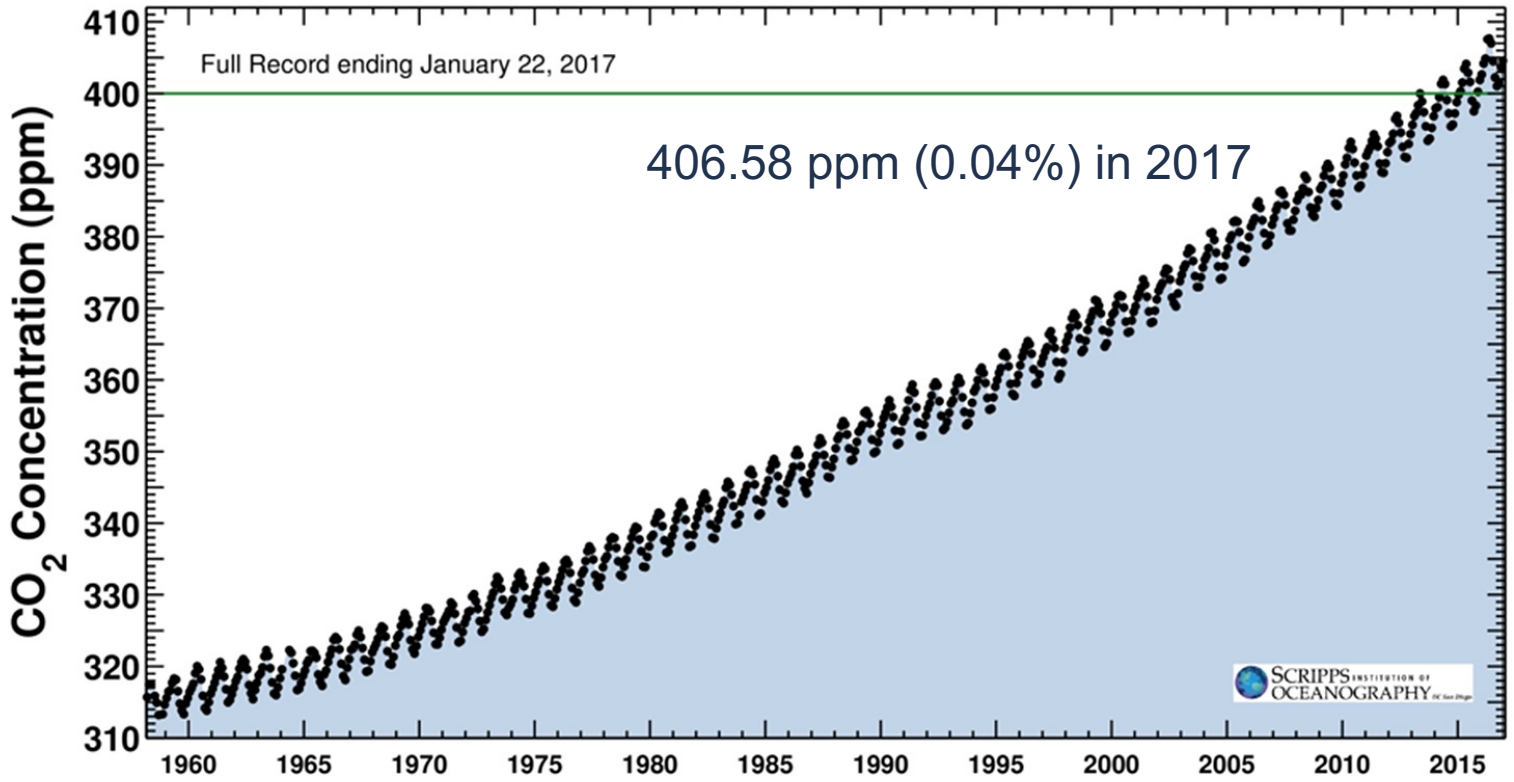
Post-Combustion Capture of CO_2

Prof. Mike McGuirk
Prof. Ryan Richards
Department of Chemistry
Colorado School of Mines

Atmospheric [CO_2], a GHG, is on the Rise



- GHGs absorb outgoing infrared radiation, warming the atmosphere

Image adapted from: https://e360.yale.edu/features/how-the-world-passed-a-carbon-threshold-400ppm-and-why-it-matters

Need the Big Picture to Truly Appreciate our Impact

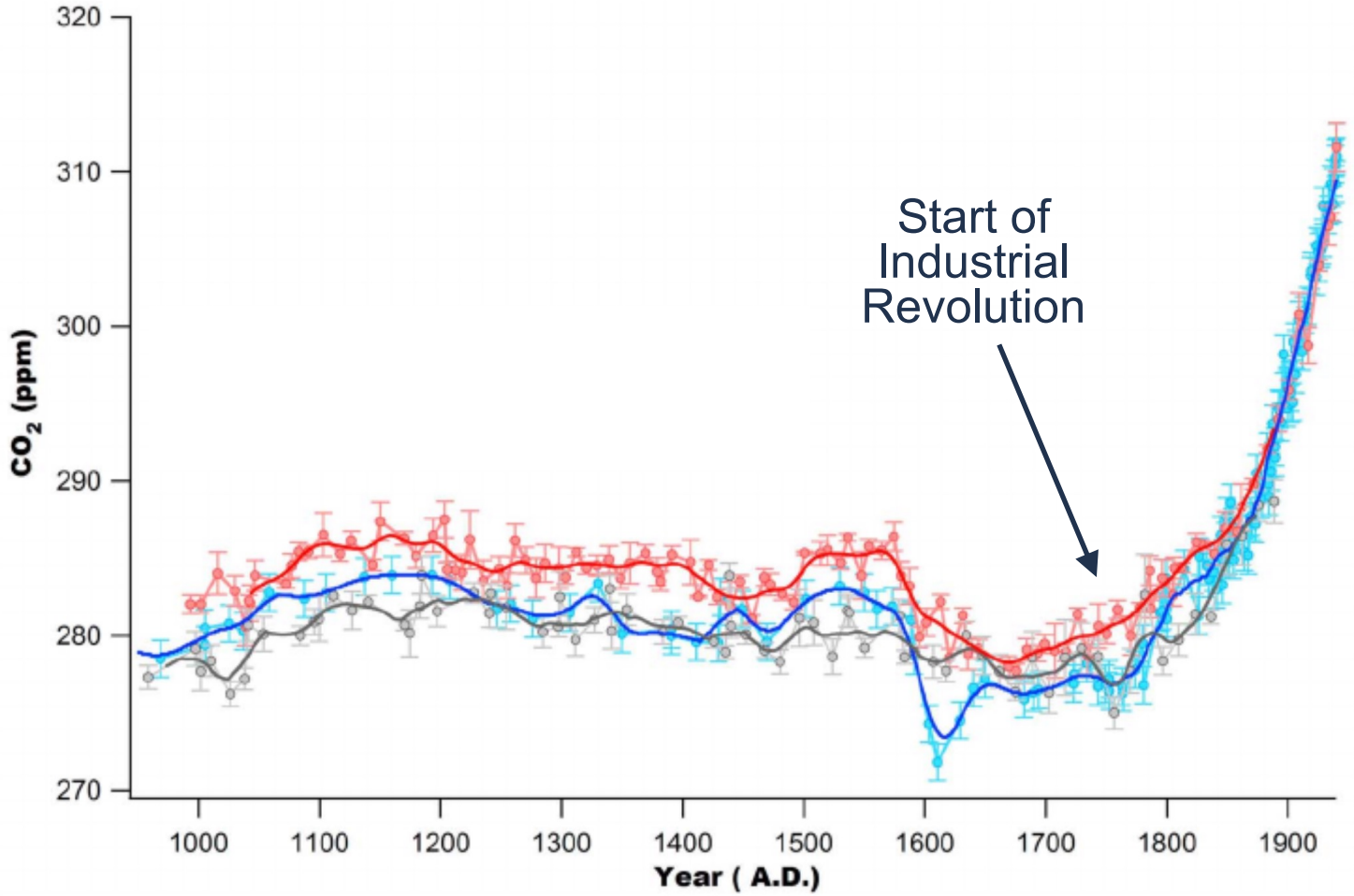


Image adapted from: Ahn, J.; Brook, E. J.; Mitchell, L.; Rosen, J.; McConnell, J. R.; Taylor, K.; Etheridge, D.; Rubino, M. *Global Biogeochem. Cycles* **2012**, *26*

Part of the Solution: Carbon Capture, Utilization, and Storage

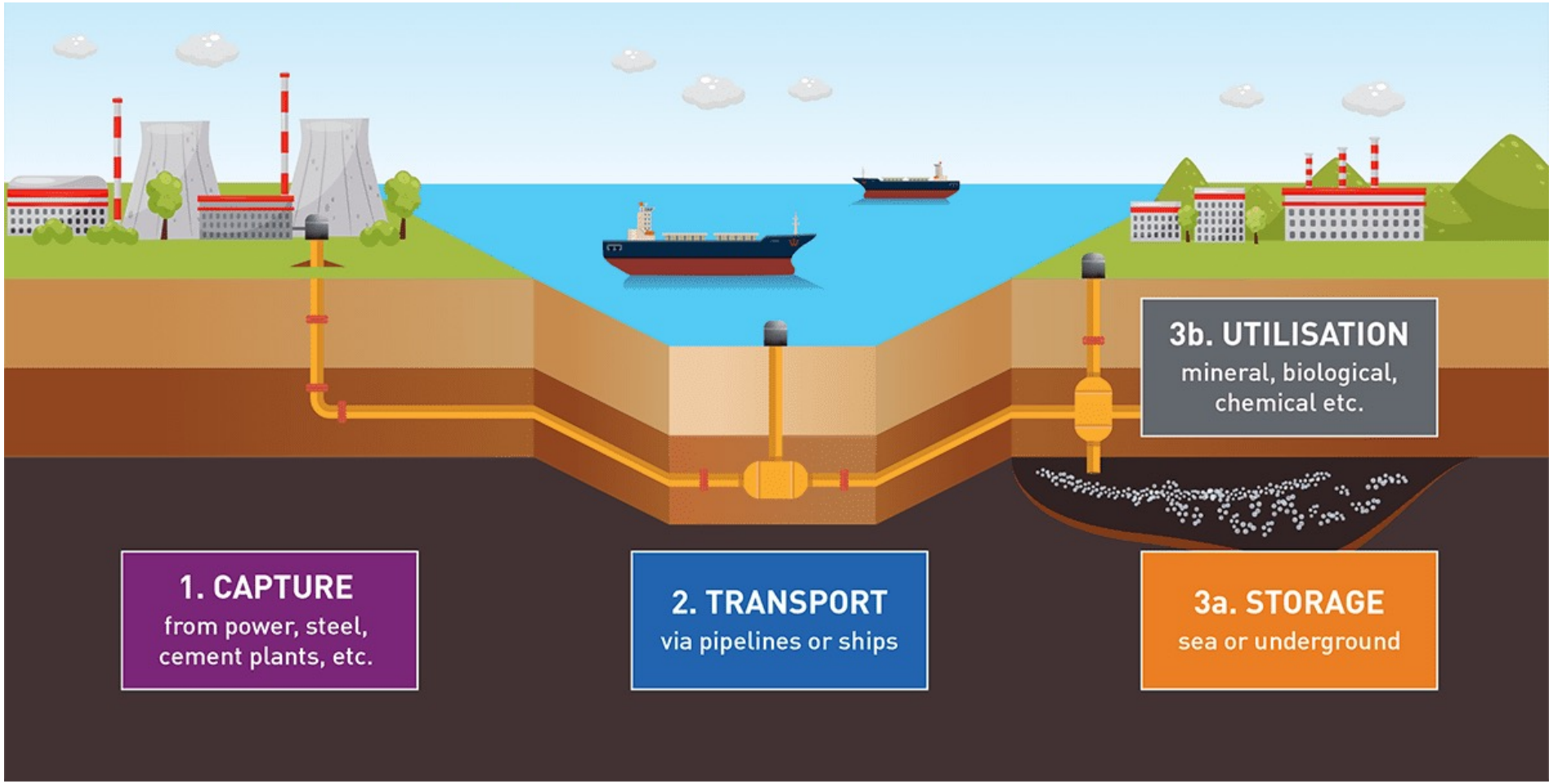
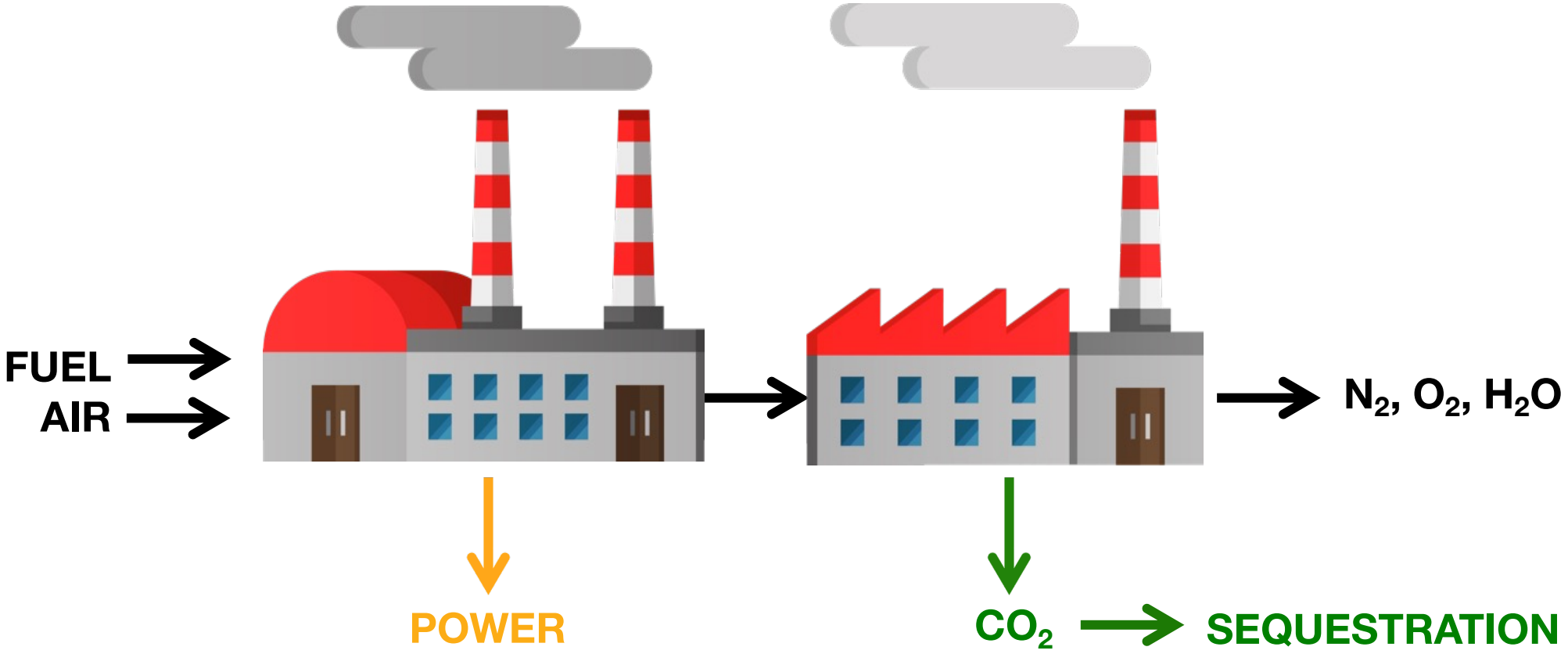


Image adapted from: https://www.iogp.org/blog/news/developing-low-carbon-technologies/

Post-Combustion Capture from a Point-Source

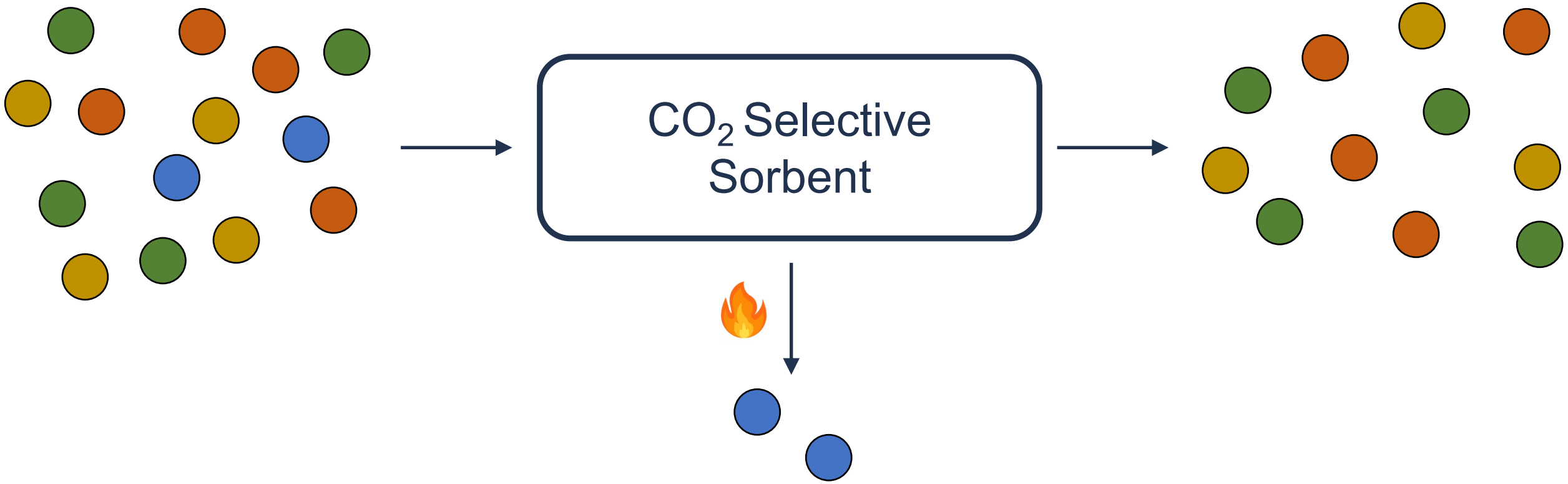


- 70% of cost of CCUS is associated with selective capture of CO_2

Capture: Selective Removal of CO_2 from Gas Mixtures

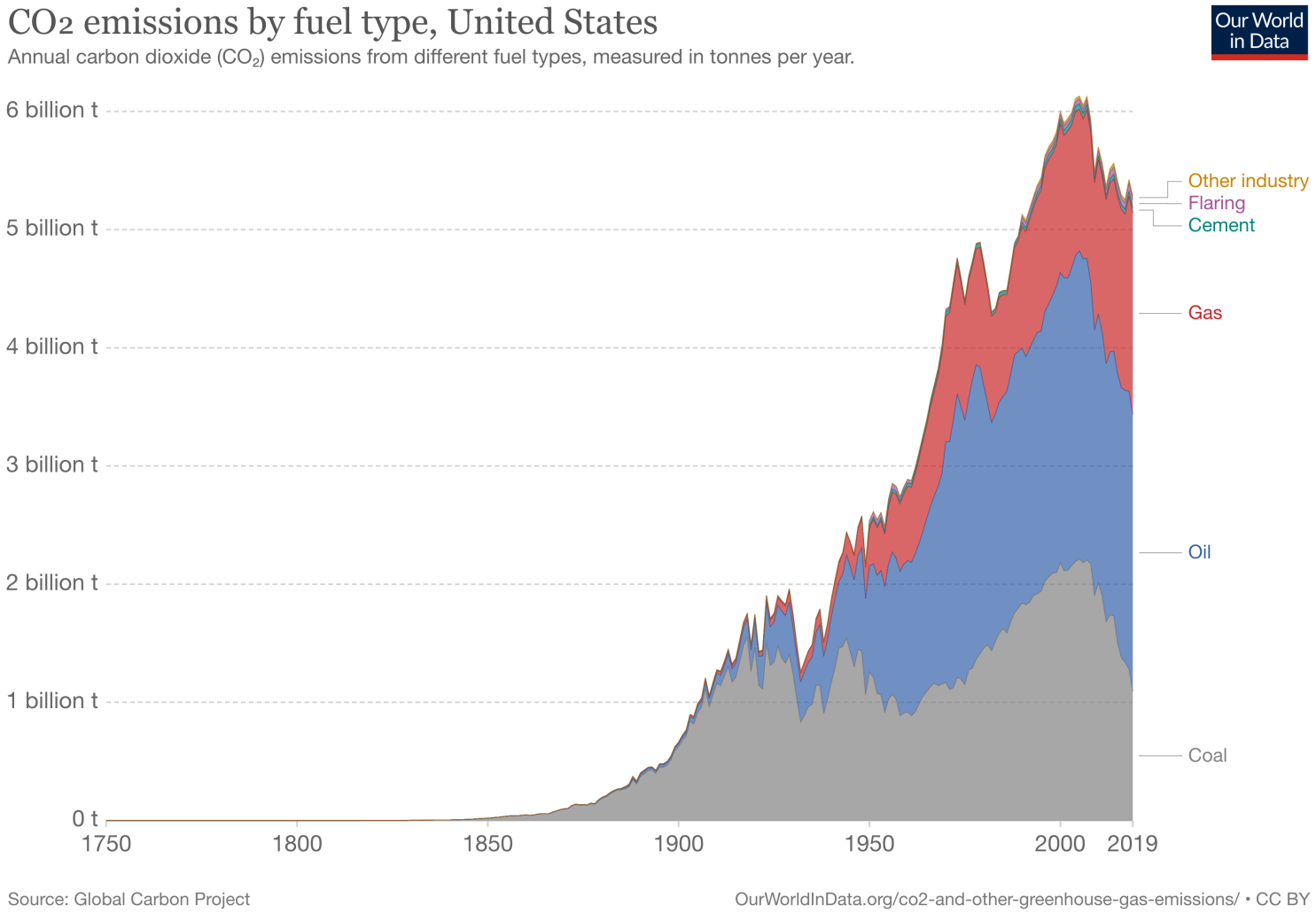
- **Grand Scientific Challenge:** Need to selectively remove a minority component from a complex mixture, **BUT** also release the gas on demand without massive energy penalties

Capture: Selective Removal of CO_2 from Gas Mixtures



- **Grand Scientific Challenge:** Need to selectively remove a minority component from a complex mixture, **BUT** also release the gas on demand without massive energy penalties

Diverse Sources of Anthropogenic CO_2 Emissions



Diverse Targets for CO_2 Capture

Iron, Steel and Cement Production

~20% CO_2
Target: ≤ 20 mbar

Post-Combustion Natural Gas and Coal Flue

NG: 3-5% CO_2
Target: ≤ 3-5 mbar
Coal: 12-14% CO_2
Target: ≤ 12-14 mbar

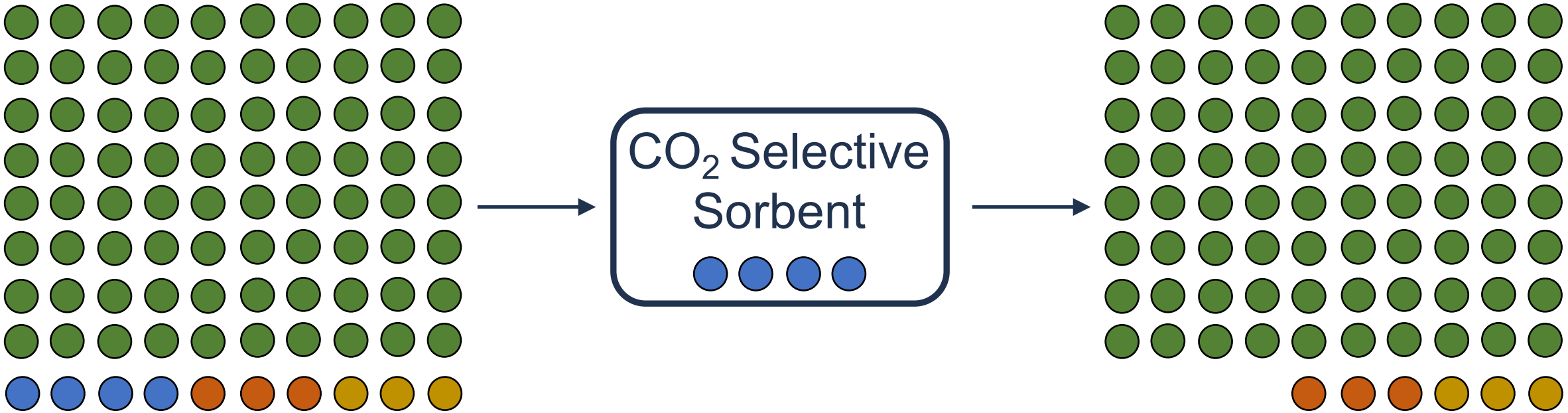
Direct Air Capture

~0.040% CO_2
Target: ≤ 0.04 mbar

- Want ≥ 90% reduction in [CO_2] from a given source

Herron, S.; Zoelle, A.; Summers, M."Cost of Capturing CO_2 From Industrial Sources", NETL, **2014**

A Representative Picture of Selectivity Required



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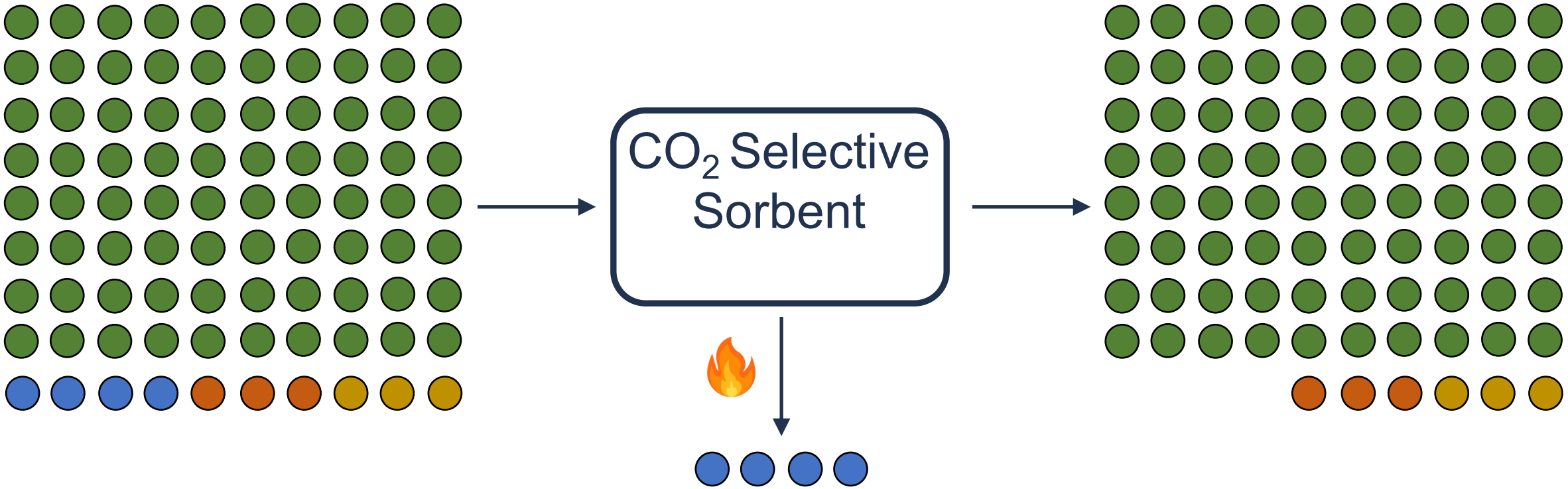
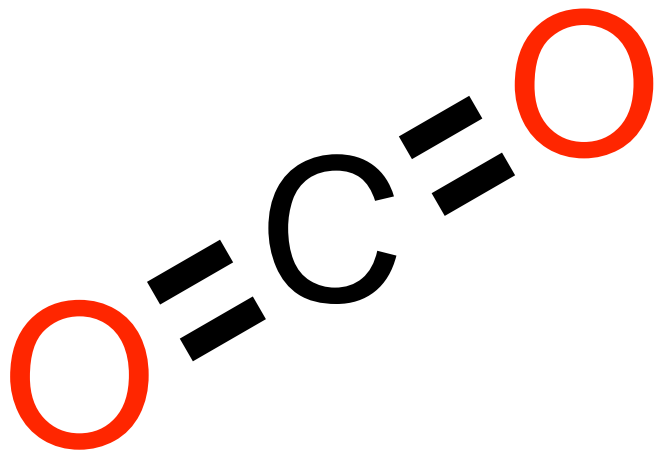
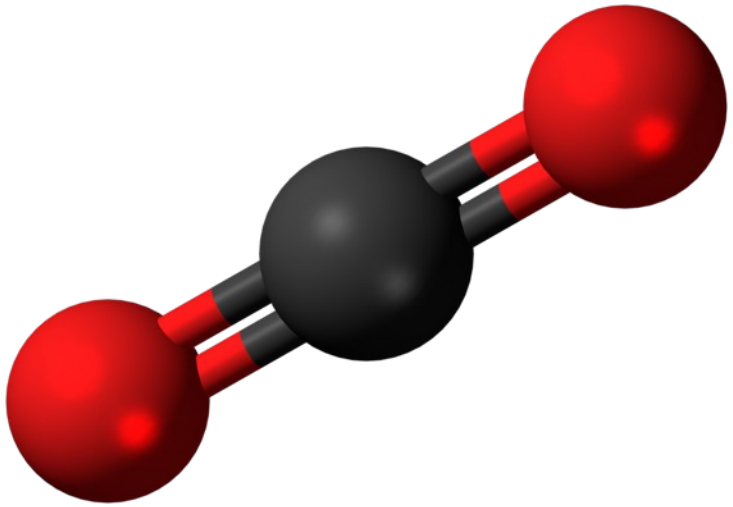
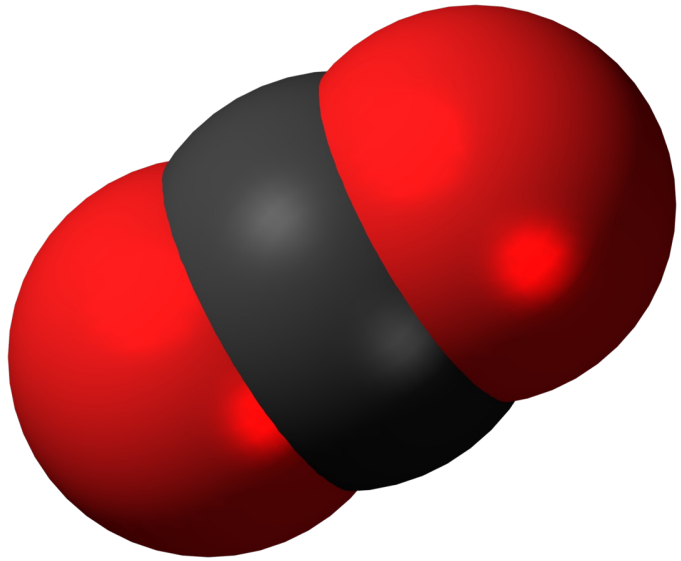


We Are Lucky That CO_2 is a Reactive Molecule







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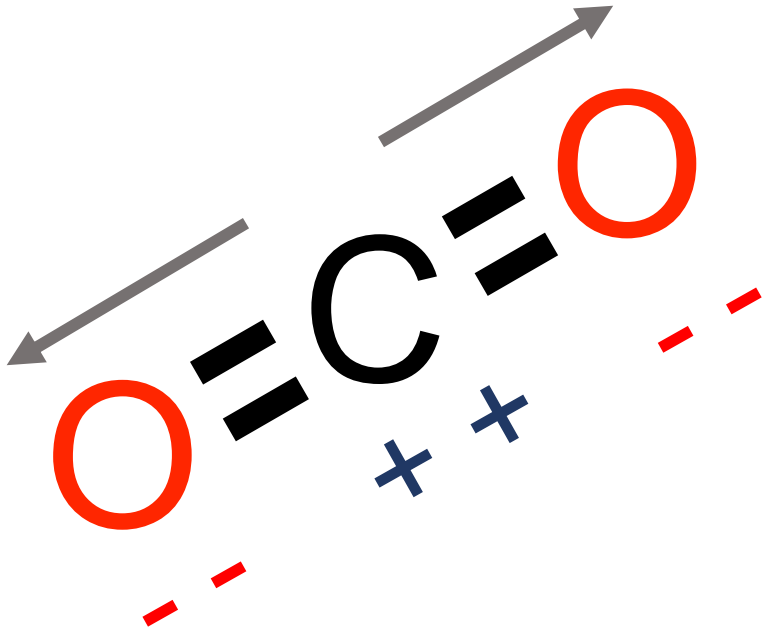

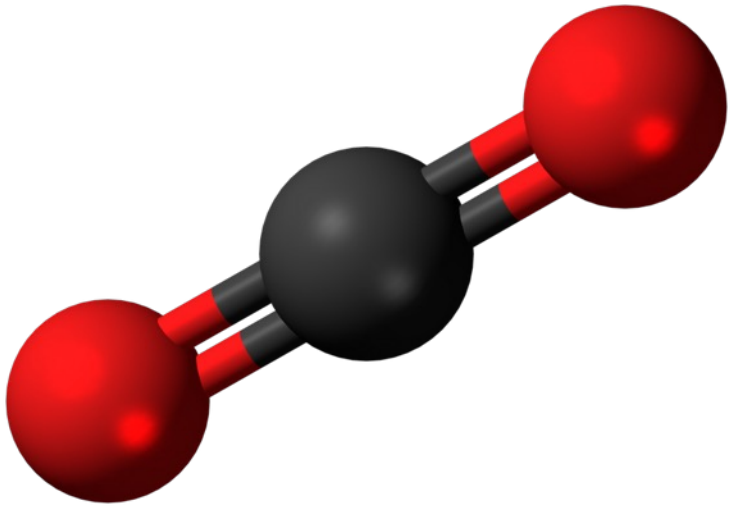

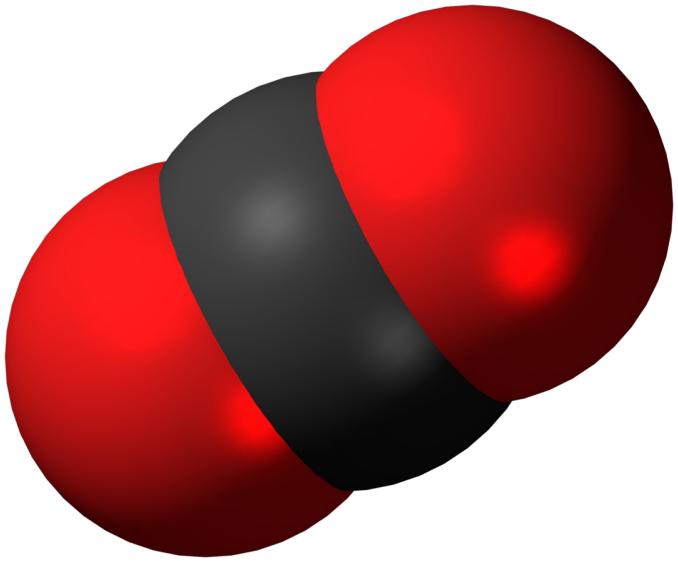

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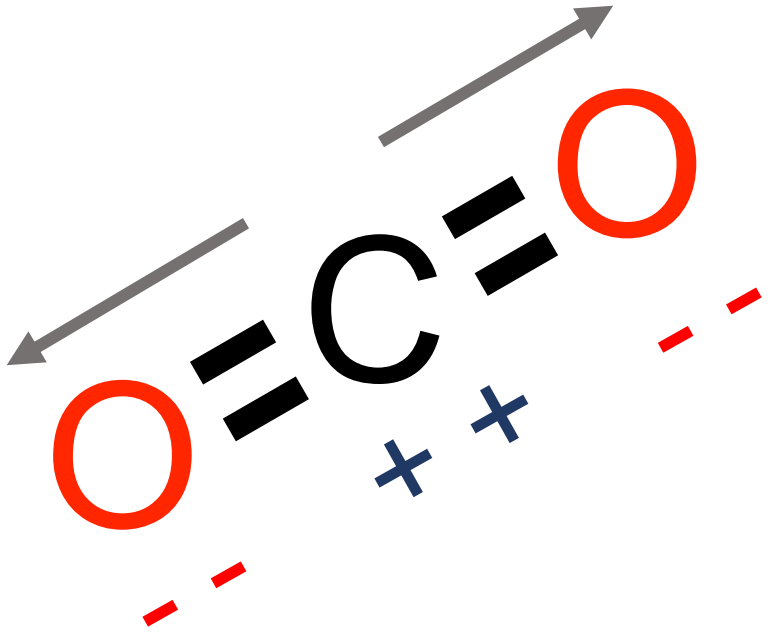
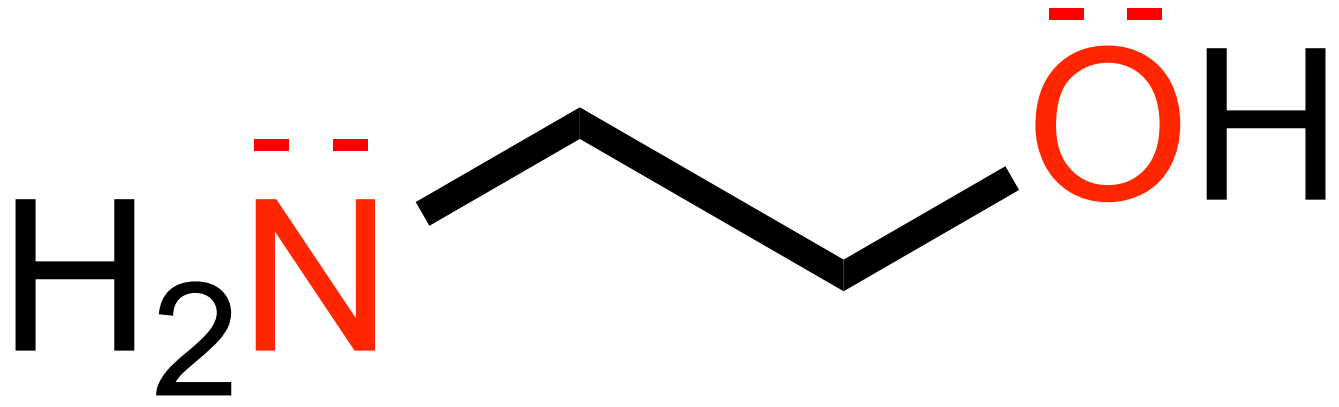
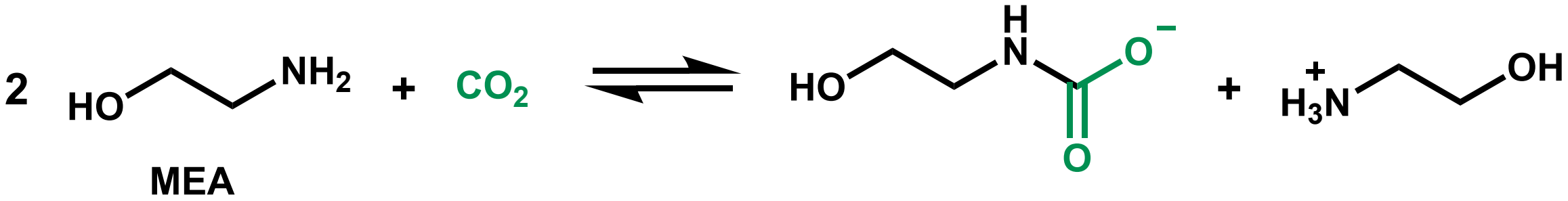




Aqueous Amine-Based Scrubbing of CO_2

In use since the **1930s**



- High selectivity for CO_2
- Operates in presence of water

Rochelle, G. T. *Science* **2009**, *325*, 1652
Sumida, Rogow, Mason, McDonald, Bloch, Herm, Bae, Long. *Chem. Rev.* **2012**, 112, 724
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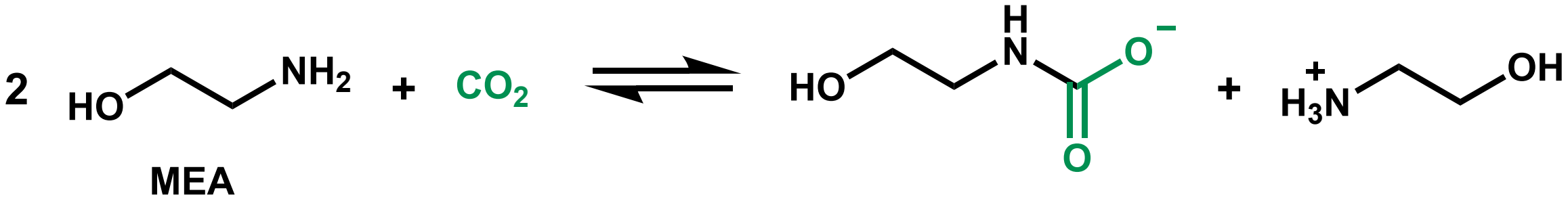

- High selectivity for CO_2
- Operates in presence of water

- Low working capacity (3–5%)
- Thermally degradable
- Corrosive
- High regeneration energy penalty (35%)
  - Huge heat capacity of water

Rochelle, G. T. *Science* **2009**, *325*, 1652
Sumida, Rogow, Mason, McDonald, Bloch, Herm, Bae, Long. *Chem. Rev.* **2012**, 112, 724
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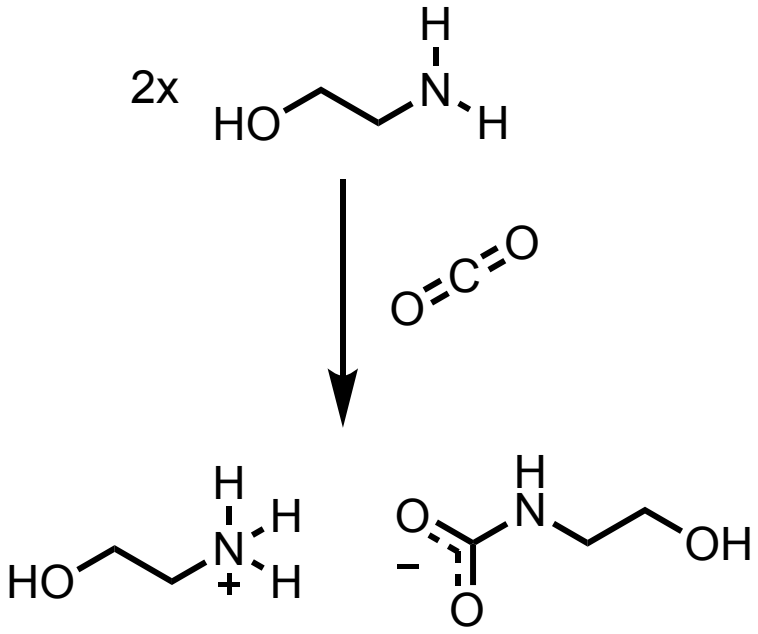
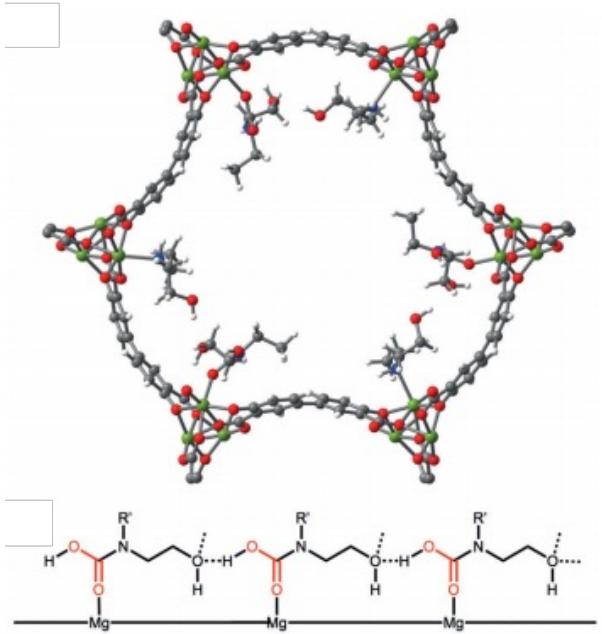
Moving to Solid Adsorbents for Chemical CO_2 Capture

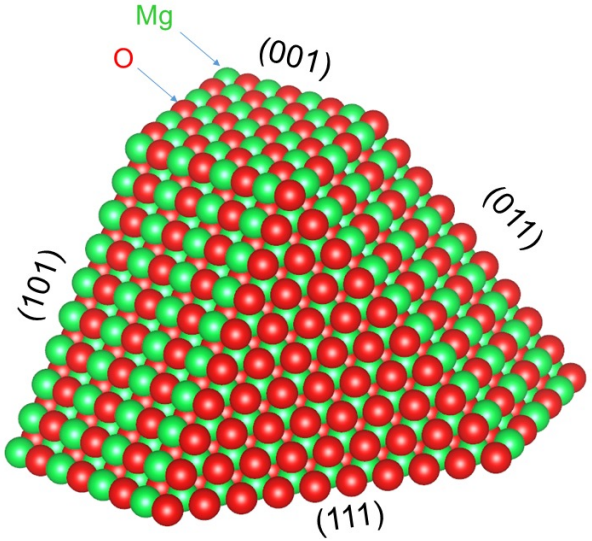
Aqueous Amines



Porous Frameworks



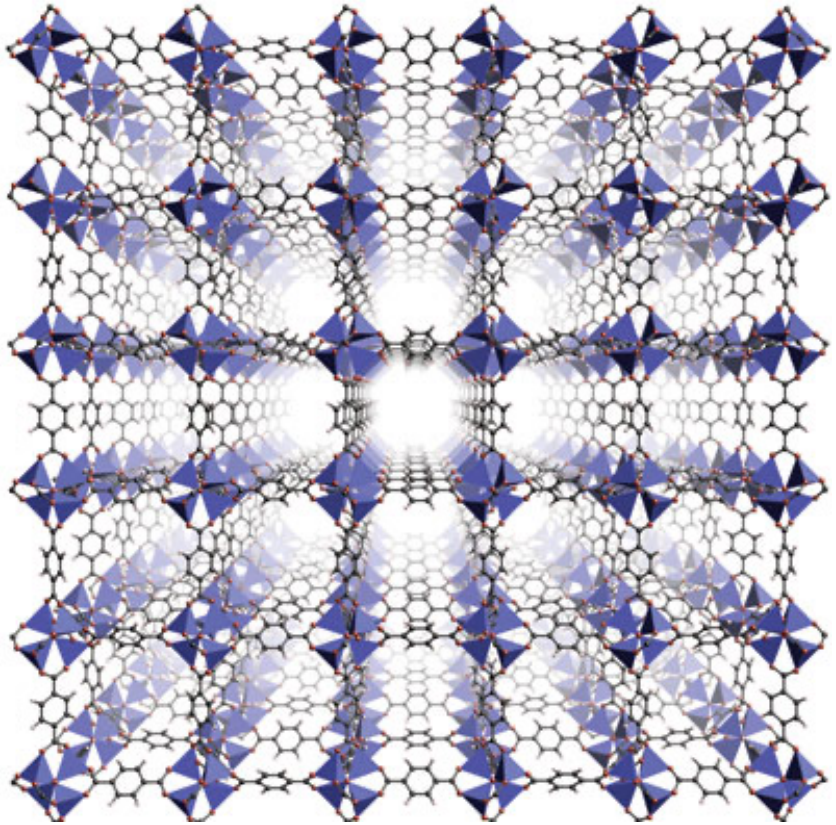
Faceted Metal Oxides



https://carbonengineering.com/our-technology/

Mao, V.; Milner, P. J.; Lee, J.-H.; Forse, A. C.; Kim, E.; Siegelman, R. L.; McGuirk, C. M.; Porter-Zasada, L.; Neaton, J.B.; Reimer, J. A.; Long, J. R. *Angew. Chem. Int. Ed*. **2020**, *59*, 19468– 19477

Metal–Organic Frameworks: Nanoscale Synthetic Sponges



$Zn_4O(1,4\text{-benzenedicarboxylate})_3$

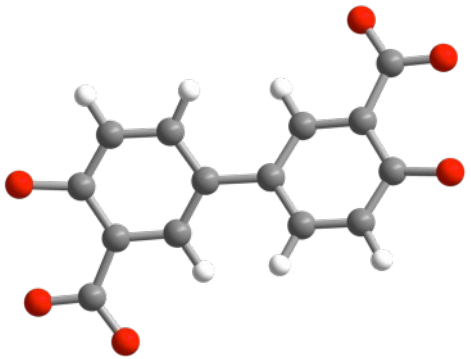
MOF-5

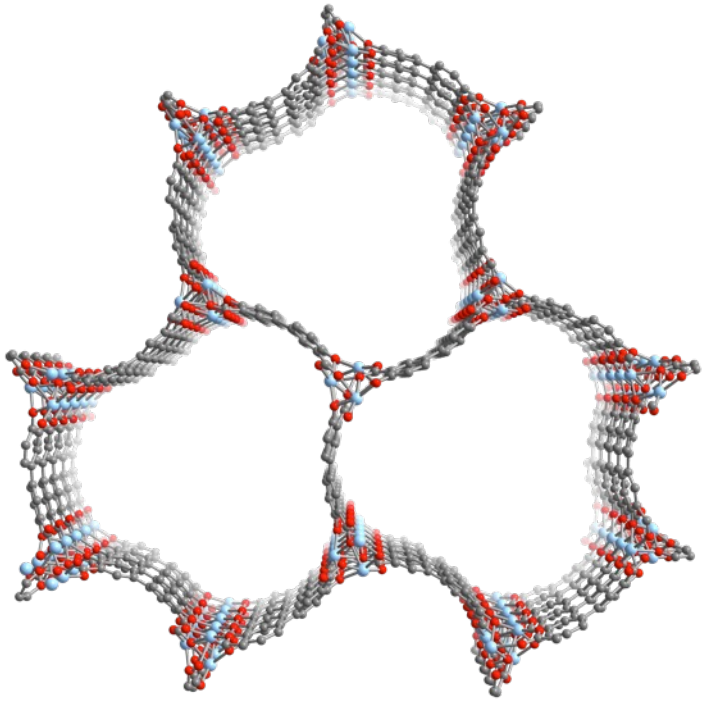
- BET surface areas up to 7100 m^2/g
- Density as low as 0.13 g/cm^3
- Tunable pore sizes up to 10 nm
- Channels connected in 1-, 2-, or 3-D
- Internal surface can be functionalized

Yaghi et al. *Nature* **2003**, *423*, 705
Kitagawa et al. *Angew. Chem., Int. Ed.* **2004**, *43*, 2334
Férey *Chem. Soc. Rev.* **2008**, *37*, 191

MOFs are Customizable for CO_2 Capture

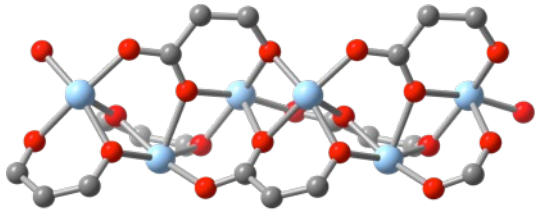
Organic Linker





Zn_2(dobpdc)

Inorganic Unit



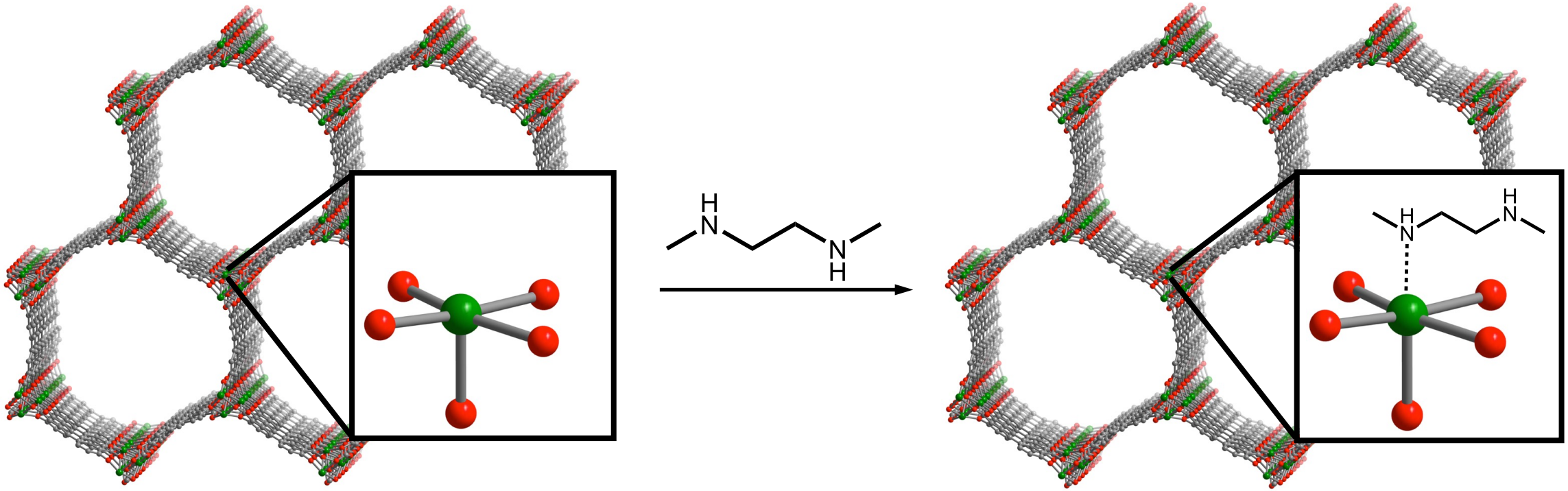
- High surface areas
- High tunability
- High working capacities

- Lower CO_2 selectivity
- **Generally do not work in the presence of water**

Sumida, Rogow, Mason, McDonald, Bloch, Herm, Bae, Long. *Chem. Rev.* **2012**, 112, 724

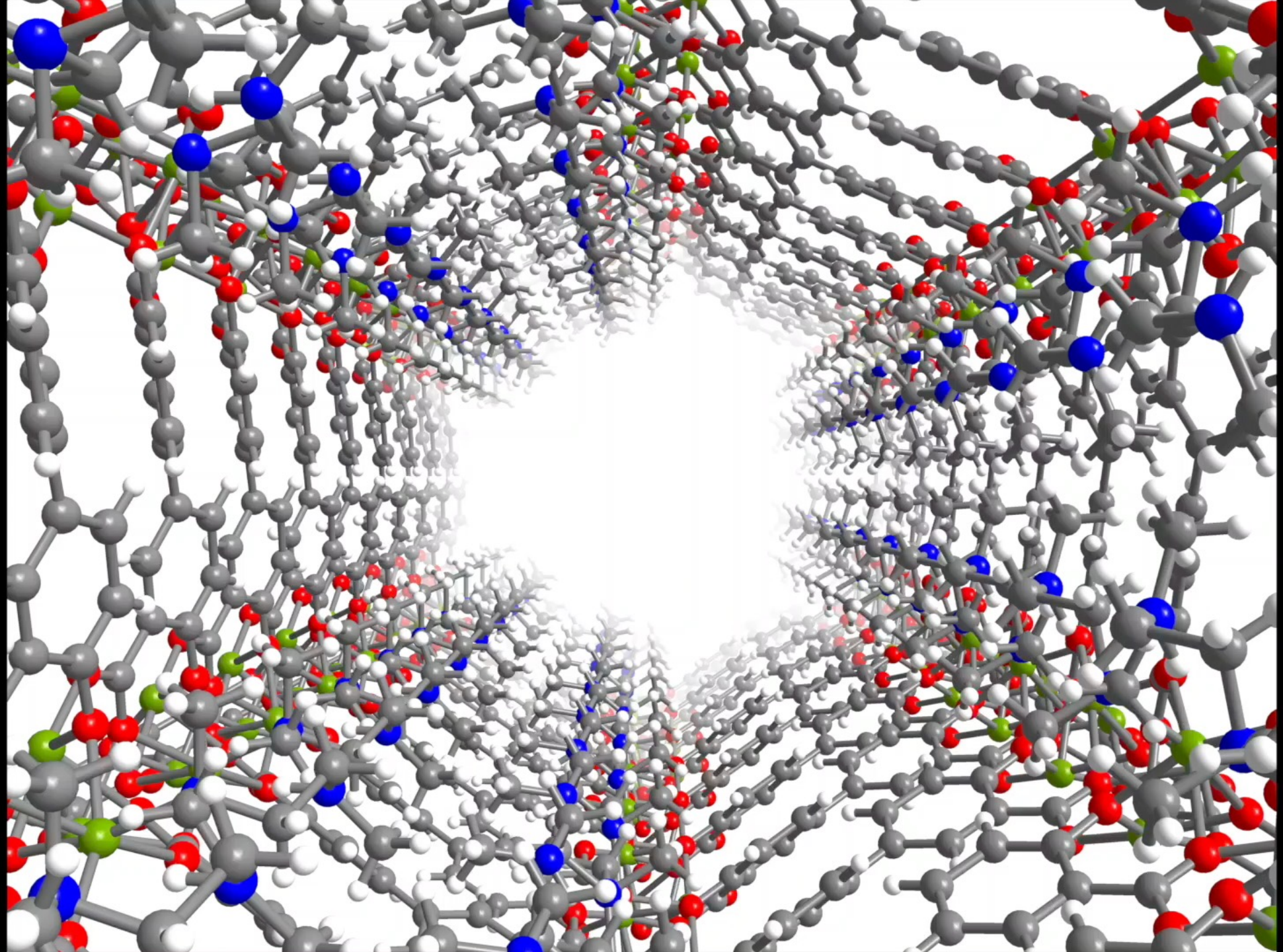
Siegelman, McDonald, Gonzalez, Martell, Milner, Mason, Berger, Bhown, Long. *J. Am. Chem. Soc.* **2017**, 139, 10526

Amine-Chemistry Can be Incorporated into MOF Adsorbents

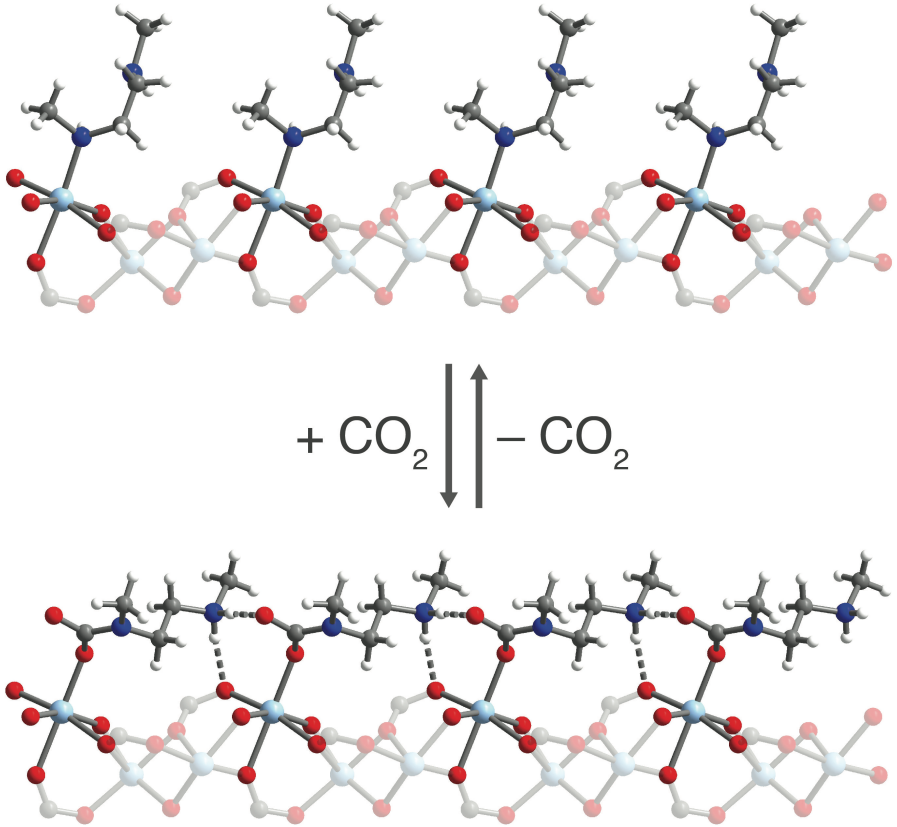


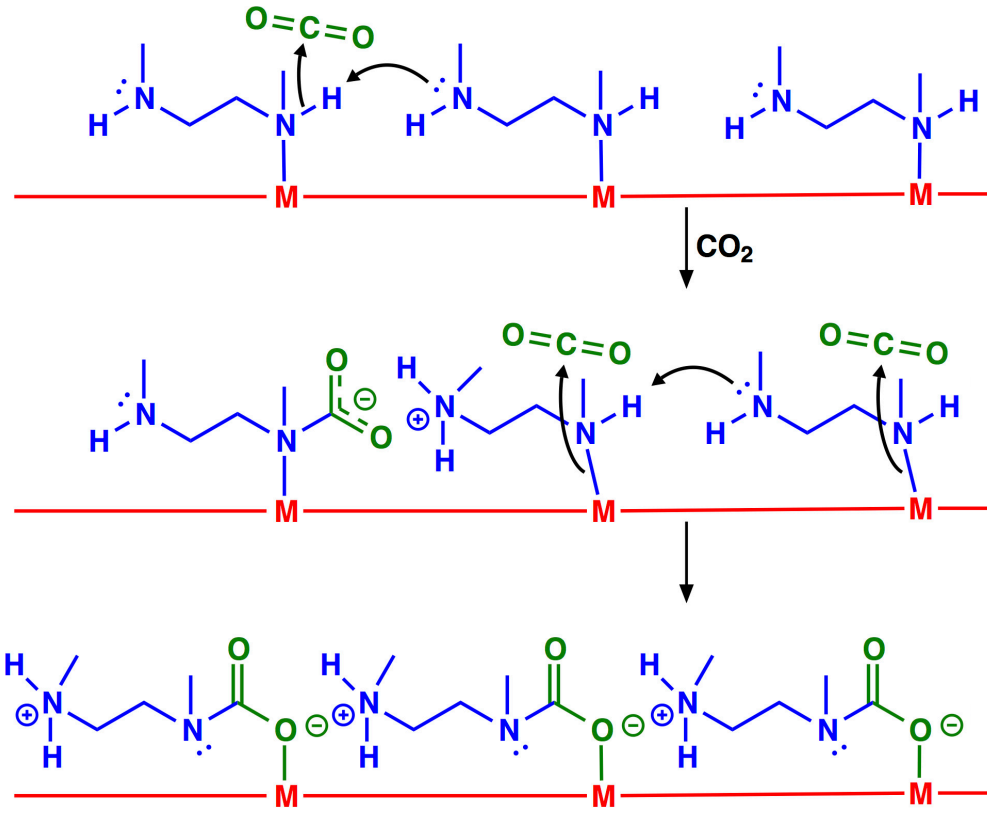
- This gives the combined benefit of solid adsorbent with low heat capacity and the chemical adsorption of amines

McDonald, Mason, Kong, Bloch, Gygi, Dani, Crocellà, Giordano, Odoh, Drisdell, Vlaisavljevich, Dzubak, Poloni, Schnell, Planas, Kyuho, Pascal, Prendergast, Neaton, Smit, Kortright, Gagliardi, Bordiga, Reimer, Long *Nature* **2015**, *519*, 303



Same Chemistry as Aqueous Amines, but on a Solid





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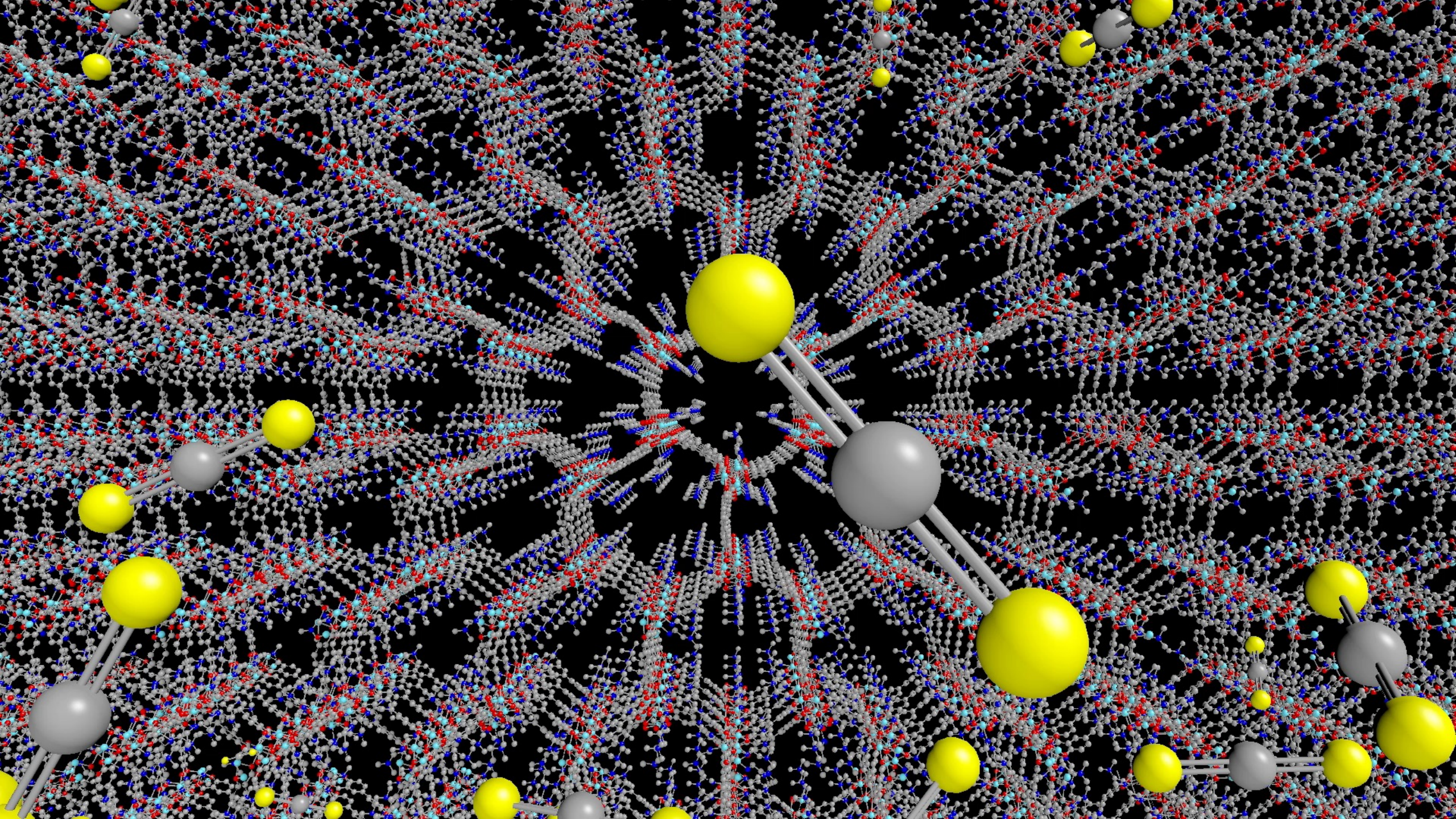
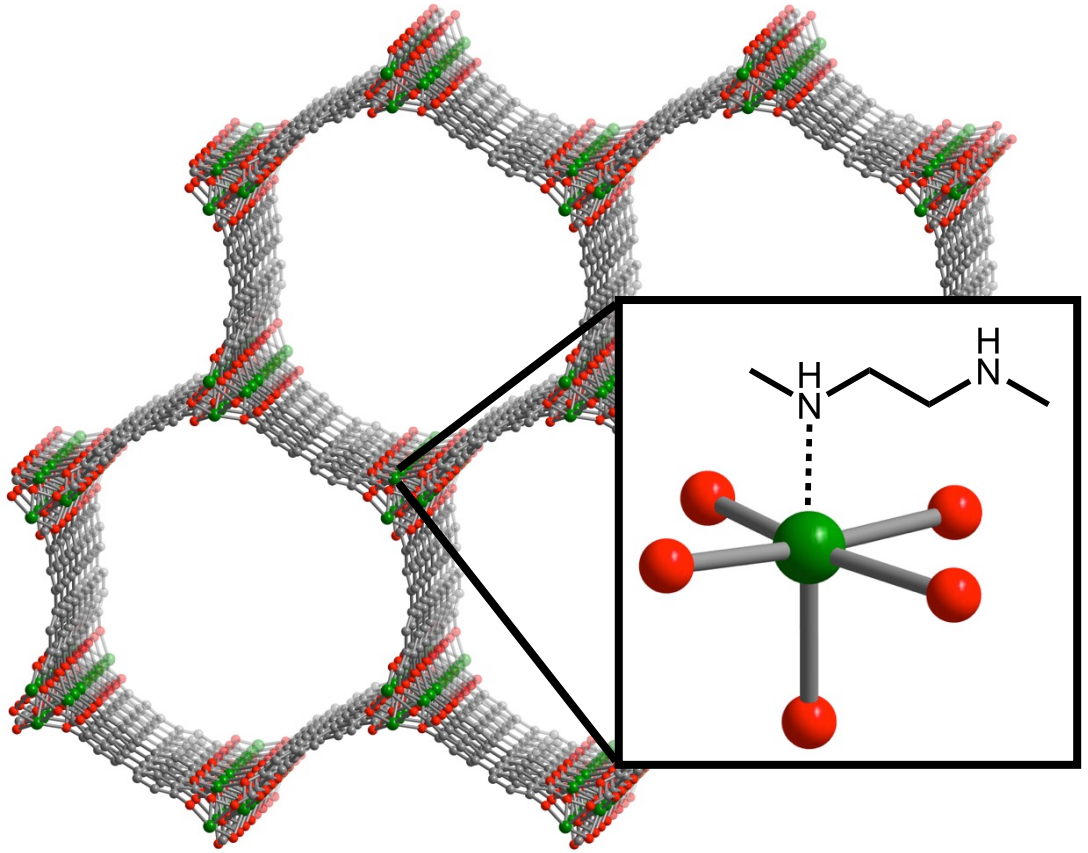


Metal–Organic Frameworks for CO_2 Capture

- Low Regeneration Energy
- Tunability for Different Point Sources
- CO_2 Selectivity from Mixed Streams
- High capacities

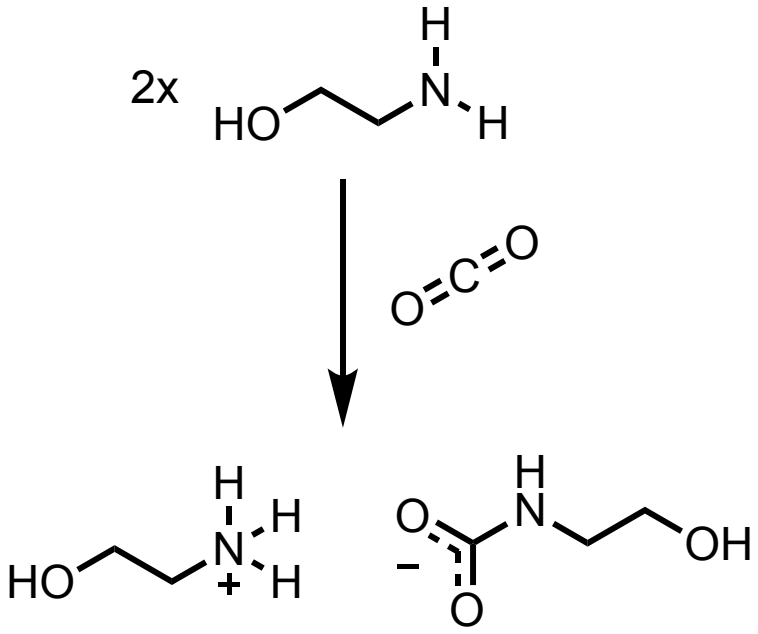
- Questions around long-term use
- Production Cost

- But both are getting better everyday!!



Using Earth-Abundent Minerals for CO_2 Capture

Aqueous Amines



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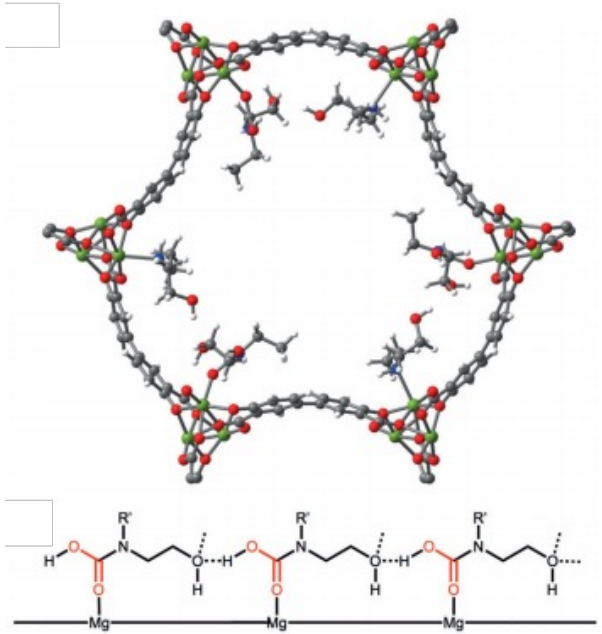

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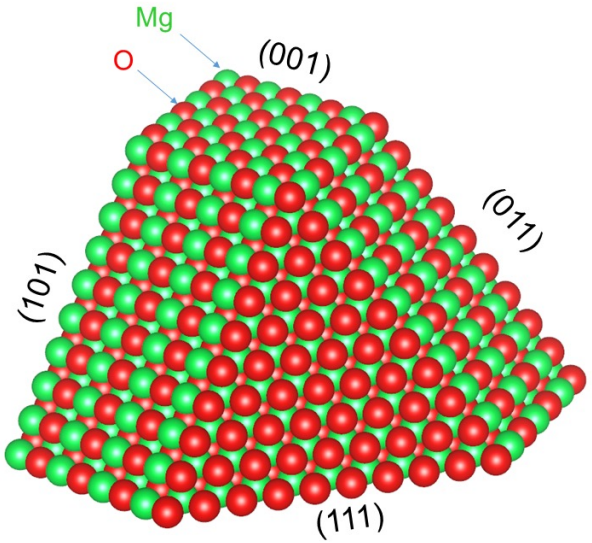

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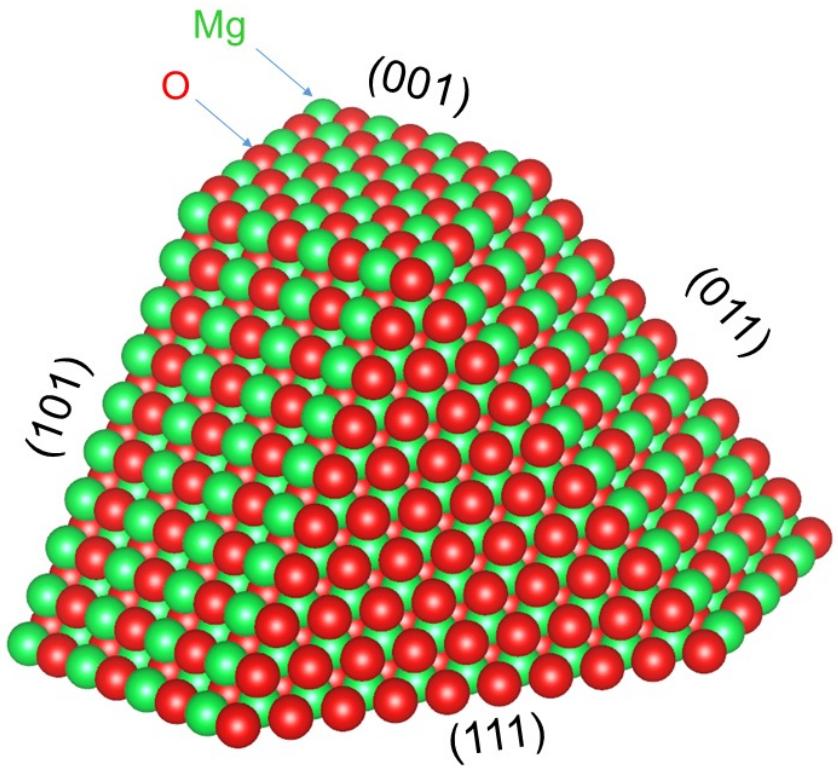
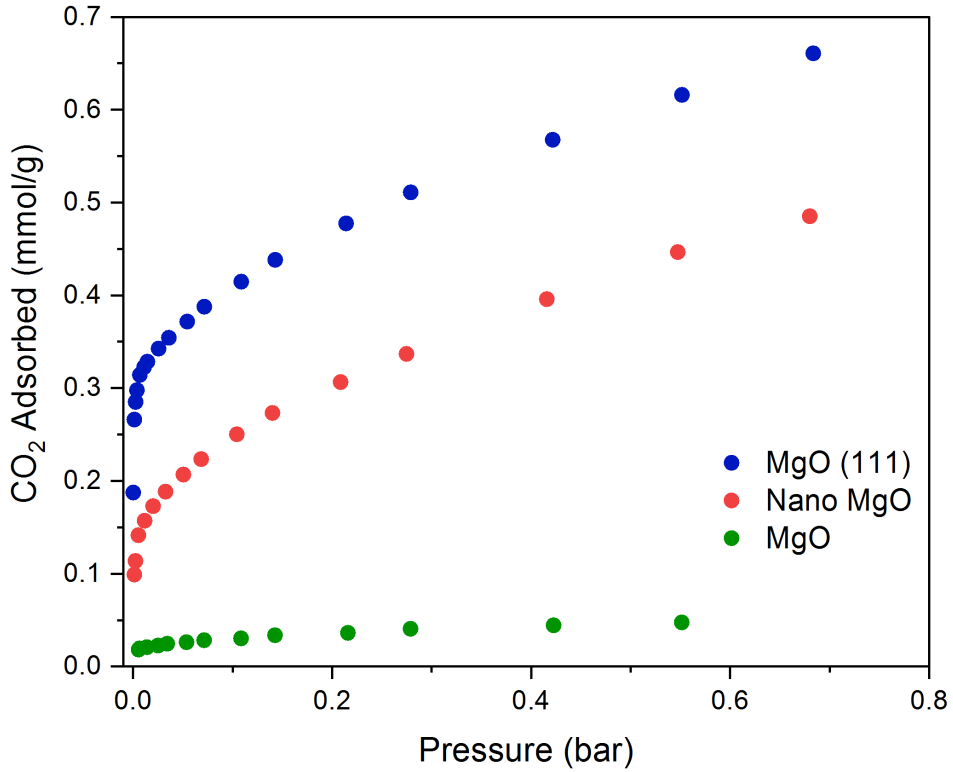
We Can Turn Rocks into Potent CO_2 Capture Adsorbents





- Bulk MgO shows very poor CO_2 adsorption
- Faceted MgO shows very enhanced CO_2 adsorption, particularly at low partial pressures

Mutch, G. A.; Shulda, S.; McCue, A. J.; Menart, M. J.; Ciobanu, C. V.; Ngo, C.; Anderson, J. A.; Richards, R. M.; Vega-Maza, D. *J. Am. Chem. Soc.* **2018**, *140*, 4736−4742

How Synthetic MgO Stacks Up for Point Source Capture

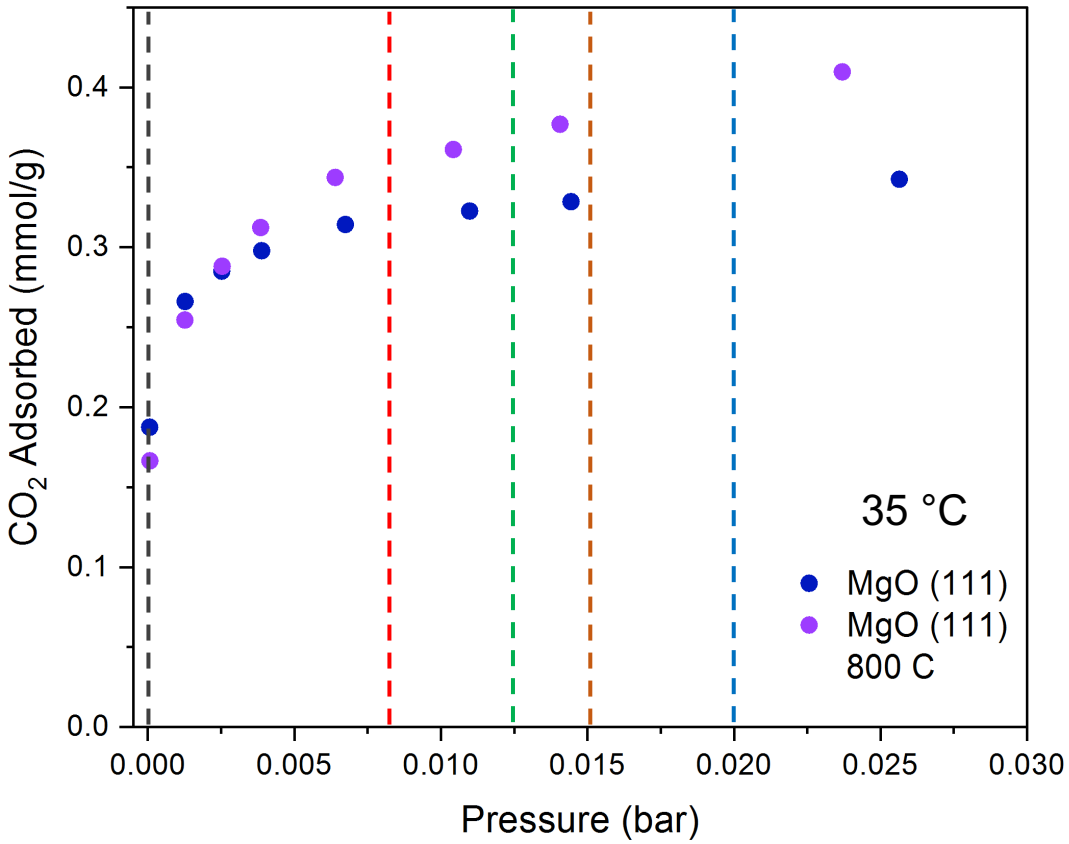
Direct Air Capture
Target: ≤ 0.04 mbar

Natural Gas Flue
Target: ≤ 8-10 mbar

Coal Flue
Target: ≤ 12-14 mbar

Tailpipe
Target: ≤ 14-16 mbar

Cement/Iron/Steel
Target: ≤ 20 mbar



- Targets for ***90 %*** capture from respective post-combustion sources

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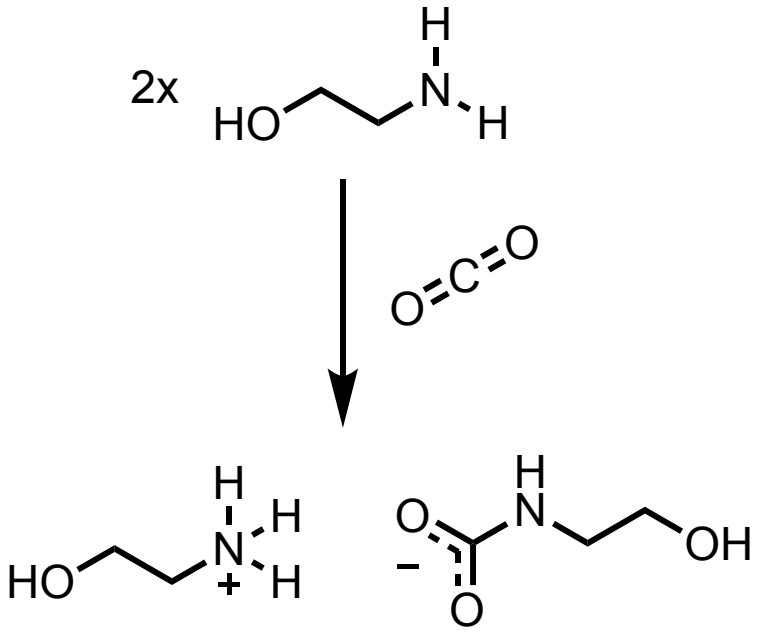
A Diverse Problem Requires Diverse Chemical Solutions

Aqueous Amines



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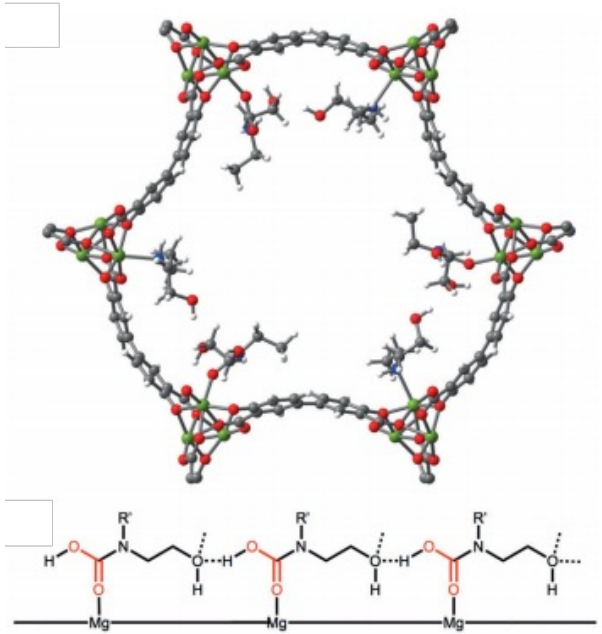

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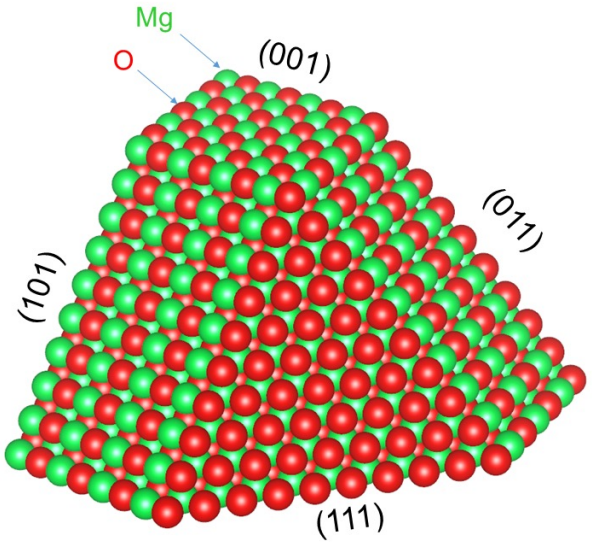

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