FOUR PHASES IN SYSTEMS MODELING -

PHASE I: CONCEPTUAL-MODEL DEVELOPMENT

- Define the problem
- State the model objectives
- Determine the system boundary
- Categorize the components within the system-of-interest
- Identify the relationships among the components and construct causal diagrams
- Sketch the expected patterns of model behavior

1. Define the problem
   - What is the problem to be solved?
   - What is the phenomenon to be understood?
   - What are the questions to be addressed?

2. State the model objectives
   - What do you want to accomplish with a model specifically?
   - Objectives provide:
     - the framework for model development
     - the standard for model evaluation
     - the context for interpretation of model results

3. Determine the system boundary
   - To determine what to be included or what not to be included in the system-of-interest
   - What are those important components for describing the phenomenon under consideration?
   - What are the minimum set of components that must be included in the model in order to achieve the objectives?

4. Categorize the components within the system-of-interest
   - To define distinctive classes of system components
   - To classify components into the following types of variables:
     - State variables (accumulations, levels, or stocks)
     - Rate variables (flows)
     - Auxiliary variables (neither accumulations nor flows; intermediate variables for calculating rates and other variables)
     - Constants (coefficients and other unchanging numerical values)
     - Driving variables (that affect but are not affected by the rest of the system)
     - Sources and sinks (origination and termination points)
5. Identify the relationships among the components and construct causal diagrams

A. Two Ways That System Components Are Related:
   1) Through material flow
   2) Through information flow

B. Feedback, Causal-Loop Diagramming, And System Structure

(1) Causation and Causal Links

- Causal thinking is a powerful way of organizing ideas, generate hypotheses about mechanisms, and formulate theories.

- Positive influence (effect or relationship) versus negative influence (effect or relationship) for pairs of variables
  
  o Positive influence: All other things being equal, if a change in one variable generates a change in the same direction in the second variable relative to its prior value, then the relationship between the two variables is positive.
  
  o Negative influence: When a change in one variable produces a change in the opposite direction in the second variable, the relationship between the two variables is negative.

- Graphical representation of causal links (arrows, signs, and conventions).

- **Correlation is not equal to causation**, but the former can still be used to form (non-mechanistic) relationships between variables if the correlative relationship is consistent or robust.
# Causal-loop Diagram Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
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<tbody>
<tr>
<td><img src="arrow.png" alt="Arrow Symbol" /></td>
<td>The arrow is used to show causation or influence. The variable $X$ at the tail of the arrow causes a change in (or influences) the variable $Y$ at the head of the arrow.</td>
</tr>
<tr>
<td><img src="plus.png" alt="Plus Symbol" /></td>
<td>The “+” sign near the arrowhead indicates that the variable $X$ at the tail of the arrow and the variable $Y$ at the head of the arrow change in the same direction. That is, if $X$ increases, $Y$ increases; if $X$ decreases, $Y$ decreases.</td>
</tr>
<tr>
<td><img src="minus.png" alt="Minus Symbol" /></td>
<td>The “−” sign near the arrow head indicates that the variable $X$ at the tail of the arrow and the variable $Y$ at the head of the arrow change in the opposite direction. That is, if $X$ increases, $Y$ decreases; if $X$ decreases, $Y$ increases.</td>
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<tr>
<td><img src="positive_feedback.png" alt="Positive Feedback" /></td>
<td>This symbol, found in the middle of a closed loop, denotes a positive feedback loop. It indicates that the loop continues going in the same direction, often causing either systematic growth or decline, behavior that unstably moves away from an equilibrium point.</td>
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<tr>
<td><img src="negative_feedback.png" alt="Negative Feedback" /></td>
<td>This symbol, found in the middle of a closed loop, denotes a negative feedback loop. It indicates that the loop has an odd number of negative influences (or causal links), causing the system to fluctuate or to move toward equilibrium.</td>
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(2) Feedback (Loops)

- The process whereby an initial cause ripples through a chain of causation ultimately to re-affect itself
- The process in which output affects input.

![Diagram of feedback loop](image)

(i) Positive feedback (loop)
- A feedback loop that amplifies changes of any variable in the loop
- Response to a variable change **reinforces** the original perturbation
- Synonyms: “snowball effect”, “vicious circles”, “virtuous circles”, “band wagon effect”
- Generates “run-away” behavior; a special, yet common, example - exponential growth (or decay)

(ii) Negative feedback (loop)
- Feedback loop that **counteracts** changes of any variable in the loop
- Response to a variable change **opposes** the original perturbation
- Characterized by goal-directed, goal-seeking, or “under-control” behavior

**Examples:** Thermostat heating system and population regulation

- Determination of the loop polarity
  - Add up the number of **negative** signs around the loop
  - If even, the feedback loop is positive.
  - If odd, the loop is negative.

(3) Causal-loop diagramming
- Identification of the relationship between individual pairs of variables
- Draw causal links between variables [with signs: + or - by the arrow]
- Link variables together to form feedback loops [with signs: (-) or (+)]

(4) Feedback loop structure
- A key element in systems modeling is to identify closed, causal feedback loops because:
  - The most important causal influences usually are exactly those that are enclosed within feedback loops, and identifying them, thus, helps define the system’s boundary.
  - Identification of causal loops is a powerful tool to help understand the system structure and possible mechanisms.
- Most real systems have multiple and mixed (both positive and negative) feedback loops.
(5) Some General Principles of System Structure

- All state variables represent accumulations; they can be changed only by moving their contents between state variables, sources, or sinks.

- Information is not a conserved flow. Information from a single source can be transmitted to other variables in the system without diminishing the source.

- Rate and auxiliary variables represent information in the system, and are not conserved through time as state variables are.

- In any conserved flow subsystem, the rate and state variables must alternate.

- Levels are changed only by rates in most if not all cases.

- Rates depend, in principle, only on levels and constants.

- The only inputs to rates are information links. There can be, in principle, no rate-to-rate connections in a model because most rates are not instantaneously knowable by most variables in the system and because no rate can, in principle, control another rate without an intervening level.

- In practice a rate may be expressed directly in terms of another rate when the time constant of the intervening levels is very small relative to the other time constants.

- Every feedback loop in a model must contain at least one level.

- Without a level, rate-to-rate connections or simultaneous auxiliaries result.

- In every model equation, the units of measure must be consistent.

- Dimensional analysis can NOT prove an equation is correct, but it can certainly prove some equations to be incorrect!

- Levels (state variables) and rates can not be distinguished only by their units of measures.
  - E.g., A level could be an average flow rate over a period of time!

- Within any subsystem of conserved flows, all levels have the same units of measure and all rates are measured in those same units divided by time.

- Like every variable in a model, every parameter should have a meaningful interpretation or counterpart in the real system.
- An Example of Conceptual Model Using STELLA: A model of population dynamics (from Wu and Barlas 1989; a PDF of the paper is available at the class web site).

![Causal-loop diagram of a generalized model of population dynamics, showing the basic feedback loops in natural population systems.](image-url)
6. Sketch the expected patterns of model behavior

- Sketch general patterns of the dynamics of the system based on:
  1) the feedback loop structure of the system
  2) your knowledge of the system (or phenomenon)
  3) information from other sources

- Consider them as preliminary hypotheses or speculations