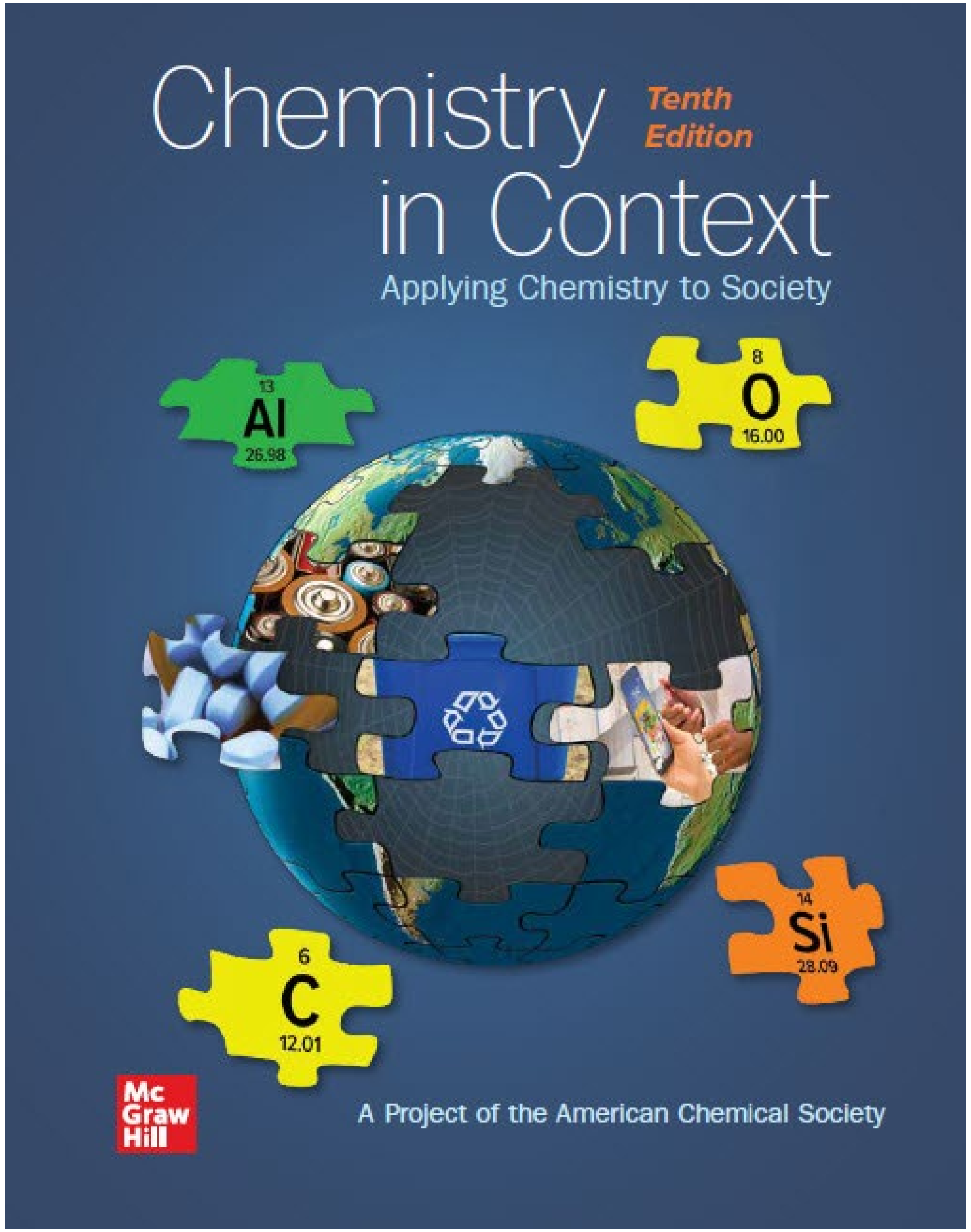
General Chemistry (CH101): Chemistry around Us

Department of Chemistry

KAIST

Chapter 03

Radiation from the Sun



Chapter 3
Radiation from the Sun

- What is sunlight and what are its properties?
- How do different types of radiation differ in energy?
- What is the link between sun exposure and skin cancer?
- How does Earth's atmosphere naturally protect us from the Sun?
- Can this source of natural protection be eliminated, and if so, can it be restored?
- How do sunscreens and sunblocks work?

Reflect

Protection from the sun

Watch the opening video. If you were outdoors on a sunny day. list the ways that you would protect yourself from sunlight. Rank them from what you think is most effective to least effective.

Chapter 3 video

https://www.acs.org/education/resources/undergraduate/chemistryincontext/interactives/radiation-from-sun/chapter-opening.html

Sun Damage

Your Turn 3.2 Sun Damage.

To get you started thinking about the Sun and the damage it can cause, discuss the following questions with a classmate:

a. What is emitted from the Sun?

b. Why do you think exposure to the Sun can cause damage?

c. What kinds of damage can the Sun cause?

d. What are some of the positive effects of the Sun?

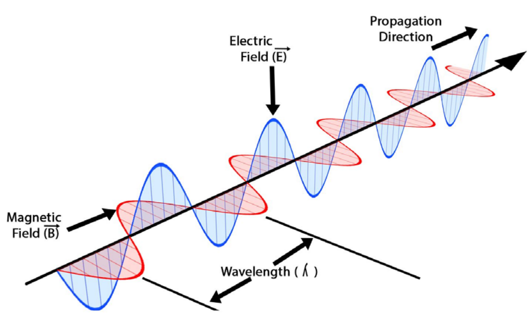
Dissecting the Sun: The Electromagnetic Spectrum

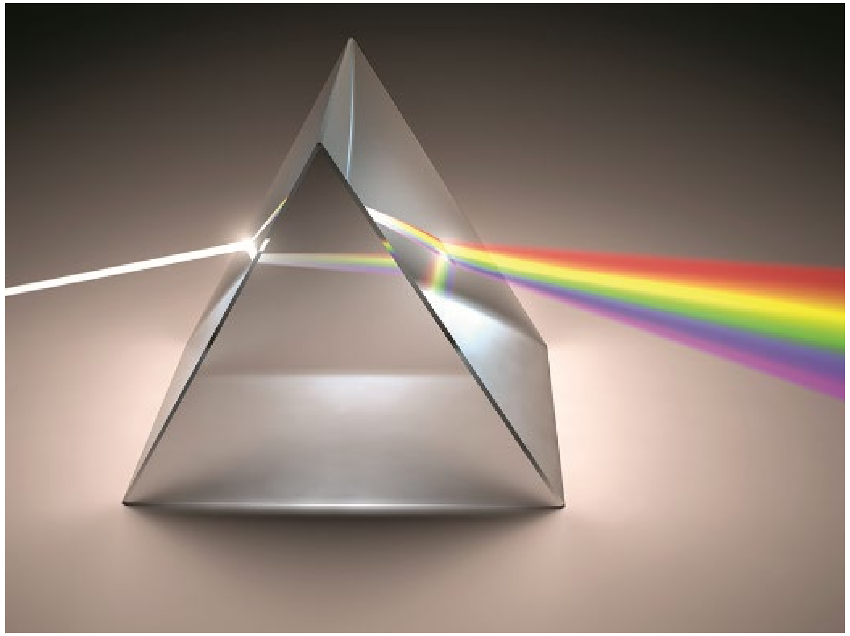
Electromagnetic radiation are waves composed of both electric and magnetic fields

This radiation may be visible or invisible

- Infrared light.
- Visible light.
- Ultraviolet light.
- Microwaves.
- Radio waves.
- X-rays.
- Gamma rays.

…



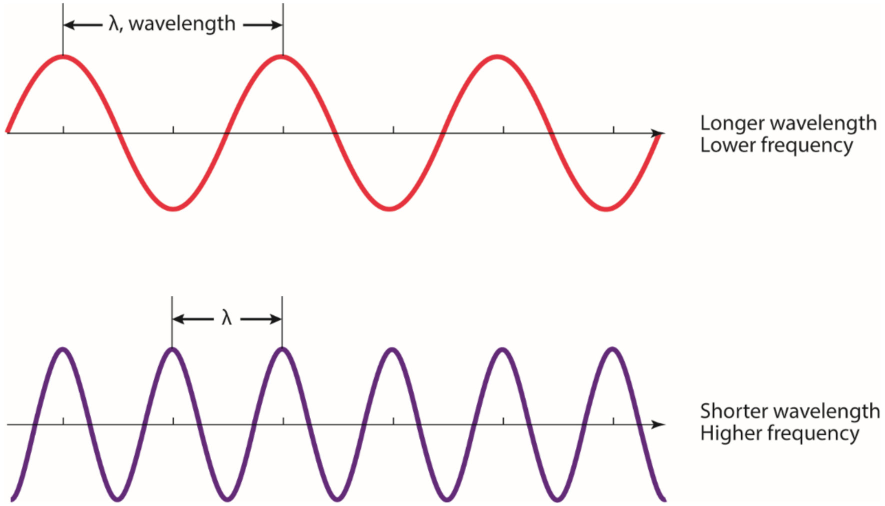


Properties of the Electromagnetic Spectrum 1

Wavelength (λ) is the distance traveled between successive peaks in the wave (distance: m, nm, etc.).

Frequency (ν) is the number of waves passing a fixed point in one second $\left(\text{oscillations per second}: \frac{1}{s}, s^{-1}, \text{or Hz}\right)$.

Wavelength and frequency are wave-like properties of light.

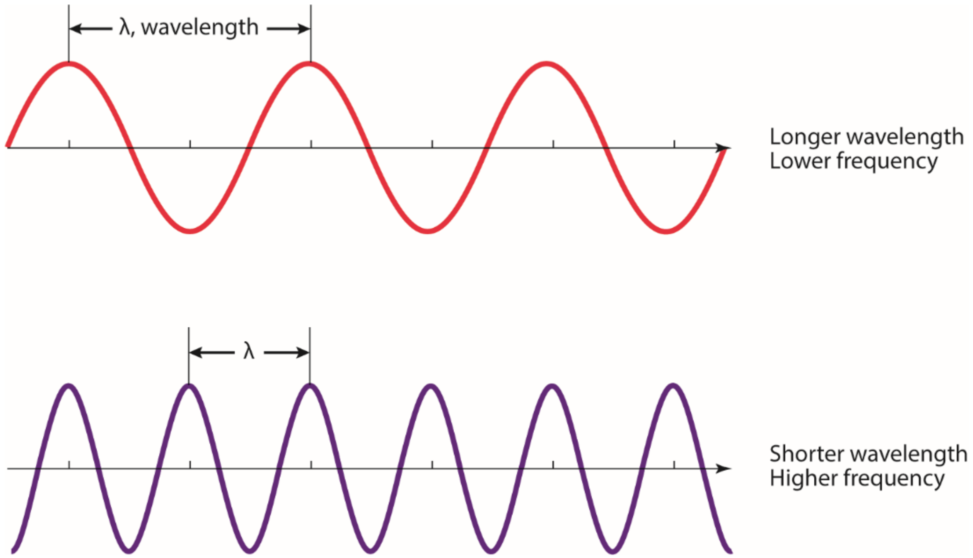


Properties of the Electromagnetic Spectrum

The **speed of light** is fixed within a given material
(for example, in air: $3.00 \times 10^{8}\,\mathrm{m/s}$)

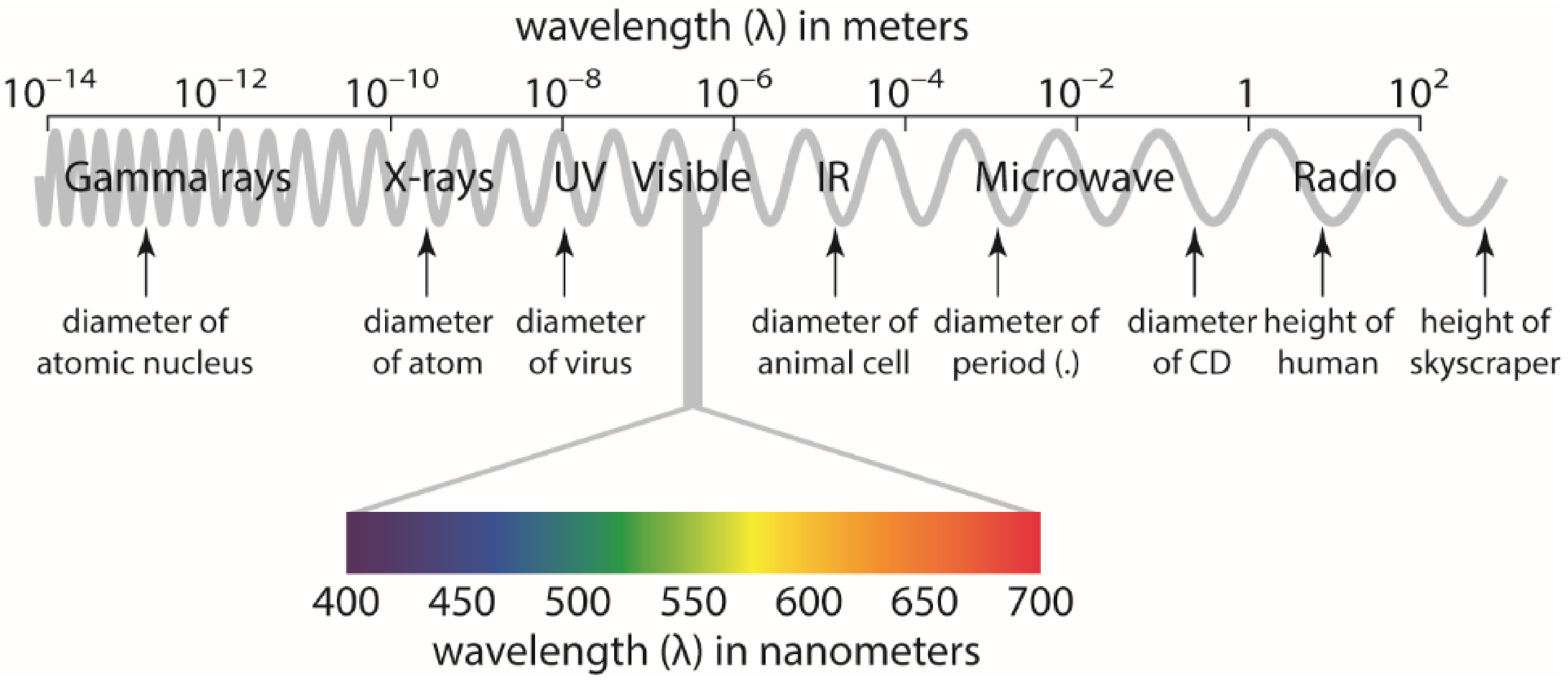
Wavelength and frequency are inversely proportional to each other, since the product of these two equals the speed of light:

$$c = \lambda v$$



The Electromagnetic Spectrum

The various types of radiation seem different to our senses, yet they *differ only in their respective* λ and v



Visualization

$$1\ \text{nm} = 1\times10^{-9}\ \text{m}$$

Your Turn 1

Your Turn 3.3 Wavelength and Frequency

Using Equation 3.1, answer the following questions:

a. What is the frequency (in Hz) of green light, with a wavelength of 525 nm?

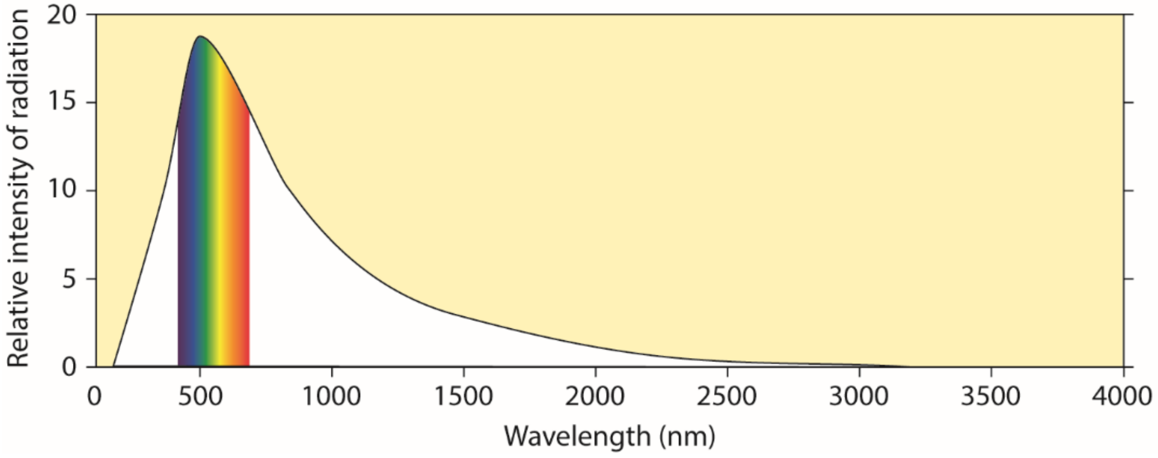
b. How many waves of green light would pass a fixed point in 1 minute? How about in 1 hour?

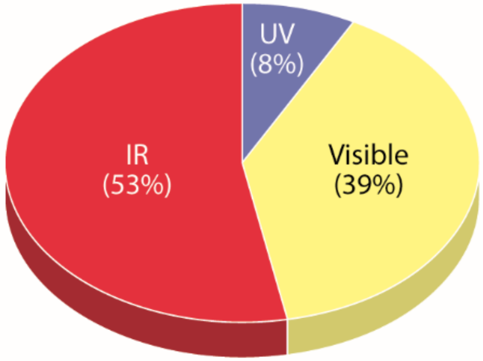
c. What is meant by the *amplitude* of a wave? Do changes in amplitude affect the wavelength or frequency of the wave? Explain.

Distribution of Energy from the Sun

Of the Sun's radiation reaching Earth, approximately 54% is infrared radiation, 39% is visible light, and 8% is ultraviolet.

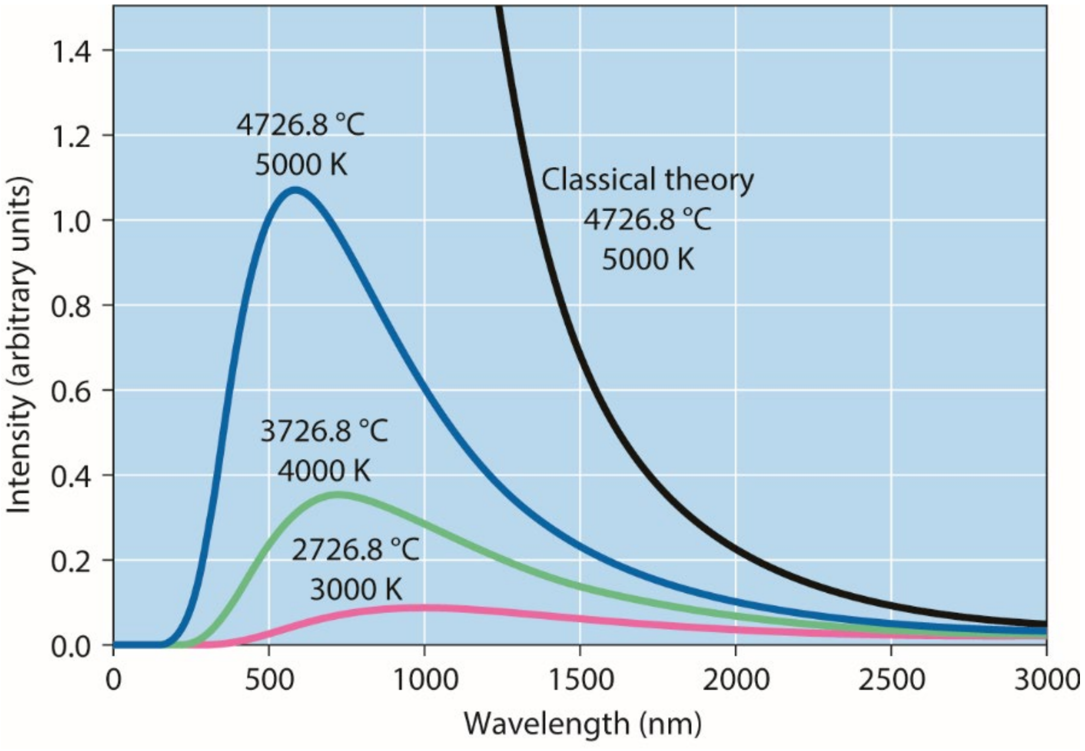
Human eyesight has evolved to see the more intense portion of the light emitted by the Sun.





Blackbody Radiation

- As an object is heated, it will glow.
- The color of the emitted light is related to the temperature.

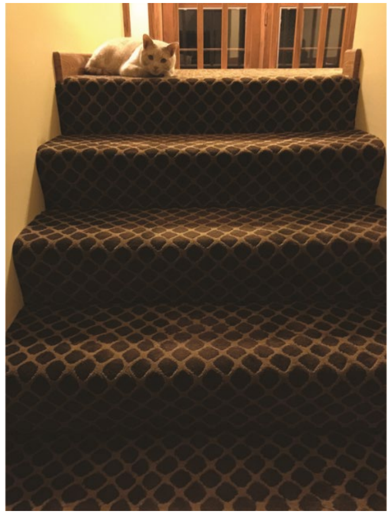


[The color temperature of lighting]

Wave-Particle Duality of Radiation

Radiation may be described as having both wave-like and particle-like properties.

- The energy of radiation is **quantized** with only certain values of energy being allowed rather than an energy continuum.
- The energy of radiation is related to its wavelength and frequency.
- $E = \frac{hc}{\lambda}$ or $E = h\nu$ where *h* is Planck's constant $= 6.626 \times 10^{-34}\ \text{J s}$

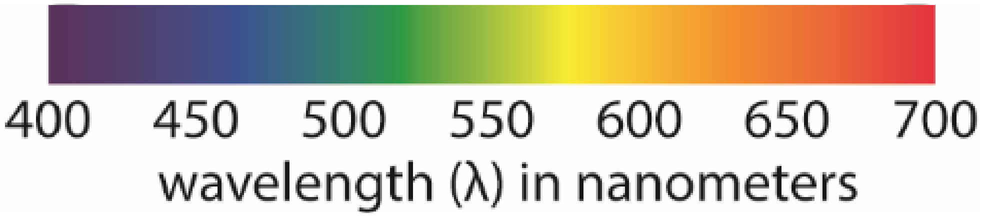


Your Turn 2

Your Turn 3.3 Wavelength, Frequency, and Energy

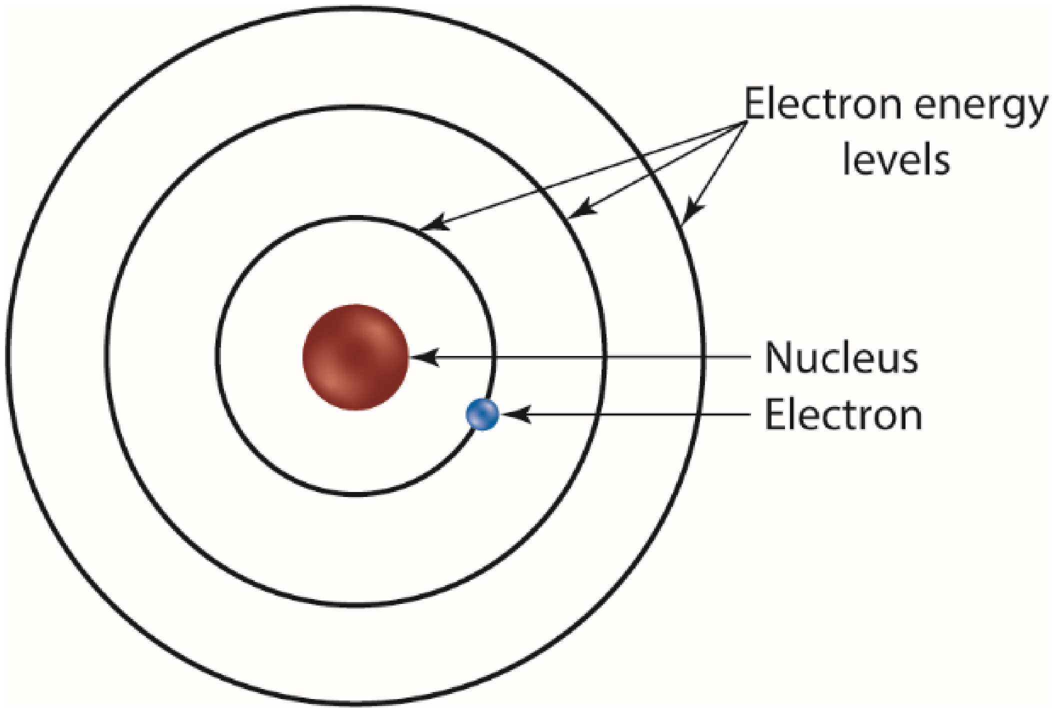
Return to Figure 3.4, and calculate the amount of energy present in a wave of red light and a wave of blue light. Do they have the same amount of energy? Why or why not?

In the not-too-distant past, many people used film exposure to take pictures. A “dark” room was a place where this film was developed into the actual images based on how light exposed the film during the taking of the pictures. These dark rooms used red lights during film development because a special dye was added to the film that was not affected by light with a wavelength between 620 and 750 nm. Do you think these rooms could have also used blue lights? Why or why not?



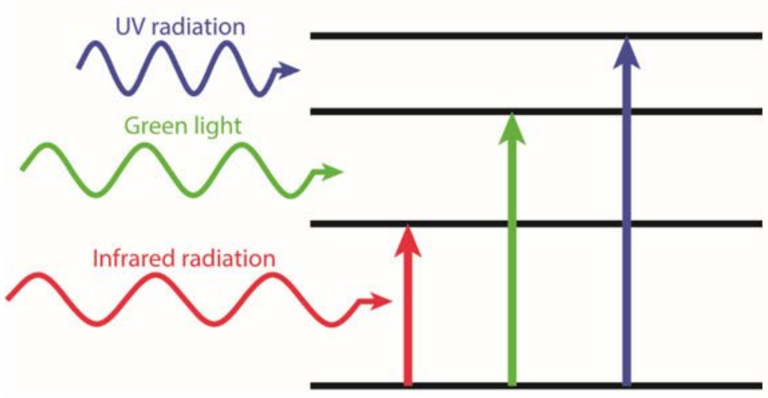
Electron Energy Levels

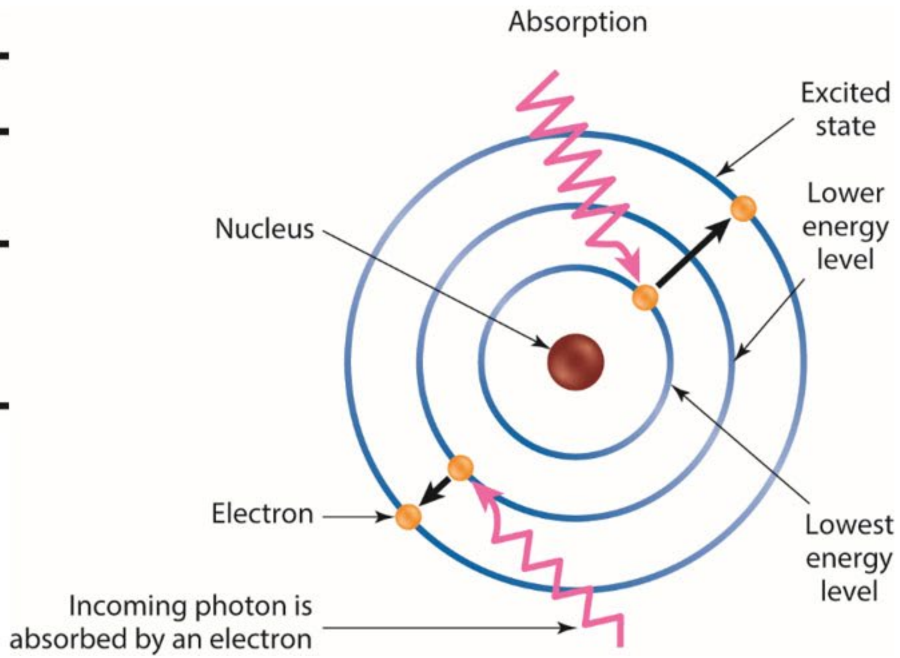
- Electrons in an atom reside in energy levels around the nucleus.
- Electrons that are closer to the nucleus have a lower energy than those further from the nucleus.



Electronic Energy Level Transitions

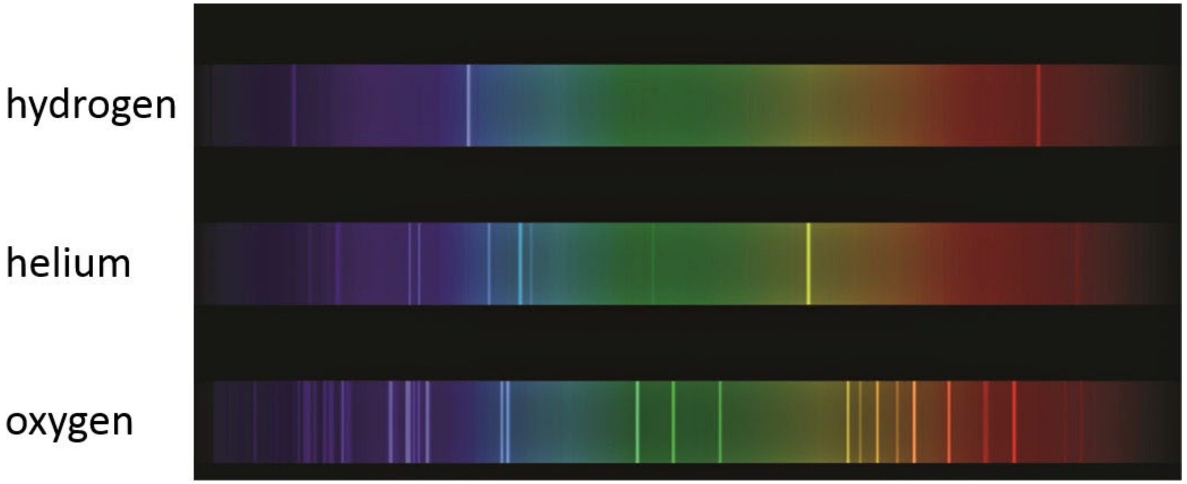
- Electrons can be moved from one level to higher level by absorbing light energy.
- Electrons moving from a higher level to a lower level emit light.

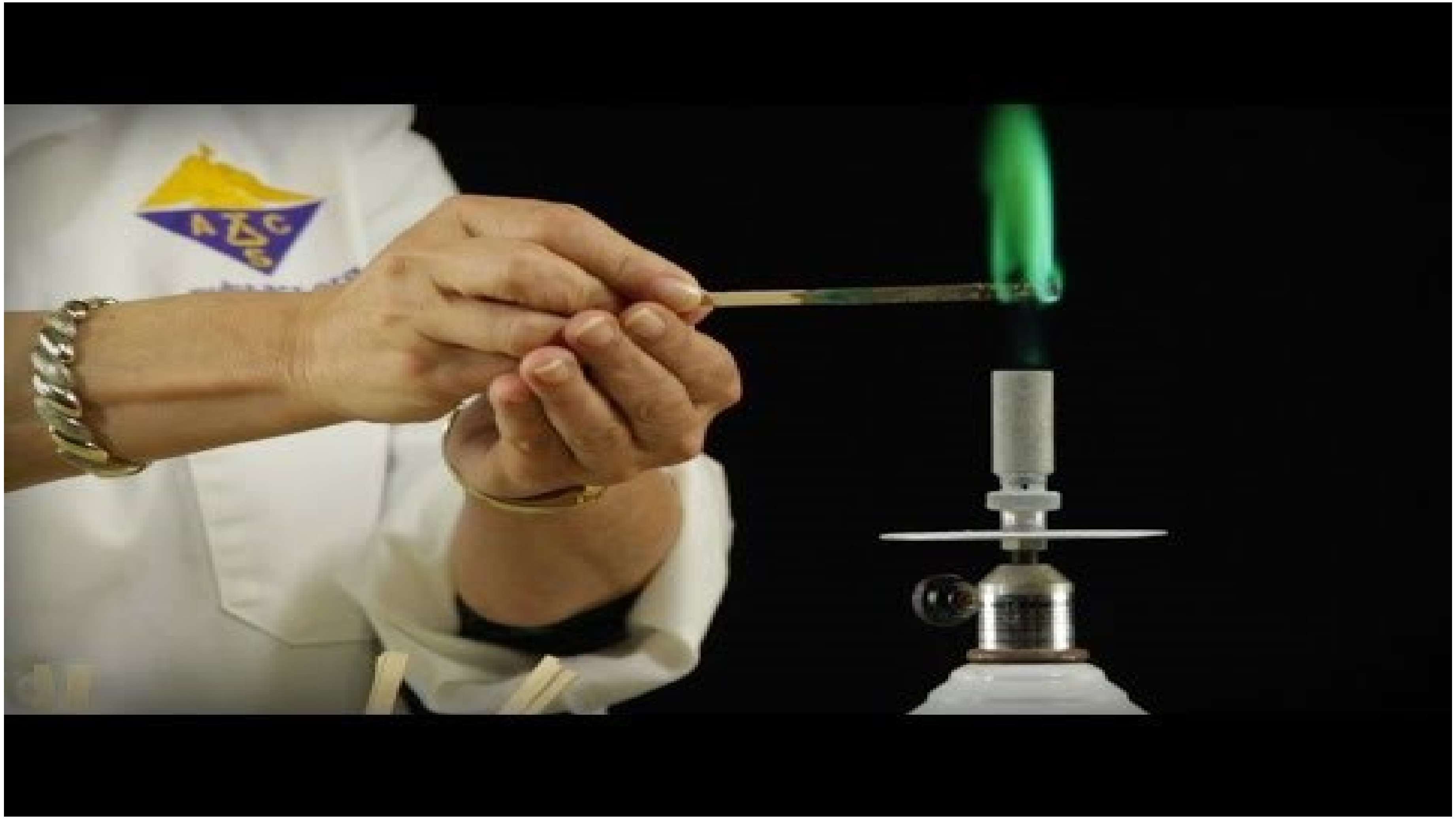




Line Spectra

- Different elements emit light at different energies due to differences in their electron energy levels.
- Since the energy levels of electrons are quantized, the light emitted appears as lines in an emission spectrum.





https://youtu.be/kkBFG1mTSBk

Your Turn

Your Turn 3.9 Fireworks!

A fireworks display is one of life's most pleasurable sensory experiences. The observed colors are related to the emission of light energy by various compounds that are burned in the flame.

a. Draw a simple energy diagram similar to that shown in Figure 3.11 that illustrates the electronic transition and region of the EM spectrum that would result in a yellow-colored flame.

b. What color would result from emission of a photon of energy with a wavelength of 522 nm?
Hint: Use Equation 3.3.

c. Perform an Internet search to determine the elements commonly found in green colored fireworks. What are some environmental hazards of compounds that contain these elements, and what alternatives have been proposed that are more environmentally friendly?

Types of Ultraviolet Light

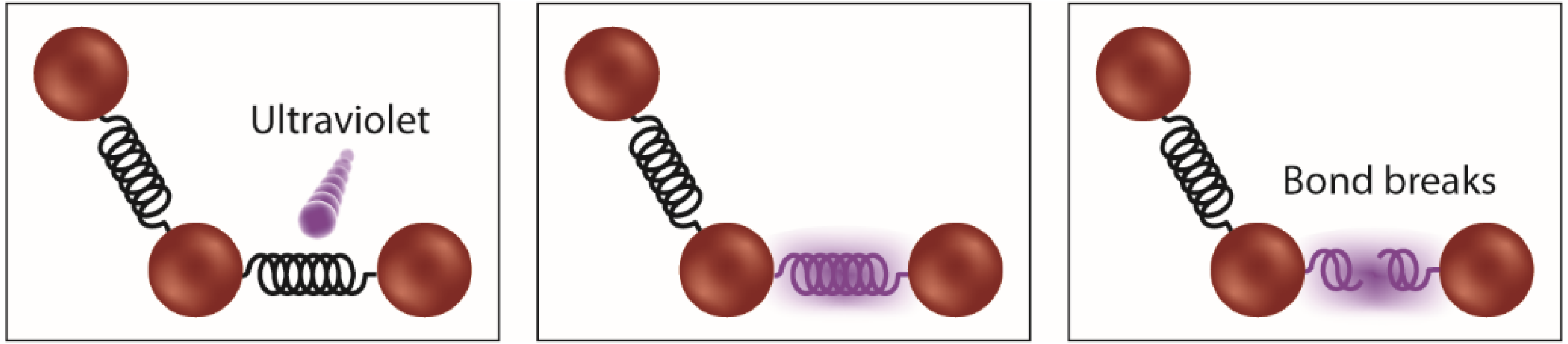
Table 3.1 Types of UV Radiation

Type	Wavelength	Relative Energy	Comments
UVA	320 to 400 nm	Lowest energy	Reaches Earth's surface in the greatest quantity and penetrates farthest into the skin.
UVB	280 to 320 nm	Medium energy	Most UVB is absorbed by ozone (O_3) in the stratosphere. UVB damages the outermost layer of skin.
UVC	200 to 280 nm	Highest energy	Although UVC radiation is very harmful, it is completely absorbed by O_2 and O_3 in the stratosphere.

Ultraviolet Radiation

UV radiation has enough energy to cause some molecular bonds to break.

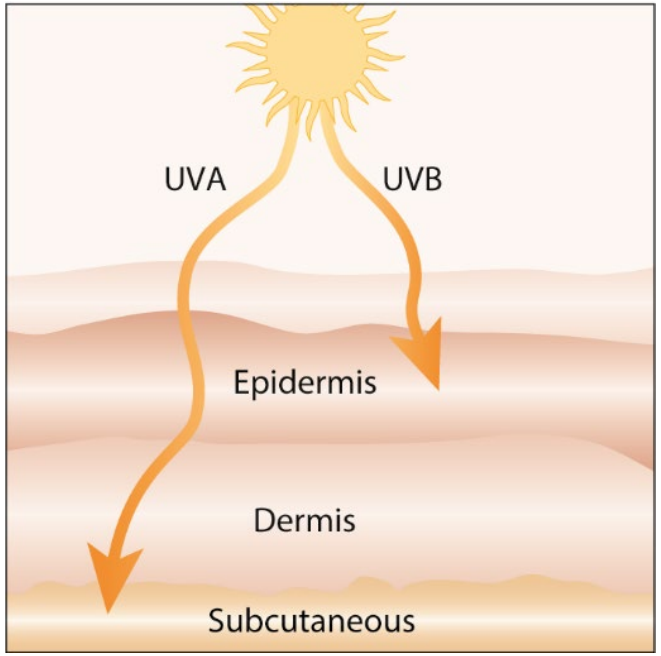
- Photons with wavelengths of < 242 nm (UVC) can break O_2 bonds.
- Photons with wavelengths of < 320 nm (UVB) can break apart O_3 bonds (ozone).



Skin Damage by Ultraviolet Light [1]

When UV radiation is absorbed by skin:

- Lower-energy UVA light removes electrons from molecules like water, creating free radicals and other reactive oxygen species.
- Higher energy UVB light causes some chemical bonds to break.
- DNA molecules are damaged by free radicals or UVB absorption.
- This results in the release of melanin or can cause skin cancer.



Source: U.S. Surgeon General's report, July 2014

Skin Damage by Ultraviolet Light

UVC radiation is highly energetic and is absorbed completely by oxygen molecules

- Causes oxygen-oxygen bonds to break.

UVB is partially absorbed in the stratosphere

- Some UVB reaches Earth's surface where it is rapidly absorbed at the surface of the skin.

UVA is not absorbed by the atmosphere

- Since it is not as energetic as UVB, it penetrates deeper into skin causing more damage to the underlying tissue.

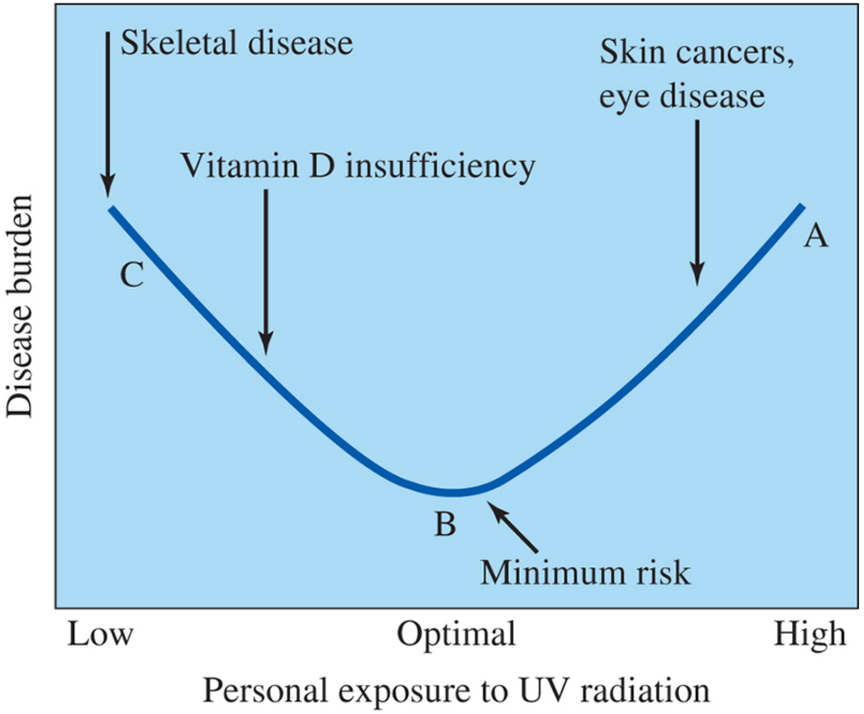
Are anti-aging creams legit?

https://youtu.be/2ueEEwg7bck?si=oBmDDI1CdPhaMqQ_

Quick write: Sunlight is composed of radiation across the electromagnetic spectrum. Why is it that sunscreen lotions typically only block UV radiation and not visible light or IR radiation?

https://youtu.be/z3RGwdJGzOo?si=IVwMaAAfBQ_L-nZm

Skin Cancer: The Facts



- Although some UV exposure is needed for production of Vitamin D, too much exposure leads to cancers and eye disease.
- Most skin cancers are linked to the exposure to sunlight.
- Skin cancer can appear at any age, but is more common in older people.
- Can develop many years after repeated, excessive exposure has stopped.
- UVA in sunlight at Earth's surface is most strongly linked with skin cancers, but UVB may also play a role.

Source: DOI: 10.5694/j.1326-5377.2002.tb04979.x

The UV Index

- A color-coded UV index scale is used to predict the risk of sunburn from overexposure to the sun.
- Important factors: ozone concentration in upper atmosphere, elevation, cloud cover.

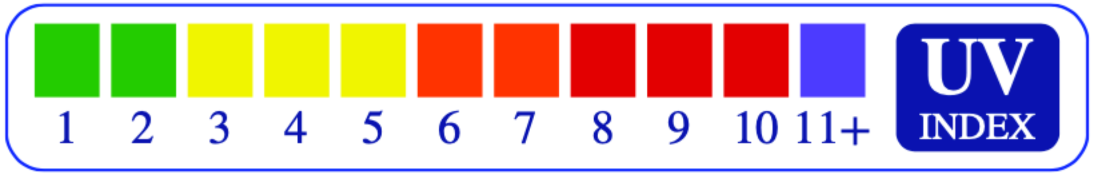
Table 3.2	Suggestions Based on the UV Index Scale	
Exposure Category	**Index**	**Tips to Avoid Harmful Exposure to UV**
LOW	0–2	If you burn easily, cover up and use sunscreen.
MODERATE	3–5	Stay in the shade when sunrays are strongest.
HIGH	6–7	Cover up, wear a hat and sunglasses, and use sunscreen. Reduce exposure between 10 AM and 4 PM.
VERY HIGH	8–10	Be especially careful if you are outside on sand, snow, or water, as these surfaces reflect UV, increasing your exposure. Minimize exposure between 10 AM and 4 PM.
EXTREME	11+	Take full precautions against sunburn. Unprotected skin can burn in minutes. Avoid the Sun between 10 AM and 4 PM.

DNA, the genetic material of living organisms, can be damaged by:

A. Free radicals generated by UVA absorption
B. UVB radiation
C. UVC radiation
D. Both A and B

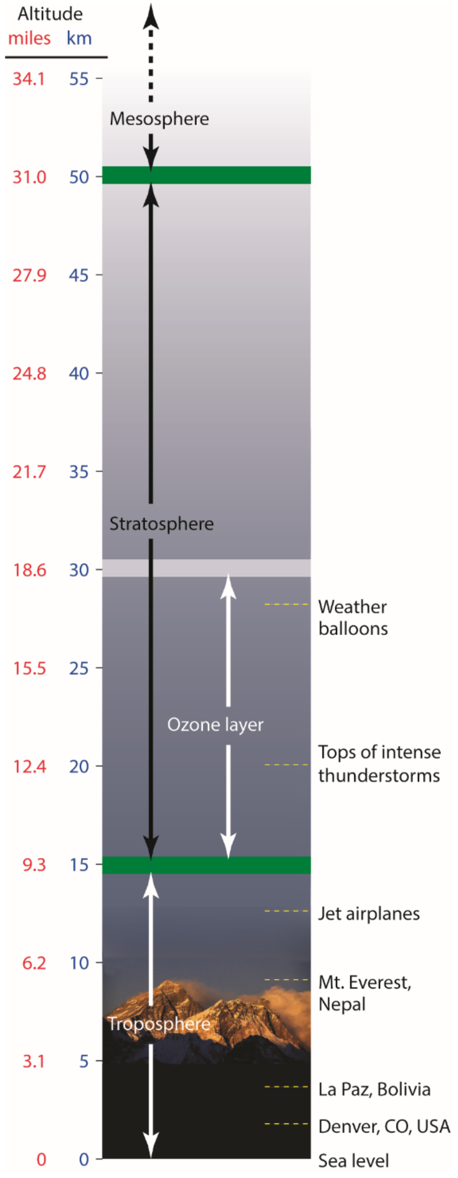
The morning newspaper reports a UV Index Forecast of 6.5. What precautions, if any should you take?

A. none
B. Only sunglasses and a hat are recommended
C. Reduce exposure between 10 a.m. and 4 p.m. in addition, cover-up and where SPF 15+ sunscreen.
D. All precautions must be taken; this is an extreme UV day.



The Regions of the Atmosphere

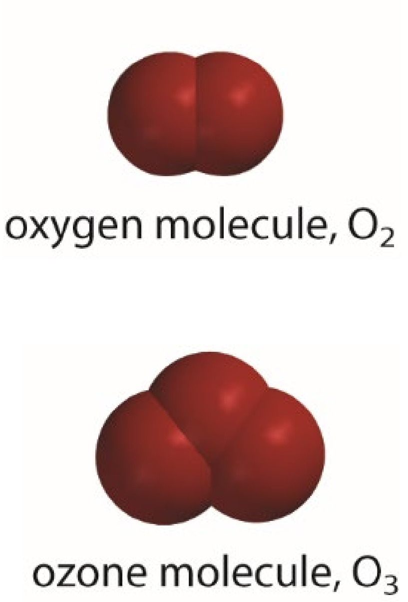
- Atmospheric pressure decreases with increasing altitude.
- There are fewer air molecules at higher elevations.
- It is harder to breathe … headaches, more easily tired.
- Water boils at a lower temperature.

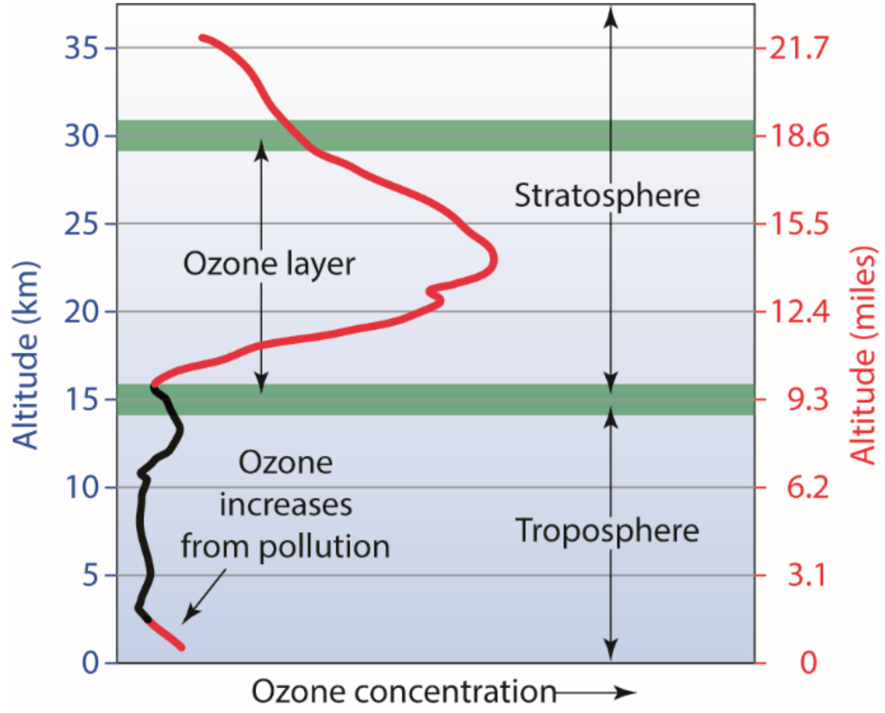


The Ozone Layer

The ozone layer is a region in the stratosphere with maximum ozone concentration

- Concentration in layer is : $12,000$ ppb, compared to 20 to 100 ppb in troposphere.





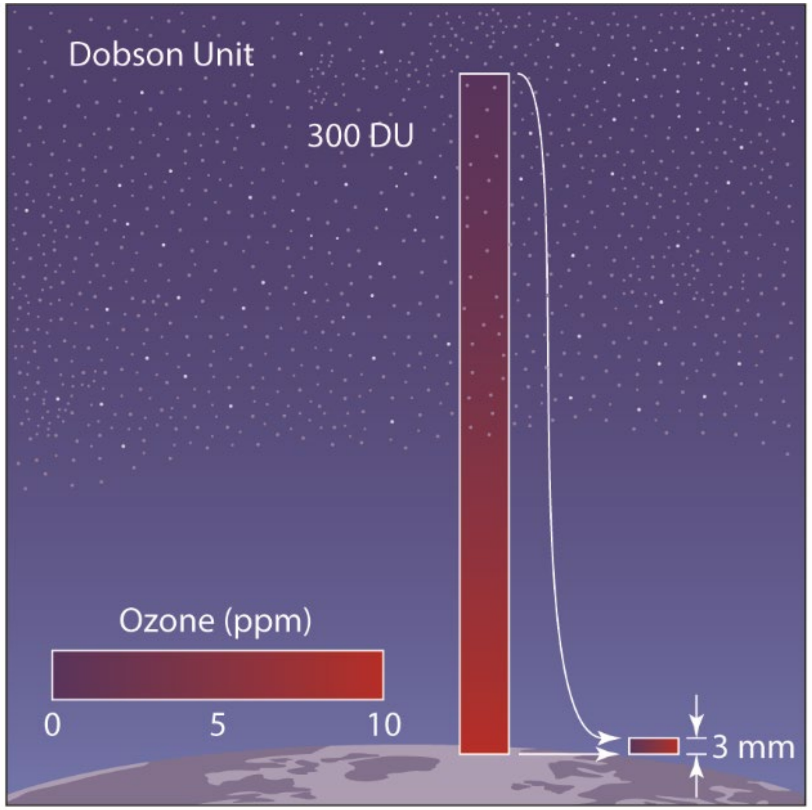
https://www.acs.org/education/resources/undergraduate/chemistryincontext/interactives/radiation-from-sun/ozone-in-atmosphere.html

How is Ozone Concentration Measured?

GMB Dobson (1889-1975)

By measuring the amount of UV radiation reaching a detector on Earth's surface

An ozone concentration of 300 Dobson units (DU) corresponds to compressing the ozone at 0°C to form a 3 mm thick slab of ozone with a pressure of 1 atm.



Arrangement of Electrons: Valence Electrons

- Only a limited number of electrons can reside in the energy levels around the nucleus.
- The electrons in the outermost energy level are called **valence electrons**.
- The group number (for example, Group 13) of the element on the periodic table indicates the number of valence electrons in an atom of that element.

Reactivity and Electrons

Atoms react in order to completely fill a shell of electrons

- To meet the “octet rule” of a stable set of eight valence electrons.
- Electrons are shared between two atoms as a **covalent bond**, which are found in molecular compounds.

$$\mathbf{H - H}$$

- Electrons are transferred from one atom to another to form an **ionic bond**, as found in ionic compounds.

$$\mathbf{Na^{+}Cl^{-}}$$

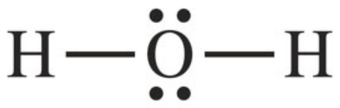
Lewis Structures are representations of molecules that demonstrate sharing of electrons

How to Draw Lewis Structures

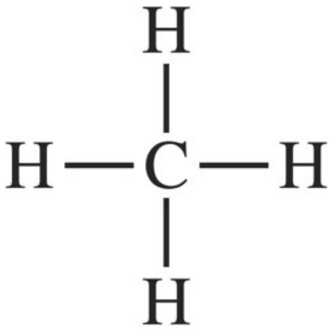
1. Count the number of valence electrons contributed by each atom in the molecule.
2. Add the valence electrons contributed by individual atoms to obtain the total number of valence electrons.
3. Arrange the atoms: place atoms closest to left-bottom of periodic table in the middle, arrange others on outside (H always on outside).
4. Place electrons as pairs of dots on atoms until meet the octet rule.
    - Start on outside atoms first.
    - H only needs 2 electrons.
5. <u>If necessary</u>, form double bonds to meet the octet rule <u>only after</u> all electrons are assigned.

Lewis Structure Examples

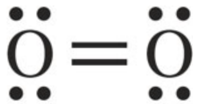
Covalent bonds are usually drawn with lines that represent a pair of shared valence electrons.



H_2O



CH_4



O_2

N_2

Your Turn

Your Turn 3.20 More Lewis Structures

Draw the Lewis structure for each of these molecules.

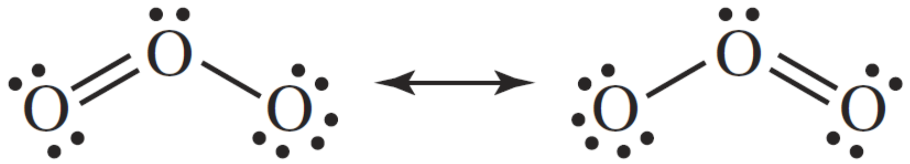
a. hydrogen sulfide (H_2S).

b. dichlorodifluoromethane (CCl_2F_2).

Lewis Structure of Ozone

Some molecules, like ozone, can be drawn with two equivalent Lewis structures, called **resonance structures**.

- Bond lengths decrease from single, to double, to triple bonds.
- Bond strength increases from single, to double, to triple bonds.
- For ozone, the actual oxygen-oxygen bonds have properties between that of a single and double bond (only one type of bond is actually present!).



Your Turn 5

Your Turn 3.21 Lewis Structures with Multiple Bonds

Draw the Lewis structure for each compound. Indicate resonance forms, if appropriate.

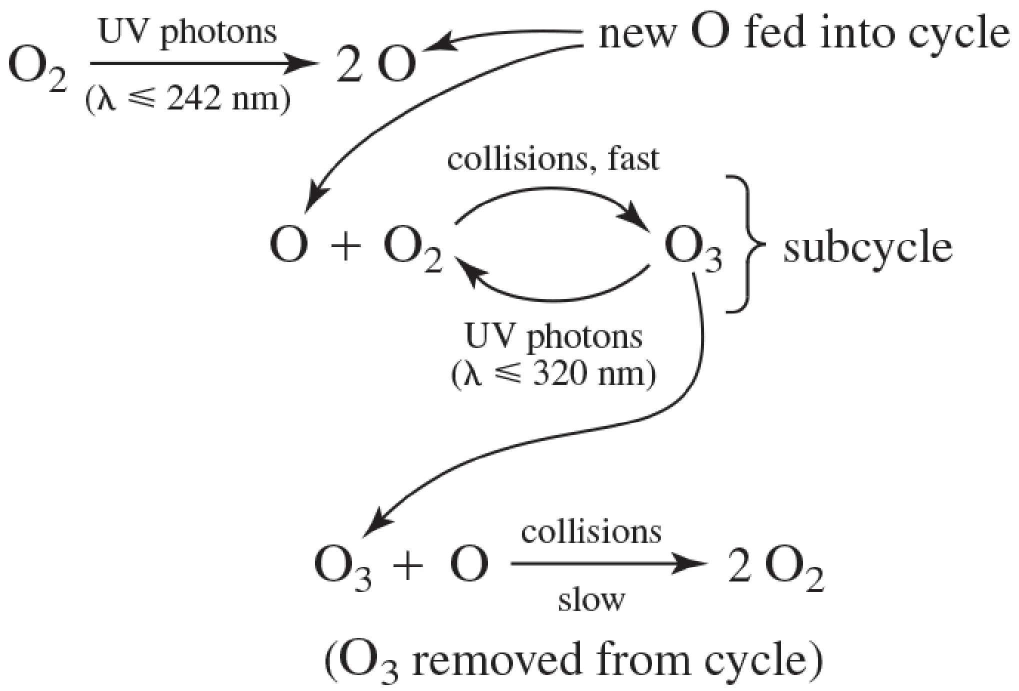
a. carbon monoxide (CO).

b. sulfur dioxide (SO_2).

c. sulfur trioxide (SO_3).

The Chapman Cycle

- Set of reactions that occur naturally in the upper atmosphere results in a ***steady-state*** concentration of ozone in the stratosphere.

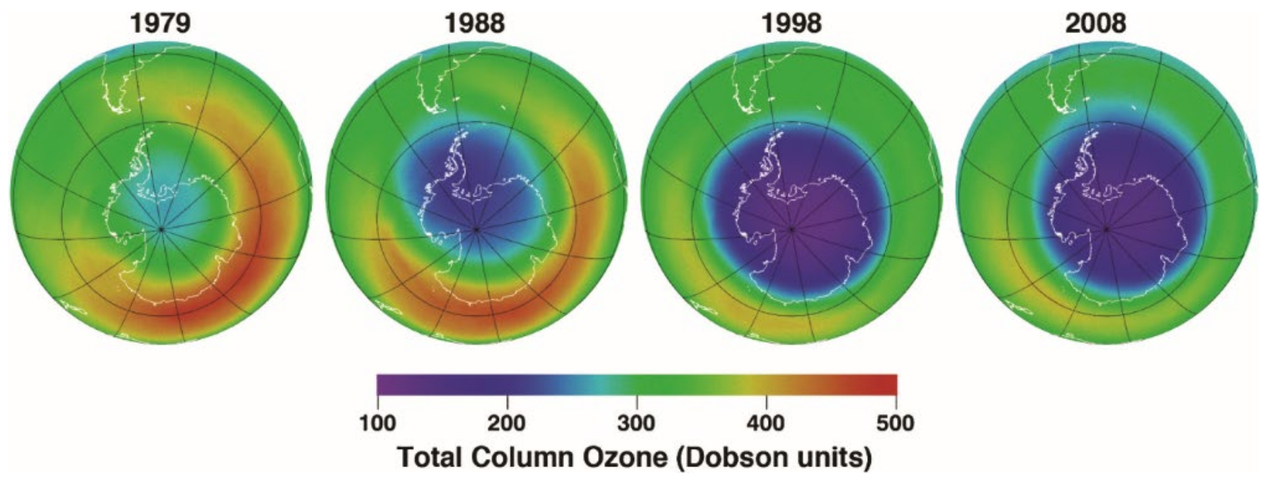


- UV light break bonds in both O_2 and O_3, but higher energy light is required to break the double bonds in O_2.

How Safe is Our Protective Ozone Layer?

The ozone layer provides a natural source of protection against harmful UVB radiation

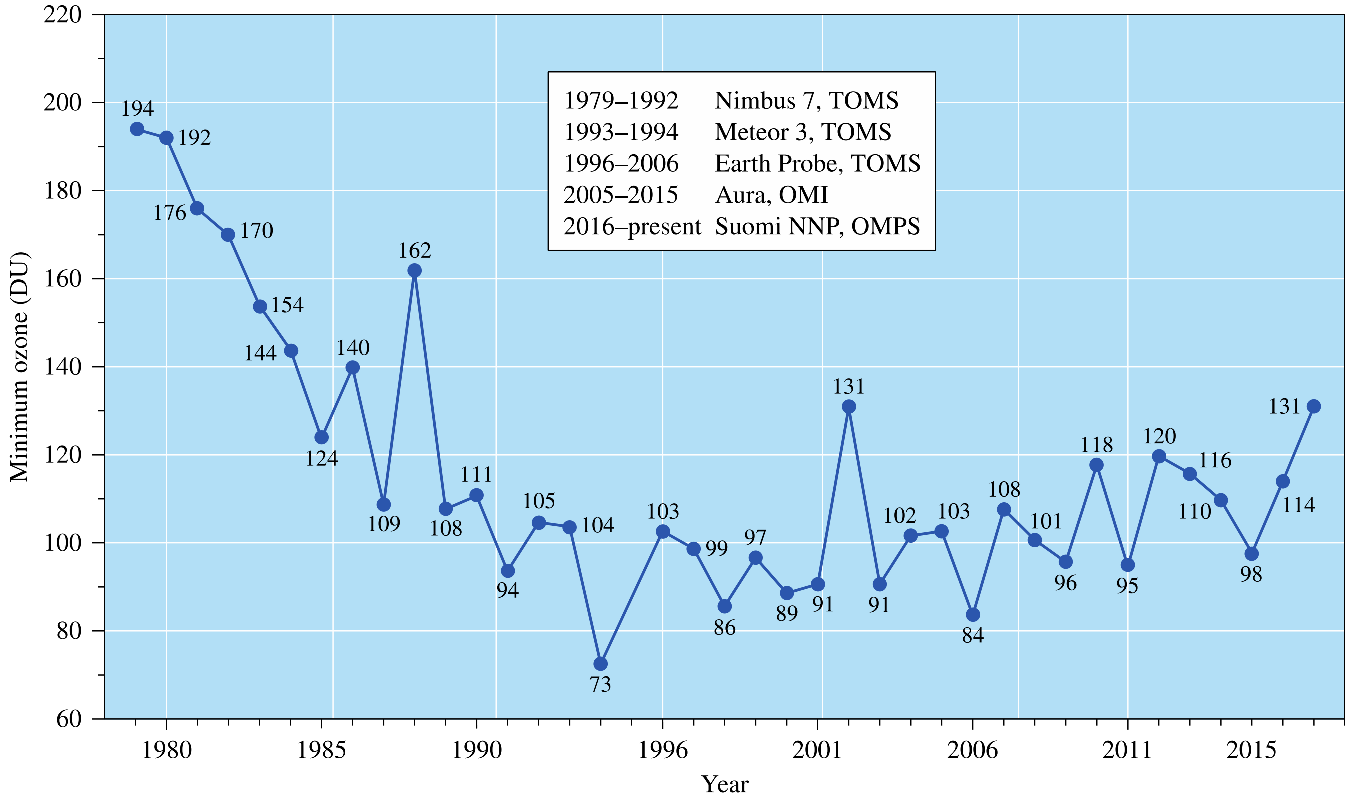
- Ozone can be naturally destroyed by dissociation of water molecules into free radicals (atoms or molecules with unpaired electrons: $H\cdot$ and $\cdot OH$).
- But data suggested that something beyond natural sources was responsible for destroying atmospheric ozone.



Source: NASA Ozone Watch

Antarctica Ozone Concentration

The concentration of ozone has decreased dramatically since 1989, but varies by year (min. conc. was 73 DU in 1994).



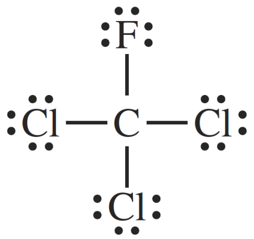
Source: NASA Ozone Watch

https://youtu.be/PT38gaGciP4?si=6sYe8ZSd-qMWwoRL

Chemistry to the Rescue or Detriment? [1]

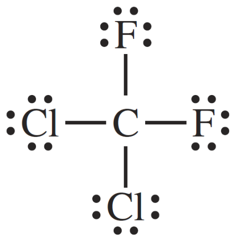
CFCs are nontoxic, nonflammable, inexpensive and widely available

- Revolutionized the air conditioning and refrigeration industries.
- Previously used gases such as ammonia, sulfur dioxide, and methyl chloride.



CCl_3F
trichlorofluoromethane
Freon-11

and



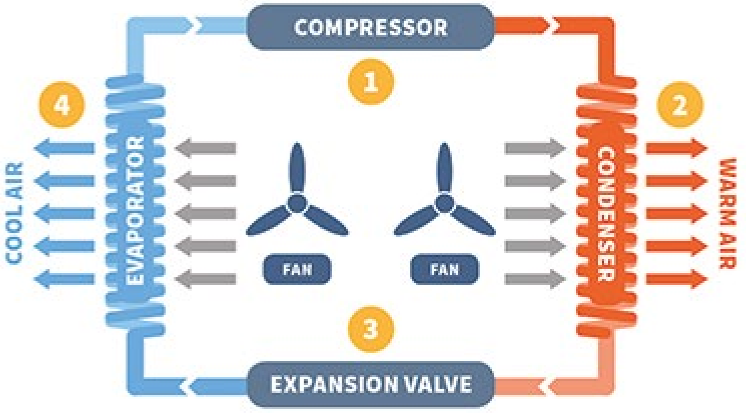
CCl_2F_2
dichlorodifluoromethane
Freon-12

[How Air Conditioning Works]

[Periodic graphics: The chemistry of air-conditioning]

THE CHEMISTRY OF AIR-CONDITIONING

Air-conditioning units can help you beat the heat on a hot summer day. Here, we take a look at how these systems work and the changing refrigerant compounds that help the units blast cool air.



1. In the compressor, refrigerant vapor gets pressurized, which also increases its temperature.
2. The hot, high-pressure vapor moves through condenser coils and loses heat, which gets vented outside by fans.
3. The refrigerant, now a liquid, is forced through an expansion valve. This turns the liquid into a mist and rapidly cools it.
4. The cold mist travels through evaporator coils. Air blown over the coils gets cooled. Heat from the air vaporizes the refrigerant.

CURRENT REFRIGERANTS

Chlorofluorocarbons (CFCs) were discovered in 1928 and replaced more toxic refrigerants such as ammonia, methyl chloride, and propane.

CFCs → Cl F C

HCFCs → Cl F C H

HFCs → F C H

In the upper atmosphere, ultraviolet radiation triggers reactions with CFCs that produce chlorine atoms, which destroy ozone. A 1987 international agreement, the Montreal protocol, required CFC production to stop. Hydrochlorofluorocarbons (HCFCs), used as CFC replacements, will be phased out in coming years.

Hydrofluorocarbons (HFCs) have replaced CFCs and HCFCs. These replacements do not contain chlorine atoms, so they pose no harm to the ozone layer.

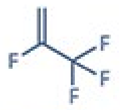
CFC-12	HCFC-22	HFC-23
ODP = 1.0	ODP = 0.05	ODP = 0
GWP = 10,900	GWP = 1,810	GWP = 14,800

ODP = ozone depletion potential (scale 0–1.0)
GWP = global warming potential (CO_2 = 1)

HFCs have a higher global warming potential than CFCs and HCFCs. As a result, a 2016 amendment to the Montreal protocol plans a phaseout of HFCs.

THE NEXT GENERATION

Hydrofluoroolefin (HFO) refrigerants could replace HFCs. They have a lower global warming potential, but they are also more expensive.

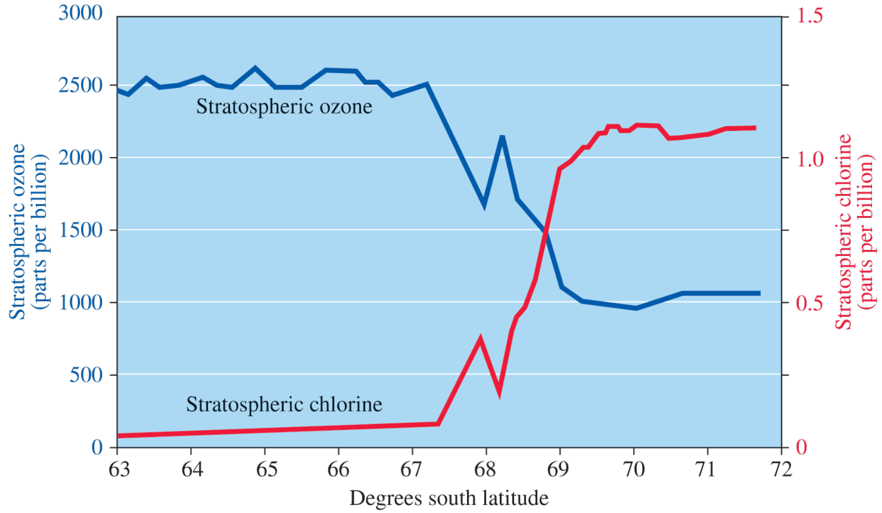


O=C=O

HFO-1234yf	CO_2
ODP = 0	ODP = 0
GWP = 4	GWP = 1

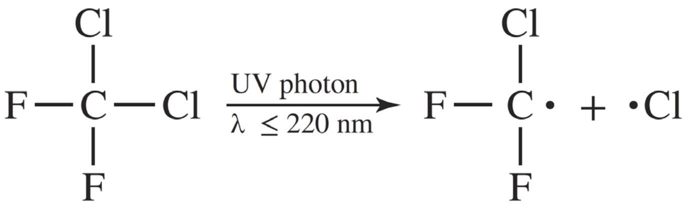
Some car air-conditioning units use HFO-1234yf. But scientists are concerned that it is flammable, so some manufacturers are using carbon dioxide instead. Some experimental systems in development do not use any refrigerant gases to cool air.

Chemistry to the Rescue or Detriment? 2



Although CFCs are inert (unreactive), they do react when exposed to UVC radiation in the upper atmosphere

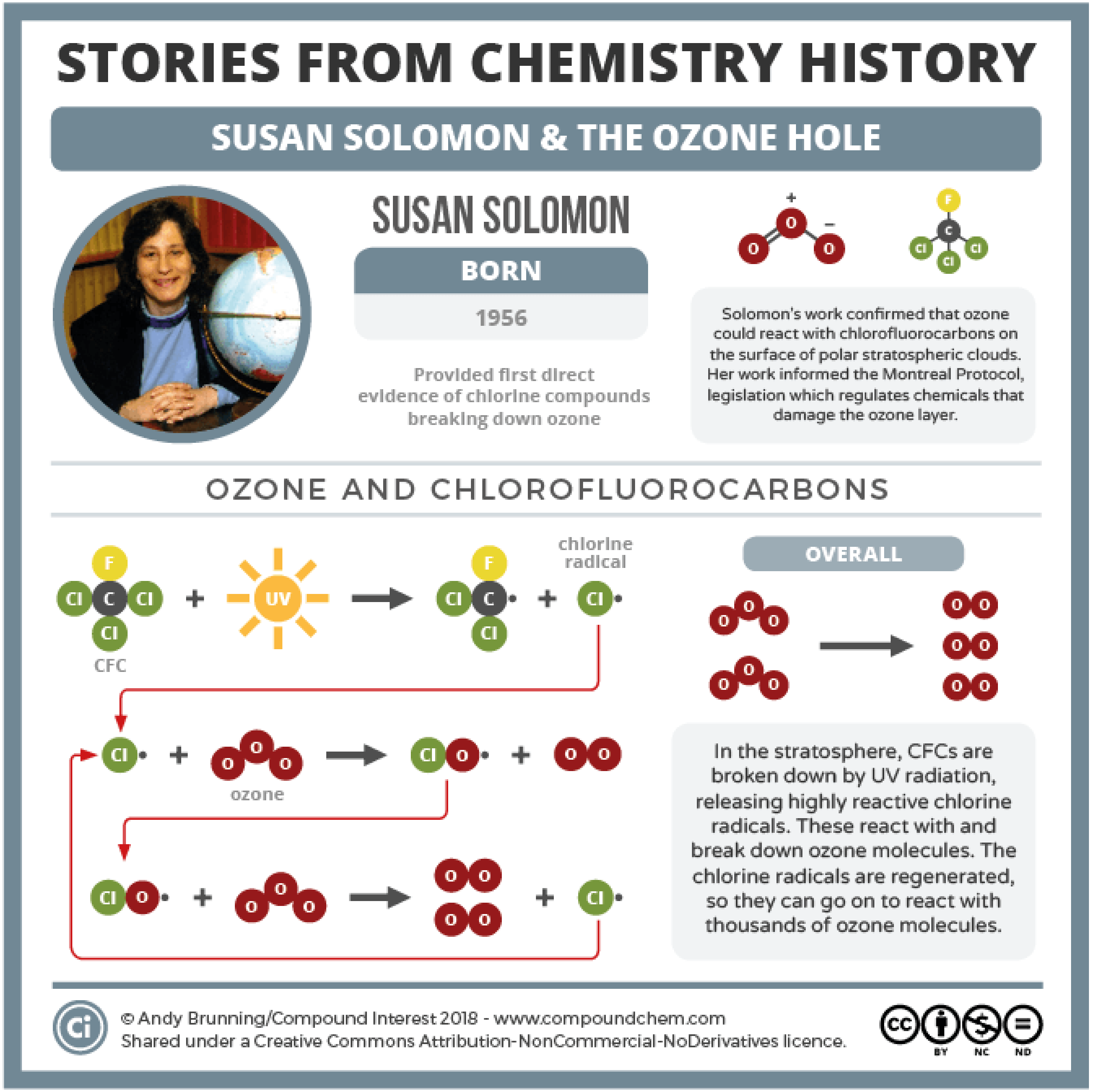
- The resulting atomic chlorine results in ozone destruction through a series of reactions.
- Chlorine is used in an early reaction, then regenerated later: acts as a catalyst.



$$Cl\cdot + O_3 \longrightarrow ClO\cdot + O_2$$

$$ClO\cdot + O \longrightarrow Cl\cdot + O_2$$

[Today in Chemistry History]


STORIES FROM CHEMISTRY HISTORY
SUSAN SOLOMON & THE OZONE HOLE
SUSAN SOLOMON
BORN
1956
Provided first direct evidence of chlorine compounds breaking down ozone
Solomon's work confirmed that ozone could react with chlorofluorocarbons on the surface of polar stratospheric clouds. Her work informed the Montreal Protocol, legislation which regulates chemicals that damage the ozone layer.
OZONE AND CHLOROFLUOROCARBONS
CFC
UV
chlorine radical
ozone
OVERALL
In the stratosphere, CFCs are broken down by UV radiation, releasing highly reactive chlorine radicals. These react with and break down ozone molecules. The chlorine radicals are regenerated, so they can go on to react with thousands of ozone molecules.
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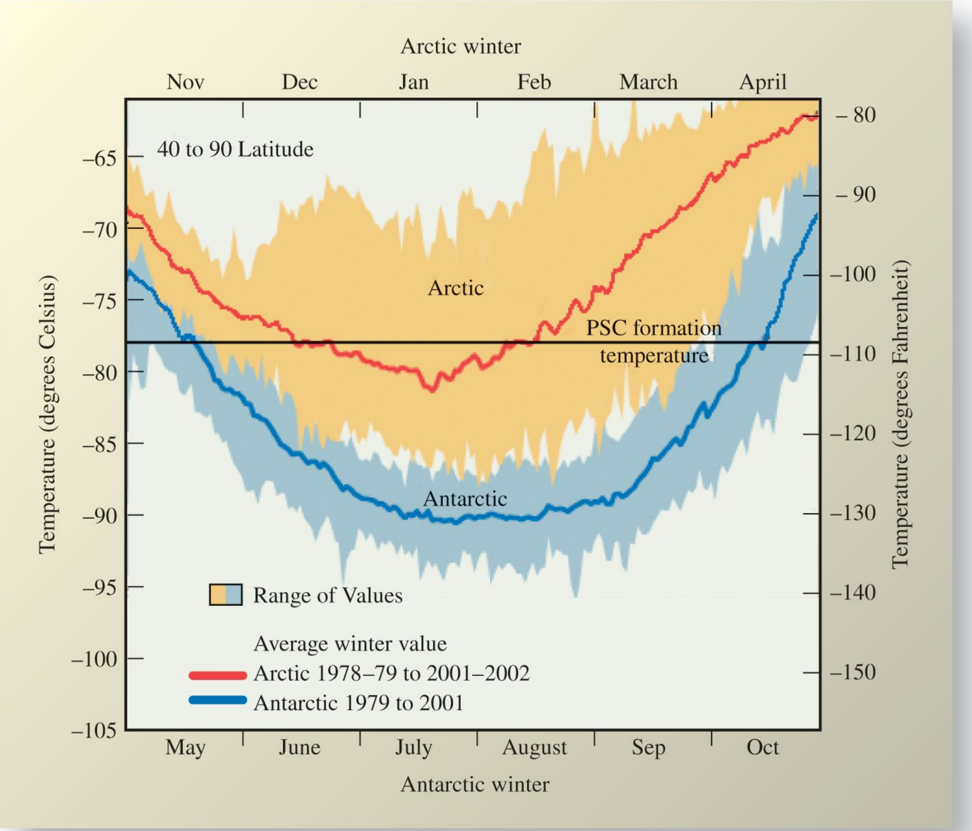
Catalytic!

https://youtu.be/PX7TIqAJRSY?si=7ltLO-m8EAJTg6Xw

The Ozone Hole: Why Over Antarctica?

The lower stratosphere over the South Pole is the coldest spot on Earth

- This creates polar stratospheric clouds (PSAs) which help support chemical reactions that produce active chlorine that catalyzes ozone destruction.
- Results in seasonal variation in ozone hole.



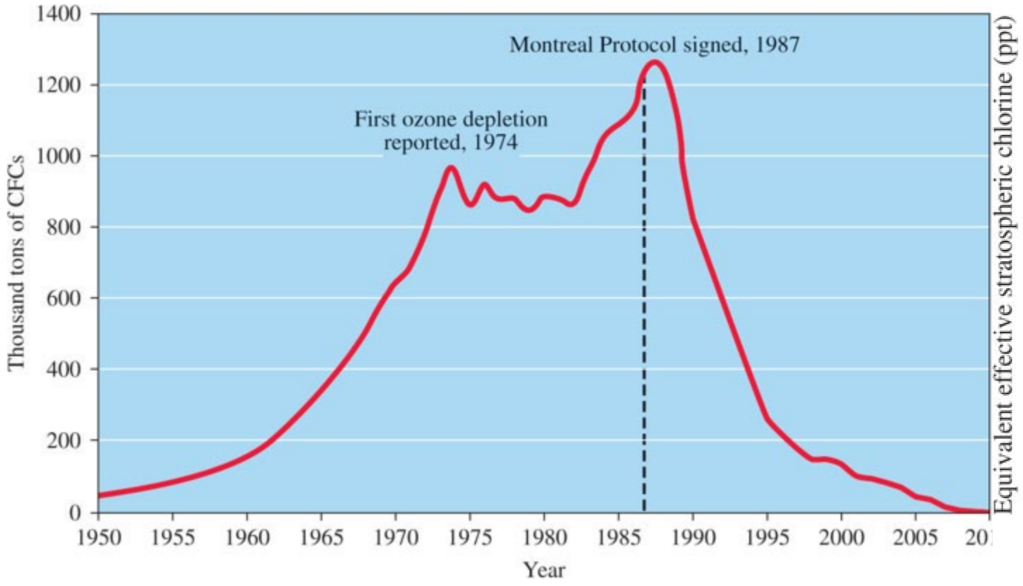
[Time-lapse satellite video of the ozone levels over Antarctica]

Source: Scientific Assessment of Ozone Depletion, 2002, World Meterological Organization (UNEP)

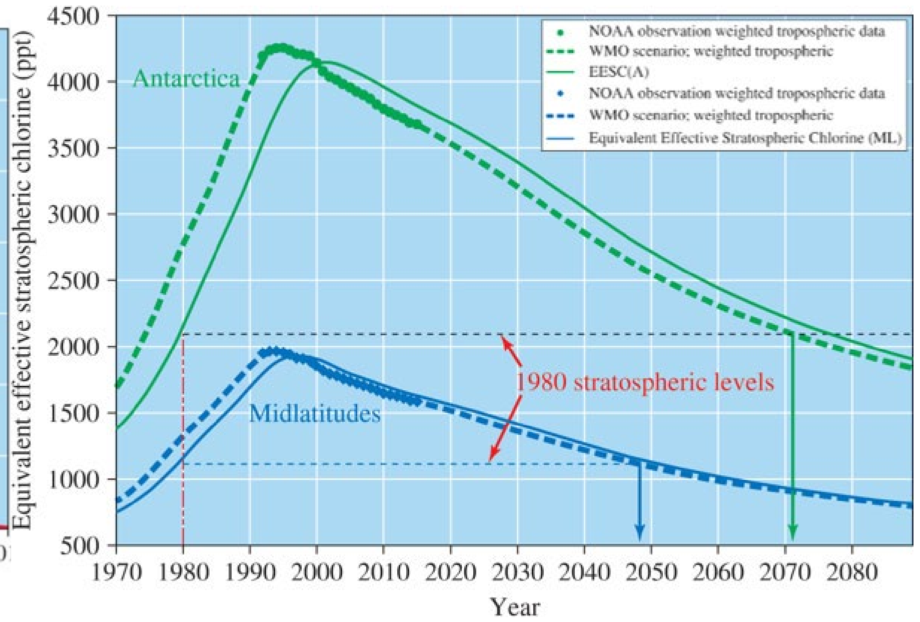
Where Do We Go From Here?

Global cooperation resulted in the Montreal Protocol in 1987

- Phased out production of CFCs by 2010.
- Recovery of ozone concentrations is slow.
- Will take until 2070 to reach 1980 levels of chlorine concentrations.



Source: UNEP



Source: The NOAA Ozone Depleting Index, 2015

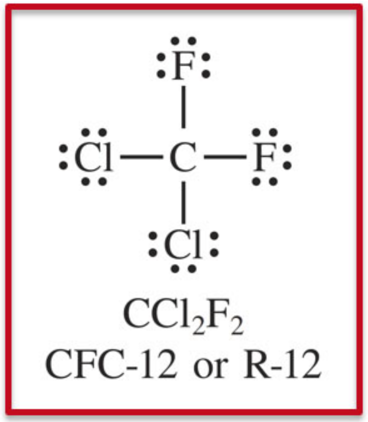
Alternatives to CFCs

Hydrofluorocarbons (HFCs) replace chlorine with hydrogen to prevent the release of atomic chlorine.

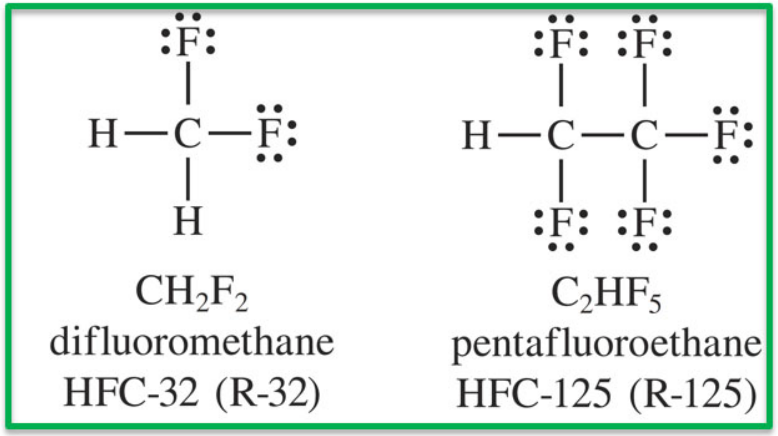
- HFCs are greenhouse gases!

Hydrofluoroolefins (HFOs) are another potential replacement.

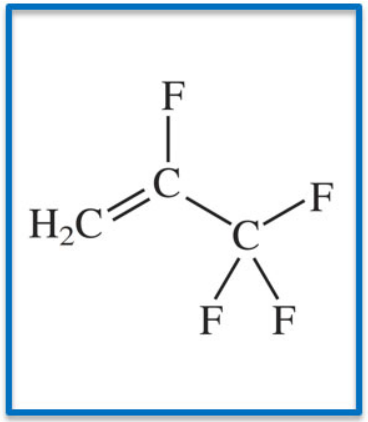
- Contain a carbon-carbon double bond, making it more reactive, shortening its lifetime in the atmosphere.



chlorofluorocarbon



hydrofluorocarbons



hydrofluoroolefin

How Do Sunscreens Work?

With the ozone layer weakened, we need additional protection from the Sun’s UV.

Sunscreens are generally one of two types: physical and chemical.

Physical sunscreens use nanoparticles made from titanium oxide (TiO_2) or zinc oxide (ZnO).

- Nanoparticles have dimensions between 1 to 100 nm, which are similar in size to antibodies or small viruses (much smaller than cells).

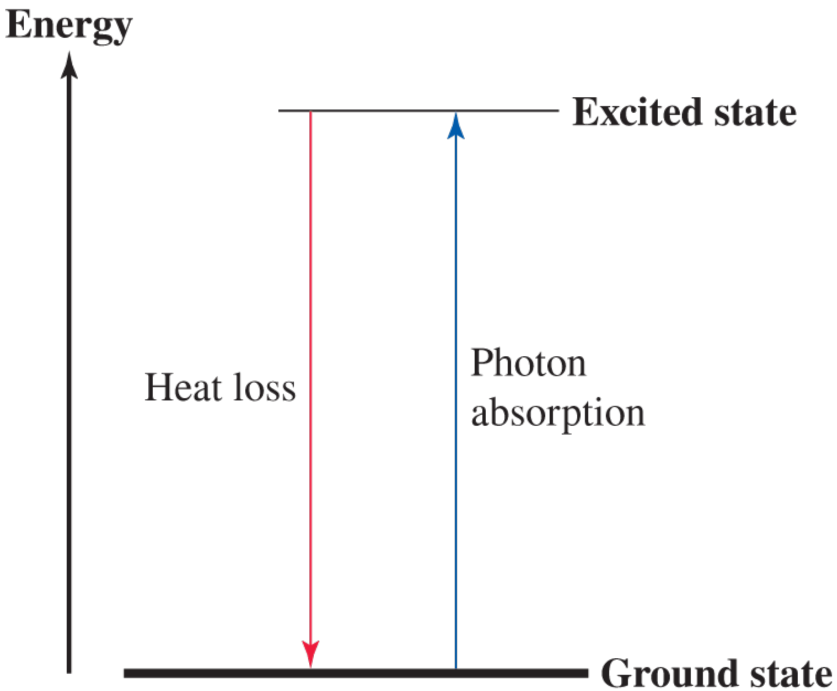
https://www.acs.org/education/resources/undergraduate/chemistryincontext/interactives/radiation-from-sun/chemistry-of-sunscreen.html

https://www.acs.org/education/resources/undergraduate/chemistryincontext/interactives/radiation-from-sun/nanoparticle-sunscreen.html

Light Absorption by Nanoparticles

When energy is absorbed, electrons are promoted from low energy "ground" states into higher energy "excited" states

- The energy of the radiation has to match the energy difference between the states for absorption to occur.
- The energy difference is dependent on the composition and size of the nanoparticles.

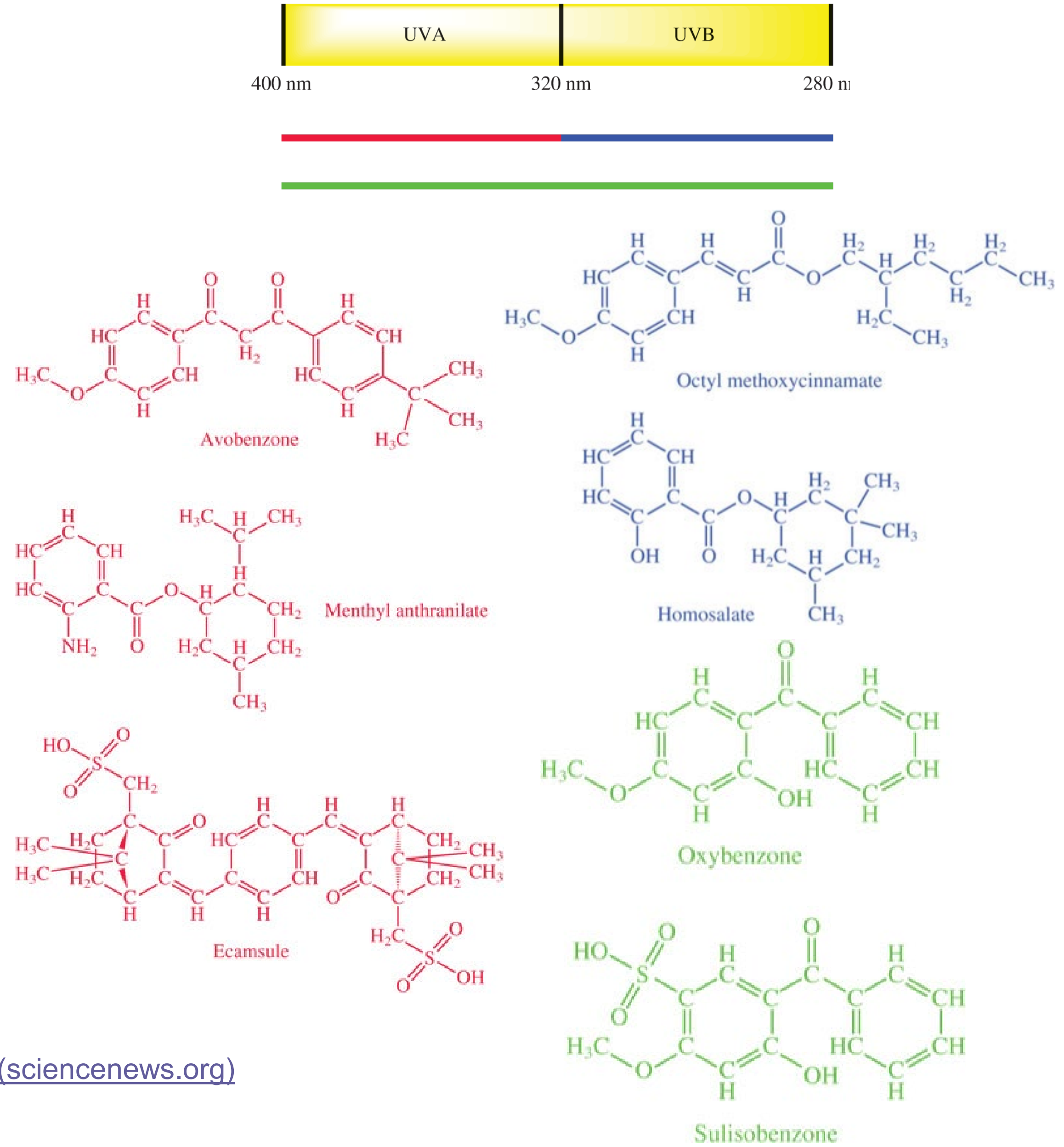


[Surface-volume-ratio]

Light Absorption by Organic Molecules

Chemical sunscreens contain organic compounds (primarily composed of carbon, hydrogen, and oxygen)

- Have parts of the molecule with alternating single and double bonds.
- Some are being banned due to health or environmental concerns.



The Science of Sunscreen & How it Protects Your Skin

Periodic Graphics: Sunscreen and coral reef damage

How some sunscreens damage coral reefs (sciencenews.org)

Example topics that you can delve into further...

1. Is there other ozone depletion reactions? What other substances can promote ozone depletion?
2. Study mechanisms of more catalytic reactions on the surface of PSCs?
3. What’s the difference between physical vs. chemical sunblock principles?
4. Which nanoparticles are most effective for sun blocking? Why?
5. What kind of side reactions can happen to the sunblock materials under light? What possible side effects?
6. While human eyes can detect the visible lights while other insects or animals are more optimized to detect IR. Why? What molecular differences are there in the light detection?

Etc..