If $\text{CO}_2$ is participating in the *enhanced* greenhouse effect, it would be good to know how much is being made with respect to how much C is in the world…

Gt=gigatonne (a billion ($10^9$) metric tons, 2200 billion pounds ($2.2\times10^{12}$))
A Different Look at US CO₂ Emissions (2002)

U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO₂**

*Includes adjustments of 42.9 million metric tons of carbon dioxide from U.S. territories, less 90.2 MCO₂ from international and military bunker fuels.
**Previous versions of this chart showed emissions in metric tons of carbon, not of CO₂.
***Municipal solid waste and geothermal energy.
Note: Numbers may not equal sum of components because of independent rounding.
Gt=gigatonne (a billion metric tons ($10^9$), 2200 billion pounds ($2.2\times10^{12}$))
How much CO₂ do you emit when you drive to Denver?

\[
60 \text{ miles} \times \frac{1 \text{ gal}}{20 \text{ miles}} \times \frac{6 \text{ lbs}}{1 \text{ gal}} \times \frac{1 \text{ kg}}{2.2 \text{ lbs}} \times \frac{1000 \text{ g}}{1 \text{ kg}} = 8,200 \text{ g gasoline used, but we want to know how much CO}_2 \text{ was produced while driving that distance}\ldots
\]

Molar mass of gasoline? (assume C₈H₁₈)
\[
8 \times 12.0 \text{ g} = 96.0 \text{ g} \\
18 \times 1.0 \text{ g} = 18.0 \text{ g} \\
= 114.0 \text{ g/mol C}_8\text{H}_{18}
\]

Converting from C₈H₁₈ to CO₂?
\[
2 \text{ C}_8\text{H}_{18} + 25 \text{ O}_2 \rightarrow 16 \text{ CO}_2 + 18 \text{ H}_2\text{O}
\]
\[
2 \text{ moles C}_8\text{H}_{18} = 16 \text{ moles CO}_2
\]

Molar mass of CO₂?
\[
1 \times 12.0 \text{ g} = 12.0 \text{ g} \\
2 \times 16.0 \text{ g} = 32.0 \text{ g} \\
= 44.0 \text{ g/mol CO}_2
\]

Building Solution here: \[
8,200 \text{ g gasoline} \times \frac{1 \text{ mol C}_8\text{H}_{18}}{114 \text{ g}} \times \frac{16 \text{ mol CO}_2}{2 \text{ mol C}_8\text{H}_{18}} \times \frac{44 \text{ g CO}_2}{1 \text{ mol CO}_2} = 25,000 \text{ g CO}_2
\]
How much CO₂ is emitted by a coal train worth of coal?

Coal train:
120 cars
120 tons/car = 14,400 tons
1 ton = 1016 kg ⇒ 1.46 × 10⁷ kg Coal

Molar mass of coal? (assume C₁₃₅H₉₆O₉NS)

\[
\begin{align*}
135 \times 12.0 \text{ g} &= 1620.0 \text{ g} \\
96 \times 1.0 \text{ g} &= 96.0 \text{ g} \\
9 \times 16.0 \text{ g} &= 144.0 \text{ g} \\
1 \times 14.0 \text{ g} &= 14.0 \text{ g} \\
1 \times 32.0 \text{ g} &= 32.0 \text{ g}
\end{align*}
\]

= 1906.0 g/mol C₁₃₅H₉₆O₉NS

Coal train = 1.46 × 10⁷ kg × \( \frac{\text{mole}}{1.906 \text{kg}} \) = 7.61 × 10⁶ moles

Converting from C₁₃₅H₉₆O₉NS to CO₂?

\[
2 \text{ C}_{135}\text{H}_{96}\text{O}_9\text{NS} + 313 \text{ O}_2 \rightarrow 270 \text{ CO}_2 + 96 \text{ H}_2\text{O} + 2 \text{ NO}_2 + 2 \text{ SO}_2
\]

2 moles \( \text{C}_{135}\text{H}_{96}\text{O}_9\text{NS} \) = 270 moles CO₂

Molar mass of CO₂?

\[
\begin{align*}
1 \times 12.0 \text{ g} &= 12.0 \text{ g} \\
2 \times 16.0 \text{ g} &= 32.0 \text{ g} \\
&= 44.0 \text{ g/mol CO}_2
\end{align*}
\]

\[
7.61 \times 10^6 \text{ moles Coal} \times \frac{270 \text{ moles CO}_2}{2 \text{ moles Coal}} \times \frac{44.0 \text{ g CO}_2}{\text{mole CO}_2} = 4.52 \times 10^{10} \text{ g CO}_2
\]

(1Gt = 1 × 10¹⁵ g)

6.6 Gt = 150,000 coal trains
### Important factors:

- **Concentration**
- **Lifetime (connected to concentration & reactivity)**
- **Light absorption efficiency**

### Table 3.2: Greenhouse Gases—Concentration Changes and Lifetimes

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>CH₄</th>
<th>N₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preindustrial</td>
<td>278 ppm</td>
<td>0.700 ppm</td>
<td>0.270 ppm</td>
</tr>
<tr>
<td>concentration (1750)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005 concentration</td>
<td>385 ppm</td>
<td>1.75 ppm</td>
<td>0.314 ppm</td>
</tr>
<tr>
<td>Average rate of</td>
<td>1.5 ppm/year</td>
<td>0.007 ppm/year</td>
<td>0.0008 ppm/year</td>
</tr>
<tr>
<td>concentration change,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990–2005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global atmospheric</td>
<td>50–200 years*</td>
<td>12 years</td>
<td>114 years</td>
</tr>
<tr>
<td>lifetime</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*A single value for the atmospheric lifetime of CO₂ is not possible. Different removal mechanisms take place at different rates, leading to variation in atmospheric lifetime.

### Table 3.3: Global Warming Potential for Three Greenhouse Gases

<table>
<thead>
<tr>
<th>Substance</th>
<th>Global Warming Potential (GWP)*</th>
<th>Tropospheric Abundance (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
<td>385</td>
</tr>
<tr>
<td>CH₄</td>
<td>23</td>
<td>1.8</td>
</tr>
<tr>
<td>N₂O</td>
<td>296</td>
<td>0.31</td>
</tr>
</tbody>
</table>

*GWP values are given for the estimated direct and indirect effects over a 100-year period and are relative to the assigned value of 1 for CO₂.
Albedo - ratio of radiation reflected relative to the amount incident on the surface - impacted by what’s on the surface. Deforestation, melting snow, etc.

Photosynthesis dependent upon CO₂ concentration & temperature.

**equilibrium**

\[
\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3
\]

Product favored by pressure, higher concentration in deep ocean

Reactants favored by higher temperatures…

Carbonic acid, the carbonate of carbonated beverages.
Soda Siphon

Demonstrates:

• Refrigeration/steam turbine

• Temperature/Pressure dependence of CO$_2$ dissolving in oceans equilibrium

• Acids & Bases
In the Soda Siphon, a small needle punctures the high pressure CO₂ cartridge. Expansion into our relative “vacuum” cools the CO₂ gas and the cartridge.

1. Compressor (B) compresses HFC gas. (compressed gas heats up as it is pressurized (orange))

2. Coils on the back of the refrigerator dissipate HFC gas heat. The HFC gas condenses into HFC liquid (purple) at high pressure

3. High-pressure HFC liquid flows through the expansion valve (C). (a small hole). On one side of the hole is high-pressure HFC liquid. On the other side of the hole is a low-pressure area (the compressor is pumping gas out of that side).

4. Liquid HFC vaporizes (light blue), its temperature dropping to -27 F. This makes the inside of the refrigerator cold (A)

5. Cold HFC gas is sucked up by the compressor, and the cycle repeats
Albedo is the ratio of radiation reflected relative to the amount incident on the surface, impacted by what's on the surface. Deforestation, melting snow, etc.

Photosynthesis is dependent upon CO$_2$ concentration & temperature.

Equilibrium:

$$\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$$

Product favored by pressure, higher concentration in deep ocean.

Reactants favored by higher temperatures...

Carbonic acid, the carbonate of carbonated beverages.

03.03.25.greenhouse-gases.html
While discussing the carbon cycle, we talk about carbon going into the ocean & coming out of the ocean & that this was an equilibrium (Fig. 3.17)

- Gaseous CO$_2$ dissolves in the water & vaporizes from water
  \[ \text{CO}_2 (g) + \text{H}_2\text{O} (l) \rightleftharpoons \text{CO}_2 (aq) \]
- Dissolved CO$_2$ reacts with H$_2$O forming H$_2$CO$_3$ (carbonic acid)
  \[ \text{CO}_2 (aq) + \text{H}_2\text{O} (l) \rightleftharpoons \text{H}_2\text{CO}_3 (aq) \]
- Dissolved H$_2$CO$_3$ reacts with H$_2$O forming HCO$_3^-$ (bicarbonate) and H$_3$O$^+$ (hydronium ion)
  \[ \text{H}_2\text{CO}_3 (aq) + \text{H}_2\text{O} (l) \rightleftharpoons \text{HCO}_3^- (aq) + \text{H}_3\text{O}^+ (aq) \]

Our definition of an **acid** is a substance that forms hydronium ions (H$_3$O$^+$) when dissolved in water

- Hydronium ion reacts with anthocyanin, the product is a different color
Concentration of Acid

Each CO₂ cartridge:  
\[ 8.0 \text{ g CO}_2 \times \frac{\text{mol CO}_2}{44 \text{ g CO}_2} = 0.18 \text{ moles CO}_2 \]

0.18 moles CO₂ in 1 L aqueous solution = 0.18 M CO₂  
\[ [\text{CO}_2] = 0.18 \text{M} \]

If the CO₂ equilibria reproduced below were to all favor products then we would have \( \sim 0.18 \text{ M H}_3\text{O}^+ \) (this would correspond to a pH of \( \sim 0.7 \))

\[
\begin{align*}
\text{CO}_2 (g) + \text{H}_2\text{O} (l) & \rightleftharpoons \text{CO}_2 (aq) \\
\text{CO}_2 (aq) + \text{H}_2\text{O} (l) & \rightleftharpoons \text{H}_2\text{CO}_3 (aq) \\
\text{H}_2\text{CO}_3 (aq) + \text{H}_2\text{O} (l) & \rightleftharpoons \text{HCO}_3^- (aq) + \text{H}_3\text{O}^+ (aq)
\end{align*}
\]

In reality \( [\text{H}_3\text{O}^+] = \sim 1.9 \times 10^{-4} \text{ M} \), corresponding to a pH of \( \sim 3.72 \) (at the pressure of our Seltzer bottle)

At atmospheric pressure \( [\text{H}_3\text{O}^+] = \sim 2.5 \times 10^{-6} \text{ M} \) (a pH of \( \sim 5.6 \))