Week 7 – Manipulator Dynamics: MATLAB Simulink Simulation

Advanced Robotic Systems – MANU2453

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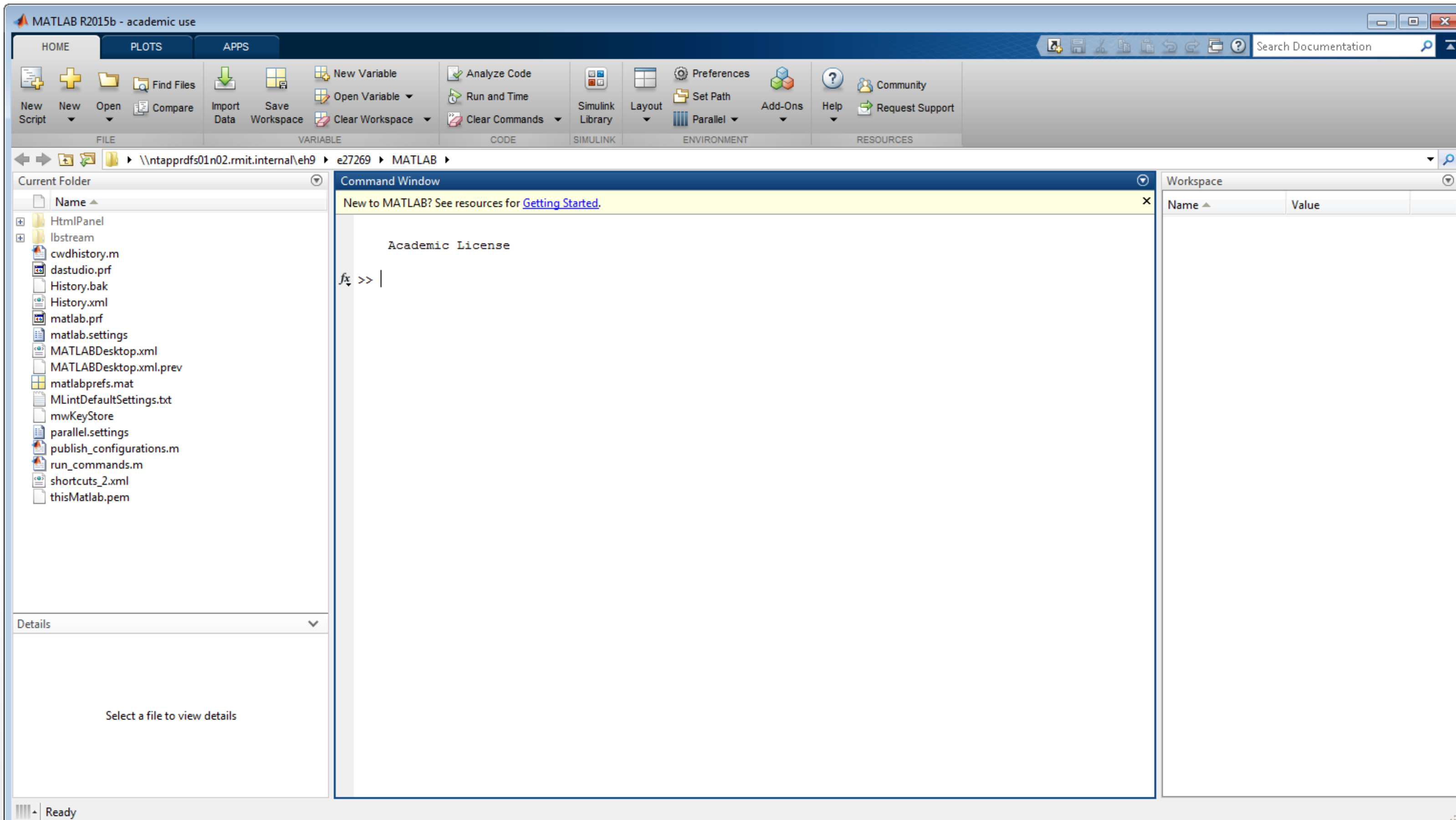
RMIT UNIVERSITY

Simulation

- As mentioned in the introduction of Lecture 6, the dynamic equations / equations of motion are useful for computer simulation:
  - If we put in certain torques in the joints, how will the robot moves (how will the joints accelerate)?
  - In the next few weeks, you will also learn how to change the torque, such that the robot moves in a way you desire. (Control problem).
- We will use MATLAB Simulink for this purpose.

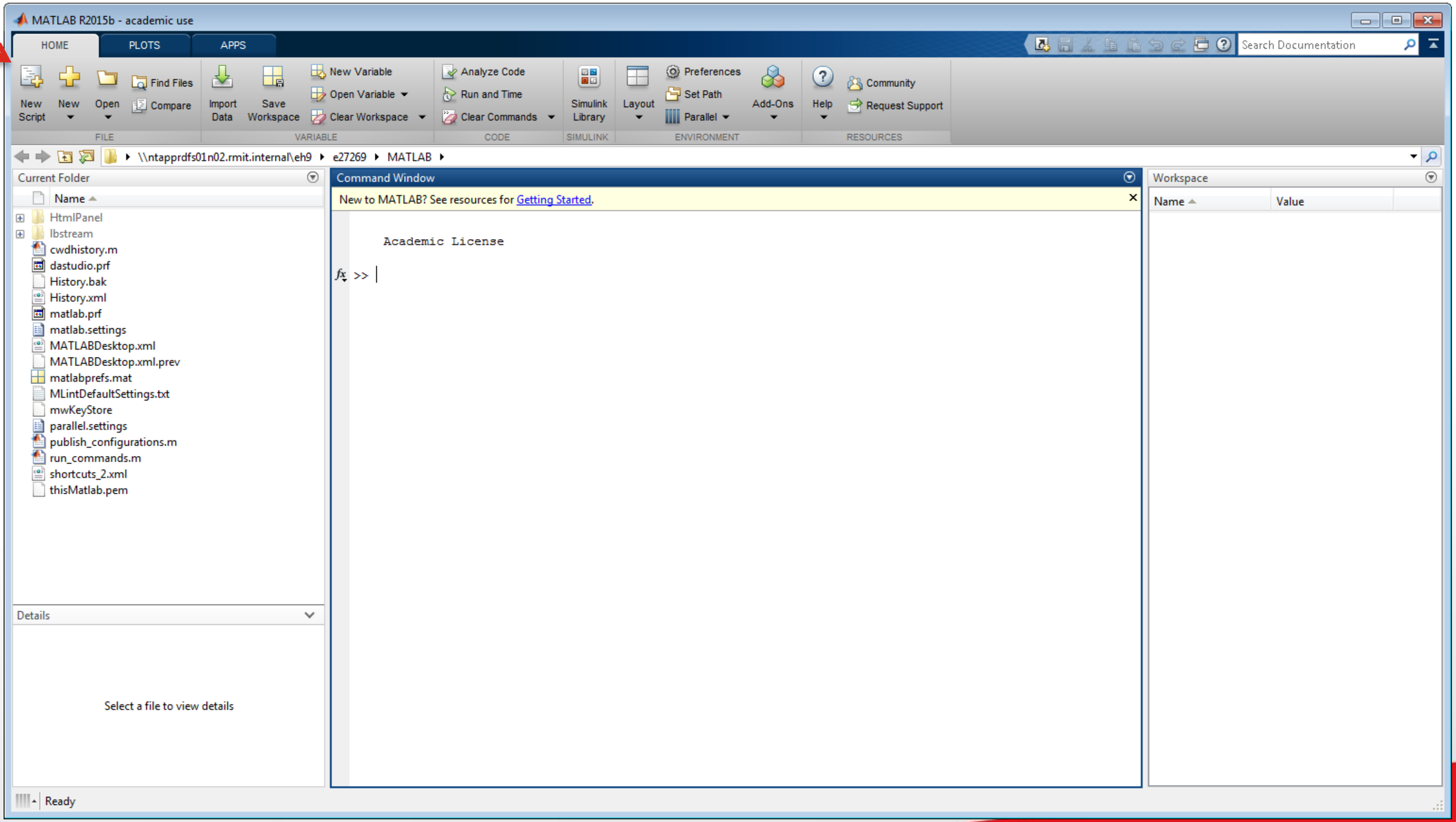
MATLAB

- First of all, start MATLAB.



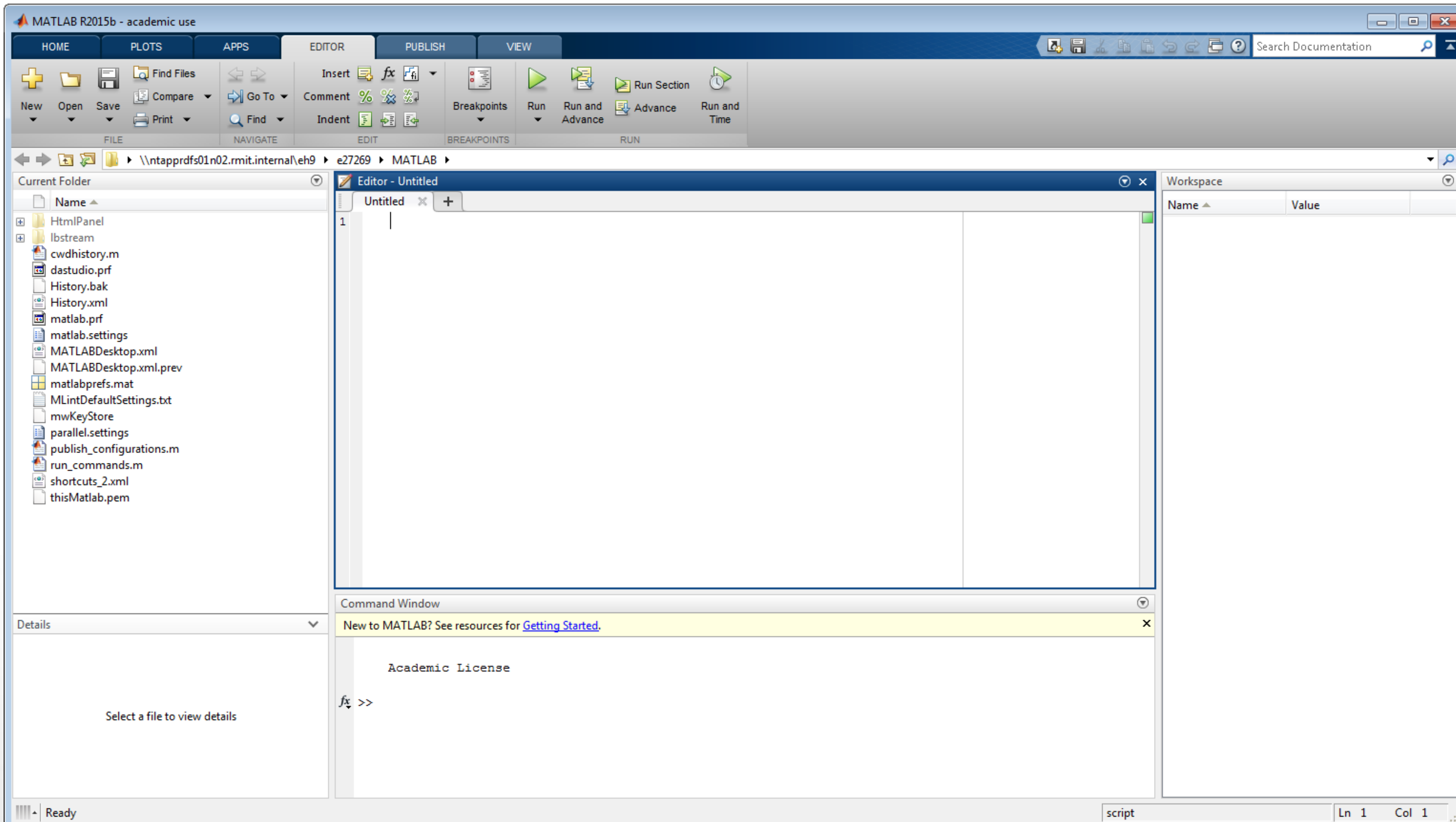
MATLAB

- We will create an m-file, where we can key in all the constant parameters.
- Click “New Script”.



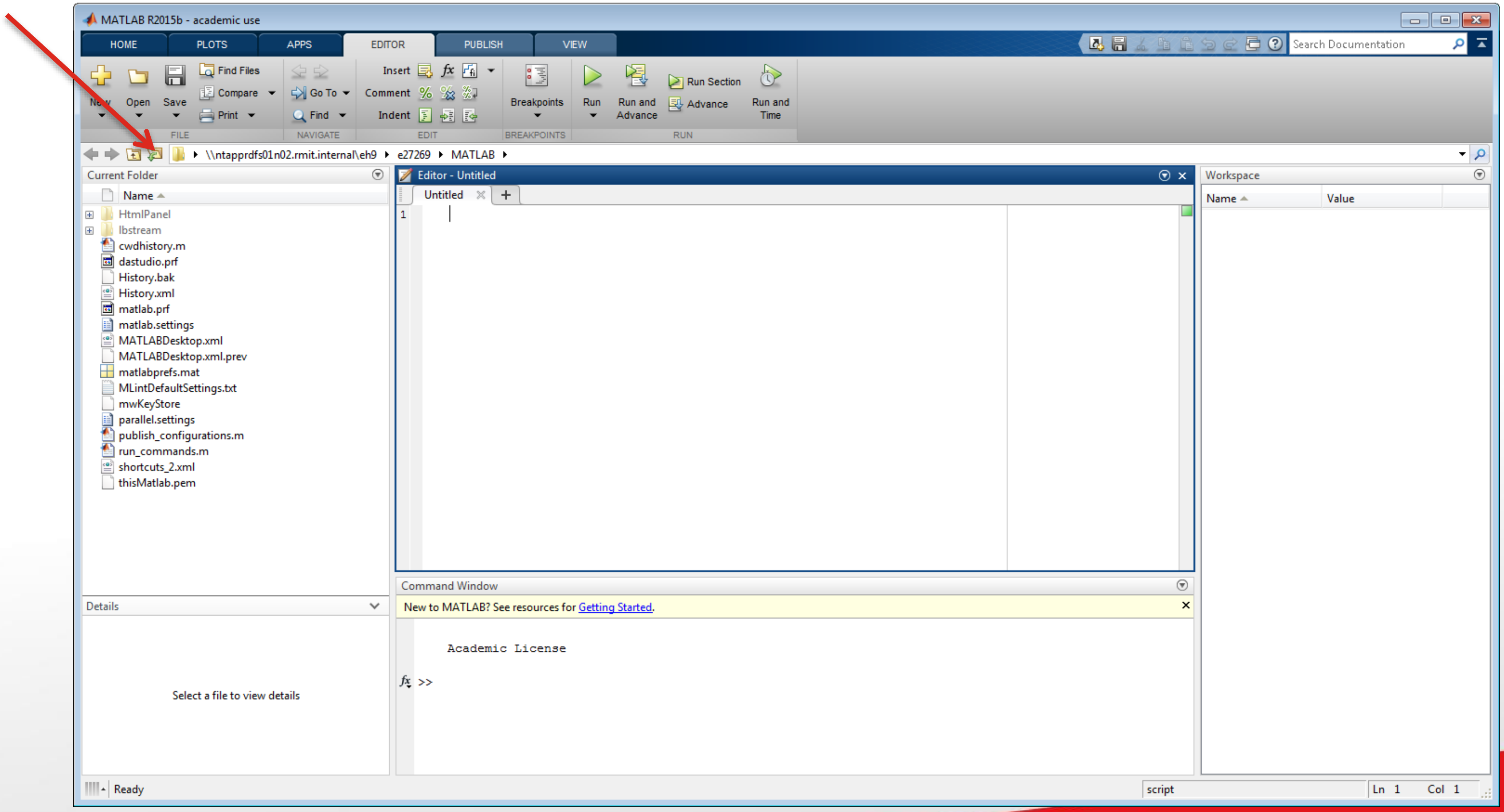
MATLAB

- An Editor will appear.
- Save it as “Parameters.m” on your desktop.



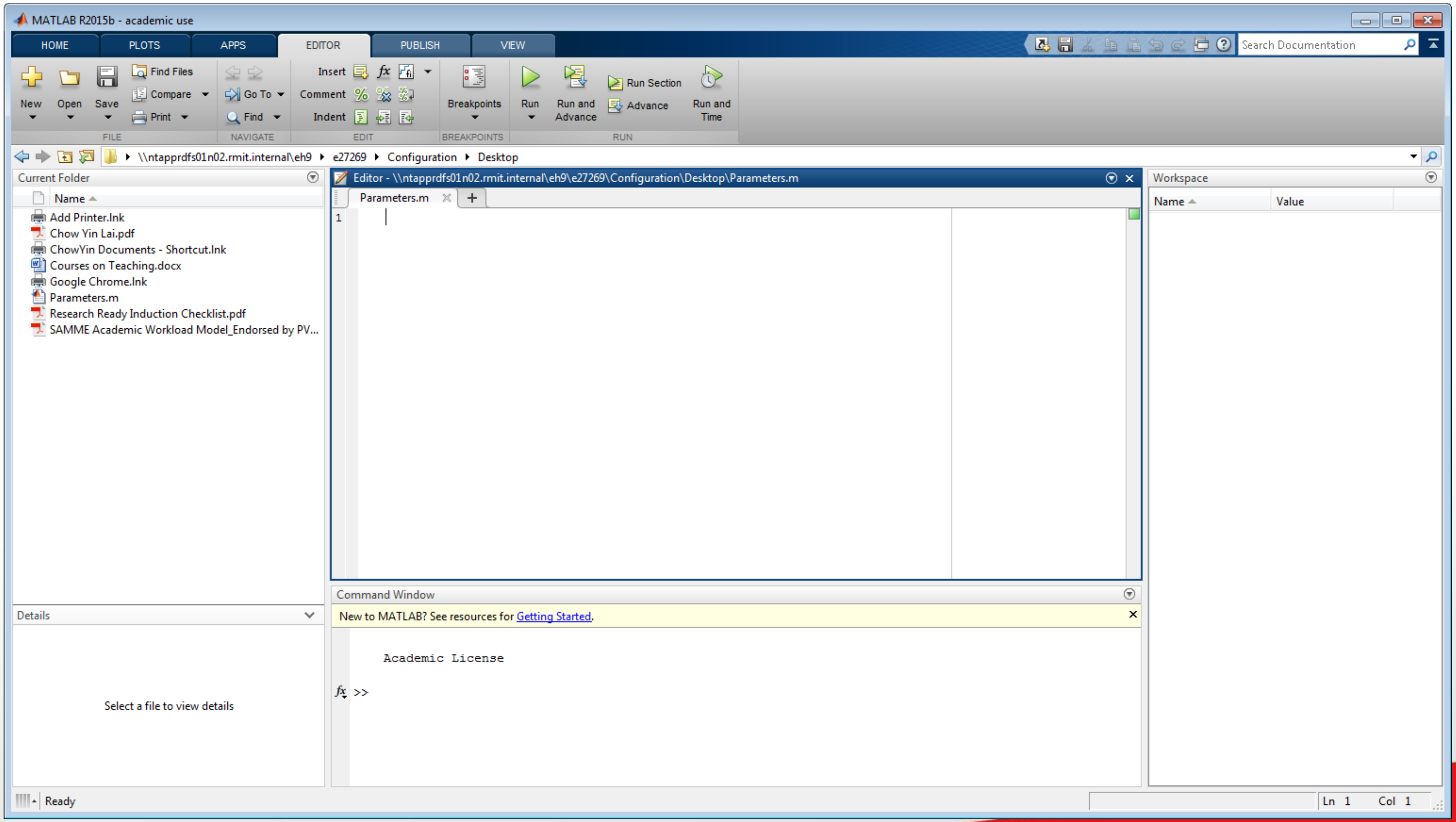
MATLAB

- At this moment, the working directory is the "MATLAB" folder.
- Change it to "Desktop" by clicking the shown button.



MATLAB

- Note that the directory is changed to Desktop.
- We will now start keying in the parameters for the robot.



MATLAB

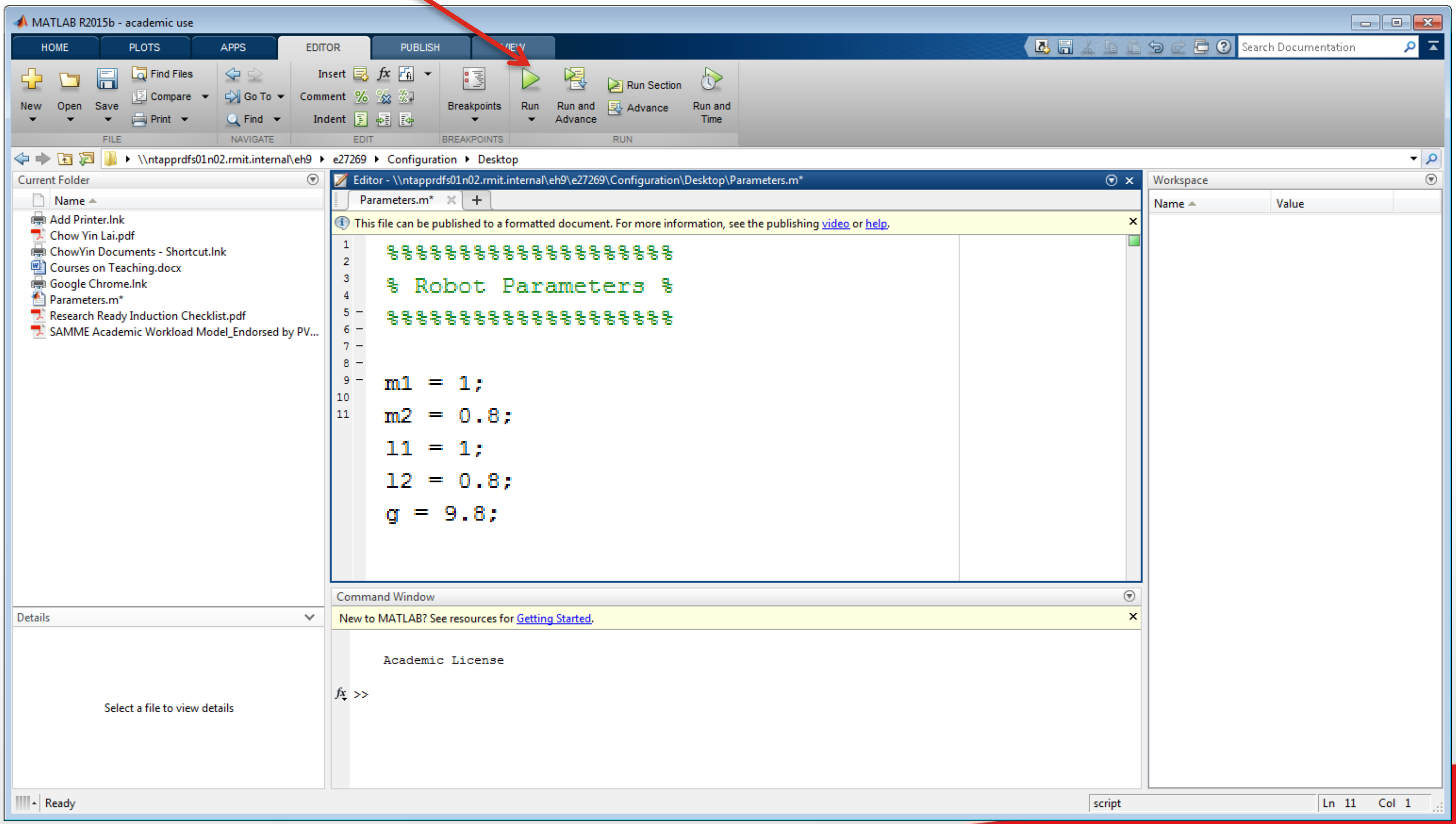
- Let's use the 2-link robotic manipulator from Week 6 Lecture as example:

$$\underbrace{\begin{bmatrix} (m_1+m_2)L_1^2 + m_2L_2^2 + 2m_2L_1L_2c_2 & m_2L_2^2 + m_2L_1L_2c_2 \\ m_2L_2^2 + m_2L_1L_2c_2 & m_2L_2^2 \end{bmatrix}}_{M(q)} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \underbrace{\underbrace{\begin{bmatrix} -m_2L_1L_2s_2\dot{\theta}_2^2 \\ m_2L_1L_2s_2\dot{\theta}_1^2 \end{bmatrix}}_{\text{Centrifugal}} + \underbrace{\begin{bmatrix} -2m_2L_1L_2s_1\dot{\theta}_1\dot{\theta}_2 \\ 0 \end{bmatrix}}_{\text{Coriolis}}}_{V(q,\dot{q})} + \underbrace{\begin{bmatrix} m_2gL_2c_{12} + (m_1+m_2)gL_1c_1 \\ m_2gL_2c_{12} \end{bmatrix}}_{G(q)} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

- The constant parameters are:
  - m1
  - m2
  - L1
  - L2
  - g

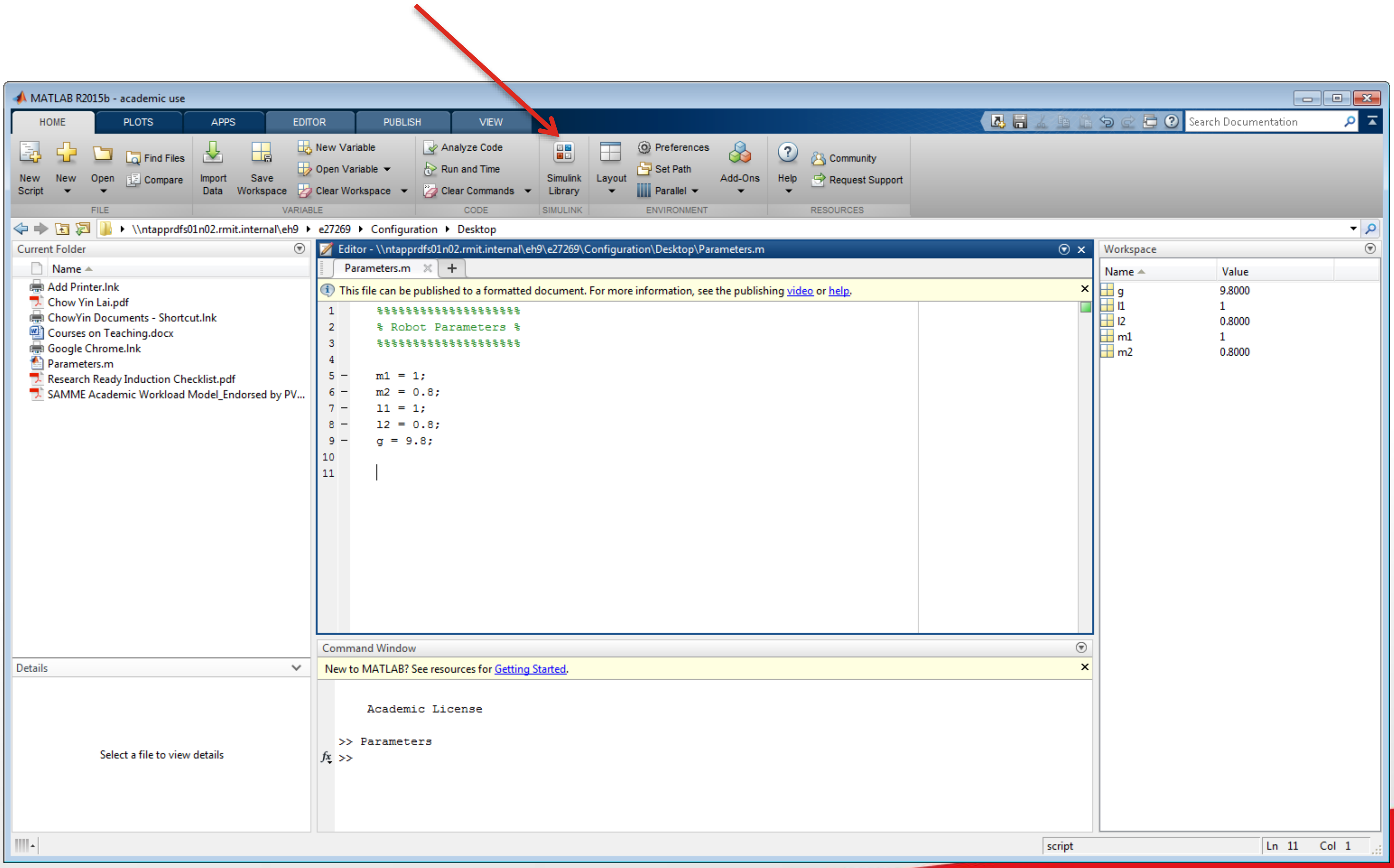
MATLAB

- Write these in (together with some assumed values) in the Editor.
- Then click the “Run” button on the top of window.



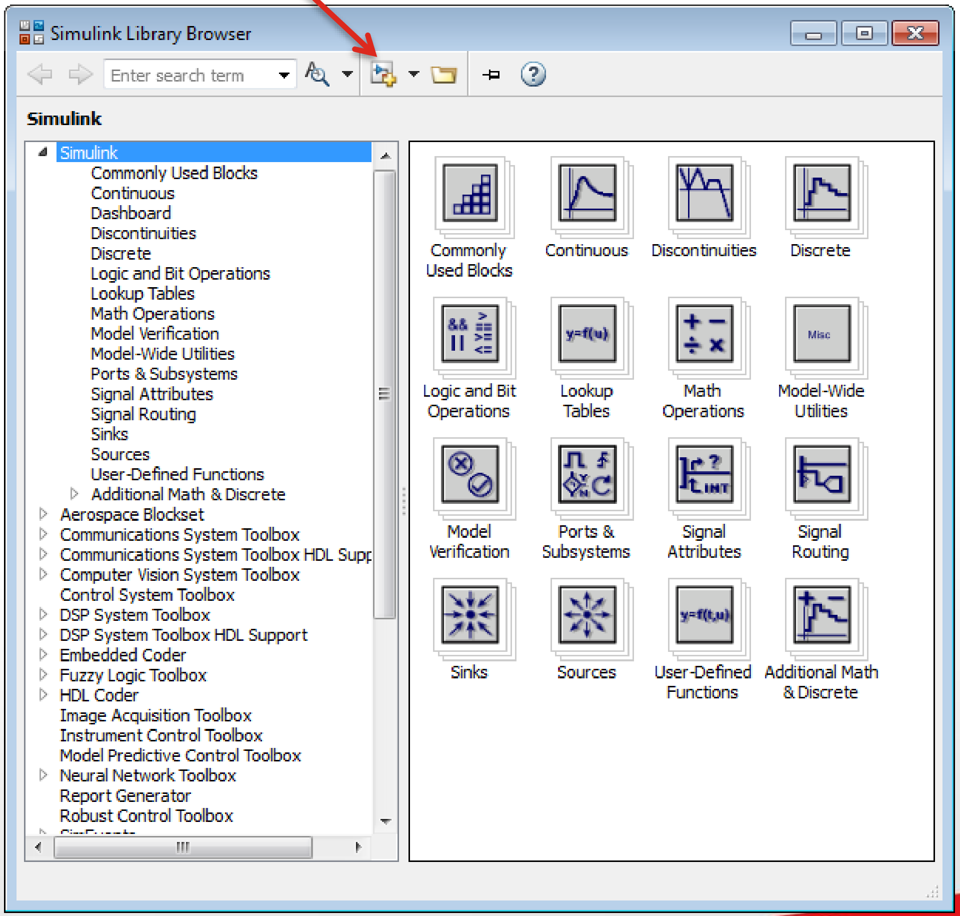
MATLAB

- Go to the “Home” tab of MATLAB, and click the “Simulink Library” button.



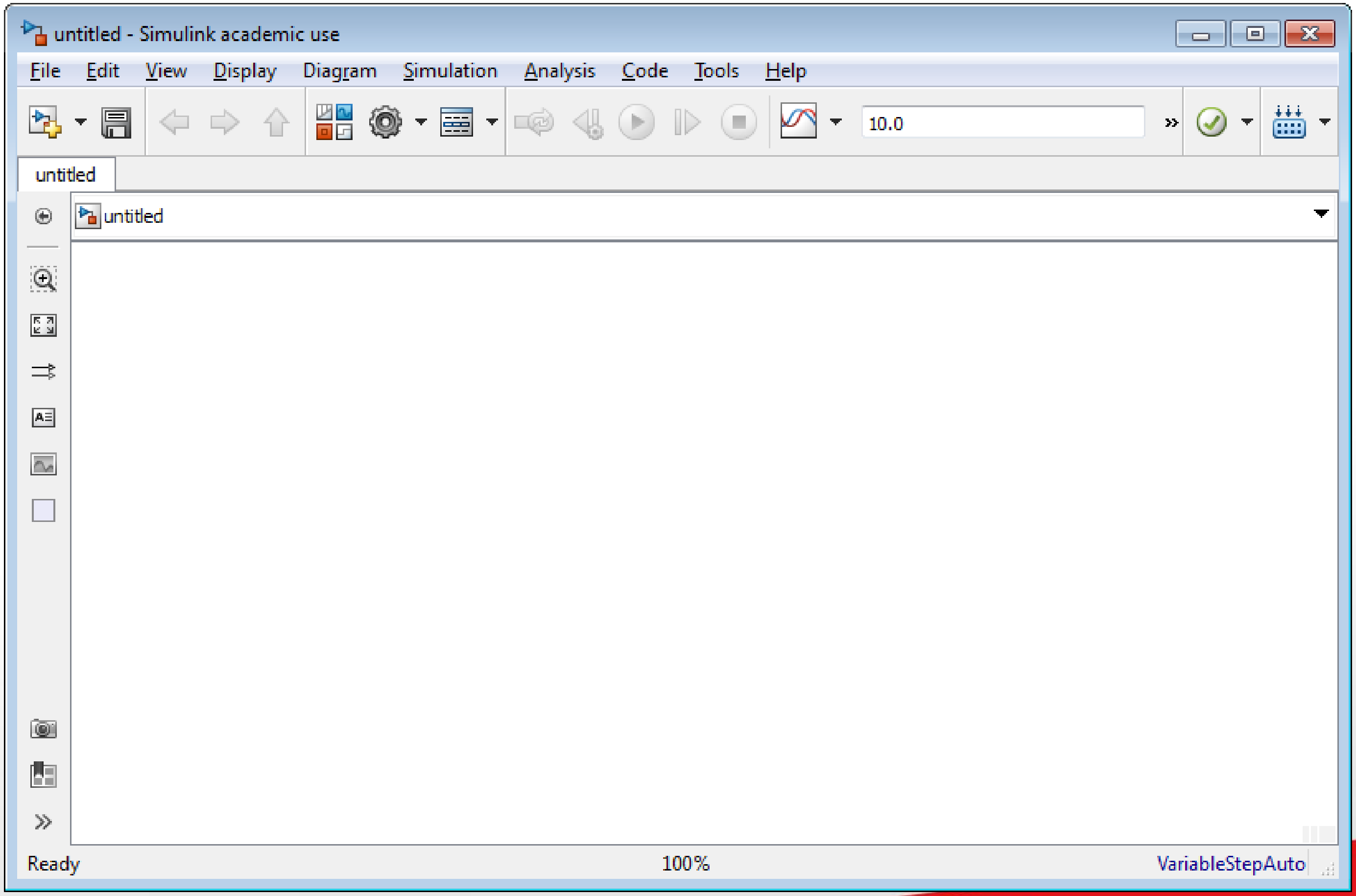
MATLAB / Simulink

- The Simulink Library will appear.
- Click the “+” button to open a new simulation window.



MATLAB / Simulink

- For the new simulation window (as shown), save it as “Simulation.slx”.

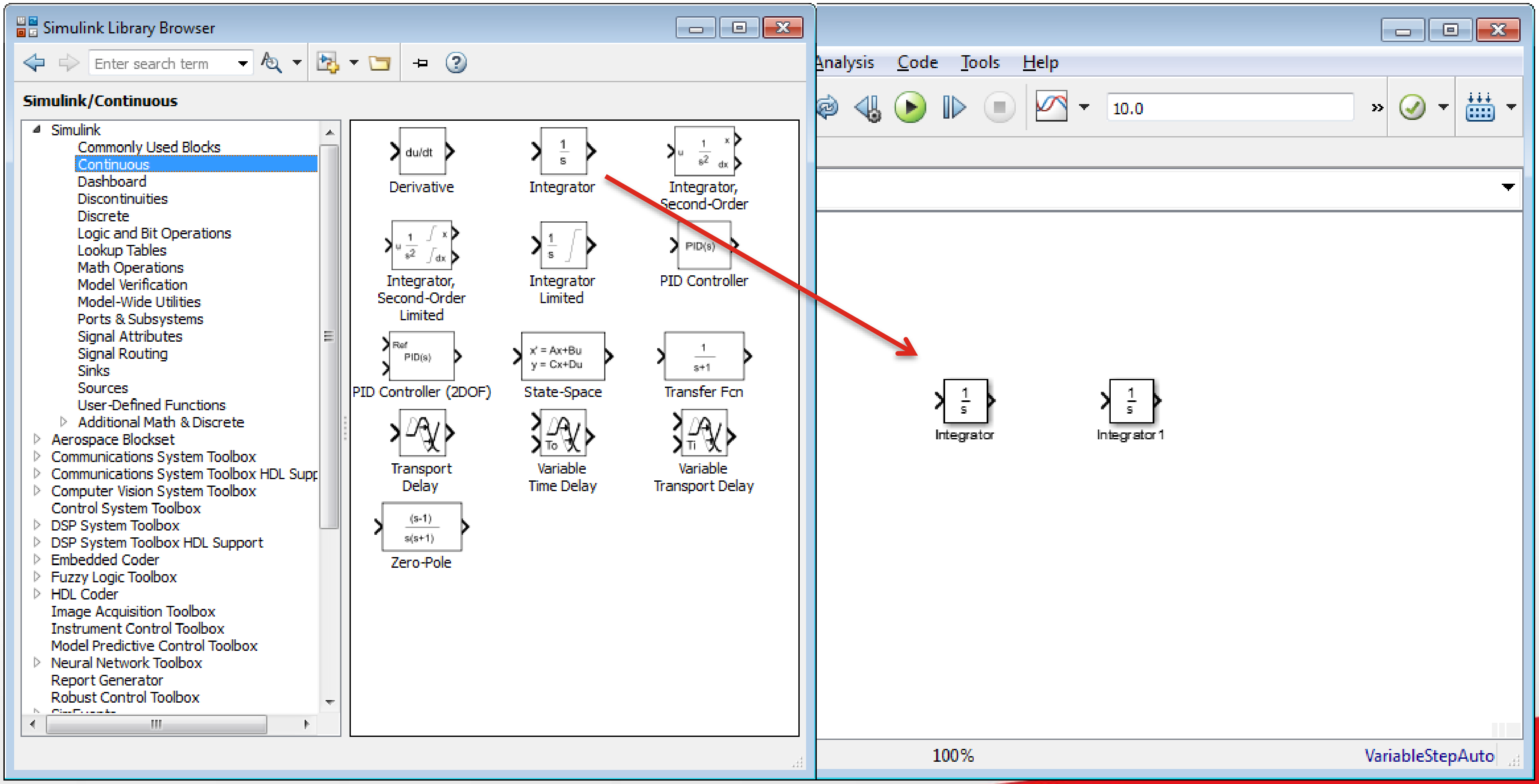


MATLAB / Simulink

- The first thing to do in Simulink is to build the signal chain, from the highest derivative to lowest derivative.
- In our case, it would be $\ddot{\theta}$ down to θ.
- How is this done?
- Imagine you have a signal $\ddot{\theta}$.
- If we integrate this signal, it would become $\dot{\theta}$.
- If we integrate this once more, it would become θ.

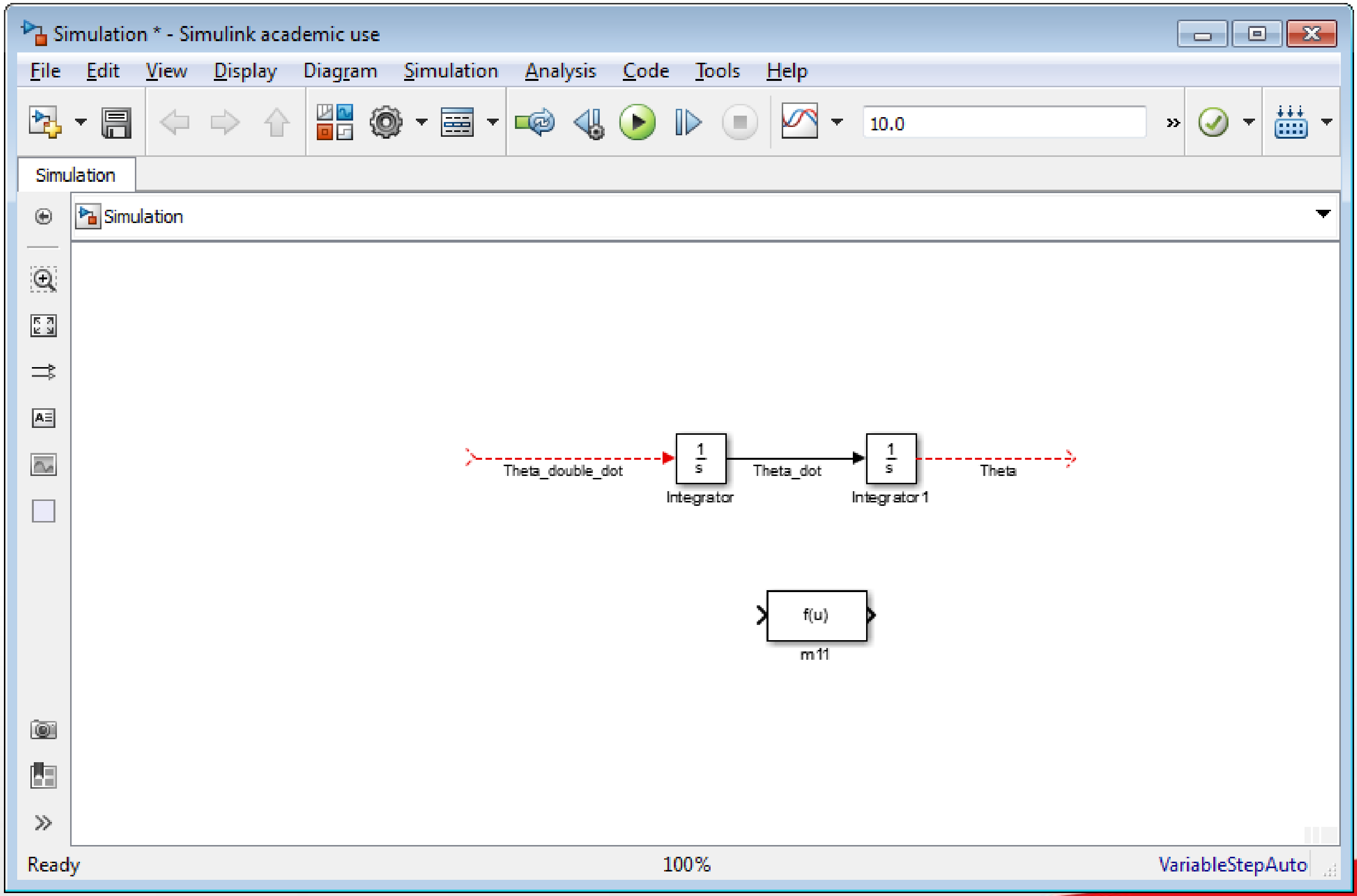
MATLAB / Simulink

- From Simulink Library, go to “Continuous” and then drag and drop “Integrator” twice into the Simulink window.



MATLAB / Simulink

- From Simulink Library, go to "User-defined Functions" and then drag-and-drop "Fcn" into Simulink Window.
- Rename "Fcn" to "m11".

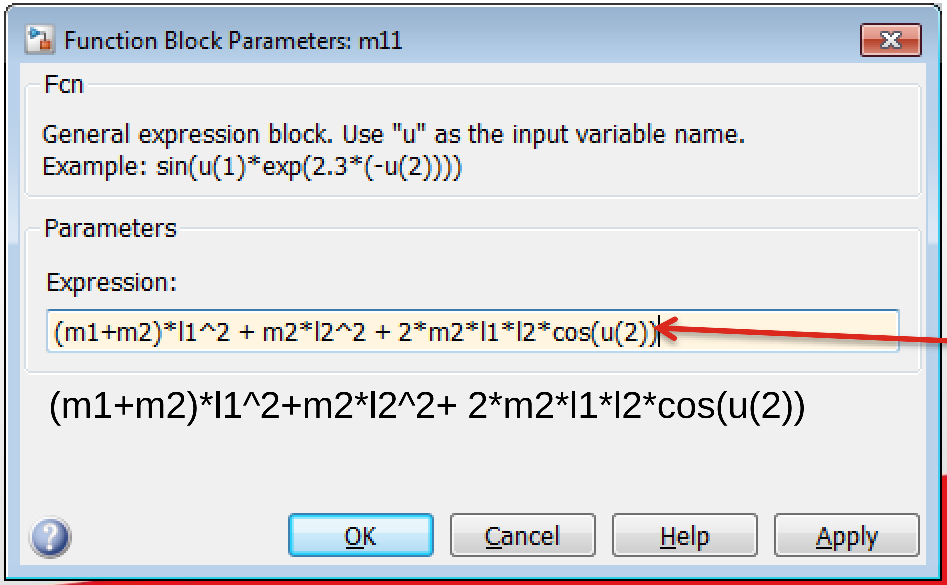


MATLAB / Simulink

- Double click the block “m11” and key in the expression for m11.

$$\underbrace{\begin{bmatrix} (m_1+m_2)L_1^2 + m_2L_2^2 + 2m_2L_1L_2c_2 & m_2L_2^2 + m_2L_1L_2c_2 \\ m_2L_2^2 + m_2L_1L_2c_2 & m_2L_2^2 \end{bmatrix}}_{M(q)} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}$$

$$+ \underbrace{\underbrace{\begin{bmatrix} -m_2L_1L_2s_2\dot{\theta}_2^2 \\ m_2L_1L_2s_2\dot{\theta}_1^2 \end{bmatrix}}_{\text{Centrifugal}} + \underbrace{\begin{bmatrix} -2m_2L_1L_2s_2\dot{\theta}_1\dot{\theta}_2 \\ 0 \end{bmatrix}}_{\text{Coriolis}}}_{V(q,\dot{q})} + \underbrace{\begin{bmatrix} m_2gL_2c_{12} + (m_1+m_2)gL_1c_1 \\ m_2gL_2c_{12} \end{bmatrix}}_{G(q)} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

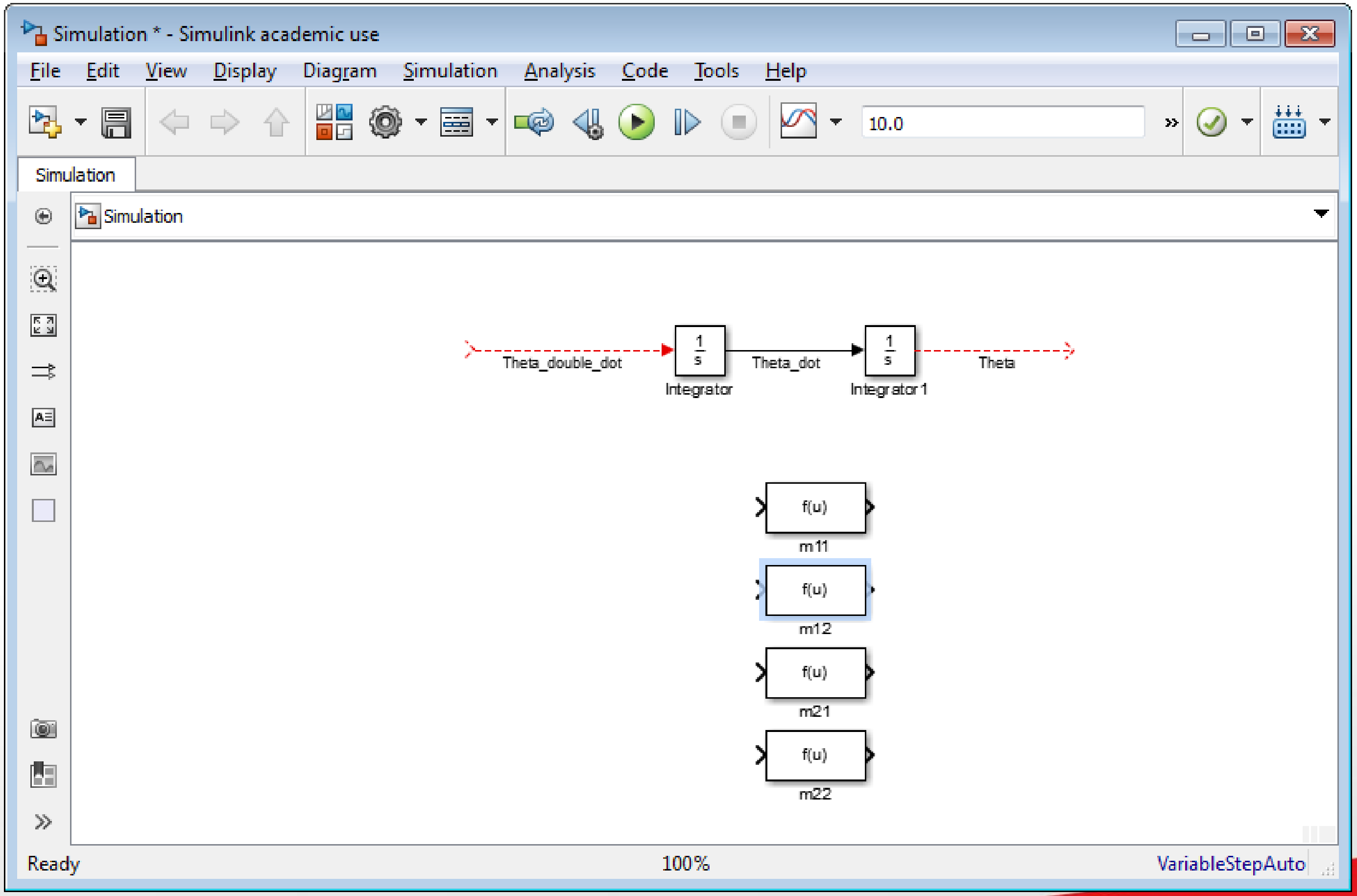


The signal is a vector of theta1 and theta2.

Theta1 = u(1)
Theta2 = u(2)

MATLAB / Simulink

- Repeat the last two steps for m12, m21 and m22.

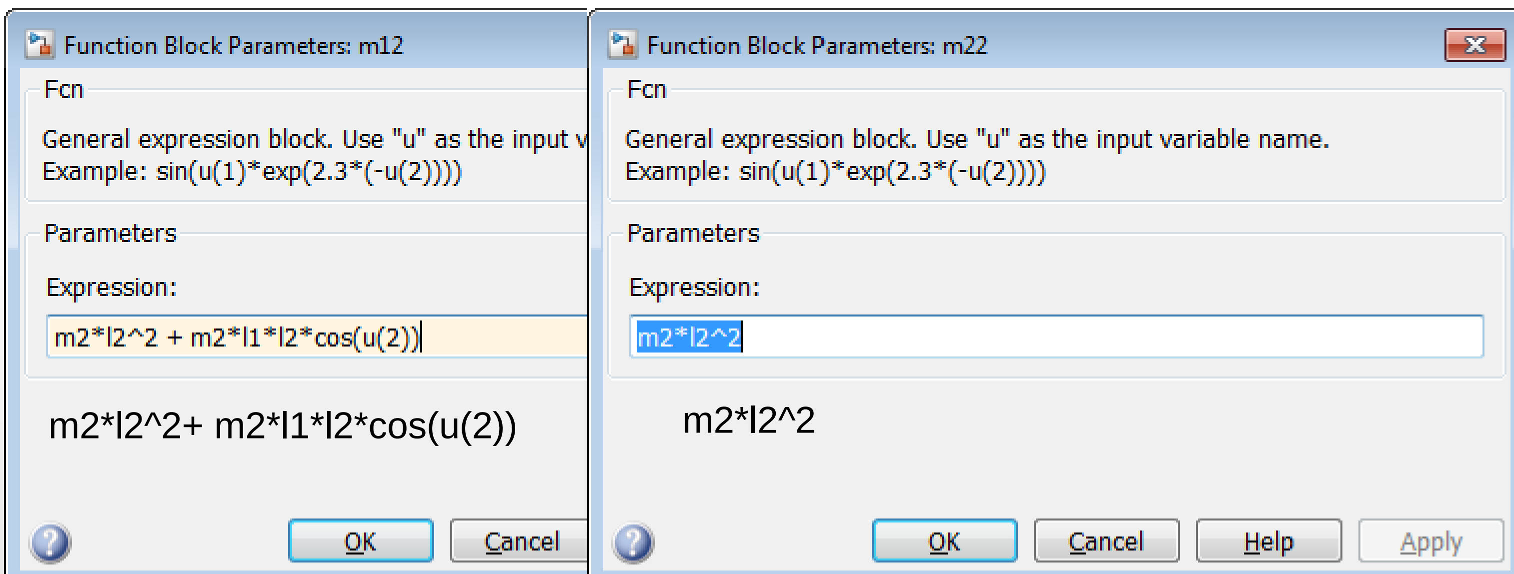


MATLAB / Simulink

- The expressions for m12, m21 (=m12), m22 should be as shown:

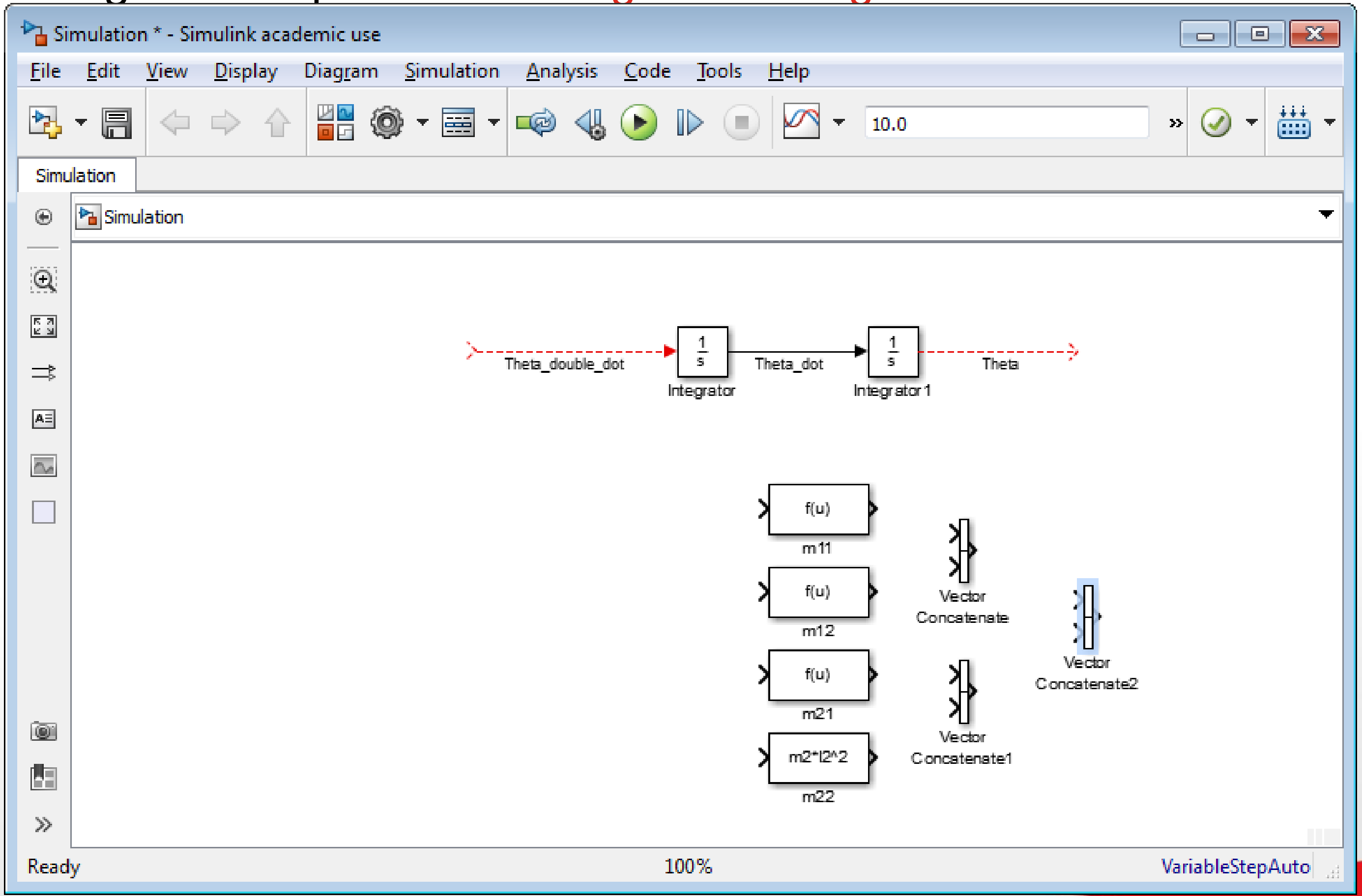
$$\underbrace{\begin{bmatrix}(m_1+m_2)L_1^2+m_2L_2^2+2m_2L_1L_2c_2 & m_2L_2^2+m_2L_1L_2c_2\\ m_2L_2^2+m_2L_1L_2c_2 & m_2L_2^2\end{bmatrix}}_{M(q)}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix}$$

$$+\underbrace{\underbrace{\begin{bmatrix}-m_2L_1L_2s_2\dot{\theta}_2^2\\ m_2L_1L_2s_2\dot{\theta}_1^2\end{bmatrix}}_{\text{Centrifugal}}+\underbrace{\begin{bmatrix}-2m_2L_1L_2s_2\dot{\theta}_1\dot{\theta}_2\\ 0\end{bmatrix}}_{\text{Coriolis}}}_{V(q,\dot{q})}+\underbrace{\begin{bmatrix}m_2gL_2c_{12}+(m_1+m_2)gL_1c_1\\ m_2gL_2c_{12}\end{bmatrix}}_{G(q)}=\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}$$



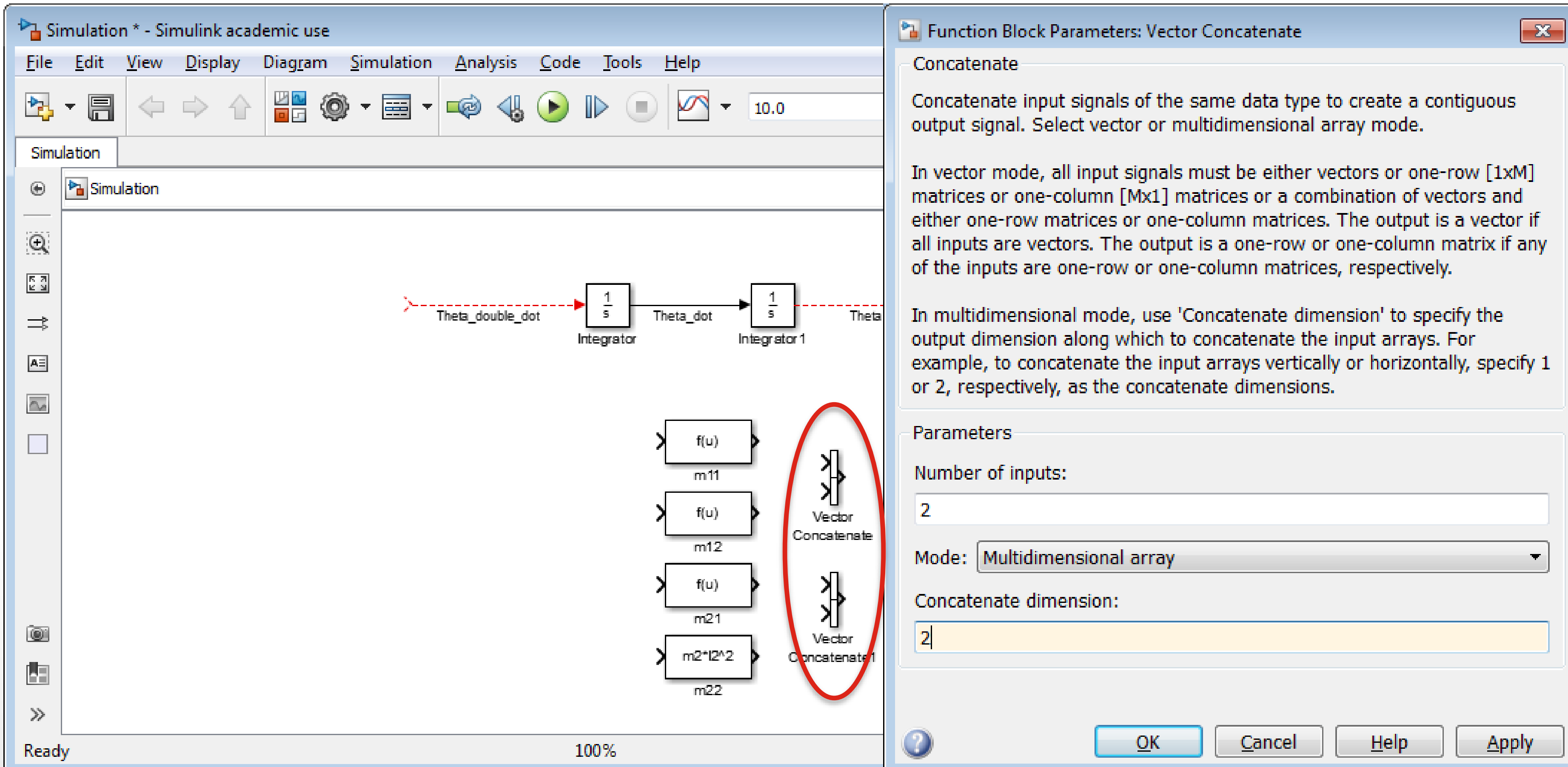
MATLAB / Simulink

- Having defined m11, m12, m21 and m22, our next step is to combine them to make the matrix M(q).
- Drag and Drop the block "Signal Routing" → "Vector Concatenate" 3 times.



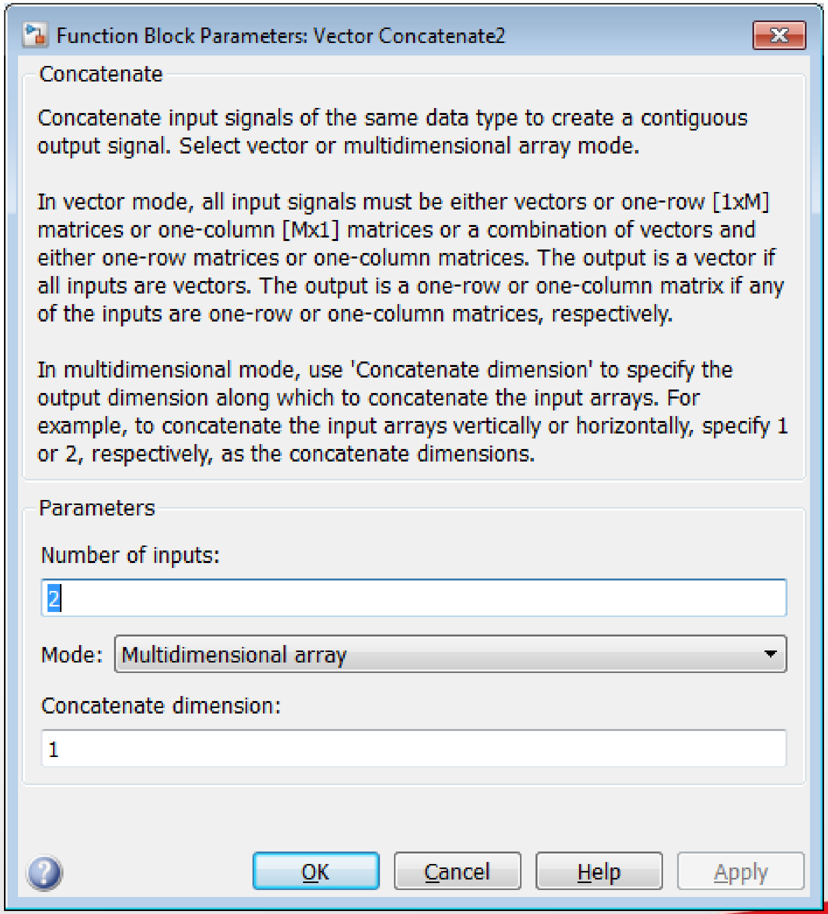
MATLAB / Simulink

- For the first two "Vector Concatenate" blocks, set the following parameters:
- (The concatenate dimension 2 means horizontal concatenation).



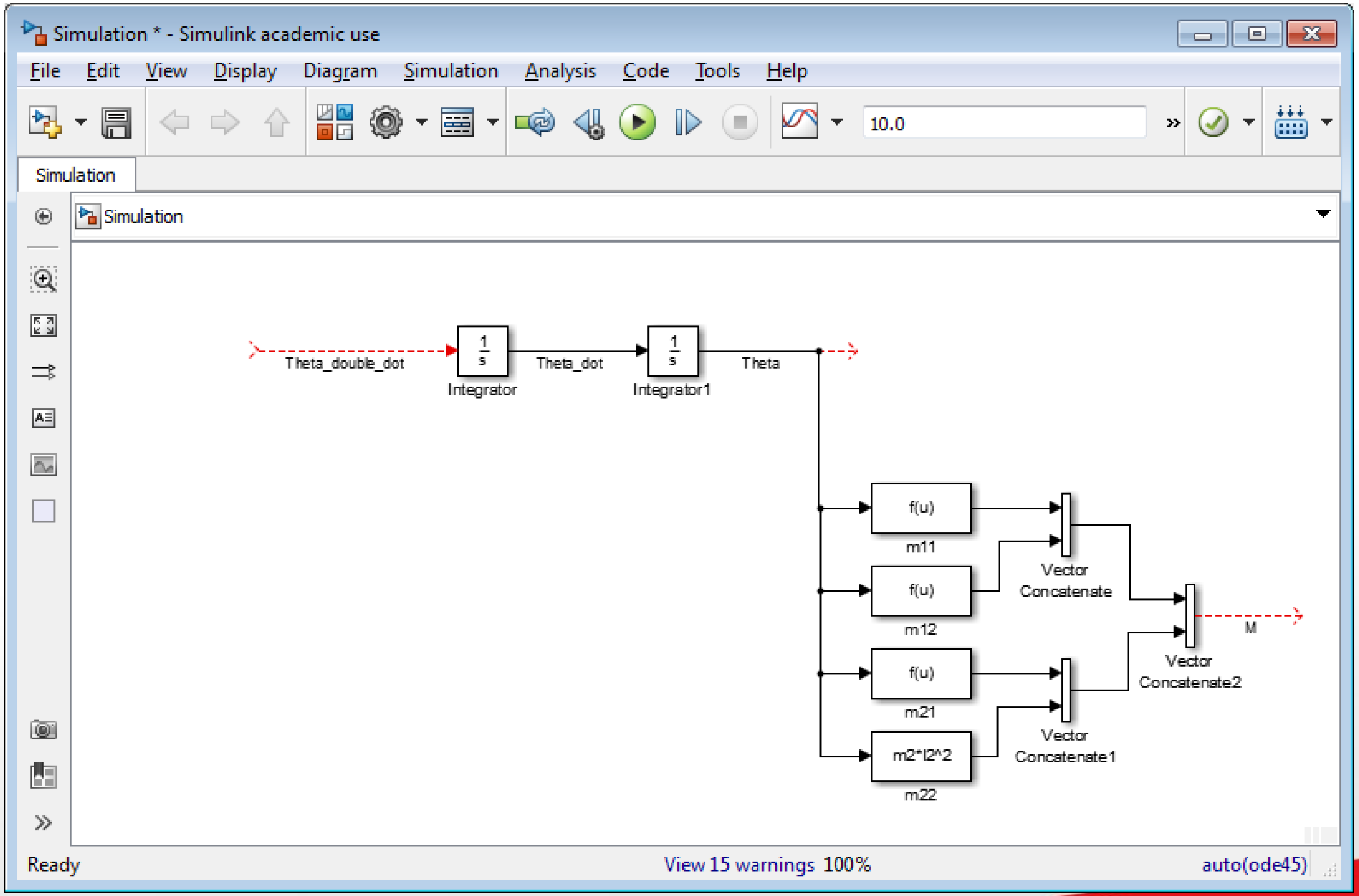
MATLAB / Simulink

- For the third "Vector Concatenate" blocks, set the following parameters:
- (The concatenate dimension 1 means vertical concatenation).



MATLAB / Simulink

- Now combine all the blocks as shown:



MATLAB / Simulink

- We are done with M(q) now, and will move on to V(q,q_dot) and G(q).

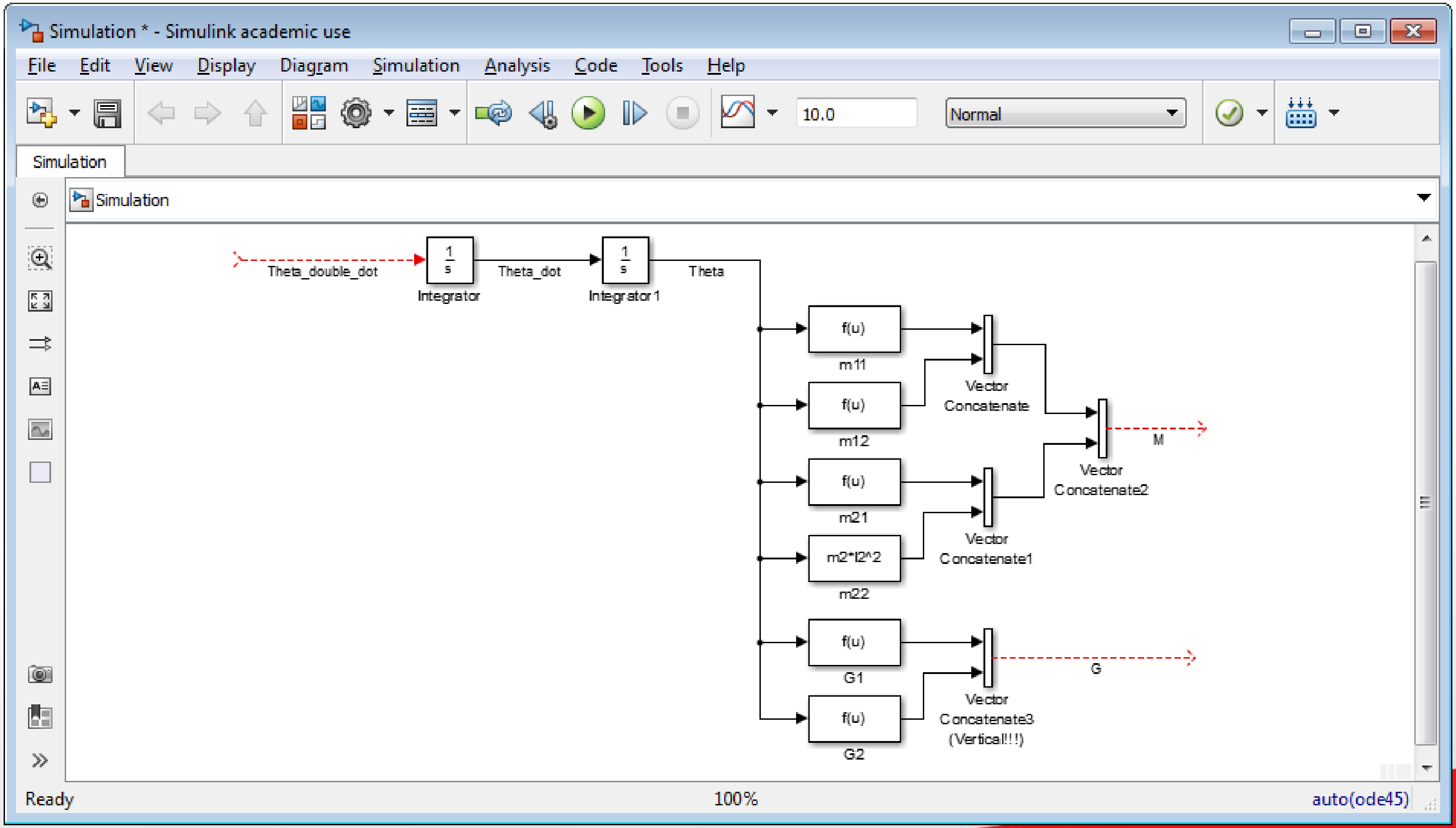
$$\underbrace{\begin{bmatrix} (m_1+m_2)L_1^2+m_2L_2^2+2m_2L_1L_2c_2 & m_2L_2^2+m_2L_1L_2c_2 \\ m_2L_2^2+m_2L_1L_2c_2 & m_2L_2^2 \end{bmatrix}}_{M(q)}\begin{bmatrix}\ddot{\theta}_1 \\ \ddot{\theta}_2\end{bmatrix}$$

$$+\underbrace{\underbrace{\begin{bmatrix} -m_2L_1L_2s_2\dot{\theta}_2^2 \\ m_2L_1L_2s_2\dot{\theta}_1^2 \end{bmatrix}}_{\text{Centrifugal}}+\underbrace{\begin{bmatrix} -2m_2L_1L_2s_1\dot{\theta}_1\dot{\theta}_2 \\ 0 \end{bmatrix}}_{\text{Coriolis}}}_{V(q,\dot{q})}+\underbrace{\begin{bmatrix} m_2gL_2c_{12}+(m_1+m_2)gL_1c_1 \\ m_2gL_2c_{12} \end{bmatrix}}_{G(q)}=\begin{bmatrix}\tau_1 \\ \tau_2\end{bmatrix}$$

- Try to build G(q) on your own. The steps are similar to M(q), except that this is just a vector instead of matrix.

MATLAB / Simulink

- You should be getting this after adding in G(q):



MATLAB / Simulink

- For V(q,q_dot), we need to combine theta and theta_dot into one longer vector.

$$\underbrace{\begin{bmatrix} (m_1+m_2)L_1^2 + m_2L_2^2 + 2m_2L_1L_2c_2 & m_2L_2^2 + m_2L_1L_2c_2 \\ m_2L_2^2 + m_2L_1L_2c_2 & m_2L_2^2 \end{bmatrix}}_{M(q)} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}$$

$$+ \underbrace{\underbrace{\begin{bmatrix} -m_2L_1L_2s_2\dot{\theta}_2^2 \\ m_2L_1L_2s_2\dot{\theta}_1^2 \end{bmatrix}}_{\text{Centrifugal}} + \underbrace{\begin{bmatrix} -2m_2L_1L_2s_1\dot{\theta}_1\dot{\theta}_2 \\ 0 \end{bmatrix}}_{\text{Coriolis}}}_{V(q,\dot{q})} + \underbrace{\begin{bmatrix} m_2gL_2c_{12} + (m_1+m_2)gL_1c_1 \\ m_2gL_2c_{12} \end{bmatrix}}_{G(q)} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

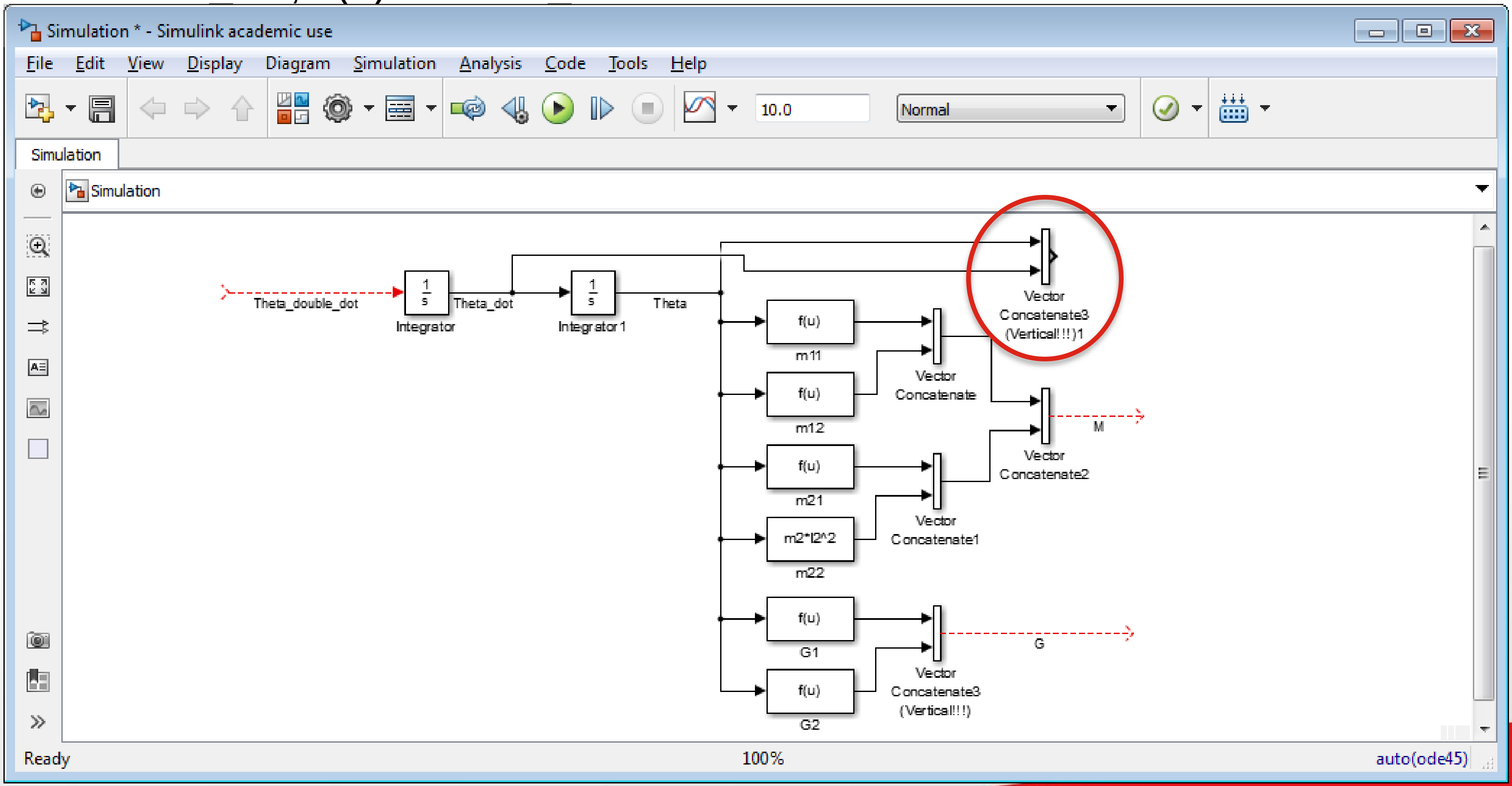
- You can also use “Vector Concatenation” in vertical direction, to create the vector [theta1, theta2, theta1_dot, theta2_dot]^T.

G1 = m2*g*l2*cos(u(1)+u(2))+(m1+m2)*g*l1*cos(u(1))

G2 = m2*g*l2*cos(u(1)+u(2))

MATLAB / Simulink

- The combined vector is built as shown:
- Then, the output of the block will be u(1) = theta1, u(2) = theta2, u(3) = theta1_dot, u(4) = theta2_dot.

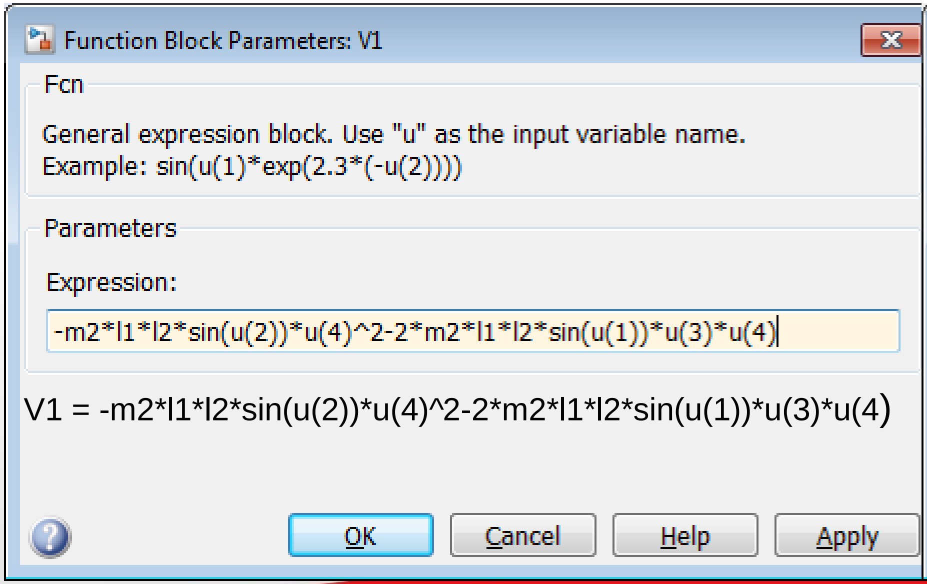


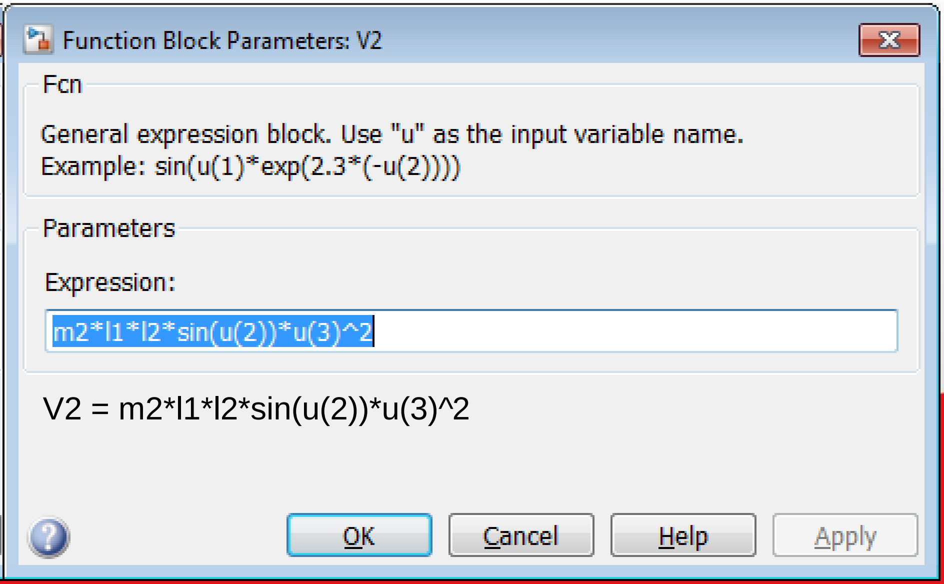
MATLAB / Simulink

- With this, you should be able to give the expression for V(q,q_dot):

$$\underbrace{\begin{bmatrix} (m_1+m_2)L_1^2 + m_2L_2^2 + 2m_2L_1L_2c_2 & m_2L_2^2 + m_2L_1L_2c_2 \\ m_2L_2^2 + m_2L_1L_2c_2 & m_2L_2^2 \end{bmatrix}}_{M(q)} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}$$

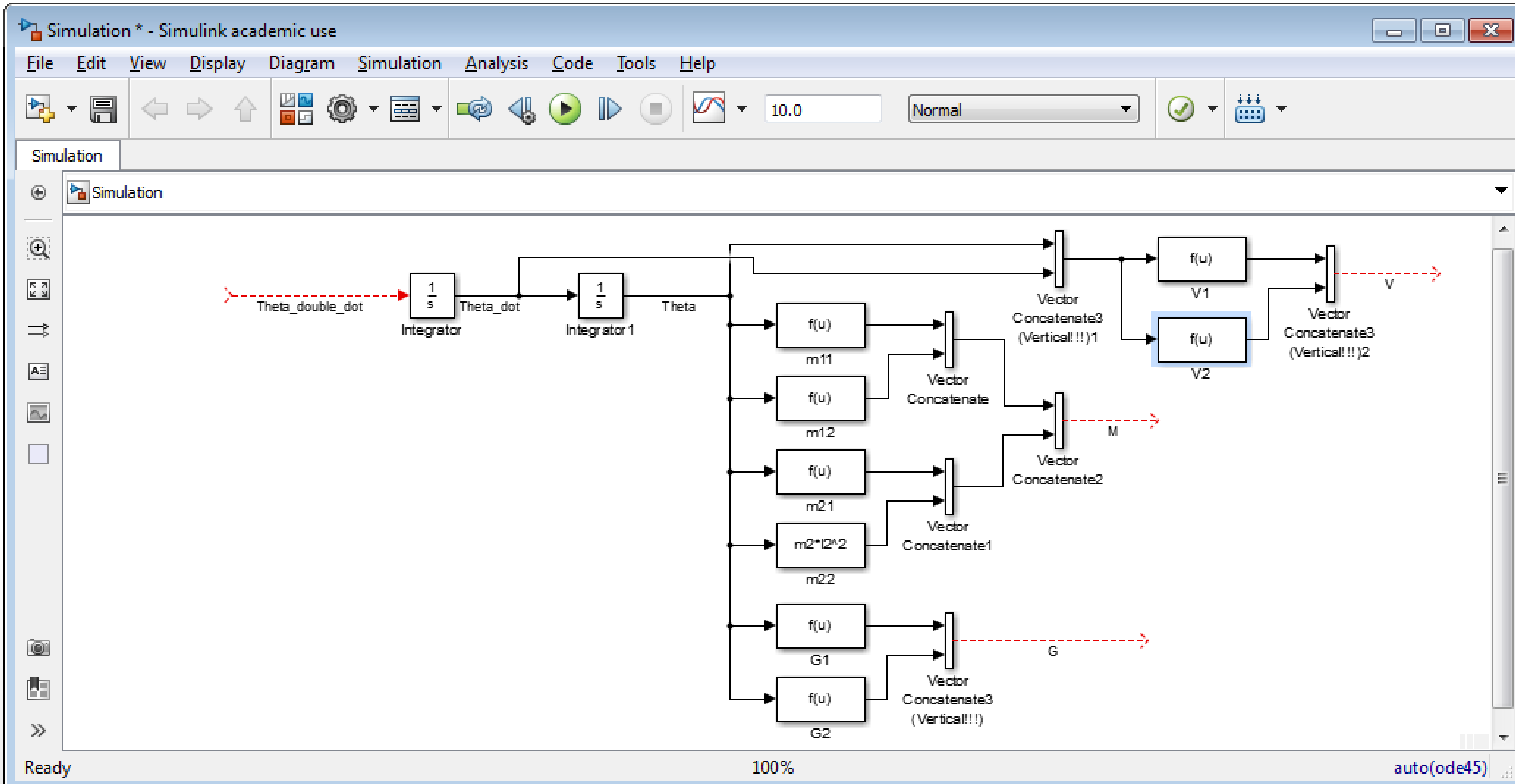
$$+ \underbrace{\underbrace{\begin{bmatrix} -m_2L_1L_2s_2\dot{\theta}_2^2 \\ m_2L_1L_2s_2\dot{\theta}_1^2 \end{bmatrix}}_{\text{Centrifugal}} + \underbrace{\begin{bmatrix} -2m_2L_1L_2s_2\dot{\theta}_1\dot{\theta}_2 \\ 0 \end{bmatrix}}_{\text{Coriolis}}}_{V(q,\dot{q})} + \underbrace{\begin{bmatrix} m_2gL_2c_{12} + (m_1+m_2)gL_1c_1 \\ m_2gL_2c_{12} \end{bmatrix}}_{G(q)} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$





MATLAB / Simulink

- The block diagram now looks like this:

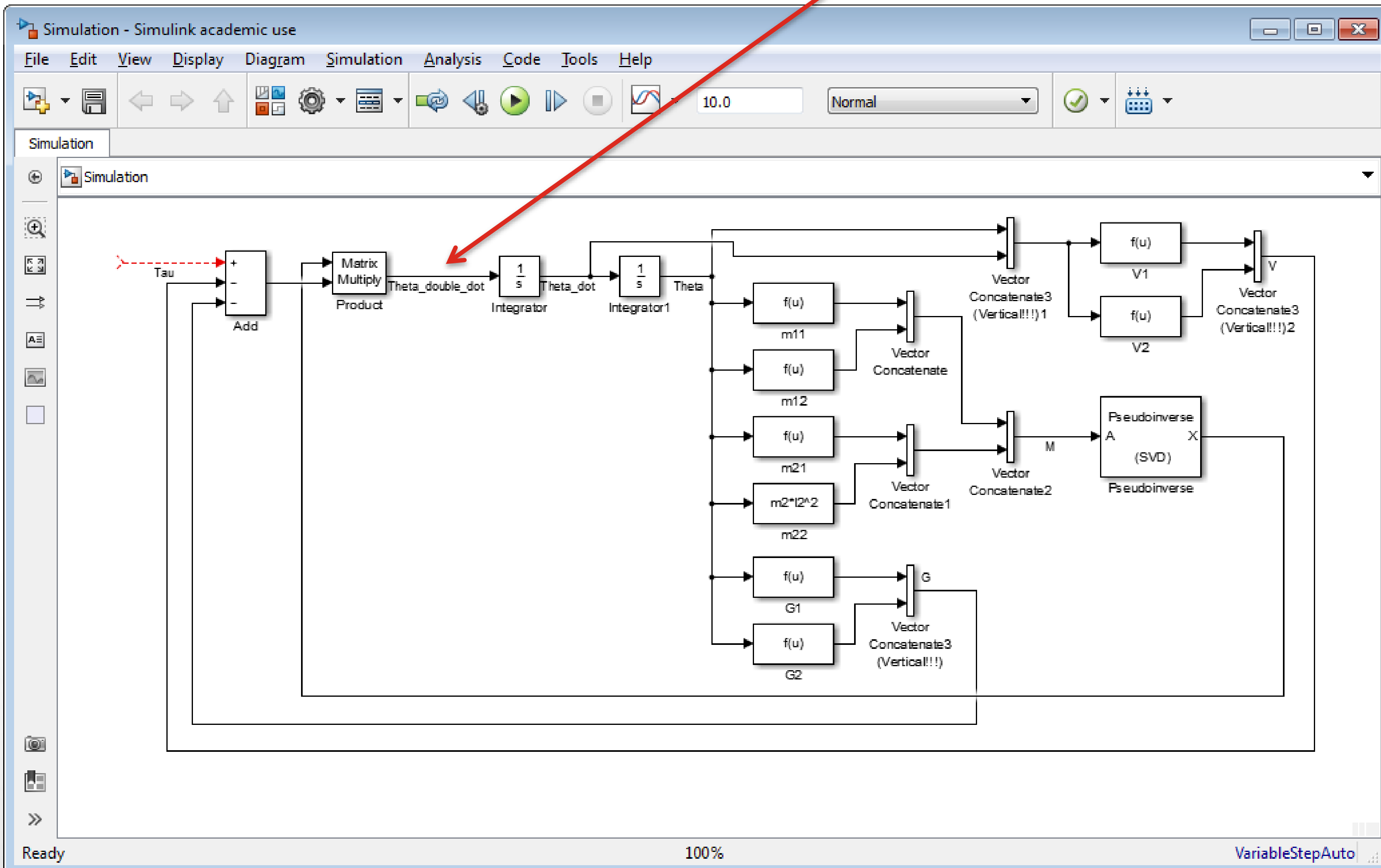


MATLAB / Simulink

- We have built M, V and G by now.
- Next, we need to add in the torques, and see how they affect the acceleration.
- From our dynamic equation: $M(q)\ddot{q}+V(q,\dot{q})+G(q)=\tau$
  - We can write: $$\ddot{q}=M(q)^{-1}[\tau-V(q,\dot{q})-G(q)]$$
- Thus we need to invert the M matrix, and multiply this with (Tau – V – G).
- All these are done in a straightforward manner in Simulink.
- Just get "Add", "Product" from "Math Operation" and connect everything as shown in next page. ** The "Product" parameters should be changed to "Matrix".
- We also need "Pseudoinverse" block. Use search function to look for it.

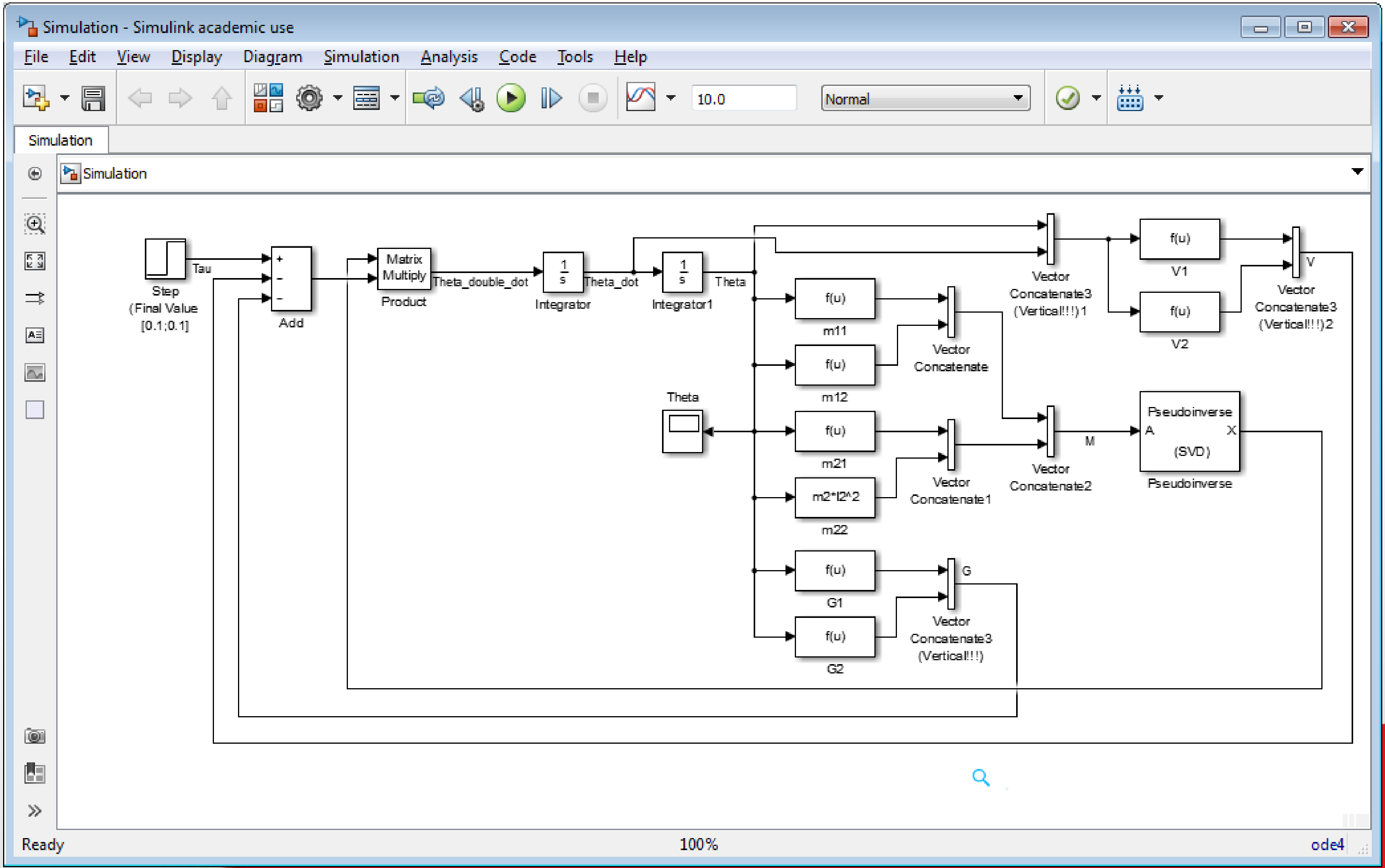
MATLAB / Simulink

- The Blocks should be connected as follows: $\ddot{q} = M(q)^{-1}[\tau - V(q,\dot{q}) - G(q)]$



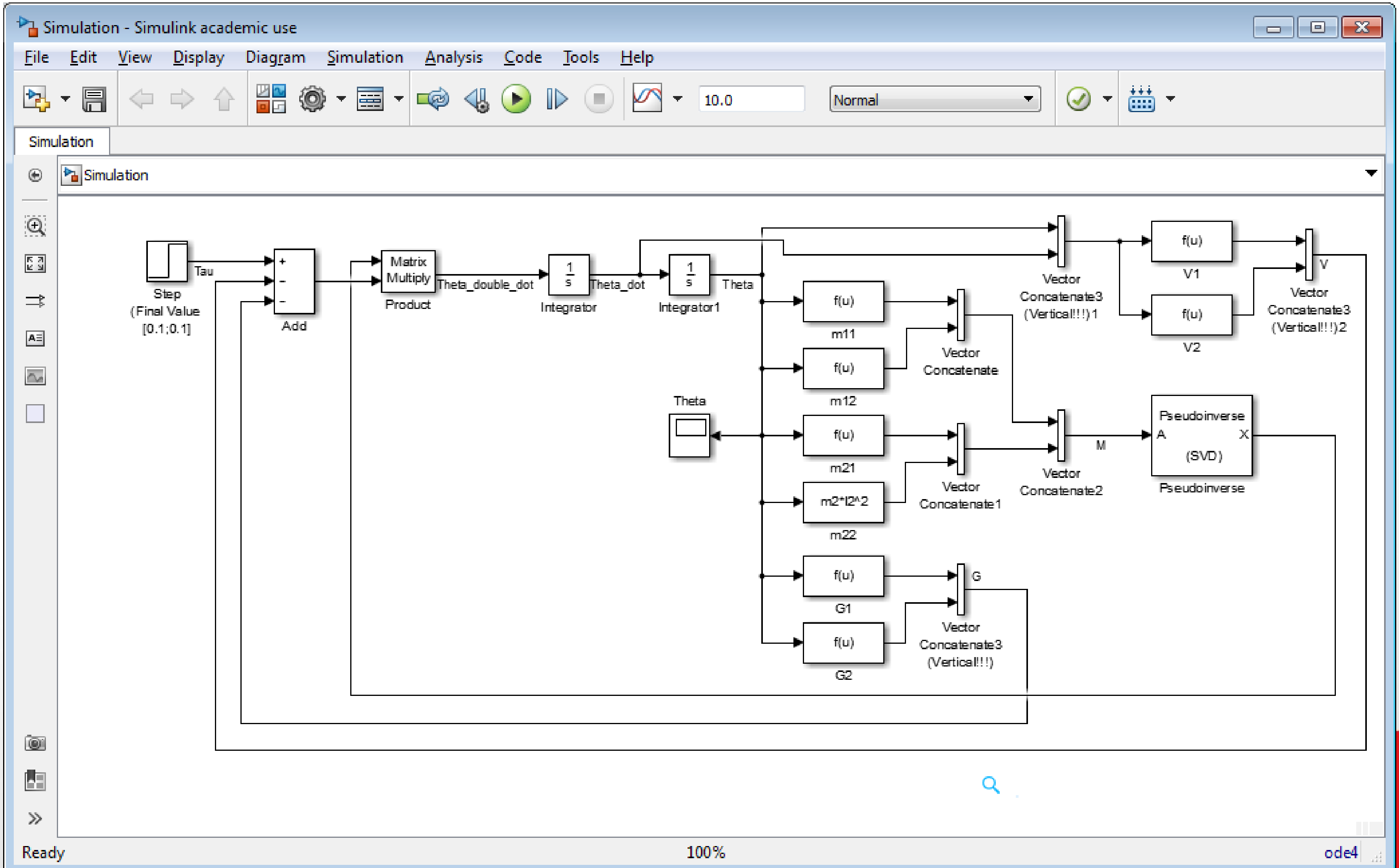
MATLAB / Simulink

- The final steps are to add "Source" for torques and "Scope" to view Theta.



MATLAB / Simulink

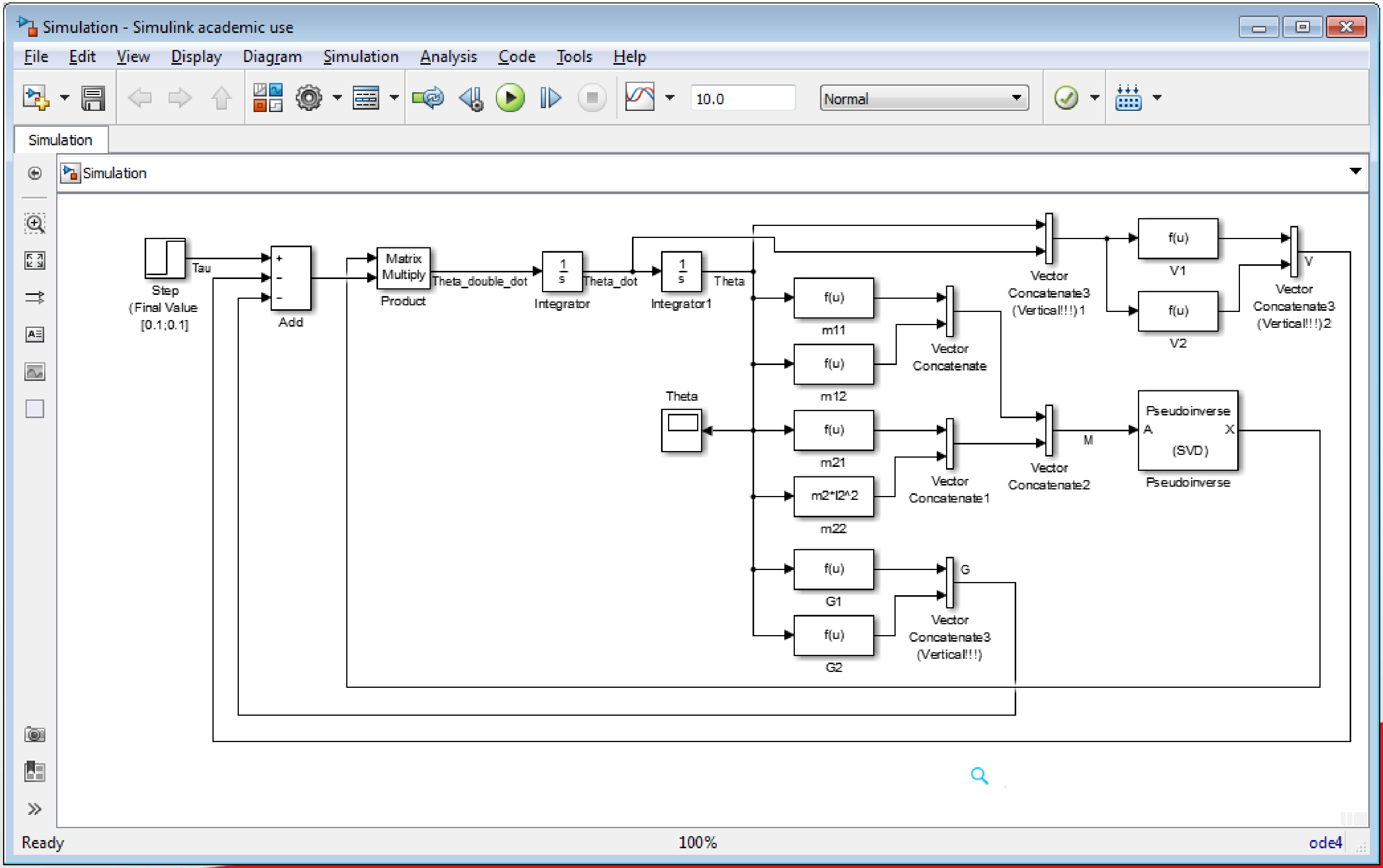
- This model would have run perfectly in an most version of Simulink…



MATLAB / Simulink

Only if there is an error in Vector Concatenate due to MATLAB Version

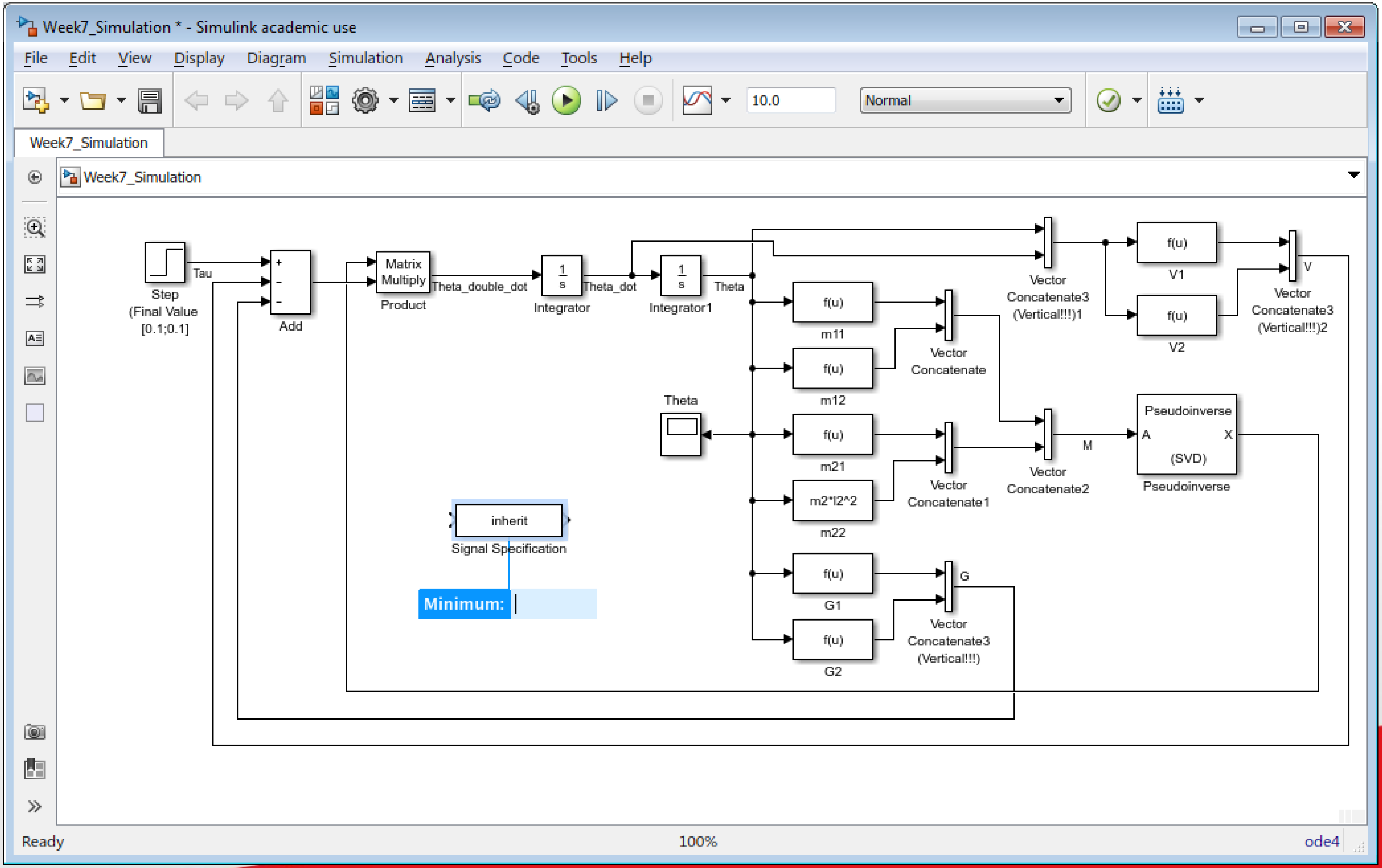
- But for some software/MATLAB versions, we need to add a few more items.



MATLAB / Simulink

Only if there is an error in Vector Concatenate due to MATLAB Version

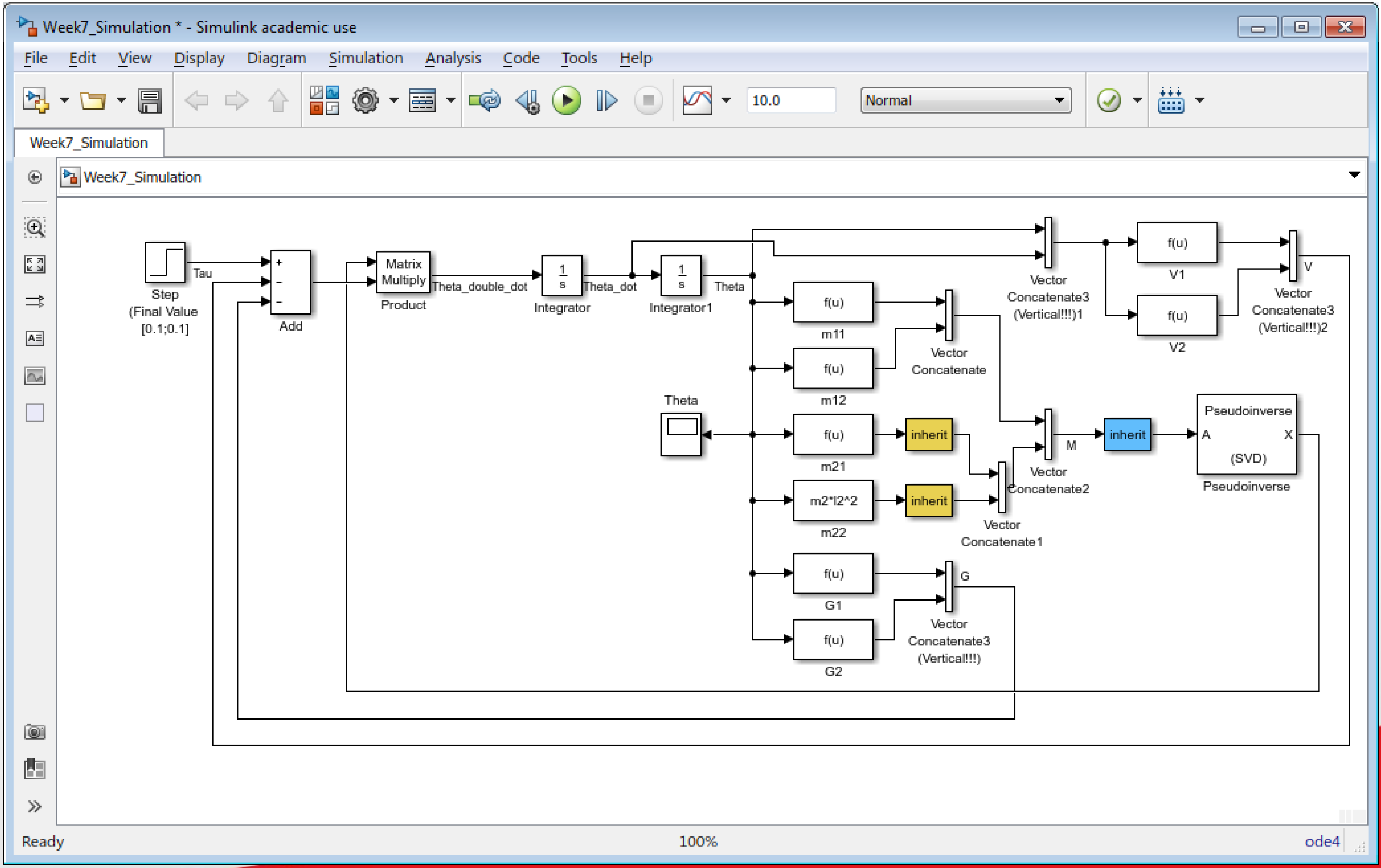
- Bring in "Signal Specification" block under "Signal Attributes".



MATLAB / Simulink

Only if there is an error in Vector Concatenate due to MATLAB Version

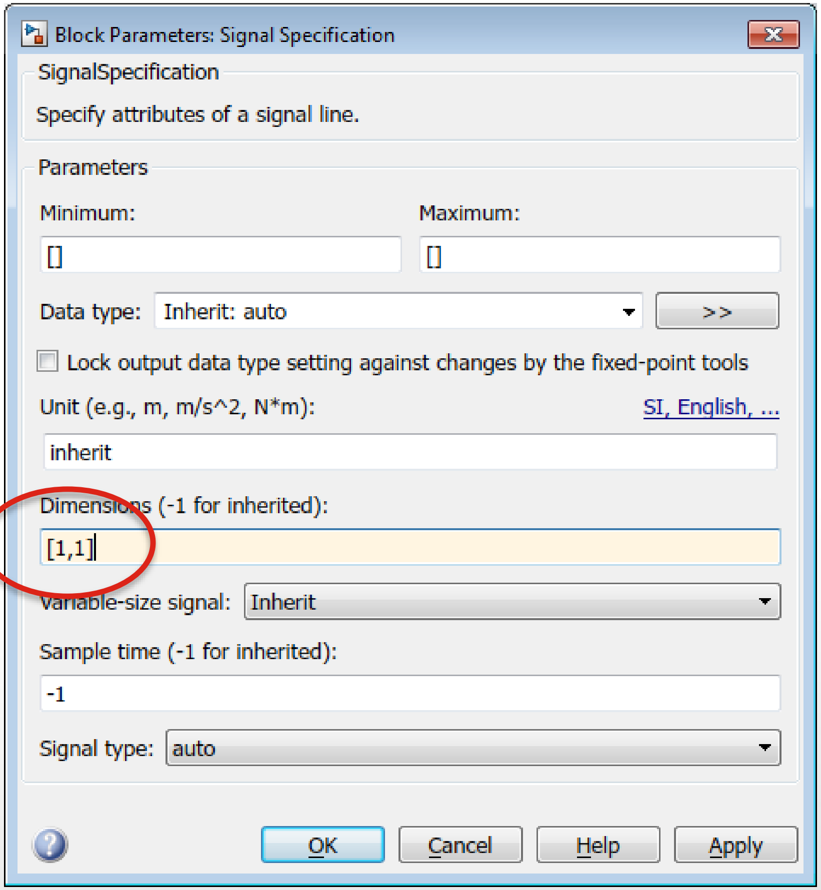
- Add this block at three locations as shown:



MATLAB / Simulink

Only if there is an error in Vector Concatenate due to MATLAB Version

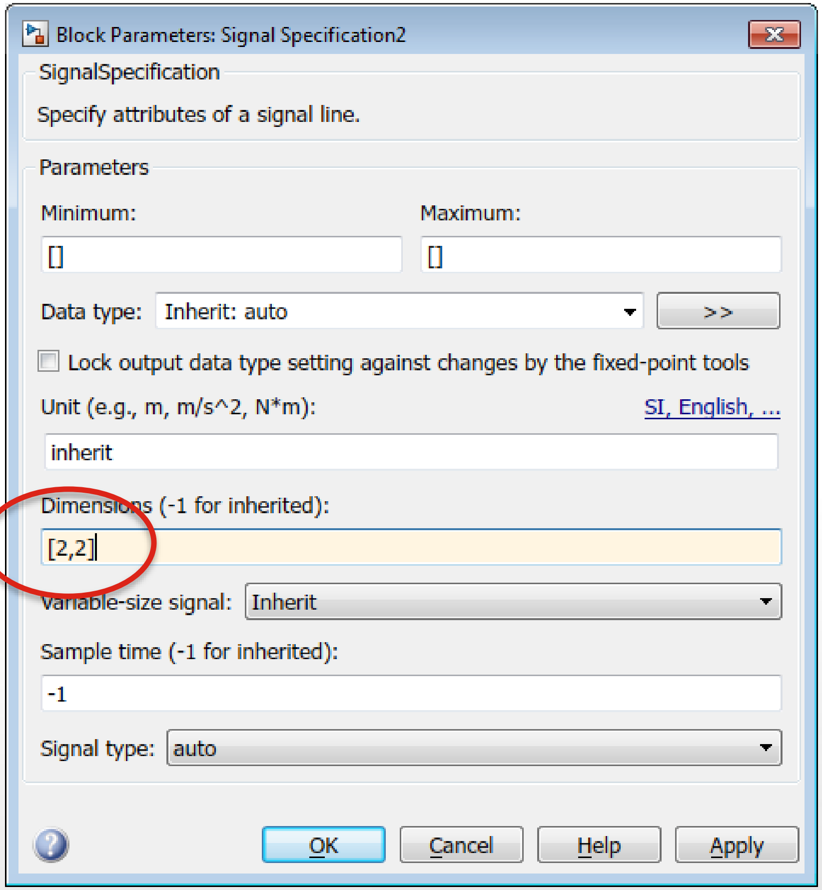
- Double click on the yellow blocks, and set the following parameter:



MATLAB / Simulink

Only if there is an error in Vector Concatenate due to MATLAB Version

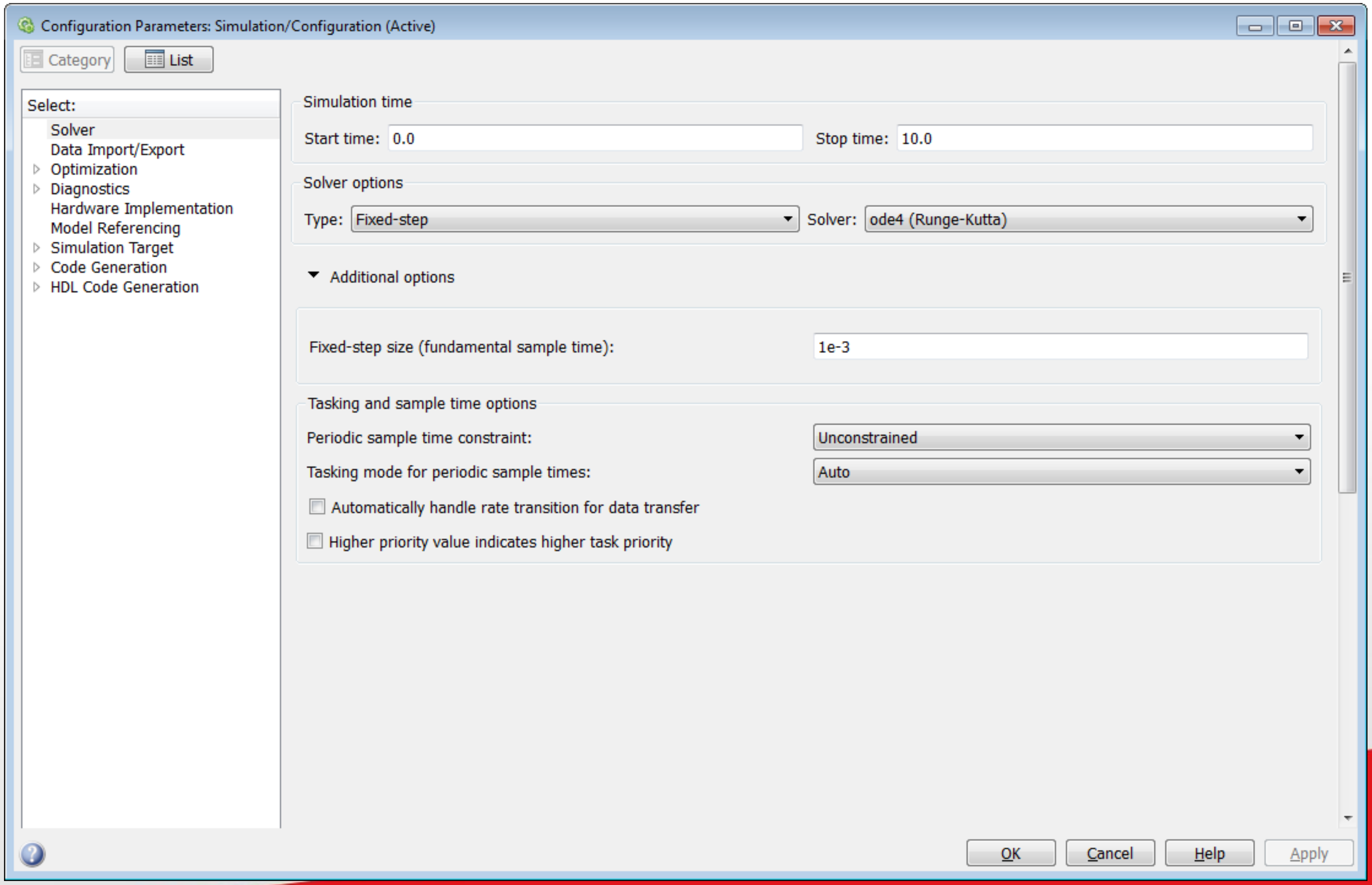
- Double click on the blue block, and set the following parameter:



MATLAB / Simulink

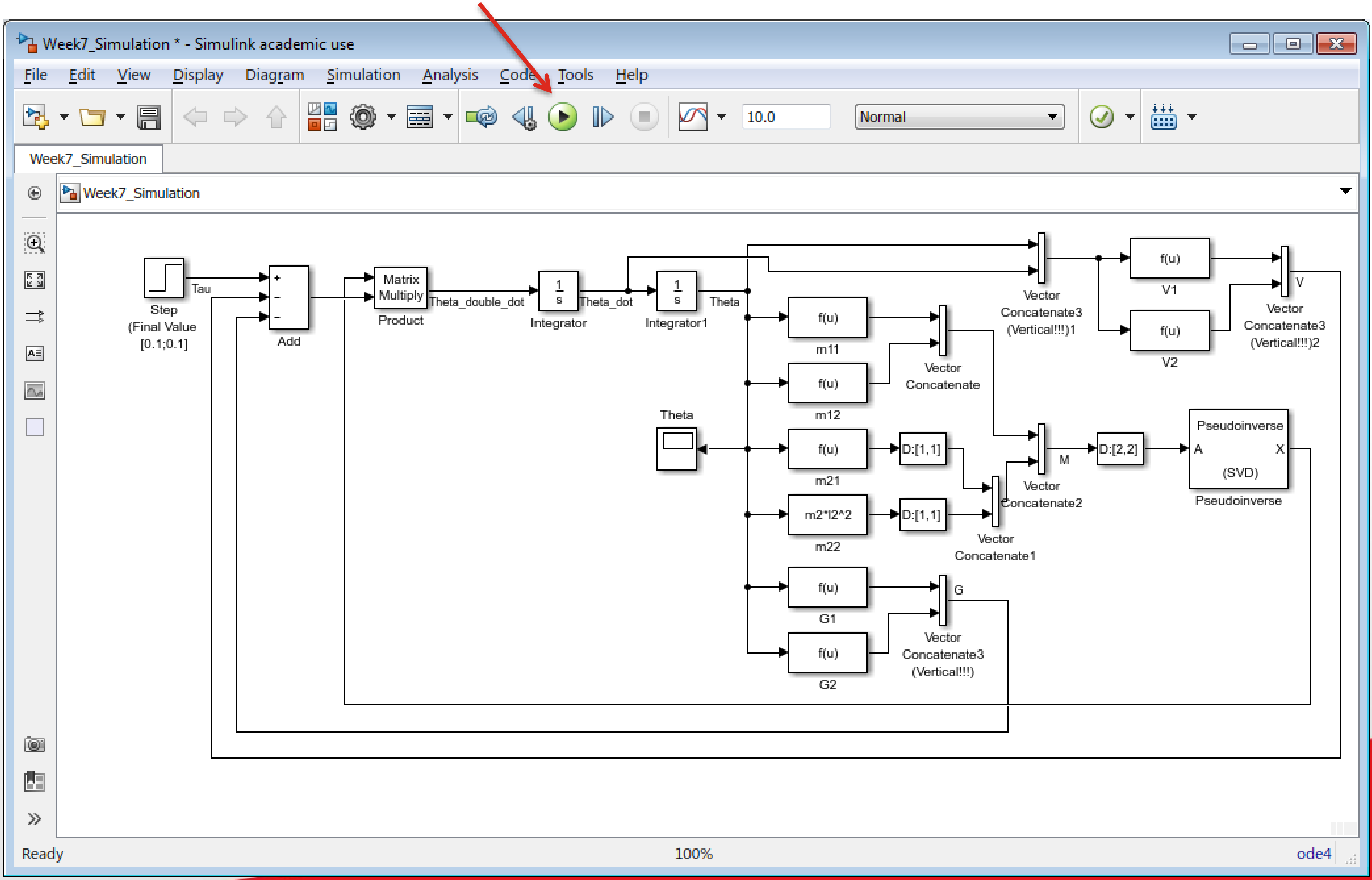
Continue from here

- Before we run the simulation, we would like to configure the simulation parameters.
- Click "Simulation" on top of Simulink window → Model configuration parameters → set the parameters as follows:



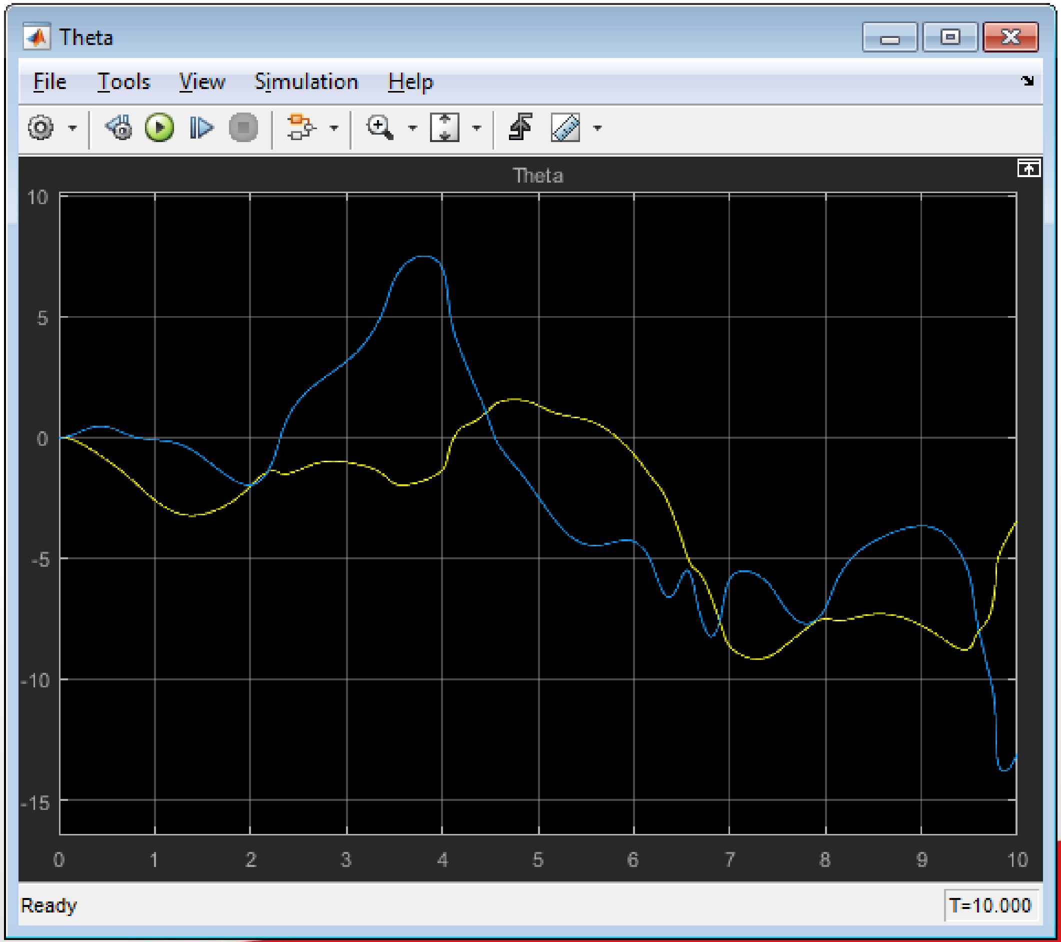
MATLAB / Simulink

- Now click the "play" button.



MATLAB / Simulink

- When simulation ends, double click "Theta" scope and you can see the Theta variations.
- This is the reaction of the robot, when given constant torques of 0.1Nm at each joint.

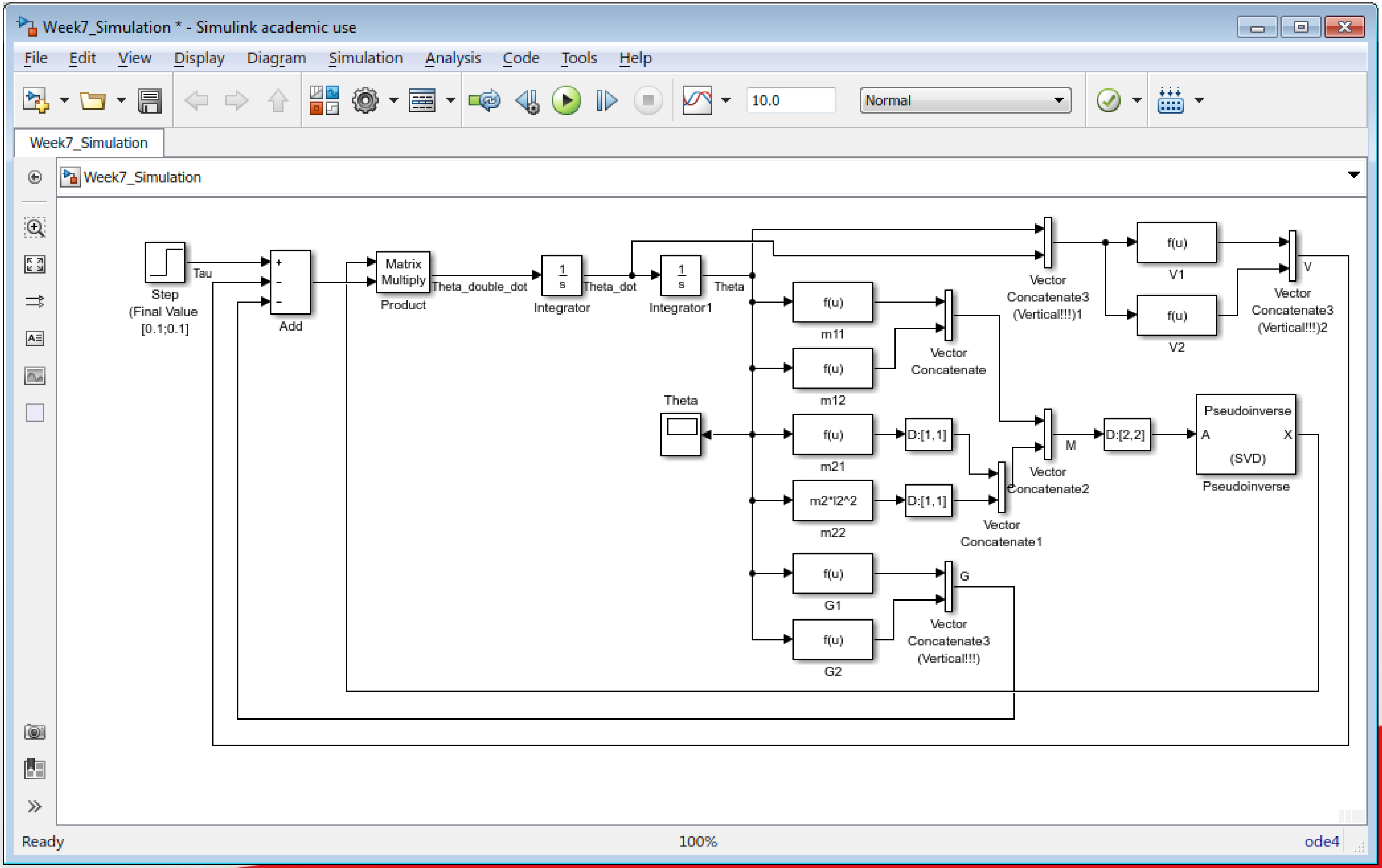


Yellow = Theta1

Blue = Theta2

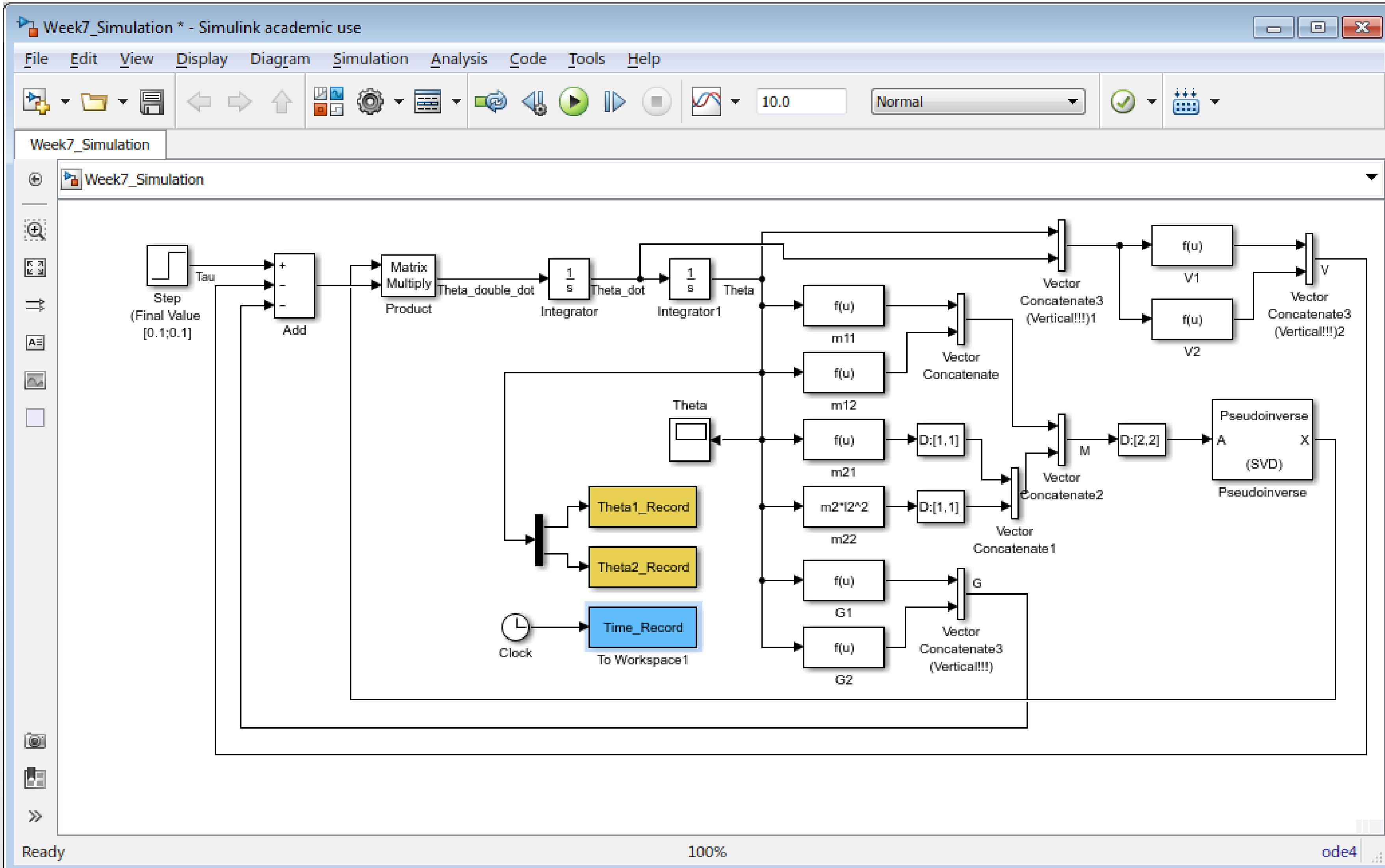
MATLAB / Simulink

- In order to better visualize the robot motion, we can run animation.



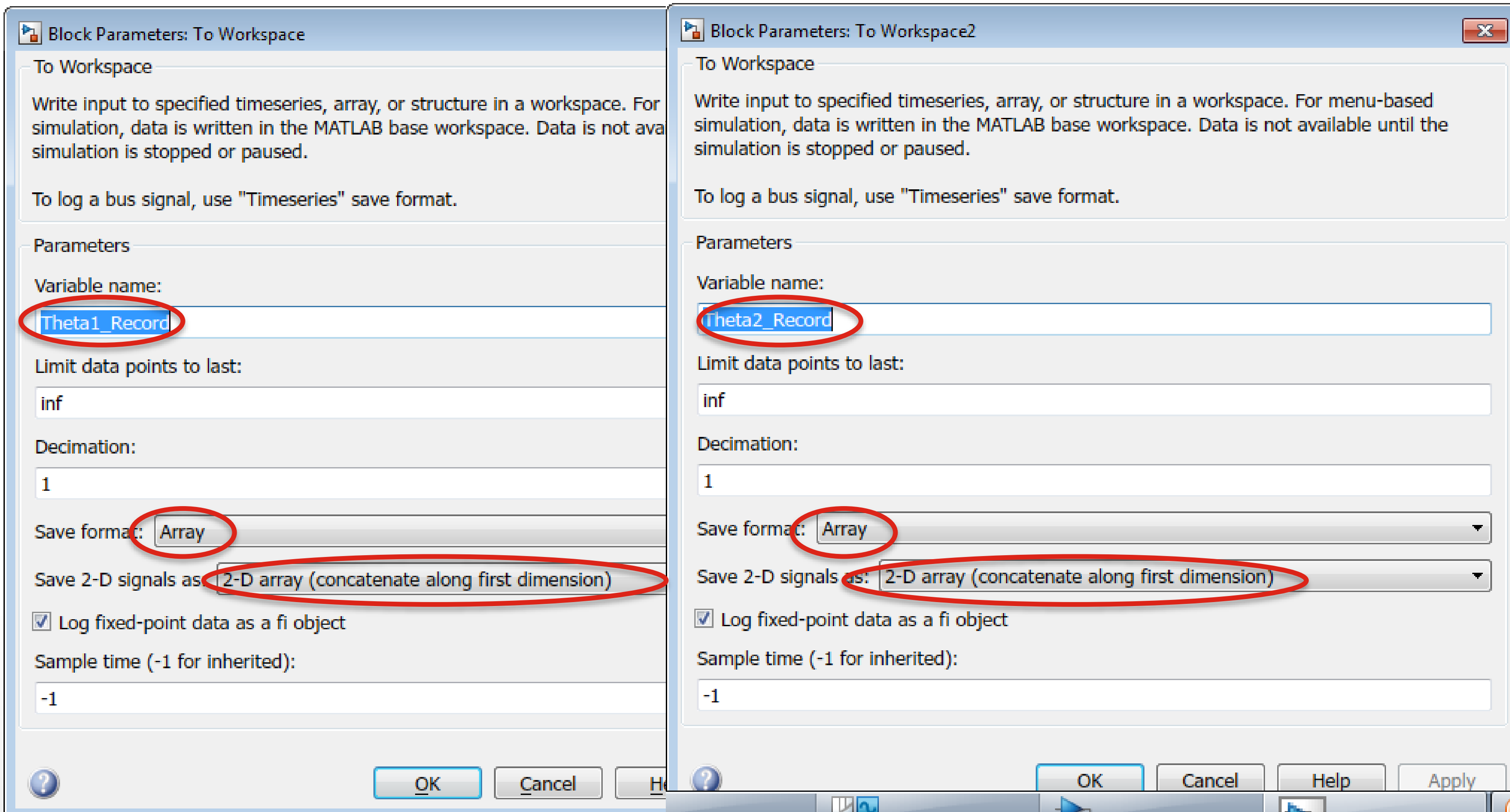
MATLAB / Simulink

- For that, we need to collect the data. Add the "To Workspace" blocks:



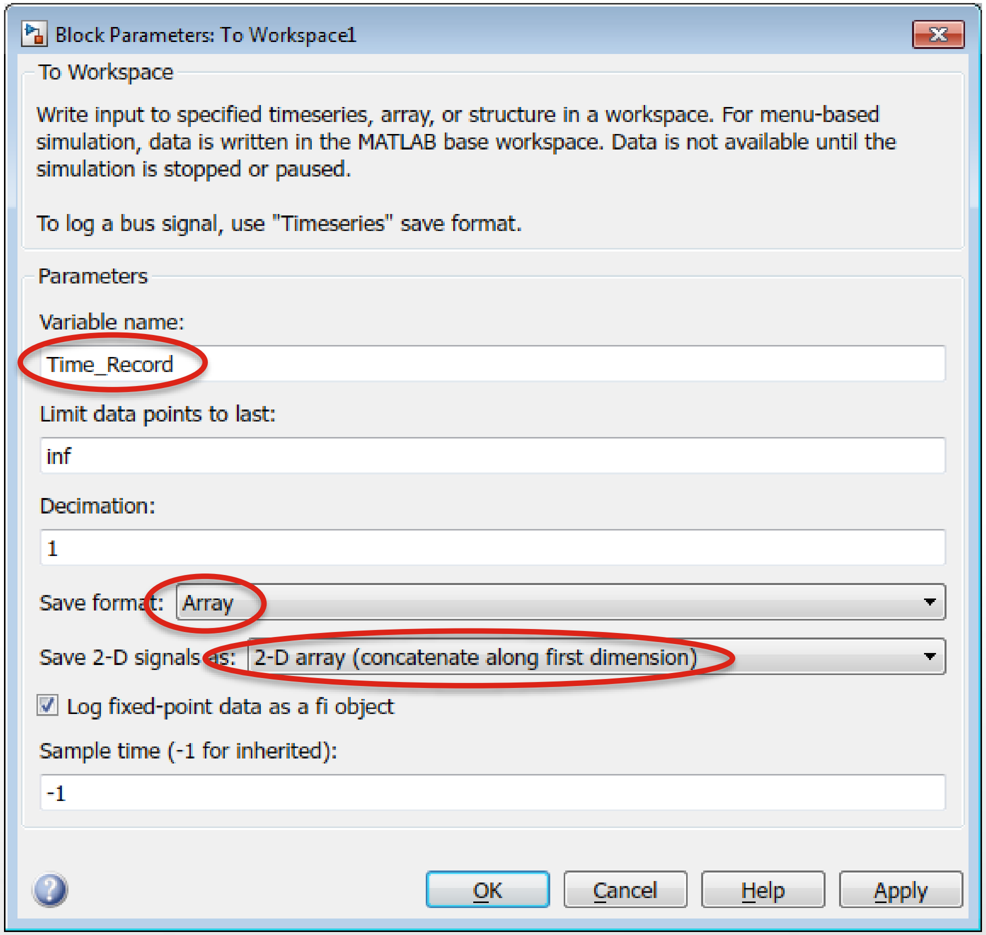
MATLAB / Simulink

- Configure the yellow blocks as follows:



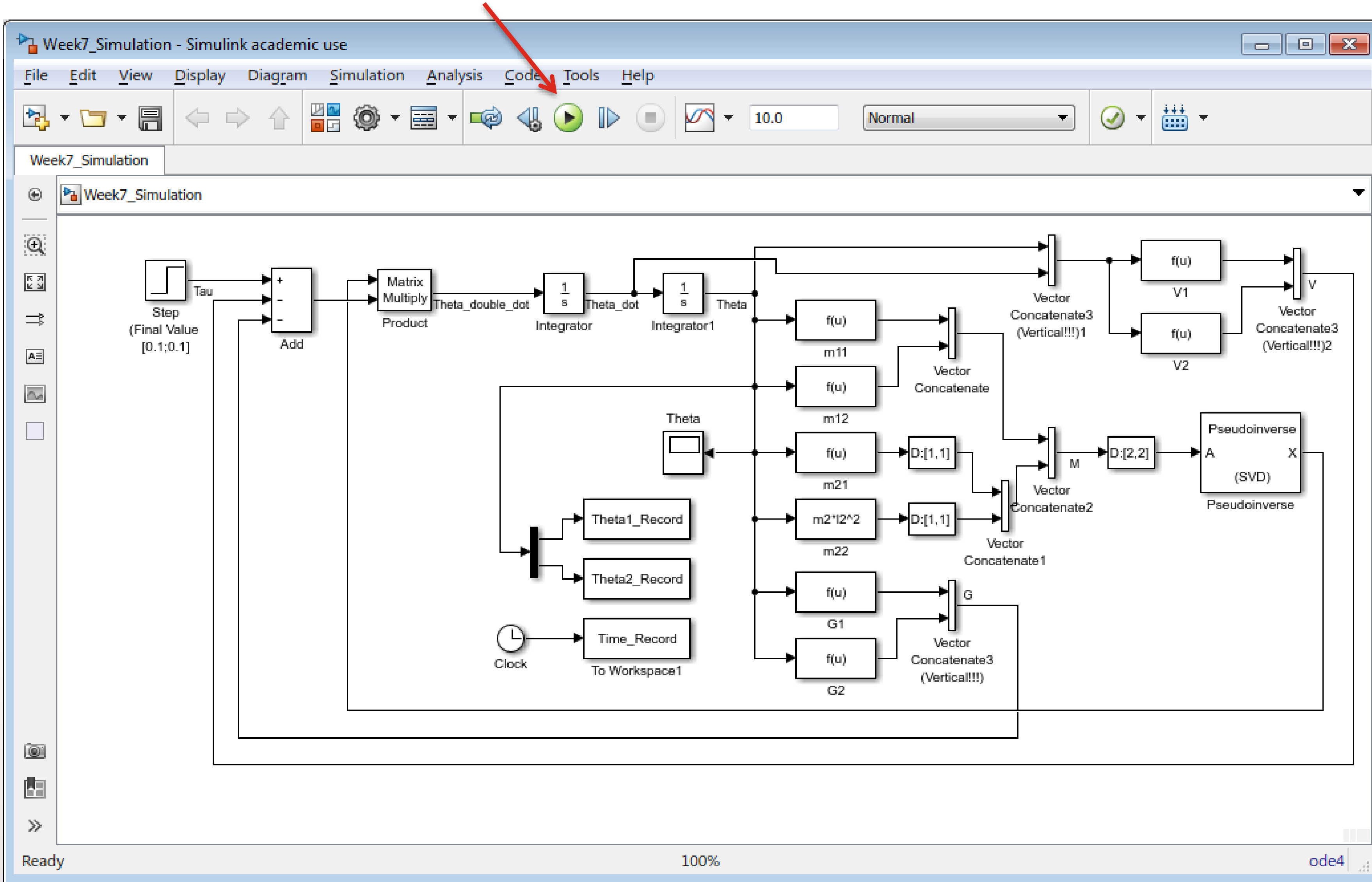
MATLAB / Simulink

- Configure the blue block as follows:



MATLAB / Simulink

- Now click the "play" button.



MATLAB / Simulink

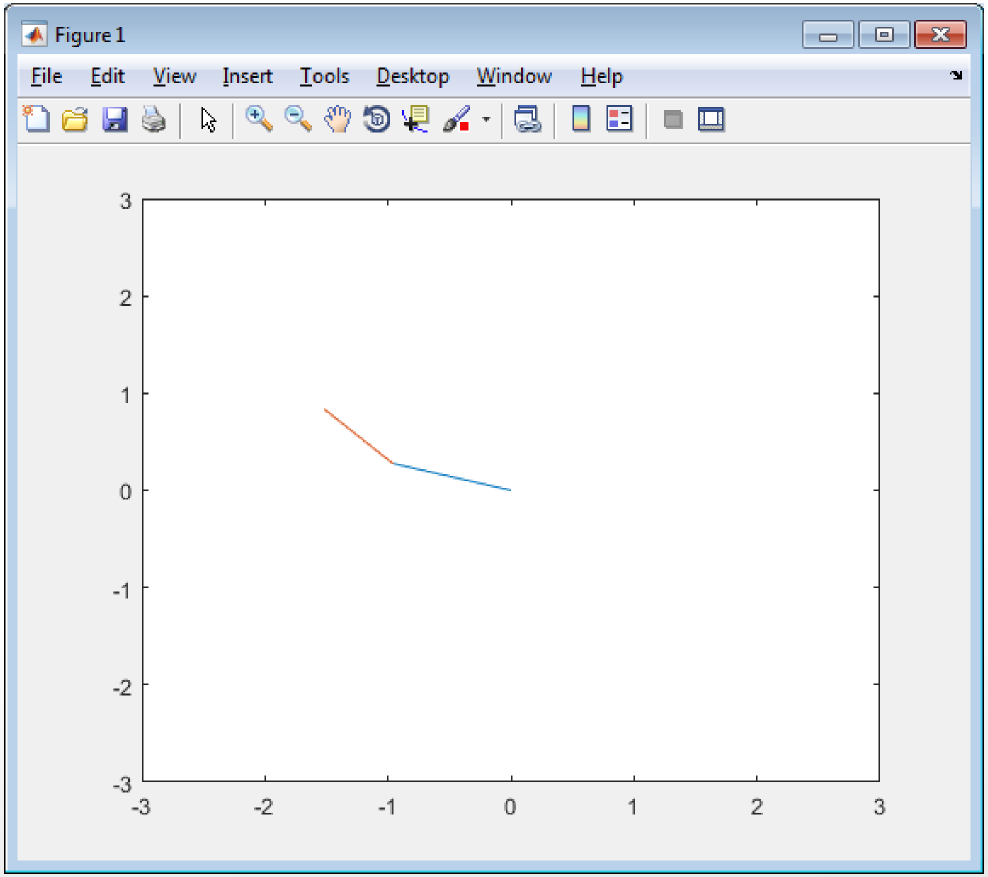
- Create another new script (m-file) and name it “animation”.

```
%%%%%%%%%%%%%%%%%%%%
% Robot Parameters %
%%%%%%%%%%%%%%%%%%%%

m1 = 1;         % kg
m2 = 0.8;       % kg
l1 = 1;         % m
l2 = 0.8;       % m
g = 9.8;        % m/s^2
```

```
%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate End Points %
%%%%%%%%%%%%%%%%%%%%%%%%

x1 = l1*cos(Theta1_Record);
y1 = l1*sin(Theta1_Record);
x2 = x1 + l2*cos(Theta1_Record+Theta2_Record);
y2 = y1 + l2*sin(Theta1_Record+Theta2_Record);

%%%%%%%%
% Plot %
%%%%%%%%

for i = 1:100:length(x1)
    clf;                % Clear figure before new plot
    plot([0 x1(i)],[0 y1(i)]);
    axis([-3 3 -3 3]);
    hold on,plot([x1(i) x2(i)],[y1(i) y2(i)]);
    pause(0.1);
end
```

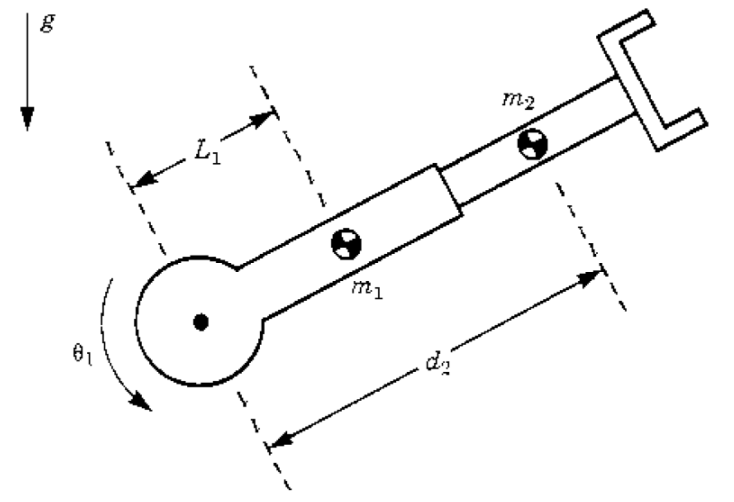
MATLAB / Simulink

- Run the m-file and you shall see the animation:



Exercise

- Try different torque values (including zero) and see the response.
- Add in viscous friction and see the response.
- Rebuild the model and animation based on the second robot example of today's class.



$$\underbrace{\begin{bmatrix} m_1 l_1^2 + I_{zz_1} + m_2 d_2^2 + I_{yy_2} & 0 \\ 0 & m_2 \end{bmatrix}}_{M(q)} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{d}_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 2 m_2 d_2 \dot{d}_2 \dot{\theta}_1 \\ -m_2 d_2 \dot{\theta}_1^2 \end{bmatrix}}_{V(q,\dot{q})} + \underbrace{\begin{bmatrix} m_1 l_1 g c_1 + m_2 d_2 g c_1 \\ m_2 g s_1 \end{bmatrix}}_{G(q)} = \tau$$

Thank you!

Have a good evening.