

# Instructions for Lab #6

## The Geochemical Carbon Cycle

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### Carbon Cycle

For the following exercises, you will use the GEOCARB model, which simulates the earth's carbon cycle.

The GEOCARB model has two time periods:

- First, it runs for 5 million years with the “*Spinup*” settings in order to bring the carbon cycle and climate into a steady state. Only the last 1000 years of the *spinup* are saved.
- Then, at time zero, it abruptly changes the parameters to the “*Simulation*” settings and also dumps a “spike” of CO<sub>2</sub> into the atmosphere and runs for another 2 million years with the new parameters to see how the climate and carbon cycle adjust to the new parameters and the CO<sub>2</sub> spike.

The quantities that are graphed in the online version of the model include:

**pCO2** is the concentration of CO<sub>2</sub> in the atmosphere, in parts per million.

**WeatC** is the rate of CO<sub>2</sub> being weathered from carbonate rocks and moved to the oceans.

**BurC** is the rate of carbonate being converted into limestone and buried on the ocean floor.

**WeatS** is the rate of SiO<sub>2</sub> being weathered from silicate rocks and moved to the oceans.

**Degas** is the rate at which CO<sub>2</sub> is released to the atmosphere by volcanic activity

**tCO2** is the total amount of CO<sub>2</sub> dissolved in the ocean, adding all of its forms:

$$tco2 = [CO_2] + [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}].$$

**alk** is the ocean alkalinity: the total amount of acid (H<sup>+</sup>) necessary to neutralize the carbonate and bicarbonate in the ocean. The detailed definition is complicated, but to a good approximation,  $alk = [HCO_3^-] + 2[CO_3^{2-}]$ . This is not crucial for this lab.

**CO3** is the concentration of dissolved carbonate (CO<sub>3</sub><sup>2-</sup>) in the ocean, in moles per cubic meter.

**d13Cocn** is the change in the fraction of the carbon-13 (<sup>13</sup>C) isotope, relative to the more common carbon-12 (<sup>12</sup>C) isotope, in the various forms of carbon dissolved in the ocean water.

**d13Catm** is the change in the fraction of <sup>13</sup>C, relative to <sup>12</sup>C in atmospheric CO<sub>2</sub>.

**Tatm** is the average air temperature.

**Tocn** is the average temperature of ocean water.

## Running the GEOCARB model from R

I have provided functions for running the GEOCARB model from R:

To run the model:

```
run_geocarb(co2_spike, filename, degas_spinup, degas_sim,
            plants_spinup, plants_sim, land_area_spinup, land_area_sim,
            delta_t2x, million_years_ago, mean_latitude_continents)
```

You need to specify **co2\_spike** (the spike in CO<sub>2</sub> at time zero, measured in billions of tons of carbon).

The other parameters will take default values if you don't specify them, but you can override those defaults by giving the parameters a value.

The arguments to the function are:

**filename** an optional file to save the results of the run to. You can read them back in using the `read_geocarb()` function: `r = run_geocarb(spike = 1000, filename = "test_run.txt")` `data = read_geocarb("test_run.txt")`

**degas\_spinup and degas\_sim** the rates of CO<sub>2</sub> degassing from volcanoes for the spinup and simulation phases, in trillions of molecules per year.

**plants\_spinup and plants\_sim** TRUE or FALSE values for whether to include the role of plants in weathering (their roots speed up weathering by making soil more permeable and by releasing CO<sub>2</sub> into the soil), and **land\_area** is the total area of dry land, relative to today.

**land\_area\_spinup and land\_area\_sim** The amount of land area, compared to today (1.0 means the same amount of land as today).

**delta\_t2x** The climate sensitivity (the amount warming for each time CO<sub>2</sub> is doubled), in degrees Celsius.

**million\_years\_ago** Simulate past climates when the sun was not as bright as today. The value of this variable is how many million years ago the year zero of the simulation should be. This is not currently working because of a bug in the web version of GEOCARB.

**mean\_latitude\_continents** The mean latitude, in degrees, of the continents.

The default values are: `degas = 7.5`, `plants = TRUE`, and `land_area = 1` for both the spinup and the simulation.

The default value for `delta_t2x` is 3.0, `million_years_ago` is 0, and `mean_latitude_continents` is 30, which corresponds to today's world.

`mean_latitude_continents` and `land_area` allow you to explore conditions in earth's past, where the continents had different areas and were located in different parts of the world.

`million_years_ago` is meant to allow you to explore how the silicate weathering thermostat worked in earth's past, when the sun was a lot less intense than it is today. However, this part of the model is not working now.

After you run `run_geocarb`, you would read the data in with `read_geocarb(filename)`. This function will return a data frame with the columns `year`, `co2_total`, `co2_atmos`, `alkalinity_ocean`, `delta_13C_ocean`, `delta_13C_atmos`, `carbonate_ocean`, `carbonate_weathering`, `silicate_weathering`, `total_weathering`, `carbon_burial`, `degassing_rate`, `temp_atmos`, and `temp_ocean`.

## Refresher on Plotting Several Variables

You may want to go back to the documentation for Lab #2 and refresh your memory about the `pivot_longer()` function for manipulating data frames and tibbles, and the different ways we can use `ggplot` to plot several variables on the same plot.

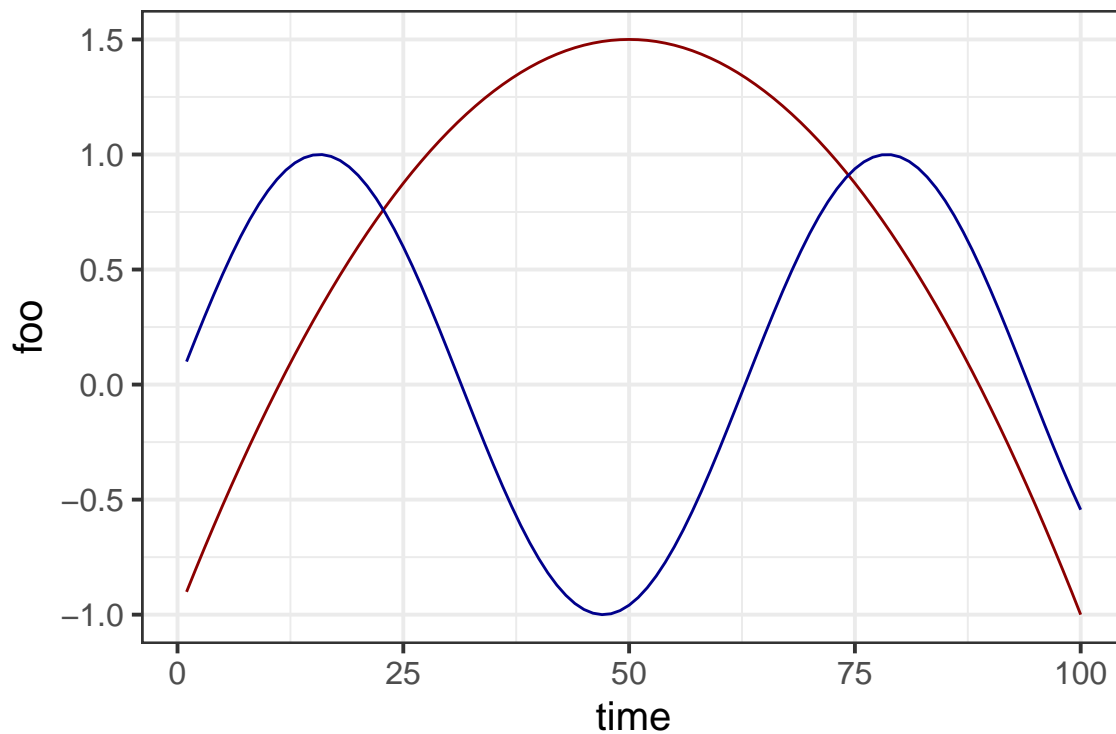
Suppose you have a tibble with columns `time`, `foo` and `bar`, as shown below:

```
df = tibble(time = seq(100), foo = -1 + 0.1 * time - 0.001 * time^2,
            bar = sin(time / 10))
kable(head(df), digits = 2)
```

time	foo	bar
1	-0.90	0.10
2	-0.80	0.20
3	-0.71	0.30
4	-0.62	0.39
5	-0.52	0.48
6	-0.44	0.56

Now, suppose you want to plot foo and bar on the same graph. You can do

```
ggplot(df, aes(x = time)) + geom_line(aes(y = foo), color = "darkred") +
  geom_line(aes(y = bar), color = "darkblue")
```



But it is more elegant to write

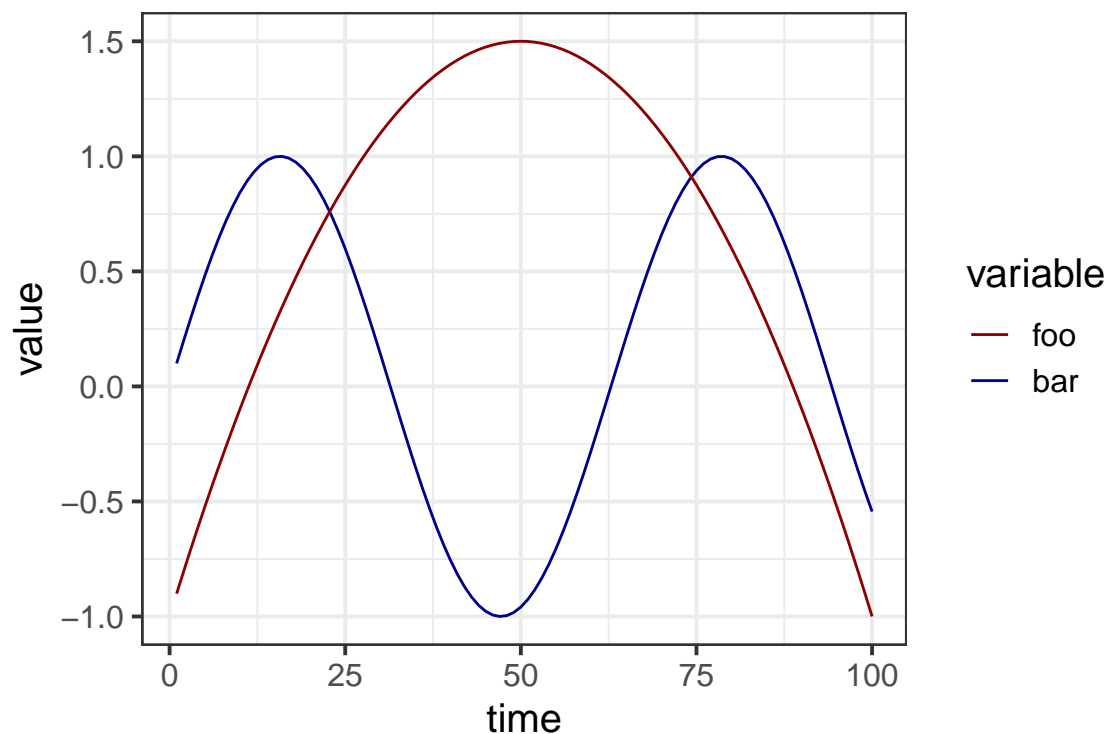
```
df_tidy = pivot_longer(df, cols = -time, names_to = "variable",
  values_to = "value")
kable(head(df_tidy))
```

time	variable	value
1	foo	-0.9010000
1	bar	0.0998334
2	foo	-0.8040000

time	variable	value
2	bar	0.1986693
3	foo	-0.7090000
3	bar	0.2955202

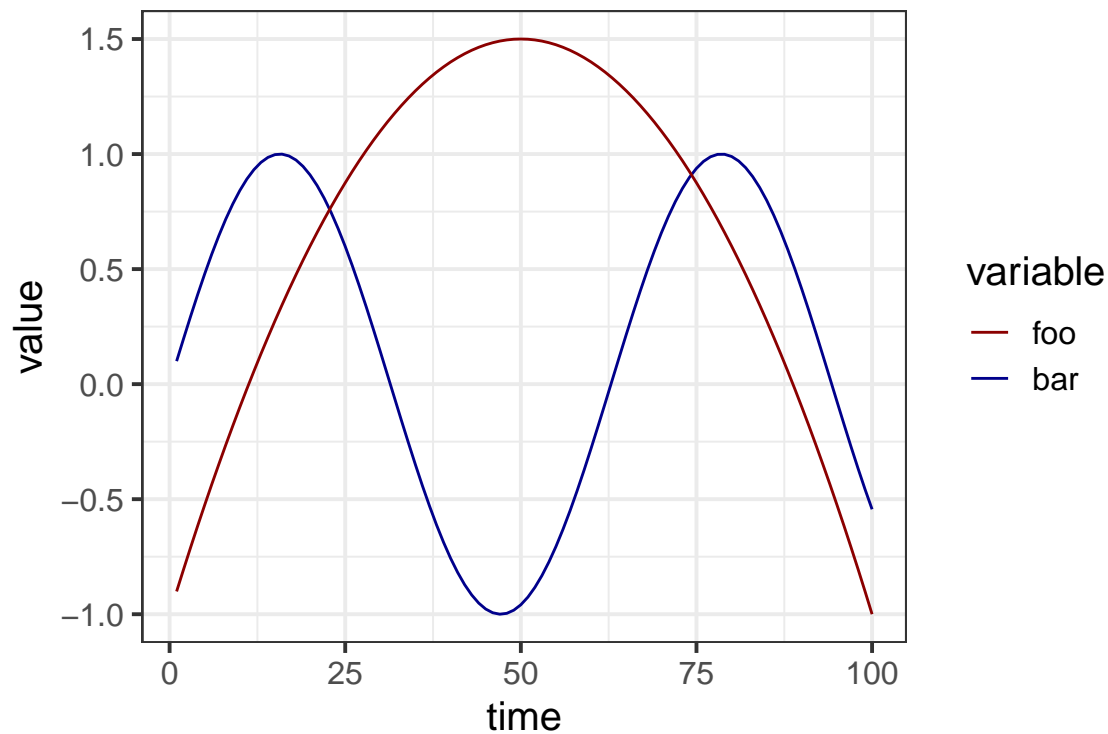
Now you can plot this:

```
ggplot(df_tidy, aes(x = time, y = value, color = variable)) + geom_line() +
  scale_color_manual(values = c(foo = "darkred", bar = "darkblue"))
```



And you can put this all together in a single expression using pipes:

```
pivot_longer(df, cols = -time, names_to = "variable",
  values_to = "value") %>%
  ggplot(aes(x = time, y = value, color = variable)) + geom_line() +
  scale_color_manual(values = c(foo = "darkred", bar = "darkblue"))
```



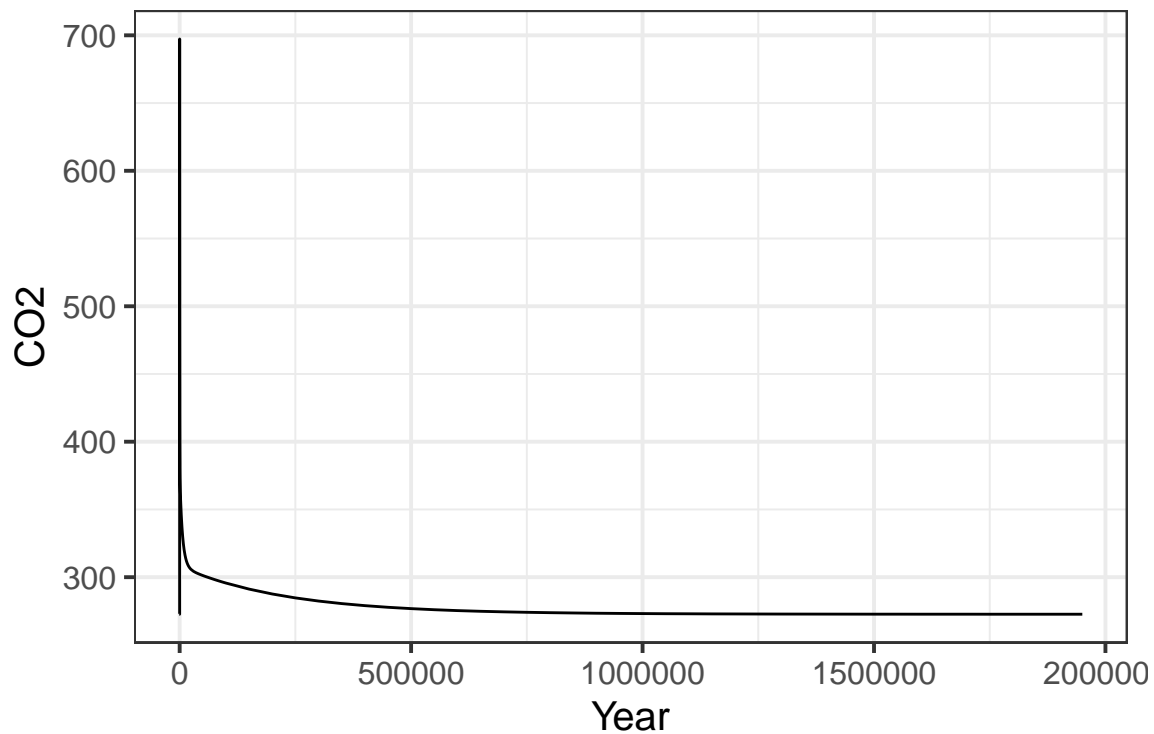
## Modifying the Axes of a Plot

Sometimes you have a lot of data and you just want to plot a small part of it. Consider the following GEOCARB model run:

```
geocarb_data = run_geocarb(1000)

## Rows: 140 Columns: 14
## -- Column specification -----
## Delimiter: ","
## dbl (14): year, tco2, alk, d13Cocn, pCO2, d13Catm, CO3, WeatC, WeatS, TotW, ...
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.

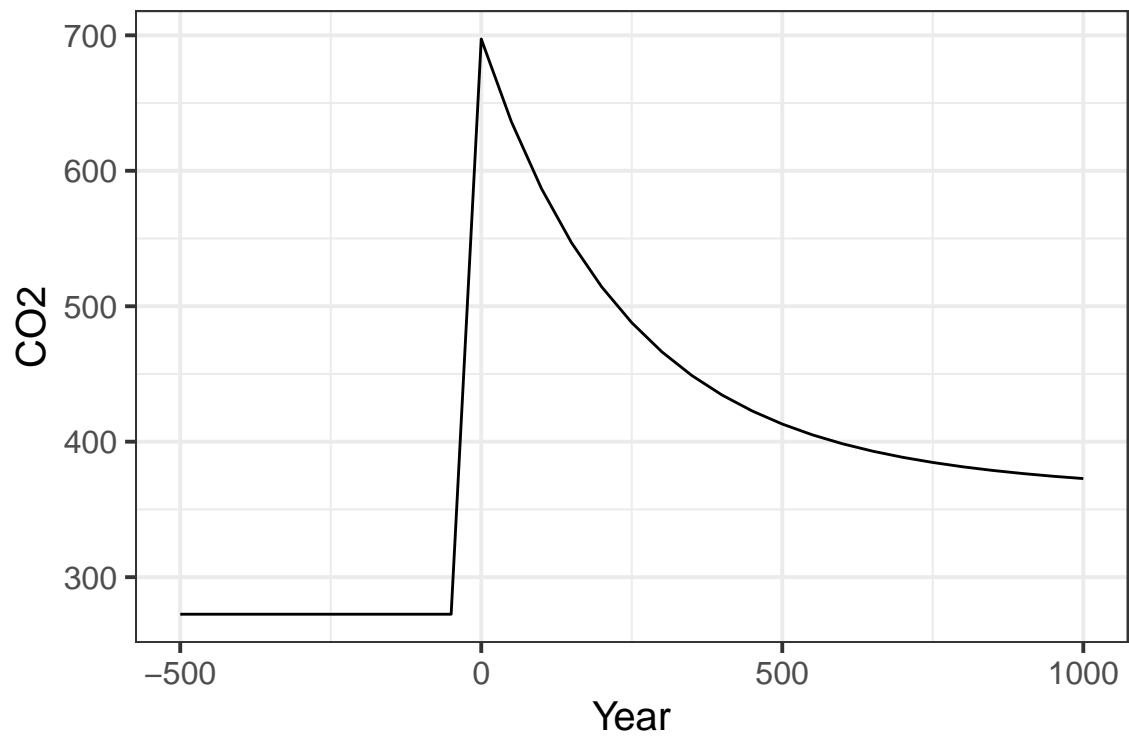
ggplot(geocarb_data, aes(x = year, y = co2_atmos)) + geom_line() +
  labs(x = "Year", y = "CO2")
```



This shows us all 2 million years of the model run, but we can't see the detail of what's happening near year zero. There are several ways we can zoom our plot in to look only at the region near year zero:

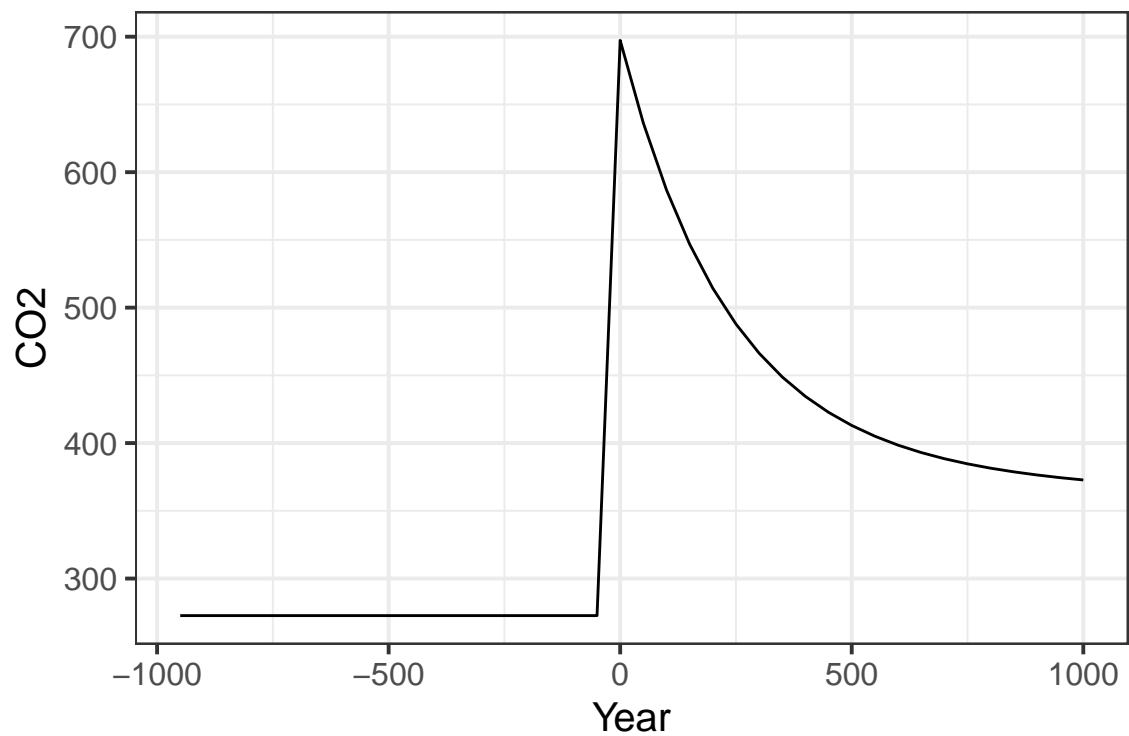
1. Use the `xlim` and `ylim` functions to set limits:

```
ggplot(geocarb_data, aes(x = year, y = co2_atmos)) + geom_line() +  
  xlim(-500, 1000) + labs(x = "Year", y = "CO2")
```



If you only want to change one limit, and leave the other at its default, you can put NA for the limit you want to leave alone:

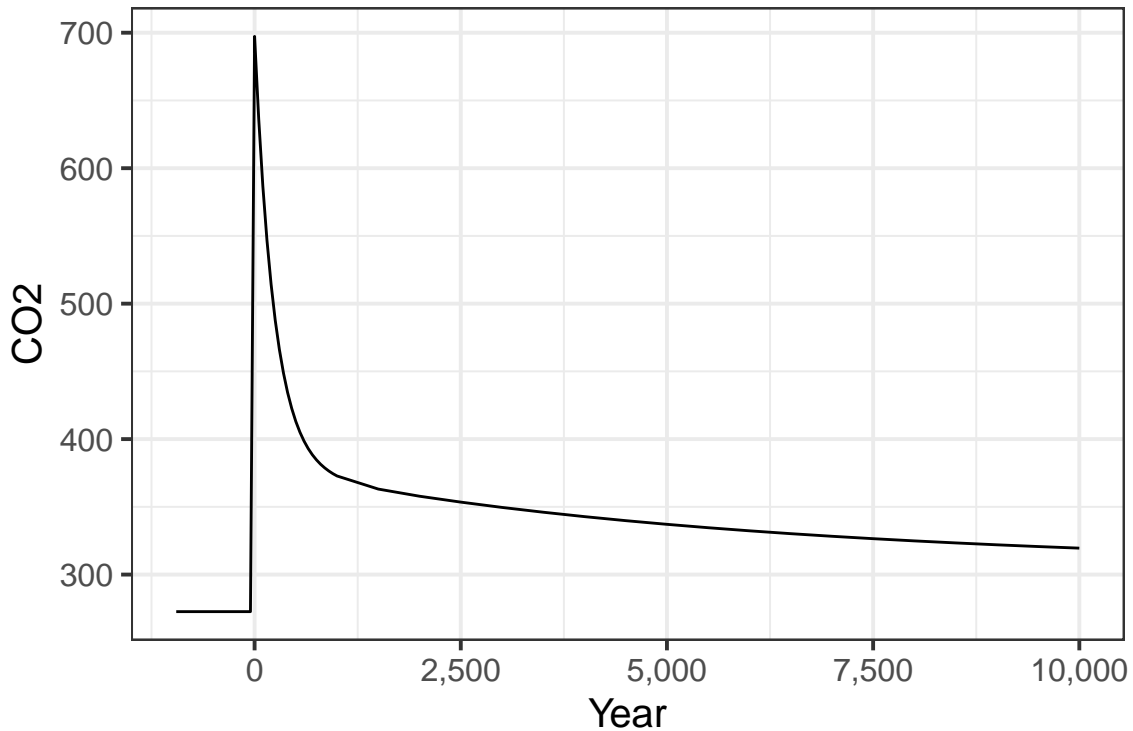
```
ggplot(geocarb_data, aes(x = year, y = co2_atmos)) + geom_line() +  
  xlim(NA, 1000) + labs(x = "Year", y = "CO2")
```





2. Use the `scale_x_continuous` and `scale_y_continuous` functions

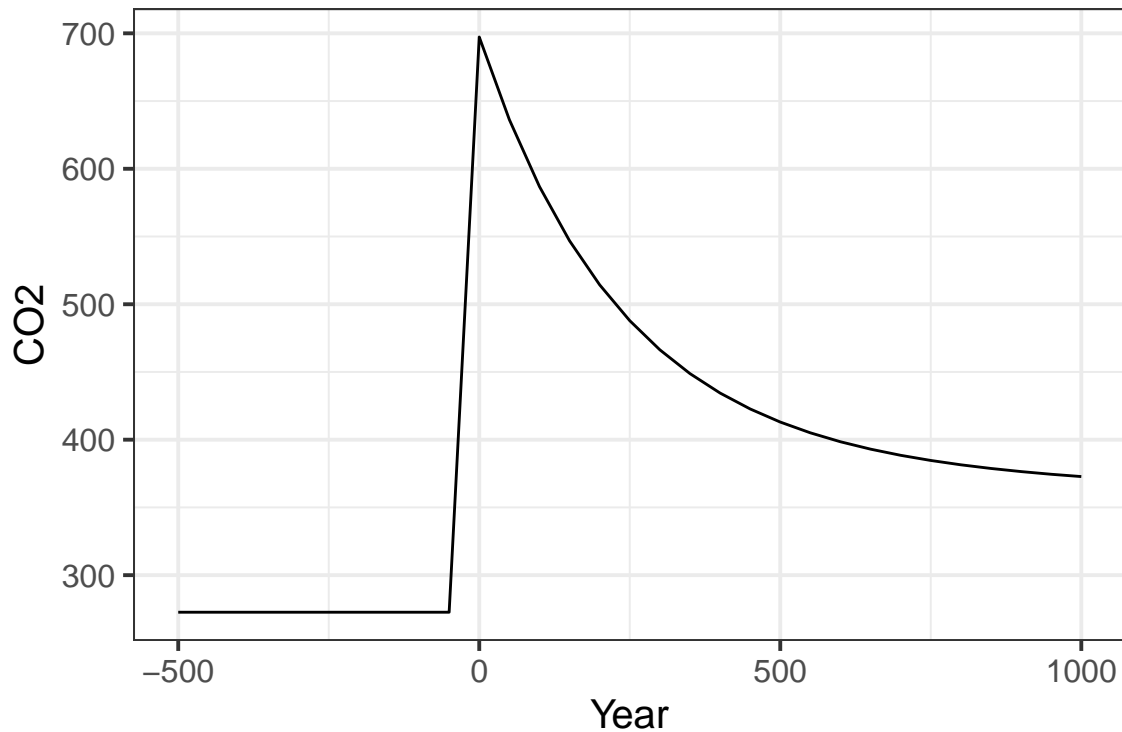
```
ggplot(geocarb_data, aes(x = year, y = co2_atmos)) + geom_line() +  
  scale_x_continuous(limits = c(NA, 1E4), labels = label_comma()) +  
  labs(x = "Year", y = "CO2")
```



Using the `scale_x_continuous` and `scale_y_continuous` functions lets you also modify the way numbers are formatted on the axis. Here, I used the `label_comma()` function to insert commas in the thousands and millions places. Other label commands include `label_percent`. You can read more about these at the web page for the scales package.

3. Another approach to limiting the extent of the plot is to filter the data before you call `ggplot`

```
geocarb_data %>% filter(year >= -500, year <= 1000) %>%  
  ggplot(aes(x = year, y = co2_atmos)) + geom_line() +  
  labs(x = "Year", y = "CO2")
```



## Exercises for Lab #6

### Exercise 1: Weathering as a Function of CO<sub>2</sub>

In the steady state, the rate of weathering must balance the rate of CO<sub>2</sub> degassing from the Earth, from volcanoes and deep-sea vents.

Write this exercise up as a discussion of what happens when the rate of volcanic degassing changes. This rate has changed many times in Earth's history.

- Discuss how CO<sub>2</sub> and temperature change both in the first thousand years after the rate of degassing changes, and also in the longer term, over the course of one or two million years.
- Discuss what causes the amount of CO<sub>2</sub> in the atmosphere to stabilize after the degassing rate changes.
- Discuss how the size of the change in degassing rate affects the amount of change in CO<sub>2</sub> and temperature between the original climate and where they finally stabilize with the new degassing rate.
- Explain the role of the silicate weathering thermostat in stabilizing the amount of CO<sub>2</sub>, and what determines the final stable value of CO<sub>2</sub>.

#### Details:

Run a simulation with `co2_spike` set to zero, and set the model to increase the degassing rate at time zero (i.e., set `degas_sim` to a higher value than `degas_spinup`). Leave `degas_spinup` at

7.5 and start out by setting `degas_sim = 10`.

- a) Does an increase in CO<sub>2</sub> degassing drive atmospheric CO<sub>2</sub> up or down? How long does it take for CO<sub>2</sub> to stabilize after the degassing increases at time zero?

For the purposes of this exercise, consider that CO<sub>2</sub> has stabilized when the rate of change in `co2_atmos` for a time-step in the model is less  $2 \times 10^{-5}$  ppm per year.

**Hint:** Look back to the discussion of the `lag()` function in Lab #2. The expression `co2_atmos - lag(co2_atmos)` will tell you the change in `co2_atmos` from the previous row to the current one in a tibble or data frame, and the expression `year - lag(year)` will tell you the number of years that passed from the previous row to the current one. Then `(co2_atmos - lag(co2_atmos)) / (year - lag(year))` will tell you the rate of change of CO<sub>2</sub>, in ppm per year.

If you have a tibble of data from a GEOCARB run, you can use the `mutate` function to add a new column to your tibble, and then use the `filter` function to select only the rows where `year > 0` (so you're looking after the change in degassing) and where the rate of change of CO<sub>2</sub> is less than  $2 \times 10^{-5}$  ppm per year. Remember that in R, you would write  $2 \times 10^{-5}$  as `2E-5` or `2.0E-5`.

- b) Check that the model balances silicate weathering against CO<sub>2</sub> degassing when the CO<sub>2</sub> in the atmosphere stabilizes. Use `ggplot` to make a graph illustrating this balance. What is causing the silicate weathering rate to change?

**Hint:** This is a good place to use the `pivot_longer` function to make a plot with two different variables, as I described above.

- c) Repeat this run with a range of degassing values for the simulation phase and make a table or a graph of the equilibrium CO<sub>2</sub> concentration versus the degassing rate.

Does the weathering rate always balance the degassing rate when the CO<sub>2</sub> concentration stabilizes?

- d) Take the last row from each of the the simulations you ran in part (c). This gives the values of all the variables 1.95 million years after the simulation began. Combine these into a single data frame, or tibble, and plot the silicate weathering rate versus the atmospheric CO<sub>2</sub> concentration. What does the relationship look like?

- e) Take the same data you used in part (d) and plot the silicate weathering rate versus the atmospheric temperature.

What does this relationship look like?

## Exercise 2: The long-term fate of fossil fuel CO<sub>2</sub>

Write this exercise up as a discussion of what happens if 2000 billion tons of carbon is released into the atmosphere as CO<sub>2</sub>. What do you learn from GEOCARB about where that CO<sub>2</sub> ends up and how the earth removes it from the atmosphere. Discuss how long the removal takes and what the implications are for how we should think about CO<sub>2</sub> in comparison to other kinds of pollution.

## Details

Use the GEOCARB model in its default configuration.

- a) Run the model with no CO<sub>2</sub> spike at the transition. What happens to the weathering rates (Silicate, Carbonate, and Total) at the transition from spinup to simulation (i.e., year zero)?

This is not a trick question. The answer should be obvious and simple.

- b) Now set the CO<sub>2</sub> spike at the transition to 2000 (2000 billion tons of carbon).

- What happens to the weathering at the transition? How does weathering change over time after the transition?
- How long does it take for CO<sub>2</sub> to roughly stabilize (stop changing)?

- c) In the experiment from (b), how do the rates of total weathering and carbonate burial change over time?

- Plot what happens from shortly before the transition until 10,000 years afterward.

**Hint:** See the discussion at the beginning of the lab instructions where I describe how to plot only a certain range of the data.

- Now plot the carbon burial and total weathering for the range 1 million years to 2 million years. How do the two rates compare?

## Exercise 3 (Graduate Students Only): How the Land Plants Changed the Carbon Cycle

The roots of plants accelerate weathering by two processes: First, as they grow, they open up the soil, making it more permeable to air and water. Second, the roots pump CO<sub>2</sub> down into the soil.

Write this exercise up as a report on the effects plants have on atmospheric CO<sub>2</sub> concentrations. If you turn off the plants during the spinup and then turn them on during the simulation, this simulates vascular land plants (plants with roots, stems, etc.) suddenly appearing in a world where they did not previously exist. How would this have affected the global carbon cycle and the composition of the atmosphere?

## Details

Run a simulation with no CO<sub>2</sub> spike at the transition and with no plants in the spinup, but with plants present in the simulation.

- a) What happens to the rate of weathering when plants are introduced in year zero? Does it go up or down right after the transition? What happens later on?
- b) What happens to atmospheric CO<sub>2</sub>, and why?
- c) When the CO<sub>2</sub> concentration changes, where does the carbon go?