Part 8

Electricity and Magnetism, Sound Recording and Reproduction

Brief History of Sound Recording and Reproduction
1853 Leon Scott de Martinville: *Phonoautograph* paper recorder
1877 Thomas Edison invents sound reproduction on tin foil *Phonograph*
1885 Bell and Tainter introduce *wax cylinder*
1887 Emile Berliner invents the disc *Gramophone*
1925 Western Electric *Orthophonic* electrical system
1920s, 1930s Wire recorders
1929 Edison production ends. Introduction of *lacquer disc*
1947 *Magnetic tape* in production use, e.g. Ampex 200A
1948 *33.33 rpm long playing (LP)* record introduced
1958 *Stereophonic LP* on sale
1963 Magnetic *tape cassettes*
1980 Phillips and Sony: *Compact Disc* (CD), alternative to vinyl disc and audiocassette
1995 Toshiba and Time Warner: *Digital Versatile Disc* or *Digital Video Disc* (DVD)
1999 USB *flash drive* invented, 2000 first commercial *flash drives* sold
2001 Apple *iPod*

Milestones of Video Production (for comparison)
1964 Videocassette for consumers developed
1968 Sony Portapak first consumer 2-piece video recorder
1969 Bell Labs develops the first Charged Couple Device (CCD)
1975 Betamax decks by Sony
1976 VHS decks by JVC
1980 First consumer camcorders by Sony and JVC
1981 IBM introduces the PC
1984 Apple introduces the Macintosh
1985 Sony introduces the Video8 format
1985 VHS-C developed
1987 S-VHS introduced
1988 Hi8 introduced
1990 First non-linear video editing system introduced by Newtek
1991 First CD burner
1992 Sharp introduces the first LCD screen for camcorders
1992 First smartphone introduced by IBM
1995 Panasonic introduces the Mini DV
1996 First DVD-ROM players
1997 D-VHS introduced
1999 Digital8 introduced
2000 Hitachi introduces first DVD-RAM camcorder
2001 First DVD burner
2003 High definition video (HDV) standardized
2003 First HDV camcorder by JCV
2004 Panasonic and Sanyo release first flash memory camcorders
2005 Samsung introduces the DuoCam, a still camera and video camera combined
2007 Steve Jobs introduces the iPhone
2008 Nikon releases D90, the first DSLR to shoot video
2010 Apple releases the iPad
2011 Apple releases the iPad 2, with TV
2011 Canon announces the first 4K consumer camcorder
(From: The History of Video, Videomaker, April 2012, p.62.)

Basic Concepts of Electricity and Magnetism

Voltage V (Volt, V)

Current I (Ampere, A)

Power P (Watt, W)

Work and energy W (Joule, J)

Resistance R (Ohm, Ω)

Impedance Z (Ohm, Ω)

Ohm's law of electricity: $V = RI$ (only for simple DC circuits in this form)

Faraday's law of electromagnetic induction

Electric generator
Microphone

Electric motor
Loudspeaker

Amplifiers

Compact Disc (CD)

Cell telephone, electromagnetic waves

DC and AC circuits, Ohm's Law of Electricity

When a constant voltage V such as that from a battery is applied to a load resistance R, the result is a constant, *direct current I* (DC).
When an alternating, time-varying voltage such as from a household outlet or an audio amplifier is applied to a load, the result is an *alternating current I* (AC). In this case the reaction by the load to the applied voltage is called the *impedance Z*.
For pure resistances such as electric heaters and incandescent light bulbs, Z = R. But if the circuit contains other elements such as *inductances* or *capacitances*, the impedance Z and resistance R of the circuit are different. We shall ignore this difference.

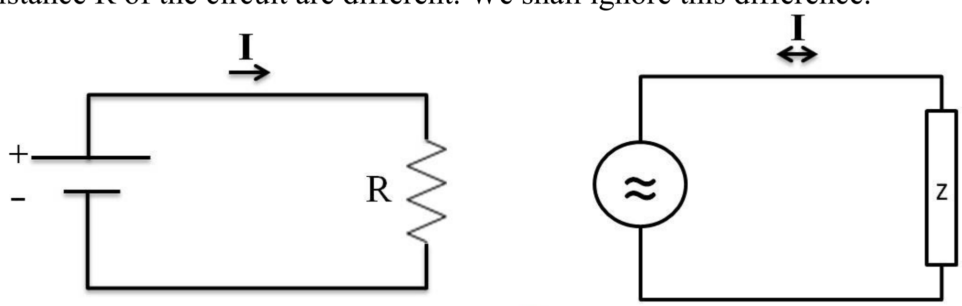

Figure. Left: DC circuit. The voltage source is a battery, photovoltaic cell etc. The load resistance is R, and the current I flows in one direction. Right: AC circuit. The voltage source is an audio amplifier, generator etc. The load is called the impedance Z. The current changes direction between clockwise and counterclockwise in the loop.

Ohm's Law of Electricity

For a DC circuit, the relation between voltage V (in Volt V), resistance R (in Ohm Ω), and current I (in Ampere A) is given by *Ohm's law of electricity* (not to be confused with Ohm's law of acoustics!):

$$\mathbf{V = RI}$$

Example 1

You connect an 8 Ω loudspeaker to an audio amplifier. The amplifier supplies a voltage of 12 V to the speaker. What is the current flowing at that instant?
Answer: I = V/R = 12V/8Ω = 1.5 A (P.S.: This would give a rather loud sound.)

Example 2

A current of I = 0.5 A flows through an incandescent old-style light bulb. The resistance of the light bulb when hot is R = 240 Ω.
What is the voltage across the contacts of the light bulb?
Answer: V = RI = 240Ω x 0.5A = 120 V (effective household voltage in the USA)

Demonstrations

1. Show a flashlight circuit with two 1.55 V batteries in series, 3.1 V total, I = 0.29 A. Measure V and I. The resistance is R = 3.10/0.29 = 10.7 Ω.
2. Show a circuit with three light bulbs: 60W old-style incandescent, 14 W compact fluorescent (CFL), and 6 W light emitting diode (LED). Read the currents through the light bulbs. The power consumptions are very different, but the light outputs are similar.

Electric Power, Work and Energy

When a voltage V is applied to a load such as a loudspeaker or light bulb, a current I flows and electrical power P is delivered.
The power can be calculated from the formula: **$P = V \cdot I$**
The physical unit of power is Volt·Ampere (V·A) or **Watt** (**W**)

Exercise: Show that alternative expressions are: **$P = I^2R = V^2/R$**
Answer: Use Ohm's law V = RI in the formula P = VI and eliminate either V or I.

Example and Demonstration
A loudspeaker with an impedance Z = 8 Ω receives a voltage of 12 V from an audio amplifier at a certain instant. What is the value of the instantaneous electrical power to the speaker? (Assume that the values of impedance Z and resistance R are the same.)
Answer: The current is I = V/R = 12V/8Ω = 1.5 A.
The power is P = VI = 12V x 1.5 A = 18 W.
Also get the same answer from $P = V^2/R = I^2R = 18$ W.
This is the *electrical power* delivered to the loudspeaker. The *acoustical power* emitted by the speaker is much lower, for example 0.1% of the electrical power.

Note: **Energy is the ability to do work, power is the rate at which energy is used.**
Energy (Work) = Power·time or **W = P·t. Power = Work/time** or **P = W/t.**
The physical unit of work and energy is 1 Watt·second = **1 W·s = 1 Joule = 1 J**.

Question: An incandescent 60 W light bulb is on for 20 minutes. What is the electrical work done or the energy delivered?
Answer: W = Pt = 60W·1200s = 72000 J.

Question: A current of 0.5 A flows through a standard incandescent light bulb. What is the power rating of the light bulb? (Use 120 V for the household voltage.)
Answer: P = IV = 0.5·120 (V·A) = 60 W (a standard light bulb).

Question: Where does the electric energy go in a standard incandescent light bulb?
Answer: Most of it goes into heat. About 5% of it is converted into useful light.

We can do better than this by using more efficient compact fluorescent light bulbs (CFLs) that produce 4 to 5-times more light output (i.e. 20-25%) for the same electrical input. Therefore about 5-times less electricity is used. CFLs may cost twice as much, but they last 10-times longer (10,000 hours). Not only is energy saved, money is saved as well.

Demonstrations
1. Apply power from a signal generator at 500 Hz to a PASCO loudspeaker. Measure the electrical power with a General Radio Power Meter (e.g. 0.5 W). Does it sound loud?
2. Touch the contacts of a loudspeaker (Z = 8 Ω) with a 1.5 V battery. See how the speaker cone moves. Calculate the current I and the electric power P.

Difference between Energy and Power

Energy is a total amount that can be used. One gallon of gasoline contains energy (work potential W). Power is the amount of energy used in a certain time. An automobile engine delivers power from one gallon of gasoline (energy) in 30 minutes (work/time).

Question

a) When do you pay for energy? b) When do you pay for power?

Answer: a) We pay for energy (W) in the form of gasoline, natural gas, or electricity.

Answer: b) We pay for power when we buy equipment with the desired power output. A 500 W audio amplifier costs more than a 100 W amplifier. When the equipment is on, power P is delivered ($P = W/t$).

Understanding Your Electric Bill

When we get our monthly electric bill, we pay for the amount of electricity used in kilowatt·hours (kWh). Note that 1 kWh = 1000W·3600s = 3,600,000 W·s = 3.6×10^6 J.

Example 1. The electric bill for a 30-day month shows an amount of 700 kWh of electricity used. What is the average power delivered to the house or apartment during these 30 days?

Answer: Use $P = W/t$

We first have to convert to proper physical units of *Joule* and *second*:

700 kWh = $700 \times 3.6 \times 10^6$ J = 2.52×10^9 J

30 days = $30 \times 24 \times 3600$ s = 2.59×10^6 s

Therefore the average power is $P = W/t = 2.52\text{x}10^9\ \text{J}/2.59\text{x}10^6\ \text{s} = 972\ \text{W} \approx 1\ \text{kW}$.

(This power fluctuates greatly during the day. It could be as high as 10,000 W when the air conditioner, electric dryer, and stove are on. Or it could be as low as 60 W when only a light bulb is on or some electronic equipment on standby.)

Example 2 The above electric bill for 700 kWh is $77.00. What is the cost of electricity in cents/kWh? ____________

Incandescent Light Bulbs versus Compact Fluorescent Light Bulbs (CFL)

When you use a 14 W compact fluorescent light bulb (CFL), it delivers about the same light output as a 60 W incandescent bulb. But CFLs use only about one fourth to one fifth of the electricity. So we pay correspondingly less for the same light output.

Question

A 14 W CFL costs $1.50. A 60 W incandescent light bulb costs $0.60. The CFL lasts10-times longer than the incandescent light bulb. The light bulbs are turned on for 200 hours in a 30-day month. The cost of electricity is 13 cents/kWh.

a) How long does it take to recover the higher cost of the CFL?

b) How much money do you save over the life of 10,000 hours of the CFL?

Answer: Time to recover the cost = ________months, money saved = $________

A Fun Question About Weightlifting

Estimate how many repetitions you have to do for 1 kWh of work when you raise a weight of 20 kg through by 1 meter. Answer: 18,000 repetitions! (Any conclusions?)

Audio Systems

The possible signal inputs into an audio system are:
Microphone
CD/DVD Player
AM/FM tuner
Cassette player, record player – almost obsolete
The signals from these components go into a preamplifier and amplifier.

The preamplifier, amplifier, and AM/FM tuner found in Hi-Fi systems today genereally are combined into a *receiver.* Some receivers may have a frequency *equalizer* with sliders or knobs, one per octave, for "tuning" a room for optimal frequency response.

Impedance Matching
The output impedance of a component should be matched to the input impedance of the next component for maximum signal transmission (minimal signal reflection). For instance, the output impedance of a microphone should match the input impedance of the preamplifier or receiver. Even more importantly, the output impedance of the receiver or amplifier should match the impedance of the loudspeaker to which it is connected.

The *preamplifier* is the heart of an audio system. It accepts low-level signals in the μV to mV range from audio sources such as a CD player or microphone. It then produces a *line level signal* output of about 1.5 Volt, applied to the power amplifier. The preamplifier also contains the controls for volume, left-right balance, and possibly an equalizer.

The *amplifier* has an input impedance of about 50 kΩ and accepts line level signals from the preamplifier at about 1.5 Volt with power levels in the milliwatt range. The electric power to the speakers is in the range 1 to 100 W or sometimes even higher. Most of this ends up as heat and very little as acoustic power. A loud sound in a living room may require 0.2 W of acoustical power. For an assumed speaker efficiency of 0.1%, the electrical output from the amplifier hence needs to be around 200W.
The output impedance of the amplifier should match the input impedance of the speakers, e.g. 4 Ω, 8 Ω, or 16 Ω, with 8 Ω being the most common.

System Linearity
For the faithful reproduction of sound, all components of an audio system should have a *linear response.* That means that the shape of the input waveform should not be distorted at any loudness level. Preamplifiers and amplifiers are highly linear to better than ±0.5 dB. Good microphones are linear to within ±1 dB over most of the audible range. Loudspeakers have the least linear response, especially in the bass region. A frequency *equalizer* can restore some of the linearity. A power amplifier working at full output during loud sound bursts may show increased distortion and non-linearity. Maintaining system linearity is a primary justification for buying a power amplifier with a higher output than normally needed.

Microphones

Demonstrations. Show various types of microphones

Condenser Microphones
A fixed charge is placed on a capacitor resembling a system of two parallel plates. One of the plates acts as a diaphragm moving with the arriving sound waves. This changes the plate separation and produces a changing voltage between the capacitor plates.

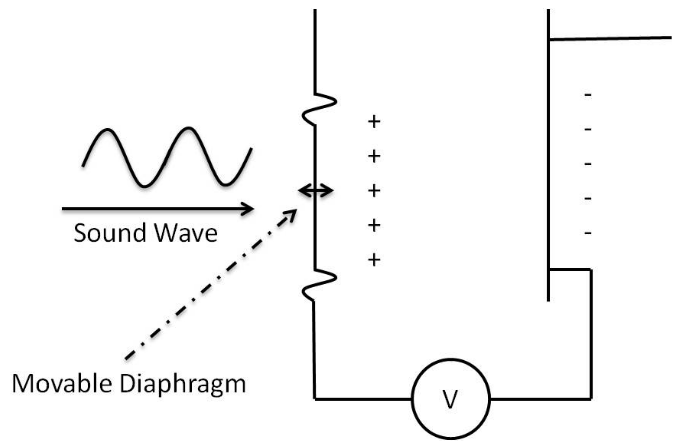

Figure. Schematic of a condenser or electrostatic microphone. The condenser plates are pre-charged with a phantom voltage from an outside source. As the distance between the plates changes, the voltage changes in tune with the arriving waveforms. The voltage changes are amplified and ultimately reach the loudspeakers. (From Berg and Stork, Fig. 7-5, p. 189.)

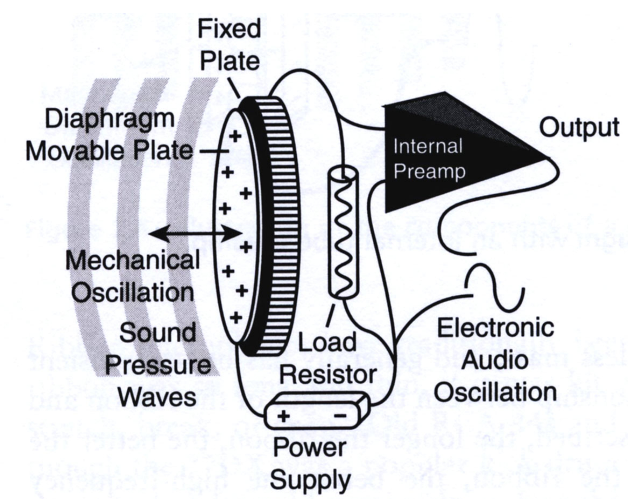

Figure. A more detailed view of the components of a condenser microphone.
(From Tom Lubin, The Microphone Book, Course Technology – Cengage Learning 2010, page 20.)

Faraday's Law of Electromagnetic Induction

A voltage is induced by a changing magnetic flux through a coil of wire

Induced voltage $\varepsilon = - N\Delta\Phi/\Delta t$

The induced voltage ε is equal to the change of magnetic flux $\Delta\Phi$ with time Δt through a wire coil of N turns. Note that the magnetic flux through a wire coil has to change with time to get an output voltage.

Important Applications
Dynamic microphone
Electric generator
Electric transformer
Electromagnetic waves: cell phones, radio, television, radar

Dynamic Microphones
Dynamic microphones work on the principle of Faraday's law of electromagnetic induction, published by Michael Faraday in England in 1831.

When a sound wave arrives at a dynamic microphone, the pressure fluctuations move a diaphragm fastened to a light coil of wire. The coil moves inside a magnet and the magnetic field in the coil changes. This induces a time-varying output voltage between the ends of the coil. The voltage tracks the arriving waveform and reproduces it as an electric output. The time-varying voltage is amplified and applied to a loudspeaker.

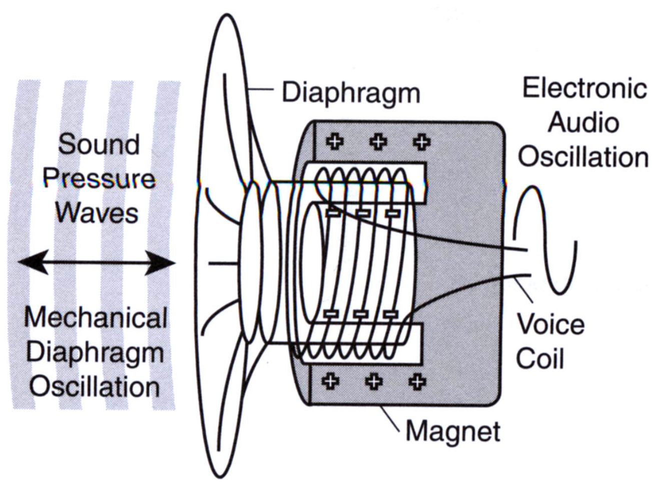

Figure. Dynamic microphone and its major components. Note the movable coil attached to the microphone cone. The coil oscillates inside a permanent magnet and produces an induced voltage at its output according to Faraday's law of electromagnetic induction. (From Tom Lubin, The Microphone Book, Course Technology – Cengage Learning 2010, page 16.)

Demonstrations of Faraday's Law of Electromagnetic Induction

1. A bar magnet moves in and out of a solenoid coil (or the coil moves with respect to the magnet; only the relative motion counts). While the magnet moves, a voltage is induced between the ends of the coil. When this is applied to a galvanometer, a small current flows in tune with the applied voltage. This demonstrates the operating principle of a *dynamic microphone*.

2. Show a small model electric generator. Crank the shaft and see a flickering light.

3. Play a *Theremin*. The device is the only musical instrument which the musician does not touch when playing it. It is based on Faraday's law of electromagnetic induction and the transmission of electromagnetic waves through space.

4. Faraday's law "in reverse". Apply a voltage to a wire coil. Hold the coil near a magnet. Observe how the coil moves as a changing voltage is applied. This is the reverse of the above demonstration and shows the principle of *an electric motor and loudspeaker*.
See the Figure in the next page of the basic components of a dynamic microphone.

5. Show a "toy loudspeaker" made from a plastic cup. A coil is taped to the bottom of the cup. Connect the earphone output from a radio or the output from a signal generator to the coil. As you approach the coil with a strong magnet the music starts playing!
Question
Why is there no sound when the magnet is far away from the speaker?
Answer: ____

6. Use a dynamic loudspeaker with the grill removed so that you can see the cone. Apply a slowly varying voltage (e.g. 5 Hz) to the speaker and see the movement of the cone. Touch the speaker terminals with a battery and see the speaker move and hear the clicks when you touch. Reverse the battery polarity. Such a loudspeaker works on the same principle (i.e. Faraday's law in reverse) as an electromagnetic motor.

Sample Calculation of the Induced Voltage from Faraday's Law (not required)
Use a coil with N = 100 turns, a cylindrical toy magnet with a maximum magnetic flux of $\Delta\Phi = 10^{-6}$ units (V·s) through a 1 cm^2 opening of the coil, and change this flux in $\Delta t =$ 0.01 s by rapidly inserting the magnet into the coil. By moving the magnet in and out of the coil an AC voltage is induced as can be seen on the galvanometer. Calculate the maximum induced voltage.
Answer: Use $\varepsilon = - N\Delta\Phi/\Delta t$ or $\varepsilon = - 100\cdot 10^{-6}/0.01 = - 0.01$ V = - 10 mV.
This would be considered a large signal from a dynamic microphone.
(The minus sign in Faraday's law is unimportant here. It signifies the validity of the principle of conservation of energy.)

Principle of Electric Generator (Microphone) and Electric Motor (Loudspeaker)

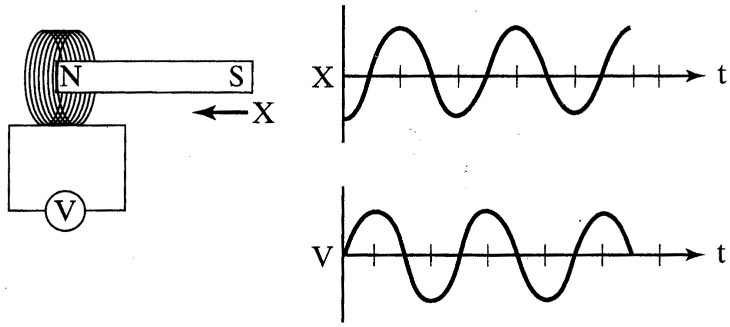

Figure. Electric generator based on Faraday's law of a changing magnetic field through a wire coil. A voltage V is induced by electromagnetic induction. It does not matter whether the magnet or the coil moves. (From Berg & Stork, Fig. 7-3, p. 188.)

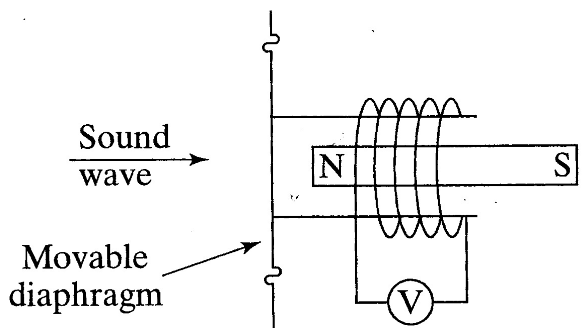

Figure. Dynamic microphone. A wire coil moves with respect to a stationary magnet. A voltage is induced between the ends of the coil. The coil is fastened to a diaphragm that moves with the sound waves. The induced voltage tracks the arriving waveform. (From Berg & Stork, Fig. 7-4, p. 188.)

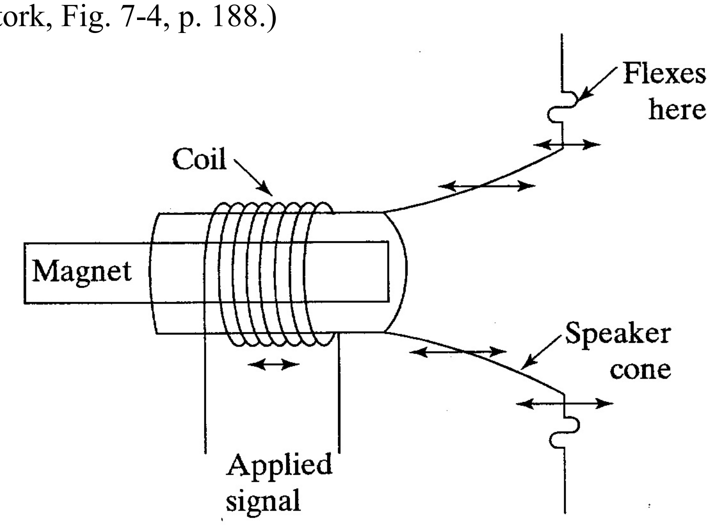

Figure. Dynamic loudspeaker. A time-varying voltage is applied to a moving wire coil attached to the loudspeaker cone. The magnet inside the coil is fixed. (This also is the basic principle of an electromagnetic motor, which is the reverse of an electric generator.) (From Berg & Stork, Fig. 7-10, p. 192.)

Directional Characteristics and Frequency Response of a Microphone

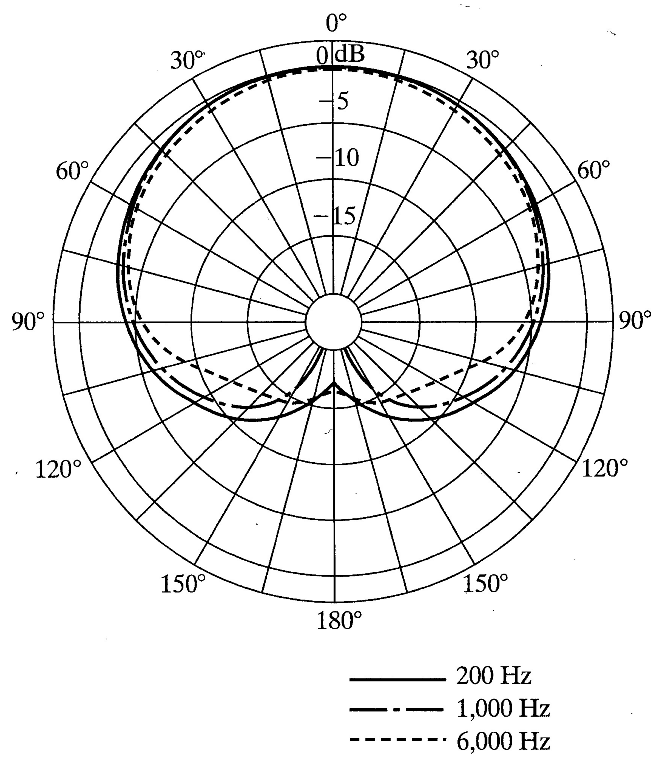

Figure. Directional response of an electret condenser microphone. Shown is a cardioid response resembling the shape of a heart. An angle of 0^0 indicates the forward direction toward the sound source. (From Berg & Stork, 7-6. p. 189.)

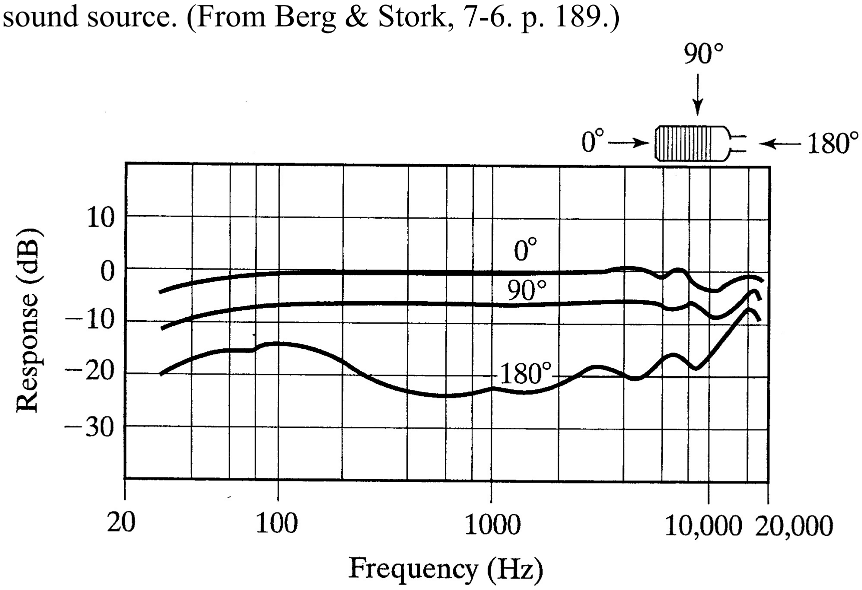

Figure. Frequency response of an electret condenser microphone. The response is uniform in the forward direction to within 1 dB between 100 and 8000 Hz. It is similarly uniform at right angles of 90^0. In the backward direction, for which the microphone is not intended, the response is lower and non-uniform.
(From Berg & Stork, Fig. 7-7, p. 191.)

Loudspeaker Types

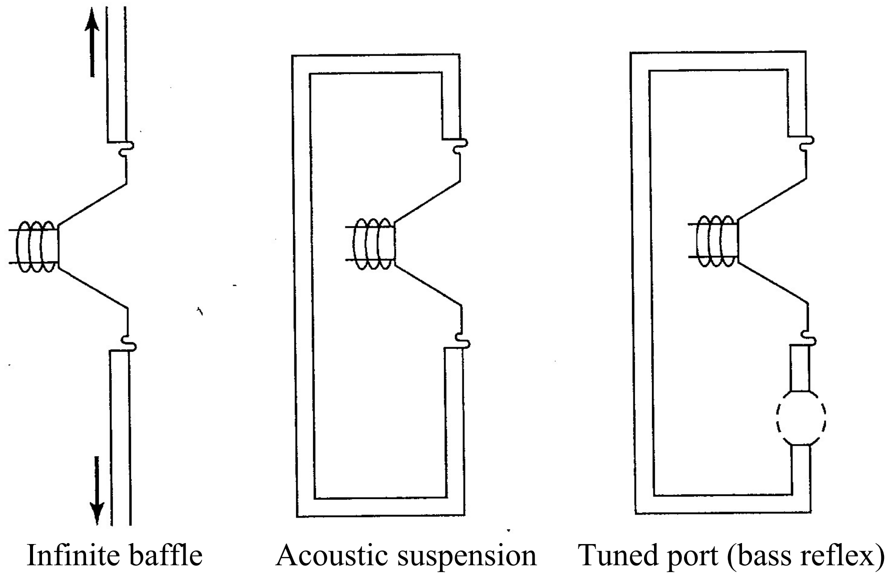

Figure. Three loudspeakers types. The infinite baffle can be a wall or ceiling. The acoustic suspension speaker is in an airtight box. Waves cannot get out from the back and interfere with waves from the front. For a tuned port speaker the box is a Helmholtz resonator and extends the bass response. (From Berg & Stork, Fig. 7-11, p. 193.)

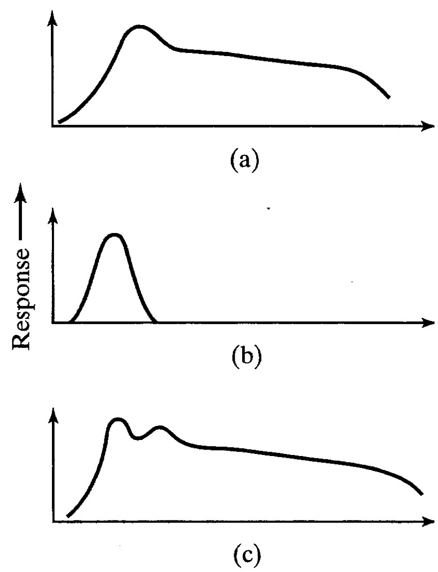

Figure. (a) Frequency response of an acoustic suspension speaker. The bump at low frequencies is due to speaker resonance (at about 100 Hz). (b) Frequency response of an empty box having a tuned port that acts as a Helmholtz resonator. (c) Overall response with the speaker in the box. The dimensions of the box and port are tuned to extend the frequency range farther into the bass region. (From Berg & Stork, Fig. 7-12, p. 193.)

Demonstration

Compare the bass response of an open speaker and a similar one in a bass reflex box.

Efficiency of a Loudspeaker and Double Bass

Loudspeaker

We did an experiment where we applied an electric power of $P_{electric} = 1.5$ W from a sine wave generator to a loudspeaker at 1000 Hz. The measured sound intensity level SIL at a distance r = 1 m in front of the speaker was SIL = 93 dB. The corresponding sound intensity I can be obtained from the formula $I/I_0 = 10^{SIL/10}$.
With $I_0 = 1x10^{-12}$ W/m^2 and SIL = 93 dB, we got $I = 2.0x10^{-3}$ W/m^2
In order to obtain the loudspeaker efficiency, we assumed that the sound intensity was emitted uniformly into *half* a hemisphere in front of the speaker.
The area of this surface at a distance r = 1 m was $A = \pi r^2 = 3.14$ m^2.
Hence the total emitted acoustical power was $P_{acoustic} = I \cdot A = 2x10^{-3}x3.14$ m$^2 \approx 0.0063$ W.
Designating the loudspeaker efficiency by the Greek letter η, we finally obtained

$$\eta = P_{acoustic} / P_{electric} = 0.0063/1.5 = 0.0042 \text{ or } 0.42\%.$$

Double Bass

Professor Mark Morton from the TTU School of Music visited our class in Spring semester 2017 and played the double bass. We performed an experiment to determine roughly the efficiency for converting the mechanical power from bowing a string to the acoustical power emitted.
The mechanical power was given by $P_{mech} = F \cdot v$, where F is the force from the bow on the string and v the speed of bow across the string in (open A-String).
On a spring scale, we simulated the force of the bow and found approximately F = 5 N.
We also estimated the speed of the bow across the bow as v = 0.5 m/s.
Hence the mechanical power was $P_{mechanical} = 5x0.5 = 2.5$ Watt.
At a distance of 1 m from the string, we measured the sound intensity level SIL = 90 dB.
The corresponding sound intensity I, with the same formula $I/I_0 = 10^{SIL/10}$ as above, was then $I = 1x10^{-3}$ W/m^2.
Assuming that the sound intensity was emitted uniformly into half of a hemisphere at a distance of =1 m in front of the double bass, as in the above example, we obtained for the acoustical power
$P_{acoustical} = I \cdot A = I \cdot \pi r^2 = 1x10^{-3}x3.14 \approx 0.0031$Watt.
The efficiency then was given by $\eta = P_{acoustic} / P_{mechanical} = 0.0031/2.5 = 0.0012$ or 0.12%.

This efficiency is small again and of the same order of magnitude as for the loudspeaker above. In both cases, the sound was quite loud because of the high sensitivity of the ear.

There is an extra energy conversion in the case of the loudspeaker from electrical to mechanical energy of the vibrating speaker cone, with an efficiency less than 100%. It seems therefore, that at least in our two examples, the efficiency for converting mechanical to acoustical energy is larger in the loudspeaker than in the double bass.
(P.S.: In both cases more than 99% of the input energy is converted to heat before any useful sound energy is emitted.)

The Compact Disc (CD)

1980-81 CD standards established
1980-85 CD development

CD Characteristics

High fidelity
Low noise
Large dynamic range > 90 dB
Frequency range ≥ 22 kHz
Data Storage ≈ 700 MB

Rotation with constant linear velocity of 1.2 m/s
Width of pits 0.5 μm
Depth of pits 0.2 μm
Row spacing center-to-center 1.6 μm (limited by optical diffraction of laser beam)
CD readout by red laser
In distinction to a CD, a DVD. It uses a blue or ultra-violet laser of shorter wavelength, together with multiple layers, and has a much greater storage capacity of 4.7 GB.

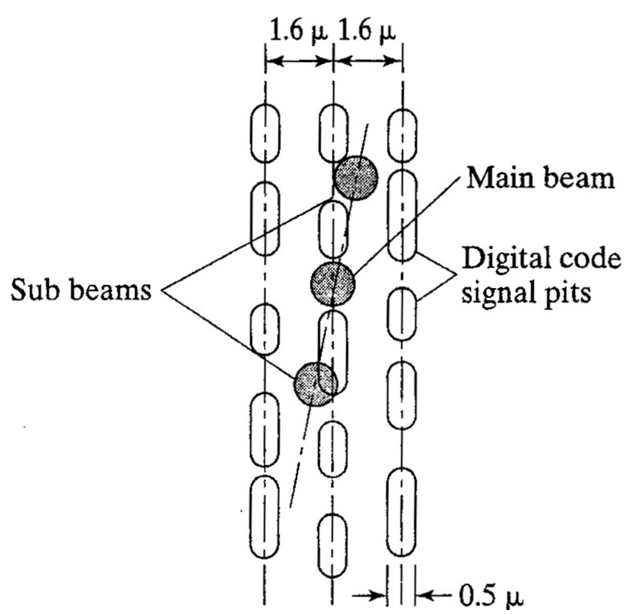

Figure. Tracking of the pits on a CD by a laser. Three laser beams are used. The main beam scans the signal pits, the two sub-beams guide the main beam along the pits. The pit length is not to scale. (From Berg & Stork, Fig. 7-21, p. 208.)

Demonstration
Show a CD and DVD and observe the different colors resulting from diffraction of light.

Calculation of Compact Disc Parameters

A CD has pit tracks placed between radii of 2.3 cm and 5.7 cm.
The spacing between tracks is 1.6 μm.

Questions

a) How many tracks are on a CD?
Answer: The region on the CD occupied by the tracks is 5.7 cm – 2.3 cm = 3.4 cm
Number of tracks N = $0.034\text{m}/1.6\text{x}10^{-6}\text{m}$ = **21250 tracks**

b) What is the total length of the spiral track on the CD?
Answer: The average radius of the tracks is r_{ave} = (5.7 cm + 2.3 cm)/2 = 4.0 cm
The total length of the spiral track is $L = 2\pi r_{ave}N = 2\pi$ x 0.04 m x 21000 m = **5278 m**
= 5.278 km = 3.28 miles.

c) The total playing time of the CD is 72 minutes and 6 seconds.
What is the speed with which the laser reads the recording?
Answer: v = L/t = 5278m/4326s = **1.22 m/s**.
(Note that this linear track speed is constant. Therefore the angular velocity changes from high on the inner tracks to lower on the outer tracks.)

d) The data points on the disc consist of 16-bit binary numbers, read at a rate of 44000 numbers/second for each of the two stereo channels.
How many binary bits per second are read?
Answer: Number of bits/s = 16 bits 44000/s x 2 (stereo) = **$1.41\text{x}10^6$ bits/s**

e) What is the average length for one binary bit along the track?
Answer: l = (1.22m/s)/(1.4112x10^6 bits/s) = 0.86 x 10^{-6} m = **0.86 μm**
About half, or **0.43 μm**, is occupied by the burnt pit of a bit, the other half is empty space between successive pits.

f) What is the storage capacity of the CD?
Answer: Use the data from parts c) and d):
Storage = 1.4112 x10^6 bits/s x 4326 s = 6.106 x 10^9 bits = 6.106x10^6 kilobit
Convert to Bytes: Use 8192 kilobit = 1 megabyte (8 bits = 1 byte)
The storage capacity is 6.106x10^6/8192 = 745 Megabyte ≈ **700 MB.**
This is the familiar "700 MB" storage capacity of a CD.

Dynamic Range of a CD

A CD can cover a wide amplitude range in electrical signal of 2^{15}:1.
This corresponds to a range in dB of $10\cdot\log(2^{15}/1) = 150\cdot\log 2$ = 45.2 dB.
Sound intensity is proportional to amplitude squared.
Hence the dynamic range of a CD, expressed as a range in sound intensity level, is
SIL = $20\cdot\log(2^{15}/1)$ = 90.4 dB ≈ 90 dB. This is a very large range compared to older means of sound reproduction such as tapes or vinyl records.