Let’s start with a concept that we all have some knowledge of - the water cycle. Suppose you want to use a dynamic model to illustrate the relationships among the various parts of the cycle. Before building the model, we must plan it out, making decisions along the way.

**Decision 1:** What is the purpose of our water cycle model?

Do we want to represent this complex cycle from the USGS?
Lesson 1: Always start simple! Once the simple model is built and tested, you can add other features to it.
**Decision 2:** Where will you find the numbers and equations for your model? How do you quantify something like the water cycle?

Let’s start with a physical model of a closed water cycle. Imagine the diagram below represents water in an aluminum pan with a clear cover. If we place the pan over a heat source, the processes of evaporation, condensation and precipitation would cause the water molecules to move from the pan to the air to the cover and back to the pan again.

![Diagram of a water cycle]

- To build a model of this, we need to know how much water will be in the pan, in the air and on the cover before we place the pan over a heat source.
- Next we need to estimate the rates at which water will evaporate into the air, condense onto the cover and fall back into the pan via precipitation.
- Think of the evaporation rate as the amount of water per minute that changes from its liquid form to its gaseous form.
- Think of the condensation rate as the amount of water per minute that changes from its gaseous form to its liquid form.
- Think of the precipitation rate as the amount of water per minute that drops from the cover to the pan.
- Although these rates are difficult to measure, we can safely say that some fraction of the water in the pan will evaporate into the air each minute, some fraction of the water in the air will condense on the cover each minute, and some fraction of the water on the cover will drop into the pan each minute.

**Lesson 2:** Have in mind a physical model of your problem so you can quantify the variables and the actions that cause those variables to increase or decrease.
Decision 3: There are usually a number of outside factors that may affect the behavior of a systems model. Identify some factors that you may want to include in the water cycle model. Keep in mind the concepts you wish to illustrate with this model.

- One factor is the quality of the seal on the cover of the pan. A perfectly sealed pan should illustrate conservation of matter. If there is a leak, the total amount of water (liquid and gas) in the closed pan should decrease.
- Another factor is variability in the rates of evaporation, condensation and precipitation as the simulation progresses.

Lesson 3: Don’t include these outside factors until you have a working basic model.
Building the Basic Model

**Step 1:** Analyze the physical model to determine the box variables and the rates of change for the systems model. Start by telling the story of the physical model.

**The Story:** We place 100 ml of water in an aluminum pan and cover it tightly with a clear cover. Then we place the pan on a hot plate set at a moderate temperature. We observe that water eventually condenses on the cover. We can’t tell how much water is in the air as water vapor.

The major players and actions: Put a B next to the box variables. Put an R next to the rates of change.

<table>
<thead>
<tr>
<th>Water in the pan</th>
<th>Water in the air</th>
<th>Water on the cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation</td>
<td>Condensation</td>
<td>Precipitation</td>
</tr>
</tbody>
</table>

Make a sketch of the Vensim model based on the box variables and rates chosen. When you have finished, turn the page to compare your model to the one shown.
Pan Water Cycle – Stage 1

Notice that by following the arrows, the model illustrates that water leaves the pan as water vapor and returns to the pan as precipitation after condensing on the cover.

Step 2: Build the Stage 1 Model – Box Variables and Rates

Need a refresher on the building blocks of Vensim?

- Open Vensim. If a previous model appears, under the File menu, select New Model.
- If the Model Settings window opens, enter these values, then click OK.
  - INITIAL TIME = 0
  - FINAL TIME = 10
  - TIME STEP = 1
  - Units for Time: Minute
  - Integration Type: Euler
- There are two very important icons on the menu bar – the **hand** and the **pacman**. The hand is the icon to use when you want to browse, move or resize the model. The pacman is used to delete a mistake.
- To build the basic water cycle model:
  - Click and release on the **Box** icon, click in the white space, type Water on Cover in the rectangle that appears, hit Enter. Use the tiny circle in the lower right hand corner of the box to adjust the box size so the words are easy to read.
  - Since the Box icon is still active, you can click in the white space below Water on Cover to position Water in Pan. Then you can click in the white space to the left to position Water in Air.
  - You should now have 3 box variables on your model. We will color them appropriately later.
  - Click and release on the **Rate** icon. Move the cursor on top of the words Water on Cover, click and release, move the cursor straight down into the Water in Pan box, click and release again. In the rectangle that appears, type Precipitation and hit Enter.
  - Since the Rate icon is still active, you can move your cursor on top of the words Water in Air to connect that box variable to Water on Cover, naming that rate Condensation. However, to get the corner bend in the arrow, you will need to add an intermediate step to the rate process. After the initial click and release on Water in Air, move the cursor straight up. When the cursor is level with Water on Cover, hold down the shift-key, click and release the mouse, then release the shift-key. You have just placed a corner. Now move the cursor to the right until the cursor is inside the Water on Cover box. Click and release again.
  - Repeat similar steps to connect Water in Pan to Water in Air.

**Putting the math in the model – Box Variables only**

Click on the $Y=x^2$ button. Notice that all variables are shaded in black. That means we haven’t given Vensim any numbers yet. At this time, we will deal only with the box variables.

- Click on the box called Water in Pan. Enter 100 in the Initial Value box and ml in the Units box.
- Note that Vensim has filled in for you that Water in Pan is the Integral of Precipitation - Evaporation. If your students are taking calculus, you can tell them Vensim is solving differential equations numerically. For the rest of the world, you can simply say that Vensim will be adding Precipitation to and subtracting Evaporation from the Water in Pan to get the amount of Water in Pan a minute from now.
- Note the Comment box for documentation.
- Click OK to close the window.
- Follow similar steps for Water in Air and Water on Cover except the initial values for those boxes should be set to 0. You should be able to set the Units to ml by using the dropdown menu since Vensim includes any new units you enter to its list of units for this model.
Step 3: Adding Variables and Arrows

The rates on the model at this stage show no dependency on anything. Is that realistic? Will the rate of evaporation always be the same? Does rainfall occur at a constant rate? In a global water cycle, there would be many factors affecting these rates. In our simple pan water cycle model, we can narrow the factors down to a manageable number. Let’s start with the observation that the amount of precipitation has to depend on the amount of water on the cover. No water on the cover (in the clouds), no rain. So, we need to introduce blue arrows.

- Click and release on the **Arrow** icon. Move the cursor over the words Water on Cover and click and release. Then move the cursor over the word Precipitation, and click and release. A blue arrow should appear. The head of the arrow should be pointing to Precipitation. You can make the blue arrow curve by pulling on the tiny circle attached to the arrow.
- Using the same action, connect Water in Pan to Evaporation.
- Then connect Water in Air to Condensation.

Next we will introduce fractions that we can use to express the idea that a fraction of the water on the cover will drop as precipitation each minute. And that a fraction of the water in the pan will evaporate into the air each minute. And that a fraction of the water in the air will condense on the cover each minute.

- Click and release on the **Variable** icon. Move the cursor next to the Precipitation rate, click and release, and type Precipitation Fraction in the rectangle that appears. Hit Enter.
- Using the same action, insert variables for Evaporation Fraction and Condensation Fraction.
- Now, add blue arrows to show that each rate depends not only on its supplying box variable, but also on its corresponding fraction.
- Your model should look like the picture below.
Putting more math in the model – Rates and Variables

Click on the $y=x^2$ button. Let’s start with the rates. Since we want a fraction of the water in each box to leave that box and enter the next box, we will use multiplication in our equations.

- Click on the rate precipitation. The window that opens will show precipitation fraction and water on cover in the Variables box if the blue arrows have been drawn correctly. If those words don’t appear, click on Cancel and re-do the blue arrows.
- Enter precipitation fraction*water on cover by clicking on the names in the Variables box and the symbol * on the keypad or on your keyboard.
- Enter ml per min in the Units box.

- Click OK to close the window.
- Follow similar steps for the rates evaporation and condensation.
Now the only parts of the model needing information are the three variables that are meant to hold the fractions for the rates.

- Click precipitation fraction and enter 0.5. Also enter the values seen below for Minimum Value, Maximum Value, and Increment. These will be used for the slider bars you will use later.

- Follow similar steps for the evaporation and condensation fractions. Set evaporation fraction to 0.1. Set condensation fraction to 0.5.

**Step 4: Making a Custom Graph**

1. Click on the Control Panel icon at the far right end of the top bar.
2. Click on the Graphs tab. Then click on New.
3. Fill in the window so it looks like the one below. Note the following:
   a. We are plotting all three box variables on the same graph. We use the Sel button to select the variable name from a list.
   b. We click on the boxes to the left of the variable names to indicate that each variable should be plotted on the same scale.
   c. We fix the Y-min and Y-max at 0 and 100, respectively. Since the scale boxes are checked, we would not have to set the Y-min and Y-max for water in air and water on cover.
   d. We do need to set LineW to 3 for each variable to make each graph plot the same thickness.
4. Click OK to close this window. Then click Close to close the Control Panel window.

5. To attach the graph to the white space in the model, click on the Input Output Object. Click in the model white space to bring forth a window.

6. Click in the circle by Output Custom Graph. Then use the drop-down menu at the bottom of the box to select the name of the graph you wish to display (GRAPH). Click OK and a graph box will appear on the screen. You may resize it by dragging on the small circle in the lower right-hand corner of the box.
Step 5: Running the Model

- **Run** the model by clicking on the green running man next to the white box that says Current. If a dialogue box appears saying “Dataset Current already exists. Do you want to overwrite it?”, click on Yes.
- **Run AutoSim** the model by clicking on the green running man with horizontal bars to the right of the other green man. Note the mini-graphs that appear in each box variable and rate. Use the slider bars to vary the three fractions.
- Click the Stop Sign to return the model to its original state.

Step 6: Color Coordination

To make the boxes around the box variables match the colors of the curves in the graph,

- Click on the Hand icon. Then move the cursor on top of one of the box variables, such as Water in Pan. Right-click on Water in Pan to open this Options window.

- Click on the rectangle next to Shape Color to open the color palette. Type in 3 for the thickness. You may also change the font type or size or color, if you wish.

Step 7: Using the Model as an Inquiry Tool

We have now completed the basic model. Save it as BasicWC. Then experiment with it before answering these questions.

1. What could your students learn by manipulating the fraction sliders?
2. How could the model be used to simulate a world with no precipitation?
3. What does it mean when the three graphs flatten out?

Stop here and save the model as ModifiedWC. You should now have 2 versions of the model, the BasicWC which will not be changed and the ModifiedWC to which you will add new features.
Step 8: Adding more factors

Let’s start with the addition of a variable – total water - that will help us illustrate conservation of matter in a closed system. Change your model so it looks like this:

![Diagram of water cycle model]

Next, modify the y-axis scale on your graph and add total water to the list of variables to plot so your graph looks like this:

![Graph showing PAN-AIR-COVER content over time]
Step 8: Hints

Steps to create the total water variable:

- Use the Variable icon to create total water in the model.
- Using the hand icon, right-click on the words total water to bring forth the window where the shape can be set to circle and the shape color can be set to gray with thickness 3.
- Use the Arrow icon to draw the blue arrows from each box variable to total water.
- Click on the $Y=x^2$ button. Then click on total water to bring forth its equation window. You should see the three box variables listed in the Variables part of the window. Click on each with a + sign in between to enter the equation for total water.
- Run the model.

Steps to modify the graph so total water is plotted with the other water variables:

- Click on the Control Panel icon. Click on the Graphs tab. Then select GRAPH in the window, and click on Modify.
- Make changes so the window looks like this:
Step 9: Adding a leak

Now, let’s introduce the possibility of a leak in the system. In the model below, the rate called water vapor leak will subtract some of the water in the air based on the leak fraction. Modify your model to look like this:

![Model diagram]

Step 10: Testing the model

Experiment with the leak fraction slider to test its effect on the model. How does the graph change when a leak is introduced? Is this still a closed system?

Step 11: Allowing the fractions to change during the simulation

In the current version of the model, sliders can be used to easily change the fractions for different runs of the model; but each fraction is one fixed constant during a single run. What if you wanted the evaporation fraction to vary during a run? There are 2 ways to do this: built-in functions or lookup tables/graphs.

- To show that the evaporation fraction will change with time, we need to use the Shadow Variable icon. Click on the icon; then click in the white space near evaporation fraction. This brings up a window from which you can choose your shadow variable. Scroll down and select Time.
- Connect <Time> to evaporation fraction with a blue arrow to get this:
• Click on the $Y=x^2$ button; then on evaporation fraction. The word Time is now in the Variable box in the window. This signifies that Time must be used in the definition of evaporation fraction.

• One way to do this is by using a built-in function. The Functions tab will show us the functions available for selection. Suppose we would like to set the evaporation fraction to 0.1 for the first 5 minutes of the simulation and 0.7 for the last 5 minutes. The IF THEN ELSE function will allow us to do that.
  
  o But first, delete the number that is currently in the large box in the evaporation fraction window.
  
  o Then, scroll down the Functions window until you find IF THEN ELSE. Highlight that and click the Add Sel button. You should now see the function rule appear in the large box.

• {cond} stands for the condition that determines whether evaporation fraction takes on the value in {ontrue} or {onfalse}. We want to convey the idea that IF time<5 THEN evaporation fraction is 0.1, ELSE it is 0.7. So we will write:
  
  \[
  \text{IF THEN ELSE( Time<5 \ , \ 0.1 \ , \ 0.7 )}
  \]

• Click OK to close the window. Set the leak fraction to 0. Set the other two fractions to 0.5. Run the model and you should see this graph:
Whenever we make a change like this in a model, we need to verify that the results make sense. Answer these questions:

- Does the graph from time = 0 to time = 5 look as it did when the evaporation fraction was a constant 0.1? To find out, we can do one of two things.
  - We can save our current model, and then open the BasicWC. Set evaporation fraction to 0.1 and run it. Observe the graph shape during the first five minutes.
  - Or, we can change 0.7 to 0.1 in the ModifiedWC model, run the model and look at the first 5 minutes of the graph.
- Does the graph from time = 5 to time = 10 make sense? Why do the curves experience so much fluctuation?
  - One of the reasons that we see irregular behavior in the graph after the 5 minute mark is that our time-step is set at 1. That means that values are calculated every minute and the graph is drawn by connecting the dots with line segments. Since the water cycle is changing continuously, it would be more realistic to use a smaller time-step.

Follow these steps to adjust the time-step to 0.125:

- Under the Model menu, select Settings.
- Use the drop-down box labeled TIME STEP to select 0.125.
- Click OK and run the model to generate new data.
- The new graph is a smoothed version of the previous one, except for the jump at 5 minutes caused by the if-then-else statement.

Now let’s look at an alternative to built-in functions. They are called **Lookup Tables/Graphs**.

- Click on the \( Y=x^2 \) button; then on evaporation fraction. Delete the IF THEN ELSE expression in the box.
- Note the two boxes under the word Type. The first box should read Auxiliary (use the drop-down menu). The second box should read with Lookup (use the drop-down menu).
Click on the Variables tab so you can select Time to place in the box where the IF THEN Else expression used to appear. You are telling Vensim that evaporation fraction will be defined based on a table or graph of values in which Time is the independent variable.

- Click on As Graph. Enter the information shown below.
  - Note that the x-axis is automatically set to a min and max of 0 and 10 since Time is the independent variable and your model is set to run from time = 0 to time = 10.
  - However, you must set Y-min and Y-max. Why did we choose 0 and 1?
  - As you fill in the Input and Output columns, note that the graph is drawn for you.
  - Note the comment in the top box. It explains the reasoning behind the graph.
  - Click on OK when you are finished.
- You should notice that the Look-up box is now filled with ordered pairs of numbers, reflecting the values you just entered.
- You may also notice that the Minimum Value, maximum Value and Increment that we set in the Basic model are still in place even though we have over-ridden the slider bar by making evaporation fraction dependent on time.

- Click OK to close the window. Set the leak fraction to 0. Set the other two fractions to 0.5. Run the model and you should see this graph:

![Graph of PAN-AIR-COVER Content over time](image)

- Does this graph make sense? Justify your answer based on the settings for the model.

**Step 12: Making a Custom Table and Exporting Data**

If we would like to see the data generated by the model and possibly export it to a spreadsheet for analysis, we can make a custom table.

1. Click on the Control Panel icon at the far right end of the top bar.
2. Click on the Graphs tab. Then click on New.
3. At the bottom center of the window, click on As Table.
4. In the window that appears,
   a. Enter a title. I used Water Values.
   b. Click on the Variable box. In the window that appears, scroll down until you see water in air. Select water in air and click OK. Notice that water in air now appears in the white text box next to Variable. Click the Add button on the right to move water in air into the Table Content box.
c. Repeat to add **water in pan**, **water on cover**, and **total water** to the Table Content box.
d. Click in the Running down box to get a vertical display of numbers.
e. The window should look like the one below. Ignore the Table Name. It will be filled in automatically later. Click OK to close the window.

![Table Content Window with Water Values](image)

5. You should now see the Control Panel window open with GRAPH and Water_Values in the white space. Click on Water_Values to highlight it. Then click on the Display button. You should see a table of values like the one below.

<table>
<thead>
<tr>
<th>Time (Minute)</th>
<th>water in air</th>
<th>water in pan</th>
<th>water on cover</th>
<th>total water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>0.125</td>
<td>0.1562</td>
<td>99.84</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>0.25</td>
<td>0.4585</td>
<td>99.53</td>
<td>0.0098</td>
<td>100</td>
</tr>
<tr>
<td>0.375</td>
<td>0.8964</td>
<td>99.07</td>
<td>0.0378</td>
<td>100</td>
</tr>
<tr>
<td>0.625</td>
<td>1.460</td>
<td>98.45</td>
<td>0.0915</td>
<td>100</td>
</tr>
<tr>
<td>0.75</td>
<td>2.137</td>
<td>97.69</td>
<td>0.1770</td>
<td>100</td>
</tr>
<tr>
<td>0.875</td>
<td>2.920</td>
<td>96.78</td>
<td>0.2995</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>3.796</td>
<td>95.74</td>
<td>0.4633</td>
<td>100</td>
</tr>
<tr>
<td>1.125</td>
<td>4.755</td>
<td>94.57</td>
<td>0.6715</td>
<td>100</td>
</tr>
<tr>
<td>1.25</td>
<td>5.788</td>
<td>93.29</td>
<td>0.9268</td>
<td>100</td>
</tr>
<tr>
<td>1.375</td>
<td>6.884</td>
<td>91.89</td>
<td>1.231</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>8.033</td>
<td>90.38</td>
<td>1.584</td>
<td>100</td>
</tr>
<tr>
<td>1.625</td>
<td>9.225</td>
<td>88.79</td>
<td>1.987</td>
<td>100</td>
</tr>
<tr>
<td>1.75</td>
<td>10.45</td>
<td>87.11</td>
<td>2.439</td>
<td>100</td>
</tr>
<tr>
<td>1.875</td>
<td>11.70</td>
<td>85.36</td>
<td>2.940</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>12.97</td>
<td>83.54</td>
<td>3.488</td>
<td>100</td>
</tr>
<tr>
<td>2.125</td>
<td>14.25</td>
<td>81.67</td>
<td>4.081</td>
<td>100</td>
</tr>
<tr>
<td>2.25</td>
<td>15.53</td>
<td>79.75</td>
<td>4.716</td>
<td>100</td>
</tr>
</tbody>
</table>
6. Run your mouse over the table menu in the upper left-hand corner to see the meaning of each icon. The disk icon will allow you to save the table as a text file, which you may then import into a spreadsheet for further data analysis. The icon to the left of the disk icon allows for direct export of the data to a spreadsheet if your system is set up to do that.

7. Close the table window and then the control panel to return to the model. To attach the table to the white space, click on the Input Output Object icon. Click in the model white space to bring forth a window. Click in the circle by Output Custom Graph. Then use the drop-down menu at the bottom of the box to select the object you wish to display (Water_Values).

8. Click OK and a table box will appear on the screen. You may resize it by dragging on the small circle in the lower right-hand corner of the box. Run the model to make the table data appear.

**Building the Complex Model**

Now that we've built a simple model of the water cycle, we may tackle the more complex one. Working in groups, determine the box variables and rates of change you want to include. Draw a sketch of your model. Be prepared to share out your model with other groups.

**Building Other Models**

If you are looking for topics that lend themselves to systems modeling, check out [http://mvhs.shodor.org](http://mvhs.shodor.org). Click on the topic of your choice and explore the models that other teachers have used in their classrooms.