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Bar Magnets, Horseshoe Magnets, and Iron Filings

*For visualization of magnetic field lines.*

Description: The instructor lays a permanent magnet of either type on a transparent tray, and places the tray on an overhead projector. The field lines may be imaged by sprinkling iron filings on the tray and tapping gently.

Comments: Most students are likely to have seen this in secondary school if not before. They should now be pointed out 1) the regions of most intense field, and 2) the strong similarities between electric and magnetic dipole fields.

Upgrade suggestions: The field lines are more spectacular in three dimensions. Suspend iron filings in a jar of oil (kitchen-grade corn oil works fine) and place the magnet against the side of the jar. Students enjoy this quite a bit; unfortunately, the three-dimensional image cannot be projected as easily as the two-dimensional one, and therefore lends itself better to a classroom-scale demonstration.

As the iron filings eventually settle to the bottom of the bath, provision should be made for shaking up or stirring the oil. I have not tried immersing the magnet itself in the bath, but I suspect this would work as well.

Sketch:
Lorentz Force on Electrons I

To note the behavior of cathode rays in the presence of magnetic fields.

Description: A permanent magnet outside a cathode ray tube deflects the beam in accordance with the Lorentz force equation.

Comments: An extremely concrete demonstration of magnetic forces. In order for the demonstration to be most effective, the instructor should explicitly indicate:

1) The direction of propagation of the beam
2) The direction of the magnetic field lines introduced
3) That cathode rays are in fact negatively charged.

Upgrade suggestions: As the CRT is only a few inches long, visibility is a problem with this demonstration. The closed-circuit television camera might be appropriate here.

D.O. made a nice tie-in with the workings of oscilloscopes and television sets. Perhaps a dissected example of one or both could be made available for inspection. Students did not necessarily realize their own familiarity with the device.

Sketch:
Lorentz Force on Electrons II

To show the trajectories of charged particles in regions of constant field.

Description: In this case, a Helmholtz coil is used to generate the magnetic field, and the cathode rays are generated in a bulb at its center. By aiming the rays at right angles relative to the field lines, the instructor can show that electrons in regions of constant field do in fact travel in circular orbits.

The instructor fixes the radius of the orbit by selecting the current in the Helmholtz coil, and hence the magnetic field.

The most general trajectory is helical, as can be shown by rotating the coils until the beam has a component of velocity parallel to the field.

Comments: As 1/2, very effective. As a historical note, it could be pointed out that Thomson (?) used this apparatus to determine the charge-to-mass ratio of the electron.

Note that students at this point have no experience with the Helmholtz coil, and must take it for granted that the field is relatively constant over the central region. Again, as in 1/2, the initial direction of propagation of the beam is not immediately obvious.

Upgrade suggestions: None.

Sketch:
Magnetic Force on a Current-Carrying Wire

To note the behavior of current-carrying conductors in the presence of magnetic fields.

Description: A current flows through a horizontal rod suspended like a swing. The rod passes through the yoke of a magnet. Deflection of the rod from the vertical is visible when the current is switched on.

Comments: Elementary but necessary. Although the deflection is quite easy to see, the directions of the current and field are not immediately obvious. A good candidate for practice with the Right Hand Rule.

Upgrade suggestions: None.

Sketch:
Measurement of Lorentz Force with Balance

*Magnetic forces can be measured with a beam balance.*

Description: As 2/1, with the following modifications: the field is oriented such that the force acting on the rod is vertical rather than horizontal. The rod is suspended from one arm of a beam balance. The weight required to equilibrate the balance is equal to the magnitude of the Lorentz force.

Comments: Of limited usefulness in lecture, unless the instructor is prepared to devote the time necessary to do a quantitative verification of the Lorentz force law. May be better suited to a hands-on approach in lab.

Upgrade suggestions: Using a known current, this apparatus may be used to determine magnetic field strengths. It might be interesting to compare results obtained with the balance and the Hall probe (coming up).

Sketch:
Magnetism and Audio Speakers

An application: investigating the operation of loudspeakers using basic magnet physics.

Description: The instructor uses the coil assembly of an old loudspeaker to demonstrate how and why an oscillating current can bring about the vibration of the speaker cone. To show that the cone does vibrate, he feeds the speaker an AC signal in the low audible range. He then trains a strobe light on the cone and tunes it close to the frequency of oscillation.

Comments: An extremely important application of magnetism and worth spending some time on. Follows nicely from 2/1. One should clarify that any time-varying current will make the speaker vibrate and the signal need not be periodic. Music is also generated in this fashion!

Upgrade suggestions: Visibility is a problem; ensure that the strobe is as bright as possible and the room lights are dimmed. Also, the coil assemblies of most speakers are too small to see from anywhere but the front row. Perhaps a few could be passed around.

Sketch:
The Hall Probe

Demonstrates the Hall effect and its use in measuring field strengths.

Description: A small semiconductor sample (about 8 by 3 mm) carries a current in the yoke of a conducting magnet. Transverse leads measure the Hall voltage, which is shown on a galvanometer. A commercial field probe is also demonstrated, and used to measure the field strength of an audio speaker magnet. All displayed on closed-circuit television.

Comments: Effective if exploited well. It is important to explain the purpose of each of the four leads on the sample and describe the sample’s orientation with respect to the field. One can easily demonstrate that the Hall voltage changes sign when the current direction is changed.

Upgrade suggestions: A good teaching tactic here is to have the students guess the sign of the charge carriers given the sign of the Hall voltage. To this end it would be advantageous to have two samples prepared: one with positive charge carriers and one with negative charge carriers.

The commercial unit had a nominal resolution of about 1 gauss -- if possible, it would be interesting to measure the earth’s field.

Sketch:
**Torsional Balance**

*Shows the torque on a current-carrying loop.*

Description: The torsional balance is essentially a DC motor without a commutator. A baffle in an oil bath damps oscillations. A HeNe laser reflects off of a mirror attached to the axis; the position of the speculum may be used to measure the rotation of the coil. See sketch.

Comments: D.O. used this apparatus to explain the workings of the galvanometer. As a historical note it could be mentioned that a device of this type was first used by Coulomb (?) in 17xx to quantitatively investigate magnetic forces. The particulars of the device are largely invisible to the audience and require some detailing.

Upgrade Suggestions: A demonstration of motors and generators would follow quite smoothly from here.

Sketch:
Lorentz Force on Parallel Wires

Magnetic forces need not involve permanent magnets.

Description: Two vertical, parallel wires are arranged to carry both parallel and antiparallel currents. The attraction and repulsion of the wires is noted in each case. A Hall probe may be used to measure the field strength near the wires. Displayed on closed-circuit television.

Comments: Unequivocal. Good practice with the Right Hand Rule. Could be preceded with the arguably more fundamental Oersted demonstration of compass deflection near a current-carrying wire.

Upgrade suggestions: None.

Sketch:
Field of a Current-Carrying Wire

*Shows the pattern of magnetic field lines around a current-carrying wire.*

Description: The instructor lays out several compasses on a horizontal sheet of Plexiglas surrounding a vertical wire. The compasses orient in the direction of the field lines when the current is switched on. In addition iron filings may be sprinkled on the Plexiglas to give added sense of the field pattern. The entire demonstration may be placed on an overhead projector.

Comments: The compasses are not as visually compelling as the filings, but are important in that they show the direction of the field lines. As a historical note it may be mentioned that Oersted saw this effect by fortuitous accident during a physics lecture in Copenhagen in 1820.

Upgrade Suggestions: Some of the compasses were a bit decrepit; otherwise, none.

Sketch:
Magnetic Field of a Solenoid
Displays the field lines inside and outside a helical coil of wire

Description: A copper solenoid (about 12 turns, 1 turn per cm) is embedded in a Plexiglas sheet and placed on an overhead projector. Iron filings shaken onto the sheet show the field pattern when the current is switched on.

Comments: This is quite effective in showing that a) there is no field outside the coil, and b) the field is axial and constant inside the coil.

It is very difficult to see the sense of the coil winding when the solenoid is projected onto a screen, so it is important to clarify this.

Upgrade Suggestions: A compass small enough to fit inside the solenoid would also allow you to see the direction of the field lines, offering a substantial improvement.

Sketch:
Field of a Planar Circular Coil

To check formula for the magnetic field on axis/at center of a current-carrying coil derived from the Biot-Savart Law.

Description: A 5A power supply puts a current through one of a pair of Helmholtz coils. A commercial gaussmeter may then be used to measure the field strength on the coil’s axis (or at any point chosen). For visibility, the gaussmeter panel is displayed on closed-circuit television.

Comments: The instructor (D.O.) measured 26 gauss where the formula predicted 26.9 gauss; a convincing enough demonstration. It may be unclear to the audience that only one of the pair of Helmholtz coils is being employed in this case.

Upgrade suggestions: A stand-alone coil would clarify the demonstration somewhat. As it stands the demonstration is most useful for purposes of verification of known phenomena rather than introduction to new ones.

Sketch:
7/1  **Introduction to Faraday’s Law**

*A straightforward realization of the principle that changing magnetic fields produce electric fields.*

Description: This is a “canned” apparatus consisting of a solenoid tunnel and a magnet on a trolley; the trolley rolls through the tunnel on miniature railroad tracks. A large display galvanometer measures the current through the coil as the instructor pushes the trolley through.

Comments: Effective, clear, and easily executed. For maximum benefit the instructor can point out: 1) the validity of Lenz’s law (direction of induced current should oppose change in magnetic flux threading the solenoid); 2) the dependence of the current direction on the polarity of the magnet; 3) that the velocity of the trolley decreases substantially by the time the trolley exits the tunnel, showing conversion of kinetic energy to electrical energy.

Upgrade suggestions: Perhaps a sign could be placed on the trolley labeling the poles of the magnet; it would also be clarifying to somehow show the sense of the coil winding.

I can’t think of an easy way to do this, but it would be quite nice to quantitatively display the velocity of the trolley in real time. This would in principle allow the class to verify conservation of energy in this system.

Sketch:
Description: Two rather massive circular coils: one connected to a variable 60 Hz current source, the other connected to a small light bulb. The instructor orients the coils coaxially and switches on the current. The light bulb lights up. The light is intensified considerably by placing an iron bar along the coil axes.

Comments: Conceptually this carries the previous demonstration one step further: the changing magnetic field that generates the electromotive force may itself be generated by a time-varying current in another coil. Since in this case no motion is evident, it is important to state explicitly that the current is time-varying, and that the transformer would not work at all with direct current.

Stress (or show) that non-ferrous materials do not concentrate magnetic flux.

Upgrade suggestions: We could make a simple improvement by displaying the e.m.f in either coil on an oscilloscope. The time-variation would then be explicit. Recall that at this point in the course students have only a dim idea of why line current is alternating.
The Railgun

Changing magnetic fields exert forces on the currents they induce.

Description: Materials include an enormous solenoid tower, a single-turn coil, a single-turn coil with a gap in it, a many-turn coil, and liquid nitrogen. The tower serves as the cannon and the coils as ammunition (see sketch). Flux expelled from the tower during power-up induces a current in the coil; the Lorentz force on the coil in the solenoid’s field is sufficient to launch it spectacularly. Note that a gap in the coil precludes any current from flowing and hence precludes any Lorentz forces. Increasing the number of turns or decreasing the coil resistance (by dunking it in LN2) increases range significantly.

Comments: A crowd-pleaser. Be careful when aiming at the audience. Stress that the coil need be a conductor, but need not be magnetic. D.O. discussed the fact that the radial components of the field (as opposed to the vertical ones) are responsible for the vertical forces on the coil.

Ohmic heating of the coils is quite noticeable and can be taken as evidence that the coils do in fact have large currents flowing through them.

The innards of the inductor tower are invisible. Reassure the audience that it is only a large solenoid.

Upgrade suggestions: Display sense of coils in the tower so the students can verify Lenz’s Law. Note that if Lenz’s Law’s opposite held, the force on the ammunition coils would be attractive.

Sketch:
Current Generation in Magnetic Fields

An application of Faraday’s Law to static magnetic fields.

Description: A copper loop encompasses two permanent magnets such that the field is transverse to the loop plane -- see sketch. The copper circuit has one sliding leg. Sliding the leg back and forth effectively changes the area of the circuit and therefore the amount of flux threading it; induced e.m.f. can be seen on a display galvanometer.

Comments: This is the first instance the students have seen of changing magnetic flux at constant field strength. This aspect of the demonstration should be stressed. As the drama factor here is relatively low, this should precede the railgun (7/3).

Upgrade suggestions: If the magnets were electromagnets, they could be used to do the work of moving the bar. The symmetry in Faraday’s Law is an interesting one; it would be instructive to condense both aspects into a single demonstration.

Sketch:
Eddy Currents I

Conductors entering or leaving regions of magnetic field experience retarding forces.

Description: A pendulum bob swings through the yoke of a permanent magnet. Students note that:
1) Q is very high with a nonconducting bob
2) Q is somewhat lower with a slotted copper bob
3) The system is almost critically damped with a substantial copper block for a bob.

Comments: This demonstration, though very modest in terms of effort needed to set up, is an eye-opener. Students are not likely to be acquainted with the effect. It could be pointed out that the damping effect is independent of the field orientation.

As it is impossible to discern any difference between the bobs from a distance, it is important to explicitly state the nature of each.

Upgrade suggestions: Electromagnets could be used to show the dependence of the damping on magnetic field strength.

Sketch:
8/2  **Eddy Currents II**

*Magnets moving near conductors experience retarding forces.*

Description: A copper slab (about 30 cm x 15 cm x 2 cm) is precooked (before lecture) to liquid N2 temperatures. Its conductivity at 77K is about a factor of seven higher than it is at room temperature, and eddy currents generated by nearby magnets have spectacular effects. Try: dropping a magnet onto the slab, rolling a cylindrical magnet down the slab when held as an inclined plane, standing a magnet on the slab and tipping it over, levitating a magnet on the slab and spinning it.

Comments: An excellent demonstration; highly recommended. Have students find the direction of the eddy current loops using Lenz’s Law.

Upgrade suggestions: Commercially available samples of high-Tc superconductor can levitate small magnets indefinitely and are available through most scientific supply catalogues. Such a demonstration is much smaller in scale and would have to be shown on the monitors; it would however provide a nice complement to 8/2.

Sketch:
AC/DC Power Generation

*Shows the utility of Faraday’s Law in generating alternating and direct electric currents.*

Description: The output of a hand-cranked generators is displayed on an oscilloscope, in turn displayed on closed-circuit TV. A pair of electromagnets supplies the static magnetic field for the generator, so a current source is necessary. The particular generator D.O. used had both DC and AC terminals, so the behavior of the split-ring commutator is easily shown.

Comments: Much rich physics here, but can be time-consuming to exploit fully. Difficult to see the details of the apparatus from afar; if done too quickly the demonstration amounts to a blurry picture of a sine wave.

That the motor is simply the DC generator operated in reverse is also simple to show.

Upgrade suggestions: Even a small light bulb would help drive home the point that useful power is being generated. One cute way to show the symmetry of the two devices (generator and motor) is to run a small motor with a solar cell, and then use an identical generator to light a bulb.

Sketch:
9/1  **Direct Current Motors**  
*To show current usage and the effects of back-emf in D.C. motors.*

Description: A ND-B-Fe magnet motor is driven with a 10A current source. A propeller attached to the drive shaft gives a sense of the motor’s rotational speed. The voltage and current meters are displayed on a monitor.

The instructor varies the voltage supplied to the motor, pointing out that the current drawn is roughly constant over a very wide range of rpm. The back-emf in the coil can be reduced by placing a larger load torque on the drive shaft, at which point the current can be seen to jump considerably.

Comments: Requires some familiarity with the operation of motors. The ND-B-Fe motors themselves are quite impressive.

Upgrade suggestions: I think D.O. introduced this demonstration this quarter (spring 1996).

Sketch:
**Magic Carpet**

*Eddy currents can act like magnetic dipoles.*

Description: Ali Baba sits atop his magic carpet, which has a permanent magnet embedded in it. The carpet sits on an aluminum disc spun by a high-rpm motor (see sketch). When the revolution time is short compared to the time scale of the eddy current dissipation, the dipole fields produced by the eddy currents are sufficient to levitate the carpet.

The carpet must be stabilized by a guide wire.

Comments: In principle very effective; requires a good understanding of eddy currents. Note that from the audience it is not obvious what is a magnet and what is a conductor.

Upgrade suggestions: In one lecture D.O. had some trouble getting this to work. If the disc is not securely fixed to the drive shaft, it slips and makes horrible noises. This is a potential safety hazard, and should be remedied before the next usage.

Sketch:
Para- and Diamagnetism

Shows the behavior of two classes of magnetic materials in magnetic fields.

Description: Materials include aluminum and glass slugs (about 1 cm in length and a few mm in diameter) and a strong permanent magnet. The slugs are suspended (one at a time) with a thread so they are free to swing in the yoke of the magnet.

Aluminum aligns with the field, whereas glass is at equilibrium at right angles to the field. Aluminum is classified as paramagnetic, glass as diamagnetic.

Closed-circuit television is a must for this one.

Comments: The effect is weak but convincing. This demonstration can be played up for shock value, since most students will be familiar with ferromagnetism only.

Upgrade suggestions: At present the slugs are suspended with threads, and the torsional torque of the twisting thread is comparable to the torque produced by the magnet (particularly for glass). The demonstration would be enhanced considerably if some other means of suspending the slugs could be found. One possibility is to float the slugs on small cork rafts.

Sketch:
11/1  **Levitating Oxygen**

*The paramagnetic susceptibility of liquid oxygen at 90K produces observable magnetic effects.*

Description: Pre-cool a petri dish down to 77K with LN2, then fill it with LO2. One can raise “hills” in the surface of the liquid by holding a strong permanent magnet slightly above the surface of the fluid. Closed-circuit television a must.

Comments: Requires some preparation but is, to many students, an agreeable surprise. Drew many comments after lecture.

The instructor can use LN2 to show the null effect.

Upgrade suggestions: Water vapor condensing around the dish obscures the surface of the fluid; a small fan might increase visibility.

For a slightly more dramatic demonstration one can pour LO2 directly into the yoke of a high-field magnet. In this case the apparatus may be placed on an overhead projector.

Sketch:
Ferromagnetic Domains

One can “hear” the alignment of magnetic domains when soft iron is placed in a strong external field.

Description: A sample of magnetically soft iron (D.O. used a piece about 10 by 5 by 0.5 cm) spans a sensing coil of about 10,000 turns. The coil is connected to an audio amplifier so that induced voltages in the coil are translated into audio frequency signals and heard by the audience.

As the instructor passes a strong permanent magnet along the length of the sample, the domains flip. When this happens the flux threading the coil changes slightly, inducing a voltage. The flipping of an individual domain is heard as a click.

Comments: Somewhat obscure, but effective if presented in detail. It is especially important to point out the difference between the permanent magnet (whose domains do not reorient) and the magnetically soft sample. Clarify that the leads on the coil are not carrying a current from the amplifier -- the coil is a sensing coil rather than a solenoid.

Upgrade suggestions: Samples of non-magnetic and magnetically hard materials would provide null-effect demonstrations.

Sketch:
**Introduction to Inductors**

*Self-inductance creates a back-electromotive force in a circuit.*

Description: A large inductor (>100 mH) is connected in series with a light bulb and an AC source. The light bulb is observed to dim when an iron core is introduced into the inductor: as the voltage drop across the inductor increases, the drop across the bulb must decrease correspondingly.

Comments: It is important to clarify that this effect depends on the presence of alternating current; if there is no changing magnetic field in the inductor, then it will be invisible to the circuit.

One student asked if the bulb and inductor were linked in parallel or in series, so it may be profitable to present a circuit diagram of the apparatus.

Upgrade suggestions: This demonstration would benefit considerably from the addition of an oscilloscope to trace the source voltage. The current’s time dependence would then be explicitly shown.

Sketch:
Mutual Inductance: the Tesla Coil

Inductive coupling can generate high voltages.

Description: A $15\,\text{kV}$ rms. flash current source generates rapidly changing magnetic flux. A Tesla coil placed adjacent to the current source experiences high induced voltages in its primary. Owing to the mutual inductance of the coils, the voltage induced in the secondary is higher still. The potential at the tip of the secondary is sufficient to achieve breakdown in air. The potential drop across the length of a fluorescent tube light bulb held close to the secondary will cause it to glow.

Comments: Very strong. Although the dramatic value is such that it is tempting to use this demonstration as an introduction to inductance, be advised that the students will not be able to explain the behavior of the device after only one lecture. As such it may be worth presenting twice.

Upgrade suggestions: None.

Sketch:
14/1  **RL Circuits**

The current in series RL circuits shows an exponential time dependence.

Description: A variable resistor, a function generator, and an inductor (~1000 turns, 40 ohm, 110 mH) are connected in series. The function generator outputs a square wave. Both the voltage across the inductor and the current flowing in the circuit are shown on an oscilloscope. As R is varied, the time constant is also seen to vary in qualitative accordance with L/R.

Comments: As this may be the students’ first time seeing a time-dependent voltage signal, it may be worth taking the time to describe the traces in some detail. The equivalence of the square wave and a switch may not be clear to some.

Upgrade suggestions: The oscilloscope traces show up well on the closed-circuit TV monitors. For clarity one might also show the square wave driving signal.

Sketch:
RLC Circuits I

In analogy with classical harmonic motion, a series RLC circuit will undergo oscillations at a fundamental frequency.

Description: As 14/1, with a variable capacitor. The capacitor may be inductively coupled to the rest of the circuit. The decay brought about by losses in the inductor coils is very visible and it is not necessary to add resistance if one wants to demonstrate damping.

Comments: Although D.O. did not pursue the topic in much detail, some instructors might want to draw a strong analogy between this circuit and a damped mechanical oscillator. There are demonstrations available for this purpose.

Upgrade suggestions: Again, it may help to display the driving signal.

Sketch:
This demonstration investigates the particulars of introducing a ferromagnetic core into the inductor.

Description: As 14/2, but the variable capacitor is not necessary; in fact, the input capacitance of an oscilloscope is quite sufficient. The instructor inserts a large iron core into the inductor and points out its effects on the oscilloscope trace of the voltage across the capacitor.

Comments: Inserting the iron has two noteworthy effects: 1) it increases the inductance of the coil, thereby decreasing the oscillation frequency of the circuit, and 2) it makes the oscillations decay away faster. The latter effect is due to eddy current dissipation in the core.

This demonstration may be worth revisiting following a discussion of transformer design.

Upgrade suggestions: As 14/1, 14/2, display driving square wave.
Jacob’s Ladder
Step-up transformers may be used to generate high voltages.

Description: A rheostat is used to supply current to a step-up transformer. (The particular transformer that D.O. had was a neon sign transformer that stepped the line voltage up to about 10,000 V.) The high voltage electrodes are oriented in a V-shape (see sketch). The electric field in between the electrodes is high enough to cause arcing; the hot plasma then rises until it reaches the tops of the electrodes, at which point the circuit is broken. The arc re-forms at the bottom of the ladder.

Comments: Forever immortalized by Dr. Frankenstein, this demonstration has comic associations for non-physicists. It is rare to find a device so rich in physics with whose phenomenology the students are very well acquainted, so this is worth spending some time on.

Upgrade suggestions: At one of D.O.’s lectures, air currents in the room prevented the plasma from rising. A simple windscreen might help.

Sketch:
16/2  The Sparkler

*Step-down transformers may be used to generate high currents.*

Description: Line voltage is fed to a 400:8 step-down toroidal transformer. (The secondary may be wound by hand with a few turns of thick copper wire.) The instructor attaches a nail across the terminals of the secondary. After the current is switched on, the nail will glow cherry red, spark, and oxidize quickly until the circuit breaks.

Comments: Dim the lights for greater effect; it’s quite spectacular. It is important to point out that without the transformer there, you would blow a fuse or trip the building’s circuit breaker. The transformer increases the effective resistance of the circuit as seen at the wall.

Upgrade suggestions: Use more often.

Sketch:
Current-Voltage Relationships in the RLC Circuit

Capacitors lead, inductors lag.

Description: Current vs. time and voltage vs. time traces for the three components in an RLC circuit are displayed on a large screen oscilloscope. The department has a multi component Plexiglas breadboard with banana plug jacks that allows you to select from several values of $R$, $L$, and $C$. An external signal generator modulates the driving voltage at audio frequencies (about 800 Hz here).

Comments: This is the students’ first visual encounter with phase relationships. As it is difficult to tell one trace from another on the scope, it may pay to be fairly explicit. As the voltage across the resistor is in phase with the driving voltage, that trace is taken as the reference.

Upgrade suggestions: Find a way to tag the three traces. A first-order way of doing this is simply to scale the three traces to be of very different apparent sizes.

Sketch:
Impedance in the AC RLC Circuit

Shows the relative contributions of the three components to the overall impedance.

Description: There is a canned RLC demonstration circuit whose “R” is a light bulb. The components have switches that allow you to short them out of the circuit. Shorting the capacitor extinguishes the light bulb (because the R/L time constant is long compared to the driving period), whereas shorting the inductor only dims the bulb (to a greater or lesser extent, depending on the value of RC and hence C).

Comments: Relatively obscure.

Upgrade suggestions: A demonstration in which the driving frequency could be varied would be, I think, slightly more clear. It could be shown that the capacitor’s behavior approaches a wire’s in the limit of high frequency, whereas an inductor approaches this behavior in the limit of low frequency.

Sketch:
Mechanical Resonance

An oscillator’s response to a driving force shows a peak near its so-called natural frequency. Presented in analogy with RLC circuits.

Description: This is a one-piece demonstration of a motor-driven mass-on-a-spring. The amplitude of the vibrations increases dramatically as the driving frequency nears resonance.

Comments: This was shown in Physics 43, but shows such an important idea and takes so little set-up time that it is probably worth going over again.

Upgrade suggestions: None.

Sketch:
Resonance in RLC Circuits

Impedance shows a minimum at resonance; other quantities, such as the charge on the capacitor, show maxima.

Description: A Pasco 9301 dual function generator both supplies an oscillating driving voltage to an RLC circuit and sweeps the driving frequency from one side of resonance to the other. D.O. used a circuit constructed from the breadboard of 16/3. The large-screen oscilloscope displays the voltage across the resistor as a function of time (which may also be interpreted as the charge on the capacitor). Because the frequency is being swept through resonance, the voltage shows a marked peak. A diode may be used to rectify the signal and obtain a Lorentzian.

Comments: This is a strong demonstration, but requires some time to explain thoroughly. If left unexplained it is likely to create more confusion that it removes.

Upgrade suggestions: Change some of the component values in real time and note their effect on the quality factor Q.

Sketch:
18/1 Filters
Resistors, inductors, and capacitors may be used to construct high- and low-pass filters.

Description: As 17/2, with high-pass filter instead of series RLC circuit. See sketch.

Comments: Difficult if rushed.

Upgrade suggestions: The Pasco does not sweep the frequency far enough to obtain a full trace of the filter’s behavior. It may not have been clear to some students precisely what the filter accomplishes.

Sketch:
EM waves have definite polarization and propagate rectilinearly.

Description: The department has available small microwave transmitters and receivers; one of the receivers is equipped with a bell and indicator light to make reception more obvious. The demonstration consists in placing a transmitter and receiver several meters apart and blocking the transmission in various ways: by interposing one’s body, by rotating the receiver so that its antenna is oriented at right angles to the transmitting antenna, and by placing a wire cooling rack in the path of the beam. Note that in the latter case the axis of the cooling rack must be aligned with the polarization axis of the beam to achieve any attenuation.

Comments: There is a nice opportunity here to play a guessing game with the students: have them hypothesize what will happen for various orientations of the receiving antenna and cooling rack.

One can see a signal at the receiver when the antennae are at right angles and the polarizer (rack) is at 45 degrees to either of them (see sketch) -- note that this will be difficult for the students to grasp if this is their first time seeing polarization.

Upgrade suggestions: The bell on the receiving antenna is a little grating.

Sketch:
Radiometer

*EM waves carry momentum (sort of).*

Description: The spindle of a radiometer will turn when exposed to reasonably intense light, such as that from a flashlight.

Comments: Astute students will realize that the radiometer turns in the opposite direction than one would expect it to given conservation of momentum considerations; the torque on the spindle is generated by hot gas expanding against the relatively warm black faces of the spindle, rather than by radiation pressure. It may be best to postpone this until a lecture or two after the students have absorbed the idea of radiation pressure.

Upgrade suggestions: As the radiometer is quite small, it may be worthwhile displaying the demonstration on the monitors.

Sketch:
21/2  **Radiation Pressure**

*Radiation pressure can be faked.*

Description: Materials include two aluminum pie tins, one blackened, and a xenon flash lamp. If you pulse the lamp directly in front of a pie tin, you can hear a slight pop.

Comments: As in 21/1, the effect is actually not due to radiation pressure, as is evidenced (again) by the fact that the blackened pie tin makes a louder sound. Conceivably deceiving.

Upgrade suggestions: Is there any lecture demonstration-scale apparatus capable of exhibiting the effects of radiation pressure?

Sketch:
Brewster’s Angle

Polarization components normal to a surface are not reflected at Brewster’s angle.

Description: Light from a HeNe laser is polarized and incident on a piece of smoked glass oblique to the beam. The reflection is displayed on a screen. By adjusting the incident polarization and the angle between the screen and the beam, it is possible to make the reflected speculum disappear completely.

Comments: As an introduction, fairly obscure. The students should be told that the light coming out of the laser is initially unpolarized, hence the need for the polaroid. As there are two free parameters to tweak, the instructor might be better off leaving one fixed and adjusting only the other.

Upgrade suggestions: To make this more accessible, one might mention that it can be done with a pair of sunglasses and light reflected off of a table top.

Sketch:
21/4  **Crossed Polarizers and Malus’ Law**  

A canonical problem in optics:  *what happens when a third polarizer is interposed between two crossed polarizers?*

Description:  One needs only a laser and three polaroids, oriented as in the sketch. The transmitted light is observed to be a maximum when the central polarizer’s axis is at 45 degrees to either of the others.

Comments:  If this is the students’ first brush with polarizations, they may not have enough familiarity with the subject to fully appreciate the weirdness of this phenomenon. Could be stashed for later in the course.

Upgrade suggestions:  Can also do this on an overhead projector with three sheets of polaroid.

Sketch:
Birefringence I

Some materials change the relative phases of the two polarization components incident on them.

Description: A sample of cellophane tape placed between crossed polarizers on an overhead projector will display different colors depending on its thickness (the polarizations of different colors are dephased through different angles because of the dispersion in the material, and the second polaroid lets only one of these through). There are some nice prepared samples in the inventory.

Comments: Even better than stained glass. This is a more subtle phenomenon than it might first appear; the instructor has to invoke both birefringence and dispersion. Will be passed off as a mystery by most students until Physics 47.

Upgrade suggestions: Some plastics change their refractive index under deformative stress. Also nice to display.

Sketch:
Birefringence II

As 21/5; polarization components may also be chosen by scattering.

Description: D.O. put this demonstration together and most of the apparatus belongs to him. An extended polarized light source is set behind the centerpiece of the demonstration, a scene etched into a sheet of birefringent material. Part of the image has polaroid laid over it and part of it does not. Hence when one looks directly at the “painting” one sees colors in some parts (see 21/5) and no color in others.

However, if one stands over the reflector at approximately Brewster’s angle, one sees the colored parts of the image as black and the white parts of the image as colored. The reflector acts as a polaroid, attenuating the polarized, colored light and selecting one polarization of the white light.

Comments: Spectacular. Much rich physics here; be forewarned that the students have no chance of understanding this in any deep sense until Physics 47.

Note that if one views the painting through a polaroid filter, one sees the same prismatic effect as in 21/5.

Upgrade suggestions: Use more often.

Sketch:
Michelson Interferometer

A sketch of the apparatus used in Michelson and Morley’s disproof of the notion of the ether.

Description: Interferometer, HeNe laser, and evacuatable air cell. Martin has interferometers available for the 47 labs; with a laser one can find fringes in just a minute or two. D.O. had the interferometer set up at an angle to the horizontal so that the fringes could be projected on the wall.

The air cell is placed in one of the interferometer arms; one can see fringes in the pattern disappear when the cell is pumped out and appear again when the cell is repressurized. By counting the number of fringes one can arrive at a very accurate measurement of the index of refraction of air.

Comments: Very much worth showing, if only because the subject of special relativity lends itself so poorly to demonstrations. Interference and refractive index are both very hazy concepts before Physics 47, so one does well to go slowly.

Upgrade suggestions: It might be worthwhile setting this on a lazy susan, to show that there is in fact no perceptible shift in the fringes as the arms of the interferometer are exchanged. If you do so indicate which direction is west (upwind, if you are lecturing in the daytime) and which is north (across the wind). I tried this on a gurney and found that the vibrations were troublesome -- it was difficult to rotate the apparatus ninety degrees without losing at least one fringe. Perhaps something midway between this and M&M’s stunt of floating the entire apparatus in mercury could be devised.

Sketch:
Atomic Spectra

Atomic species may be identified even if redshifted.

Description: A TV camera is trained on a 14,500/in diffraction (reflection) grating. Mercury and hydrogen lamps are placed in its field of view. One is to point out that even if the entire pattern is shifted to the red or the blue, the spacing of the lines and hence the signature of the element will be preserved.

Comments: As 24/1; any opportunity to demonstrate while teaching special relativity should be seized upon.

Upgrade suggestions: During a similar demonstration in Physics 47 last fall, Stan Wojcicki made available a diffraction grating slide to each of the students in the lecture. This personalizes the demonstration somewhat and also dispels the “magic box” sensation some students will get when they look at the spectrograph.

Sketch:
Critical Opalescence

Spontaneous symmetry breaking takes place in a fluid at its critical temperature.

Description: A freon cell undergoes a phase transition at 80 degC. A slide projector and a couple of lenses project its contents onto the wall (see sketch). The freon cell is steam-heated and left to cool; as it passes through its critical temperature, minute condensing droplets form which scatter the light very effectively. The projection is therefore completely black during the phase transition.

“Also Sprach Zarathustra” must be playing in the background.

Comments: An end-of-quarter crowd-pleaser that will have little relevance until the students begin their study of thermodynamics in Physics 47. In fact, Stan Wojcicki did this very demonstration in 47 last fall.

Upgrade suggestions: Is there some way to see the scattered light rather than the transmitted? At present the students miss out on the opalescence.

Sketch: