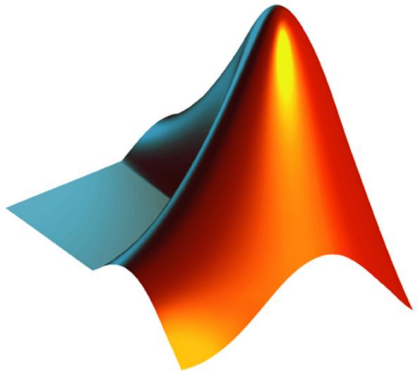
Teaching Chemical Engineering with MATLAB, Simulink and TCLab



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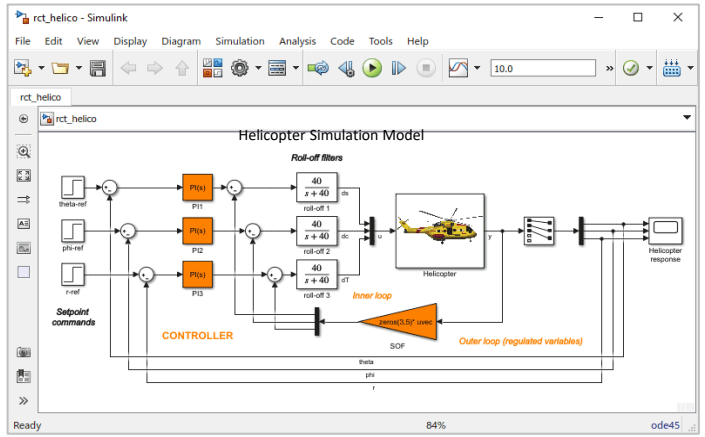
Associate Professor, Brigham Young University

Our Products

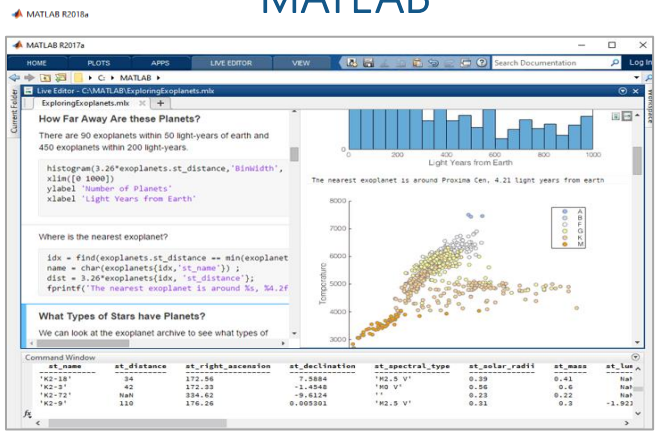
MATLAB® & SIMULINK®

- MATLAB is a programming environment for algorithm development, data analysis, visualization, and numeric computation.
- Simulink is a graphical environment for designing, simulating, and testing systems.
- 100 add-on products for specialized tasks.

Simulink



MATLAB



Integrating Computational Thinking to Chemical Engineering Curriculum

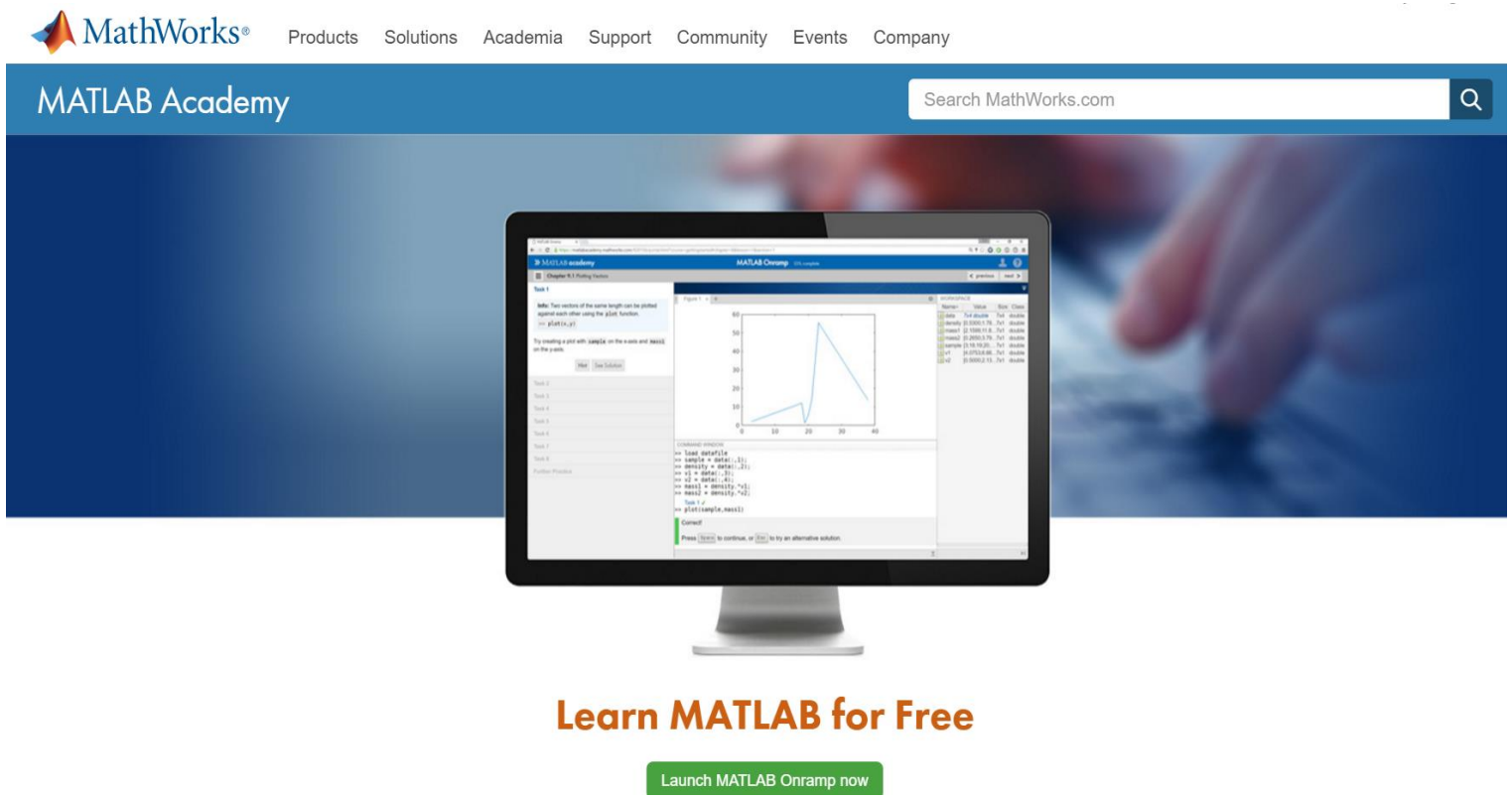
Introduce

Reinforce

Industry Applications

Getting Help

Self-paced courses



https://www.mathworks.com/academia/targeted/online-learning.html
https://matlabacademy.mathworks.com/

FREE COURSES (1-3 hours)

- MATLAB Onramp
- Simulink Onramp
- Machine Learning Onramp
- Deep Learning Onramp
- Reinforcement Learning Onramp
- Image Processing Onramp
- Signal Processing Onramp
- Simscape Onramp
- Stateflow Onramp
- Control Design Onramp with Simulink
- Optimization Onramp

FOCUSED COURSES

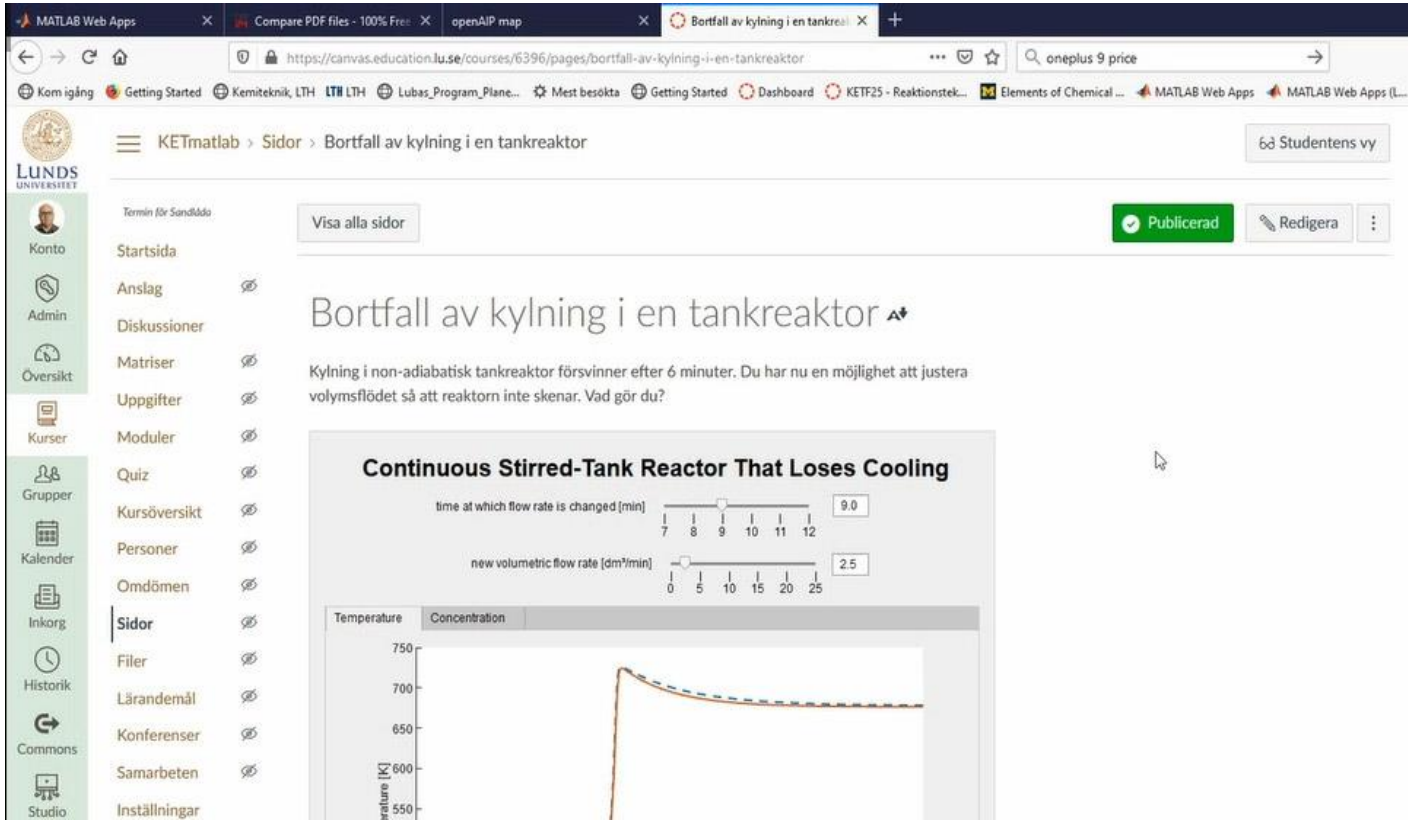
FOUNDATIONAL COURSES (17-21 hours)

- MATLAB Fundamentals
- MATLAB Programming Techniques
- MATLAB for Financial Applications
- MATLAB for Data Processing and Visualization
- Image Processing with MATLAB
- Machine Learning with MATLAB
- Deep Learning with MATLAB

COMPUTATIONAL MATH COURSES (2-3 hours)

- Introduction to Linear Algebra
- Solving Ordinary Differential Equations
- Introduction to Statistical Methods
- Solving Non-Linear Equations
- Introduction to Symbolic Math

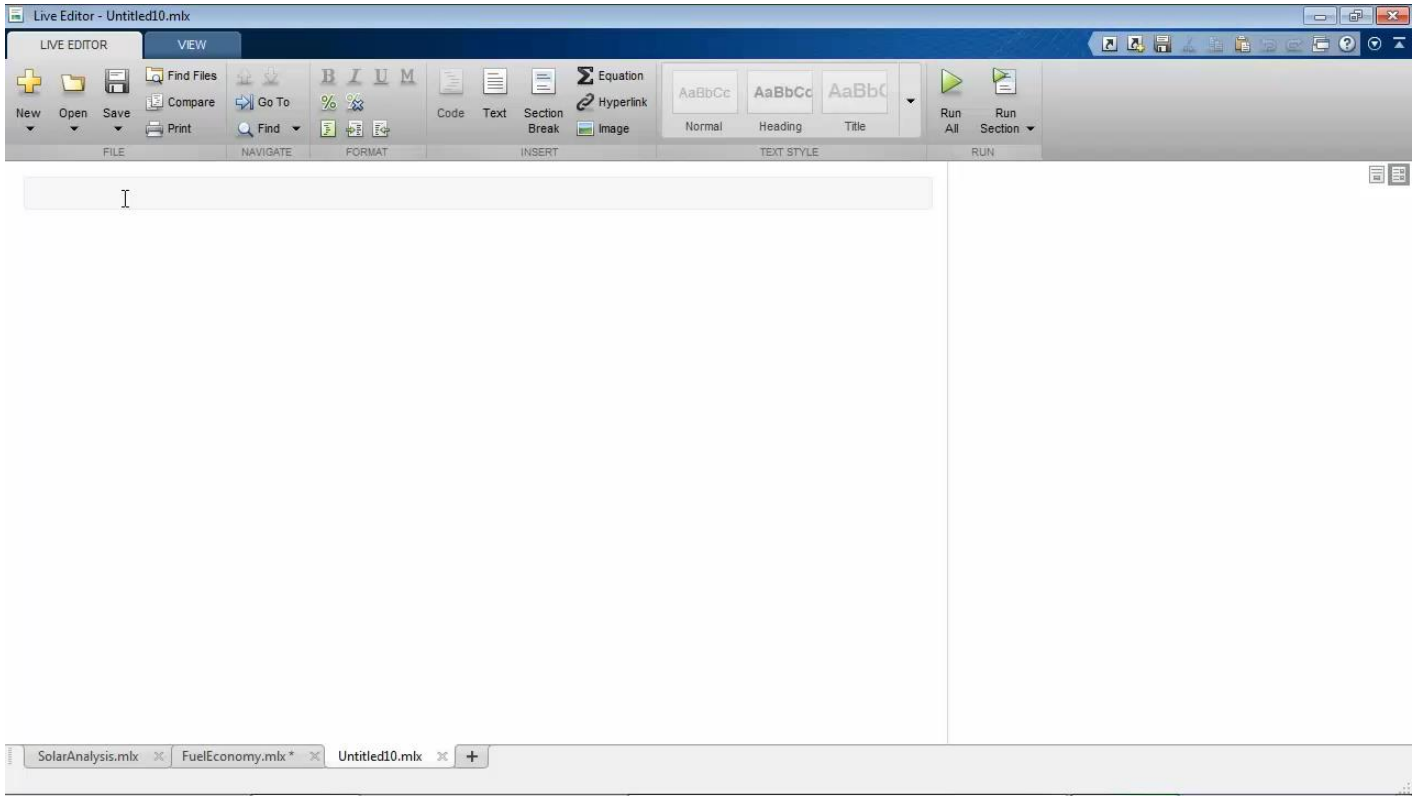
Creating and Hosting Custom Apps



[MATLAB Apps]

[Using Virtual Labs to Teach Reaction Engineering] at Lund University

Interactive programming with Live Editor

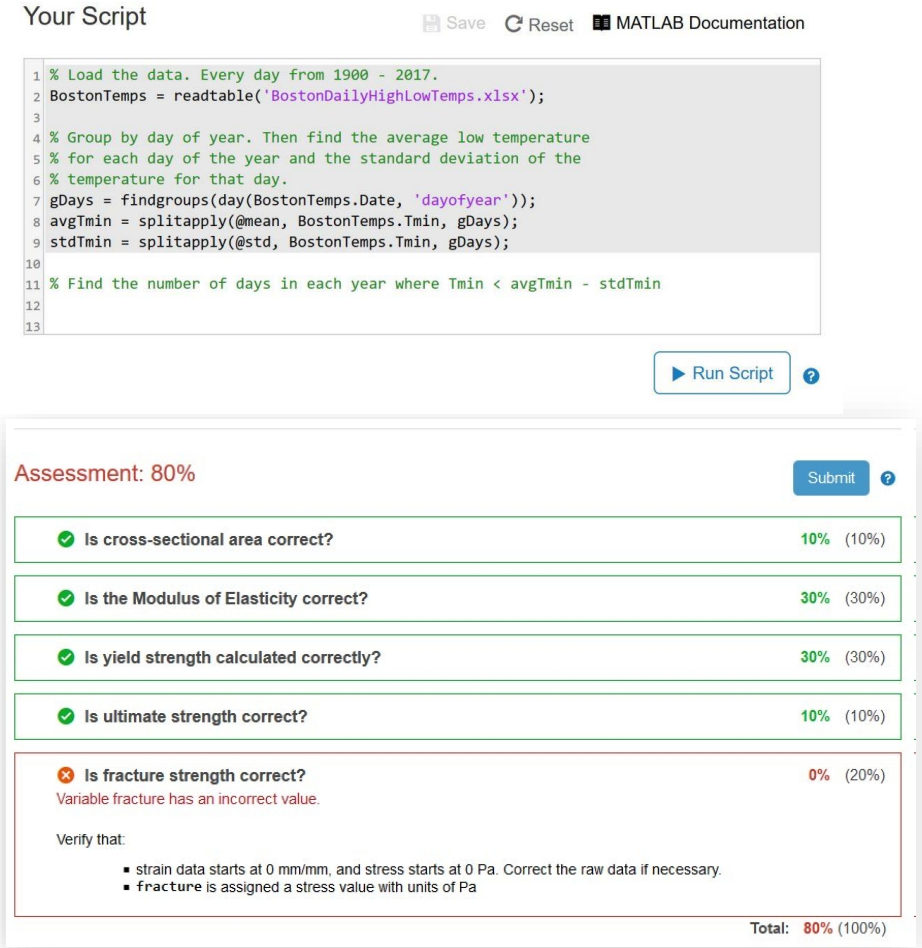


Features

- Teach with interactive documents
- Accelerate exploratory programming
- Create an interactive narrative
- Publish consistent reports

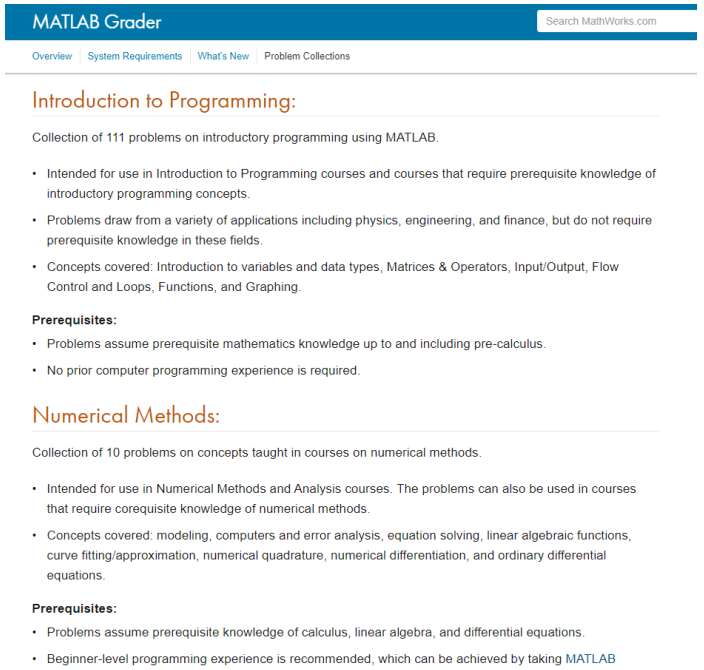
www.mathworks.com/products/matlab/live-editor.html
https://www.mathworks.com/products/matlab/live-script-gallery.html

MATLAB Grader for automatically grading MATLAB code in any learning environment



"The approach enables students to learn more quickly from their mistakes on their own."

– Dr. Bob Canfield, Virginia Tech



https://www.mathworks.com/products/matlab-grader.html

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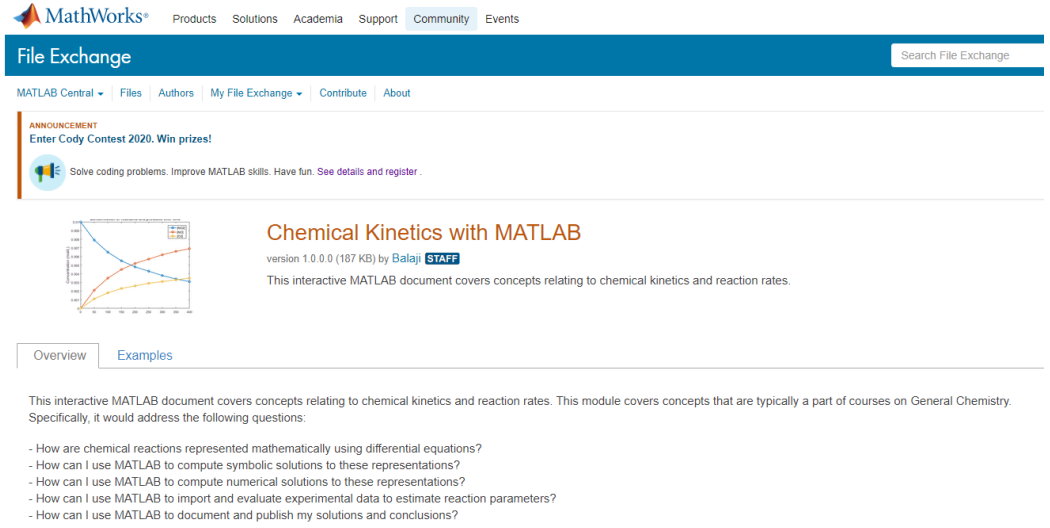
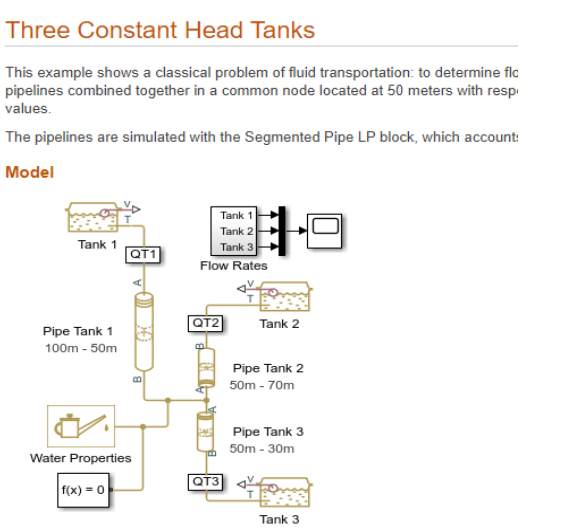
Resources for Chemical Engineering Courses with MATLAB

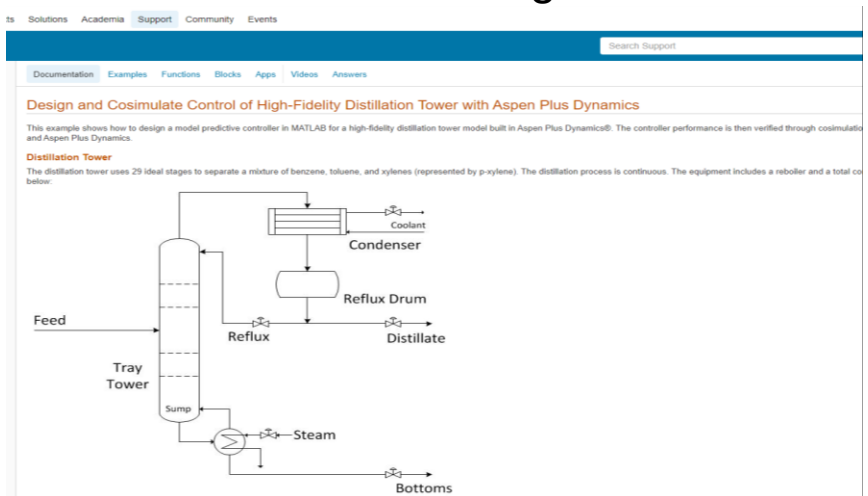
Reaction Kinetics



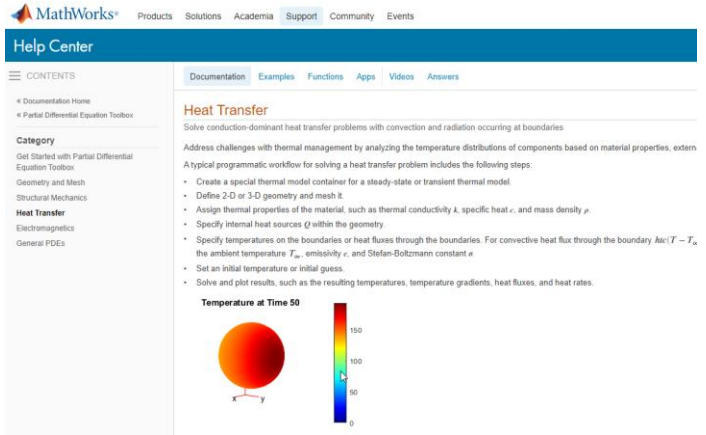
Fluid Dynamics



Process Design



Heat Transfer



Teaching Data Science to Chemical Engineers

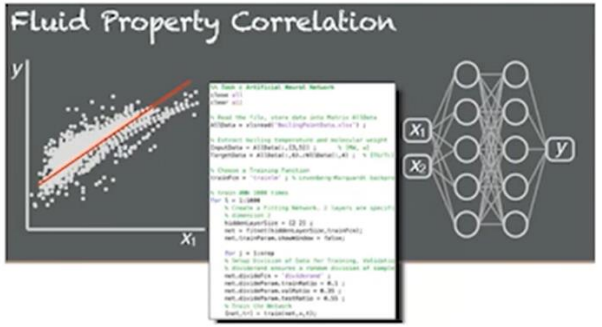
Imperial College London

Employing Machine Learning to Correlate Fluid Properties

Classroom Examples with MATLAB

Erich A. Müller

Department of Chemical Engineering
Imperial College London U.K.



https://www.mathworks.com/academia/courseware/teaching-data-science-with-matlab.html
https://www.mathworks.com/videos/employing-machine-learning-to-correlate-fluid-properties-1622032109572.html

Integrating Computational Thinking to Chemical Engineering Curriculum

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MATLAB and Simulink for Process Control in Industry

Customer Example: TATA Steel optimizes cooling tower operation via MPC on digital twin

Challenge

- High energy consumption in cooling tower
- Changing weather conditions caused substantial variation in operation

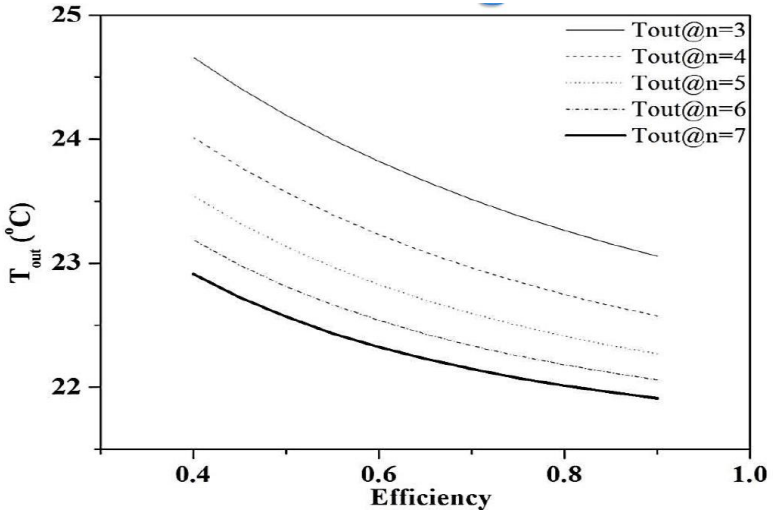
Solution

- Mass and energy balance equations modeled in MATLAB
- Model optimized and parameters calibrated with plant data
- MPC controller implemented

Results

- Savings of $40K per year for one CT
- Variation in outlet water temperature reduced
- Hundreds of tons of CO_2 reduction per year

Water cooling tower for the blast furnace



Effect of Murphree efficiency on number of stages

http://www.digitalcreed.in/tata-steel/
Link to TATA Steel's talk

Customer Example: Company Eliminates Environmental Impact of Discharged Wastewater with pH Control System

Challenge

- To control pH levels in a wastewater treatment facility that was performing inconsistently
- No programming experience

Solution

- Model plant in Sys Id Toolbox using process data
- Use Control System Toolbox to develop a controller to find best parameter settings graphically
- Implemented on Yokogawa DCS

Results

- Acceptable pH levels rose to 100% from 84%
- Controller performance improved
- Development streamlined in just 3 months

Main Control Panel

"Using Model-Based Design with MATLAB and Simulink enabled us to quickly try out multiple control strategies and validate the system before putting it into operation. This approach saved us time and ensured a better product."

- Process Engineer

Customer Example: Genentech Builds a Supervisory Control Algorithm Development Platform for Bioreactors

Challenge

Accelerate the development of control algorithms for microbial fermentations

Solution

Use MATLAB and OPC Toolbox to develop a continuous-uptime supervisory control platform that enables rapid development, debugging, and verification of algorithms

Results

- Algorithm development time cut from months to weeks
- Flexible, reliable infrastructure deployed
- Potential errors identified in minutes

A Genentech microbial pilot plant bioreactor

"By partnering with MathWorks Consulting, we developed a robust platform for supervisory control with MATLAB and transitioned our pilot plant to a modern automation control system. This enabled our researchers to rapidly take algorithms from idea to implementation, simulation, and deployment."

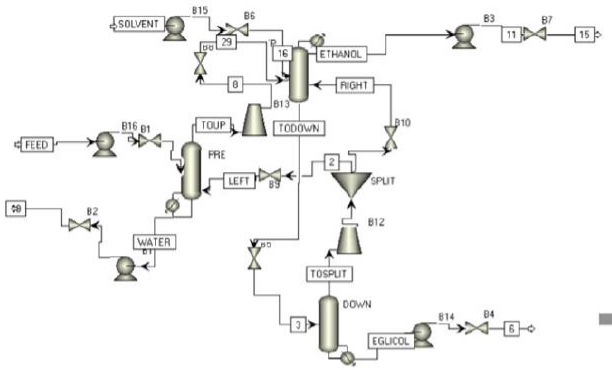
Dr. Ryan Hamilton

Genentech

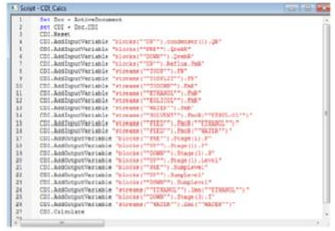
Link to user story

Import Aspen Dynamics and gPROMS models into Simulink to develop your control strategy

Aspen Plus
Dynamic Simulation



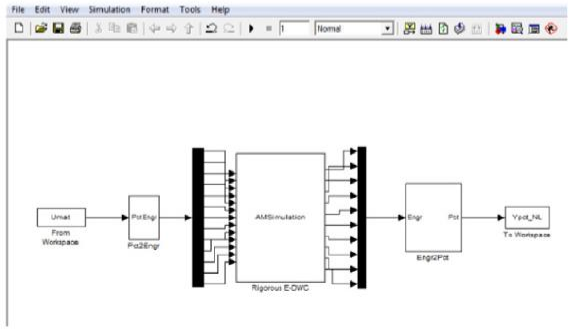
Aspen Plus
Control Design Interface



Generates

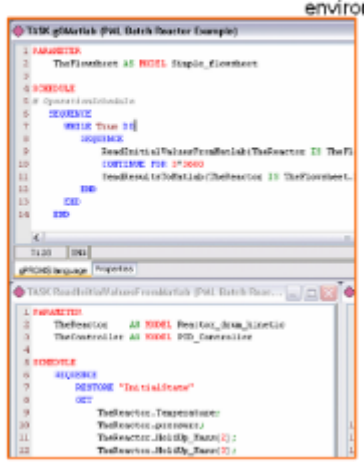
MATLAB
Linearized
state space
model

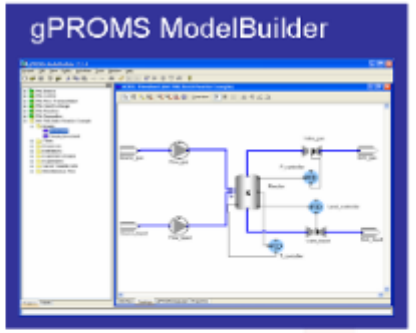
Linear model
validation



Simulink wrapper. Rigorous simulation

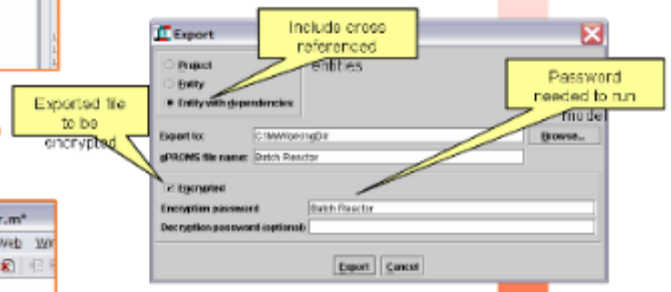
Step 1: Develop and test the gPROMS model inside the gPROMS ModelBuilder environment.

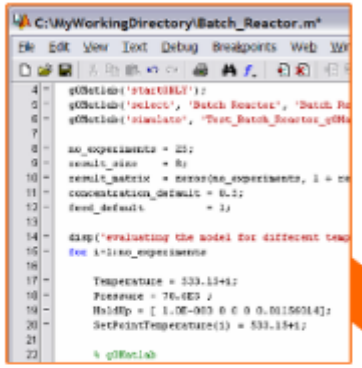




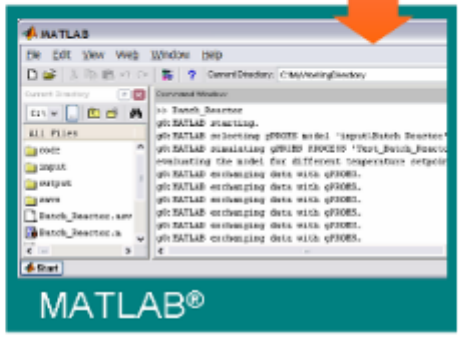
Step 2. Create a gPROMS schedule that periodically exchanges relevant data between gPROMS and MATLAB.

Step 3: Export the model gPROMS model





Step 4: Create a MATLAB script file (e.g. cstr.m)



Step 5: Execute the gPROMS model from within MATLAB.

Link to download

Simulink is the preferred platform for APC

IGCC - Current scenario

IGCC Power plants in US

- Wabash River Power Station, West Terre Haute, IN
- Polk Power Station, Tampa, FL (350 MW)
- Pinon Rine, Reno, NV (failed)

Obstacles

- High cost (without carbon regulation)
- Political – Recent emerging IGCC emission controversy
- Supreme court decision requiring Environment Protection Agency to regulate carbon

Wabash

Polk

Plant-wide IGCC Simulation

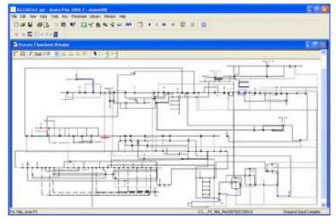
Aspen Plus to *Aspen Dynamics* to *MATLAB*

IGCC Base Case in Aspen Plus

Modify base case

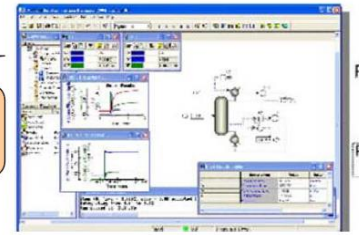
Separate Sub-sections

Prepare for export to Aspen Dynamics



Process.bkp

Export Simulation



Process.dynf

ProcessDYN.appdf

Add simple inventory control PID loops

Identify relevant inputs-outputs

Interface w/ MATLAB/Simulink

Implement control strategies

PLANT-WIDE

Interconnect sub-sections

Decentralized plant-wide MPC and MMPC

Link to Slides

Customer Example: Tüpraş implements Control Loop Performance Assessment Solution in MATLAB

Challenge

- Control loop performance deteriorates with time
- 5900 control loops spread across 4 refineries
- Expensive and non customizable enterprise software

Solution

- Use a variety of signal processing techniques – spectral analysis, correlation analysis, pattern recognition, nonlinearity analysis, etc to diagnose the controller problems based on unique digital ‘signatures’

Results

- **$12-20 Million annual savings**
- Analysis automated, customized and simplified through in-house solution
- Savings of 250 man days annually for control engineers

Controller health monitoring system dashboard

“MATLAB saved us a significant amount of time and expense by enabling us to develop our own software in-house. It also enabled us to save millions of dollars in costs that would have resulted from poor controller performance.”

- Mehmet Yagci, Tüpraş

Link to user story

Sign up for capstone project – ‘Monitoring and control of a bioreactor’

- Motivation & Benefits
  - Help transition pharmaceutical manufacturing to Industry 4.0 through application of APC
  - Learn about real industrial challenges
  - Learn MATLAB and Simulink
- Capstone Project on Github
  - Modeling a penicillin bioreactor
  - Analyze industrial ‘big data’ set (2.5 GB)
  - Identify CPPs
  - Develop control strategy

Source

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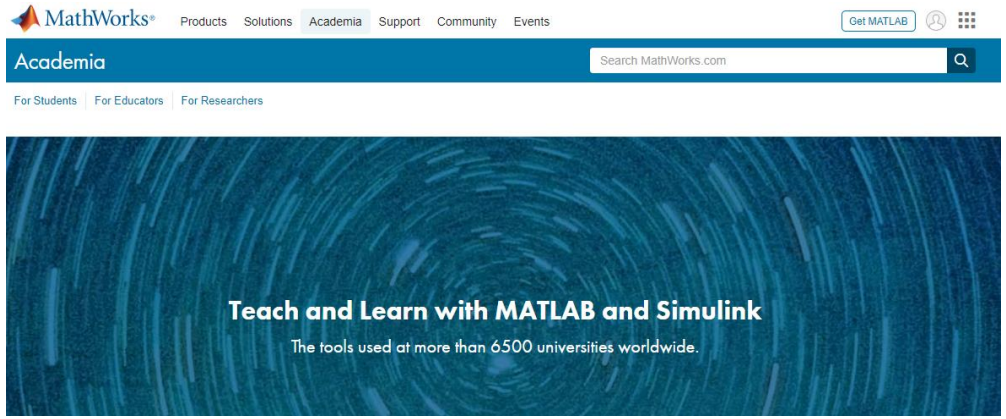
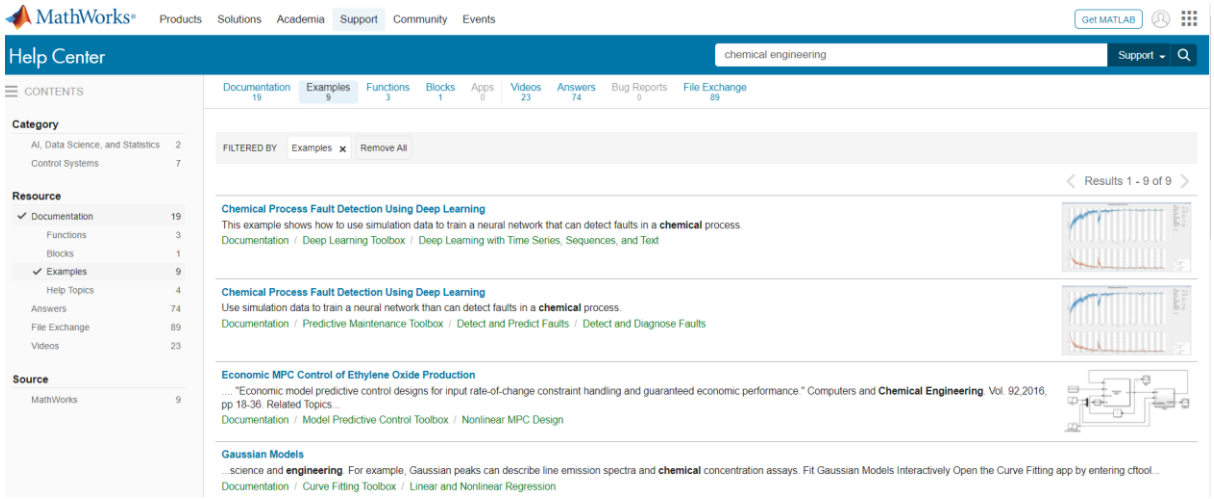
Getting Help

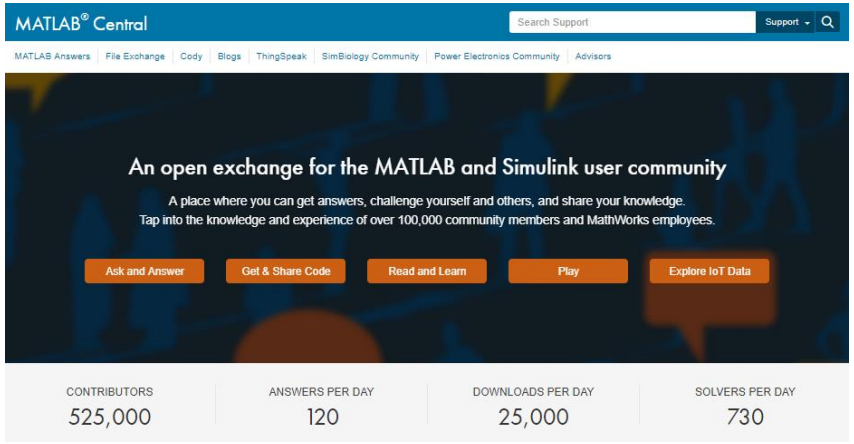
MATLAB for Academia



Help Center



MATLAB Central

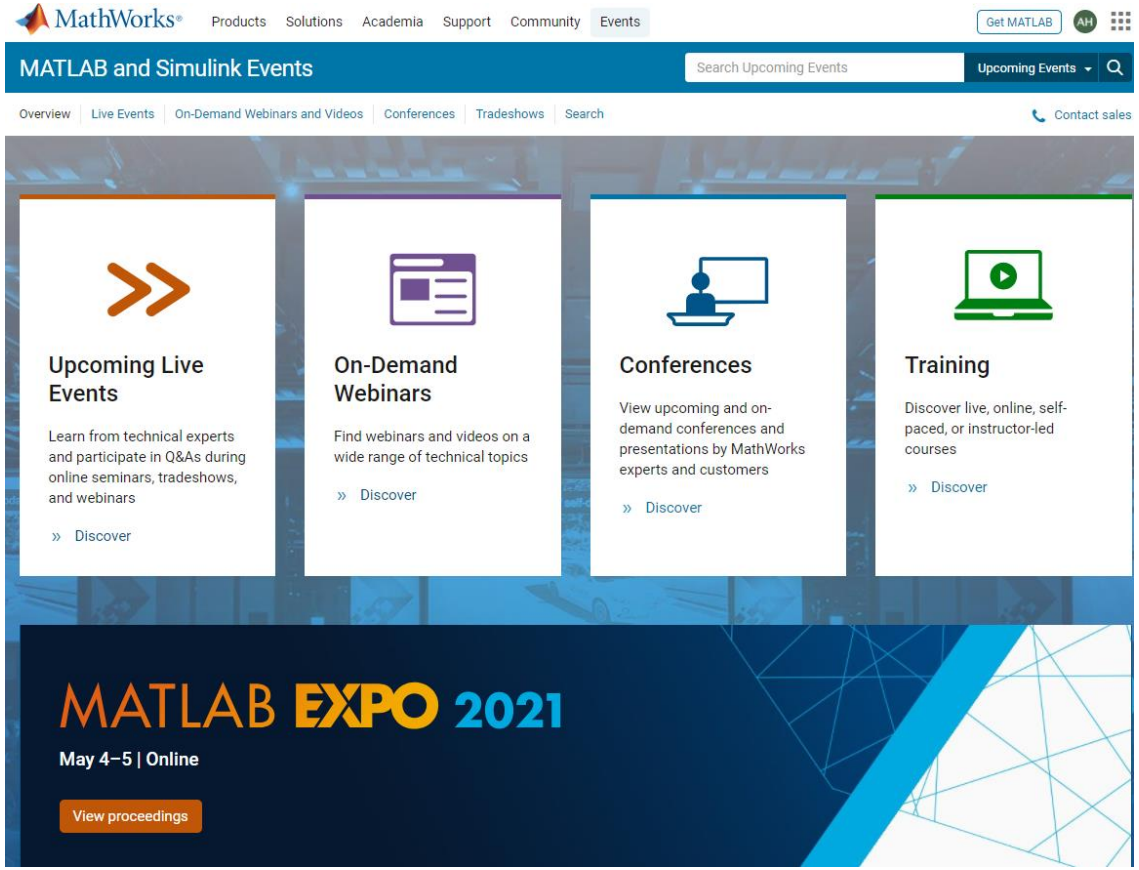


Customer Success Team

- Curriculum Support
- Research Support
- Awareness Resources

MATLAB and Simulink Events

2021 AIChE Annual Meeting



- Integrating Data Science to Chemical Engineering Curriculum Using MATLAB
- Teaching Hands-on Process Control Courses with Arduino Based TCLab, MATLAB and Simulink
- Prediction of Atoms in Molecules with MATLAB Graph Convolutional Network
- Parallel and GPU Computing with MATLAB and Simulink for Chemical Engineering

https://www.mathworks.com/company/events.html

https://aiche.confex.com/aiche/2021/meetingapp.cgi/ModuleProgramBook/0

Resources

MathWorks - Academia
MATLAB and Simulink for the Chemicals and Petrochemicals Industry

Fluid Dynamics
- Simscape Fluids
- Three Constant Head Tanks Documentation Example
- Hydraulic Resistive Tube Documentation Example

Reaction Kinetics
- SimBiology
- Chemical Kinetics with MATLAB File Exchange Entry
- Teaching Chemistry with MATLAB
- SimBiology Documentation Example for Reaction Kinetics

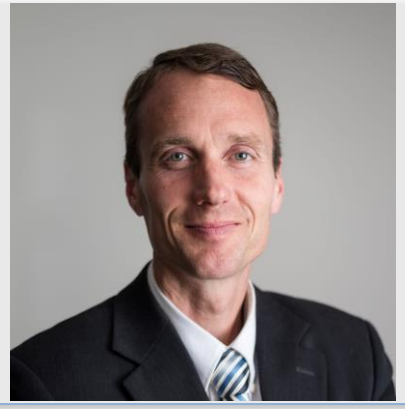
Heat Transfer
- Partial Differential Equation Toolbox
- Heat Transfer Documentation Examples

Process Control
- Simulink
- Control System Toolbox
- Water Tank Simulink Model Documentation Example
- Design Internal Model Controller for Chemical Reactor Plant Documentation Example
- Teaching Controls with MATLAB and Simulink

Process Design
- Linking MATLAB to Process Simulators
- Design and Cosimulate Control of High-Fidelity Distillation Tower with Aspen Dynamics Documentation Example

Teaching Chemical Engineering with MATLAB, Simulink and TCLab

Joshua Hammond
Research Assistant
John Hedengren
Associate Professor
Brigham Young University



BYU PRISM
MODEL OPTIMIZE CONTROL

Webinar and Interactive Module Interest

John Hedengren
Associate Professor
View full profile

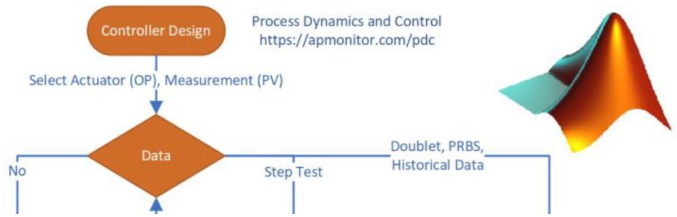
John Hedengren
Associate Professor
6d •

35 NEW interactive modules in MATLAB, Simulink, and Live Scripts for Dynamics and Control. Join the MathWorks webinar on Teaching Chemical Engineering with MATLAB, Simulink and TCLab on Tuesday, Aug 17.

Webinar Registration: https://lnkd.in/etEs4DP
35 Modules (GitHub): https://lnkd.in/e6hpFrc9
Course Schedule: https://lnkd.in/eDEJPqP

The flowchart guides students through the course with one or more modules for each block. Thanks to Joshua Hammond, Colin Anderson, and Nathanael Martin-Nelson, EIT for their development work on these new modules over the past year and to MathWorks for technical and financial student support.

#chemicalengineering #teaching #matlab #simulink #processcontrol #processautomation #education



449 · 15 comments

Reactions

Like Comment Share Send

20,495 views of your post in the feed

Your post posted on August 10, 2021
449 reactions · 15 comments

20,497 views 27 reshares

172 people from MathWorks viewed your post

ExxonMobil	148
Shell	77
Brigham Young University	71
Honeywell	54
Baker Hughes	35
Schlumberger	34
Halliburton	32

1,278 people who have the title Engineer viewed your post

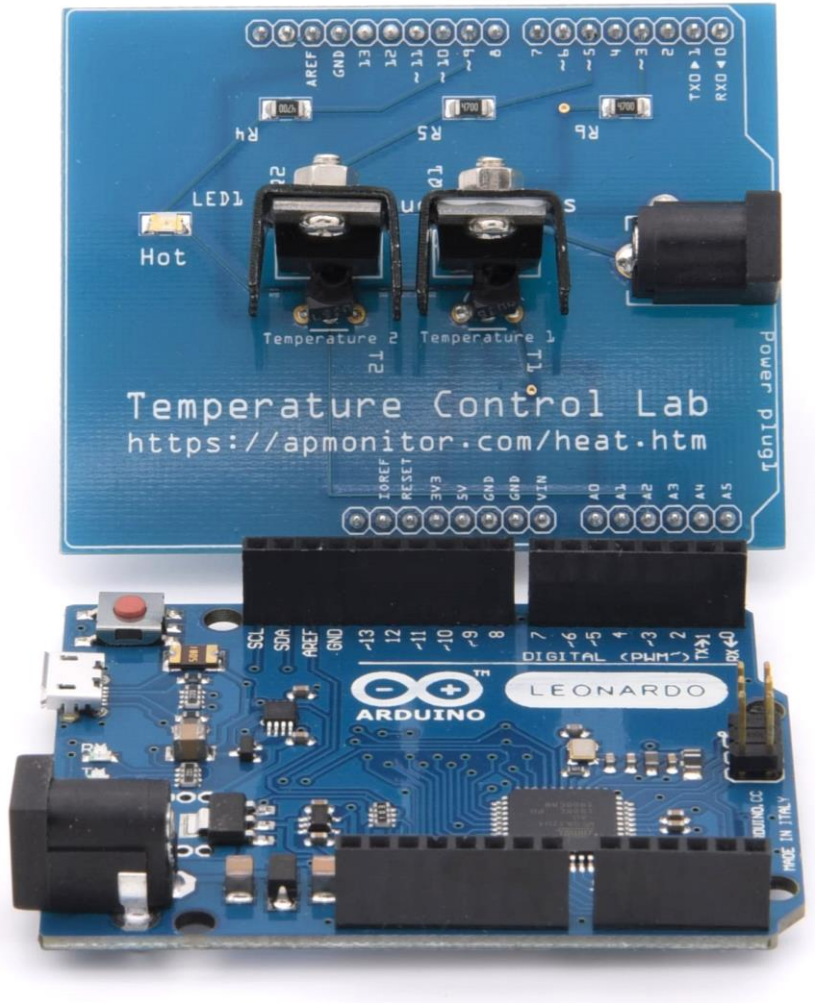
Research Fellow	908
Software Developer	847
Student	739
University Professor	700
Manufacturing Operations Manager	343
Hardware Engineer	307
Laboratory Scientist	287

530 people viewed your post from Houston, Texas Area

Bengaluru Area, India	348
San Francisco Bay Area	257
Provo, Utah Area	233
São Paulo Area, Brazil	200
Mumbai Area, India	181
Greater Boston Area	176
Kalyan Area, India	174
Chennai Area, India	169

Overview

- Automation needed across industries
- 35 Lesson Modules
- Pocket-sized lab overview
  - Teaching resource with learning objectives
  - MATLAB, Simulink, and Live Script demos
- Collaborative community resources



Medical Automation

People Transportation

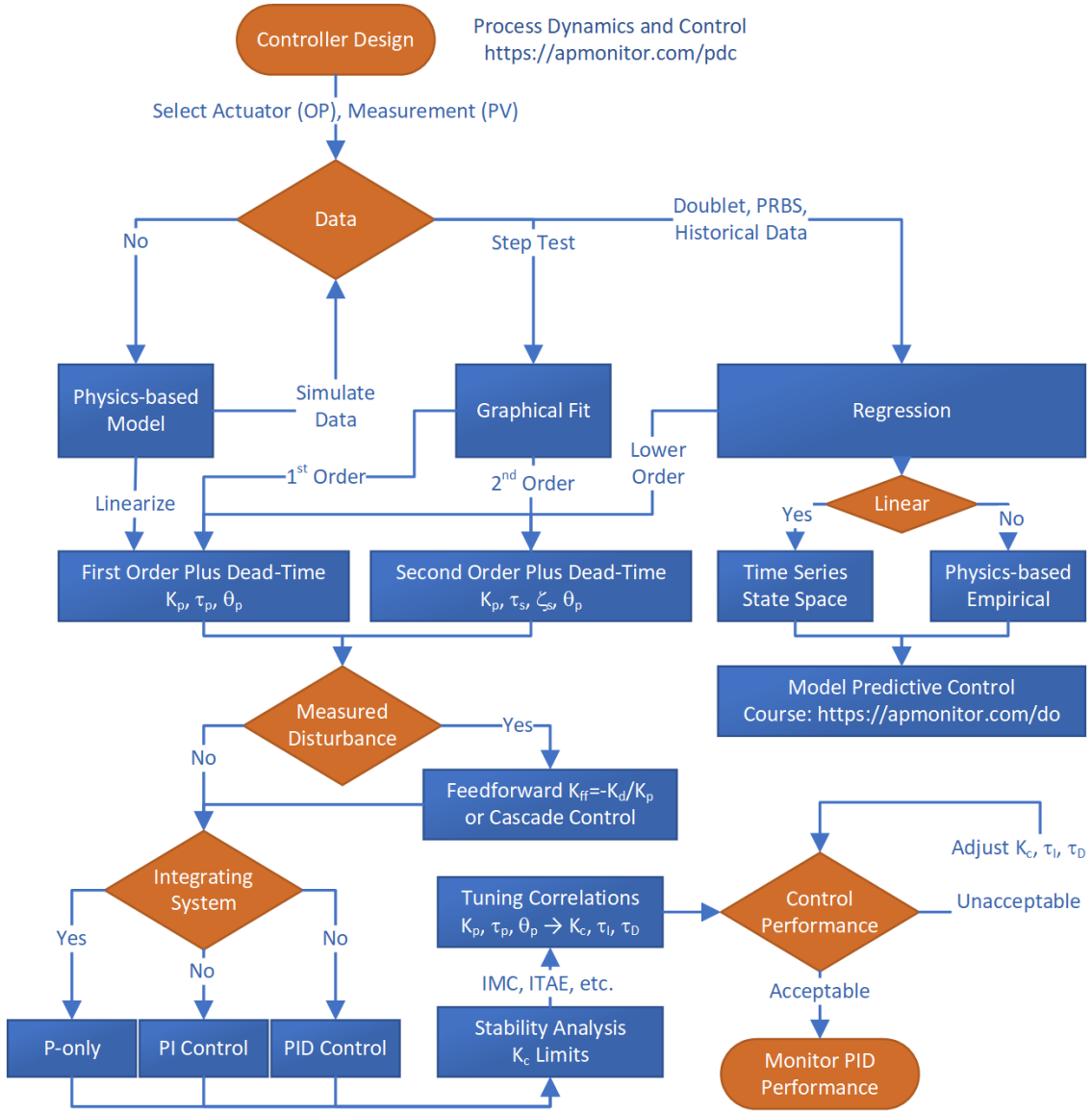
Product Transportation

Oil and Gas Industry

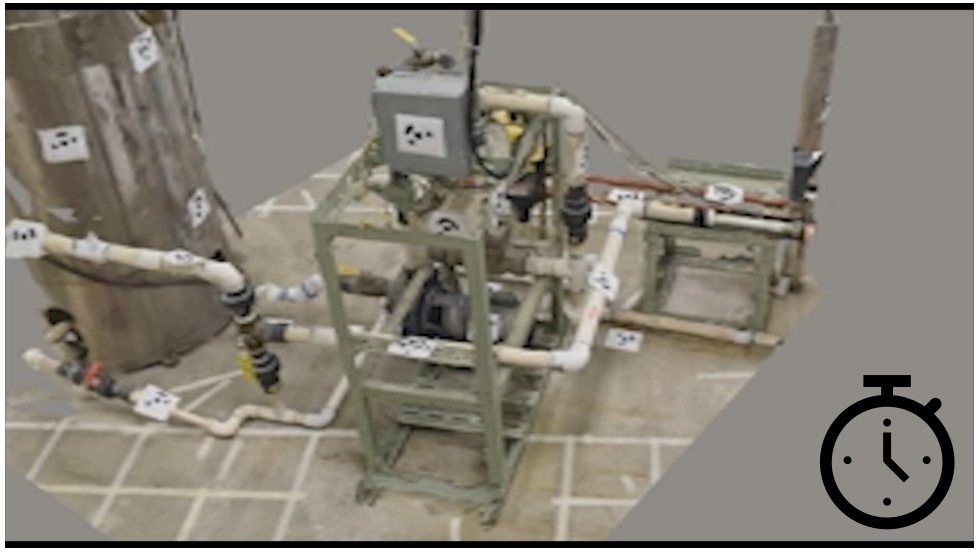
New Topics: Data Science, Analytics, Machine Learning, Cybersecurity, Digitalization

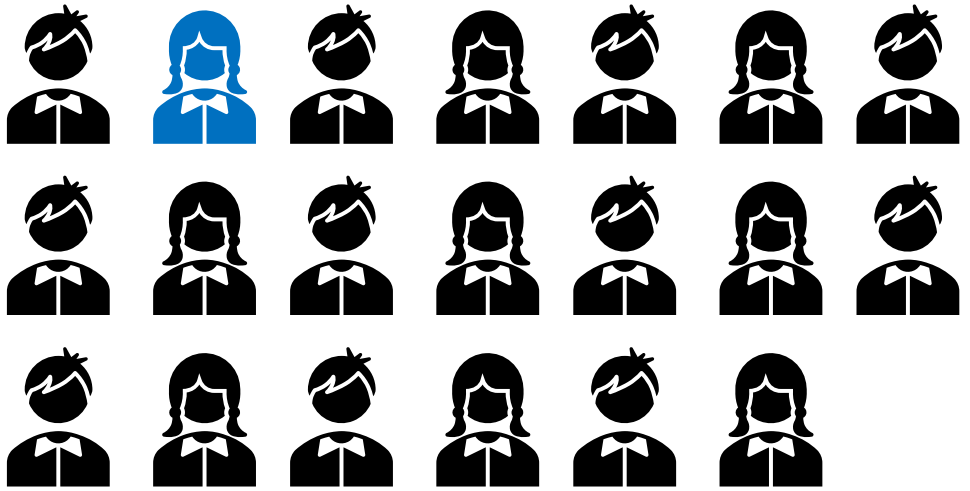
MATLAB, Simulink, and Live Script Resources

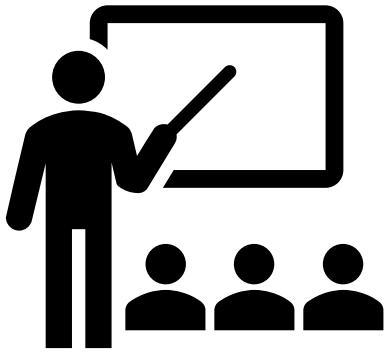
- Dynamics and Control Course
  - Learning Modules (35)
  - Theory: Lesson
  - Simulation: Assignment
  - Lab: Temperature Control
  - Course
    - https://apmonitor.com/pdc
  - MathWorks Modules
    - https://github.com/APMonitor/mdc

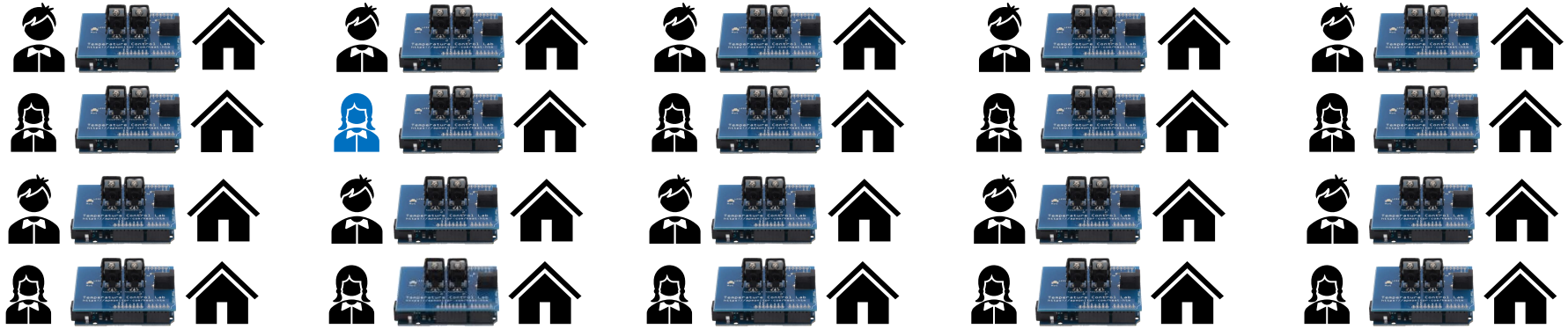


Learning from Instructor Perspective



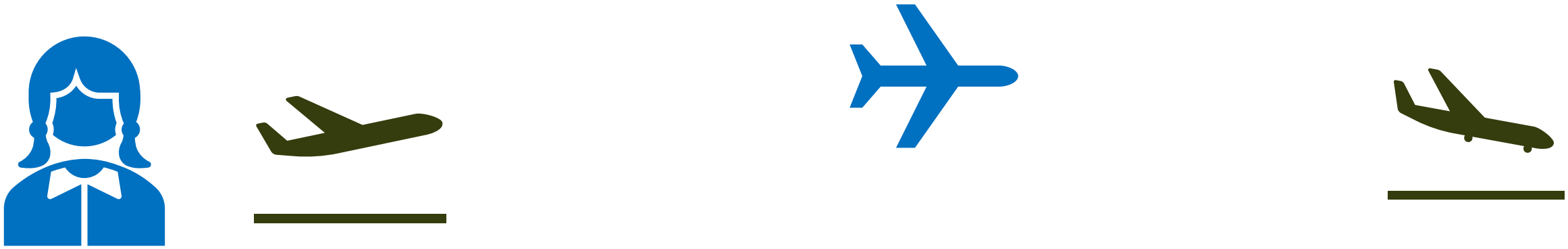


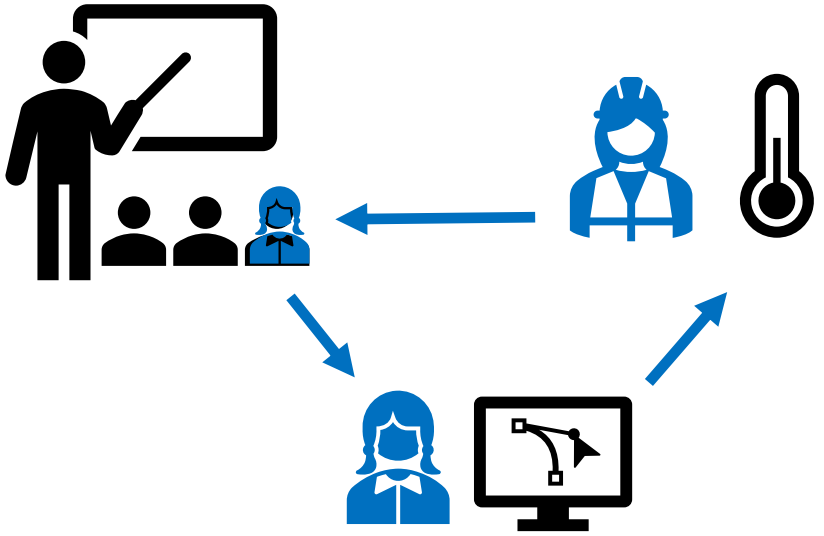




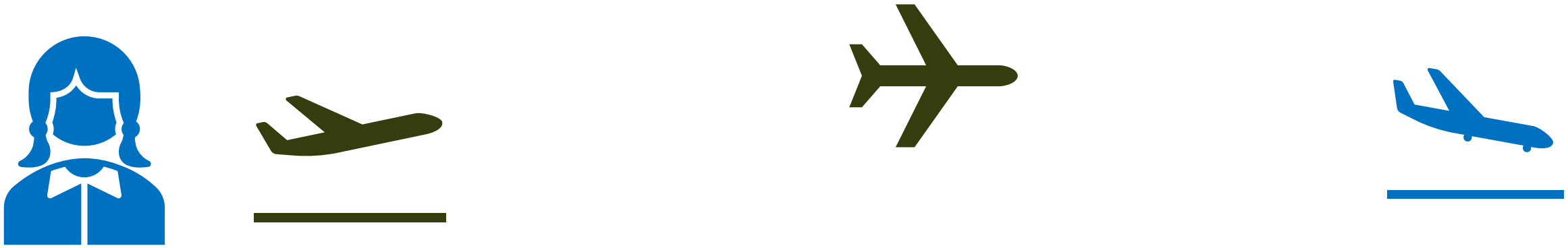
Learning from Student Perspective: Foundations

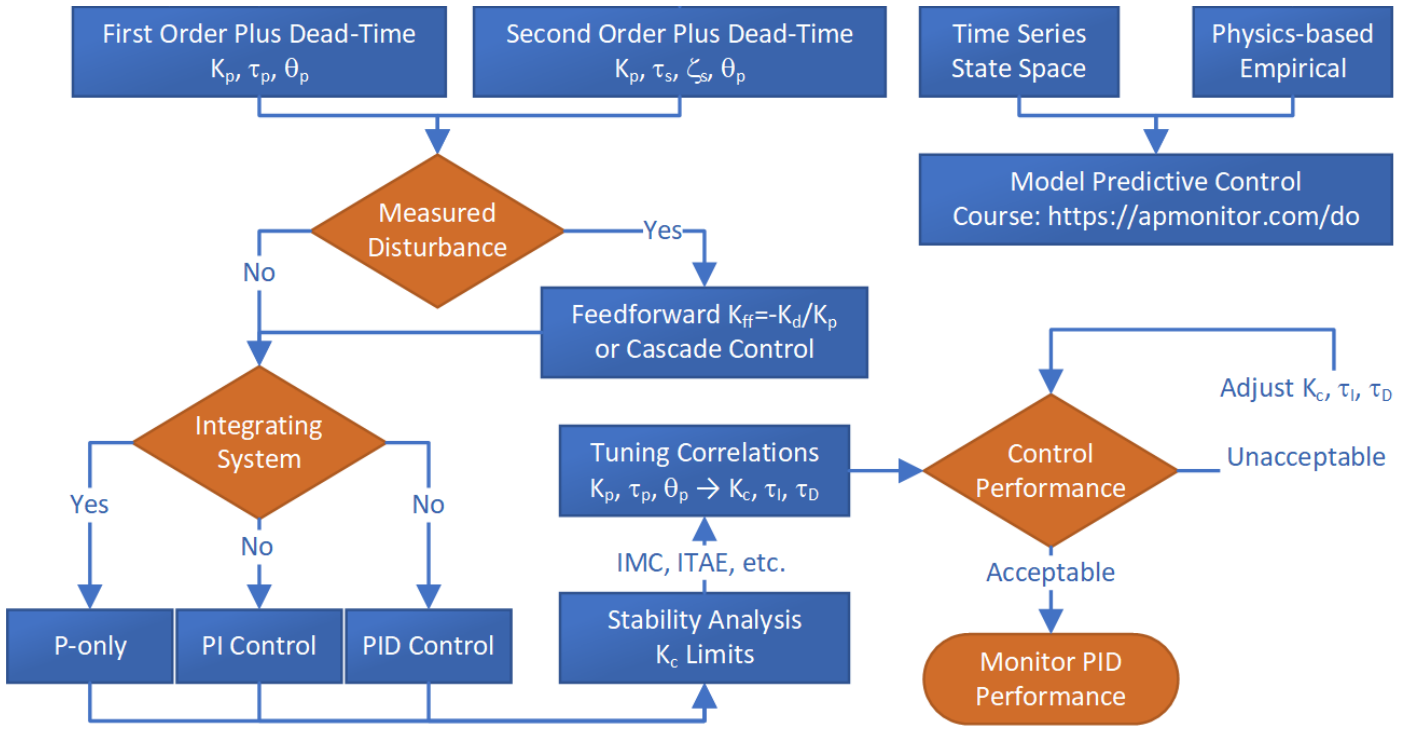
Learning from Student Perspective: Active Learning

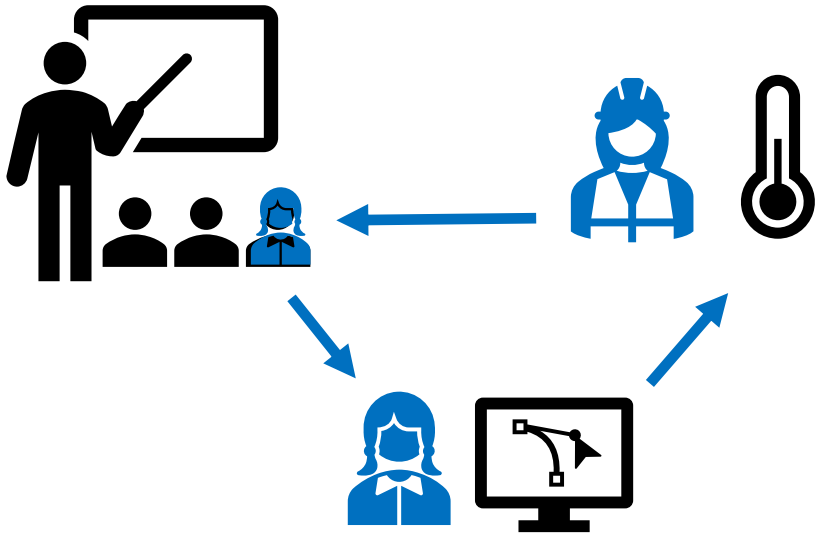


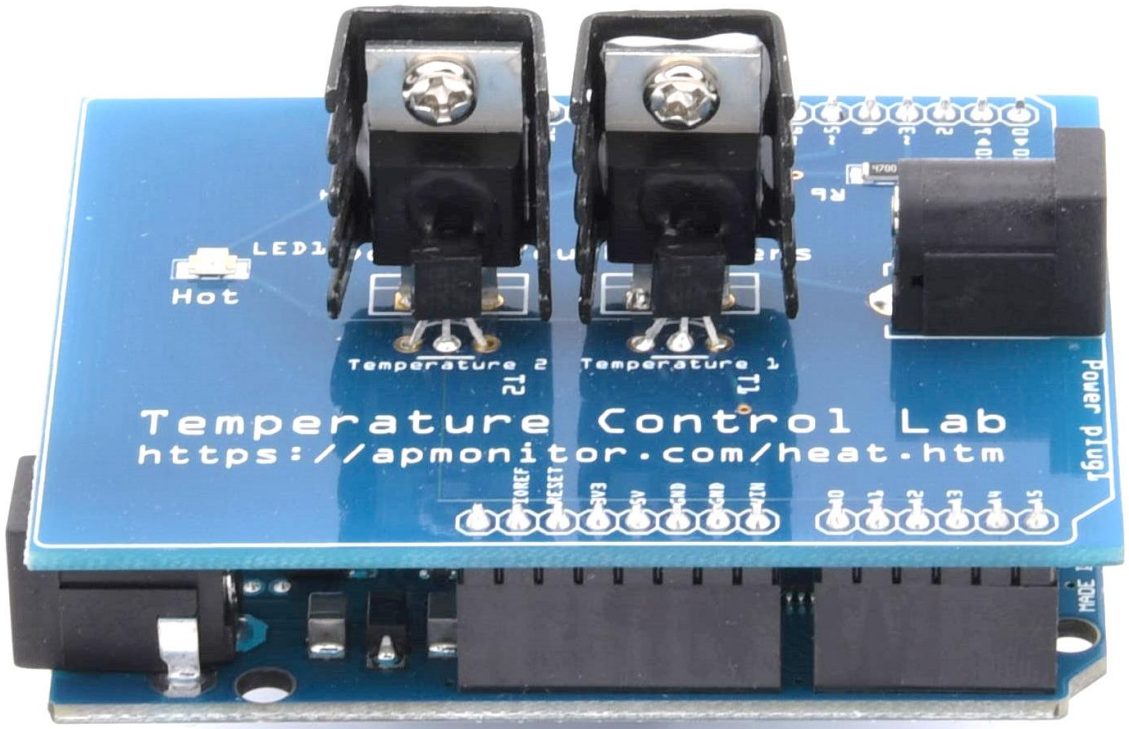


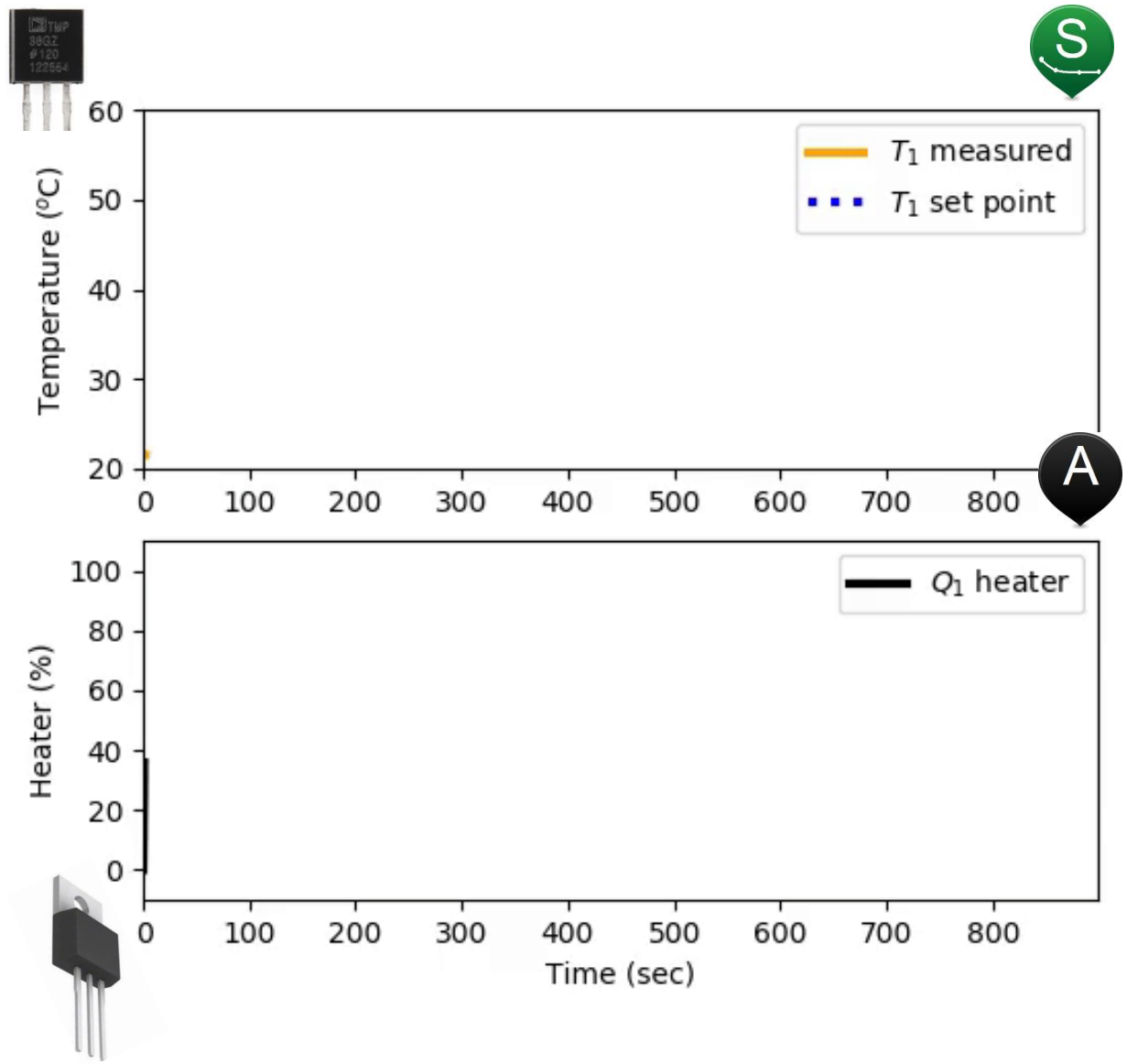
Learning from Student Perspective: Synthesize

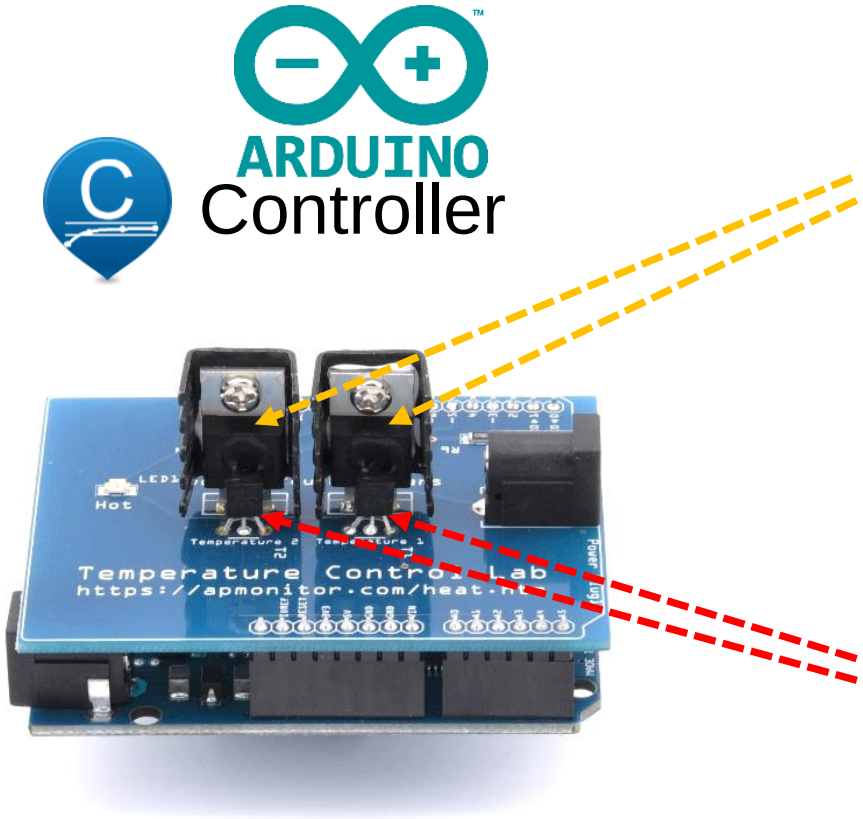




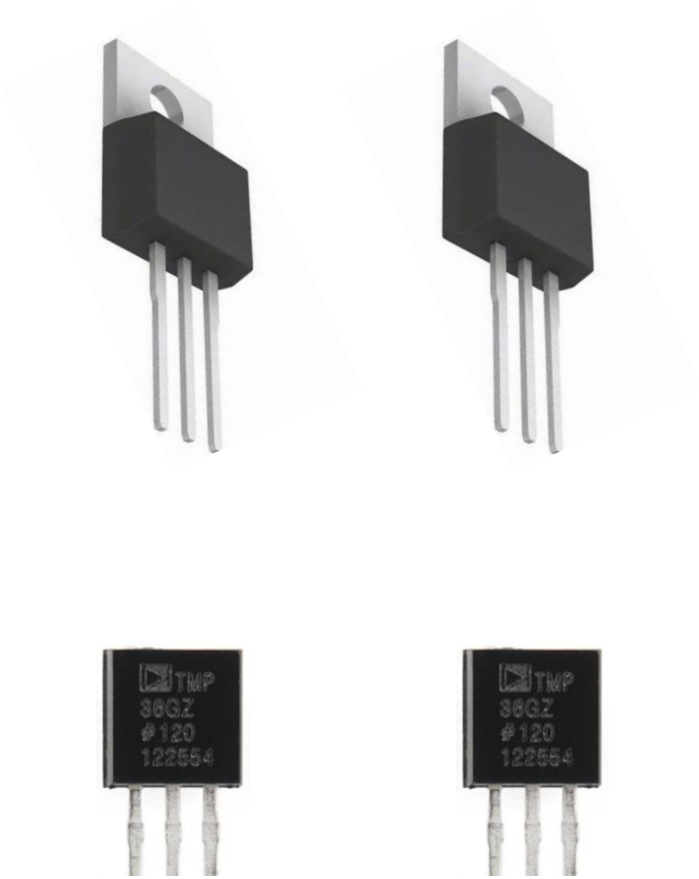



Hot
Temperature 2
Temperature 1
Temperature Control Lab
https://apmonitor.com/heat.htm
Power Plug


Temperature (°C)
60
50
40
30
20
0
100
200
300
400
500
600
700
800
T_1 measured
T_1 set point
Heater (%)
100
80
60
40
20
0
Q_1 heater
Time (sec)



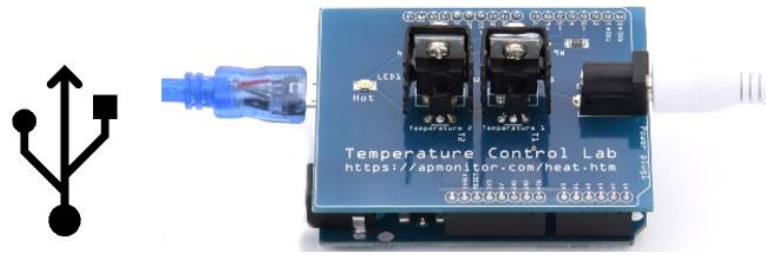
apmonitor.com/heat.htm



Actuator
Heaters

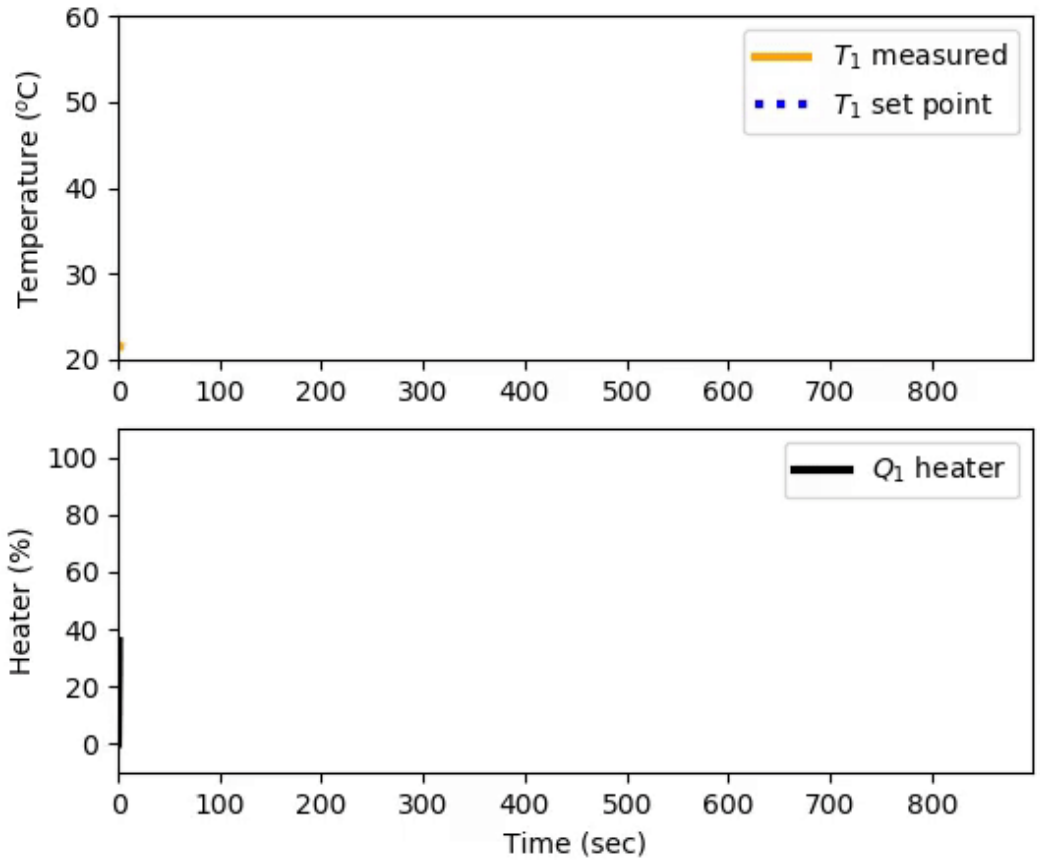
Sensors
T (ºC)

```
lab = tclab; % load TCLab
```



```
lab.LED(80)
```

```
disp(lab.T1)
```

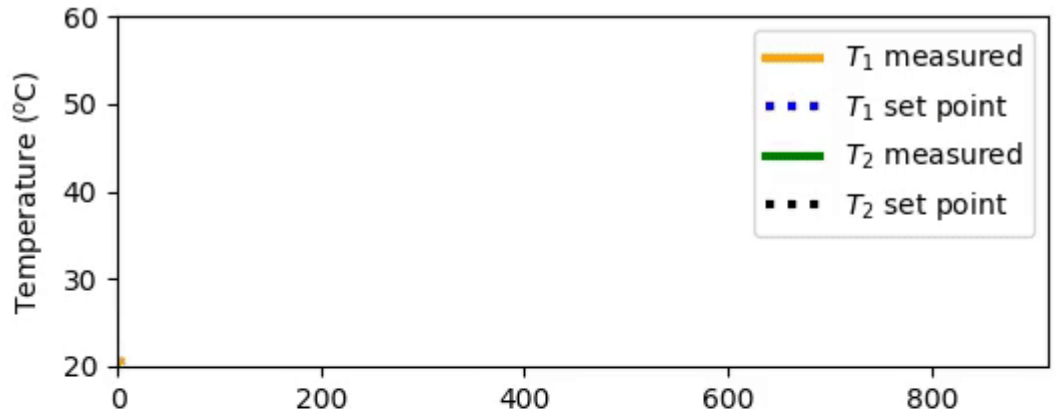


```
lab.Q1(50)
```

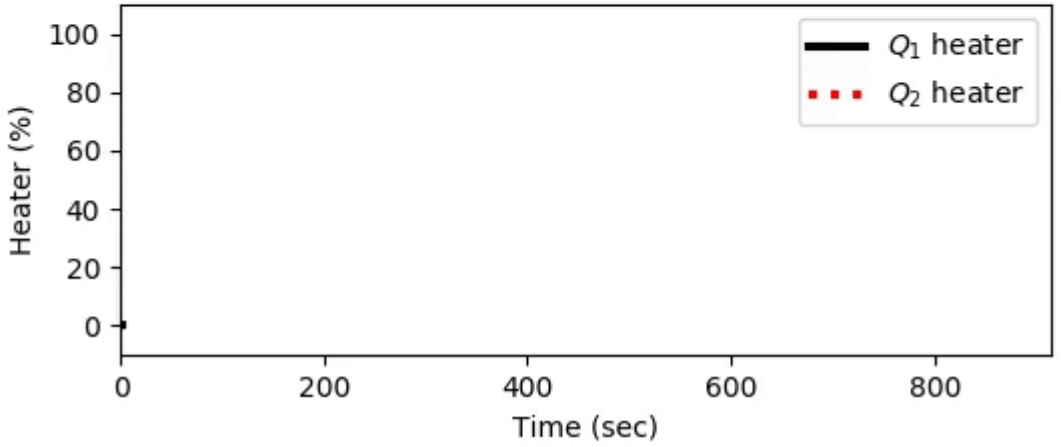
```
lab = tclab; % load TCLab
```

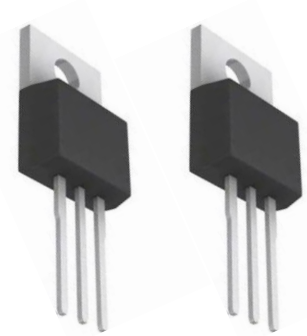
```
lab.LED(80)
```

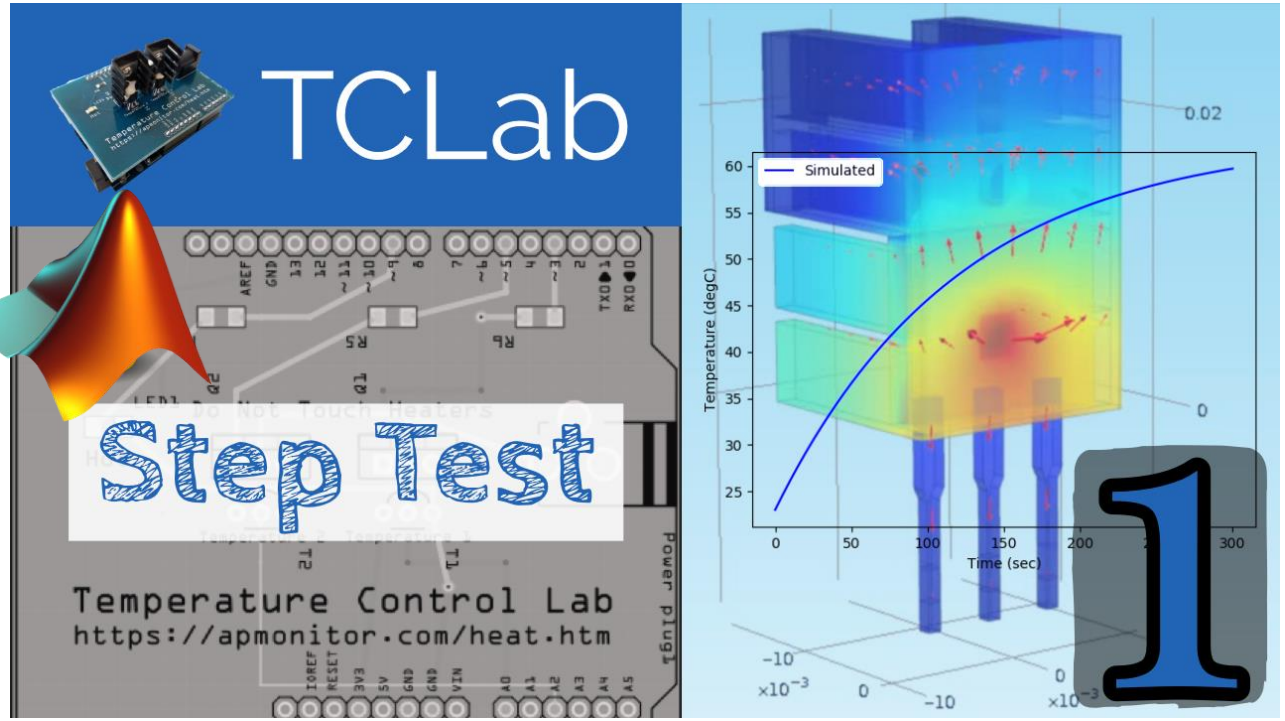

```
disp(lab.T1)
disp(lab.T2)
```



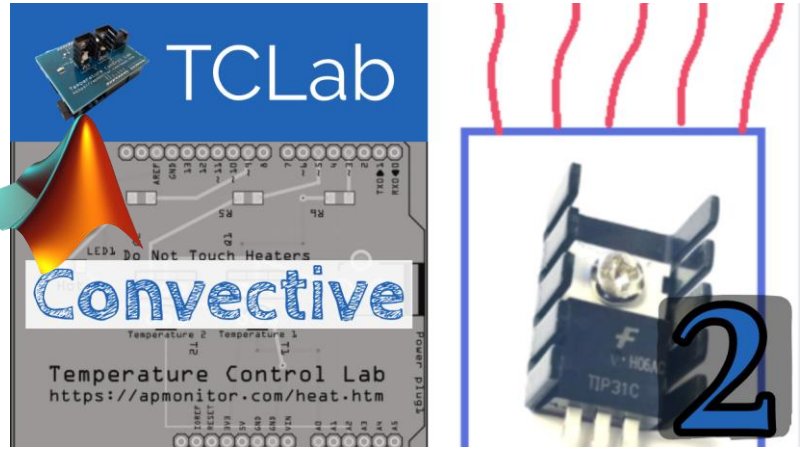
```
lab.Q1(50)
lab.Q2(0)
```



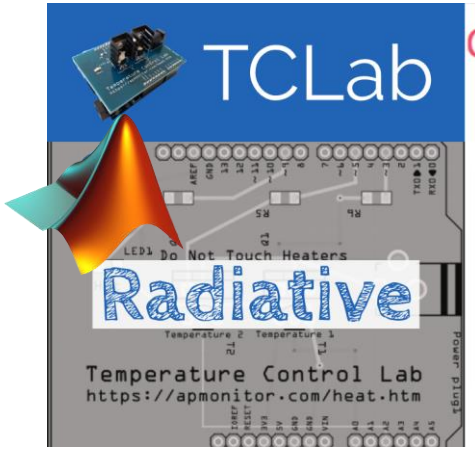


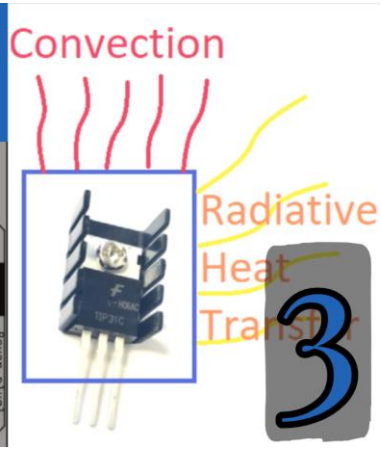

TCLab
Step Test
Temperature Control Lab
https://apmonitor.com/heat.htm
Simulated
Temperature (degC)
Time (sec)
1

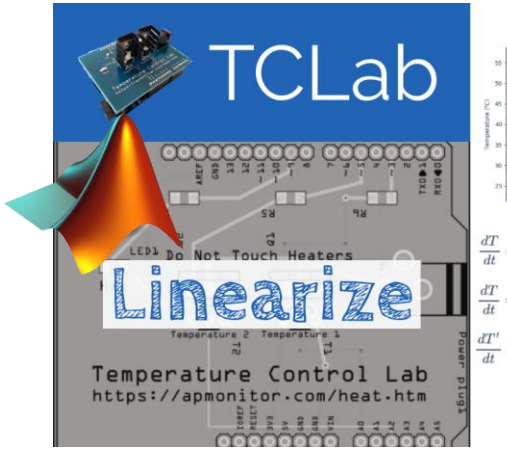

Temperature Control Lab
https://apmonitor.com/heat.htm

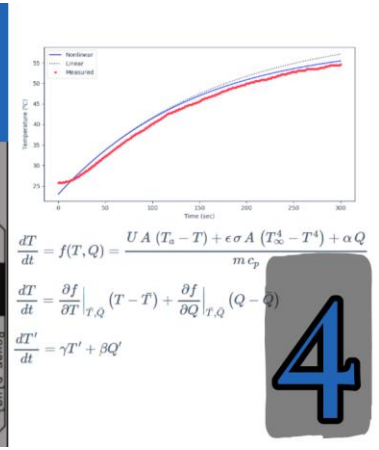

TCLab
Convective
Temperature Control Lab
https://apmonitor.com/heat.htm

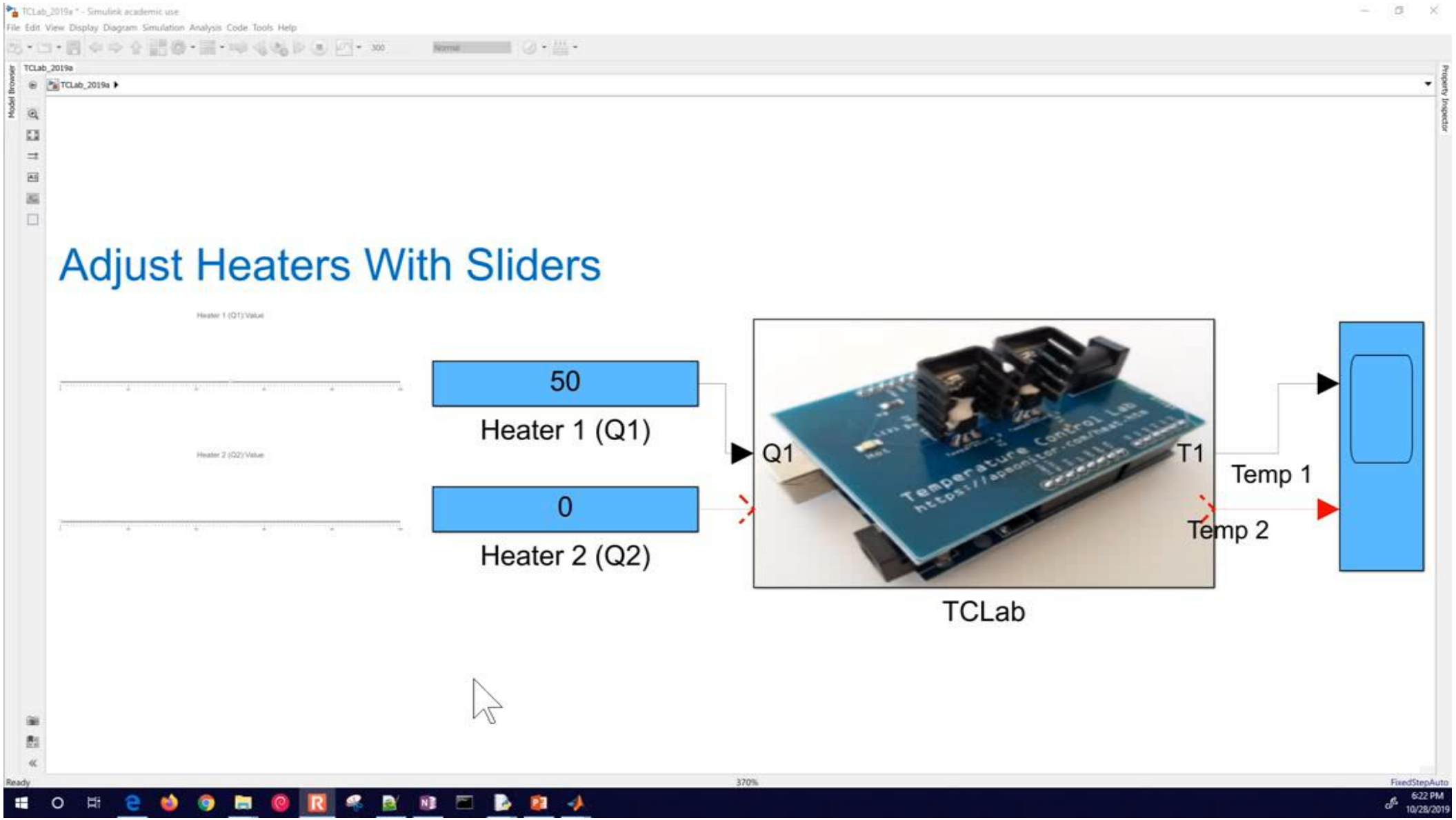
TIP31C
2

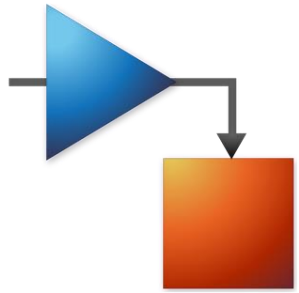

TCLab
Radiative
Temperature Control Lab
https://apmonitor.com/heat.htm

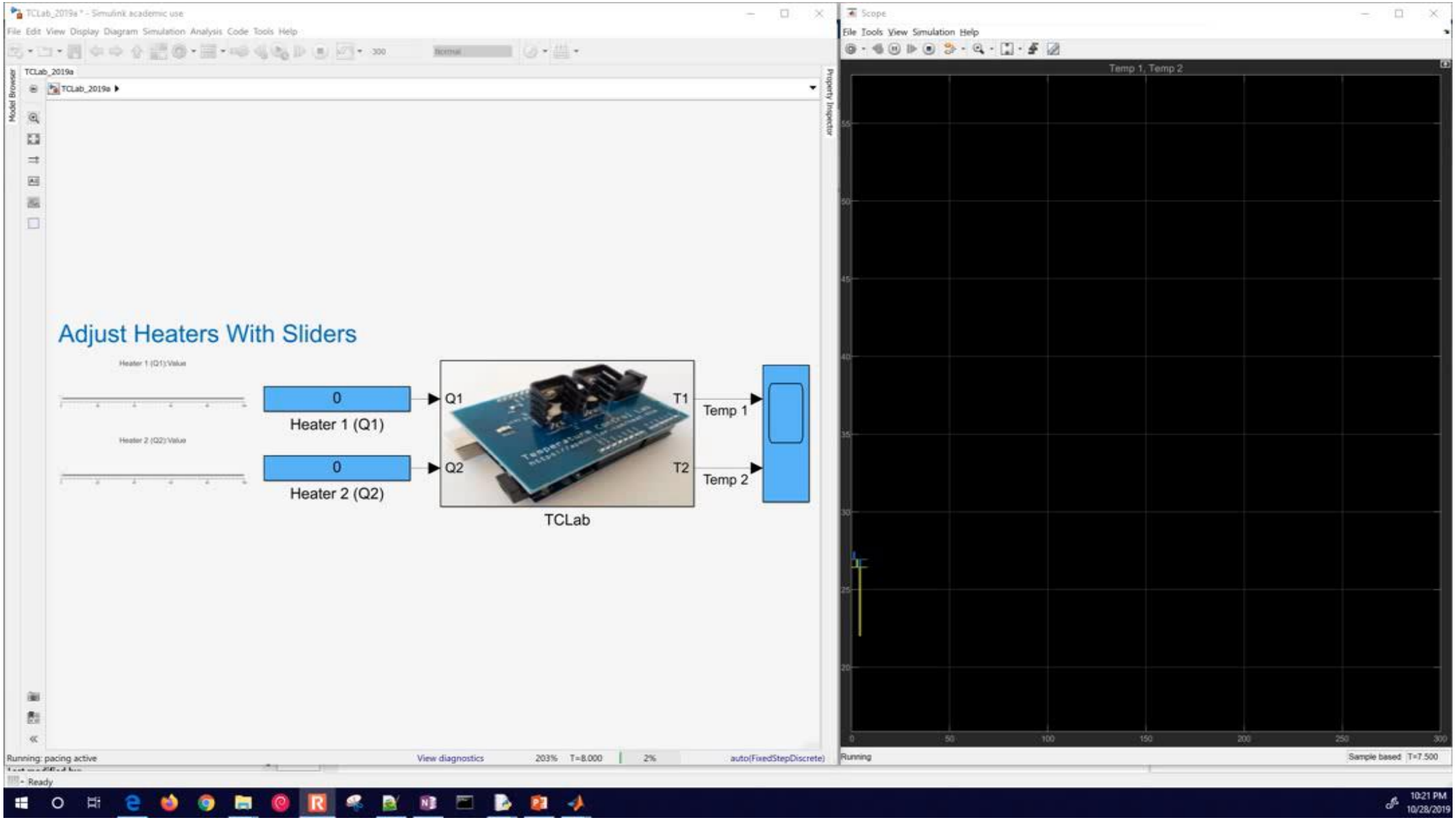

Convection
Radiative
Heat
Transfer
TIP31C
3

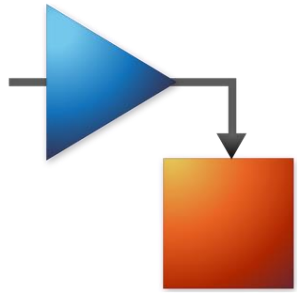

TCLab
Linearize
Temperature Control Lab
https://apmonitor.com/heat.htm

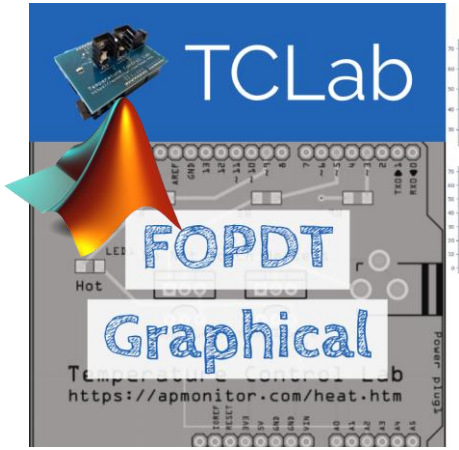

4

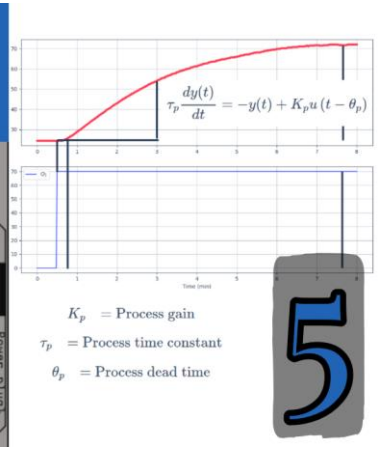

TCLab_2019a * - Simulink academic use
File Edit View Display Diagram Simulation Analysis Code Tools Help
TCLab_2019a
Model Browser
Property Inspector
Adjust Heaters With Sliders
Heater 1 (Q1) Value
50
Heater 1 (Q1)
Heater 2 (Q2) Value
0
Heater 2 (Q2)
Q1
T1
Temp 1
Temp 2
TCLab
Ready
370%
FixedStepAuto
6:22 PM
10/28/2019

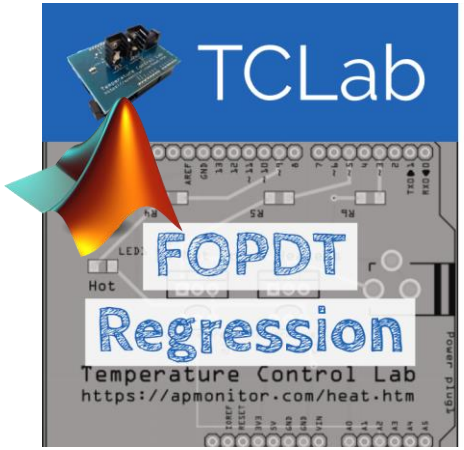


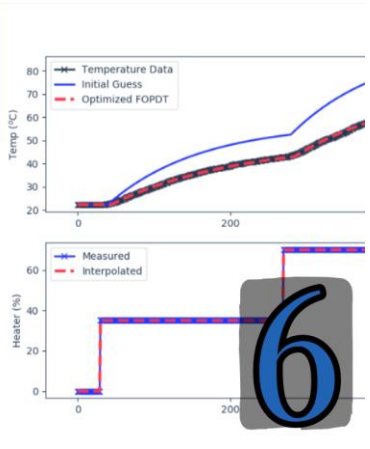

TCLab_2019a * - Simulink academic use
File Edit View Display Diagram Simulation Analysis Code Tools Help
TCLab_2019a
Adjust Heaters With Sliders
Heater 1 (Q1):Value
0
Heater 1 (Q1)
Heater 2 (Q2):Value
0
Heater 2 (Q2)
Q1
Q2
T1
T2
Temp 1
Temp 2
TCLab
Running: pacing active
View diagnostics
203%
T=8.000
2%
auto(FixedStepDiscrete)
Ready
Scope
File Tools View Simulation Help
Temp 1, Temp 2
Running
Sample based
T=7.500
10:21 PM
10/28/2019

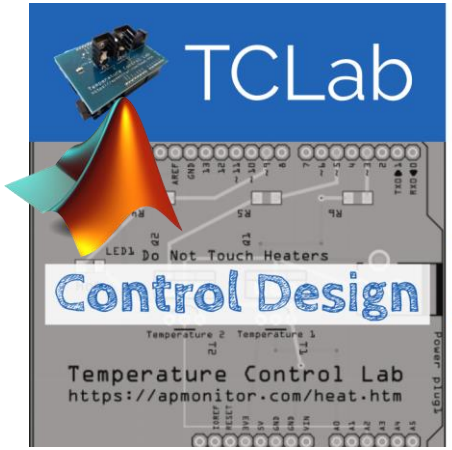


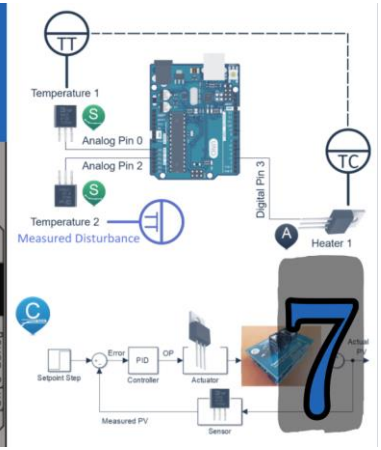

TCLab
FOPDT
Graphical
Temperature Control Lab
https://apmonitor.com/heat.htm


$\tau_p \frac{dy(t)}{dt} = -y(t) + K_p u(t - \theta_p)$
K_p = Process gain
τ_p = Process time constant
θ_p = Process dead time
5

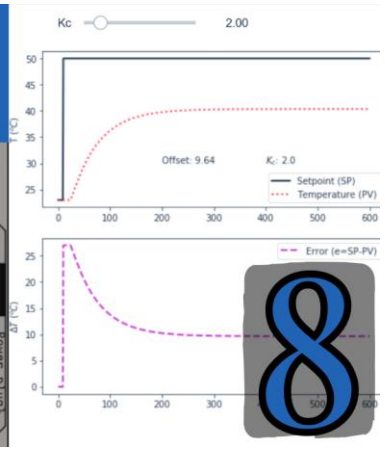

TCLab
FOPDT
Regression
Temperature Control Lab
https://apmonitor.com/heat.htm

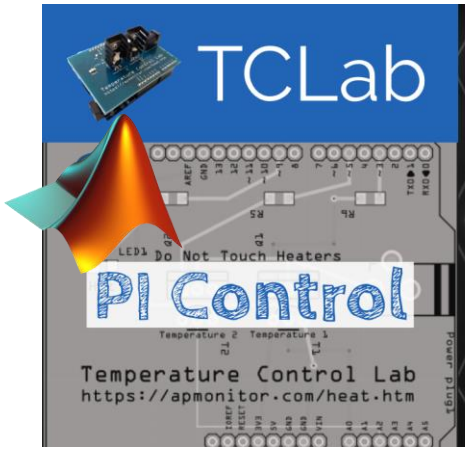

Temperature Data
Initial Guess
Optimized FOPDT
Temp (°C)
Measured
Interpolated
Heater (%)
6

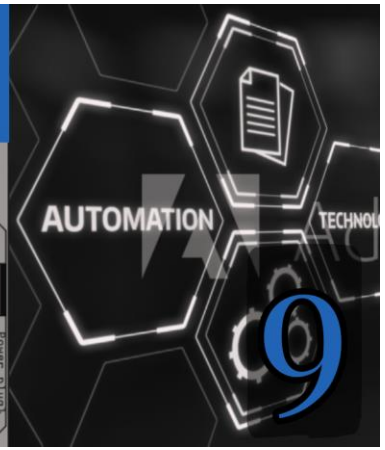

TCLab
Control Design
Temperature Control Lab
https://apmonitor.com/heat.htm

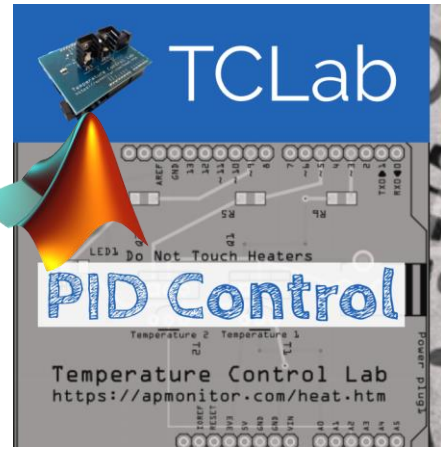

Temperature 1
Analog Pin 0
Analog Pin 2
Temperature 2
Measured Disturbance
Digital Pin 3
Heater 1
7


TCLab
Offset with
P-only Control
Temperature Control Lab
https://apmonitor.com/heat.htm

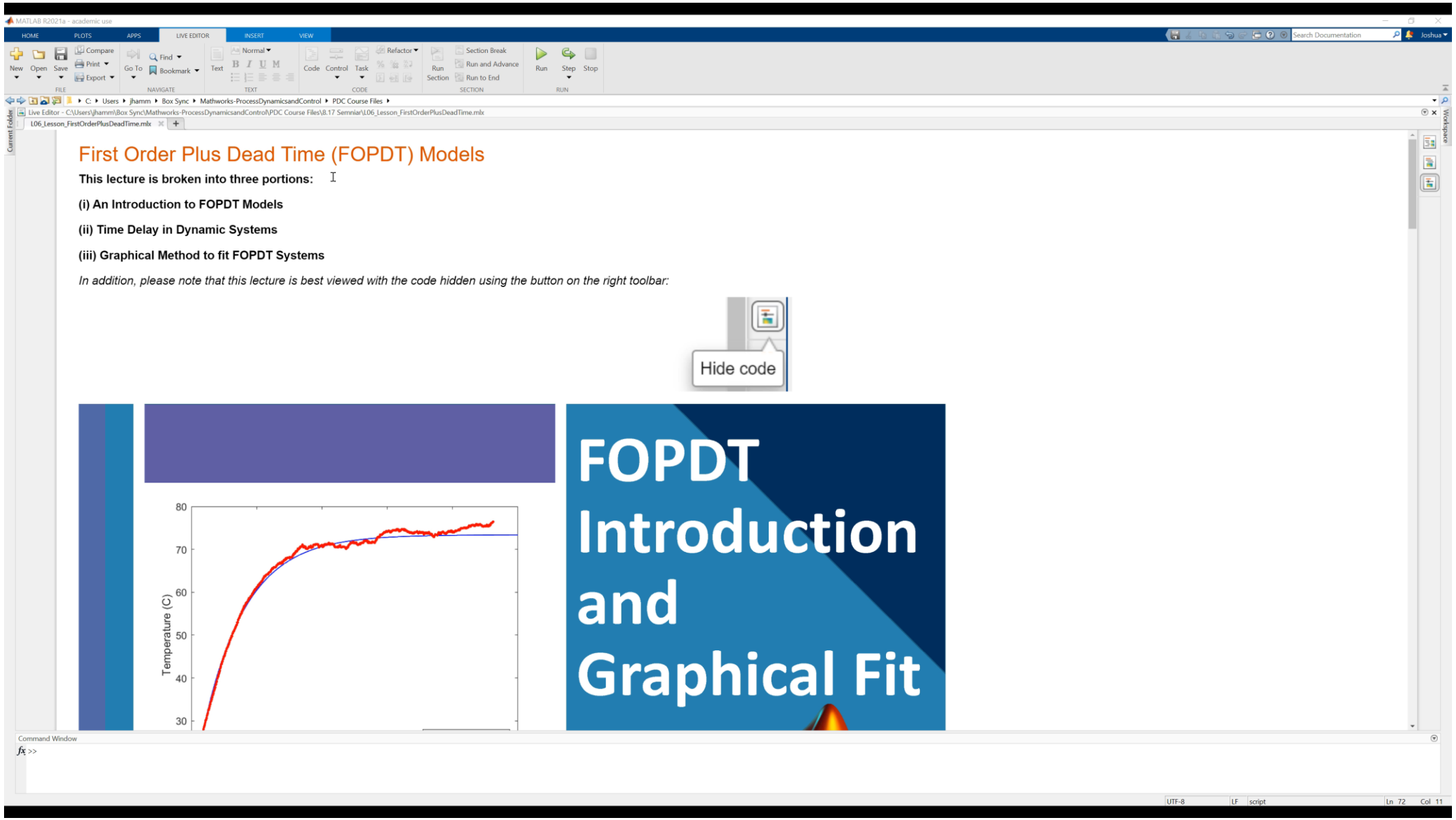

Kc
2.00
Offset: 9.64
Setpoint (SP)
Temperature (PV)
Error (e=SP-PV)
8

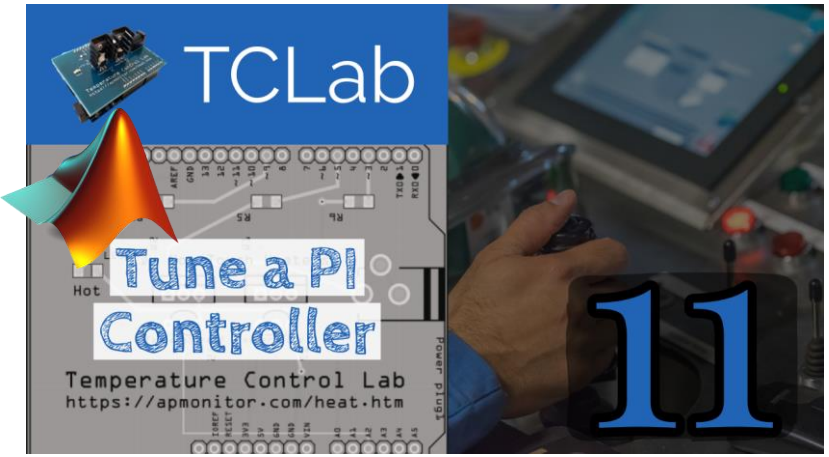

TCLab
PI Control
Temperature Control Lab
https://apmonitor.com/heat.htm

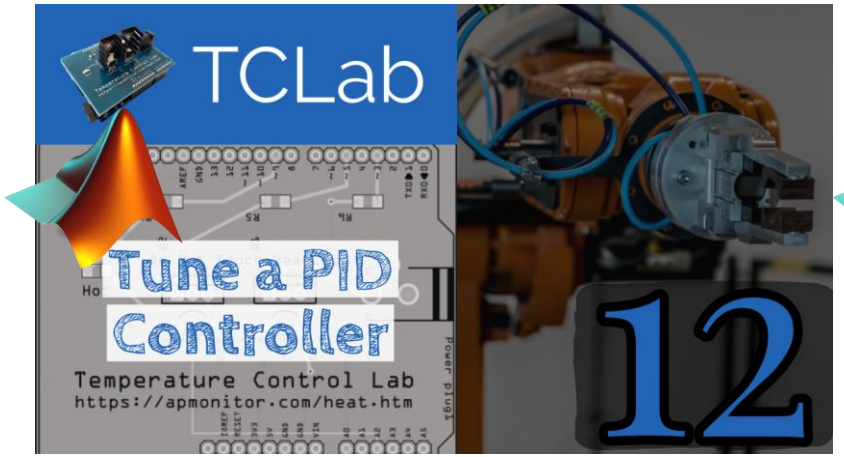

AUTOMATION
9

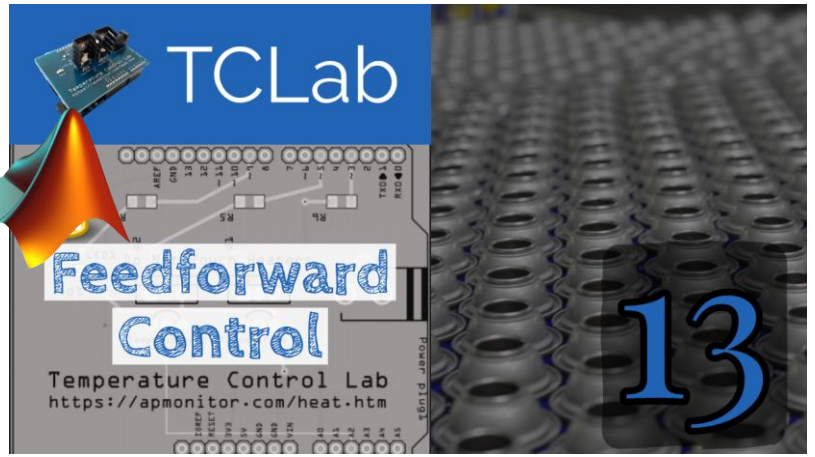

TCLab
PID Control
Temperature Control Lab
https://apmonitor.com/heat.htm

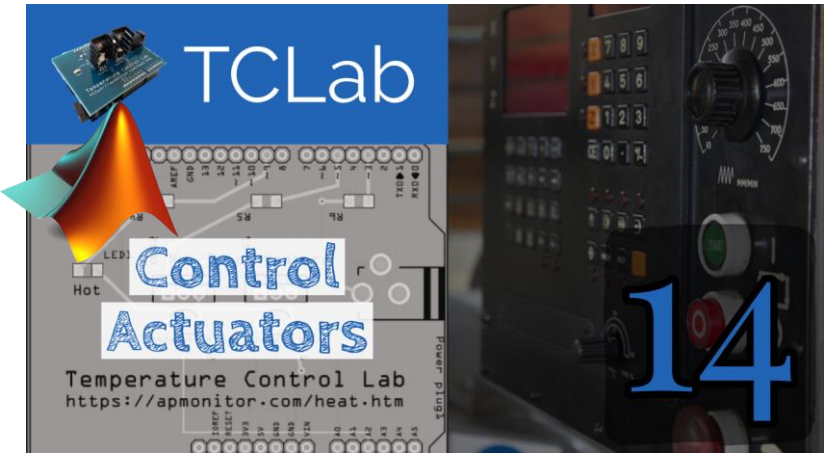

AUTOMA
10

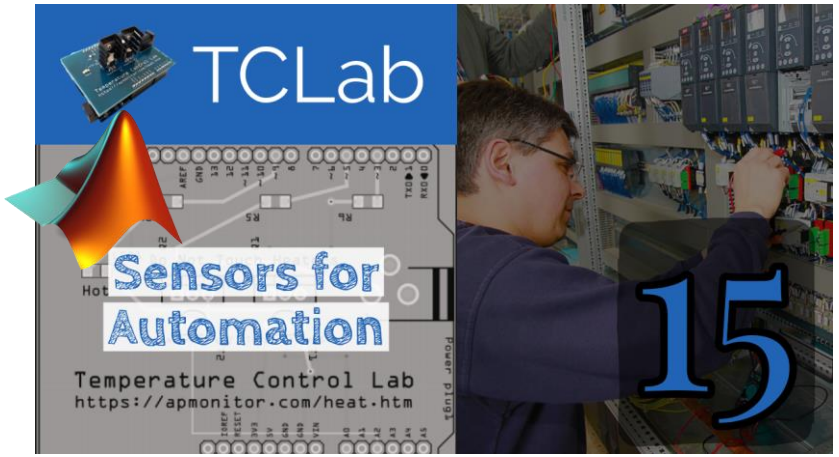

First Order Plus Dead Time (FOPDT) Models
This lecture is broken into three portions:
(i) An Introduction to FOPDT Models
(ii) Time Delay in Dynamic Systems
(iii) Graphical Method to fit FOPDT Systems
In addition, please note that this lecture is best viewed with the code hidden using the button on the right toolbar:
Hide code
Temperature (C)
FOPDT Introduction and Graphical Fit

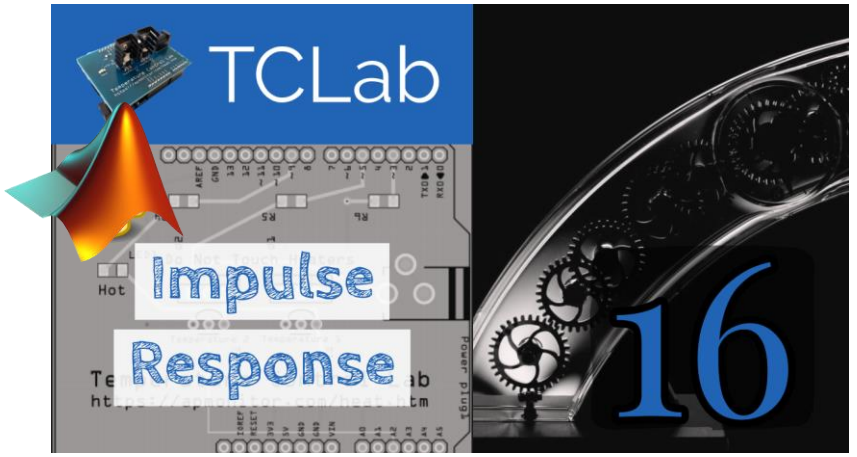

TCLab
Tune a PI Controller
Temperature Control Lab
https://apmonitor.com/heat.htm
11


TCLab
Tune a PID Controller
Temperature Control Lab
https://apmonitor.com/heat.htm
12


TCLab
Feedforward Control
Temperature Control Lab
https://apmonitor.com/heat.htm
13


TCLab
Control Actuators
Temperature Control Lab
https://apmonitor.com/heat.htm
14


TCLab
Sensors for Automation
Temperature Control Lab
https://apmonitor.com/heat.htm
15


TCLab
Impulse Response
16

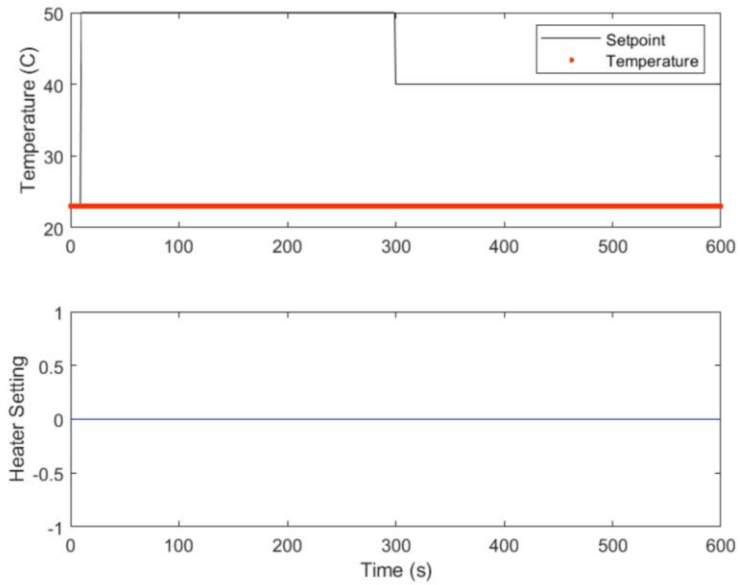
PID Tuning

Objective: Tune a discrete PID controller and test the performance with a series of setpoint changes over 10 min in the sequence from initially, 50°C at 10 sec, and 40°C at 300 sec. Modify the tuning parameters to achieve a low Integral Absolute Error between the measured temperature and the setpoint.

TCLab PID Control Simulator

A simulator is a useful tool to help evaluate changes in tuning before testing on a physical system. Use the PID simulator to find acceptable control performance that minimizes the integral absolute error between the setpoint and measured temperature.

```
Kc =   0 ;
tauI =  180 ;
tauD =   0 ;
pidPlot(Kc, tauI, tauD)
```



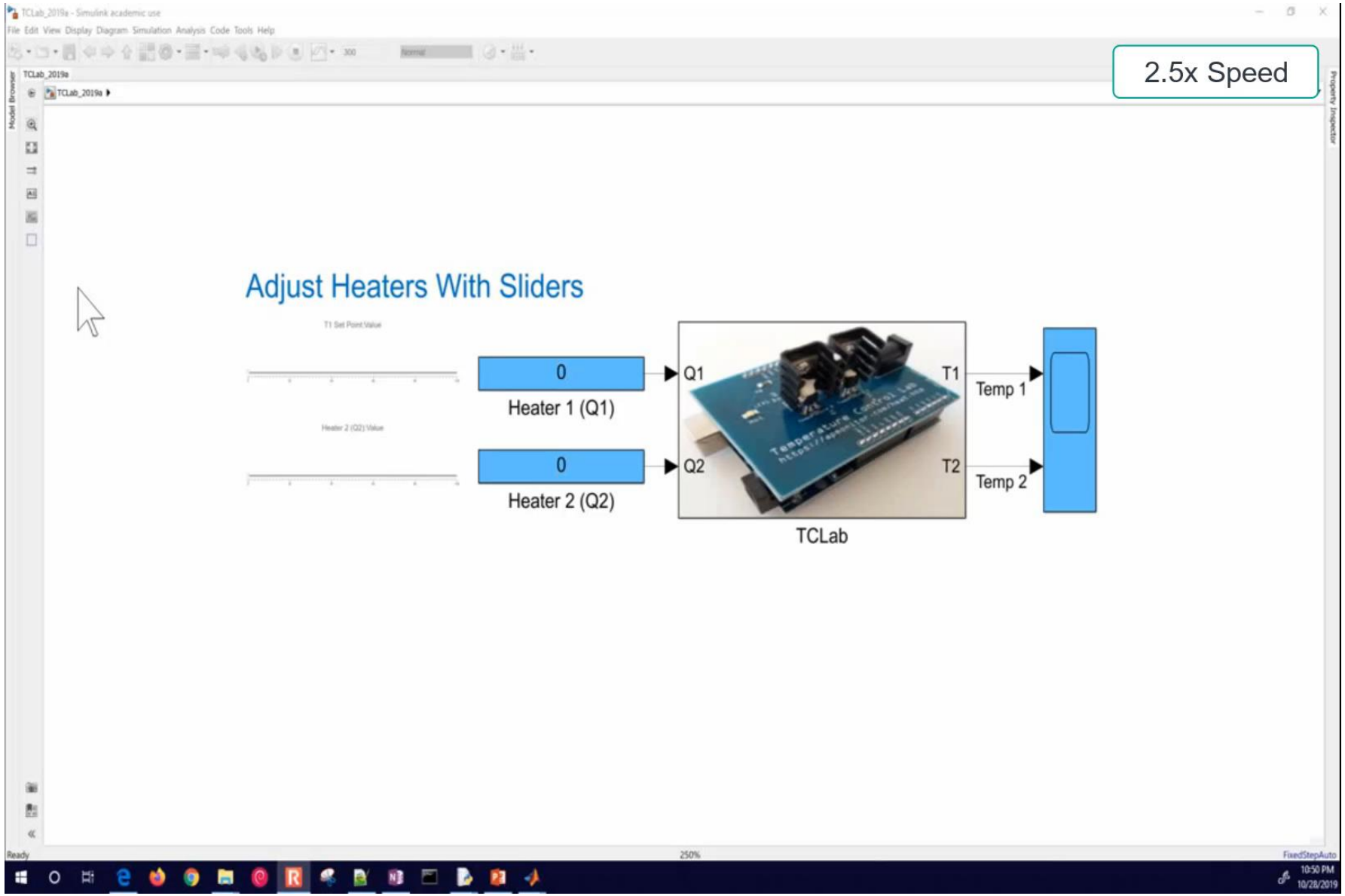
TCLab PID Control Test

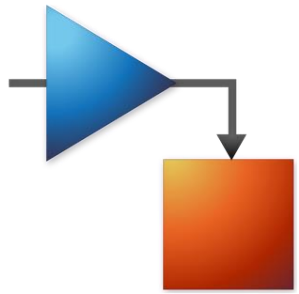
```
viewSolution( )
```

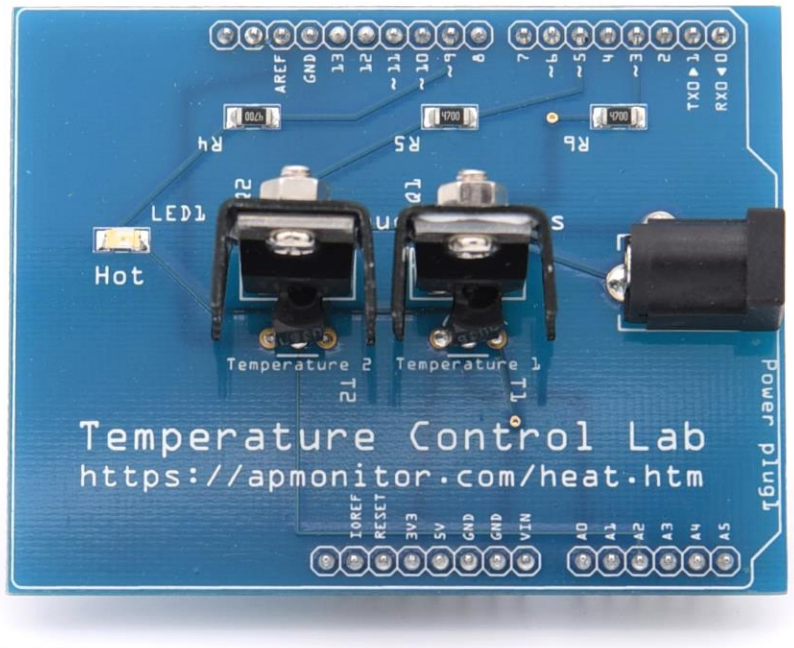
Using the PID Parameters from the simulation, implement PID control in the TCLab with a series of setpoint changes over 10 min in the sequence from 23°C initially, 50°C at 10 sec, and 40°C at 300 sec.

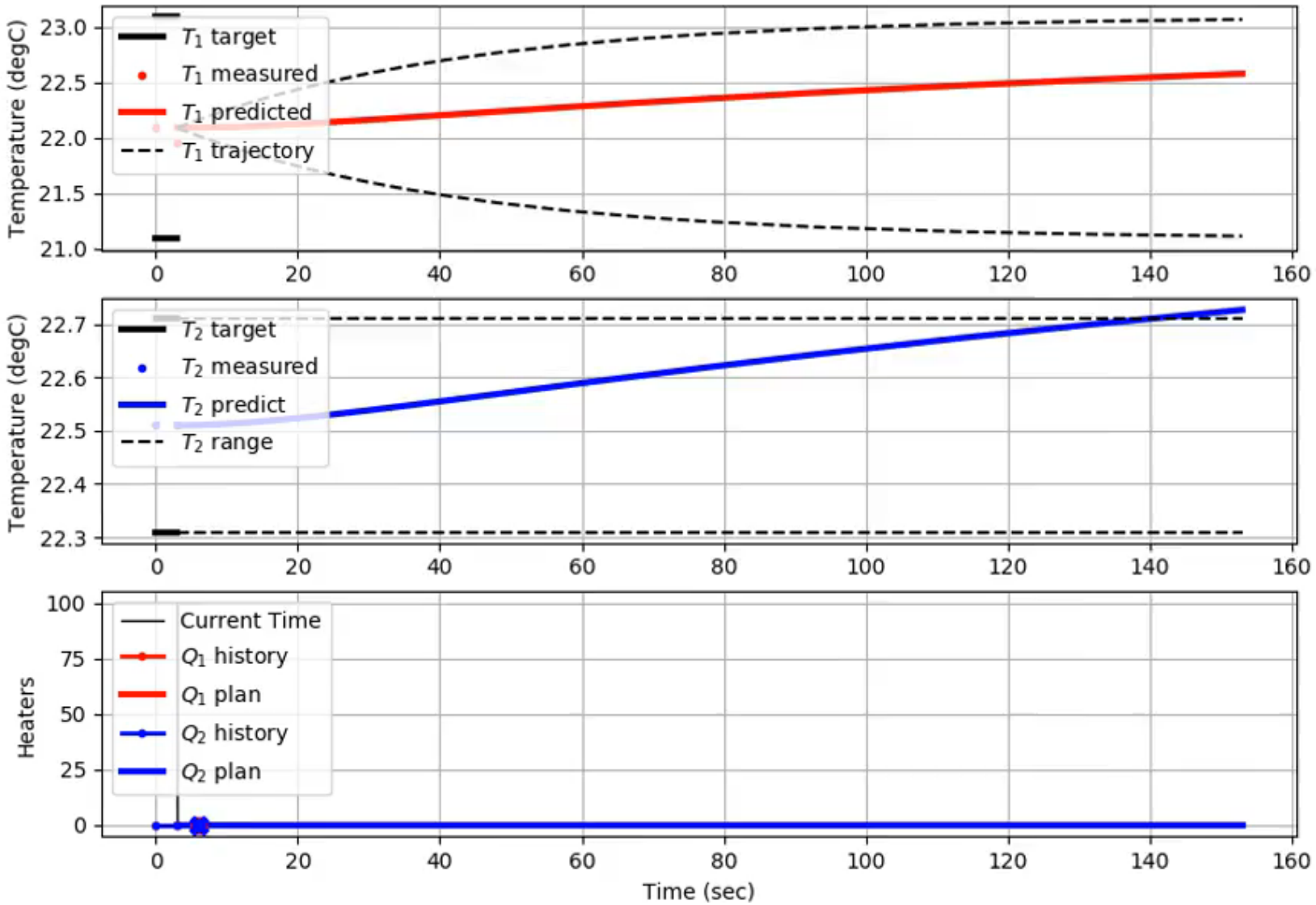
```
params = [Kc tauI tauD];
```

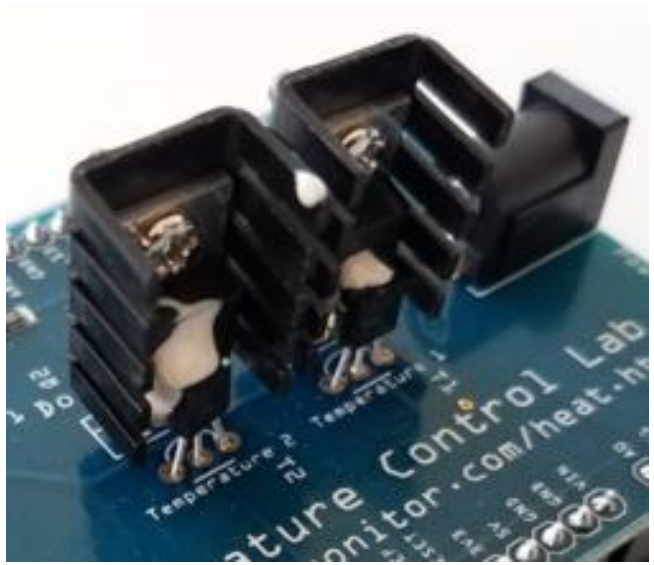
```
'TCLab heaters and LED off'
>> clear lab
>>
```

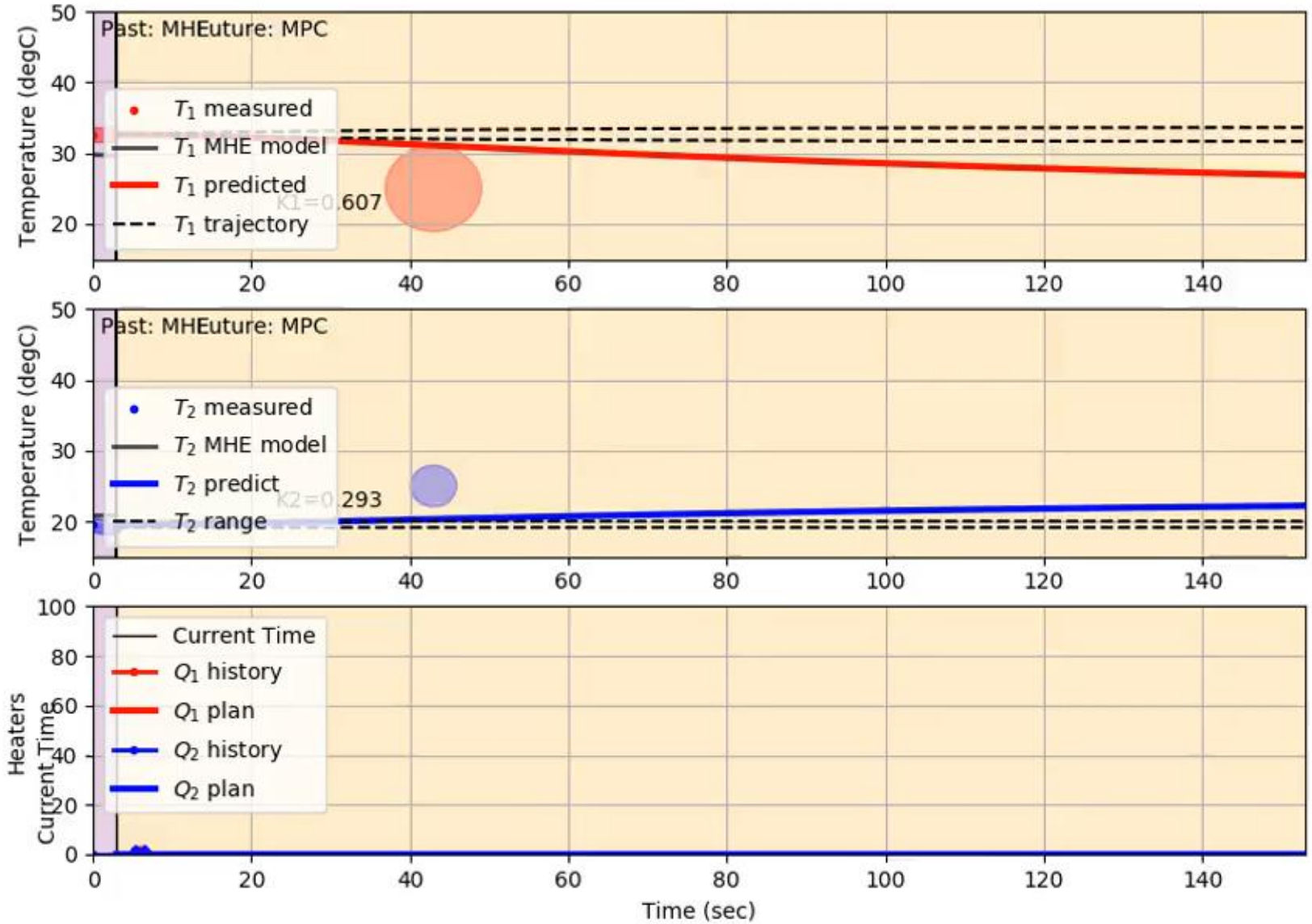

2.5x Speed
Adjust Heaters With Sliders
T1 Set Point Value
0
Heater 1 (Q1)
Heater 2 (Q2) Value
0
Heater 2 (Q2)
Q1
Q2
T1
T2
Temp 1
Temp 2
TCLab




Hot
Temperature 2
Temperature 1
Temperature Control Lab
https://apmonitor.com/heat.htm

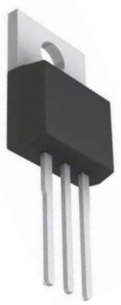

Temperature (degC)
T_1 target
T_1 measured
T_1 predicted
T_1 trajectory
Temperature (degC)
T_2 target
T_2 measured
T_2 predict
T_2 range
Heaters
Current Time
Q_1 history
Q_1 plan
Q_2 history
Q_2 plan
Time (sec)

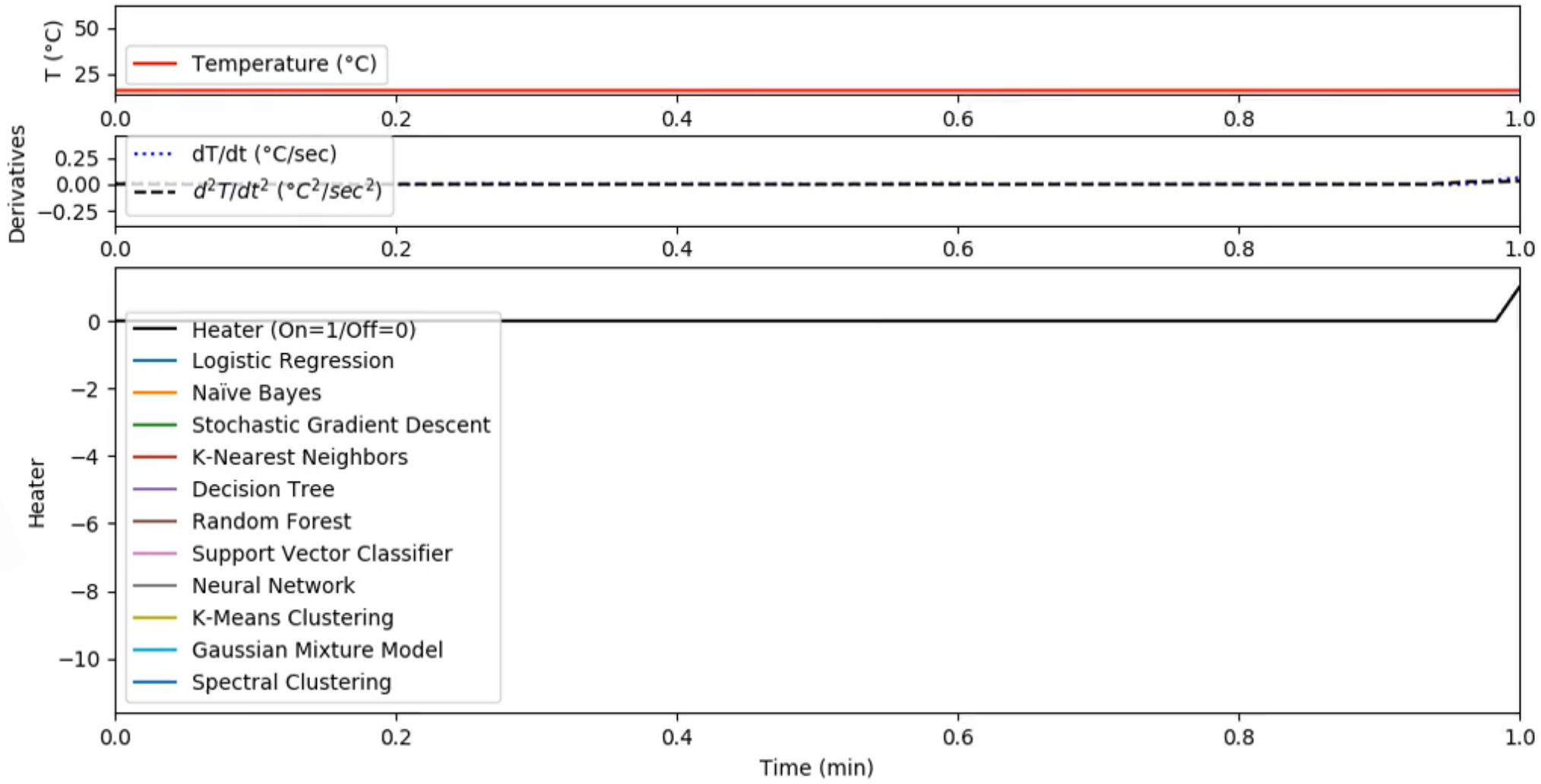



Past: MHEuture: MPC
Temperature (degC)
T_1 measured
T_1 MHE model
T_1 predicted
T_1 trajectory
K1=0.607
Past: MHEuture: MPC
Temperature (degC)
T_2 measured
T_2 MHE model
T_2 predict
T_2 range
K2=0.293
Current Time
Q_1 history
Q_1 plan
Q_2 history
Q_2 plan
Heaters
Current Time
Time (sec)

English
https://github.com/APMonitor/data_science

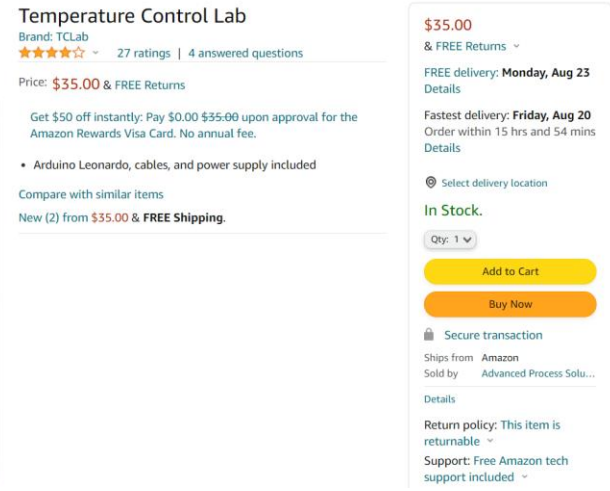
Spanish
https://github.com/APMonitor/ciencia_de_datos




T (°C)
50
25
Temperature (°C)
0.0
0.2
0.4
0.6
0.8
1.0
Derivatives
0.25
0.00
−0.25
dT/dt (°C/sec)
d^2T/dt^2 (°C^2/sec^2)
Heater
0
−2
−4
−6
−8
−10
Heater (On=1/Off=0)
Logistic Regression
Naïve Bayes
Stochastic Gradient Descent
K-Nearest Neighbors
Decision Tree
Random Forest
Support Vector Classifier
Neural Network
K-Means Clustering
Gaussian Mixture Model
Spectral Clustering
Time (min)

TCLab for Instructor Evaluation

- Send email to john.hedengren@byu.edu
  - Name
  - Shipping Address
  - Course Information
- Arrives in 2-3 business days (US)
- Arrives in 6-20 business days (International)
- Student lab kits on Amazon
  - https://amzn.to/2FopcMp

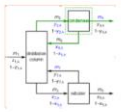
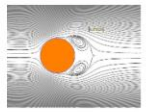
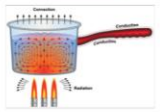
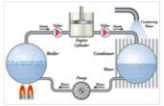
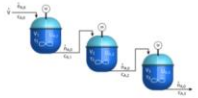
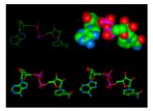
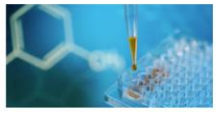


Community Teaching Resources

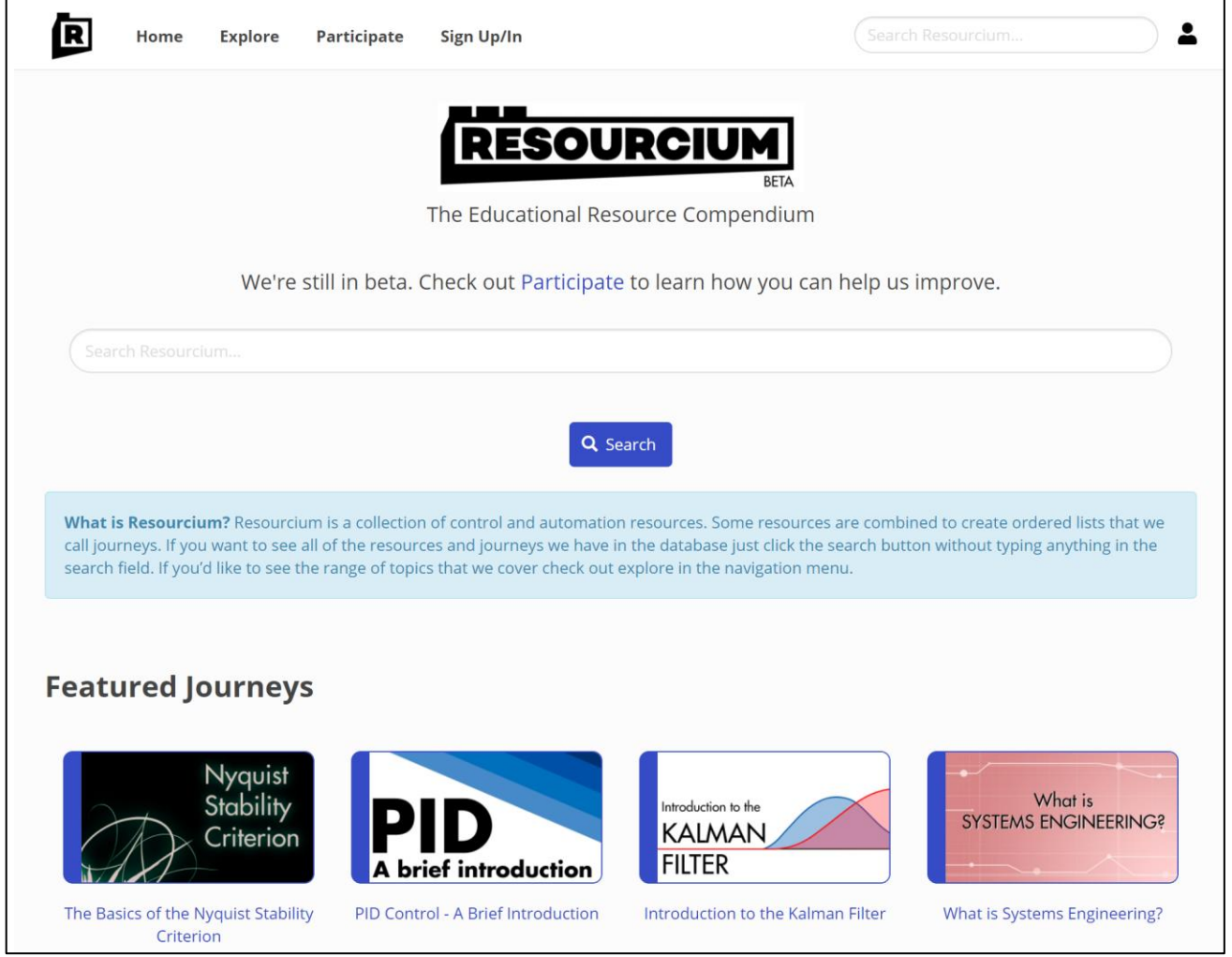
CACHE Teaching Resources

Teaching Resources

Teaching resources for faculty are organized here mostly by courses. These resources include syllabi, schedules, computer-aided tools, interactive simulations, screencasts, concept questions, textbook information, useful links, and in some cases, complete course notes. Send suggestions and corrections to cache@umass.edu.

Intro to Chemical Engineering 	Material/Energy Balances 	Fluid Mechanics 	Heat Transfer 
Process Data Analytics 	Engineering Mathematics 	Thermodynamics 	Kinetics/Reaction Engineering 
Separations/Mass Transfer 	Materials/Polymer Science 	Process/Product Design  Process and Product Design	Process Control 
Molecular Modeling 	Bioengineering 	Safety 	Conventional/Renewable Energy 
Teaching Topics 	Computer Programming 		

Resourcium.org



Thanks to Collaborators

- Many collaborators have enabled this community resource
  - Melda Ulusoy @ MathWorks
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  - Colin Anderson @ BYU
  - Nathanael Nelson @ BYU
  - Jeff Kantor @ Notre Dame
  - Carl Sandrock @ Univ. of Pretoria, proquo ai
  - Paulo Moura Oliviera @ UTAD in Portugal
  - John Anthony Rossiter @ Univ. of Sheffield

Additional Information

References

- Moura Oliveira, P.B., Hedengren, J.D., Solteiro Pires, E.J., Swarm-Based design of Proportional Integral and Derivative Controllers using a Compromise Cost Function: An Arduino Temperature Laboratory Case Study, Special Issue: Algorithms for PID Controller, Algorithms, 13(12), 315, DOI: 10.3390/a13120315, 2020. **Article**
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- Moura Oliveira, P., Hedengren, J., Rossiter, J.A., Introducing Digital Controllers to Undergraduate Students Using the TCLab Arduino Kit, 21st IFAC World Congress, Berlin, Germany, July 12-17, 2020.
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- Park, J., Martin, R.A., Kelly, J.D., Hedengren, J.D., Benchmark Temperature Microcontroller for Process Dynamics and Control, Computers & Chemical Engineering, Special Issue in Honor of Thomas F. Edgar, 135, 6 April 2020. **Preprint** | **Article**
- Rossiter, J.A., Jones, B.L., Pope, S., Hedengren, J.D., Evaluation and Demonstration of Take-Home Laboratory Kit, Invited Session: Demonstration and poster session, 12th IFAC Symposium on Advances in Control Education, July 7-9, 2019, 52 (9), pp. 56-61, Philadelphia, PA, USA. **Preprint**
- Hedengren, J.D., Martin, R.A., Kantor, J.C., Reuel, N., Temperature Control Lab for Dynamics and Control, AIChE Annual Meeting, Orlando, FL, Nov 2019. **Abstract**
- Moura Oliveira, P., Hedengren, J.D., An APMonitor Temperature Lab PID Control Experiment for Undergraduate Students, 24th IEEE Conference on Emerging Technologies and Factory Automation (ETFA), Sep 10th - 13th, 2019, pp. 790-797, Zaragoza, Spain. **Preprint** **Paper**
- Park, J., Patterson, C., Kelly, J., Hedengren, J.D., Closed-Loop PID Re-Tuning in a Digital Twin By Re-Playing Past Setpoint and Load Disturbance Data, AIChE Spring Meeting, New Orleans, LA, April 2019.

Questions and Discussion