PHYSICS 102N
Spring 2022

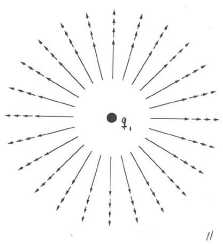
Week 7

Electromagnetism and Light

Remember PHYS101…?

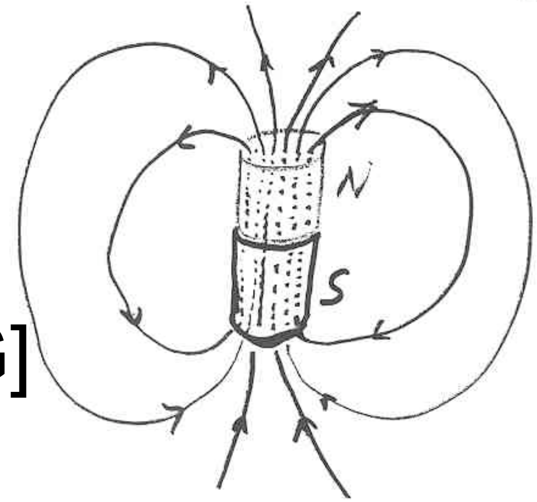
- Electrostatic force (*e.g.*, Coulomb: $F = k\frac{Qq}{r^2}$)

  charges q,Q at distance r



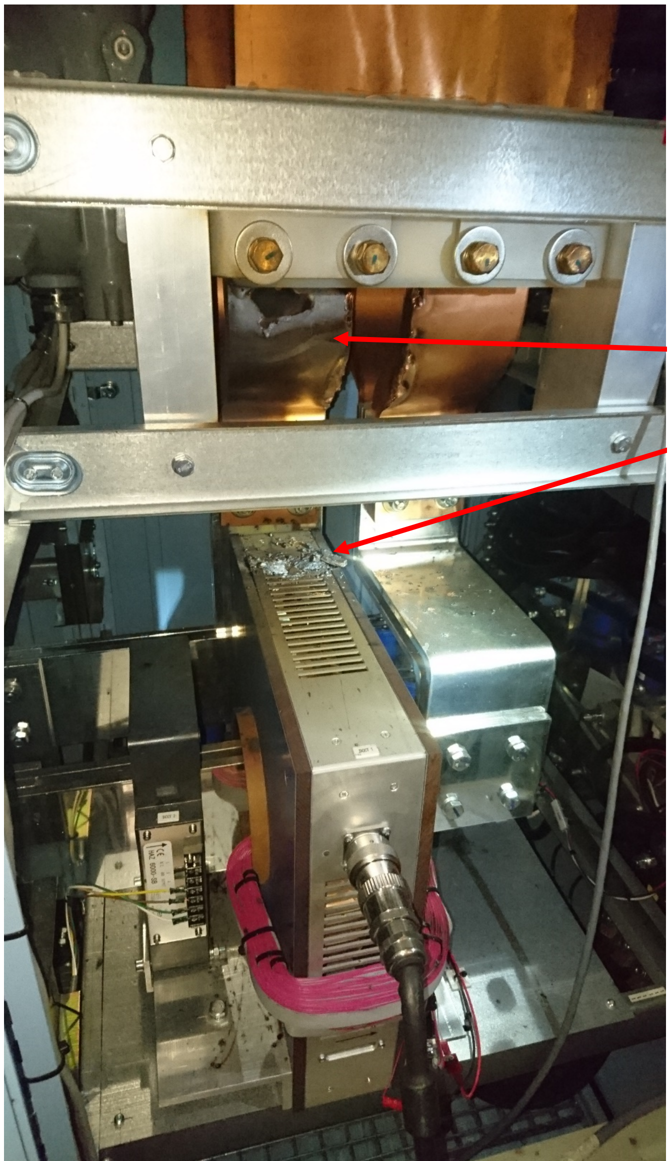
- Electric field: $\mathbf{E} = \mathbf{F}/q$ [N/C], $\mathbf{F} = q\mathbf{E}$
- Electric potential V [V], electric potential energy qV [J]
- Current I [A]; Ohm's Law $\Delta V = RI$ [V = ΩA]
- Power: P = $\Delta V \cdot I$ [W]; Circuits (AC/DC)

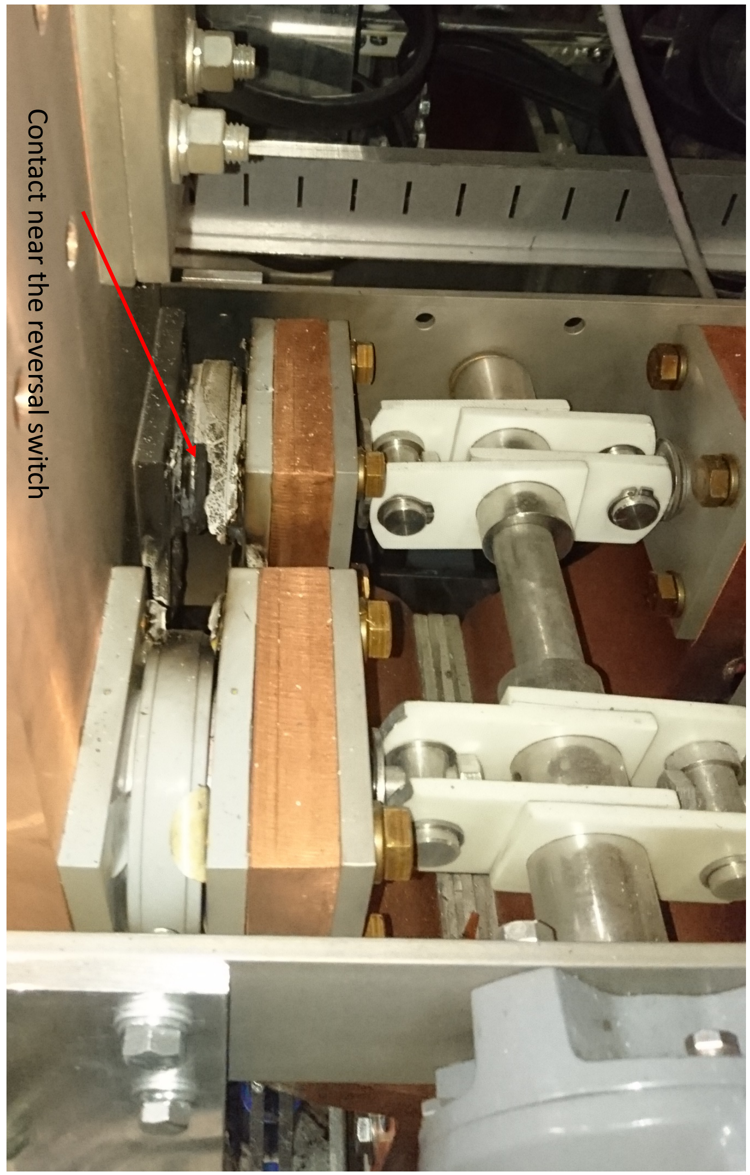
Remember PHYS101….?

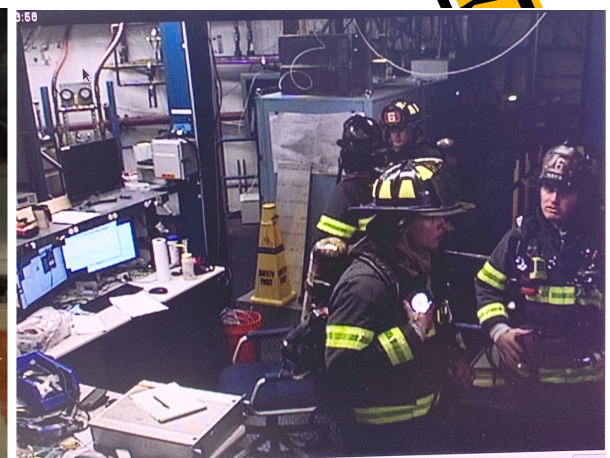


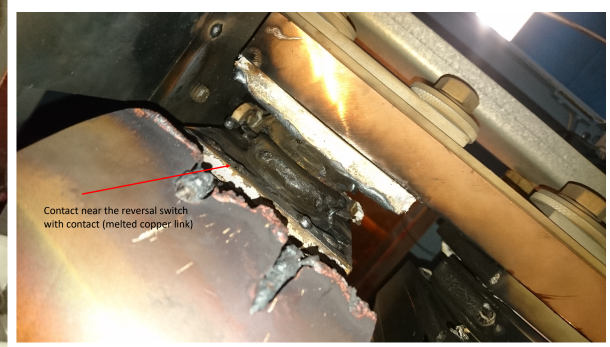
- Magnets and Magnetism
- Magnetic field **B** [T = 10,000G] (ultimately due to currents)
- **Acts** on moving charges = currents ($F = ILB$)
- Connection to electric field:
  - if charge q moves in stationary **B** - Force $\propto q,v,B$
  - if magnet moves relative to charge - Force $\propto q$ => electric field E due to changing magnetic field
  - same if **B** simply changes for other reasons (induced **E** field)

Faraday and Lenz









- (cont'd): While static magnetic fields cannot do work on moving charges, ***changing*** magnetic fields ***can*** do work (through induced **E**) and therefore magnetic fields can ***store energy***

Closing the loop: Maxwell

- Changing **B** -> **E** (Faraday)
- Changing **E** -> **B**!!! Maxwell's Law
  - Proportional to the rate of change of **E**, perpendicular to **E** (circling around it)
  - Usually a small effect

Closing the loop: Maxwell

- Changing **B** -> **E** (Faraday)
- Change in the changing of **B** -> changing **E**
- Changing **E** -> **B**!!! Maxwell's Law
  - Proportional to the rate of change of **E**, perpendicular to **E** (circling around it)
- Changing **B** -> **E,** Changing **E** -> **B,** Changing **B** -> **E,** Changing **E** -> **B,** Changing **B** -> **E,** Changing **E** -> **B,**

  Changing **B** -> **E,** Changing **E** -> **B,** Changing **B** -> **E,** Changing **E** -> **B,...**
- Electromagnetic Waves!

Solving the equations of electromagnetic fields…

- …Maxwell found that they give rise to a solution for oscillating electric and perpendicular magnetic fields (in phase) forming a plane wave with wave velocity - 300,000 km/s = *c*!
  - “We can scarcely avoid the conclusion that light is an electromagnetic wave” - the wave velocity of light was known before!

Note: EM wave doesn’t need a medium - electric and magnetic fields ARE the medium. *c* is universal constant and turns out to be a property of space and time!

Properties of EM waves

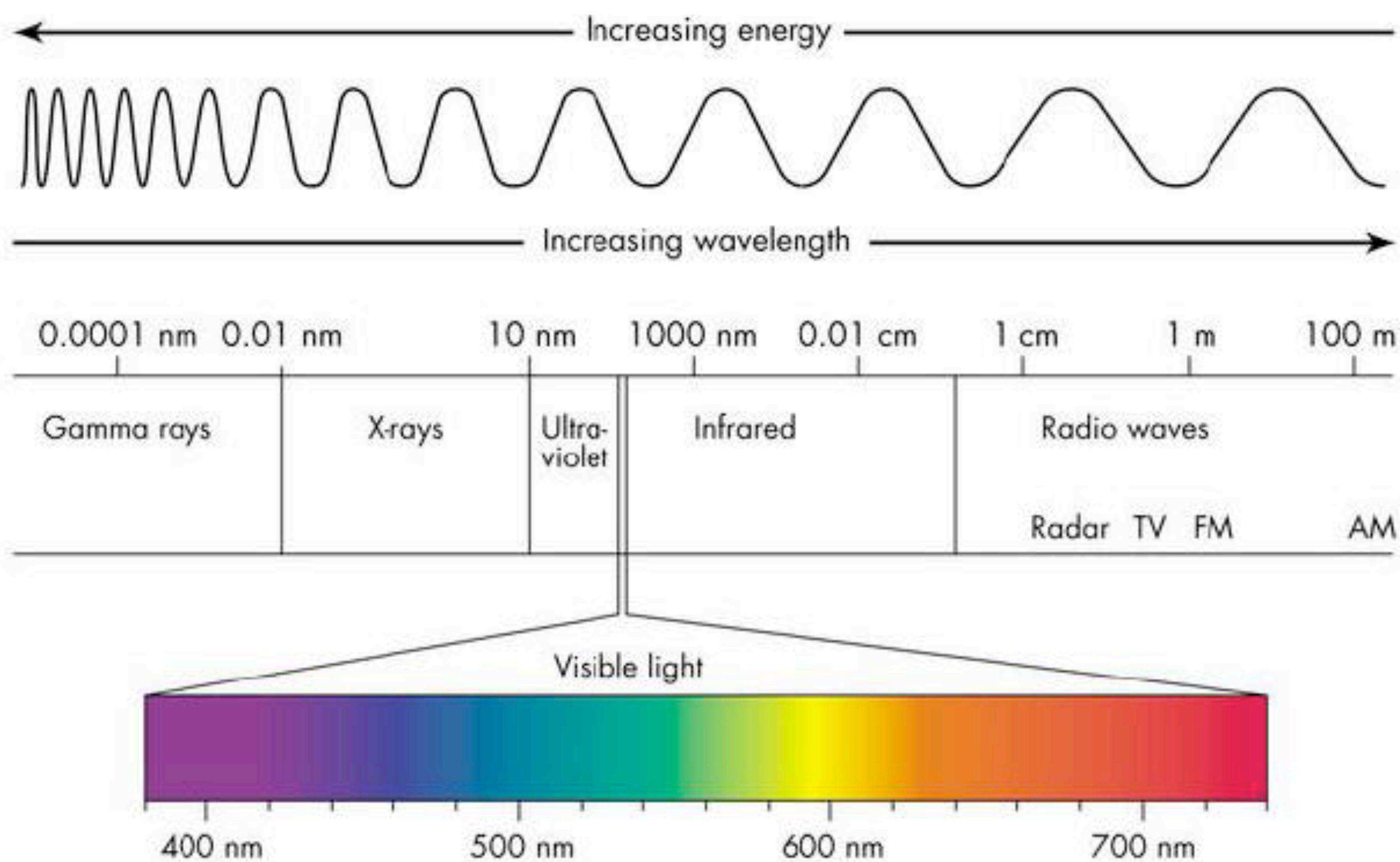
- **E**, **B** and propagation all perpendicular to each other
- B = E/c (magnetic field much smaller)
- Can have 2 directions of polarization - up-down or left-right (direction of oscillation of **E**-field) - Polaroid glasses
- Wave velocity always c in vacuum (and other “dilute” media)

All EM waves are created by **accelerated** electrical charges: (Changing)^2 **E** -> changing **B** ->…
Example: Radio antenna, oscillating molecules (IR), electrons in atoms (light-UV-Xrays), protons in nuclei (gamma-rays)…

Propagation of Light

- Simple model:
  - In free space, light waves follow straight lines (“rays”).
    - Example: rays from outer edges of sun make angle of 1/2 degree, sun is 150 Mio km away -> sun diameter = 1.4 Mio km
  - In medium, 3 possibilities:
    - Reflection: wave reflected; ray “bounces back”
      - Some reflection present at nearly all interfaces; max. for metals because of free electrons; smooth surfaces – imaging!
    - Absorption: EM energy transferred to oscillating atoms/molecules; ray is “stopped”
      - max. for resonance frequency; e.g. UV in glass, IR in CO_2…
      - shadow (only rays that avoid medium continue)
    - Propagation (often with reduced wave velocity <=> reduced **E**):
      - waves absorbed and re-emitted (possibly with phase delay)

EM wave spectrum

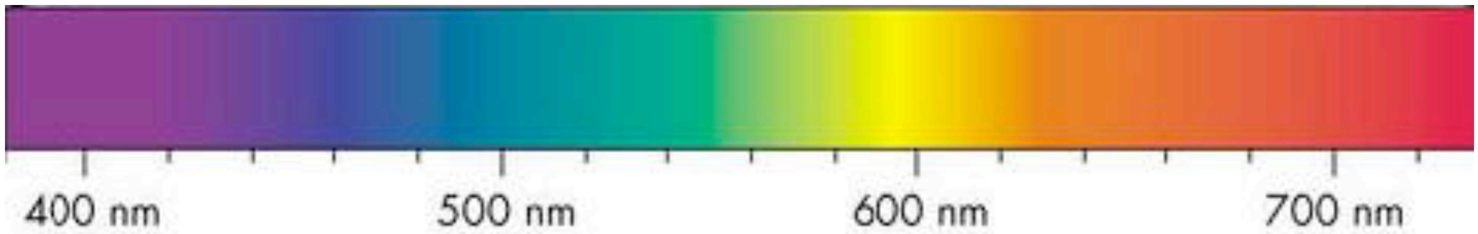


$f = c/\lambda$ (like all waves)

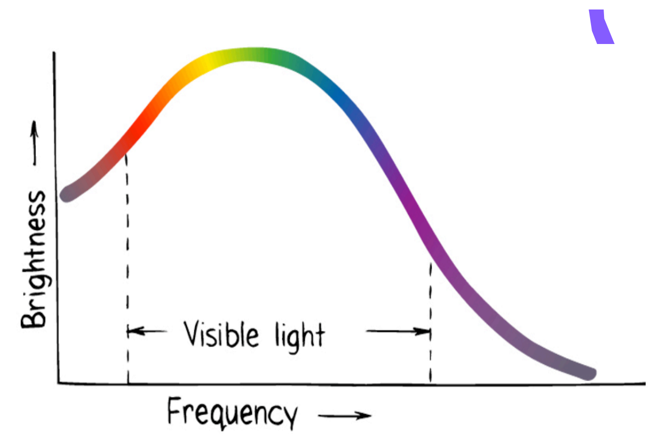
200 m -> 1500 kHz; 3 m -> 100 MHz; 10 mm -> 30 GHz

10 μm -> 30 THz; 600 nm -> $0.5 \cdot 10^{15}$ Hz, 10^{-13} m - $3 \cdot 10^{21}$ Hz

Color and wavelength



- Human eyes are sensitive to electromagnetic waves between 380 nm and 740 nm (nearly 1 "octave")
- In this range, there are ∞ many different "colors", each given by a single wavelength (frequency)
- "Black body" radiators like the sun emit a whole spectrum of radiation (peaked around "greenish-yellow" for the 6000 K surface of the sun)
- Combining all these colors (with their relative strength) appears "white" to our eyes (for obvious reasons)



- Combining just some of the "pure" colors yields even more colors (magenta, brown, …)

Sources of color

- Selective emission:
  - Black body radiation: Most prominent color related to heat (red glow - bluish white hot)
    - Stars, fire, incandescent lights, welding arcs, anything hot
  - Atoms = Harmonic oscillators with fixed frequencies (Na = yellow, Cu = blue, He = red,…)
    - evaporation lamps (incl. fluorescent light), lasers, LEDs, phosphors (CRT or plasma screen)
- Selective Absorption
  - Atoms/molecules tend to re-emit some frequencies while absorbing others (= converting into heat) - selective removal of some colors
    - Transmission: colored filters (LCD screen, theater lights), water…
    - Reflection: Shiny surface - all light gets reflected; dull surface - only light which doesn’t get absorbed gets reflected.
      => Color of all passively illuminated objects, dyes, paints…

Sources of color cont’d

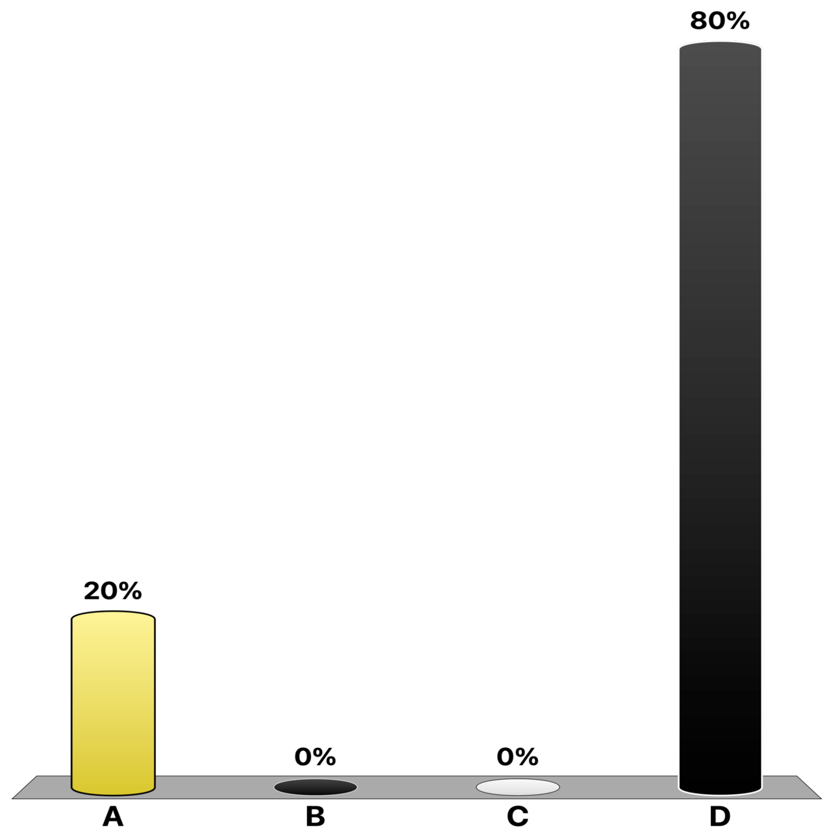
- Selective scattering:
  - dilute impurities in otherwise transparent medium absorb light and reemit in all directions = scatter
    - milk, clouds, dust, smoke, haze/humidity
  - small objects (dust, clusters, molecules, atoms) tend to scatter short-wavelength (blue) light more than long-wavelength (red) light =>
    - Blue sky, red sunset
      (light has to travel through greatest amount of atmosphere)
    - silt in “deep blue” lakes
    - yellowish-brownish air pollution

Color perception

- Retina of human eye: rods (black/white), cones (red - green - blue = primary colors)
- Perceived color: % excitation of each type of cones
  - Example: Orange - 75% red, 25% green - additive mixing
  - Efficient way to categorize millions of colors, but can be fooled:
    - TV/Computer screens: 3 types of dots; also for posters
    - Just 3 colored beams (single frequency) needed to imitate "white"
  - Complementary colors: yellow, cyan, magenta - subtractive mixing
    - yellow subtracts blue, cyan subtracts red, magenta subtracts green
    - Prints, magazines, computer printouts (plus black)

Which of the following electromagnetic waves travels the fastest in vacuum?

A. The bright blue light from a “blue giant” star?
B. The faint infrared glow from an object at 300 K?
C. Radio waves
D. All the same



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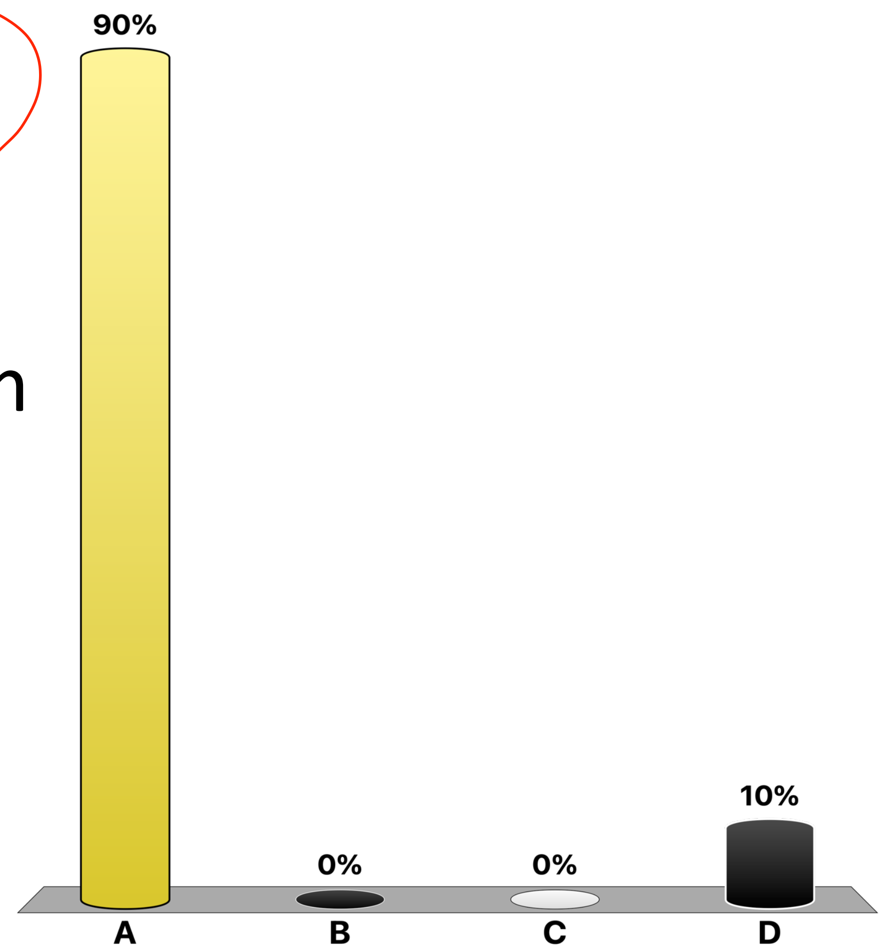
Which of **these** electromagnetic waves travels the fastest?

A. The bright blue light from a "blue giant" star through empty space

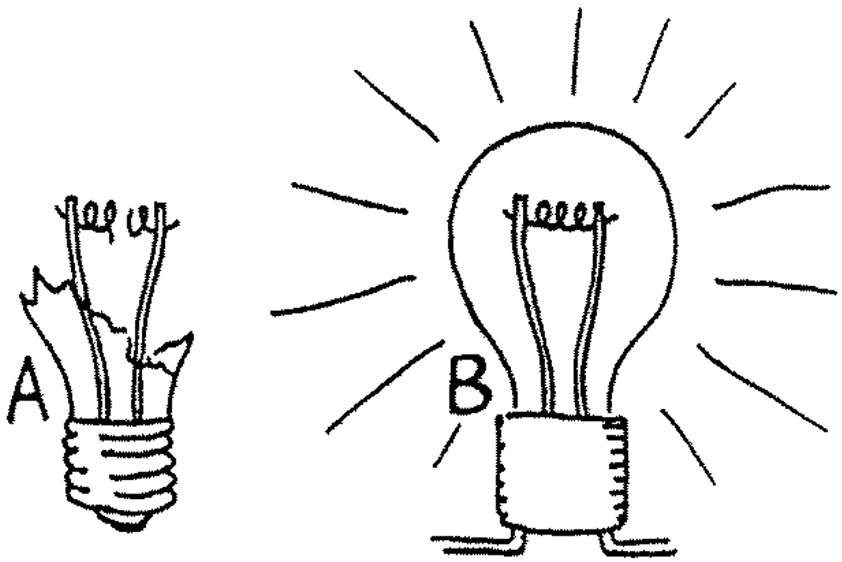
B. The faint infrared glow from an object at 300 K through Earth's atmosphere

C. Radio waves in water

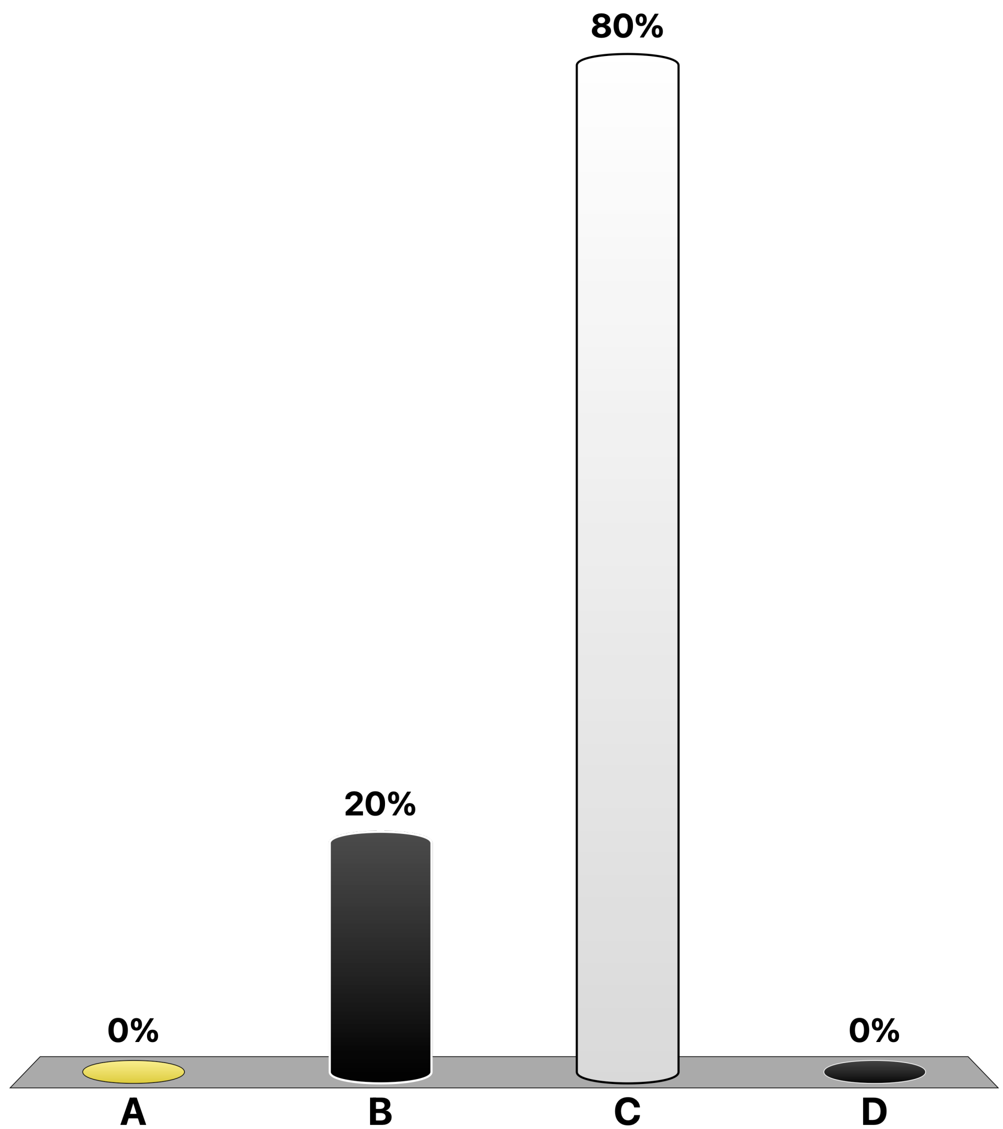
D. All the same



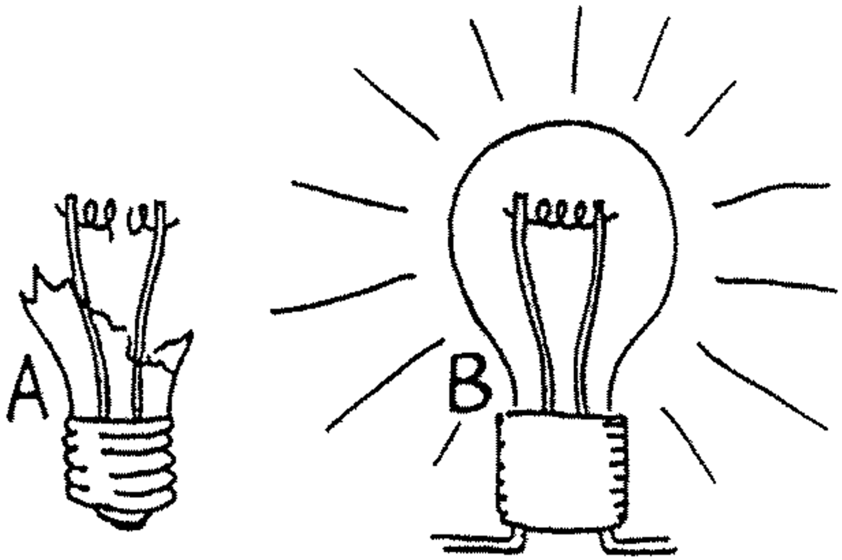
Which of these lamps is emitting electromagnetic radiation?



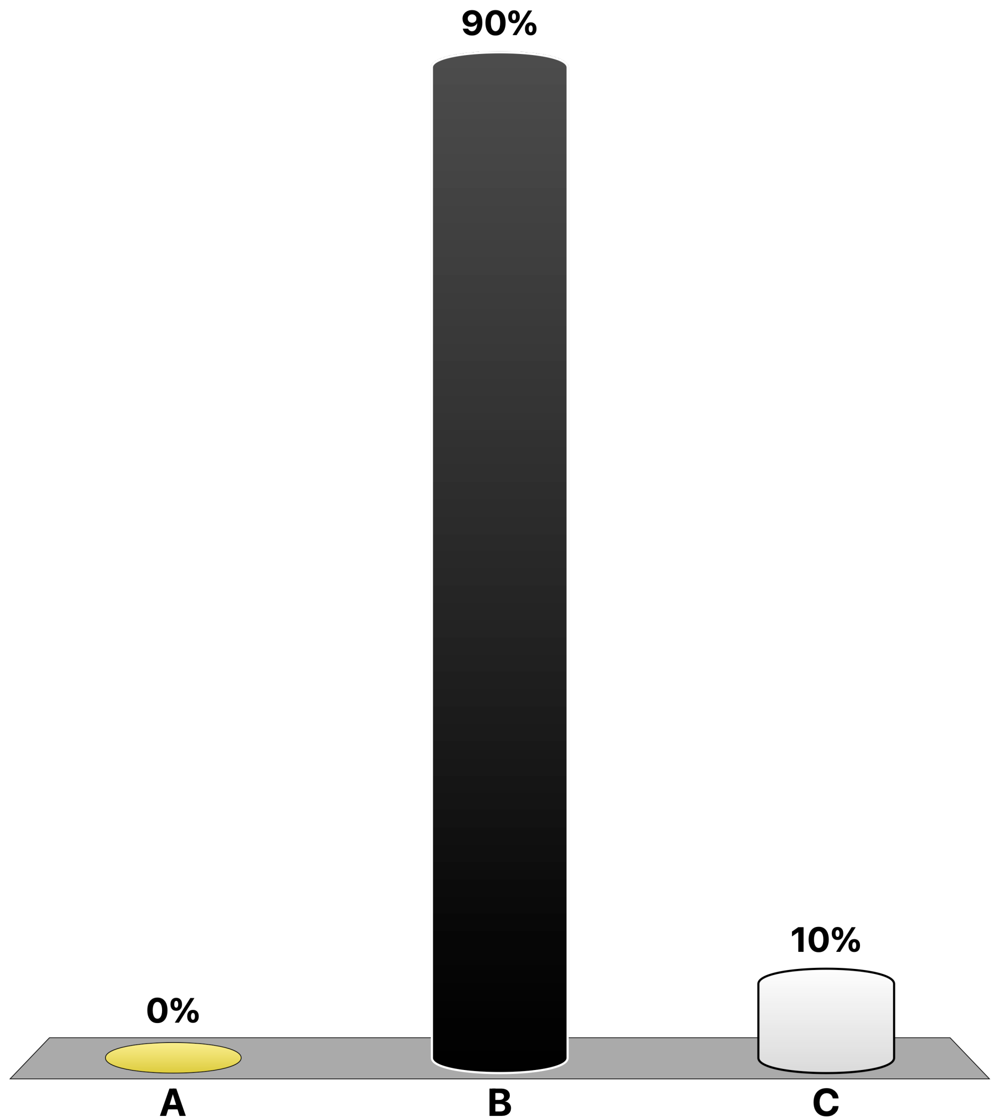
A. Lamp A.
B. Lamp B.
C. Both.
D. Neither.



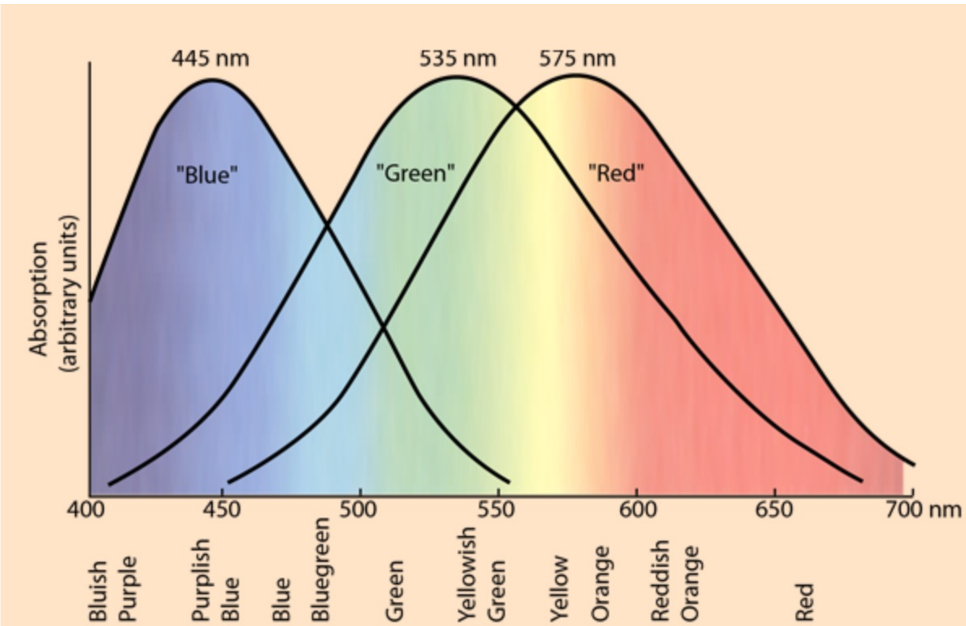
Which of these lamps is emitting the **higher frequency** electromagnetic radiation?



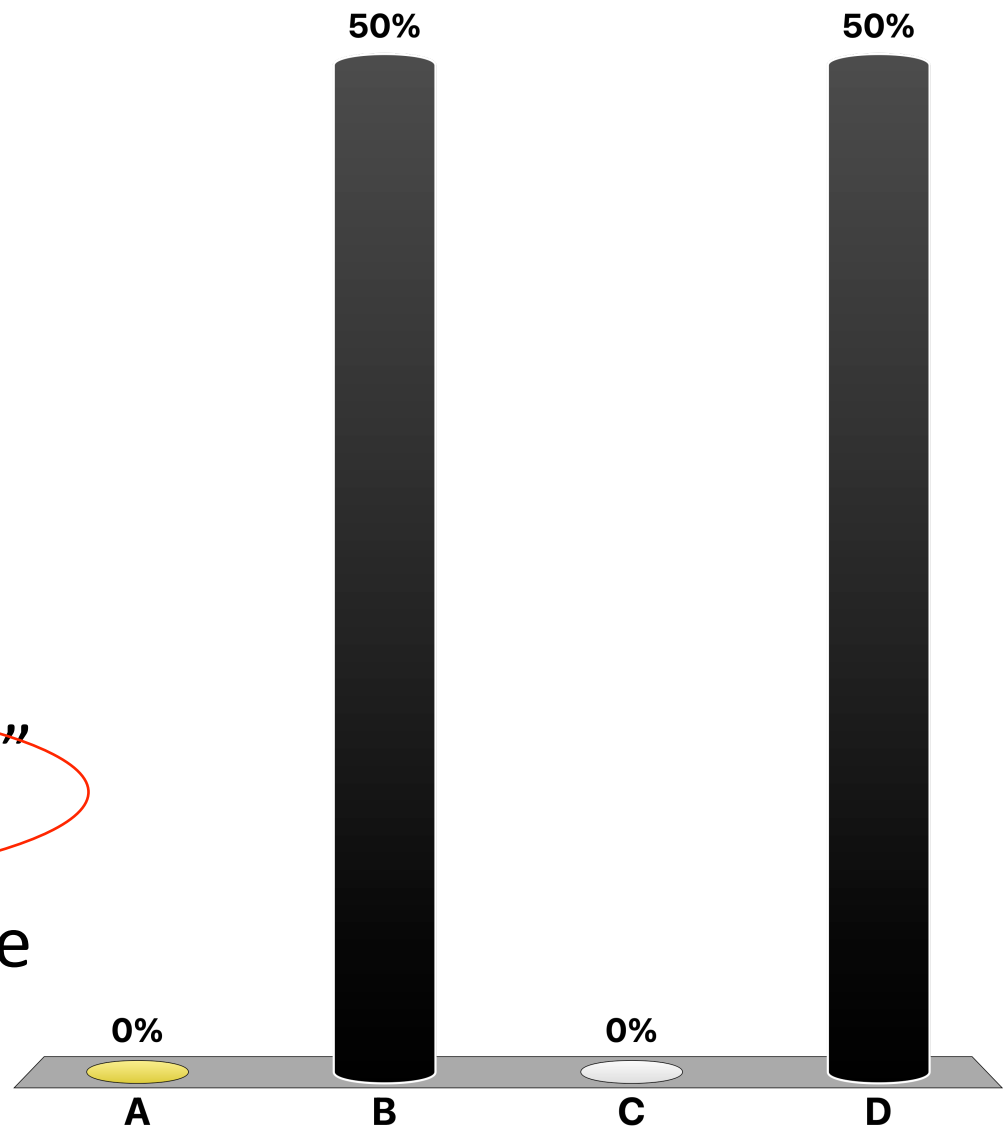
A. Lamp A.
B. Lamp B.
C. Both equal.



Given the light sensitivity of the 3 different types of cones, a light wave with λ = 580 nm will…



A. Excite all 3 cones
B. Excite the "green" and "red" cones
C. Excite only the "green" cone
D. Excite only the "red" cone



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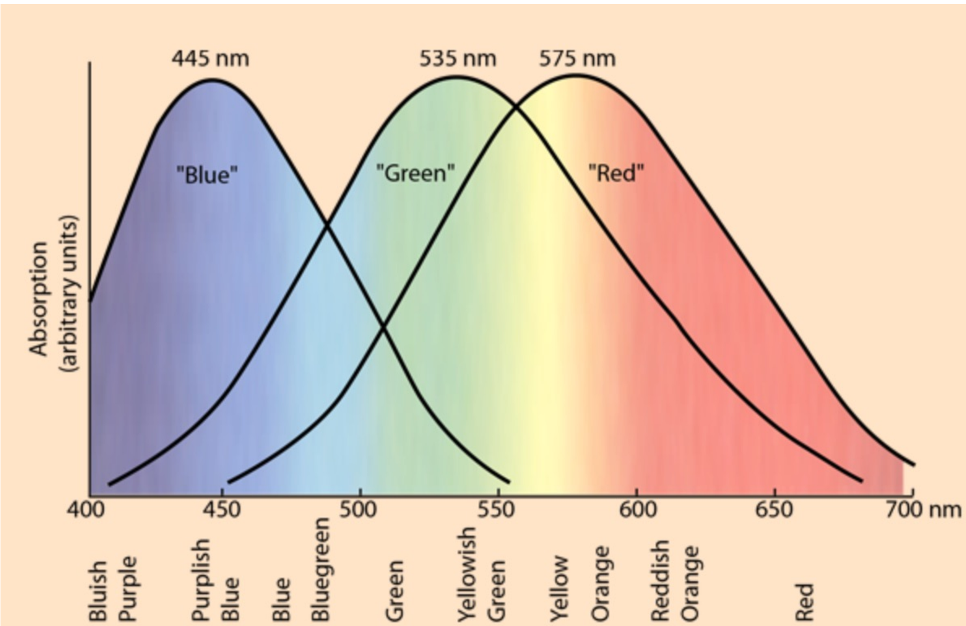

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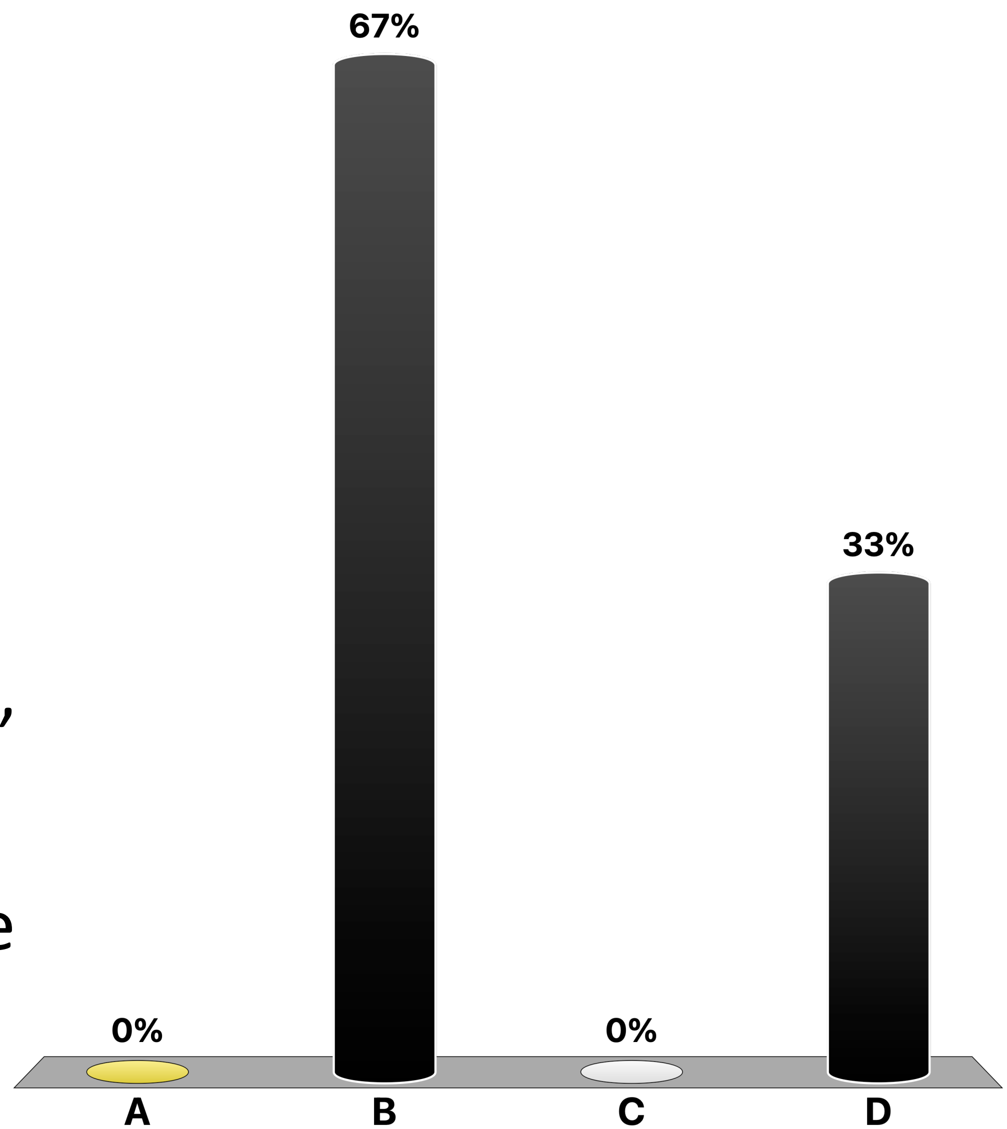

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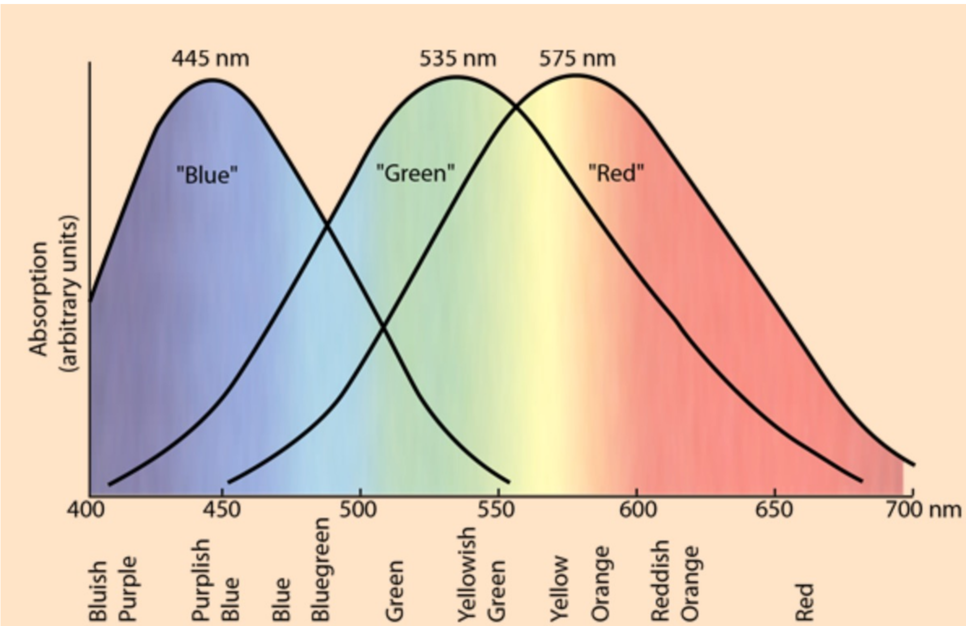

A. Look red
B. Look green
C. Look blue
D. Look yellowish-orange