- These slides contain animations, when the PowerPoint file is played
- The content gradually appears with clicks
- Questions appear before their answers

Carbon Dioxide – It's not all bad

- Carbon dioxide results from the combustion of carbon containing fuels (= most of the ones we use)
- As a consequence, we have certainly heard about carbon dioxide (CO_2) as the main culprit for the greenhouse effect and global warming
- It is a problem because we are emitting truly massive amounts of it into the atmosphere from combustion (37 billion tons in 2023)

However, it is a very useful substance with many attractive properties

- It is effectively non-toxic
- It is chemically stable
- It has useful melting/boiling/critical points

https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide#:~:text=Since%20the%20middle%20of%20the,the%20Global%20Carbon%20Budget%202023.

Carbon Dioxide – It's not all bad

- As a gas that is part of our normal physiological functioning, it is not particularly toxic. The air we breath out contains about 5% CO_2!

<u>Composition of air during breathing</u>

	Inhaled	Exhaled
N_2	78%	78%
O_2	21%	~16%
Ar	1%	1%
CO_2	0.04%	~5%
H_2O	varies	saturated

What else changes between inhaled and exhaled air?

Carbon Dioxide – It's not all bad

CO_2 is a very useful substance with many attractive properties

Name some familiar uses of CO_2:

Drink carbonation
Fire extinguishing
Refrigerant – dry ice
Leavening (raising) bread
CO_2 lasers
As a "green" solvent

Carbon Dioxide – Drink Carbonation

- Sodas and other sparkling drinks get their bubbles from carbon dioxide

Why not use some other gas to make drinks bubbly?

Some reasons:

- Toxicity – clearly a problem! (e.g. NH_3, SO_2, H_2S, CO, NO_2)
- Odor – 4/5 of the examples above (NH_3, SO_2, H_2S, NO_2 also have unpleasant odors)
- Cost – CO_2 is quite cheap and readily available
- Solubility - the gases from air (N_2, O_2, Ar) meet the criteria of low toxicity, no odor, and low cost. However, they have very poor solubility in water.

Carbon Dioxide – Drink Carbonation

Why not use some other gas to make drinks bubbly?

- Solubility – CO_2 has good solubility in water.
- Henry's Law tells us that the amount of gas that can dissolve in a liquid is proportional to the pressure of the gas above the liquid.
- We see this when opening a soda bottle, the pressure over the liquid reduces and so the CO_2 solubility reduces, leading to gas coming out of solution in the form of bubbles
- Also, a small amount of CO_2 reacts with water:

$$CO_2 + H_2O \rightleftarrows H_2CO_3$$

- H_2CO_3 is an acid, making the water more acidic (pH 3-4). This contributes to the flavor of carbonated drinks and water.

Carbon Dioxide – Drink Carbonation

How does the CO_2 get in the drinks?

- Some drinks, like soda, are pressurized with CO_2 e.g. from a gas cylinder
- A typical soda can or bottle is pressurized to about 30-50 psi at room temperature. That's around 2-3 times atmospheric pressure

Car Tire
~2 atm

Soda bottle
~3 atm

Narrow Bike Tire
6-8 atm

Propane tank
10-13 atm

Nitrogen cylinder
~145 atm

- Inflating a balloon - ~ 0.1 atm

Carbon Dioxide – Drink Carbonation

How does the CO_2 get in the drinks?

- Other drinks, like beer and champagne, get their CO_2 from the fermentation process that produced their alcohol:

$$\underset{\text{sugar}}{C_6H_{12}O_6} \rightarrow 2\ \underset{\text{ethanol}}{C_2H_5OH} + 2\ CO_2$$

https://images.app.goo.gl/WxYZdZrS7jr1okNCA

https://physicsworld.com/a/six-secrets-of-champagne/

Carbon Dioxide – Fire Extinguishing

- CO_2 is used in some fire extinguishers
- It works by displacing air - no oxygen, no fire

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- CO_2 is not flammable; it is already the product of combustion!

e.g. $CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$

methane

Carbon Dioxide – Fire Extinguishing

- CO_2 gas at atmospheric pressure is more dense than air so it tends to sink and smother a fire

Density -	Air	1.29 kg per m^3
	CO_2	1.98 kg per m^3

- It can't absorb much heat, like water can. So, fires can reignite when the CO_2 disperses, so it is best suited to small fires.

What makes it a better choice than water for electrical fires?

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Carbon Dioxide – Fire Extinguishing

Some other facts about CO_2 and fire extinguishing:

- CO_2 is not flammable, but it can serve as an oxygen source for some very reactive substances, like reactive metals. It can't be used on that type of fire because it can make the fire worse!

  e.g. $2\,Mg + CO_2 \rightarrow 2\,MgO + C$ (+ heat)

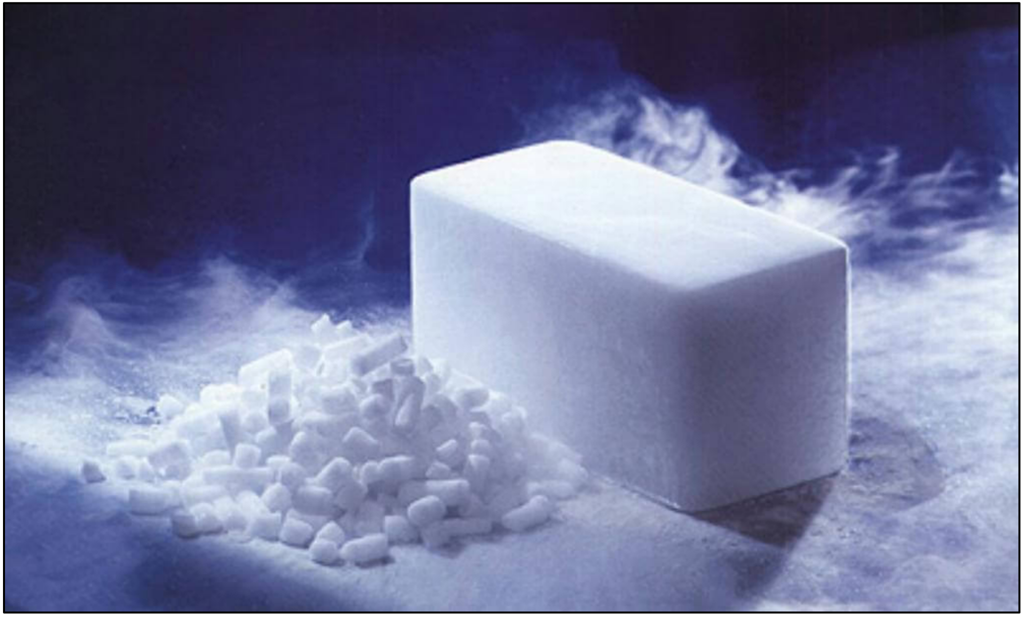
- A CO_2 fire extinguisher is at sufficient pressure to liquefy the CO_2 inside (59 atmospheres at room temp).

- Interestingly, some older fire extinguishers worked by mixing acid with sodium bicarbonate. That reaction releases CO_2, but its major function in that case was to pressurize the container to squirt the liquid (mostly water) out at the fire

  e.g. $^{-}HCO_3(aq) + H^+(aq) \rightarrow H_2CO_3$

  $H_2CO_3 \rightleftarrows CO_2(g) + H_2O$

Carbon Dioxide – Dry Ice



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Carbon Dioxide – Dry Ice

- CO_2 does not exist as a liquid at atmospheric pressure
- Instead, if cooled sufficiently (-78 °C) it changes directly from a gas to a solid "dry ice"
- Dry ice is useful as a cooling agent

What are some advantages of dry ice vs water ice?

- It can cool things to a much lower temperature than water ice
- Water ice melts leaving a liquid that has to be dealt with
- As dry ice sublimes (equivalent term to "evaporates" when talking about the solid → gas phase change) the gas diffuses away, leaving no residue to deal with

Carbon Dioxide – Leavening

- Leavening adds volume to baked goods (bread, cake, etc.)
- Bubbles of gas (usually CO_2) expand within the dough or mix, "raising" it
- When the mixture sets, the trapped bubbles are responsible for the sponge-like structure that we see in bread and cake.

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Carbon Dioxide – Leavening

- There are two common ways that the CO_2 gas is produced:

1. **<u>"Biological"</u>** – Baker's yeast

The fermentation reaction produces CO_2 and ethanol. The process is usually slower than with the chemical leavening agents

$$\underset{\text{sugar}}{C_6H_{12}O_6} \rightarrow 2\ \underset{\text{ethanol}}{C_2H_5OH} + 2\ \mathbf{CO_2}$$

2. **<u>"Chemical"</u>** – Bicarbonate + acid

Baking powders contain a bicarbonate salt (e.g. $NaHCO_3$) an acid salt (e.g. potassium acid tartrate (cream of tartar) $KC_4H_5O_6$), and starch powder (to keep the salts from getting wet and from contacting each other). When the mixture gets wet the following reactions occur:

$$\text{e.g.}\quad {}^{-}HCO_3(aq) + H^+(aq) \rightarrow H_2CO_3$$

$$H_2CO_3 \rightleftarrows \mathbf{CO_2} + H_2O$$

Carbon Dioxide – Lasers

- The carbon dioxide laser is one of the most useful laser types
- They are used in industrial and medical applications

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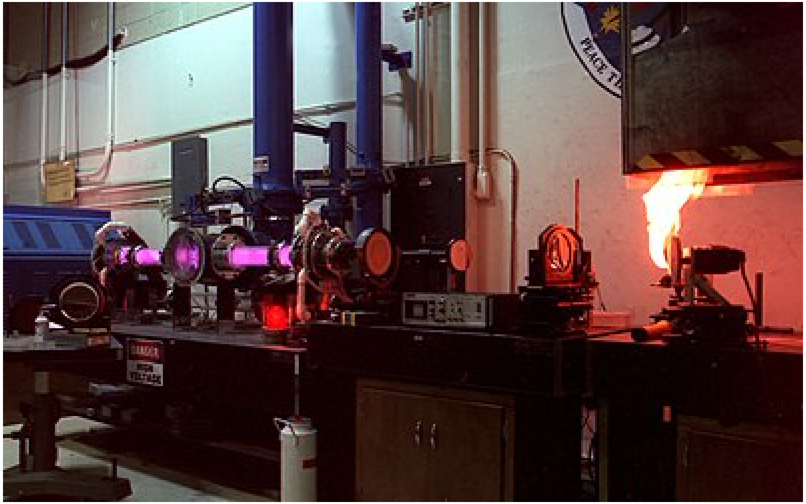
https://en.wikipedia.org/wiki/Carbon-dioxide_laser

Carbon Dioxide – Lasers

- It is a gas laser where CO_2 is the radiative emitter
- It is easy to produce high power levels at reasonable cost
- They are used for industrial cutting and welding
- They are also used for medical applications, such as in laser surgery to cut, ablate, vaporize, and coagulate
- The emitted laser light is infrared, it is invisible!

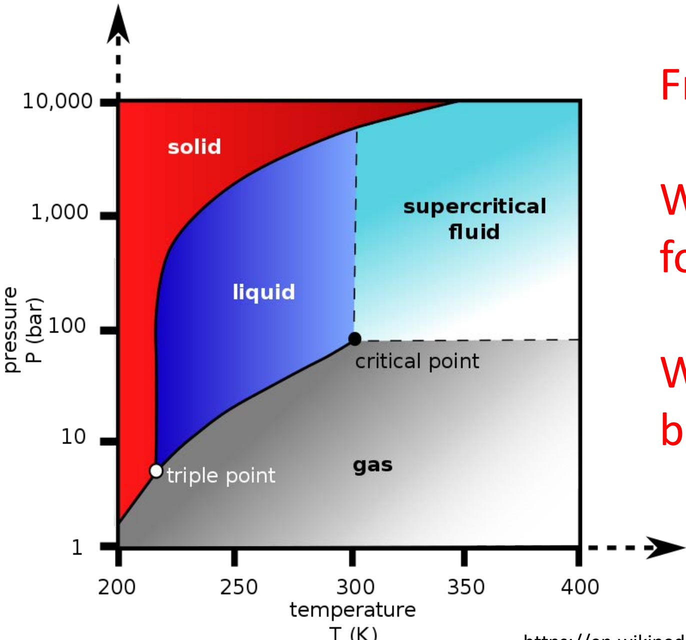


https://en.wikipedia.org/wiki/Carbon-dioxide_laser

Carbon Dioxide – A Green Solvent

- We know that CO_2 is a gas and that dry ice has the unusual property of subliming (phase changing directly from a solid to a gas) at normal pressure

- But CO_2 can certainly exist in liquid form and also finds use when in a supercritical state



https://en.wikipedia.org/wiki/Carbon_dioxide

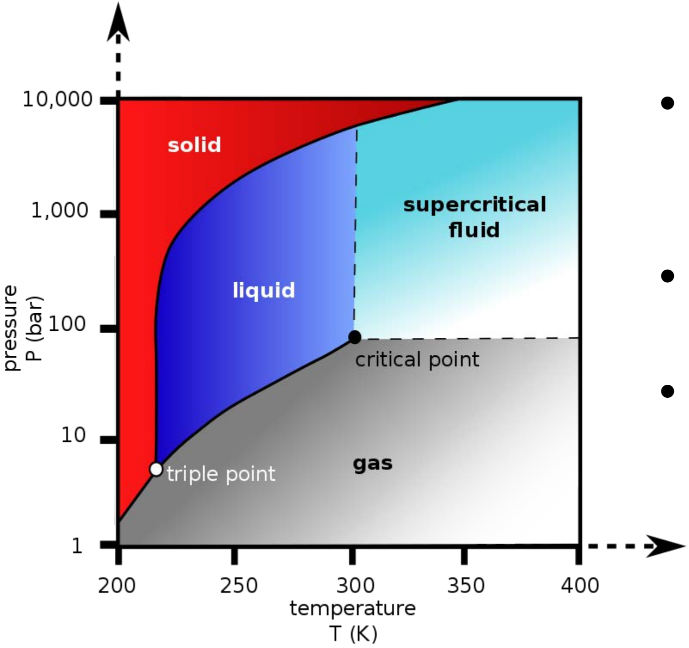
From this image –

What is the lowest pressure required for CO_2 to exist as a liquid?

What pressure is required for CO_2 to be a liquid at room temperature?

Carbon Dioxide – A Green Solvent

- Supercritical – What does that mean?
- Above the critical point temperature, a substance cannot be liquified, at any pressure.

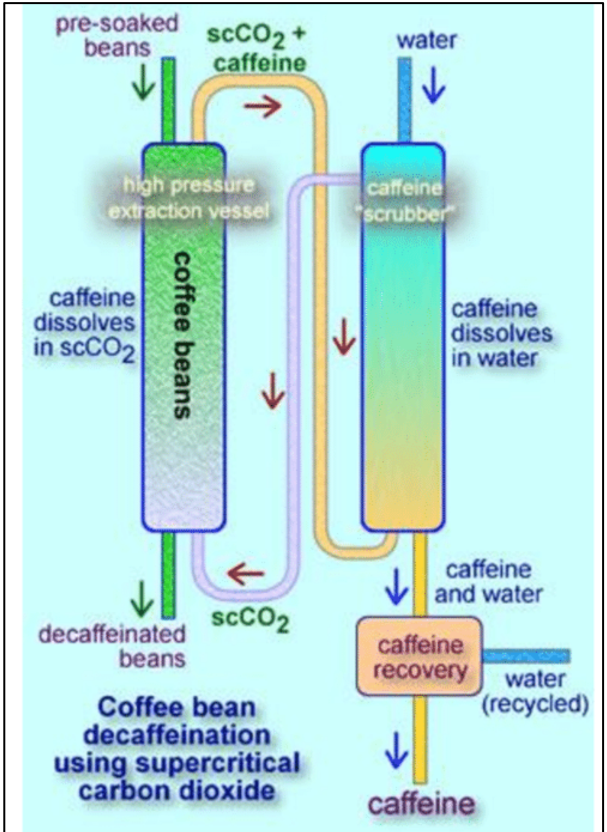


- Supercritical fluids display properties of both liquids and gases.
- Fills the volume of its container, like a gas
- Can more effectively dissolve other substances, like a liquid

https://en.wikipedia.org/wiki/Carbon_dioxide

Carbon Dioxide – A Green Solvent

- Supercritical CO_2 is used as a solvent



- A substance that is dissolved can be recovered by releasing the pressure, all the CO_2 will evaporate away!
- For example, supercritical CO_2 can be used to extract caffeine from coffee
- This is a greener process than using the major alternative, methylene chloride (CH_2Cl_2), which is toxic and an ozone depleting substance

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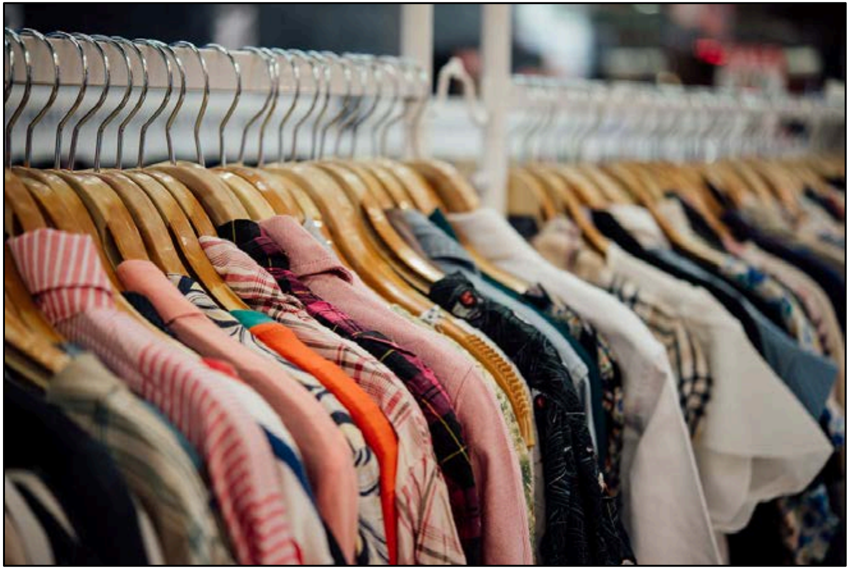
Carbon Dioxide – A Green Solvent

- Another example involves using supercritical CO_2 for "dry cleaning"
- This is also a greener alternative to the standard solvent, perchloroethylene



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Carbon Dioxide – A Green Solvent

How can using CO_2 as a solvent be green?

- Most importantly, it is safe and effectively non-toxic

The reasoning is simple,

- CO_2 is obtained from the environment
- If it is then, released back into the environment, there is no overall change to the amount in the environment

- This is very different to burning fossil fuels, which releases CO_2 into the air that was not there before