


Faraday Cages and Microwaves

Shielding
Communications, Cooking
Microwave Oven Mysteries

Shielding and Faraday Cages

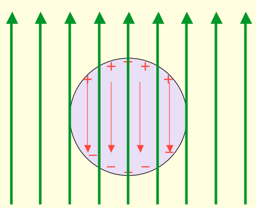
- What keeps microwaves in the microwave?
- Why is cell reception terrible in elevators?
- Why is it safe to be in a car in a lightning storm?
- How can satellite dishes work with just a mesh you can see through?

- All of these relate to the behavior of metal in the presence of an electric field
  - and electromagnetic radiation consists (at least partly) of an oscillating electric field

---

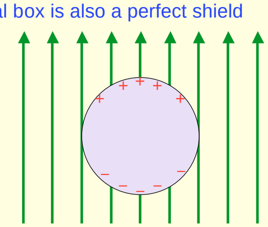
Electrons on the move

- Electrons are free to move in metals
  - this is why they are good conductors
- Instantly respond to electric field, moving accordingly
- Imagine a conducting sphere placed in an electric field:



Internal Electric Field is Zero

- Net result is zero electric field inside conducting sphere
- Same thing happens even if the sphere is hollow:
  - the electrons are all pushed to the surface anyhow
  - so a metal box is also a perfect shield



Faraday Cages in Practice

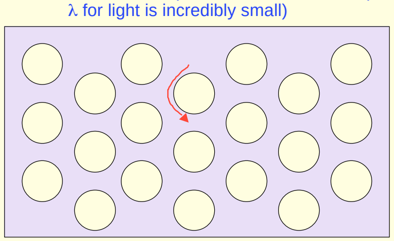
- Your car is sort-of a Faraday cage:
  - lightning will flow on the outer skin, leaving the inside relatively quiet
- Elevators are notoriously bad for reception
  - metal walls shield electromagnetic radiation: no E-field inside
- The microwave oven is a Faraday cage inside-out
  - generate strong electric fields *inside*, but outside is zero electric field
- Bottom line is that a metal sheet shields electric fields
  - in the context of electromagnetic waves, we can say that metal surfaces *reflect* incident EM waves
  - can either confine E-fields within box, or keep them out

Metallic Reflection: Wiggling Electrons

- Why does metal reflect EM waves?
  - because the surface electrons are made to vibrate with the oscillating E-field
  - this acceleration of the electron itself produces electromagnetic radiation
  - phase is such that transmitted wave is perfectly canceled
- So the microwave has all these metal (reflective) walls, which keeps the microwaves inside. But how does the mesh on the front door do the job?
  - after all, light can get through, and light is also EM radiation
- Key issue is: can electrons redistribute themselves quickly enough?
  - for a certain frequency of EM radiation, need charge redistribution on timescale shorter than wave period

Getting around the holes

- Free flow of electrons is hampered by holes
- Need to traverse around hole much faster than period of EM wave
  - redistribution of electrons in metal happens close to speed of light
  - if electrons have time, they will "patch up" holes with appropriate electric field across the void: *as if hole isn't there*
- Can easily show that timing is satisfied if hole size is much smaller than wavelength of EM wave in question
  - distance = rate × time is equivalent to $\lambda = c/f = cT$ (T is wave period)
  - meshes work provided hole size $\ll \lambda$ (but can still see through, since λ for light is incredibly small)



Electrons must redistribute around hole, but this does not require a *single* electron to make the journey. Just like in the case of electrical current, electrons push each other. The *signal*, or *request* to move travels near light speed, though individual electrons do not.

Microwaves: Just Another EM Wave

- Microwaves are like any other electromagnetic wave
  - occupying region between radio and infrared
- Wavelengths from 1 mm to 1 m are microwaves
  - this definition is not necessarily strict
  - think of a meter stick: every set of marks: from 1 mm to 1 m are all in the microwave category
- Microwaves used for lots of things
  - trans-continental communications
  - cell phones
  - microwave ovens
  - weather radar
  - astronomy (confirmed Big Bang)

Microwave Communications

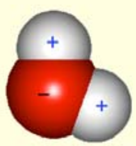
- You've seen microwave towers before
  - these are relay stations forming a communication link across the country
  - much of our telephone, internet, etc. connections run this way
- Principle advantage over radio: BANDWIDTH
  - TV station, for instance, requires 6 MHz of bandwidth
  - At 60 MHz (like channel 2, 3), this is 10% of the frequency
    - Over one octave of frequency, from 60 MHz to 120 MHz, you would only fit 10 TV stations
  - At 10 GHz (3 cm), one octave (from 7–14 GHz, e.g.) could fit over 1000 TV stations (or LOTS of phone activity)
- Also penetrates haze, fog, smoke, light rain, snow, clouds
  - makes this a reliable means for communication

Communications Demo:

- We can amplitude-modulate the signal strength of a microwave transmitter
- Receiver gets varying signal strength, and can relate the signal strength to a speaker
- Important parameters of communication:
  - polarization must match
  - pointing/beaming must be okay
  - no opaque junk in the way

Microwave Ovens

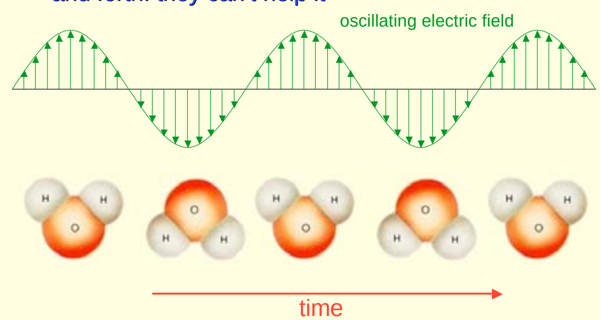
- Water is a polar molecule



- This means it will try to orient itself a particular way in an electric field
- Once oriented, a net force exists on molecule
  - one side is a tiny bit closer to source, so kQq/r^2 is larger
  - net effect is attraction

Microwave Oven, continued

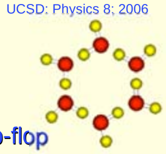
- Microwave means time-varying electric field
- As electric field changes direction, water flips back and forth: they can't help it



Microwave Frequency

- Microwave ovens use a frequency of 2.45 GHz
  - 12 cm wavelength
- This is ideally suited for the time it takes to flip a water molecule around
  - half-cycle is 200 picoseconds
- Imagine microwaving steam
  - molecules are far apart
  - they flip back and forth, but who cares: they don't heat up
    - turn off microwaves, and nobody has *moved* anywhere
    - thermal energy is, after all, kinetic motion
- Now crowd molecules into liquid water
  - no "elbow" room to do their exercise
  - bump into each other and get mad (heat up)

Steam, Water, and Ice



- In ice, molecules are locked into bonded arrangements, and can't break loose to flip-flop
- So of steam, water, and ice, only liquid water is heated by microwave
- More on the bumping: how does this make heat?
  - imagine hydrogen atoms as being like boxing gloves
  - when they smack a neighboring molecule, it gets set into motion (kinetic energy→heat)
  - one bump leads to another, and pretty soon, the whole pile of molecules (a.k.a., hot dog) gets hot

Thawing Food in Microwave

- If ice is unaffected, how can a microwave defrost food?
  - this is actually hard for the microwave to do
  - some few molecules will be loose and *can be* wiggled,
  - these will quickly heat up their surroundings, making more liquid
  - runaway process in little pockets: ice still unaffected
- Defrost cycling: allowing time for diffusion
  - rather than let a few pockets run away with all the heat, turn off magnetron and allow time for thermal diffusion
- Thermal diffusion is natural time it takes heat to propagate through a medium
  - relates to thermal conductivity: the ease with which heat is transported

Thermal Conductivity

- Different materials have different efficiencies for distributing heat

Material	Therm. Cond. (W/m/K)	Comments
Silver	406	why room-T metals feel cold
Copper	385	why cooking pots have this
Aluminum	205	
Stainless Steel	14	why cooking spoons are S.S.
Ice	1.6	
Glass, Concrete, Wood	0.8	our buildings
Many Plastics	0.4	plastics feel warm to touch
Air (stagnant)	0.02	but usually in motion
Styrofoam	0.01	better than air!

Conventional ovens rely on conduction

- Heating food from the outside, one relies entirely on thermal conduction/diffusion to carry heat in
- Relevant parameters are:
  - thermal conductivity, κ (how fast does heat move) (W/m/K)
  - heat capacity, c_p (how much heat does it hold) (J/kg/K)
  - mass, m (how much stuff is there) (kg)
  - size, R—like a radius (how far does heat have to travel) (m)
- Just working off units, derive a timescale:
  - $\tau \approx (c_p/\kappa)(m/R) \approx 4(c_p/\kappa)\rho R^2$
  - where ρ is density, in kg/m^3: $\rho \approx m/((4/3)\pi R^3) \approx m/4R^3$
  - faster if: c_p is small, κ is large, R is small (these make sense)
  - for typical food values, $\tau \approx$ 6 minutes $\times$ $(R/1\text{ cm})^2$
  - egg takes ten minutes, turkey takes 5 hours

The microwave shortcut

- At 2.45 GHz, microwaves penetrate into food (looks partially transparent) and excite water molecules internally
  - 2.45 GHz is a good compromise: lower frequency would not be readily absorbed (food too transparent); higher frequency would not penetrate well, heating the outside (food too opaque)
- Ideally, food cooks uniformly throughout
  - eliminating restriction of thermal diffusion time
  - except for ice, which isn't warmed by microwaves
- Still, cold spots can develop if radiation pattern is not uniform
  - microwaves are reflected by walls, and set up standing-wave interference patterns leaving hot spots and cold spots
  - helps to rotate food through this stationary radiation pattern

Metal in the Microwave

- Electrons are free to move in metal
  - charges are forced to flow in response to the electric field
  - if the metal is thin (foil, twist-tie, decorative trim), it can't carry much current, and gets very hot → risk of fire
- Also, sharp points concentrate the electric field and promote sparks
  - foil edges, twist-ties, decorative trim (same culprits) present sharp, thin edges where sparks are likely to form
- Bulky metallic objects with smooth edges present NO PROBLEM to microwaves
  - the walls are, after all, metal
  - spoons, juice concentrate lids, metal plates okay
  - forks, ragged-edged can-opened lids not okay

Are microwaves harmful?

- The only thing microwaves can do to you is vibrate water molecules
- As long as the flux is low (e.g., outside microwave, or from cell phone antenna), no harm is done
  - nowhere is there a high-enough concentration to develop significant heat/boiling
- But if the microwave door is open (and safety is defeated), you're asking for trouble
- Also standing in front of microwave transmission antenna could cook you
  - mildly, but potentially lethally

Microwave Experiments

- Boiling water in cup of ice
  - described fully in book
- Marshmallow
  - stop microwave before marshmallow explodes: a heck of a mess
- CD
  - do this only for a few seconds to see sparky light-show
  - only works on metallic-layer CDs (not organic CD-Rs)
  - CD will be destroyed
  - abort before CD turns into a pile of goo (awful mess)
- Do these only in a microwave that you take full responsibility for in case you break it or make an un-cleanable mess
- Never run microwave for more than 10 seconds without some form of water inside to absorb energy
  - alternative is overheating and possibly destroying magnetron ($$)

References and Assignments

- Check out:
  - http://rabi.phys.virginia.edu/HTW/microwave_ovens.html
  - for an excellent question/answer forum from a guy who has his head screwed on straight. You'll get little misinformation here
- HW 5 due today
- HW 6 due 5/25: 13.E.19, 13.E.21, 13.E.22, 13.E.24, 13.E.25, 13.E.26, plus additional required problems accessed via assignments web page
- Q/O #4 due next Friday (5/26)