

This instructional guide describes the types of models found in [Model Builder](#) and how they can be used with students in more depth. Key sections include learning targets tailored to educators.

	Educator Learning Target	Section of the Guide
1	Explain what a model is and provide examples of models you already use in teaching.	What is a Model?
2	Explain the importance of using models in teaching.	Using Models in Teaching
3	Identify the components of a conceptual model.	The Parts of Conceptual Models
4	Identify the components of a causal model.	The Parts of Causal Models
5	Describe approaches for integrating conceptual models into teaching using <i>Model Builder</i> .	Teaching Science with Conceptual Models
6	Identify the components of a stock and flow model and how they can be connected.	The Parts of a Stock and Flow Model
7	Describe approaches for integrating stock and flow models into teaching using <i>Model Builder</i> .	Teaching Science with Stock and Flow Models
8	Compare and contrast advantages of conceptual and causal models vs. stock and flow models for teaching science concepts.	Teaching with Conceptual and Causal Models vs. Stock and Flow Models

A full table of contents is provided below. Select each section to go directly to that part of the guide.

- [What is a Model?](#)
- [Using Models in Teaching](#)
- [Conceptual Models](#)
 - [What is a Conceptual Model?](#)
 - [The Parts of Conceptual Models](#)
- [Causal Models](#)
 - [What is a Causal Model?](#)
 - [The Parts of Causal Models](#)
 - [Teaching Science with Conceptual and Causal Models](#)
 - [Limits of Conceptual and Causal Models](#)
- [Stock and Flow Models](#)
 - [What is a Stock and Flow Model?](#)
 - [The Parts of a Stock and Flow Model](#)
 - [Teaching Science with Stock and Flow Models](#)
 - [Limits of Stock and Flow Models](#)
- [Teaching with Conceptual and Causal Models vs. Stock and Flow Models](#)
 - [Example: Central Dogma Models](#)
- [References](#)
- [APPENDIX: Advanced Concepts for Stock and Flow Models](#)
 - [Open and Closed Systems](#)
 - [Feedback and Nonlinear Behavior with Connectors](#)
 - [Stocks are Context Dependent](#)

More resources for *Model Builder*, including a user guide and implementation suggestions, can be found on [this resource's webpage](#).

What is a Model?

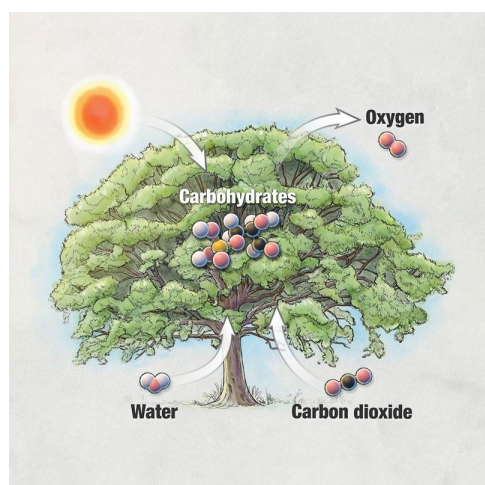
Educator Learning Target 1: Explain what a model is and provide examples of models you already use in teaching.

A **model** is a representation of a system of interrelated ideas, events, or processes. The representation may take many forms. For example, models may be diagrams, mathematical formulas, chemical equations, computational programs, or physical models.

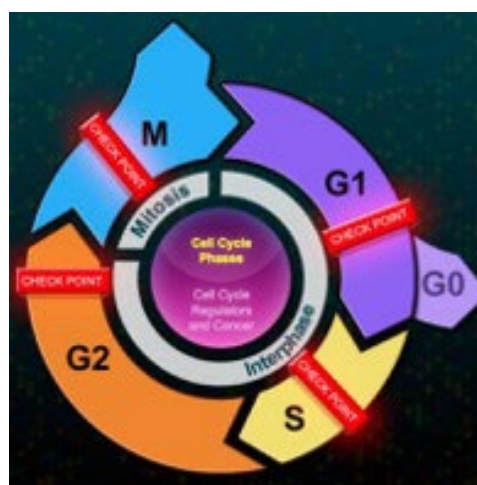
Models can be used to make predictions about the behavior of a system. This is a foundational aspect of science and can be explored more fully with other BioInteractive resources, such as the activity [“Asking Scientific Questions”](#) and the interactive tool [How Science Works](#).

The process of building a model is referred to as **modeling**. This includes determining the ideas, events, or processes that should and should not be included; the time and spatial scale of the system being represented; and whether the model explains the available evidence. Modeling can help us understand the relationships of the parts of the system and any cause-and-effect mechanisms between the parts.

You likely already use many models in your teaching. Below are examples of **diagrams**, which are a type of model that you may use to teach complex processes.



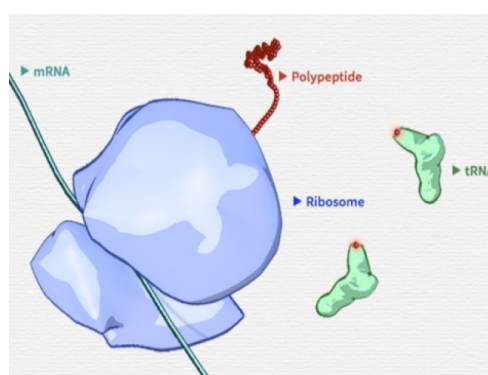
Inputs and outputs of photosynthesis



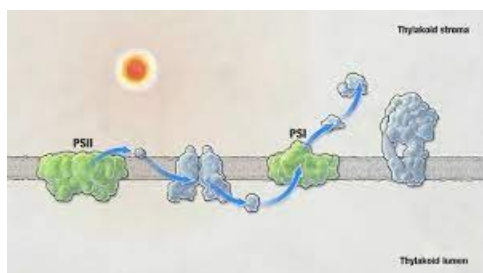
Cell cycle



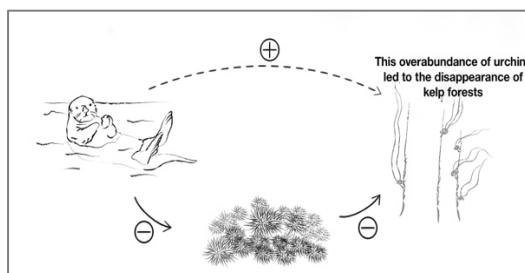
Inorganic carbon cycle



Central dogma



Molecular detail of photosynthesis



Trophic cascade

Using Models in Teaching

Educator Learning Target 2: Explain the importance of using models in teaching.

Having students use models and create their own models is a valuable teaching method. For example, diagram-based models:

- provide a visual representation of complex relationships among the parts of a system
- may be easier to understand than explanations of complex interactions in paragraphs of text
- provide a representation for students to discuss, understand, and learn from
- allow students to explore how the different components of a model interact and to make predictions about the behavior of the system (including how the system may change under different conditions)

Students express their own mental models when they create diagrams of systems and processes. This presents an excellent opportunity for teachers to evaluate students' understanding of concepts and provide feedback. Students may then make iterative revisions of their diagrams and, in turn, refine their own mental models ([Bryce et al. 2016](#)).

This guide provides recommendations for using *Model Builder* in science teaching to increase student learning. More general resources that you may want to consult include:

- [Modeling in the Classroom](#): A freely available online guide to using modeling in the classroom, including summaries of relevant literature.
- [Using Systems and Systems Thinking to Unify Biology Education](#): A helpful review of research and approaches for integrating systems thinking into life science education.
- [Creative Learning Exchange](#): A website devoted to integrating systems thinking and system dynamics modeling in K–12 education.

Conceptual Models

What is a Conceptual Model?

Conceptual models are diagrams that show associations among the components of a system. In Model Builder, the components are referred to as **objects**, and associations between objects are represented by **neutral connectors**, which do *not* imply causation (i.e., no cause-and-effect relationships are indicated). Figure 1, a diagram of phylogenetic relationships, is an example of a conceptual model.

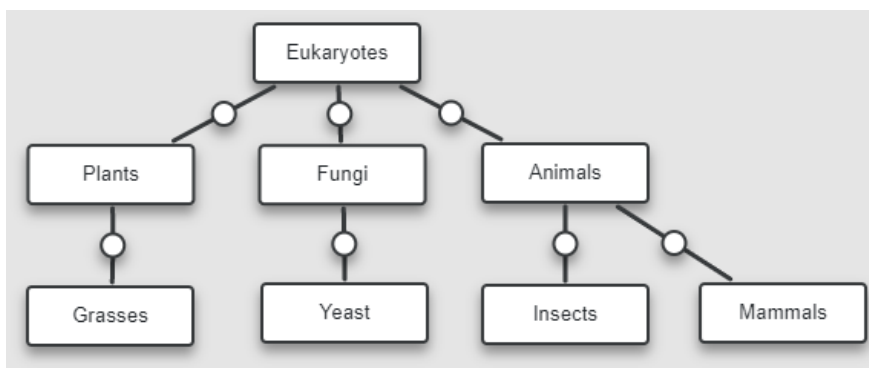
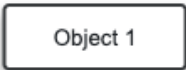
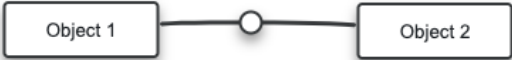


Figure 1. A conceptual model of phylogenetic relationships.

The Parts of Conceptual Models

Educator Learning Target 3: Identify the components of a conceptual model.

The following table summarizes the main parts of a conceptual model.

Part	Image	What It Represents
Object		Objects are the components of a conceptual model that are linked together. They can represent any entities, such as concepts, structures, processes, relationships, or quantities.
Neutral connector		A neutral connector shows that two objects are associated but does <i>not</i> indicate a causal relationship.

Causal Models

What is a Causal Model?

Causal models are diagrams that show the cause-and-effect relationships among the components of a system. As in conceptual models, the components of causal models are referred to as **objects**, but the connectors in causal models are arrows that show the direction of the effect and whether the effect is **positive** or **negative** (i.e., the polarity). Figure 2, a diagram of the carbon cycle, is an example of a causal model with both positive and negative connectors:

- Sunlight has a *positive* effect on photosynthesis because increased sunlight causes increased photosynthesis. This is represented by a positive connector (blue “+” arrow) with “Sunlight” as the cause (where the arrow starts) and “Photosynthesis” as the effect (where the arrow ends).
- Photosynthesis has a *negative* effect on carbon in the atmosphere. Since photosynthesis uses carbon from the atmosphere to make carbohydrates, as photosynthesis increases, carbon in the atmosphere decreases. This is represented by a negative connector (red “-” arrow) with “Photosynthesis” as the cause and “Carbon in the Atmosphere” as the effect.

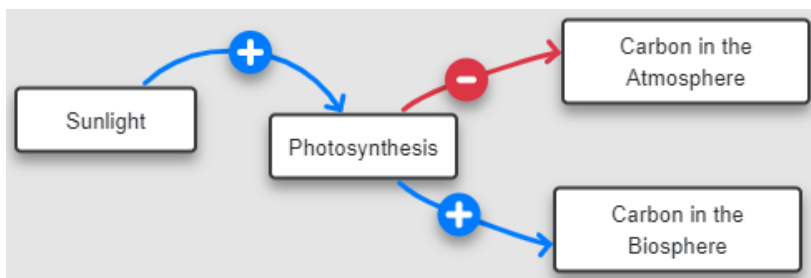





Figure 2. A causal model of the carbon cycle.

The Parts of Causal Models

Educator Learning Target 4: Identify the components of a causal model.

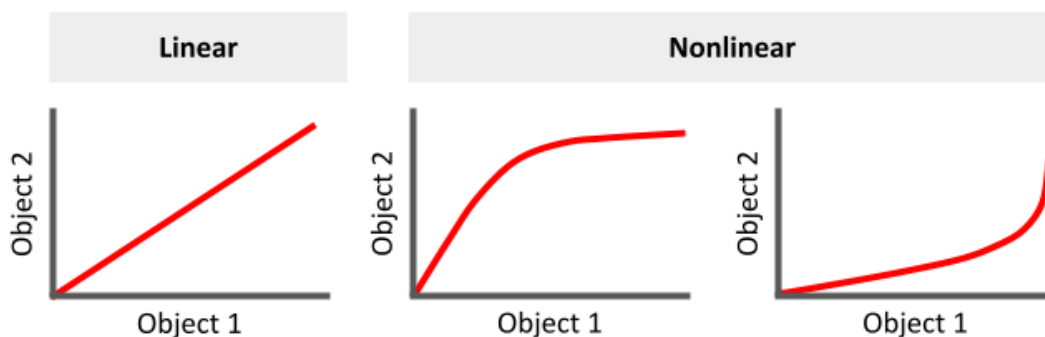
The following table summarizes the main parts of a causal model.

Part	Image	What It Represents
Object		Objects are the components of a causal model that are linked together. They can represent structures, processes, relationships, or quantities.
Positive connector		A positive (+) connector shows a positive causal relationship. <ul style="list-style-type: none"> An <i>increase</i> in Object 1 causes an <i>increase</i> in Object 2. A <i>decrease</i> in Object 1 causes a <i>decrease</i> in Object 2.
Negative connector		A negative (–) connector shows a negative, or inverse, causal relationship. <ul style="list-style-type: none"> An <i>increase</i> in Object 1 causes a <i>decrease</i> in Object 2. A <i>decrease</i> in Object 1 causes an <i>increase</i> in Object 2.

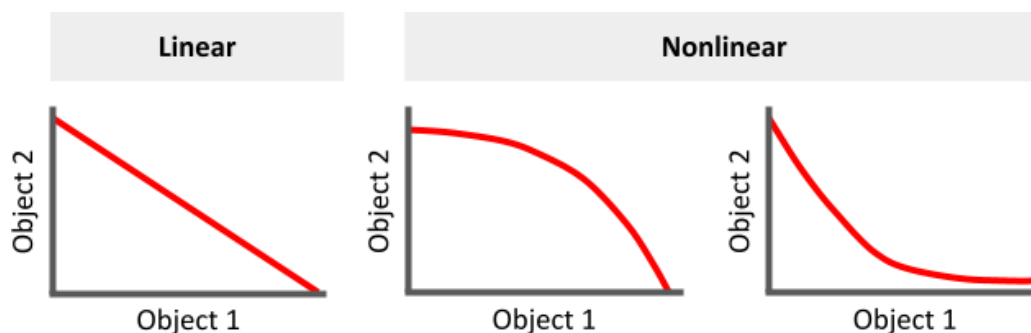
Positive and Negative Relationships

Model Builder does not include mathematical equations for the relationships between objects, but students may find it helpful to discuss the implied relationships using equations or graphs.

Examples of **positive relationships** are shown in the graphs below. A positive connector could represent any relationship like these. Note that linear relationships are more intuitive and nonlinear relationships are more complex.



Examples of **negative relationships** are shown in the graphs below. A negative connector could represent any relationship like these. Again, linear relationships are more intuitive and nonlinear relationships are more complex.



Teaching Science with Conceptual and Causal Models

Educator Learning Target 5: Describe approaches for integrating conceptual and causal models into teaching using *Model Builder*.

One common use for *Model Builder* is having students use a “self-check” or “assessment” model file to build a model from parts. More information about how this works is provided in the “User Guide” on the [Model Builder webpage](#). In brief, students are provided with a list of the objects in a model and are tasked with connecting the objects together.

The steps below outline a sequence for a lesson that uses *Model Builder* in this way.

Step 1: Explore the Objects

First, ensure that students understand the meaning and assumptions of the different objects. For models with causal relationships (positive and negative connectors), it is frequently helpful for students to consider the units for each object.

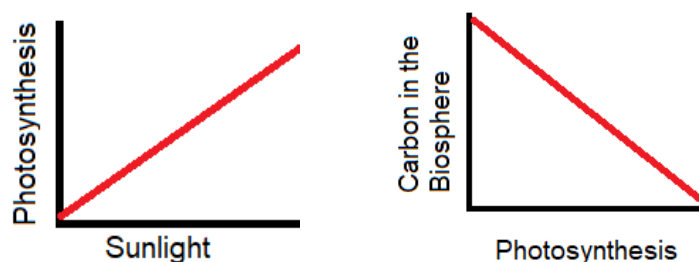
Step 2: Explore the Relationships

Once students understand the objects, they can begin learning about the relationships among them. You can use a variety of approaches to provide students with information about these relationships, including the following:

- **Interactive learning activities.** Ask students to identify relevant information to be modeled by completing interactive learning activities (e.g., BioInteractive resources).
- **Published data sets.** Provide students with graphs or tables of data from textbooks or other published sources (e.g., BioInteractive [Data Points](#)).
- **Student experiments and observations.** Have students use data collected from their own experiments or observations.
- **Computer simulations.** Provide students with online simulations with which they can make observations and collect data.
- **Narrative descriptions.** Provide students with narrative text or videos that contain the information to be modeled.

- **Student discussion.** Give groups of students a prompt to describe a concept, system, or process based on their prior knowledge of the information to be modeled.
- **Lecture.** Present information to be modeled as part of a lecture to students.

For causal models, consider having students draw simple graphs that show [positive and negative relationships](#) between specific pairs of objects. For example, for the carbon cycle model in Figure 2, students could draw simple relationships like the ones shown below.



Step 3: Build the Model

Once students understand the intended meaning of the selected relationships, they can begin building a model that shows these relationships among the objects.

Instruct students to begin working in *Model Builder*. You may have them work as a class, in groups, or individually — either synchronously or asynchronously. As students are building their models, you may interact with the students to provide support and guidance.

If the students are working with a self-check model file, encourage them to check their model early and frequently to identify errors. The automated feedback from the tool can provide help and reduce frustration.

Step 4: Apply the Model

After students have completed their models, you may use additional practices to extend the application of the models. These practices include the following:

- **Think-aloud.** Encourage students working in small groups to verbalize their reasoning for relationships.
 - Example prompt: “Explain to your group why those objects are connected, why the connector goes in that direction versus the opposite direction, and/or why you chose a positive, negative, or neutral connector linking those two objects.”
- **Make predictions.** Prompt students to use their model to predict the outcomes of changes in quantities, effects, and other parameters affecting the system.
 - Example prompt (based on the model in Figure 1): “Draw a graph or describe how carbon in the biosphere would be affected when sunlight is low versus high. Then explain how the model supports your predictions.”
- **Re-representation.** Have students use their model to create a narrative description or drawing of the system that illustrates relationships.
 - Example prompt (based on the model in Figure 1): “Draw a picture of the biosphere when sunlight is low and another picture when the sunlight is high. Label all the objects from the model, and their relationships, in your pictures.”

- **Peer review.** Instruct students to share their models with their peers and provide each other with constructive feedback.
 - This is best implemented before students submit their models for assessment.
 - This is not recommended for self-check models since students can review and refine self-check models on their own.

Limits of Conceptual and Causal Models

Statistician George E. P. Box wrote “All models are wrong, but some are useful” (Box and Luceño 1997). After students have completed building their conceptual or causal models, it is valuable to discuss the limitations of these models. These include the following:

- **Models are simplifications.** Models are simplifications of the system they are representing, meaning that some system components are not included in the model. This is typically done to focus on the roles or actions of specific system components. As a consequence, most systems could be represented by a variety of models, depending on the modeling goals.
 - Students can be encouraged to identify other objects, if any, that could be added to the model to aid in understanding the system.
 - Students could also consider why certain objects may be more or less important to include.
- **Causal models may use connectors to represent any type of cause-and-effect relationship between two objects.** This could include the movement of material between objects or the effects of factors that regulate flows or other objects. For example, a model of the trophic structure of an ecosystem may use positive connectors to illustrate the flow of energy in a food web, or it may use negative connectors to show regulatory effects that one species has on another. Although it’s not best practice, a single causal model may even include representations of multiple relationship types.
 - To reduce confusion, guide students through a discussion of the relationship types represented by the connectors in a given model. Clarify which relationships represent the physical movement (flow) of material between objects and which represent other effects between objects.
 - It may be helpful for students to consider which units might be used to describe each relationship.
 - Relationship types can be made more explicit in [stock and flow models](#).
- **Conceptual and causal models do not show time delays.** Many causal models of scientific processes will include one or more feedback loops. Although this is rarely explicit in diagrams, all feedback loops assume a time delay (lag) in the movement of the effect along the loop’s path.
 - These delays can be made more evident in stock and flow models, which implicitly include time through the inclusion of “flows” (rates).

Limits of Conceptual and Causal Models in Model Builder

Some special considerations for conceptual and causal models in *Model Builder* are as follows:

- **Model Builder does not have a connector for indirect effects.** Students may sometimes encounter diagrams that explicitly show indirect effects (e.g., with dashed arrows in trophic cascade diagrams). In *Model Builder*, indirect effects are intended to be inferred from direct effects.
- **Model Builder does not include underlying quantitative or dynamic simulations.** Models made with *Model Builder* are qualitative, static diagrams that show relationships among objects. *Model Builder* does not have a mechanism to assign quantitative values to objects or connectors, nor can it run dynamic simulations.

- Quantitative, dynamic models can be explored using free online applications such as [SageModeler](#) and [Insight Maker](#).

Stock and Flow Models

What is a Stock and Flow Model?

Conceptual and causal models use two symbols to represent system components: objects and connectors. A more advanced approach for representing systems is **stock and flow models**, which use five symbols: stocks, flows, sources/sinks, variables, and connectors. These symbols are detailed in the next section: [“The Parts of a Stock and Flow Model.”](#)

Unlike conceptual and causal models, stock and flow models distinguish between links and the physical movement of material through the system. In this guide, **material** refers to anything in the model that flows, including both matter and energy. For more about the materials in stock and flow models, refer to the [“Consistent Materials”](#) section.


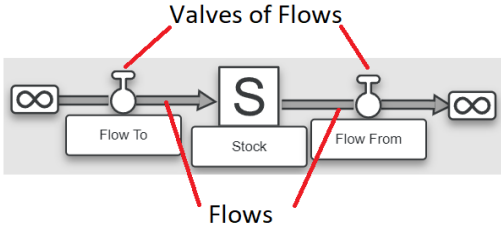
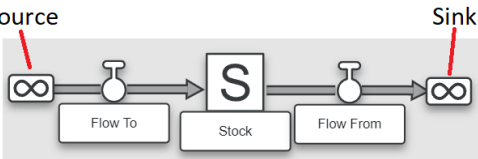
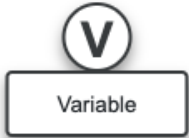
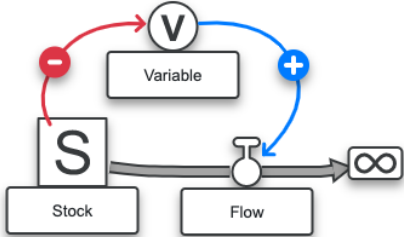
In a stock and flow model:

- Links are represented by positive and negative **connectors**.
- The movement of material is represented by **flows**.
- The things that are moving through the system are called **stocks**. They may be any material of interest that can be counted or measured (at least theoretically) and that can accumulate.
- **Variables** are factors in the system that can affect flows or other variables. They may be thought of as additional parameters that, when varied, have the potential to alter the behavior of the system.

The Parts of a Stock and Flow Model

Educator Learning Target 6: Identify the components of a stock and flow model and how they can be connected.

The following table summarizes the main parts of a stock and flow model.

Part	Image	What It Represents
Stock		Stocks, which represent the accumulation of material in a system, are typically the focus of stock and flow models. Stocks may gain or lose material. They can increase or decrease only through <i>flows</i> , so they cannot be the target of a <i>connector</i> . (But they can be the origin of connectors to flows and variables.)
Flow		Flows represent how material moves to increase or decrease stocks. An <i>arrow</i> indicates the direction of the flow. A <i>valve</i> represents how the rate of flow can be affected by other parts of the system.
Source or sink		The infinity symbol represents a source or sink of material that is unlimited, constant, or outside model boundaries. A <i>source</i> is the origin of a flow. A <i>sink</i> is the target of a flow. (When a flow is added in <i>Model Builder</i> , a source or sink automatically appears at each end. You may switch any source or sink to a connection to a stock.)
Variable		Variables represent factors in a system, other than stocks, that can affect flows or other variables. Variables can send connectors to (i.e., can affect) flows and other variables. They can receive connectors from (i.e., be affected by) stocks, flows, and other variables.
Connector		A positive (+) connector shows a positive cause-and-effect relationship. A negative (–) connector shows a negative, or inverse, cause-and-effect relationship. Connectors can originate from a flow, stock, or variable. They can target a flow or variable, but not a stock.

Example: Atmospheric Carbon Model

Figure 3 shows an example of a stock and flow model.

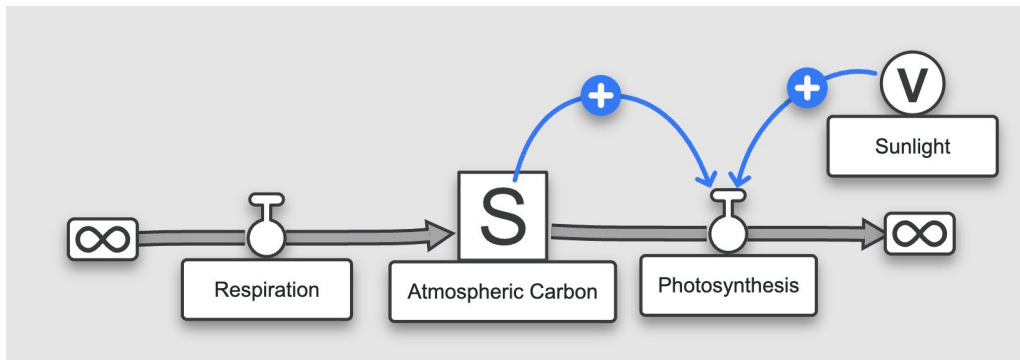


Figure 3. A stock and flow model of atmospheric carbon.

Each part described in the [table above](#) is present in this model.

- **Stock:** “Atmospheric Carbon” is a stock because the atmosphere can gain and lose carbon.
- **Flows:** There are two flows: “Respiration” and “Photosynthesis.” “Respiration” is how carbon flows *to* the atmosphere, and “Photosynthesis” is how carbon flows *from* the atmosphere.
 - An increase in “Respiration” would increase the flow of carbon into the atmosphere (by producing more CO₂)
 - An increase in “Photosynthesis” would increase the flow of carbon out of the atmosphere (by fixing carbon in plants and algae).
- **Source and sink:** “Respiration” flows from a *source* and “Photosynthesis” flows to a *sink*, because they are not limited by the ability to gain or lose carbon from the system. Sources and sinks have infinite capacity and thus do not limit the flows.
- **Variable:** “Sunlight” is a variable because it can affect the system while not being a stock.
 - Sunlight increases photosynthesis, which is shown using a positive connector. Thus, while sunlight does not *directly* cause carbon to flow from the atmosphere, it increases the rate of photosynthesis, which increases the flow of carbon from the atmosphere.
- **Connector:** There is a positive connector from the variable “Sunlight” to the “Photosynthesis” valve, because an increase in sunlight increases the rate of photosynthesis (and a decrease in sunlight decreases the rate of photosynthesis).
 - The relationship between sunlight and photosynthesis could be modeled with a simple positive linear relationship, like the one shown in the figure on the right.
 - Connectors can also allow a stock to affect a flow. In Figure 3, there is a positive connector from the “Atmospheric Carbon” stock to the “Photosynthesis” flow. This represents the positive effect of atmospheric carbon on photosynthesis; in other words, the rate of photosynthesis depends on the availability (concentration) of atmospheric carbon.

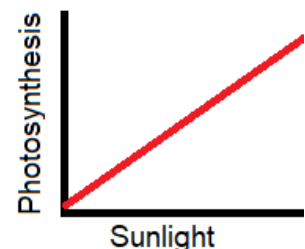


Figure 4 shows the stock and flow model from Figure 3 with a new variable, “Aerosols,” added.

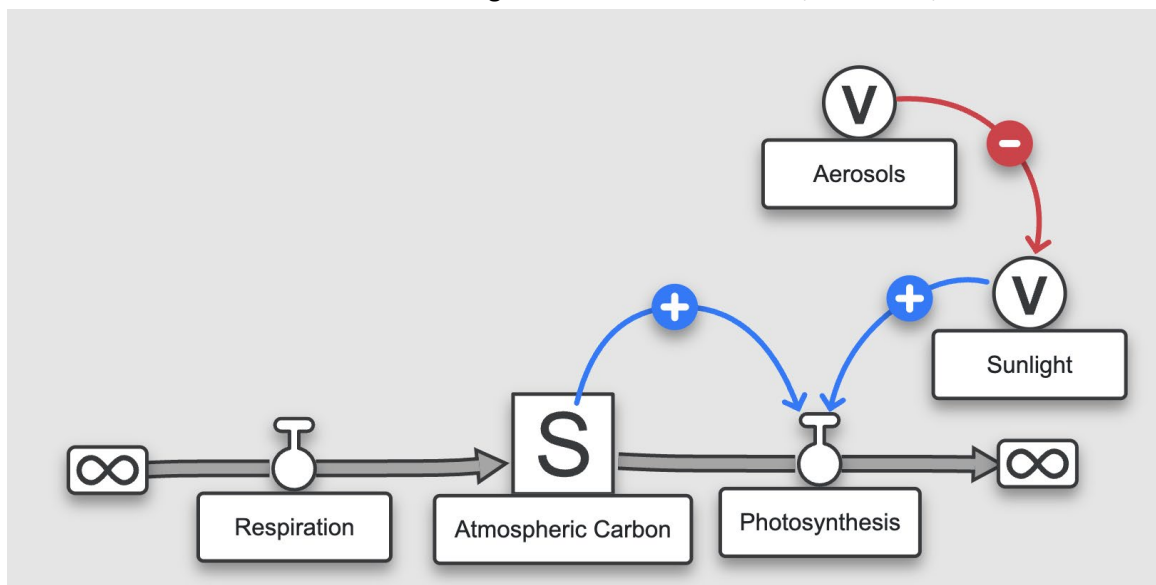


Figure 4. A stock and flow model of atmospheric carbon including the effects of aerosols.

An increase in aerosols will decrease the sunlight (as indicated by the negative connector from the “Aerosols” variable to the “Sunlight” variable), which will *indirectly* decrease photosynthesis.

Consistent Materials

A material that moves through a stock and flow system is assumed to be **consistent**. This means that the form or type of material in the system stays constant. For example, the model in Figure 3 has one consistent material: carbon. Although the carbon takes on different forms — it begins as glucose, is oxidized to carbon dioxide through respiration, and is then fixed back to glucose through photosynthesis — it remains consistent (that is, it is still carbon) as it moves into and out of the stock (“Atmospheric Carbon”) through the flows (“Respiration” and “Photosynthesis”).

If a material in a stock and flow model is *not* consistent, it should be modeled as a variable instead. For example, “Sunlight” is modeled as a variable in Figure 3 because it is a different material from carbon. Sunlight influences the rate at which carbon moves through the system by regulating the rate of photosynthesis, and some energy from sunlight is also transferred through photosynthesis. However, sunlight is not a type of carbon, and it does not flow into or out of the “Atmospheric Carbon” stock. Thus, we represent sunlight as a variable, rather than as a stock, in this system.

Some models contain multiple stock and flow systems, each with a different type of consistent material. These systems can influence each other through connectors. Figures 6 and 7 in the [“Central Dogma Models”](#) section are examples of this approach.

Teaching Science with Stock and Flow Models

Educator Learning Target 7: Describe approaches for integrating stock and flow models into teaching using *Model Builder*.

You can use the same sequence outlined in the [“Teaching Science with Conceptual and Causal Models”](#) section for teaching with stock and flow models, just with some modifications to [Step 1](#). The main difference is that, unlike conceptual and causal models, stock and flow models distinguish between different types of causation. This may help you teach some scientific concepts in more depth and better identify student misconceptions.

As with Step 1 of teaching with conceptual and causal models, first ensure that students understand the meaning and assumptions of the different objects. With a stock and flow model, students will now also need to identify each object as a stock, flow, or variable. This provides an opportunity to discuss the differences between these components of the model.

Stocks are generally the focus of a stock and flow model, and stocks can only be affected by flows. Begin by asking students to identify the **stocks** of the model and the **flows** that increase/decrease those stocks. This may be facilitated by guiding students to determine what units might be used for each object.

- Stocks track the accumulation of one type of material. They often have units of matter or energy.
- Flows are typically associated with rates. They often have units of matter or energy *per time*.

Identifying the **variables** should be done after the stocks and flows have been identified. Although variables help describe the model, they are less central to the focus than stocks.

- Variables are generally ancillary factors that regulate flows or are regulated by stocks.
- You may want to help students recognize that a component represented as a [consistent material](#) (with flows and a stock) in one model may be represented as a variable in another model. An example of this is provided in the [“Stocks are Context Dependent”](#) section of the Appendix.

After students have identified the stocks and flows of the model, they should link the stocks to the appropriate flows. Once the stocks and flows have been linked together, the rest of the lesson sequence (Steps 2–4) can be similar to the sequence described for [teaching with conceptual and causal models](#). Students can build the rest of the model to show other relationships among the objects. For example, many stock and flow models will show how variables affect the system with connectors and possibly how stocks may affect flows with connectors.

You can have students assign object types in *Model Builder* using a self-check model file. They can then check whether they have assigned the correct object types prior to connecting the objects.

Limits of Stock and Flow Models

After students have completed building their stock and flow models, it is valuable to discuss the potential limitations of these models. As discussed in the [“Limits of Conceptual and Causal Models”](#) section, all models are simplifications of the systems they are representing. Discussing what other components would be useful to add to the model (if any) provides an opportunity to link to other science concepts.

Limits of Stock and Flow Models in Model Builder

Some special considerations for stock and flow models in *Model Builder* are as follows:

- **Model Builder does not have dynamic models.** As noted for conceptual and causal models, Model Builder cannot be used to create dynamic models.
 - The free online applications [SageModeler](#) and [Insight Maker](#) can be used to build quantitative, dynamic stock and flow models that can generate real-time graphs and output data.
- **Model Builder does not simulate time delays.** In a stock and flow model, flows are analogous to rates. Consequently, time is a factor in stock and flow models, even if it is typically not explicitly included as a variable. This allows stock and flow model diagrams to represent the time lags that are necessary for feedback loops.
 - However, as noted above, models in *Model Builder* are static, not dynamic, so the model cannot be simulated.
 - The [“Feedback and Nonlinear Behavior with Connectors”](#) section of the Appendix discusses how different relationships in a stock and flow model relate to changes in a stock over time.

Teaching with Conceptual and Causal Models vs. Stock and Flow Models

Educator Learning Target 8: Compare and contrast advantages of conceptual and causal models vs. stock and flow models for teaching science concepts.

Choosing between a conceptual or causal model or a stock and flow model for teaching a science phenomenon is frequently a tradeoff between ease of understanding and representational robustness. Some considerations for each approach are summarized in the table below.

Model Type	Features/Advantages	Limitations/Disadvantages
Conceptual and causal	<p>Can show neutral or causal relationships in a system.</p> <p>Doesn't require learning as many symbols, which may be easier for students to engage with and understand.</p>	Does not distinguish between processes, reservoirs, and regulators.
Stock and Flow	<p>Differentiates between physical materials, the processes that increase and/or decrease the materials, and the factors that regulate the processes.</p> <p>May be more representative of real-life systems, which accumulate material through the flow of matter and energy.</p>	Requires students to understand more symbols, which may add cognitive load.

Since acquiring an understanding of science phenomena usually requires understanding relationships between objects, you may also want to consider the types of relationships that are important for students to understand.

- If the **relationships do not include causal effects**, consider using a conceptual model. An example is grouping objects based on shared characteristics (e.g., different organisms, cell types, viruses, rocks, chemical elements, etc.).
- If there are **cause-and-effect relationships**, consider using a causal model or a stock and flow model.
- If there are **time-dependent processes**, consider using a stock and flow model.

If understanding the system requires students to **distinguish flows from the accumulation of materials**, a stock and flow model would also be more suitable. For example, you might want students to distinguish:

- the *flow of carbon* to and from the atmosphere vs. the *accumulation of carbon* in the atmosphere
- the *infection rate* of a virus versus the *accumulation of infected individuals* in a population
- the *elimination rate* of alcohol from the blood versus the *accumulation of alcohol* concentration in the blood

Example: Central Dogma Models

Compared to a causal model of a process, a stock and flow model can more explicitly define which material is flowing vs. accumulating. This can reveal specific misconceptions that students may have about the nature of the processes being modeled.

For example, Figure 5 shows a common conceptual model of the central dogma of molecular biology. This is a useful model for showing the chain of causation. But because causal models represent every factor as the same

type of object, some students may misinterpret it as showing that DNA becomes RNA, which then becomes proteins.

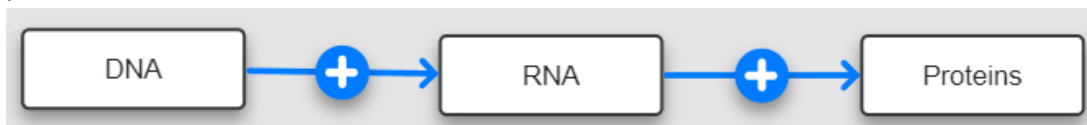


Figure 5. A conceptual model of the central dogma.

Figure 6 shows an alternative stock and flow model of the central dogma. In this model, RNA accumulates in one stock, and protein accumulates in another stock. The variable “Gene (DNA)” causes (promotes) transcription of mRNA, but DNA is not the raw ingredient of transcription. Similarly, the mRNA stock has a positive effect on (promotes) translation, but it cannot flow to translation because it is a different material.

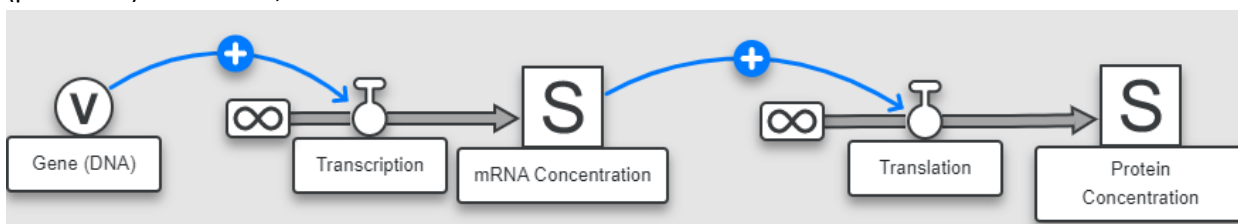


Figure 6. A stock and flow model of the central dogma.

Figure 7 extends the Figure 6 model to show the sources of the material for transcription and translation. The “Free Ribonucleotide Concentration” stock is transformed into “mRNA Concentration,” and the material is consistent as it flows from one stock to the other. The “Gene (DNA)” variable positively regulates transcription but is not itself transformed into mRNA. The material in the “Amino Acid Concentration” stock is consistent as it flows to the “Protein Concentration” stock but is not consistent with the material in the “mRNA Concentration” stock (and therefore does not flow into it).

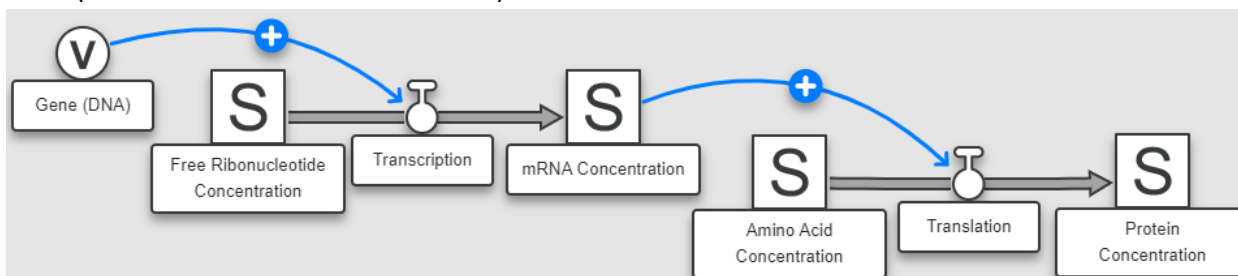


Figure 7. An extended stock and flow model of the central dogma that includes more stocks.

Figure 7 could be represented instead with the conceptual model in Figure 8. In this model, the flow of information clearly moves from DNA to RNA to protein. DNA and free ribonucleotide concentration both positively affect transcription, and mRNA and amino acids both positively affect translation. However, students may be more likely to misinterpret this process in the conceptual model; they may think that the DNA is transformed into RNA and then RNA is transformed into proteins.

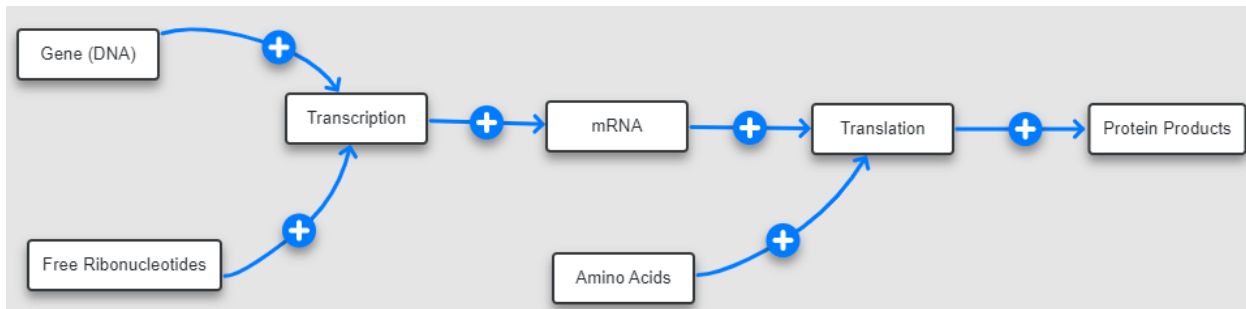


Figure 8. A causal model of the central dogma based on Figure 7.

References

- Box, G. E. P., and A. Luceño. *Statistical Control: By Monitoring and Feedback Adjustment*. John Wiley & Sons, 1997.
- Bryce, C. M., V. B. Baliga, K. L. De Nesnera, D. Fiack, K. Goetz, L. M. Tarjan, C. E. Wade, et al. "Exploring Models in the Biology Classroom." *The American Biology Teacher* 78, 1 (2016): 35–42.
<https://doi.org/10.1525/abt.2016.78.1.35>.
- Momsen, J., E. B. Speth, S. Wyse, and T. Long. "Using Systems and Systems Thinking to Unify Biology Education." *CBE—Life Sciences Education* 21, 2 (2022). <https://doi.org/10.1187/cbe.21-05-0118>.
- Wilson, K. J., T. M. Long, J. L. Momsen, and E. B. Speth. "Modeling in the Classroom: Making Relationships and Systems Visible." *CBE—Life Sciences Education* 19, 1 (2020): fe1. <https://doi.org/10.1187/cbe.19-11-0255>.

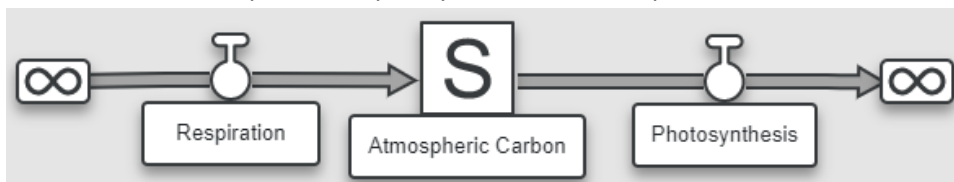
APPENDIX: Advanced Concepts for Stock and Flow Models

Open and Closed Systems

Stock and flow models track the flow of material to and from stocks within a system. Any system can be classified as open or closed.

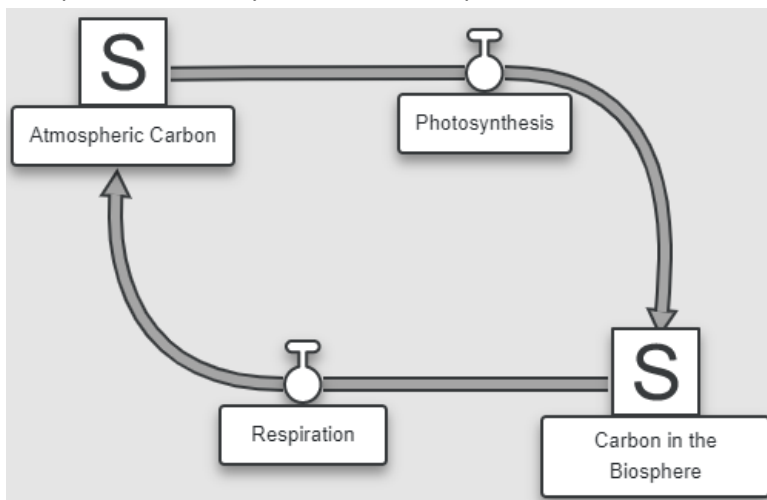
In an **open system**, the material can move between stocks, *and* it can enter or leave the system through sources and sinks. Therefore, in an open system, the total amount of the material within the boundaries of the model can change.

The model below is an example of an open system with atmospheric carbon.



In a **closed system**, the material can only move between stocks. Therefore, a closed system has no sources or sinks. Consequently, the total amount of material within the boundaries of the model remains constant.

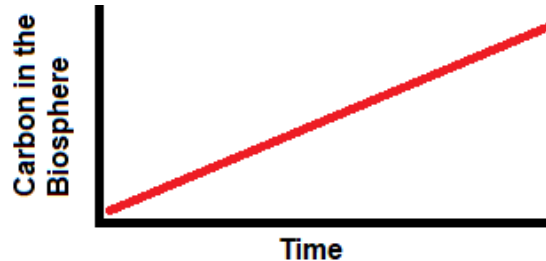
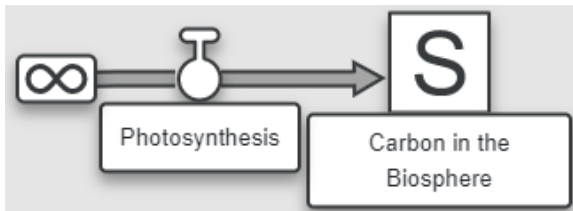
The model below is an example of a closed system with atmospheric carbon.



Feedback and Nonlinear Behavior with Connectors

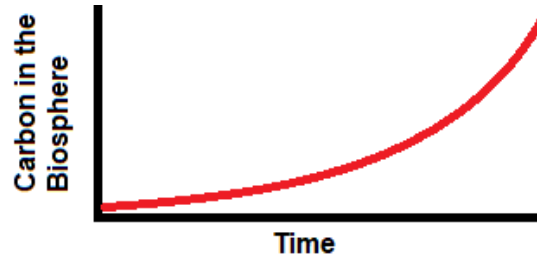
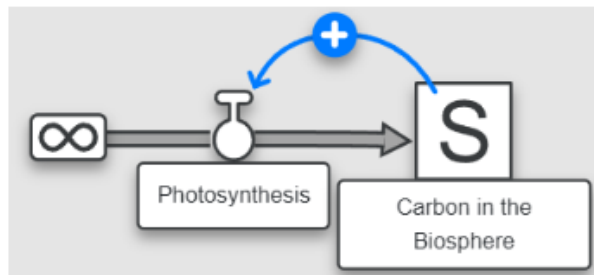
This section provides examples of some relationships that can be represented in stock and flow models.

Linear growth: A simple flow to a stock will generate a constant (linear) accumulation in the stock.



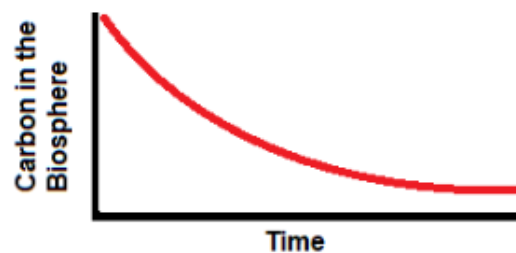
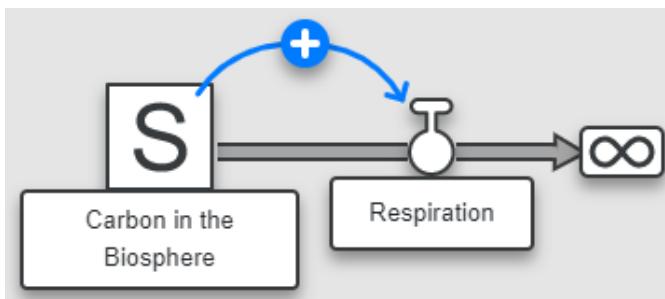
Exponential growth: If a stock has a positive connector to a flow going *into* the stock, then the inflow rate will change in proportion to the amount of the stock. This is an example of a positive feedback loop and can produce an exponential accumulation of the stock.

For example, in the model below, the positive connector indicates that the flow of photosynthesis is proportional to the amount of carbon in the biosphere. This results in an exponential *increase* of carbon in the biosphere for this model.



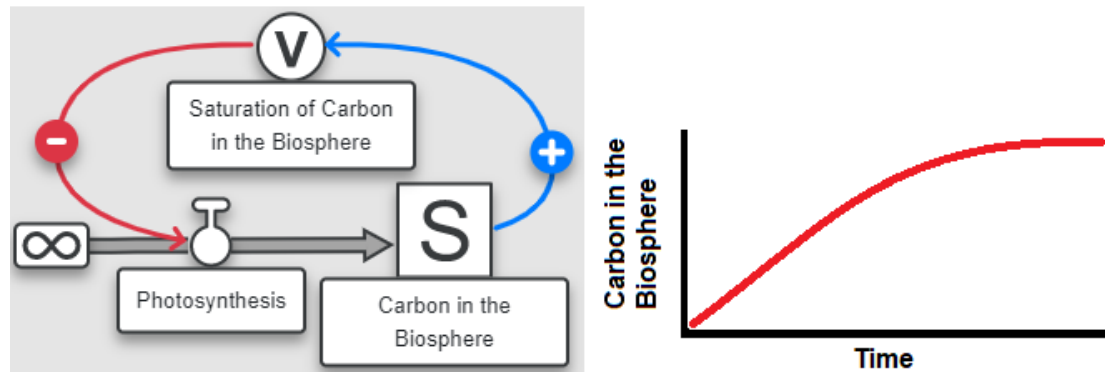
Exponential decay: If a stock has a positive connector to a flow going *out* of the stock, then the outflow rate will change in proportion to the amount of stock. This can produce an exponential decrease, also known as exponential decay.

For example, in the model below, the positive connector indicates that the flow of respiration is proportional to the amount of carbon in the biosphere. This results in an exponential *decrease* in carbon in the biosphere for this model.



Diminishing return: A diminishing return results from a stock accumulating at a rate inversely proportional to the amount of material in a stock.

For example, in the model below, carbon in the biosphere negatively affects the rate of photosynthesis through the variable “Saturation of Carbon in the Biosphere.” As more carbon accumulates in the atmosphere, the negative effects on photosynthesis increase, leading to slower accumulation of carbon in the biosphere.

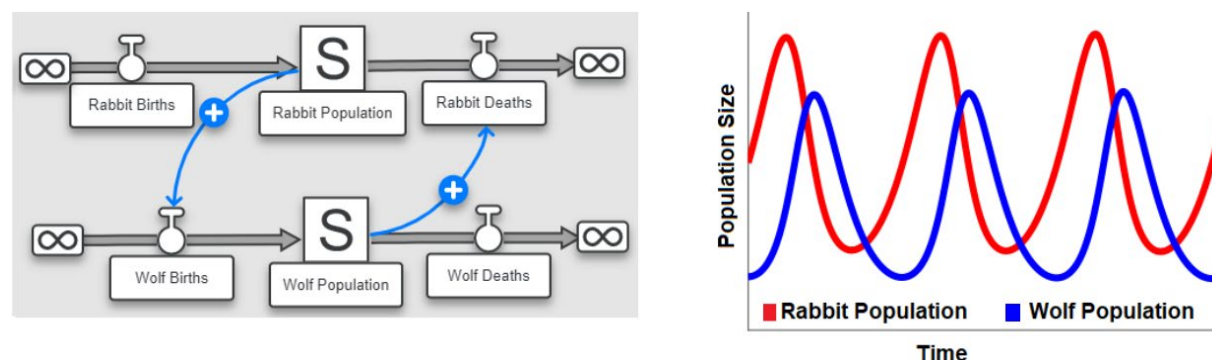


Oscillations: Oscillations can be generated through a negative feedback loop.

The example model below shows a predator-prey model for rabbits and wolves. Rabbits and wolves each increase by births and decrease by deaths. Rabbit deaths are regulated by the wolf population size, and wolf births are regulated by the rabbit population size. Therefore:

- When the rabbit population is small, the rate of wolf births is low.
- When the rabbit population is large, the rate of wolf births is high.
- When the wolf population is small, the rate of rabbit deaths is low.
- When the wolf population is large, the rate of rabbit deaths is high.

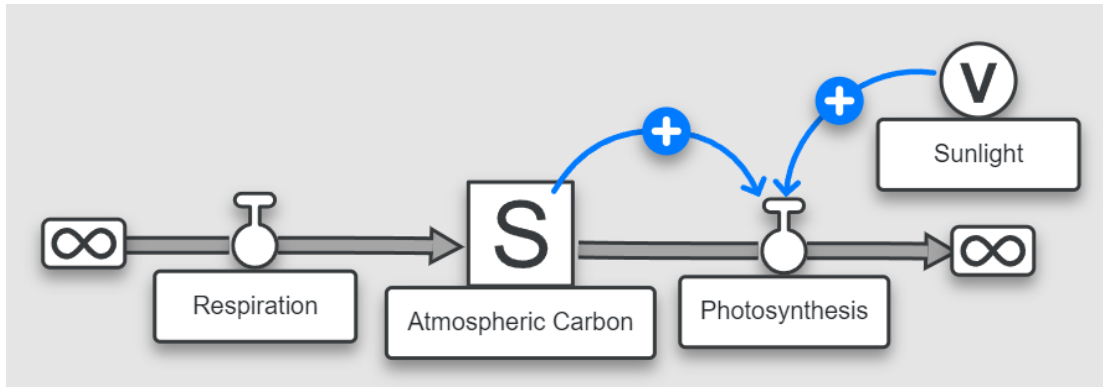
The dynamics of this model are shown in the rightmost graph below. In the beginning, the wolf population is small, so the rate of rabbit deaths is low, and the rabbit population grows. This causes the wolf population to grow, which begins to increase the rate of rabbit deaths; this causes the rabbit population to decrease, which then starts to reduce the rate of wolf births. This process continues back and forth, causing the system to oscillate.



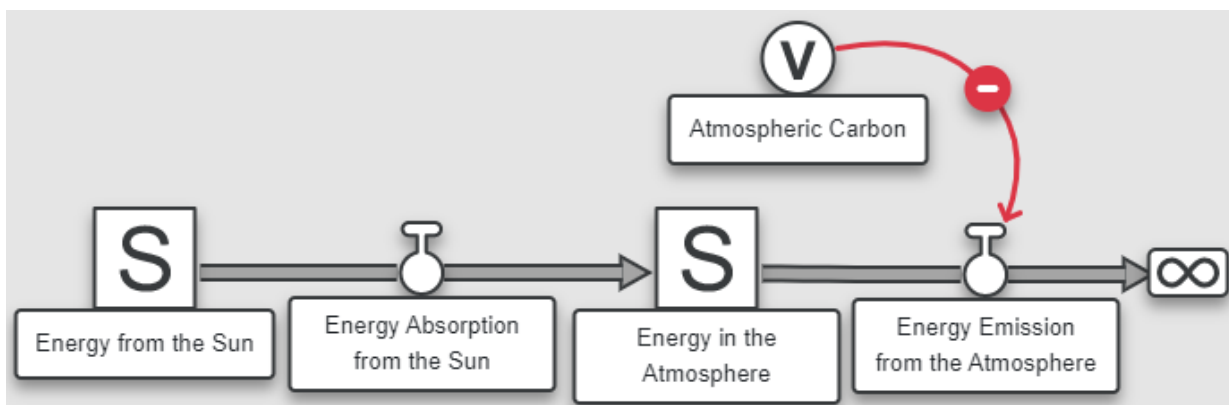
Stocks are Context Dependent

Specific components of a system may be represented as stocks and flows in one model and as variables in another. Furthermore, many systems can be represented by multiple different models (even multiple stock and flow models).

For example, in the model below, carbon is the [consistent material](#) that is accumulating in the “Atmospheric Carbon” stock.



In this next model, energy is the consistent material that is accumulating in the “Energy in the Atmosphere” stock. “Atmospheric Carbon” is no longer a stock; instead, it is a variable that affects the outflow of energy (in the form of greenhouse gases that absorb energy). It negatively regulates the “Energy Emission from the Atmosphere” flow.



The first model tracks the movement of carbon and has sunlight as a regulator. The second model tracks the movement of energy from the sun and has atmospheric carbon as a regulator.

With stock and flow models, explicitly identifying the type of matter or energy accumulating in the stocks helps students understand when objects should be assigned as stocks, flows, or variables. For this reason, it is helpful to name stock and flow models based on the material that is accumulating.