A learner-centric microbiology education framework

MicroChat: Elements of critical thinking

The Global Carbon Cycle, Geologic Time, and a Changing Climate

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Figure 1. Planet Earth, imaged by the Apollo 17 crew on December 7, 1972 (NASA photograph identifier AS17-148-22727). The hydrosphere (oceans, lakes, rivers), cryosphere (ice sheets, glaciers), atmosphere (air), biosphere (life), and geosphere (land, rocks), all of which are visible from space, dynamically interact to dictate Earth's near surface chemistry, drive biogeochemical cycles, and regulate global climate.

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Narrative: *January 28th, 2026 - Johanna, who is 15-years old and is in the eighth grade, is staying with her 70 yr old grandparents in rural Chariton, Iowa, for the week while her parents are on vacation. Her Grandpa Bill is a retired university professor. Johanna is just sitting down at the table after a bus ride home from school.*

Johanna: Grandpa, it is so noisy on the school bus. I just want to work on my homework, but it is too distracting. Did you experience this when you were growing up?

Grandpa Bill: Well, when I was growing up, I typically walked or rode my bike to school, depending on the weather. Buses were for kids that lived in the city, not for us rural kids. To make things worse, it was a lot colder than it is today and we typically had snow on the ground for several months of the year. There were days in April or May when it even snowed - things are different today and not just in how we transport ourselves to school.

Johanna: I love snow, but it doesn't snow much in Iowa anymore. How could it have snowed so much back in the 1950s when you were growing up and yet snow so little now?

Grandpa Bill: Well, understanding the answer to such a question requires deep, critical thinking. This is much of what I did before I retired as a professor at the university. I am just not sure that a student in middle school, such as yourself, is prepared to undertake such critical thinking.

Johanna: I can try Grandpa. I have taken a lot of classes in math, chemistry, and science, and next year, when I am in high school, I will have an opportunity to take an Earth sciences class where we will study geology, weather, and climate.

Grandpa Bill: Well, ok, let's give it a try by keeping things at a very basic level. Grab several pieces of paper so that you can take notes or write down questions – it is easy to find additional information on any of these topics using the internet. But this critical thinking exercise builds upon itself in its content. So please do stop me and ask questions if what I am talking about does not make sense.

Let us first consider our planet Earth as a largely closed system (**Fig. 1**) – think metaphorically of a snow globe that is encircled in glass – no new material (matter) can enter or leave the snow globe. When thinking this way, consider that the elements – essentially all the matter that makes up the air, the rocks, the soil, the water – are in the same quantities today as they were on early Earth, 4.0 billion years ago. Now, I say 4.0 billion years ago, rather than 4.54 billion years ago because Earth was still accreting, or accumulating, material during the first 540 or so million years of its history. But since 4.0 billion years ago, the matter of Earth has not changed very much.

Is this making sense thus far – Earth being a closed system, and the matter present today is essentially the same as it has been for the history of life on Earth?

Johanna: Yes, I think so. The elements, or matter, contained in the Earth globe have remained constant since about 540 million years after Earth formed.

Grandpa Bill: That is correct. However, that is not the complete story. This is where I will need you to put on your critical thinking hat. We will dive into complex concepts that are not neatly packaged in chemistry, biology, or mathematics textbooks. We need to think about these topics together at once, in what we like to call interdisciplinary thinking. This is difficult but once the links between disciplines click, they become difficult to forget. Ready?

Johanna: I am as ready as I will ever be. Let's go!

Grandpa Bill: Ok, while the elemental composition of Earth has not changed substantively over time, the reservoirs in which these elements are found, such as in the atmosphere, rocks, oceans, and biology have changed. For instance, the atmosphere has not always comprised of ~21% oxygen (O_2) and ~0.04% carbon dioxide (CO_2) like it does today. Remarkably, we know that O_2 levels on early Earth, say 2.4-2.5 billion years ago, were near zero and O_2 did not rise to present day levels until ~600 million years ago.

Johanna: Was the increase in O_2 600 million years ago due to more plant life, since they make a lot of O_2?

Grandpa Bill: That is a good question. The answer is that it was due to an increase in the activity of Cyanobacteria and algae, both of which are older than plants and both of which also make O_2. Primitive plants that are quite different than those on Earth today emerged around this time but were not likely responsible for much of the production of O_2 at this time.

What is intriguing, as we think about the history of the atmosphere, is that we can get accurate measurements of past atmosphere compositions by examining gases that were trapped in snow that ultimately became ice. In Greenland, we can find ice that is over a million years old, which allows scientists to estimate ancient CO_2 levels (**Fig. 2**). The analysis of many different ice cores, time and time again, has shown that CO_2 levels were often much higher than present levels in different periods of Earth's past, and when CO_2 levels were higher, the Earth was warmer.

Where it gets fascinating is when we start thinking about how life on Earth responded to those higher temperatures. As a general rule, organisms tend to grow faster when temperatures are warmer. As such, during warmer periods in Earth's past, the activity and growth of photosynthetic

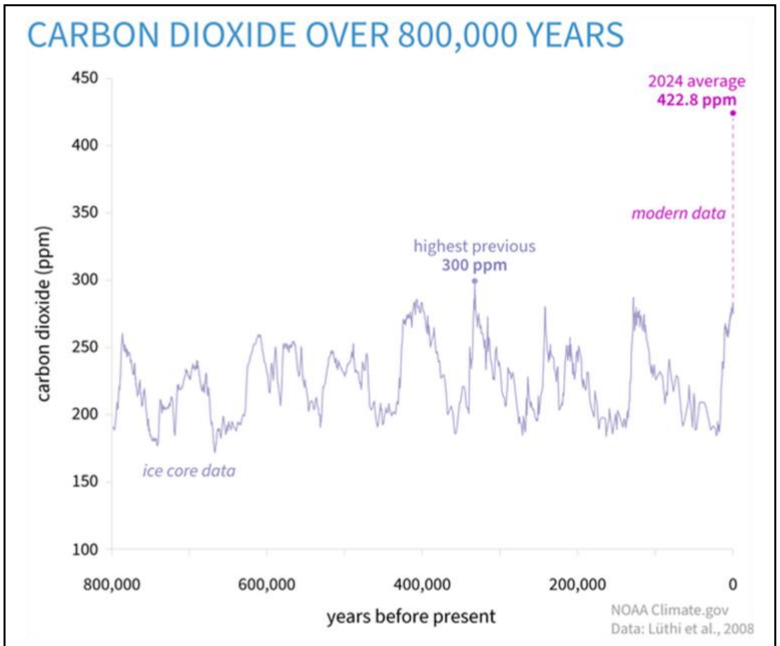

Figure 2. Atmospheric CO_2 levels over the past 800,000 years. Source: NOAA Climate.gov graph based on data from Luthi et al., 2008 (doi: 10.1038/nature06949).

Cyanobacteria and algae were stimulated. These microorganisms removed CO_2 from the atmosphere reservoir and converted the carbon to biomass that made up their cells, the so called "organic carbon reservoir." On your note paper, please write glucose (a simple sugar made of organic carbon) with the chemical formula of $C_6H_{12}O_6$. Also write down O_2. For simplicity, both of these can be considered products of cyanobacterial or algal growth. Now, the reactants for cyanobacterial and algal photosynthesis are CO_2 and water (H_2O). We can write this out as a balanced reaction according to the following formula:

$$6H_2O + 6CO_2 + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \text{Reaction 1}$$

While photosynthetic organisms that convert CO_2 into organic matter, such as glucose, are called autotrophs, there are consumers that utilize the reverse of Reaction 1 to fuel their cells, such as most microbes and all animals (including humans). Think about what all animals do – they eat organic carbon, inhale O_2, and exhale CO_2 and H_2O. In essence, consumers, or what we call heterotrophs, burn organic carbon (e.g., $C_6H_{12}O_6$) with the O_2 that they breathe, releasing CO_2 and H_2O as waste products which can be written as a balanced reaction according to the following formula:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 \qquad \text{Reaction 2}$$

Note that Reaction 2 is nearly the exact opposite of Reaction 1 and vice versa, minus the requirement for light by photosynthetic autotrophs. When autotrophs and heterotrophs grow together, their net activity is zero, which can be seen if you combine Reactions 1 and 2, as all reactants and products would cancel out through summation. Such yin-yang relationships are the basis for complex food webs that sustain all ecosystems, including those that support humans! However, we know that no food web has a net zero of waste – this is because not all the organic carbon can be degraded in a timely manner. For example, when Cyanobacteria and algae die in aquatic (water) environments, they sink. While they are sinking, some of their biomass is consumed by heterotrophs but much of it is deposited to the bottom of lakes or oceans where there is insufficient O_2 to burn the rest of that organic carbon biomass (Reaction 2). A similar phenomenon can occur with plant matter when it dies and gets inundated with water that prevents O_2 from reacting with the organic carbon, such as what can happen in wetland or swamp environments. Over many years, substantial amounts of biomass can be deposited. Ultimately, geological processes turn this buried organic material into oil (cyanobacterial or algal biomass) or coal (plant biomass) or natural gas (cyanobacterial, algal, or plant biomass).

Are you still following along ok, Johanna?

Johanna: Yes, I am surprised, but all of this makes a lot of sense. I never realized how biology, chemistry, and Earth sciences interact like this. It makes me wonder about what happens to the balance of Reactions 1 and 2 if one of the products from Reaction 1, glucose or $C_6H_{12}O_6$, is no longer being fully consumed as a reactant in Reaction 2?

Grandpa Bill: That is such an excellent question and one that I can only imagine that you were able to ask because of your ability to think critically about what we are discussing. It is so important to listen, ask questions, and push our own understanding further, like what you just did.

The answer to your question has everything to do with how animals survive on Earth and why today's atmosphere is 21% O_2. The burial of organic carbon over time has allowed atmospheric O_2 to increase ever so slightly and has helped to maintain low CO_2 concentrations – and it is all about the *imbalance* between Reactions 1 and 2. To say this another way, a system that is well balanced or in equilibrium, in which Reactions 1 and 2 are occurring at the same rate, would result in no removal of carbon from the biology reservoir where autotrophs and heterotrophs are growing together. However, if some of that organic carbon, in this case $C_6H_{12}O_6$, is deposited to the ocean floor, there is not enough oxygen to degrade the organic carbon in this environment, and it is then buried and made into oil or coal. This organic carbon effectively escapes the balanced cycle and leaves unreacted O_2 in the atmosphere. Over time, this allowed for O_2 to build up to current levels of 21%. Since animals cannot survive when O_2 is much lower than this, one can say that the burial of organic carbon also allowed for animals and humans to evolve.

That is a lot to take in and digest. Is this still making sense Johanna?

Johanna: Yes, intuitively it does make sense. But I am wondering how all of this relates to why it is warmer and less snowy today than it was when you were growing up nearly 70 years ago.

Grandpa Bill: We are getting there. The final piece of information that we need is to consider the effects of changing concentrations of chemicals in our atmosphere. We talked about changes in the

O_2 concentration and how this was beneficial for the evolution of complex life. But what about changing levels of CO_2?

Johanna: Hmm, I don't know if I have ever been asked to think about that.

Grandpa Bill: Think of CO_2 is an insulator that absorbs heat, much like a blanket helps you to hold onto heat. When CO_2 levels are high in the atmosphere, the blanket is thick and a lot of heat is retained and Earth is warmer. When CO_2 levels are low in the atmosphere, the blanket is thinner and less heat is retained and Earth is cooler. By converting atmospheric CO_2 into organic carbon via photosynthesis, two important potential outcomes can occur. First, the concentration of CO_2 in the atmosphere can be drawn down. Second, when a portion of that carbon was buried, it was removed from the atmosphere reservoir and transferred to the geosphere reservoir. Remember that the geosphere reservoir represents what is buried in the ground as oil or coal. Together, these processes function to maintain a cooler overall temperature. Yet, overconsumption of CO_2 by photosynthesis can lead to planetary glaciations which are also not conducive for plants and animals. Thus, the balance of Reactions 1 and 2 and the movement of carbon between these reservoirs must be in a fine balance to keep the planet habitable for life.

Johanna: This is a fun discussion, Grandpa. I cannot wait to try to repeat this discussion with my friends. However, I am still not clear on why it is warmer and less snowy today than when you grew up.

Grandpa Bill: Well, many scientists believe the reason for this is that, over the past 150 years, humans have increasingly mined the geosphere for oil, coal, and gas, so called fossil fuels because they were deposited into the geosphere reservoir several million years ago. Again, these fossil fuels are the buried, remnant biomass of cyanobacterial, algal, and plant cells. Excavation of fossil fuels exposes them to O_2, which humans take advantage of by combusting those fuels (Reaction 2) to generate energy to power modern life, including the bus that brought you home from school this afternoon and the heat that keeps our house warm. In essence, by excavating and burning fossil fuels, we are altering the balancing of Reactions 1 and 2, and in doing so, are causing the levels of CO_2 to increase in the atmosphere **(Fig. 3)**. In essence, the rate of release of CO_2 from the geosphere back into the atmosphere by fossil fuel combustion exceeds the rates at which Cyanobacteria, algae, and plants can convert it back into biomass, and at which it is buried. As such, the level of CO_2, or the thickness of the blanket in the atmosphere increases, and heat generated by radioactive decay of elements deep in Earth or absorbed from the sun cannot dissipate into space as easily, resulting in the warming of Earth. Historic cycles of CO_2 consumption and release have influenced global temperatures, but the rate at which CO_2 levels are currently increasing is abnormally fast – therefore warming is happening more quickly. If you think about it, we are returning carbon that was deposited into reservoirs like oil and coal over *millions* of years back into the atmosphere in *hundreds* of years.

Johanna: Is there anything that can be done to slow the release of CO_2 into the atmosphere?

Grandpa Bill: Well, one solution would be to stop burning fossil fuels. However, given how reliant modern society is on fossil fuels, this is not really a practical solution, at least within the next few years. True solutions to mitigate increased atmospheric CO_2 and to minimize downstream effects on the ecosystems that sustain humans will require a collective effort by all nations to reduce our dependency on fossil fuels over longer periods of time. We can do this by trying to use less energy, shift energy towards renewable sources, and by possibly finding ways to sequester atmospheric CO_2 in other reservoirs, such as rocks.

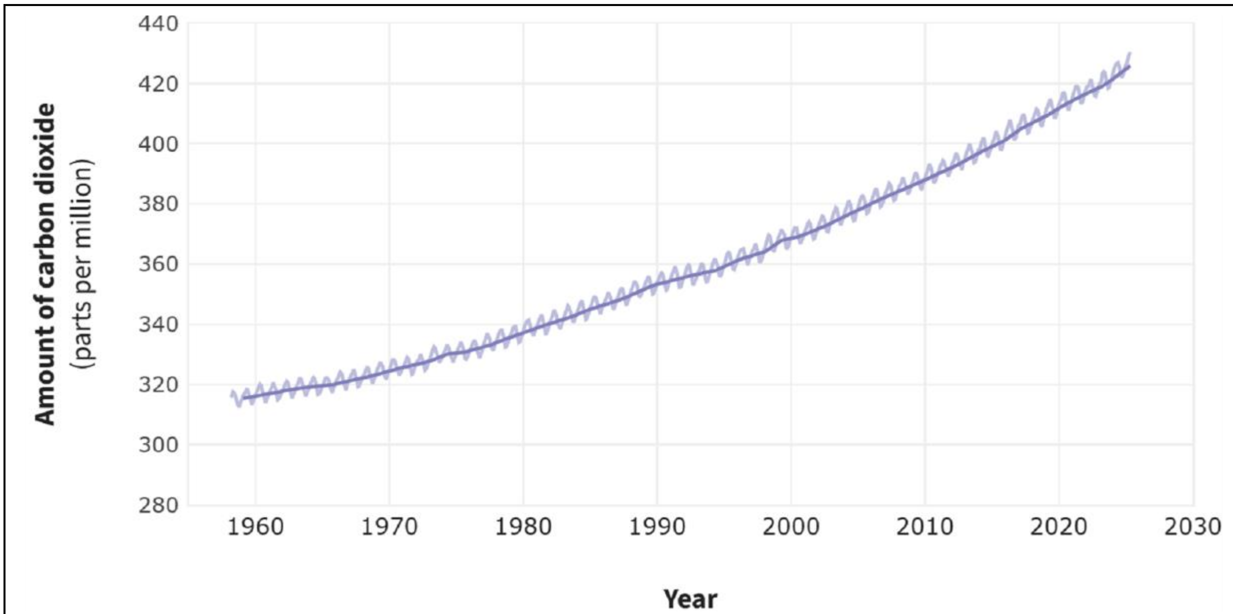

Figure 3. Modern recording of atmospheric CO_2 at Mauna Loa Observatory in Hawaii since 1958. Note that the yearly oscillations are driven by CO_2 drawdown due to photosynthesis (sequestration of CO_2 into biomass) in the Northern hemisphere during summer months. Source: NOAA Climate.gov graph based on Mauna Loa monthly mean data from NOAA Global Monitoring Lab.

Johanna: I am optimistic that we can come up with a solution.

Grandpa Bill: I am also optimistic, Johanna, especially after talking through this complex topic with you. A true solution to this complex problem will require critical thinking in ways that are different from the ways of thinking that led to this problem. In other words, you will need to think more critically than people of my generation. The only way we can do this is if we urgently start to encourage kids to ask difficult questions and seek understanding where traditional disciplines like biology, chemistry, biogeochemistry, atmospheric sciences, geology, social sciences, economics, and others overlap. This is a daunting but necessary component of critical thinking and is a skill that needs to be nurtured early and further developed as students matriculate through middle school, high school, and beyond.

Johanna: Challenge accepted. I cannot wait to discuss these ideas with my friends and then take this way of thinking into my classes next year. Grandpa, would you be willing to come to one of our Earth Science classes and talk to us about carbon cycling and its relation to climate change?

Grandpa Bill: I would be honored, Johanna. Now, let's get some dinner made before Grandma Frieda comes home.