00-3:25 pm in Spanagel 117

Circular/Harmonic Motion

Two identical pendulums are constructed with string and billiard balls. In equilibrium, the strings are vertical and the balls touch. The balls are pulled transversely aside from equilibrium, and one ball is given an initial velocity directly toward the other ball such that the latter moves approximately in a circle after the collision. Because the balls have the same mass and the collision is approximately elastic, the incident ball is at rest just after the collision and subsequently undergoes simple harmonic motion in a plane. The other ball undergoes uniform circular motion. Because simple harmonic motion is the projection of uniform circular motion, the periods of these two motions are the same. The balls thus collide at the opposite point, and the motion repeats.

At greater amplitudes, the repeating motion quickly breaks down. One reason for this is that the period of a planar pendulum increases with amplitude, while the period of a conical pendulum decreases, so the balls do not collide at the point opposite to the first collision.

Roberval Balance

Invented by Gilles Personne de Roberval in 1669, this balance has the desirable property that two equal weights balance each other regardless of the distance of each weight from a double-fulcrum. This is even true if both weights are on the same side of this fulcrum! The apparatus has two parallel arms with fixed ball bearings at the centers of the arms. The ends of the arms are connected with ball bearings to two vertical arms. As the balance tilts, the vertical arms remain vertical. Horizontal rods are connected to the vertical arms. Moving a weight along either of the horizontal rods does not alter the balance. Many modern double-pan balances employ the Roberval mechanism.

Foucault Model

A Foucault pendulum at the north or south pole can be modeled by a vibrating rod pendulum of circular cross section that is clamped to a support attached to a rotatable platform. The mass is set into oscillation in a plane, and the plane remains fixed as the platform is slowly rotated. For an observer on the platform, the plane of oscillation appears to precess 360^o for every revolution of the platform. A Foucault pendulum at an intermediate latitude can be simulated by arranging the rod to be inclined in equilibrium.

In regard to the vertical pendulum, what happens for an *anisotropic* oscillator, which has two distinct frequencies in perpendicular directions? This can be demonstrated with a plastic I-beam rod a pendulum. One of the modes of the pendulum is excited, the platform is rotated slowly, and the plane of oscillation now rotates with the table. This is an example of *adiabatic invariance*. If the platform is not rotated slowly, the other mode is observed to become excited, and a Lissajous pattern results. What happens for a rod with *square* cross section? The plane of oscillation is observed to remain fixed, which indicates that the flexural stiffness of the rod is isotropic. If the end of the rod is held horizontal and slowly rotated, the amount of flexure is constant, which shows that the flexural stiffness of a square rod is indeed isotropic.

Parallel Axis Theorem

Two identical rectangular physical pendulums with concentric holes are machined from ⅜-inch thick aluminum plates. Suitable dimensions are 5 by 15 inches with an 4-inch diameter hole. Each pivot is a knife edge, which can be an equilateral triangle machined from half the length of a ½-inch diameter brass rod. The other half is clamped to an upright. One pendulum is vertical in equilibrium, while the other is horizontal. Which pendulum has the greater period? The period of any physical pendulum depends upon the distance of the pivot to the center of mass, and the moment of inertia about the pivot. The distance to the center of mass, which is the radius of the hole, is the same for both pendulums. Surprisingly, the moment of inertia is also the same as a result of the parallel-axis theorem. The period is thus the *same* for the two cases. (In fact, the period is independent of the location of the pivot along the entire rim of the hole.) The periods of the two pendulums are observed to indeed be the same. Note that this can be considered as experimental confirmation of the parallel-axis theorem.

Hanging Picture Instability

A rectangular frame is suspended by a cord that passes through a pulley. The cord is attached to the upper corners of the rectangle, and the length of the cord is adjustable. Let α be the angle between the two segments of cord on either side of the pulley, and β the opposing angle between the two diagonals of the rectangular frame. The system is demonstrated to be stable if $\alpha < \beta$, and unstable if $\alpha > \beta$. The center of mass evidently rises in the first case for perturbations about equilibrium (similar to a ball in a valley), and falls in the second case (similar to a ball on the top of a hill). The instability condition $\alpha > \beta$ can be analytically derived, although this is not easily done, as far as we know. Note that it is easy to understand the limiting case $\alpha = 0$ and $\beta = 180^o$ (stable), as well as the limiting case $\beta = 0$ (unstable). The instability is why many hanging pictures frequently cease to be level. Static friction prevents the instability from occurring immediately, but vibrations slowly allow the instability to proceed.

Coupled Pendulums Instability

Two identical simple pendulums are constructed with string in a "V" shape such that the V's overlap, and a knot is tied at the point of intersection. Other arrangements of two coupled pendulums yield the same behavior (for example, a weak spring between two heavy masses on strings). One pendulum mass is set into motion with a small amplitude, while the other is initially at rest, and linear beating is observed. The two normal linear modes, each of which has a pure frequency, consist of symmetric and antisymmetric motion. These modes are demonstrated.

Next, the antisymmetric mode is observed to be stable at high amplitudes, whereas the symmetric mode is *unstable*. This is a general nonlinear instability which occurs for many systems of two coupled nonlinear oscillators (where Hooke's law breaks down). To understand the instability, consider approximately symmetric motion where pendulum A has a slightly greater amplitude than B. Because the frequency of a pendulum decreases with amplitude, A will lag behind B. This results in B doing a net amount of positive work on A over one cycle, so A's amplitude will increase and B's will decrease. This causes A to lag even farther behind B, which causes A to absorb even more energy from B, etc., so the mode is unstable.

Model Trebuchet

The trebuchet was used in medieval times as a siege machine. One end of a pivoted arm is connected to a heavy falling weight, and the other end is attached to a sling with a projectile. It is possible to launch massive projectiles large distances. Surprisingly, the projectile can travel farther if the apparatus is allowed to recoil by rolling on its wheels, as opposed to having the wheels locked. Trebuchets are currently popular. There is a PBS Nova program on them, and instructions for building them can be obtained on the internet. Our small model trebuchet was built from such instructions.

Coriolis force

A battery-operated submersible pump in an open rotating container of water projects a stream of water into the container. The container rests on a rotatable platform. For no rotation, the stream lies in vertical plane. For counterclockwise (CCW) rotation, the stream bends to right; for clockwise (CW) rotation, the stream bends to left. In the frame of reference of the container, the bending is the result of the Coriolis force. This force plays an important role in large weather systems and the trajectory of long-range artillery shells. The deflection can be understood by examining the particle motion in the laboratory (inertial) frame. The path of each particle is a straight line. The rotation causes a particle to have additional velocity, which causes part of deflection. Further deflection is caused by rotation of apparatus during flight of particle.

Next, diametrically opposed pumps and tubes produce two streams directed toward each other. When the apparatus is rotating, the streams appear to bend in opposite directions. However, this is not true: both bend to right of their motion for CCW rotation, and left for CW. It should be noted that, although the path of each particle in the laboratory frame lies in a vertical plane, the stream does not. This occurs because the particles are projected at continuously varying locations along the circumference as the apparatus rotates. The stream is thus bent in the laboratory frame. However, the bending in the rotating frame is due to the Coriolis effect.

Fluid Mechanics

3:25-3:40 in Spanagel 117

Giant Hydrostatic Balance

This apparatus quantitatively verifies Archimedes' law *directly*, without any calculations. It is currently only available commercially in a small size for use in an educational laboratory. Our apparatus is a large version that we built for demonstrations. It is first shown that a solid aluminum cylinder fits precisely into a cup. The volume of the cylinder thus equals the inner volume of the cup. It is then shown that a weight hanging at one end of the arm balances the cup and cylinder hanging from the other end. Next, the cylinder and cup are lifted and a large beaker of water is placed underneath. Water is then added to the cup. It is observed that the system returns to being balanced when the cylinder is completely submerged and the cup is full. Hence, the buoyant force must equal the weight of the displaced fluid!

Giant Vortex Bottle

The tops of two five-gallon plastic water bottles are adjoined with thick flexible tubing that is secured by hose clamps. The lower bottle is roughly ¾ full of water. Sandwiched between the two bottle tops is a washer with roughly half the diameter of the tops. The washer acts as an aperture to reduce the flow of water. The bottle combination is inverted and the upper bottle (now containing the water) is rotated by hand in order to give the water some rotational flow. After some time, the flow develops into a dramatic vortex in the upper bottle, with the water flowing down the wall of the lower bottle. Vortex flow also occurs in hurricanes and tornadoes. This may occur due to dissipation being a minimum for vortex flow. A smaller version of the apparatus can be constructed with two plastic soft drink bottles and a commercially-available threaded coupler. An advantage of our large apparatus is that a floating ball can be added to each container. During the vortex motion, if a ball is not hitting the wall and is not near the vortex core, the ball is observed to rotate with the flow but not spin. This is due to the fact that vortex flow is irrotational (zero curl).

Smoke Rings

Similar to vortex lines, vortex rings are stable states of a fluid (gas or liquid) in motion. A burst of fluid into a fluid can settle into a vortex ring. An air vortex ring generator can be constructed from a cardboard box by cutting a roughly 10 or 20 cm diameter hole in one face and replacing the opposite face with a thin plastic sheet that is taped to the box. The plastic is then tapped by hand, and the resultant flow through the hole can form a vortex ring that propagates outward. The existence of the rings can be inferred by having them strike a candle. More dramatic is to introduce smoke into the box before generating the rings. This is best accomplished with a commercial fog machine. The smoke allow the rings to be seen as they propagate. In this case, the rings are commonly referred to as “smoke” rings. A vortex ring is propelled by its flow, which is in the forward direction inside the ring and the backward direction outside the ring. As they propagate, vortex rings enlarge and their speed decreases.

Toroidal Bubbles

A burst of air is produced in water, and the resultant bubble forms a toroid. The apparatus employs pressurized nitrogen gas, an electrical pulse input to a solenoid valve, and a needle valve. The tank is an acrylic cylinder with diameter one foot and height four feet. A toroidal bubble is a vortex ring in a liquid, where the core of the vortex ring consists of a gas.

Current interest in toroidal bubbles is due in part to the discovery that small toroidal bubbles can occur in the cavitation collapse of a spherical bubble near the surface of a solid. This can occur near a propeller blade, causing both damage and acoustic emission. Another motivation is due to the discovery that dolphins generate a rich variety of large vortex bubbles, apparently for entertainment. Because the skill requires a substantial amount of time to acquire, another purpose may be to keep young dolphins occupied!

Electricity and Magnetism

3:40-4:00 in Spanagel 136

Electromagnetically Coupled Oscillators

Two identical setups each consist of several strong ceramic magnets end-to-end suspended by a light spring such that one pole of the combined magnet is near an end of a solenoid. The two solenoids are connected by wires, and are far apart. One magnet is set into vertical oscillation while the other is initially at rest. The motion of the first causes the second to oscillate. In the final state, both magnets oscillate with equal amplitude either in-phase or 180^o out-of-phase. This phase is reversed if one magnet is inverted. The phase is also reversed if the relative polarity of the solenoids is reversed, which can be accomplished by either changing the electrical connection or inverting a solenoid.

When one magnet is set into oscillation, the magnetic flux through its solenoid varies in time, so an oscillating emf is produced by Faraday induction. The resultant current causes the other solenoid to exert an oscillating magnetic force on its magnet, which is resonantly driven because both oscillators have the same natural frequency. In the final state, the emfs created by the oscillating magnets are 180^o out-of-phase and thus cancel. Hence, there is no current and the motion is only very lightly damped. This is one normal mode of the system. In the other normal mode, the emfs are in-phase and thus add, so this mode is substantially damped due to electromagnetic braking.

Giant Tesla Coil

The Tesla coil is a resonant air coupled transformer. High frequency alternating currents in the primary windings create a high voltage in the secondary windings through a mutual magnetic coupling between the two coils.

Typically the secondary consists of about 1000 turns of wire. The capacitance between adjacent windings creates a distributed inductance-capacitance (LC) circuit that has a natural resonant frequency of 50-500 KHz. The resonant frequency depends on the diameter of the secondary coil and the thickness of the insulation of the wire. The primary winding consists of about 10 turns of wire that surround the secondary, but with a large separation between the windings. The diameter of the primary coils must be large enough to avoid electrical discharge between the primary and secondary coils.

A key part of a Tesla coil is that the primary circuit includes a set of capacitors connected in parallel with the primary windings through a spark gap. The primary LC resonant frequency must be adjusted to be the same as the self-resonant frequency of the secondary coil. The tuning process to match the resonant frequencies of the two coils often requires some trial and error adjustment, adding and removing capacitors to achieve a common resonance.

A high voltage, 60 Hz, neon light transformer provides 10-15,000 volts at around 30 ma to excite the Tesla coil. The secondary of the neon tube transformer connected to the high voltage capacitors charges them to a high voltage, 120 times a second. When the instantaneous voltage across the ~ 1 cm spark gap becomes sufficiently large, the gap breaks down dumping a charge of $Q = CV^2/2$ ~ 0.2 Coulomb stored on the capacitors across the primary coil. For a short time 10,00 to 15,000 volts exists across the 10-turn primary coil, inducing a huge current and magnetic field that oscillates at the LC resonance frequency. With a 100:1 step up ratio of the secondary to primary windings, the secondary coil produces 100,000-1,000,000 volts between the ends.

The secondary usually has a ~10 cm metal ball connected to the ending of the secondary winding. The high voltage on the ball ionizes the atmosphere producing long sparks when energetic electrons from the secondary electrode collide with the atmospheric molecules ejecting electrons from the nitrogen and oxygen atoms in the atmospheric molecules. The light occurs when electrons within the atmospheric atoms fall back to lower energy levels vacated by collisions with the fast moving, high-voltage, Tesla-coil electrons.

Electromagnetic Can Crusher

This demonstration uses the discharge of a capacitor through a coil to crush a soda can. For large charging voltages, the soda can may also break into two pieces. A 400 μF (rated at 5 kV) capacitor is charged to about 3 kV from a 7 kV dc power supply through a 100 kΩ resistor. [The characteristic time for charging the capacitor RC = 40 sec. For a 7 kV source, charging the capacitor to a 3 kV voltage would take just about this time.] Using a relay switch, the capacitor is then rapidly discharged through a three turn coil, 3" in diameter, 1" long, in which a soda can fits snugly.

At 3 kV, the stored energy in the capacitor $CV^2/2 \approx 2000$ J. [The energy to raise one ton to a height of about 20 cm.] Also for this voltage, the stored charge in the capacitor is 1.2 C [the force between two 1 C charges 1 m apart is 10^{10} N, which is equal to the weight of a cube of water 100 m × 100 m × 100 m.]

The rapid discharge of the capacitor creates a current in the coil which increases rapidly to a large value. The peak current value can be estimated as the ratio q/τ of the charge q to the discharge time τ of the capacitor into the coil. The characteristic time τ corresponds to 1/4 of the oscillation period of an LC circuit or $\pi(LC)^{1/2}/2$. To determine the inductance of the coil, we can use the empirical formula $L(\text{in } \mu H) = d^2n^2/(18d + 40\ \ )$, where n is the number of turns, d is the diameter of the coil (in inches) and ℓ is the length of the coil (in inches). For our coil, $L \approx 1$ μH. Thus $\tau \approx 31$ μs, and $i_{peak} \approx 40$ kA. The peak power $i_{peak}V \approx 120$ MW which is roughly the power consumption of the City of Monterey.

The rapidly increasing magnetic field generated by the current in the coil, induces an azimuthal current in the aluminum can. The can experiences a force directed mainly radially inward, but with a smaller component directed outward along the axis of the can.

Optics

4:00-4:20 in Spanagel 135

Infrared Camera

Infrared camera detects the heat (infrared) radiation emitted by hot objects. The infrared wavelengths cover a wide range from 1 μm to 1000 μm. However, only two wavelength bands 3-5 μm and 8-12 μm are primarily used for imaging due to high transmission (~80%) of these wavelengths through the atmosphere. These detectors are commonly used for night vision, detection of fire and medical applications, for example, detection of skin cancers. A crude form of infrared detector is used by rattlesnakes for hunting at night. The operation of an infrared camera under a complete darkness is demonstrated.

Night Vision Scope

Acousto-Optic Transduction and Lightwave Transmission

Telecommunication networks based on optical fiber technology have become a major information-transmission system, with high capacity optical fiber links encircling the globe in both terrestrial and undersea installations. The high carrier frequency (~10^{14} Hz) associated with light waves allows the transmission of a large number of voice and video channels using a single fiber. In addition, the capability of transmitting multiple wavelengths in a single fiber provides added capacity. A basic fiber optic communication system consists of a light source, an optical fiber and a photodetector. The operation of a fiber optic communication system using two light beams having different wavelengths and a single fiber is demonstrated.

Fiber-Optic Balloon Microphone

Thermodynamics

4:20-4:40 on Spanagel lawn

The Awesome Nitrogen Cannon

This is primarily a demonstration of simple thermodynamic principles, specifically that a gas occupies more volume than a liquid. In addition, the potential energy of the chemical bonds of plastic also come into play.

Liquid nitrogen at equilibrium boils at a temperature of approximately -194 deg Celsius (about -381 deg Fahrenheit). Thus when liquid nitrogen is exposed to room temperature air, it quickly boils away.

In this demonstration, a small amount of liquid nitrogen (around 30 - 50 cc) is poured into a standard half liter plastic bottle (empty!) of Coke (Pepsi, 7-Up, and others also work, but we've found Coke is best). Immediately after pouring the liquid nitrogen, the cap is securely screwed back on the bottle.

The thermodynamic reaction is now taking place! The liquid nitrogen is boiling rapidly inside the bottle, turning from liquid into gas. However, the volume of the container remains fixed, causing an increase in the pressure within. This increase in pressure as the nitrogen boils will continue until the stress on the bottle exceeds some critical value, at which point the bottle explodes releasing a tremendous amount of energy.

We observe the release of this energy in two ways. First by dropping the bottle in a secure location (we use a sturdy trash can and provide plenty of clearance!), it takes about 5 - 10 minutes for the critical pressure to be reached. The result is a loud explosion.

The second, and more dramatic, approach involves a garbage can sized bucket of water (we even throw in a foam rubber soccer ball or a bunch of tennis balls on top for added effect). In this case, we tie an anchor onto the bottle to drag it to the bottom. When the bottle explodes, the water above it is ejected with tremendous force. Some soccer balls have been launched in excess of 200 ft! It is important to note that due to the higher thermal conductivity of the water, this reaction occurs in about 10 secs. It's also very easy to get wet.

CAUTION: One should be very careful with this demonstration, particularly when it comes to dealing with "duds". They still contain an extraordinary amount of power and can be quite dangerous. Also, be careful about what types of things you toss in the water before the explosion. Of course, things that go up must come down, so you don't want to launch anything dangerous. But you should also take care not to use balls filled with air or have pieces which could fly off when large pressures are applied (such as air valves on inflated balls).

Acoustics

4:40-5:00 in Spanagel 117

Giant Tuning Fork and Singing Rod

A normal tuning fork is struck with a small rubber mallet, and the sound is barely audible. A giant tuning fork is then struck with a large rubber mallet. The sound is very loud and continues for a surprisingly long time. The sound radiating from this tuning fork is louder due to the greater area of the vibrating tines. The effect is not due to the amplitude of vibration, which is much greater for the normal tuning fork.

Next, a solid aluminum rod with diameter ½ inch and length 6 feet is employed to demonstrate longitudinal standing waves. Circumferential notches mark the displacement nodes of various modes. Longitudinal sound modes are generated by pulling the rod between a thumb and forefinger that have been rubbed with rosin. The sound can be very loud. The rod is held at the center, so that the 1st mode is primarily excited. To show that the 3rd mode is also present, the demonstrator then holds the rod at a node of the 3rd mode other than the center. This very quickly damps the 1st mode, and the pitch jumps by a factor of 3 (an octave and a fifth). The Doppler effect can also be demonstrated with the vibrating rod.

Multipole Radiation Source and Baffled Loudspeaker

Four identical loudspeakers with enclosures are connected to a switching box, which allows each loudspeaker to be driven either in phase or 180^o out-of-phase relative to an input signal. The frequency is chosen such that the wavelength is substantially larger than the apparatus. First, the polarities of the switches are selected to be the same, so that the loudspeakers act as a monopole. Next, the polarities of two loudspeakers on a side are flipped, so that the loudspeakers now act as a dipole. Due to destructive interference, the radiated sound in all directions is significantly reduced. Finally, the radiated sound is further reduced by adjusting the switches so that the loudspeakers act as a quadrupole.

Next, a small loudspeaker is driven at a low frequency such that the wavelength is large compared to the loudspeaker. Very little, if any, sound is heard by the audience. With the loudspeaker remaining in operation, it is now pressed against the back of a large sheet of plywood, where there is a hole to accommodate the loudspeaker. The wood operates as a *baffle*, and the sound is now clearly audible. The raw loudspeaker is a dipole source (when the cone creates a compression in front, it simultaneously creates a rarefaction in back), and the two waves tend to destructively interfere. The effect of the baffle is to change the dipole to a monopole. This is partially responsible for the dramatic increase in sound level. The baffle also causes a doubling of the acoustic pressure due to a boundary condition effect.

Acoustic Radiometer

When any type of wave is incident on a surface, there can be a nonzero time-averaged pressure called *radiation pressure*. For an absorbing surface, this pressure is less than that for a reflective surface. Hence, when two such surfaces are joined back-to-back and placed in an isotropic and homogeneous wave field, there is a net force in the direction of the reflective to the absorptive side. If this device is mounted such that it is allowed to spin as a result of the net force, the system can be considered a *radiometer* because it detects the presence of the wave field. However, the well known electromagnetic radiometer spins in the *opposite* direction when exposed to light of sufficient intensity. The explanation for the electromagnetic radiometer is complicated, having to do with the mean-free path of the molecules near the edges of the vanes. The acoustic radiometer can be used to demonstrate radiation pressure. Each pane has an aluminum side and a foam rubber side. The panes are attached to a rod that is supported by a pivot that has with very little friction. When placed in an enclosure and exposed to isotropic and homogeneous acoustic noise of sufficient intensity, the apparatus spins in the direction predicted by radiation pressure.

Jetting from Resonator and Acoustic Motor

A glass flask is driven at its Helmholtz resonance frequency with a loudspeaker. A lit match placed in front of the neck. A steady flow of air jetting from the resonator extinguishes the flame. To show that the sound oscillations cannot extinguish the match, the resonator is removed and a lit match is brought near the loudspeaker. The steady flow can be explained by Bernoulli's law. The large-amplitude Helmholtz oscillations of the air in the neck lower the steady pressure there. This creates a steady in-flow of air, which must be accompanied by an out-flow. In general, an in-flow tends to occur from all directions, whereas an out-flow tends to jet.

The jetting effect can be utilized to create an acoustic motor. Two small Christmas ornaments with their stems removed are mounted on either end of an arm that is pivoted at its center. The ornaments serve as Helmholtz resonators. The assembly is placed in a closed clear square acrylic box with loudspeakers attached to the sides. To help achieve large acoustic amplitudes, the box is constructed such that its fundamental acoustic mode has approximately the same frequency as the Helmholtz resonance of the ornaments. With the ornaments assembly initially at rest, the loudspeakers are driven at resonance and the assembly accelerates to a fast angular velocity.

Acoustic Bunching and Levitation

High-amplitude standing waves are driven by a compression driver at one end of a closed clear acrylic tube, which is referred to as a *Kundt's tube* in this case. Small styrofoam disks tend to bunch at velocity nodes (pressure antinodes) because, according to Bernoulli's law, the time-averaged pressure is least there. On either side of a velocity antinode, there is a time-averaged pressure gradient that forces the disks to the velocity antinode. In addition, the Rayleigh disk effect, which is another Bernoulli effect, causes the disks to orient perpendicular to the acoustic oscillations.

If the tube is then tilted so that it is vertical, the disks can be levitated if the pressure gradient is sufficiently large to overcome gravity. When this occurs, the upward force due to the time-averaged pressure gradient balances the downward gravitational force. The disks thus levitate below the velocity antinodes. Momentarily reducing the drive level allows the disks to fall to the next lower level, which can be repeated until all of the disks are at the bottom.

Shock Tube

Sections of 2-inch inner-diameter schedule-40 PVC pipe are joined together to make a pipe roughly 40 feet long. Two high-power compression drivers are attached at one end, and are driven by function generators and a dual-channel power amplifier. At the other end is several feet of a foam rubber absorber. The tube is closed at both ends. One microphone is near the drivers, and another is near the absorber. The same function generator is used to drive both drivers to produce a low-amplitude pure tone at 1.0 kHz. (This is below the first cutoff frequency of 4.0 kHz, so that only plane waves propagate.) The waveforms on the oscilloscope are sinusoidal. As the drive amplitude is increased, the output of the first microphone remains sinusoidal, but that of the second microphone exhibits distortion in the form of a steepening of the regions of positive slope. The presence of higher harmonics can be seen on a spectrum analyzer. At a sufficiently high amplitude, shock fronts are observed. Ringing of the microphone can also be observed, and can be reduced by filtering. The distortion and eventual shocking are due to compressions traveling faster than expansions. This occurs for two reasons: the speed of sound is greater for higher temperature, and the speed of sound is boosted by the particle velocity.

Audible Sound Beam from Nonlinear Ultrasound

A ring of many small transducers transmits high-intensity ultrasound at 40 kHz. The transducers are connected in parallel to two wires from an amplifier, signal conditioner, and audio CD player. An audio microphone and preamplifier, or some other source, can be substituted for the CD player. As a result of nonlinear interactions of the sound in the air, the original audio signal is broadcast in a beam with distinct boundaries and no side lobes. The beam can be reflected from walls. This remarkable device was developed by a company (American Technology Corporation, San Diego, California, http://www.atcsd.com.)

The 40 kHz wave acts as a carrier. This is amplitude-modulated at audible frequencies, so the resultant wave consists of two relatively narrow bands that are a relatively small amount greater and less than the carrier frequency. Now, nonlinear interactions of two acoustic waves produce waves whose frequencies are the sum and difference frequencies of the primary waves. The interaction of the two bands thus produces audible frequencies as a result of the difference process. The attenuation length of the carrier wave is roughly 10 m. The audible wave is driven over this length, which is substantially greater than the size of the primary source. The resultant beam is highly directional without side lobes.