Today we will use Stella to build a simple model of the carbon cycle that approximates that shown in Figure 1. The Stella version of this model is shown in Figure 2.

Stella is a "systems modeling" computer program that is ideal for this kind of "box" model. We need only conceptualize and Stella does all of the math for us. Stella includes the principal features we need in creating geochemical box models: reservoirs ("stocks" in Stella lingo: box icon) and fluxes ("flows" in Stella lingo: pipe/valve icon) between reservoirs. "Controllers" (circle icon) and "connectors" (arrow icon) are used to express the relationship between various parts of the models. Controllers are generally values or mathematical relationships between units related by connectors.

Notice that the flux between atmosphere and ocean and between deep and shallow ocean (upwelling and downwelling) depend on the amount in the reservoir from which the flux comes. This is because these exchanges depend on concentration. The biological pump and the fluxes between the atmosphere and the biosphere and soil carbon do not depend on the amount in the reservoir from which the flux comes (rate of photosynthesis is independent of atmospheric CO$_2$ concentration).

**A. Building the Simple Model**

In building your model, use the following values for stocks:

- Atmosphere: 750 gigatons (Gt.)
- Terrestrial Biosphere: 575 Gt.
- Soil Carbon: 1400 Gt.
- Surface Ocean: 750 Gt.
- Deep Ocean: 37600 Gt.

(These units are gigatons carbon equivalent, 1 Gt carbon = 3.66 Gt CO$_2$.)

Figure 1. The Carbon Cycle. Numbers in green show the amount of carbon (in 10$^{15}$ grams or gigatons, Gt.) in the atmosphere, oceans, terrestrial biosphere, and soil (including litter, debris, etc.). Fluxes (red) between these reservoirs (arrows) are in Gt./yr. Also shown in the approximate isotopic composition of each reservoir. Magnitudes of reservoirs and fluxes are from Schlesinger (1991).
Use the following flows
Gas Exchange  (Surface_Ocean-Atmosphere)/75
Downwelling    Surface_Ocean*.03
Upwelling      Deep_Ocean*.0007048
Biopump        4 Gt./yr
Photosynthesis  110 Gt./yr
Respiration     55 Gt./yr
Death           55 Gt./yr
Decay           55 Gt./yr

Figure 2. Simple Stella model of exogenic carbon cycle.

Notice that “gas exchange” is a bi-directional flow. To make it such, double click, then click the “biflow” radio button in the upper left hand corner of the dialog box.

To track atmospheric CO₂ concentration also create the following a controller with the following function (this converts the mass of atmospheric carbon dioxide to the concentration of carbon dioxide in parts per million by volume):

\[ \text{CO}_2 \text{ concentration} = \frac{\text{Atmosphere}}{2.12} \]

Over the last few decades, the concentration of atmospheric CO₂ has been increasing by 1.5 ppm/yr while average global surface temperature has been increasing by 0.015°C per year. Let’s assume that this temperature change is due to the increasing atmospheric CO₂, and furthermore that this relationship
will continue in the future. Thus to track global temperature, add a controller with the following formula (we assume with start with an average global temperature of 20°C).

Temperature = 20 + (CO₂ concentration - 354) * 0.01

Once you have built your model, run it without fossil fuel burning (i.e., set the fossil fuel burning flow to 0). The model should be very close to steady-state. Check that it is steady state by plotting several of the reservoirs, particularly the atmosphere (round off of some of the fluxes causes the reservoirs to be very slightly non-steady state).

Once you have a steady-state model, then add the fossil fuel burning. Set your run time to 200 (our units are years) and integration method to Runge-Kutta 2 and try the following experiments.

**Simple Model Experiments**

1. According to the UN Framework Agreement on Climate Change and the Intergovernmental Panel on Climate Change, the total global anthropogenic CO₂ emission (excluding land use change) was equivalent to 6 Gt carbon= in 1990. In the United States, CO₂ emissions increased at an annual rate of 1.4% percent per year between 1990 and 1998. Let’s assume this rate of increase applies globally. So set the fossil fuel burning flow to 6*(1 + TIME*0.014). What happens to atmospheric CO₂ and temperature in your model? What final value of CO₂ do you achieve (after 200 years)?

2. Compare this scenario with one in which CO₂ emissions remain fixed. Set the fossil fuel flux to 6. Now what happens to atmospheric CO₂ and temperature? What final value of CO₂ do you achieve?

**B. Interactive Model**

Now let’s make the model interactive. In Stella, go to the map level by clicking on the up arrow in the upper left above the e². Make a “slider” to control the fossil fuel flux. Also make new numeric displays for CO₂ and temperature.

1. To begin with, allow your equation to govern fossil fuel flux. Set the fossil fuel flux to 6. Allow the model to run for about 50 years, then pause it. Now turn the fossil fuel flux down to 0. What happens? What final value of CO₂ do you achieve?

2. The “Kyoto Convention” is supposed to limit CO₂ emissions in the future. The total cut in emissions should be 5% below 1990 levels by 2012. Use you model to examine the consequences of this agreement, should it be realized. Run you model for 22 years with the fossil flux set to 6*(1 + TIME*0.014). After 22 years, set the fossil fuel flow to 5.7 (i.e., 6 less 5%) and let it run for the remaining time with this flow. The easiest way to do this is by using an if...then...else construction: IF(TIME<22) THEN(6*(1+ TIME*0.014)) ELSE (5.7). What happens? Do the limits presently proposed by the Kyoto Convention solve the global warming problem?

3. Suppose we can turn up the biological pump by fertilizing the ocean with iron. Let’s model this by making a slider for the biopump. Make a slider, assign it to biological pump, and set the minimum and maximum to 0 and 6 respectively. Run you model for 50 years with the both fossil fuel and biopump flows set to “eqn on” and the biopump set to a value of 4. Then turn the biopump to 2 and see what happens. Run again doing the same thing but turning the biopump up to 6. What happens? What final value of CO₂ do you achieve?

**C. Final Touches**

Now let’s suppose that there is some sort of feedback between atmospheric CO₂ and the terrestrial biosphere. This could be any number of effects (to be discussed in Lecture 34). For example, nitrate emissions might be correlated with CO₂ emissions and hence increasing CO₂ emissions might enhance
terrestrial biosphere productivity. Let’s model this by supposing that the photosynthesis flux will increase by 0.1 Gt. for every Gt. of the fossil fuel burning flux.

To make this work, we must convert the fluxes from absolute to proportional values. Add the following connectors:
From terrestrial biosphere to respiration
From terrestrial biosphere to death
From soil carbon to decay
From terrestrial biosphere to photosynthesis
From fossil fuel burning to photosynthesis.

Change your fluxes as follows:

<table>
<thead>
<tr>
<th>Flux</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiration</td>
<td>Terrestrial_Biosphere*0.09565</td>
</tr>
<tr>
<td>Death</td>
<td>Terrestrial_Biosphere*0.09565</td>
</tr>
<tr>
<td>Decay</td>
<td>Soil_Carbon*0.0392857</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td>Terrestrial_Biosphere<em>0.1913+Fossil_Fuel_Burning</em>0.1</td>
</tr>
</tbody>
</table>

Your final model should look like the figure below:
Use the slider to turn off the fossil fuel flux and run the model to make sure you fluxes are in approximate steady state (make sure and turn the biopump back to 4).

Figure 3. Final Stella Model of CO₂ cycle.
Modeling the Carbon Cycle

1. Run the model with the original equation for the fossil fuel flux and the above fluxes. What final value of CO$_2$ do you achieve? How does the result compare to the case where you had a constant photosynthetic flux?

Extra Credit: The concentration of atmospheric CO$_2$ in the northern hemisphere shows an annual sinusoid oscillation (e.g., figure in lecture 35). Can you modify your model to mimic these annual cycles? (HINT: Once you modify your model, you’ll probably want to decrease the integration frequency (dT) in the time specs dialog box. Try setting dT to 0.1).