This tutorial exposes you to the main ideas you'll need to use *Simulink* in ChemE 480. It reviews the material covered in week 1 of the lab.

A tutorial example

Consider the heat exchange process shown in Figure 1. Suppose that you can adjust the inlet liquid rate ($\dot{w}_i$) and temperature (T_i), and the steam temperature (T_s) independently. The liquid outlet temperature (T_o) and flow rate ($\dot{w}_o$), and the heat transfer rate ($\dot{q}$) vary accordingly.

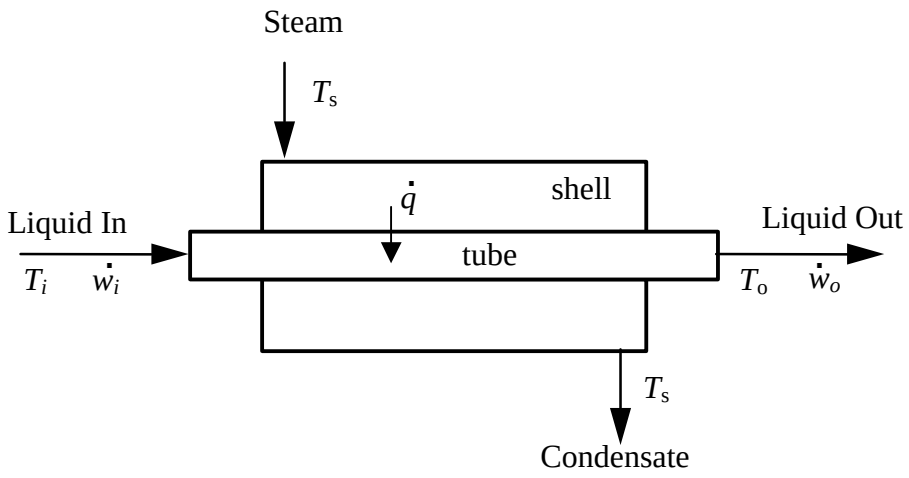


Figure 1 Shell-and-tube heat exchanger schematic

We make the following simplifying assumptions:

1. The inlet steam is saturated and the condensate leaves as a saturated liquid at the same temperature.
2. U = 800 $\frac{\text{W}}{\text{m}^2\,\text{K}}$ A = 300 m^2 , so UA = 240 kW/K (constant)
3. Other constants: liquid density, ρ_L = 800 kg/m^3; liquid holdup in tubes, V_L = 2.1 m^3; liquid heat capacity, C_p= 1.8 kJ/kg-K, all independent of temperature. Liquid is incompressible.
4. Energy accumulation in the tube wall material is negligible.
5. Liquid in tubes is well-mixed in the radial and axial dimensions (a poor assumption if the tubes are long).

Using background from previous courses (and a few additional assumptions), you should be able to obtain the following model equations:

$$\dot{w}_i = \dot{w}_o = \dot{w} \tag{1}$$

$$\dot{q} = UA(T_s - T_o) \tag{2}$$

$$wC_p \frac{dT_o}{dt} = \dot{w}C_p(T_i - T_o) + \dot{q} = \dot{w}C_p(T_i - T_o) + UA(T_s - T_o) \tag{3}$$

where

$\dot{w}$ mass rate of liquid entering and leaving the tubes, kg/s

$\dot{q}$	rate of heat transfer to the liquid in the tubes, kW
w	mass of liquid in the tubes ($=\rho_L V_L$), kg
UA	product of overall heat transfer coefficient and tube surface area, kW/K
T_S	steam temperature, ^oC
T_i, T_O	temperature of liquid entering and leaving tubes, ^oC.
C_p	specific heat of liquid at constant pressure, kJ/kg-K

Given $\dot{w}$, T_i, and T_s as functions of time – and suitable initial conditions – it should be possible to solve equations (2) and (3) for T_o and $\dot{q}$ as functions of time. One way would be to use the MATLAB techniques you used in CHEME 465. The purpose of this tutorial is to illustrate some related methods that are more convenient for CHEME 480.

NOTE: All graphics are from a PC running MATLAB Version 7, Release 14. Views may differ on other configurations.

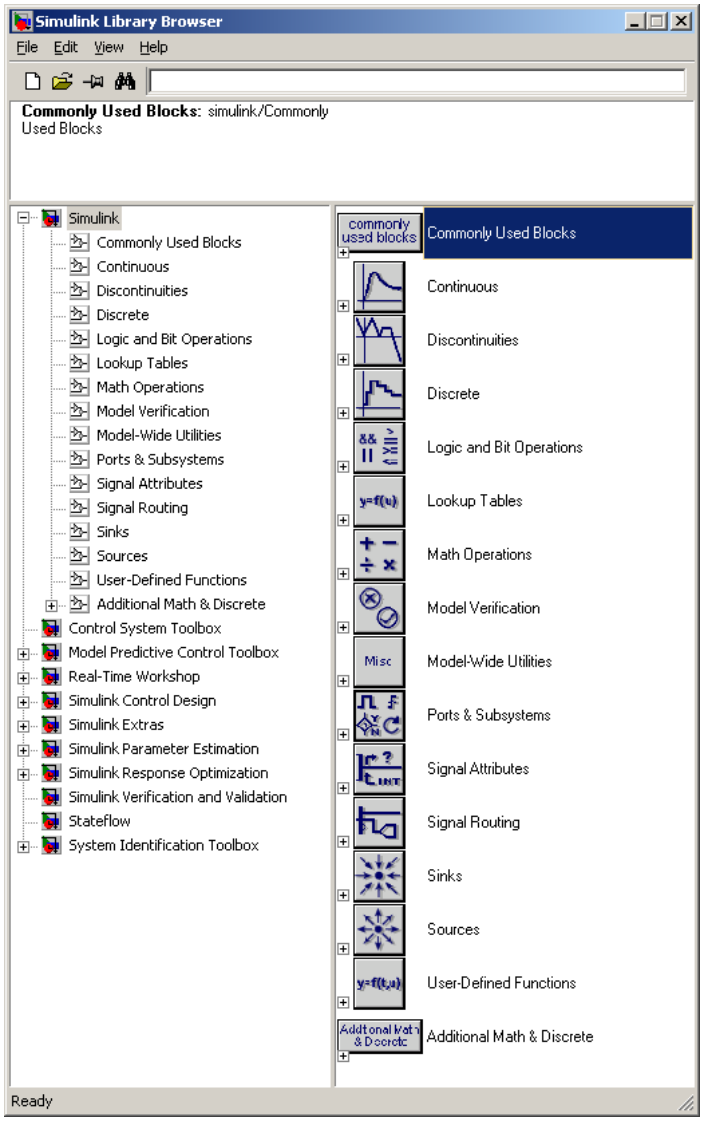


Figure 2 The Simulink Library Browser window has just been opened.

Building a Simulink model

Opening the Library Browser and model windows

With MATLAB running, type `simulink`[1] in the command window (or click the Simulink button on the MATLAB toolbar). This opens the Simulink Library Browser window (see Figure 2), which provides building blocks for model creation.

Use the Library Browser's *File* menu (or the blank document icon) to open a new model window. We will build a model by copying Library blocks into this window.

The idea is to translate each model equation into a sequence of blocks, and to connect them in the appropriate way to form a "system." The variables in the equations become *signals* that vary with time. Most Simulink blocks perform mathematical operations on input signals to generate one or more output signals.

Modeling an algebraic equation

For example, consider the linear equation, $y = mx + b$, where *m* and *b* are constants. Suppose *m=2*, and *b=3*. Let *x* be an independent function of time. Given *x*, you could easily calculate the dependent variable, *y*, without resorting to a simulation, but it's a good starting point to illustrate Simulink concepts.

Figure 3 shows one way to set it up (signal labels in green added for clarity). In this case, *x* is being modeled (arbitrarily) as a *step function* (the *Step* block). The *x* signal enters a *Gain* block, which multiplies its input by a specified constant (*m=2* in this case). Thus, the output of the *Gain* block is *2x*. To this we add the output of a *Constant* block, which is sending a value of *b=3* here. Thus, the signal going into the *Scope* is *y = 2x + 3*.

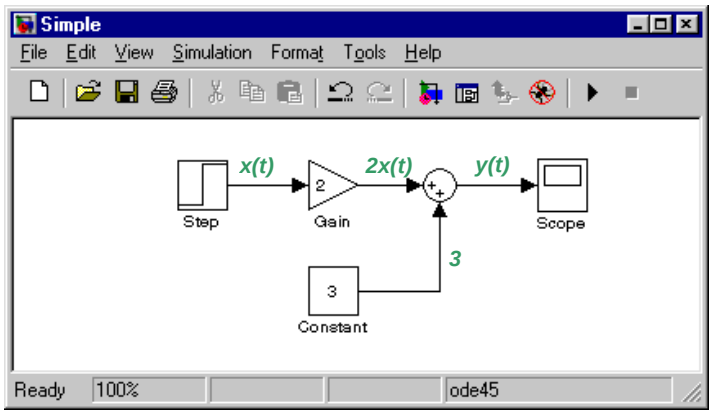


Figure 3 Simulink representation of $y = 2x + 3$, where *x* is a step function.

The *Scope* provides a graphical trend plot as a function of time, and is just one of many things we could do with our *y* signal. (Others include storing it on disk or in the MATLAB Workspace).

> NOTE: the up/down/left/right arrow directions are arbitrary and have no significance. The important concept is the flow of information from one block to another.

Copying blocks into your model

As an exercise, duplicate Figure 3 by dragging the appropriate blocks from the Library Browser to your new model window. To begin, you need to locate the *Step* block. The left Browser panel lists block categories. Click on the *Sources* category to reveal the standard Simulink signal source blocks, which

[1] A `Courier` font denotes MATLAB commands that you should type in the MATLAB Command Window.

appear in the right panel (see Figure 4). You will probably have to scroll down to find the *Step* block (blocks appear in alpha order). Once you've found it, if your model window is showing you can drag a copy of the *Step* block to it. Alternatively, you can right-click on the *Step* block. The resulting menu gives you the option to paste the block into the model window.

Next, add the remaining blocks to your model window. It can be frustrating to locate them[2]. Here are some hints: a *Constant* is another signal source, the *Gain* and *Sum* are math operations, and the *Scope* is a signal sink.

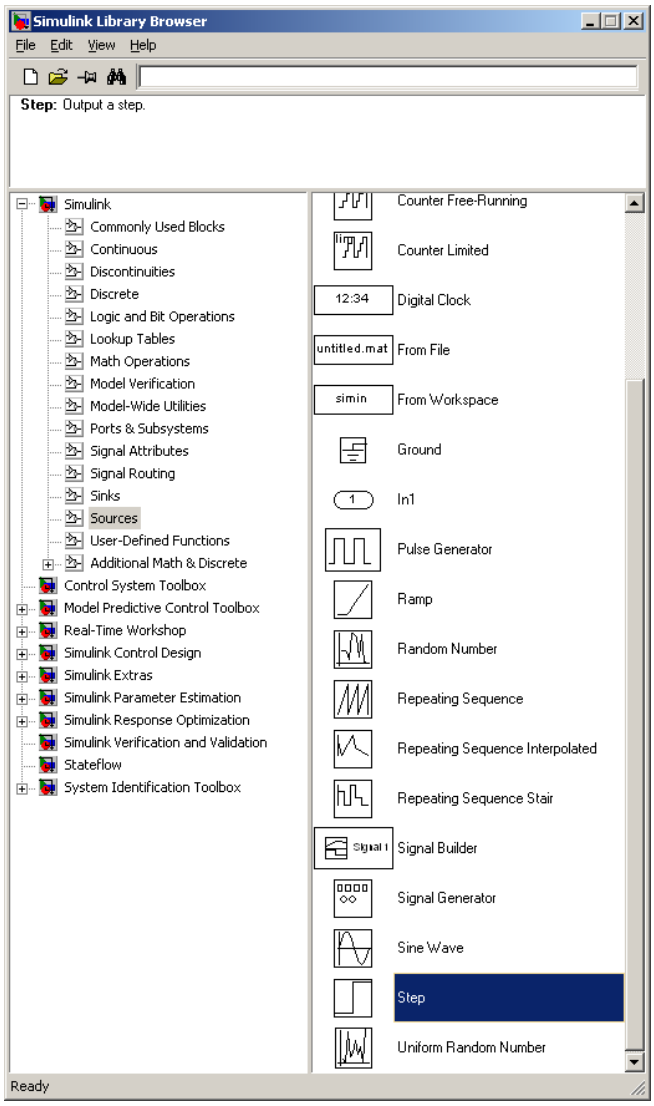


Figure 4 Simulink Library Browser after clicking on *Sources* and selecting *Step*

If you're have trouble, type `helpdesk` in the MATLAB Command Window, which opens the Help Browser. Use the Contents panel to navigate to Simulink/Using Simulink/Block Reference/Simulink Block Libraries, which lists each block by name. Clicking on a name displays a detailed description, including the block's location in the library. Similarly, if you're browsing the Library and are uncertain of a block's purpose, right-click on it and select *help* to see the detailed description. Also, the Library Browser's upper panel provides a

[2] Not only is it difficult to anticipate the operations available, but their assignments to the categories can be non-obvious, and they tend to change from one Simulink version to the next. Electrical engineers were heavily involved in Simulink's development, which makes the presentation less intuitive for us.

brief description of the selected block (see Figure 4 for the *Step* block's brief description).

Entering block parameters

You should now have the five required blocks in your model window, arranged as shown in Figure 5. The *Gain* and *Constant* values are incorrect, however (the defaults are 1). To fix these, double-click on each, and enter the desired value in the parameter box.

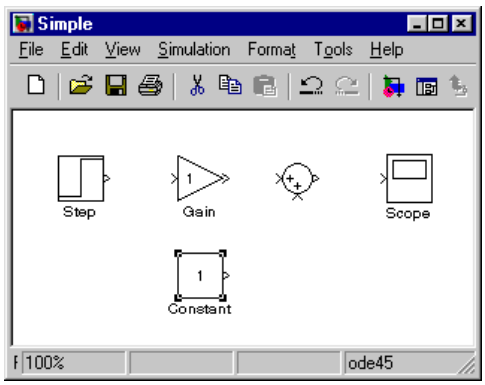


Figure 5 Blocks copied from the standard Simulink library

Connecting blocks

The small > symbol on the right side of the *Step* block marks its "outport." Note the "inport" on the *Gain* block's left side. Click and drag from the *Step*'s outport to the *Gain*'s inport to connect them. The resulting signal line *must* have a solid, filled-in arrowhead, as in Figure 3. If not, the blocks aren't connected; try again. Similarly, connect the rest of the blocks until you obtain the result shown earlier in Figure 3. Note the way Simulink automatically makes a neat right-angle connection when you connect the *Constant* to the *Sum*.

Defining input signals

Now let's set up a simulation. First, we define the input signal details. Double-click on the *Step* block to open the menu shown in Figure 6. The default values shown will cause *x* to equal zero from the initial time until the step occurs (at time = 1), when *x* will increase to 1 (instantly).

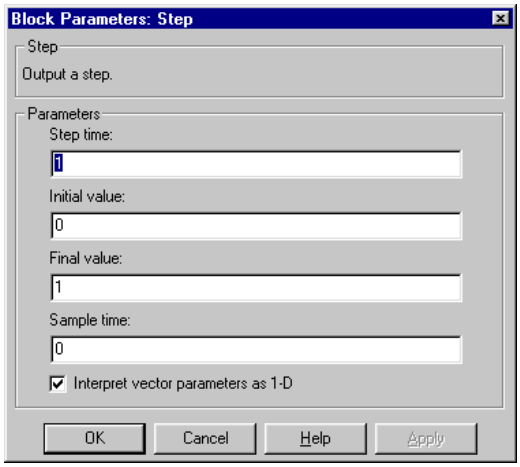


Figure 6 The *Step* block's parameter menu

The zero sample time signifies that the block's output will be a continuous function of time. If it were a positive value, the block's output would be defined at integer multiples of the sample time, but undefined at other times.

Leave all parameters at their defaults for this example.

Simulation parameters

Next we check the *Simulation Parameters*. In your model window, click on the *Simulation* menu and select *Configuration Parameters* to open the window shown in Figure 7.

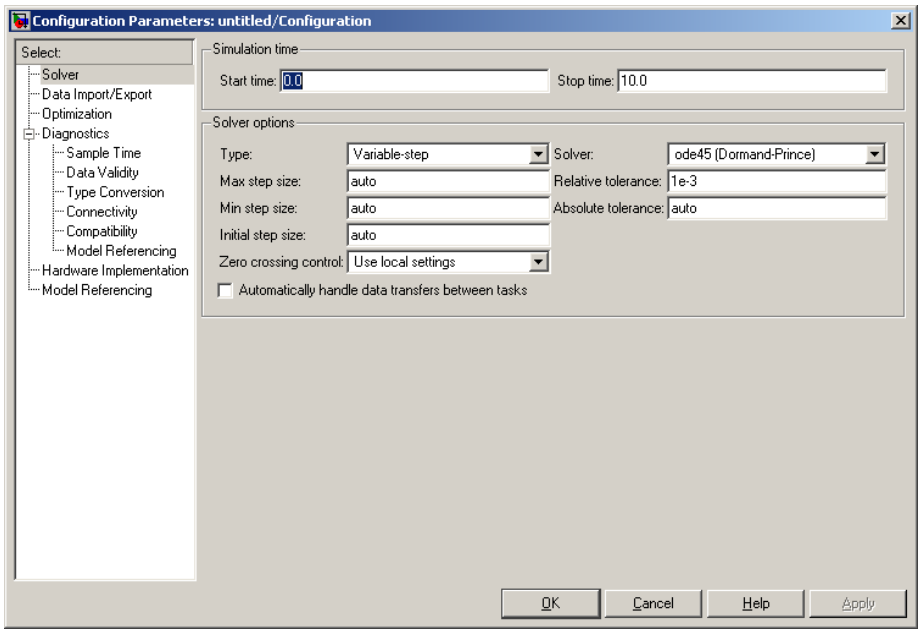


Figure 7 Simulation parameters menu, Solver panel

The left side allows you to navigate to various configuration panels. The *Solver* panel (selected in Figure 7) allows you to specify the time at which the simulation starts and stops (which depends on the time scale of your problem[3]). Note also the *Solver options*. The default solver, *ode45*, is a variable-step-size, 4th-order Runge Kutta algorithm, which is a good all-around choice, but is poor for *stiff* problems[4], and there are situations where a fixed-step-size algorithm would be better. See the *Simulink Help* for details. We'll use *ode45* in this simple example.

You can usually use the defaults for the remaining parameters on this panel, but if you suspect that your results are inaccurate, try decreasing the relative tolerance by an order of magnitude or two. If the results change significantly, decrease it even further. Direct control of the step size can also be useful, as we'll see later.

The Data Import/Export panel controls communication between MATLAB and Simulink. You might find this valuable in some cases, but we'll use the defaults for this and all other panels.

Close the configuration window. As the final preparation for the simulation, double-click on the *Scope* to open the graphical display.

[3] This can be a confusing and subtle issue. Your problem definition implicitly determines the units of time used in the simulation. All your equations must use consistent time units or the results will be incorrect.

[4] See also Riggs, Sec. 3.7, pp 123-125.

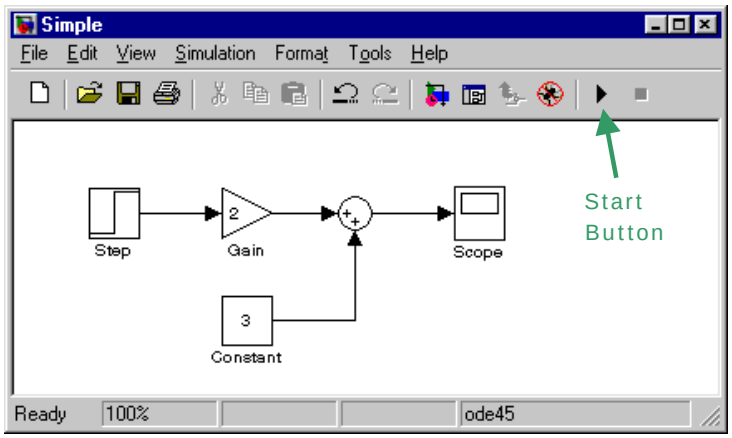


Figure 8 Ready to start the simulation

Running the simulation

Now click the *Start Button* (see Figure 8). The simulation begins (the *Start* button changes to a *Pause* icon, and the *Stop* button to its right becomes active). The elapsed time appears in the box just to the left of the simulation option (bottom of model window) and the *y* signal trace appears on the scope. (NOTE: this simulation is trivial and runs so rapidly that you probably won't be able to see things changing.) On a computer with sound you should hear a beep when the simulation ends.

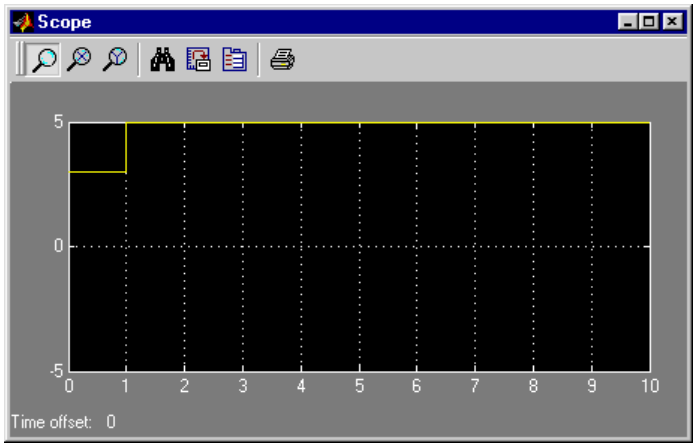


Figure 9 Scope display of the *y* signal

Figure 9 shows the final result (the yellow line). As one would expect from the problem definition, *y* starts at *3*, and increases to *5* at $t = 1$.

The default *y* scale (*-5* to *+5*) isn't a very good choice here. Try clicking on the *binocular* icon to auto-range the plot. You can also click on the plot to zoom in on that portion. Other toolbar buttons allow you to zoom in on selected parts of the plot, permanently set the axis scales (for use in a later simulation), *etc*. See the *Scope* block's detailed description for more information.

Modeling a first-order differential equation

Most of the models you'll develop in ChemE 480 derive from unsteady-state conservation equations (mass, energy, and/or momentum), usually first-order differential equations (see, *e.g.*, Equation 3). Consider a linear, first-order ODE with constant coefficients

$$\frac{dy}{dt} + 2y = 3x + 1 \tag{4}$$

where *y* is a dependent function of time, and *x* is independent. To form a Simulink model we first rearrange (4) to solve for the derivative,

$$\frac{dy}{dt} = 3x + 1 - 2y \tag{5}$$

Then we arrange Simulink blocks to compute the *y* derivative, and *integrate* it to calculate *y*. (We need the *y* value to compute the derivative, so the model must include a "feedback".) Figure 10 shows one way to set it up (the signal labels aren't part of the normal display).

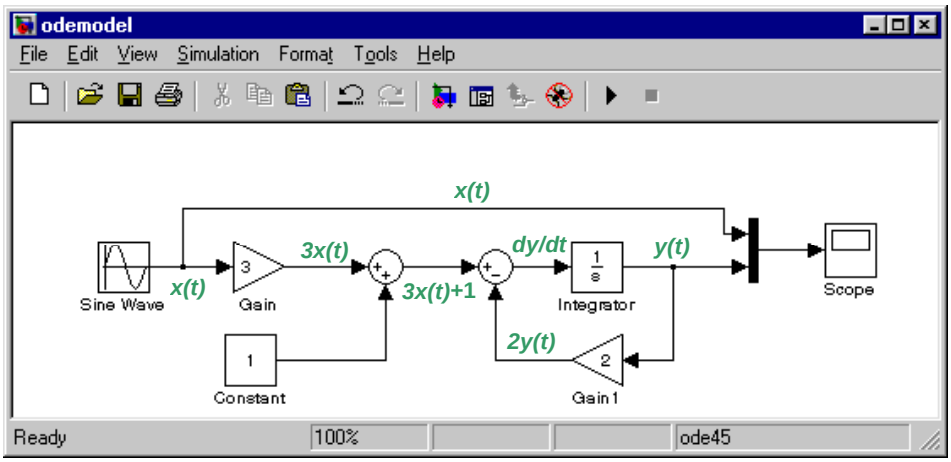


Figure 10 Simulink model of a linear, first-order ODE

Try duplicating this, keeping the following points in mind:

We're assuming (arbitrarily) that *x(t)* is a sinusoid. The *Sine Wave* block is in the *Sources* category. Use the default parameters. These provide a continuous sine wave with unity amplitude and a frequency of 1 radian per time unit (the documentation claims that the time unit is seconds, but that isn't true in general as explained previously). Thus, the sine wave's period will be 2π time units.

I dragged a *Gain* block in from the Library Browser, then used *control-click and drag* to make a copy. Simulink requires all the block names in a system to be unique. and it automatically assigns a new name to copied blocks (e.g., *Gain 1*). Then I right-clicked on the copy and selected Format/Flip Block to reverse its direction (you can also rotate, *etc*.).

I also duplicated the *Sum* block. By default, Simulink hides its name, but each is unique. (You can right-click and use the format menu to show the name if you wish.)

One of the *Sum* blocks must do a subtraction. To accomplish this, double-click on the block and edit the *sign symbols* in the block parameter box. Try different combinations of the signs (and the vertical bar), clicking *apply* each time to see the effect (or read the block help). You can add a third input by including a third sign symbol. (If you have more than three inputs, use the rectangular block shape instead.)

The *Integrator* block is from the *Continuous* category. The 1/s icon derives from Laplace transforms. Its key parameter is the *initial condition*, which sets the value of its output when the simulation begins (*i.e.*, *y*(0) in our case). Use the default (zero).

The black vertical bar just to the left of the scope is a *Mux* block (from *Signals & Systems*). It combines the scalar *x(t)* and *y(t)* signals into a *vector* signal so we can plot *x(t)* and *y(t)* on the same graph window. Another way would be to define two scopes, one connected to each scalar signal, which would be better if

the *x* and *y* magnitudes were very different. You can also define multiple axes for a single scope block, in which case the block will have multiple inports and its display window will be split to show each axis.

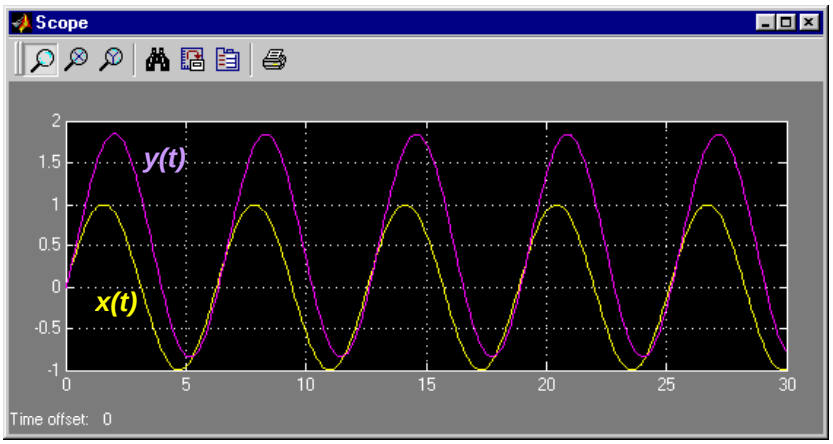


Figure 11 Simulation results for ODE example

The small black dots on two of the signal lines are *solder junctions* (another EE influence). All lines entering/leaving a solder junction carry the same signal.

To make a solder junction, move the cursor to the desired location, and then control-click-and-drag to start drawing the new signal line. After you've made a solder joint you can move it around by clicking-and-dragging. You can also move signal line sections and blocks.

It's possible for signal lines to cross without forming a solder junction (try it). In that case, the signals are independent.

Set the stop time to 30. The most convenient way is to edit the value at the top of the model window. To make the plots look better, set the maximum step size to 0.1[5]. Next, run the simulation

Figure 11 shows the results (with superimposed *x(t)* and *y(t)* signal labels for clarity). Use the *binoculars* icon to zoom in on the curves. The steady sinusoidal input, *x(t)*, eventually causes a sinusoidal output having the same frequency but a different phase. We will study such *frequency responses* in more detail later.

Using subsystems

Modeling a single algebraic or differential equation is fairly easy, but what about multi-equation models? It's really no different. You define each equation and its variables (signals), then combine equations by connecting their common signals.

One problem is that the diagram can become complicated, making it hard to understand the model. You can reduce the apparent complexity by defining *subsystems*, each of which models part of the complete system. This is conceptually similar to the use of functions and subprograms in computer languages.

For example, consider combining (5) with another differential equation:

$$\frac{dz}{dt} = 2x - y - 3z \tag{6}$$

[5] If you don't do this, Simulink will maximize the step size to speed up the calculations. As a result, some of the points will be far apart and joined by straight lines, so they won't look like smooth sinusoids. The calculated points will still be accurate, however.

Adding this to our previous model would be easy, and the diagram would still be fairly clear, but we will use subsystems to illustrate the concept.

Start with a new model window. Drag in a *SubSystem* block (from the *Ports and Subsystems* category). Edit the block name, changing it to "Equation 5". Next make a copy, naming it "Equation 6." Your model window should now resemble Figure 12 (I have named the model *TwoODEs*).

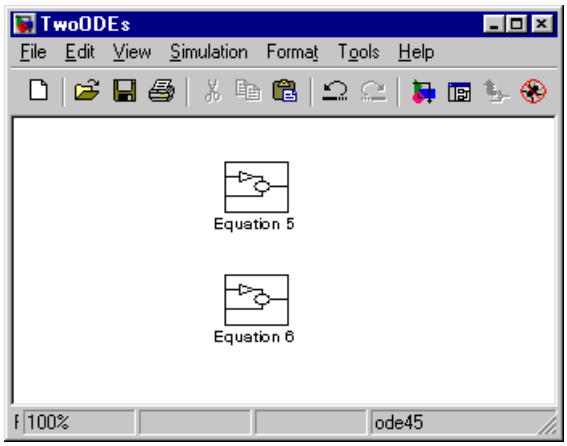


Figure 12 Two (renamed) subsystem blocks

Double-click on *Equation 5* to open its modeling window. By default, it contains a single inport (named *In1*) connected to a single outport (*Out1*). In other words, the default subsystem simply equates the output signal with the input. Equation 5 also involves one "input" variable (*x*) and one "output" (*y*). Thus, rename *In1* to "x" and *Out1* to "y". Delete the signal connecting *x* and *y*, and then insert Equation 5 using the same approach as before[6]. Figure 13 shows the completed subsystem window.

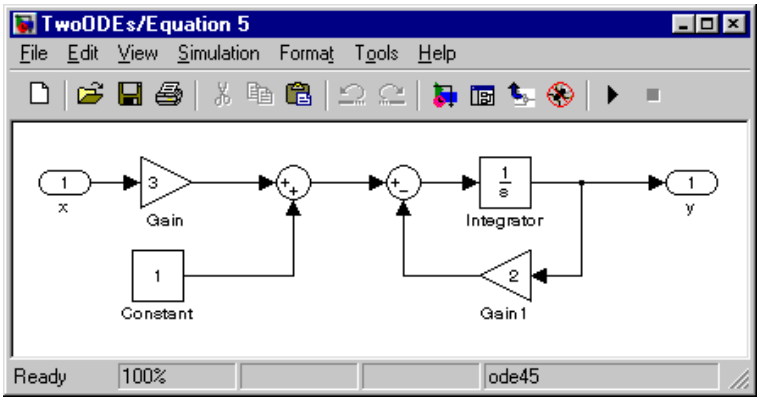


Figure 13 Equation 5 subsystem

Close Equation 5 and return to the main model window. The Equation 5 icon now labels the input and output ports with the appropriate names. Repeat the procedure to create Equation 6, which requires two inputs (*x* and *y*) and generates one output (*z*). To get the extra inport, copy the existing one or drag one from the *Ports and Subsystems* category.

[6] If you still have the model we developed in the previous section you can copy-and-paste its blocks into the Equation 5 window. Just drag a selection rectangle around the blocks you want to copy.

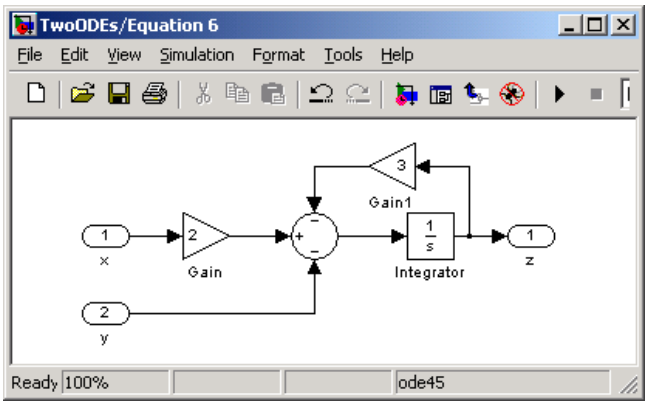


Figure 14 Equation 6 subsystem

Figure 14 shows one possible arrangement for Equation 6. Note the use of a 3-input summation block (you could also use two 2-input summation blocks). Close Equation 6 and return to the main model window.

Connect the subsystems (output y of Equation 5 to input y of Equation 6). Then define the *x(t)* signal. This time use the *Pulse Generator*. Set its period to 10 and leave its other block parameters at their defaults. Add a *Mux* (with 3 inputs – change the block parameter from 2 to 3) and *Scope*, and set up to plot *x*, *y*, and *z* on the same scope.

Figure 15 shows the final arrangement. (Note the way the *x* and *y* signals cross – they are independent.) Define the *Simulation Parameters* for a 30 time-unit run, with a maximum step size of 0.1. Then run the simulation

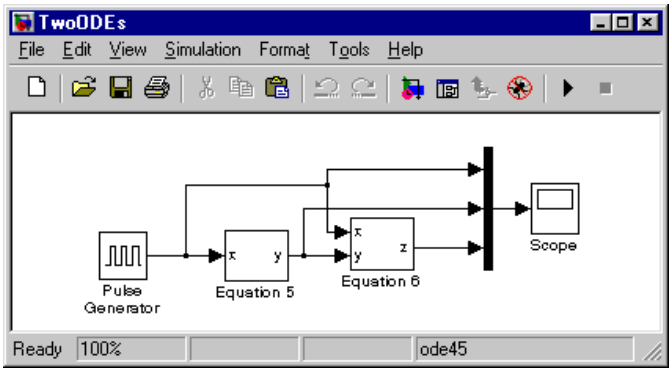


Figure 15 Main model window with defined subsystems and input

Figure 16 shows the results. The yellow trace is the periodic pulse input, *x(t)*. The magenta is *y(t)*, and the cyan is *z*(t)[7]. As with the sinusoidal input, the outputs eventually behave periodically. Would you have anticipated this result?

[7] The colors always appear in this order. There is no way to show a legend on the plot window, so you need to remember the color representing each signal. You can also right-click the y-axis and give the plot a title listing the colors and the corresponding meaning.

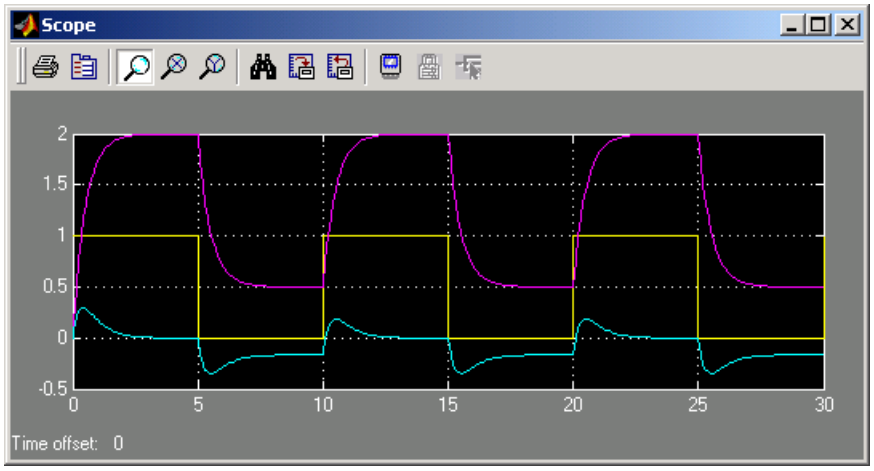


Figure 16 Simulation results for TwoODE system

Heat exchanger model development

Specifications

The previous sections have covered the tools needed to simulate the heat exchanger. As an exercise, define a Simulink model of equations 2 and 3 (you can ignore equation 1, which is just a definition). It should have three independent variables (*inputs*): T_i, T_s, and $\dot{w}$. Also define two dependent variables (*outputs*): $\dot{q}$ and T_o. The model's initial conditions should be a steady-state with the inputs at the following values:

$$T_i = 100$$
$$\dot{w} = 100/3$$
$$T_s = 150$$

Define each input to be a step starting from the above initial conditions. Plot the two outputs on separate scopes (or use a single scope with two axes). Note: the *Gain* block multiplies a signal by a constant. It can't multiply two signals. You'll need a *product* block for that.

Run three simulations. In each case, make a *unit-step* change in one of the inputs (beginning at $t = 5$), and hold the other two inputs constant. Each simulation should vary a different input. Run each simulation for 50 time units. Save the model for use later. Answer the following questions:

1. What time units are being used?
2. What are the initial conditions for the two outputs?
3. Are the responses qualitatively reasonable in each case?

A solution – Simulink diagrams

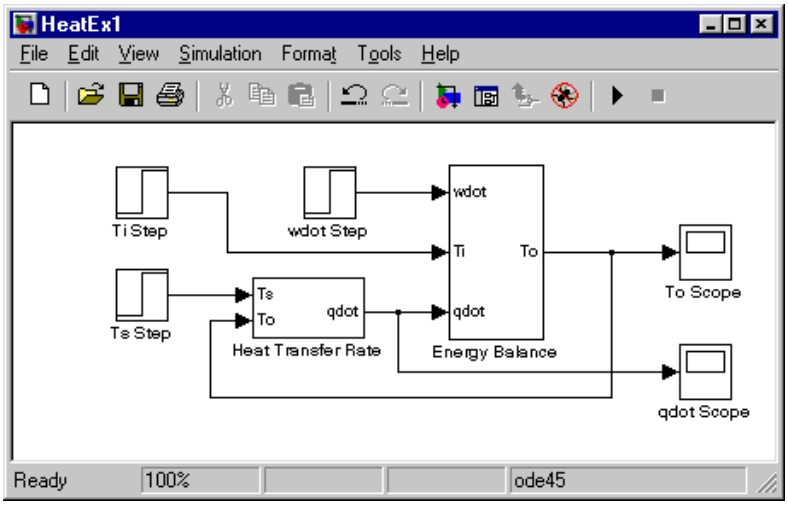


Figure 17 Heat exchanger model -- main window

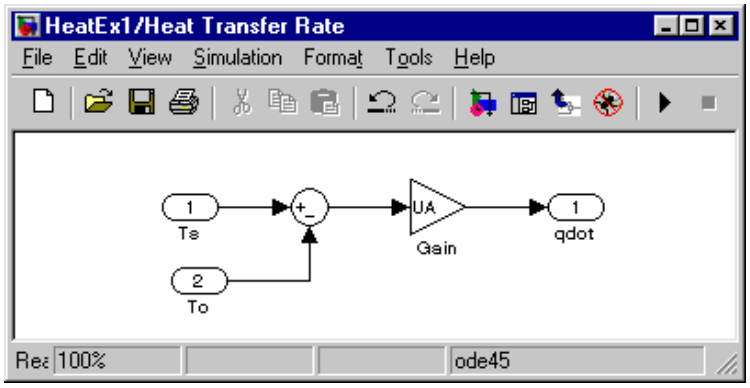


Figure 18 Heat transfer rate subsystem

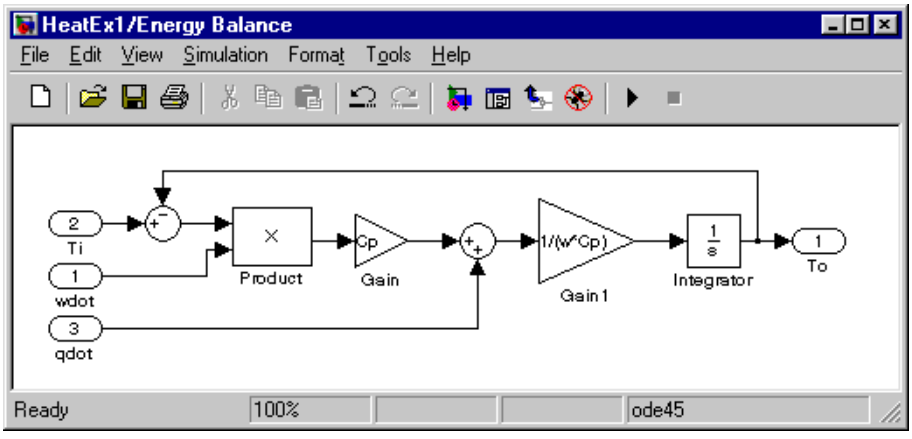
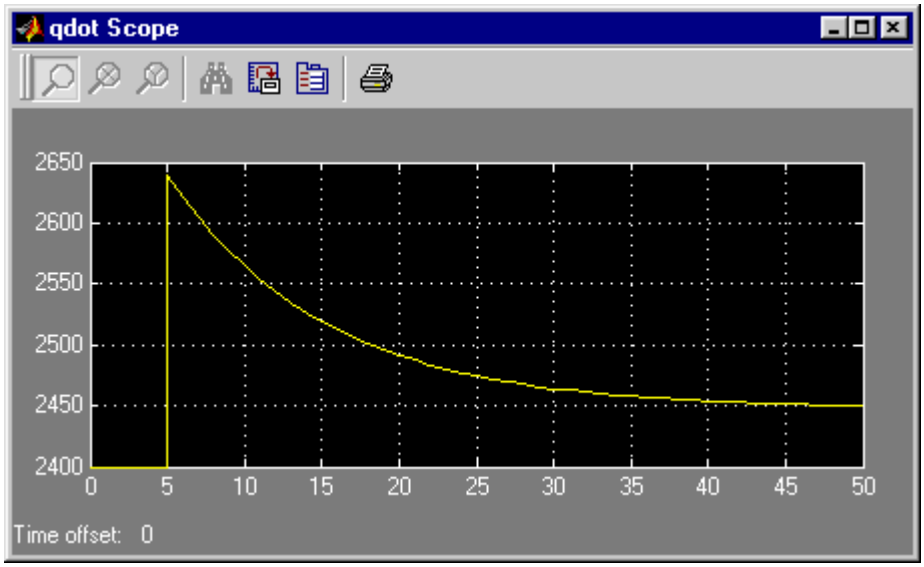
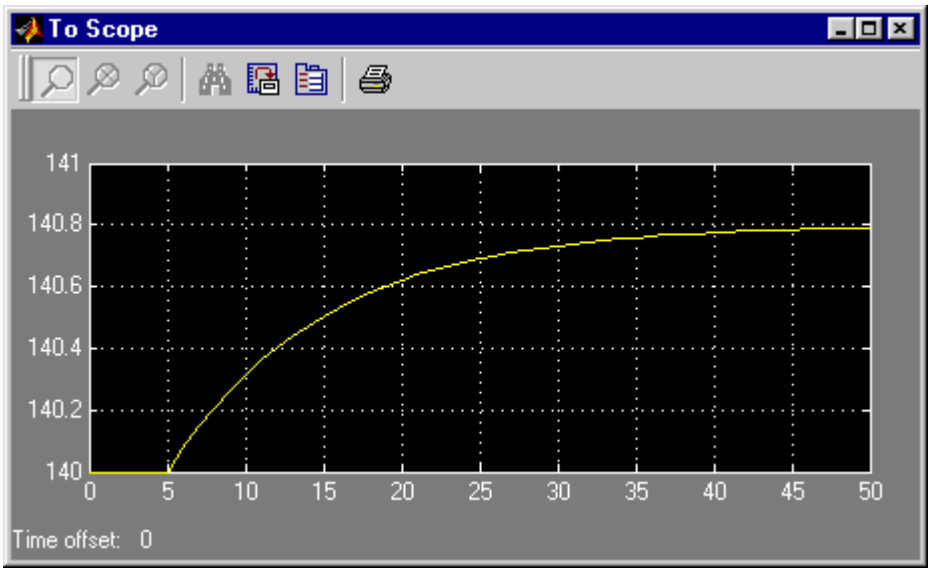


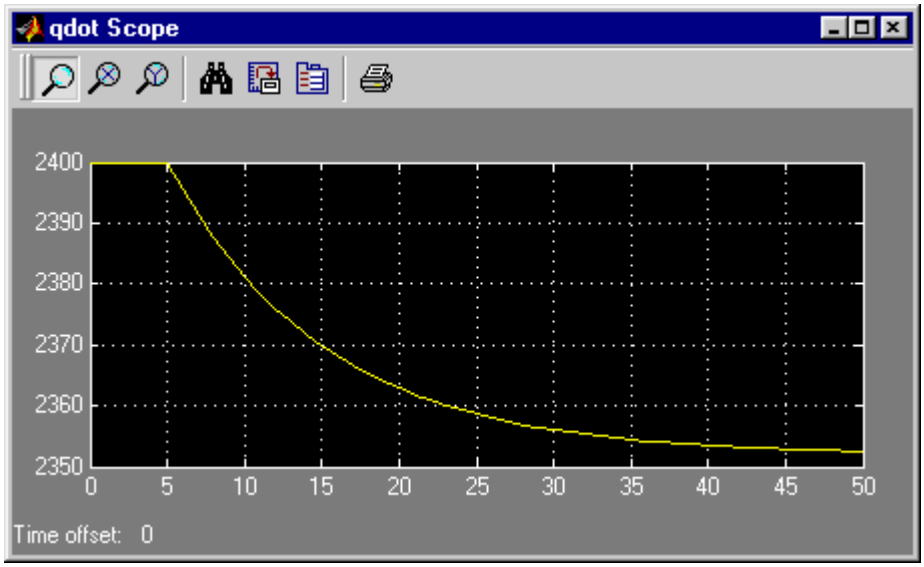
Figure 19 Energy balance subsystem

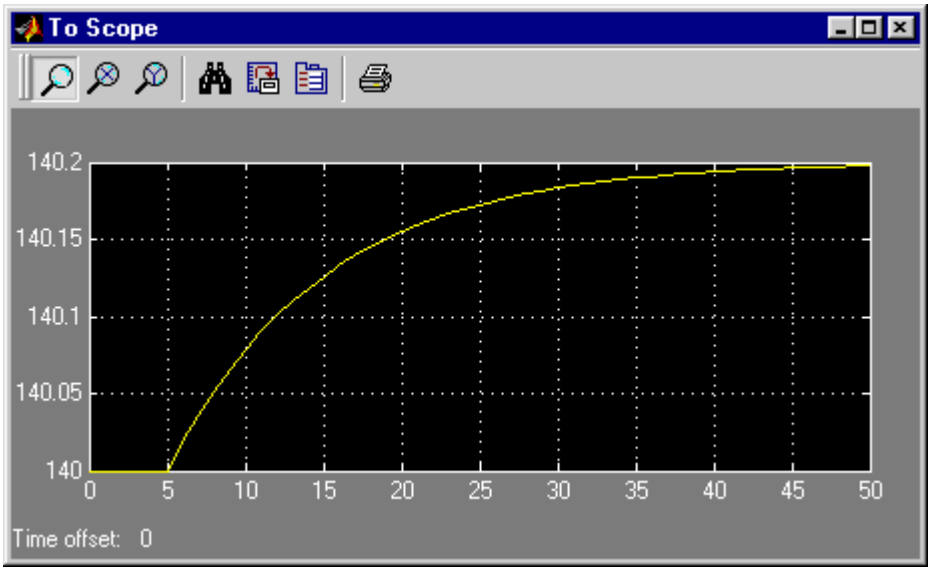
Response to T_s unit step



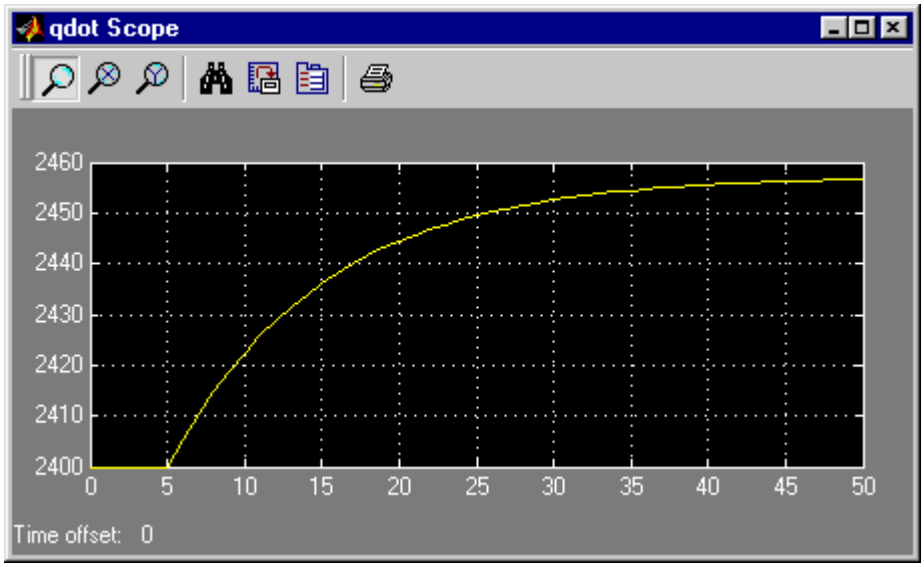


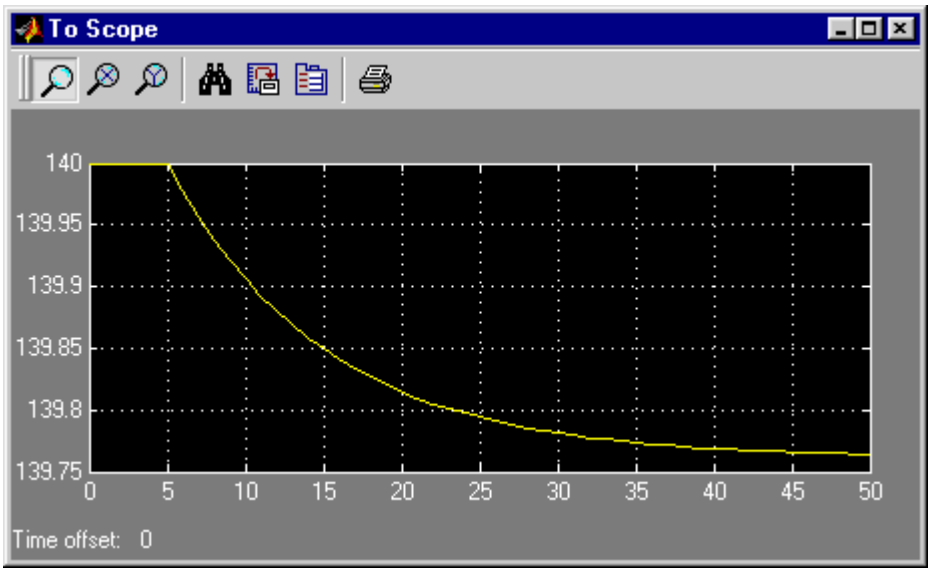
Response to T_i unit step





Response to inlet flow rate unit step





Remarks

- The initial conditions are $T_o = 140$, $\dot{q} = 2400$.
- The time units are seconds (because we defined all heat exchanger model parameters in terms of seconds).
- The integrator in Figure 19 requires an initial condition for T_o (the initial steady-state value).
- Note the use of variable names rather than numbers in the gain block parameter definitions. If you do this you must define each such variable in the MATLAB workspace before running the simulation. Thus, for example, you would type `Cp=1.8;` in the Command window to define the specific heat value. This may seem cumbersome, but it makes the model easier to understand. It also makes it easy to modify a parameter – you just change its value in the workspace instead of having to modify all the blocks in which that parameter appears.
- The response of T_o to a unit-step in T_i is the *least* realistic. If the tubes were long and the flow turbulent (*plug flow*), it would take a while for the change in T_i to show up in T_o (because the fluid temperature change would move down the tube, carried along by convection).

A more realistic heat exchanger model

To better approximate plug flow in the tubes divide the exchanger into *sections*. Each section will use the same equations and model structure developed previously. In other words, each section will have well-mixed tubes at a uniform temperature. The fluid leaving one section flows to the next. The more sections, the more closely we approximate plug flow.

Creating a masked block

To make this easy to do we introduce another Simulink feature: *creating a masked block.* (This is how the blocks in the Library were made.) You should consider doing this any time you create a subunit that could be re-used in another model[8].

To begin, create a new model window and put a single subsystem block in it, and name it *HeatX Section*. Open the subsystem window. Open your saved heat exchanger model and copy it into the subsystem block. Define T_s, T_i, and $\dot{w}$ as input ports, and T_o and $\dot{w}$ as output ports (eliminate the step function and scope blocks). All block parameters should be in terms of the variable names *w*, *Cp*, and *UA*, as shown in Figure 18 and Figure 19. Also, use the name *To_0* to represent the integrator's initial condition.

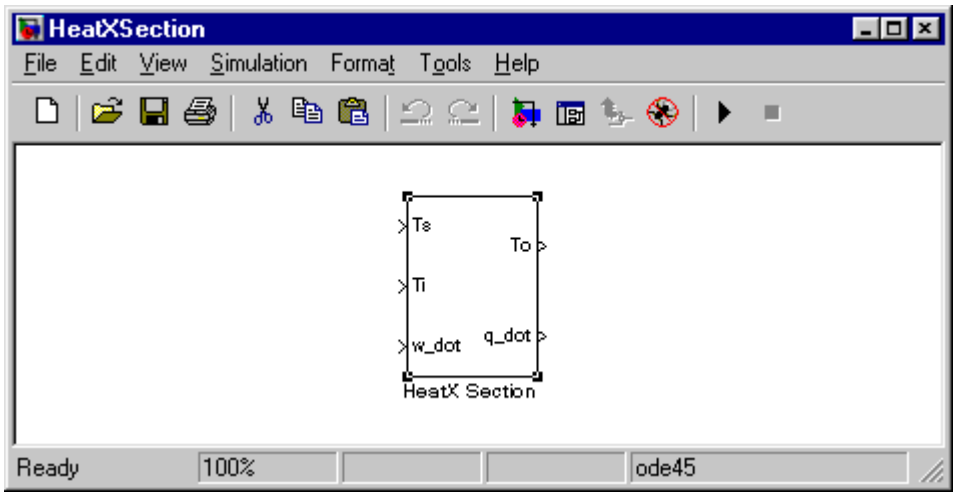


Figure 20 Block to model a heat exchanger section

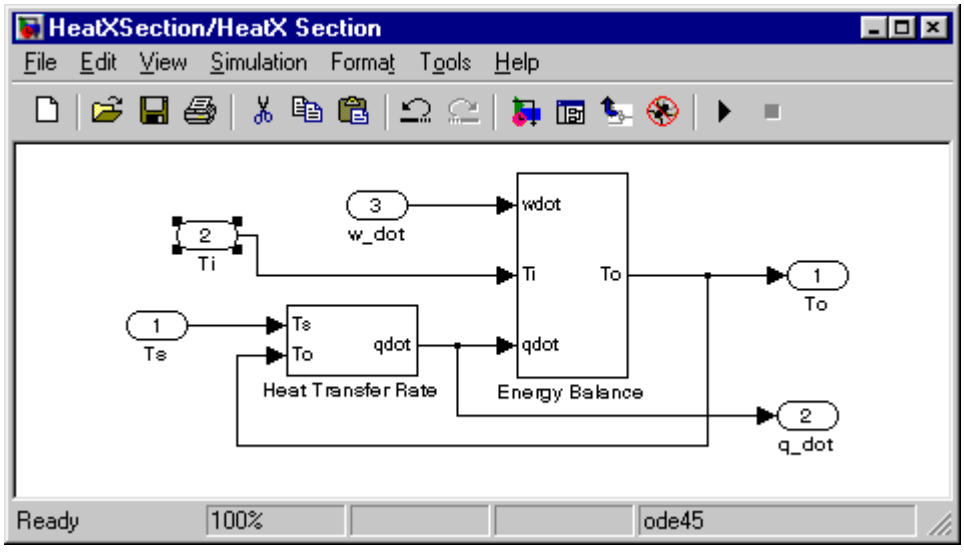


Figure 21 Heat exchanger section details

[8] You can maintain your own library of specialized blocks. See the Simulink documentation for more about libraries.

The result should resemble Figure 20 and Figure 21. Now we *mask* the block, which isolates its parameters from those of other blocks, and provides a convenient user interface. Close the subsystem block window (Figure 21), right-click on the HeatX Section block in the main window (Figure 20), and select *mask subsystem*. This opens the *Mask Editor* window (see Figure 22).

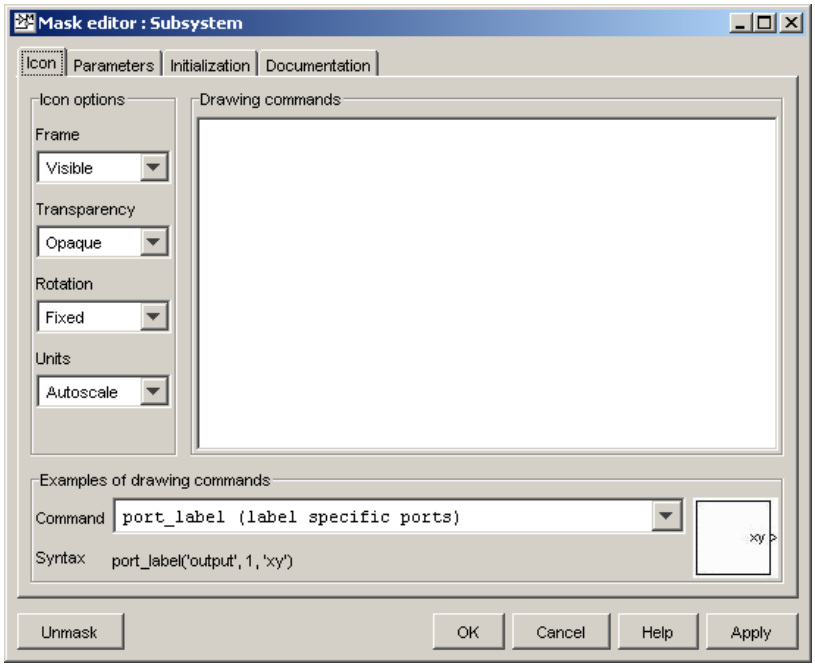


Figure 22 Mask editor -- Icon tab

The *Icon* tab allows you to create an icon for your block. We won't bother with that, but you might want to use it in the future.

Select the *Parameters* tab (see Figure 23). Its main purpose is to define variables appearing in the subsystem. We will create an interface that allows one to specify the specific heat, liquid mass, *UA* value, and initial tube fluid temperature.

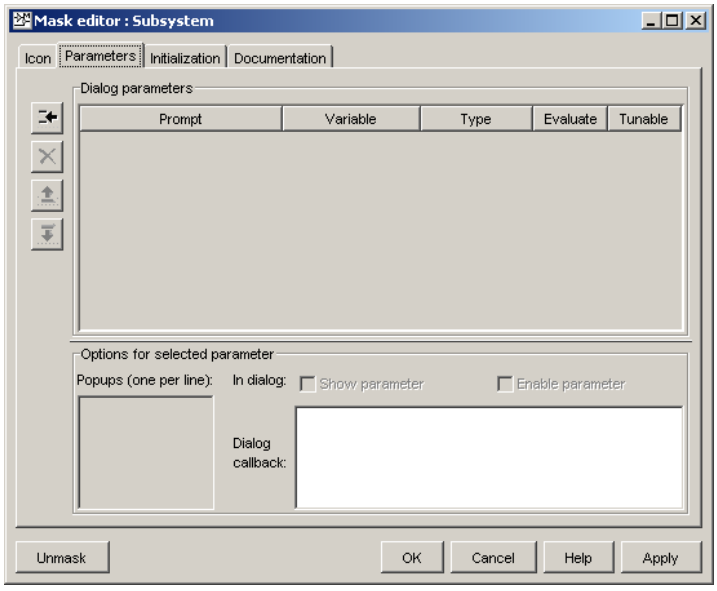


Figure 23 Mask editor -- Parameters tab

Click the "Add" button (upper left side) and type "Initial fluid temperature, C" in the resulting *prompt* box. Then type the corresponding variable name (*To_0*) in the *variable* box. Leave the *Type*, *Evaluate*, and *Tunable* settings at their defaults. Repeat to define the remaining three variables.

The Mask editor window should now resemble Figure 24. It will depend on the descriptions you used and the order in which you entered them. If you wish, you can modify the order by selecting one of the entries in the parameter list box and using the *Up* or *Down* button.

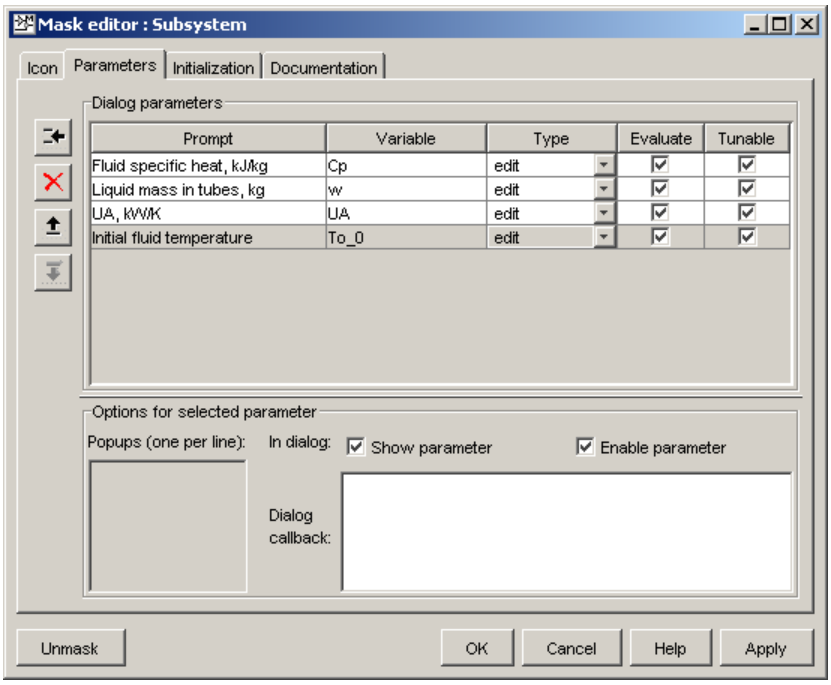


Figure 24 Mask editor with block parameters defined

The *Initialization* tab allows you to enter MATLAB commands to define anything your model needs prior to begin the simulation. This provides a great deal of flexibility, but it isn't needed for this exercise.

Now click the *OK* button to close the Mask Editor (don't use the cancel button or you'll lose your entries). Double-click your HeatX Section block. Instead of opening the subsystem window you get a block parameter dialog window, which should resemble Figure 25.

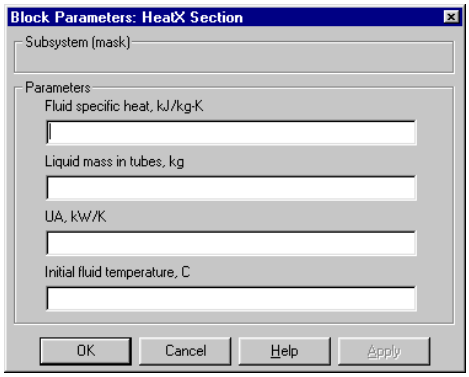


Figure 25 User interface for the HeatX Section block

The variables within the masked block are now isolated from the MATLAB workspace and all other blocks. The only way to set the parameters is through the dialog window. This makes inadvertent changes less likely.

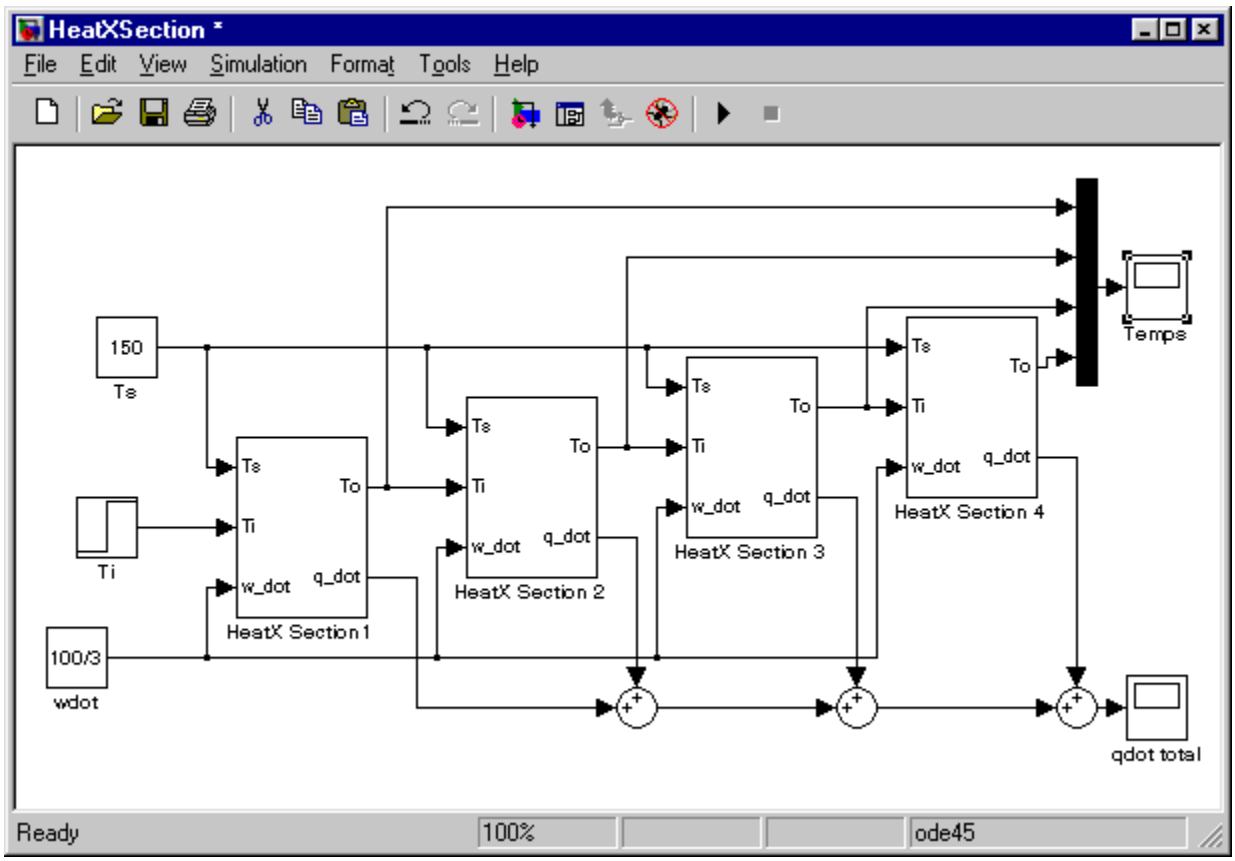
If you wish to see or modify the underlying model, right-click on the block and select *Look under mask*. Some changes may require you to modify the mask, in which case you should right-click on the block and select *Edit mask*.

Using the masked block

Before using a new block as a building block you need to test it to make sure it's working as expected. Check its operation against the results you obtained previously. When convinced that it's OK, use the block to create a 4-section heat exchanger. This should have the same *total* heat exchange area and tube volume as before, and the tube volume in each section should be ¼ of the total. Plot the outlet temperature from each section on one scope, and the total heat transfer rate on another. Answer the following questions:

1. If the inputs are the same as before, what are the steady-state outputs?
2. Is there a significant qualitative difference in the response to a unit-step in T_i?

A 4-section exchanger configuration using the masked block



Remarks

- The steady-state temperatures leaving each section are 125, 137.5, 143.75, and 146.875 C, respectively. Thus, plug flow provides more efficient use of the heat exchanger area (higher outlet temperature). A convenient way to find these values is to start the model at a reasonable

initial condition and run it with constant inputs for long enough to reach steady state. You could also solve the steady-state equations algebraically.

- The step in T_i now causes a much slower increase in T_o, including an initial delay of about 5 seconds before anything happens. To see this you will need to zoom in on the final outlet temperature, or plot it on a separate scope.