TCLab Documentation

Release 0.4.6

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Contents:

CHAPTER 1

TCLab: Temperature Control Laboratory

Master: Development: `TCLab` provides a Python interface to the Temperature Control Lab implemented on an Arduino microcontroller over a USB interface. `TCLab` is implemented as a Python class within the `tclab` package. The `tclab` package also includes:

- `clock` A Python generator for soft real-time implementation of process control algorithms.
- `Historian` A Python class to log results of a process control experiment.
- `Plotter` Provides an historian with real-time plotting within a Jupyter notebook.
- `TCLabModel` An embedded model of the temperature control lab for off-line and faster-than-realtime simulation of process control experiments. No hardware needs to be attached to use `TCLabModel`.

The companion Arduino firmware for device operation is available at the TCLab-Sketch repository.

The Arduino Temperature Control Lab is a modular, portable, and inexpensive solution for hands-on process control learning. Heat output is adjusted by modulating current flow to each of two transistors. Thermistors measure the temperatures. Energy from the transistor output is transferred by conduction and convection to the temperature sensor. The dynamics of heat transfer provide rich opportunities to implement single and multivariable control systems. The lab is integrated into a small PCB shield which can be mounted to any Arduino or Arduino compatible microcontroller.

1.1 Installation

Install using

```
pip install tclab
```

To upgrade an existing installation, use the command

```
pip install tclab --upgrade
```

The development version contains new features, but may be less stable. To install the development version use the command

```
pip install --upgrade https://github.com/jckantor/TCLab/archive/development.zip
```

1.2 Hardware setup

1. Plug a compatible Arduino device (UNO, Leonardo, NHduino) with the lab attached into your computer via the USB connection. Plug the DC power adapter into the wall.
2. (optional) Install Arduino Drivers

   If you are using Windows 10, the Arduino board should connect without additional drivers required.

   For Arduino clones using the CH340G, CH34G or CH34X chipset you may need additional drivers. Only install these if you see a message saying "No Arduino device found." when connecting.

   - macOS.
   - Windows.
3. (optional) Install Arduino Firmware

   `TCLab` requires the one-time installation of custom firmware on an Arduino device. If it hasn't been pre-installed, the necessary firmware and instructions are available from the TCLab-Sketch repository.

1.3 Checking that everything works

Execute the following code

```
import tclab
with tclab.TCLab() as lab:
    print(lab.T1)
```

If everything has worked, you should see the following output message

```
Connecting to TCLab
TCLab Firmware Version 1.2.1 on NHduino connected to port XXXX
21.54
TCLab disconnected successfully.
```

The number returned is the temperature of sensor T1 in °C.

1.4 Troubleshooting

If something went wrong in the above process, refer to our troubleshooting guide in TROUBLESHOOTING.md.

1.5 Next Steps

The notebook directory provides examples on how to use the TCLab module. The latest documentation is available at Read the Docs.

1.6 Course Websites

Additional information, instructional videos, and Jupyter notebook examples are available at the following course websites.

- Arduino temperature control lab page on the BYU Process Dynamics and Control course website.
- CBE 30338 for the Notre Dame Chemical Process Control course website.
- Dynamics and Control for notebooks developed at the University of Pretoria.

CHAPTER 2

Diagnose and Troubleshooting

The library supplies a simple way to diagnose errors with the TCLab device in a function called `diagnose`, which is called as follows:

```
from tclab import diagnose

diagnose()
```

This function will attempt to find the Arduino device, make a connection and attempt to exercise the full command set of the device to make sure everything is working correctly.

The above code can also be run from a terminal by using

```
python -m tclab
```

2.1 Problems and solutions

2.1.1 No Arduino device found

1. First confirm that the device is correctly plugged in.
2. Plug it out and back in
3. Try a different port.
4. If no configuration has worked, you may need to install drivers (see below)

2.1.2 Access denied

A device has been found but you get an error which mentions "Access denied".

If you are using Windows, this can be resolved by going to Device Manager and selecting a different port for the device. If the device shows up incorrecty in the Device Manager, you may need to install drivers (see below)

2.1.3 Setting heaters makes temperature jump

You may have plugged both of the USB leads into one computer. The device works best when the barrel-ended jack is plugged into a separate power supply or a different computer.

2.1.4 Setting heater to 100 doesn't raise temperature

You may only have plugged in your device into your computer using one cable. Your device needs to be plugged in to your computer *and* requires another connection to a power supply to power the heaters.

2.2 Software fixes

2.2.1 Install Drivers

If you are using Windows 10, the Arduino board should connect without additional drivers required.

For Arduino clones using the CH340G, CH34G or CH34X chipset you may need additional drivers. Only install these if you see a message saying "No Arduino device found." when connecting.

- macOS
- Windows

2.2.2 Update Firmware

It is usually best to use the most recent version of the Arduino firmware, available from the TCLab-Sketch repository.

2.2.3 Update TCLab python library

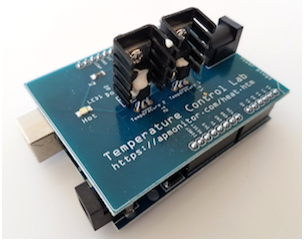
If you find that the code supplied in the documentation gives errors about functions not being found, or if you installed tclab a long time ago, you need to update the TCLab library. This can be done with the command

```
pip install --update tclab
```

CHAPTER 3

TCLab Overview

The `tclab` package provides a set of Python tools for interfacing with the BYU Temperature Control Laboratory. The Temperature Control Laboratory consists of two heaters and two temperature sensors mounted on an Arduino microcontroller board. Together, the `tclab` package and the Temperature Control Laboratory provide a low-cost experimental platform for implementing algorithms commonly used for process control.

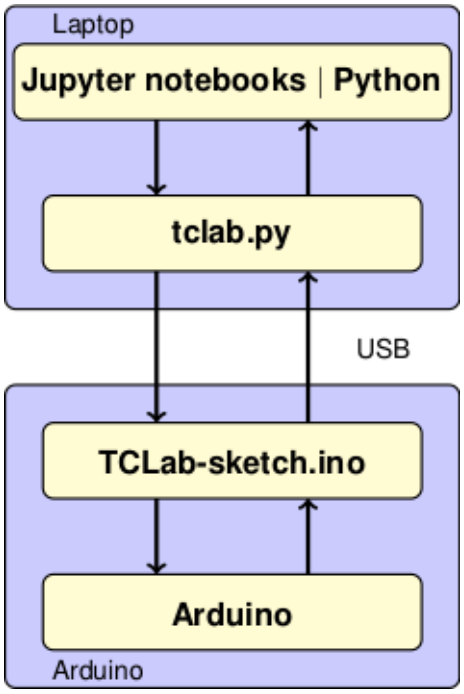


3.1 TCLab Architecture

The `tclab` package is intended to be used as a teaching tool. The package provides high-level access to sensors, heaters, a pseudo-realtime clock. The package includes the following Python classes and functions:

- `TCLab()` providing access to the Temperature Control Laboratory hardware.
- `TCLabModel()` providing access to a simulation of the Temperature Control Laboratory hardware.
- `clock` for synchronizing with a real time clock.
- `Historian` for data logging.
- `Plotter` for realtime plotting.

Using these Python tools, students can create Jupyter notebooks and python codes covering a wide range of topics in process control.



- **tclab.py:** A Python package providing high-level access to sensors, heaters, a pseudo-realtime clock. The package includes `TCLab()` providing access to the device, `clock` for synchronizing with a real time clock, `Historian` for data logging, and `Plotter` for realtime plotting.
- **TCLab-sketch.ino:** Firmware for the intrisically safe operation of the Arduino board and shield. The sketch is available at https://github.com/jckantor/TCLab-sketch.
- **Arduino:** Hardware platform for the Temperature Control Laboratory. TCLab is compatiable with Arduino Uno, Arduino Leonardo, and compatible clones.

3.2 Getting Started

3.2.1 Installation

Install using

```
pip install tclab
```

To upgrade an existing installation, use the command

```
pip install tclab --upgrade
```

The development version contains new features, but may be less stable. To install the development version use the command

```
pip install --upgrade https://github.com/jckantor/TCLab/archive/development.zip
```

3.2.2 Hardware Setup

1. Plug a compatible Arduino device (UNO, Leonardo, NHduino) with the lab attached into your computer via the USB connection. Plug the DC power adapter into the wall.
2. (optional) Install Arduino Drivers.

If you are using Windows 10, the Arduino board should connect without additional drivers required.

Mac OS X users may need to install a serial driver. For Arduino clones using the CH340G, CH34G or CH34X chipset, a suitable driver can be found here or here.

3. (optional) Install Arduino Firmware;

`TCLab` requires the one-time installation of custom firmware on an Arduino device. If it hasn't been pre-installed, the necessary firmware and instructions are available from the TCLab-Sketch repository.

3.2.3 Checking that everything works

Execute the following code

```
import tclab
with tclab.TCLab() as lab:
    print(lab.T1)
```

If everything has worked, you should see the following output message

```
Connecting to TCLab
TCLab Firmware Version 1.2.1 on NHduino connected to port XXXX
21.54
TCLab disconnected successfully.
```

The number returned is the temperature of sensor T1 in °C.

3.3 Next Steps

The notebook directory provides examples on how to use the TCLab module. The latest documentation is available at Read the Docs.

3.3.1 Course Web Sites

More information, instructional videos, and Jupyter notebook examples are available at the following course websites.

- Arduino temperature control lab page on the BYU Process Dynamics and Control course website.
- CBE 30338 for the Notre Dame Chemical Process Control course website.
- Dynamics and Control for notebooks developed at the University of Pretoria.

CHAPTER 4

Accessing the Temperature Control Laboratory

4.1 Importing `tclab`

Once installed the package can be imported into Python and an instance created with the Python statements

```
import tclab
lab = tclab.TCLab()
```

`TCLab` provides access to temperature measurements, heaters, and LED on board the Temperature Control Laboratory. When called with no arguments, attempts to find a device connected to a serial port and returns a connection. An error is generated if no device is found. The connection should be closed with

```
lab.close()
```

when no longer in use. The following cell demonstrates this process, and uses the tclab `LED()` function to flash the LED on the Temperature Control Lab for a period of 10 seconds at a 100% brightness level.

```
In [1]: import tclab

        lab = tclab.TCLab()
        lab.LED(100)
        lab.close()
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.
TCLab disconnected successfully.
```

4.1.1 A note on terminology

`TCLab` is a *class*. We *instantiate* the class by calling `TCLab()`. What is returned is an *instance* of the `TCLab` class. So in the above code, we would say `lab` is an instance of `TCLab`.

4.2 Using TCLab with Python's `with` statement

The Python `with` statement provides a simple means of setting up and closing a connection to the Temperature Control Laboratory. The `with` statement establishes a context where a `TCLab` instance is created, assigned to a variable, and automatically closed upon completion.

```
In [2]: import tclab

        with tclab.TCLab() as lab:
            lab.LED(100)
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.
TCLab disconnected successfully.
```

The `with` statement is likely to be the most common way to connect the Temperature Control Laboratory for most uses.

4.3 Reading Temperatures

Once a `TCLab` instance is created and connected to a device, the temperature sensors on the temperature control lab can be acccessed with the attributes `.T1` and `.T2`. For example, given an instance `lab`, the temperatures are accessed as

```
T1 = lab.T1
T2 = a.T2
```

Note that `lab.T1` and `lab.T2` are read-only properties. Any attempt to set them to a value will return a Python error.

```
In [3]: import tclab

        with tclab.TCLab() as lab:
            print("Temperature 1: {0:0.2f} °C".format(lab.T1))
            print("Temperature 2: {0:0.2f} °C".format(lab.T2))
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.
Temperature 1: 27.67 °C
Temperature 2: 27.03 °C
TCLab disconnected successfully.
```

4.4 Setting Heaters

The heaters are controlled by functions `.Q1()` and `.Q2()` of a `TCLab` instance. For example, both heaters can be set to 100% power with the functions

```
lab.Q1(100)
lab.Q2(100)
```

The device firmware limits the heaters to a range of 0 to 100%. The current value of attributes may be accessed via

```
Q1 = lab.Q1()
Q2 = lab.Q2()
```

Note that the retrieved values may be different due to the range-limiting enforced by the device firmware.

Alternatively, the heaters can also be specified with the properties `.U1` and `.U2`. Thus setting

```
lab.U1 = 100
lab.U2 = 100
```

would set both heaters to 100% power. The current value of the heaters can be accessed as

```
print("Current setting of heater 1 is", lab.U1, "%")
print("Current setting of heater 2 is", lab.U2, "%")
```

The choice to use a function (i.e, `.Q1()` and `.Q2()`) or a property (i.e, `.U1` or `.U2`) to set and access heater settings is a matter of user preference.

```
In [4]: import tclab
        import time

        with tclab.TCLab() as lab:
            print("\nStarting Temperature 1: {0:0.2f} °C".format(lab.T1),flush=True)
            print("Starting Temperature 2: {0:0.2f} °C".format(lab.T2),flush=True)

            lab.Q1(100)
            lab.Q2(100)
            print("\nSet Heater 1:", lab.Q1(), "%",flush=True)
            print("Set Heater 2:", lab.Q2(), "%",flush=True)

            t_heat = 20
            print("\nHeat for", t_heat, "seconds")
            time.sleep(t_heat)

            print("\nTurn Heaters Off")
            lab.Q1(0)
            lab.Q2(0)
            print("\nSet Heater 1:", lab.Q1(), "%",flush=True)
            print("Set Heater 2:", lab.Q2(), "%",flush=True)

            print("\nFinal Temperature 1: {0:0.2f} °C".format(lab.T1))
            print("Final Temperature 2: {0:0.2f} °C".format(lab.T2))
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.

Starting Temperature 1: 27.67 °C
Starting Temperature 2: 27.03 °C

Set Heater 1: 100.0 %
Set Heater 2: 100.0 %

Heat for 20 seconds

Turn Heaters Off

Set Heater 1: 0.0 %
Set Heater 2: 0.0 %

Final Temperature 1: 28.96 °C
Final Temperature 2: 29.29 °C
TCLab disconnected successfully.
```

4.5 Setting Maximum Heater Power

The control inputs to the heaters power is normally set with functions `.Q1()` and `.Q2()` (or properties `.U1` and `.U2`) specifying a value in a range from 0 to 100% of maximum heater power.

The values of maximum heater power are specified in firmware with values in the range from 0 to 255. The default values are 200 for heater 1 and 100 for heater 2. The maximum heater power can be retrieved and set by properties `P1` and `P2`. The following code, for example, sets both heaters to a maximum power of 100.

```
In [5]: import tclab

        with tclab.TCLab() as lab:
            print("Maximum power of heater 1 = ", lab.P1)
            print("Maximum power of heater 2 = ", lab.P2)

            print("Adjusting the maximum power of heater 1.")
            lab.P1 = 100

            print("Maximum power of heater 1 = ", lab.P1)
            print("Maximum power of heater 2 = ", lab.P2)
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.
Maximum power of heater 1 =  200.0
Maximum power of heater 2 =  100.0
Adjusting the maximum power of heater 1.
Maximum power of heater 1 =  100.0
Maximum power of heater 2 =  100.0
TCLab disconnected successfully.
```

The actual power supplied to the heaters is a function of the power supply voltage applied to the Temperature Control Lab shield,

The maximum power applied to the heaters is a product of the settings (`P1`,`P2`) and of the power supply used with the TCLab hardware. The TCLab hardware is normally used with a 5 watt USB power supply capable of supply up to 1 amp at 5 volts.

The TCLab hardware actually draws more than 1 amp when both `P1` and `P2` are set to 255 and `Q1` and `Q2` are at 100%. This situation will overload the power supply and result in the power supply shutting down. Normally the power supply will reset itself after unplugging from the power mains.

Experience with the device shows keeping the sum `P1` and `P2` to a value less than 300 will avoid problems with the 5 watt power supply. If you have access to larger power supplies, then you can adjust `P1` and `P2` accordingly to achieve a wider range of temperatures.

4.6 `tclab` Sampling Speed

There are limits to how quickly the board can be sampled. The following examples show values for a particular type of board. You can run them to see how quick your board is.

4.6.1 Temperature Sampling Speed

```
In [6]: import time
        import tclab

        TCLab = tclab.setup(connected=True)
```

```
        N = 100
        meas = []
        with TCLab() as lab:
            tic = time.time()
            for k in range(0,N):
                meas.append(lab.T1)
            toc = time.time()

        print('Reading temperature at', round(N/(toc-tic),1), 'samples per second.')
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.
TCLab disconnected successfully.
Reading temperature at 12.3 samples per second.
```

4.6.2 Heater Sampling Speed

```
In [7]: import time
        import tclab

        TCLab = tclab.setup(connected=True)

        N = 100
        with TCLab() as lab:
            tic = time.time()
            for k in range(0,N):
                lab.Q1(100)
            toc = time.time()

        print('Setting heater at', round(N/(toc-tic),1), 'samples per second.')
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.
TCLab disconnected successfully.
Setting heater at 8.2 samples per second.
```

CHAPTER 5

Synchronizing with Real Time

5.1 Simple use of `tclab.clock()`

The tclab module includes a function `clock` for synchronizing calculations with real time. `clock(tperiod)` is an iterator that generates a sequence of equally spaced time steps from zero to `tperiod` separated by one second intervals. For each step `clock` returns time since start rounded to the nearest 10th of a second.

```
In [1]: import tclab

        tperiod = 5
        for t in tclab.clock(tperiod):
            print(t, "sec.")
```

```
0 sec.
1.0 sec.
2.0 sec.
3.0 sec.
4.0 sec.
5.0 sec.
```

`tclab.clock()` is implemented as a Python generator. A consequence of this implementation is that `tclab.clock()` is 'blocking' which limits its use for creating interactive demonstrations. See later sections of this user's guide for non-blocking alternatives that can be used for interactive demonstrations or GUI's.

5.2 Optional Parameters

5.2.1 `tstep`: Clock time step

An optional parameter `tstep` specifies a time step different from one second.

```
In [2]: import tclab

        tperiod = 5
        tstep = 2.5
```

```
        for t in tclab.clock(tperiod,tstep):
            print(t, "sec.")
```

```
0 sec.
2.5 sec.
5.0 sec.
```

There are some considerations when using `clock`. First, by its nature Python is not a real-time environment. `clock` makes a best effort to stay in sync with the wall clock but there can be no guarantees. The default behavior of `clock` is to maintain long-term synchronization with the real time clock.

The following cell demonstrates the effect of an intermittent calculation that exceeds the time step specified by `tstep`. In this instance, a `sleep` timeout of 1.2 seconds occurs at t=2. The clock skips a step to regain synchronization at the subsequent time step.

```
In [3]: import tclab
        import time

        tfinal = 5
        tstep = 1

        for t in tclab.clock(tfinal, tstep, tol=0.5):
            print(t, "sec.")
            if 1.9 < t < 2.5:
                time.sleep(1.2)
```

```
0 sec.
1.0 sec.
2.0 sec.
4.0 sec.
5.0 sec.
```

5.3 Using `tclab.clock()` with TCLab

An important use of the `tclab.clock()` generator is to implement and test control and estimation algorithms. The following cell shows how the `clock` generator can be used within the context defined by the Python `with` statement.

```
In [4]: import tclab

        tfinal = 20
        tstep = 2

        with tclab.TCLab() as lab:
            lab.Q1(100)
            lab.Q2(100)

            print("\nSet Heater 1 to {0:f} %".format(lab.Q1()))
            print("Set Heater 2 to {0:f} %\n".format(lab.Q2()))

            sfmt = "   {0:5.1f} sec:   T1 = {1:0.1f} °C    T2 = {2:0.1f} °C"

            for t in tclab.clock(tfinal, tstep):
                print(sfmt.format(t, lab.T1, lab.T2), flush=True)
```

```
Arduino Leonardo connected on port /dev/cu.usbmodemWUAR1 at 115200 baud.
TCLab Firmware 1.3.0 Arduino Leonardo/Micro.

Set Heater 1 to 100.000000 %
Set Heater 2 to 100.000000 %
```

```
     0.0 sec:   T1 = 30.9 °C    T2 = 33.1 °C
     2.0 sec:   T1 = 30.9 °C    T2 = 33.5 °C
     4.0 sec:   T1 = 30.9 °C    T2 = 33.1 °C
     6.0 sec:   T1 = 30.6 °C    T2 = 32.2 °C
     8.0 sec:   T1 = 30.9 °C    T2 = 33.1 °C
    10.0 sec:   T1 = 30.9 °C    T2 = 33.1 °C
    12.0 sec:   T1 = 30.9 °C    T2 = 33.5 °C
    14.0 sec:   T1 = 30.9 °C    T2 = 33.8 °C
    16.0 sec:   T1 = 31.2 °C    T2 = 32.8 °C
    18.0 sec:   T1 = 31.2 °C    T2 = 34.4 °C
    20.0 sec:   T1 = 31.5 °C    T2 = 34.8 °C
TCLab disconnected successfully.
```

CHAPTER 6

TCLab Emulation for Offline Use

`TCLabModel` replaces `TCLab` for occasions where the TCLab hardware might not be available. To use, include the import

```
from tclab import TCLabModel as TCLab
```

The rest of your code will work without change. Be advised the underlying model used to approximate the behavior of the Temperature Control Laboratory is an approximation to the dynamics of the actual hardware.

```
In [1]: from tclab import TCLabModel as TCLab

        with TCLab() as a:
            print("Temperature 1: {0:0.2f} °C".format(a.T1))
            print("Temperature 2: {0:0.2f} °C".format(a.T2))
```

```
TCLab version 0.4.5dev
Simulated TCLab
Temperature 1: 20.95 °C
Temperature 2: 20.95 °C
TCLab Model disconnected successfully.
```

6.1 Choosing Real or Emulation mode with `setup()`

The `tclab.setup()` function provides a choice of using actual hardware or an emulation of the TCLab device by changing a single line of code. When emulating TCLab, a second parameter `speedup` allows the emulation to run at a multiple of real time.

```
# connect to TCLab mounted on arduino
TCLab = tclab.setup(connected=True)

# Emulate the operation of TCLab using TCLabModel
TCLab = tclab.setup(connected=False)
```

```
# Emulate operation at 5× realtime
TCLab = tclab.setup(connected=False, speedup=5)
```

The next cell demonsrates emulation of the TCLab device at 5× real time.

```
In [2]: %matplotlib inline
        import tclab

        TCLab = tclab.setup(connected=False, speedup=5)

        with TCLab() as lab:
            for t in tclab.clock(20):
                lab.Q1(100 if t < 10 else 0)
                print("t = {0:4.1f}    Q1 = {1:3.0f} %    T1 = {2:5.2f}".format(t, lab.Q1(), lab.T1))
```

```
TCLab version 0.4.5dev
Simulated TCLab
t =  0.0    Q1 = 100 %    T1 = 20.95
t =  1.0    Q1 = 100 %    T1 = 20.95
t =  2.0    Q1 = 100 %    T1 = 20.95
t =  3.0    Q1 = 100 %    T1 = 20.95
t =  4.0    Q1 = 100 %    T1 = 20.95
t =  5.0    Q1 = 100 %    T1 = 21.27
t =  6.1    Q1 = 100 %    T1 = 21.27
t =  7.0    Q1 = 100 %    T1 = 21.27
t =  8.1    Q1 = 100 %    T1 = 21.59
t =  9.0    Q1 = 100 %    T1 = 21.59
t = 10.1    Q1 =   0 %    T1 = 21.92
t = 11.2    Q1 =   0 %    T1 = 21.92
t = 12.2    Q1 =   0 %    T1 = 22.24
t = 13.2    Q1 =   0 %    T1 = 22.24
t = 14.0    Q1 =   0 %    T1 = 22.56
t = 15.2    Q1 =   0 %    T1 = 22.88
t = 16.2    Q1 =   0 %    T1 = 22.88
t = 17.2    Q1 =   0 %    T1 = 22.88
t = 18.2    Q1 =   0 %    T1 = 23.21
t = 19.0    Q1 =   0 %    T1 = 23.21
t = 20.1    Q1 =   0 %    T1 = 23.21
TCLab Model disconnected successfully.
```

CHAPTER 7

TCLab Historian

7.1 Basic logging

The `tclab.Historian` class provides data logging. Given an instance of a TCLab object, an historian is created with the commands

```
import tclab
lab = tclab.TCLab()
h = tclab.Historian(lab.sources)
```

The historian initializes a data log. The sources for the data log are specified in the argument to `tclab.Historian`. A default set of sources for an instance `lab` is given by `lab.sources`. The specification for sources is described in a later section.

The data log is updated by issuing a command

```
h.update(t)
```

Where `t` is the current clock time. If `t` is omitted the historian will calculate its own time.

```
In [1]: import tclab

        TCLab = tclab.setup(connected=False, speedup=10)

        with TCLab() as lab:
            h = tclab.Historian(lab.sources)
            for t in tclab.clock(20):
                lab.Q1(100 if t <= 10 else 0)
                print("Time:", t, 'seconds')
                h.update(t)
```

```
Simulated TCLab
Time: 0 seconds
Time: 1.0 seconds
Time: 2.0 seconds
Time: 3.1 seconds
```

```
Time: 4.0 seconds
Time: 5.0 seconds
Time: 6.0 seconds
Time: 7.0 seconds
Time: 8.0 seconds
Time: 9.0 seconds
Time: 10.0 seconds
Time: 11.0 seconds
Time: 12.0 seconds
Time: 13.0 seconds
Time: 14.0 seconds
Time: 15.0 seconds
Time: 16.0 seconds
Time: 17.0 seconds
Time: 18.0 seconds
Time: 19.0 seconds
Time: 20.0 seconds
TCLab Model disconnected successfully.
```

7.2 Accessing the Data Log from the Historian

`Historian` maintains a data log that is updated on each encounter of the `.update()` function. The list of variables logged by an Historian is given by

```
In [2]: h.columns
```

```
Out[2]: ['Time', 'T1', 'T2', 'Q1', 'Q2']
```

Individual time series are available as elements of `Historian.fields`. For the default set of sources, the time series can be obtained as

```
t, T1, T2, Q1, Q2 = h.fields
```

For example, here's how to plot the history of temperature T1 versus time from the example above.

```
In [3]: %matplotlib notebook
        import matplotlib.pyplot as plt

        t, T1, T2, Q1, Q2 = h.fields
        plt.plot(t, T1)
        plt.xlabel('Time / seconds')
        plt.ylabel('Temperature / °C')
        plt.grid()
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

A sample code demonstrating how to plot the historian log.

```
In [4]: def plotlog(historian):
            line_options = {'lw': 2, 'alpha': 0.8}
            fig = plt.figure(figsize=(6, 5))
            nplots = len(h.columns) - 1
            t = historian.fields[0]
            for n in range(1, nplots+1):
                plt.subplot(nplots,1,n)
                y = historian.fields[n]
                plt.step(t, y, where='post', **line_options)
                plt.grid()
```

```
                plt.xlabel('Time / Seconds')
                plt.ylabel(historian.columns[n])
            plt.tight_layout()

        plotlog(h)
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

7.3 Accessing log data using Pandas

Pandas is a widely use Python library for manipulation and analysis of data sets. Here we show how to access the `tclab.Historian` log using Pandas.

The entire data history is available from the historian as the attribute `.log`. Here we show the first three rows from the log:

```
In [5]: h.log[:3]
```

```
Out[5]: [(0, 20.63764871669155, 20.943170851304753, 100, 0),
         (1.0, 20.970051008953146, 21.039093002960875, 100, 0),
         (2.0, 20.82904255696425, 21.19942260552886, 100, 0)]
```

The log can be converted to a Pandas dataframe.

```
In [6]: import pandas as pd

        df = pd.DataFrame.from_records(h.log, columns=h.columns, index='Time')
        df.head()
```

```
Out[6]: T1          T2    Q1   Q2
        Time
        0.0   20.637649  20.943171  100   0
        1.0   20.970051  21.039093  100   0
        2.0   20.829043  21.199423  100   0
        3.1   20.999762  20.804944  100   0
        4.0   21.178955  21.211932  100   0
```

The following cells provide examples of plots that can be constructed once the data log has been converted to a pandas dataframe.

```
In [7]: df.plot()
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

```
Out[7]: <matplotlib.axes._subplots.AxesSubplot at 0x10e957c18>
```

```
In [8]: df[['T1','T2']].plot(grid=True)
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

```
Out[8]: <matplotlib.axes._subplots.AxesSubplot at 0x10ee00ac8>
```

7.4 Specifying Sources for `tclab.Historian`

To create an instance of `tclab.Historian`, a set of sources needs to be specified. For many cases the default sources created for an instance of `TCLab` is sufficient. However, it is possible to specify additional sources which can

be useful when implementing more complex algorithms for process control.

`sources` is specified as a list of tuples. Each tuple as two elements. The first element is a label for the source. The second element is a function that returns a value.

The following cell shows how to create a source with the label `Power` with a value equal to the estimated heater power measured in watts. This is created on the assumption that 100% of a maximum power of 200 corresponds to 4.2 watts.

```
In [9]: import tclab

        TCLab = tclab.setup(connected=False, speedup=10)

        with TCLab() as lab:
            sources = [
                ('T1', lambda: lab.T1),
                ('Power', lambda: lab.P1*lab.U1*4.2/(200*100))
            ]
            h = tclab.Historian(sources)
            for t in tclab.clock(20):
                lab.Q1(100 if t <= 10 else 0)
                print("Time:", t, 'seconds')
                h.update(t)
```

```
Simulated TCLab
Time: 0 seconds
Time: 1.0 seconds
Time: 2.0 seconds
Time: 3.1 seconds
Time: 4.1 seconds
Time: 5.1 seconds
Time: 6.0 seconds
Time: 7.0 seconds
Time: 8.0 seconds
Time: 9.0 seconds
Time: 10.0 seconds
Time: 11.0 seconds
Time: 12.0 seconds
Time: 13.0 seconds
Time: 14.0 seconds
Time: 15.1 seconds
Time: 16.1 seconds
Time: 17.0 seconds
Time: 18.1 seconds
Time: 19.0 seconds
Time: 20.1 seconds
TCLab Model disconnected successfully.
```

```
In [10]: import pandas as pd

         df = pd.DataFrame.from_records(h.log, columns=h.columns, index='Time')
         df.head()
```

Out[10]:

Time	T1	Power
0.0	21.122906	4.2
1.0	21.042728	4.2
2.0	21.089869	4.2
3.1	20.735415	4.2
4.1	21.247619	4.2

7.4.1 Functions with multiple returns

In some cases it is easier to calculate a number of different variables to be logged in one function, especially if intermediate results are used in following calculations. This can be accommodated by `Historian` by passing `None` as the function for subsequent values if a previous value returned a list of values.

```
In [11]: import tclab

         TCLab = tclab.setup(connected=False, speedup=10)

         def log_values():
             T1 = lab.T1
             T1Kelvin = T1 + 273.15
             power = lab.P1*lab.U1*4.2/(200*100)
             return T1, T1Kelvin, power

         with TCLab() as lab:
             h = tclab.Historian([('T1', log_values),
                                  ('T1Kelvin', None),
                                  ('Power', None)])
             for t in tclab.clock(20):
                 lab.Q1(100 if t <= 10 else 0)
                 print("Time:", t, 'seconds')
                 h.update(t)
```

```
Simulated TCLab
Time: 0 seconds
Time: 1.1 seconds
Time: 2.0 seconds
Time: 3.0 seconds
Time: 4.1 seconds
Time: 5.0 seconds
Time: 6.1 seconds
Time: 7.1 seconds
Time: 8.1 seconds
Time: 9.0 seconds
Time: 10.1 seconds
Time: 11.1 seconds
Time: 12.1 seconds
Time: 13.1 seconds
Time: 14.1 seconds
Time: 15.1 seconds
Time: 16.0 seconds
Time: 17.1 seconds
Time: 18.0 seconds
Time: 19.0 seconds
Time: 20.1 seconds
TCLab Model disconnected successfully.
```

```
In [12]: import pandas as pd

         df = pd.DataFrame.from_records(h.log, columns=h.columns, index='Time')
         df.head()
```

Out[12]:

Time	T1	T1Kelvin	Power
0.0	21.398474	294.548474	4.2
1.1	20.896188	294.046188	4.2
2.0	21.020920	294.170920	4.2
3.0	21.388696	294.538696	4.2

```
         4.1   21.422918  294.572918    4.2
```

```
In [13]: h.log
```

```
Out[13]: [(0, 21.39847390202538, 294.54847390202536, 4.2),
          (1.1, 20.896188106048534, 294.04618810604853, 4.2),
          (2.0, 21.020919672793628, 294.1709196727936, 4.2),
          (3.0, 21.388695634608457, 294.5386956346084, 4.2),
          (4.1, 21.422917556207384, 294.57291755620736, 4.2),
          (5.0, 21.280749815780343, 294.4307498157803, 4.2),
          (6.1, 21.21011564474363, 294.3601156447436, 4.2),
          (7.1, 21.432219179442992, 294.582219179443, 4.2),
          (8.1, 21.338012494864614, 294.4880124948646, 4.2),
          (9.0, 21.723905963683276, 294.8739059636832, 4.2),
          (10.1, 22.016211560264587, 295.16621156026457, 0.0),
          (11.1, 21.890799258407608, 295.04079925840756, 0.0),
          (12.1, 22.362670233474688, 295.51267023347464, 0.0),
          (13.1, 22.33554429445724, 295.4855442944572, 0.0),
          (14.1, 22.801111360426944, 295.9511113604269, 0.0),
          (15.1, 22.663066304511183, 295.81306630451115, 0.0),
          (16.0, 22.797209805678705, 295.94720980567865, 0.0),
          (17.1, 23.24049659958222, 296.3904965995822, 0.0),
          (18.0, 22.747918305203207, 295.8979183052032, 0.0),
          (19.0, 23.279005095865138, 296.42900509586514, 0.0),
          (20.1, 23.125870006852075, 296.2758700068521, 0.0)]
```

7.5 Sessions

It is possible to run multiple experiments using the same `Historian` and page back to them after running them:

```
In [2]: import tclab

        TCLab = tclab.setup(connected=False, speedup=10)

        with TCLab() as lab:
            h = tclab.Historian(lab.sources)
            for t in tclab.clock(20):
                lab.Q1(100 if t <= 10 else 0)
                h.update(t)
            h.new_session()
            for t in tclab.clock(20):
                lab.Q1(0 if t <= 10 else 100)
                h.update(t)
```

```
Simulated TCLab
TCLab Model disconnected successfully.
```

To see the stored sessions, use `get_sessions`:

```
In [6]: h.get_sessions()
```

```
Out[6]: [(1, '2018-02-18 17:00:41'), (2, '2018-02-18 17:00:43')]
```

The historian log shows the data for the last session, where the heater started open

```
In [12]: h.log[:2]
```

```
Out[12]: [(0, 20.90865374061689, 20.89324077368182, 100, 0),
          (1.0, 20.754672349149576, 20.91112483321418, 100, 0)]
```

To roll back to a different session, use `load_session()`:

```
In [13]: h.load_session(1)

In [14]: h.log[:2]

Out[14]: [(0, 20.90865374061689, 20.89324077368182, 100, 0),
          (1.0, 20.754672349149576, 20.91112483321418, 100, 0)]
```

7.6 Persistence

`Historian` stores results in a SQLite database. By default, it uses the special file `:memory:` which means the results are lost when you shut down or restart the kernel. To retain values across runs, you can specify a filename (by convention SQLite databases have the `.db` extension).

```
In [15]: import tclab

         TCLab = tclab.setup(connected=False, speedup=10)

         with TCLab() as lab:
             h = tclab.Historian(lab.sources, dbfile='test.db')
             for t in tclab.clock(20):
                 lab.Q1(100 if t <= 10 else 0)
                 h.update(t)

Simulated TCLab
TCLab Model disconnected successfully.
```

Every time you run this cell, new sessions will be added to the file. These sessions can be loaded as shown in the Sessions section above. There is currently no support for managing sessions. If you want to remove the old sessions, delete the database file.

CHAPTER 8

TCLab Plotter

When operating in a Jupyter Notebook, a `Plotter` can be used together with the `Historian`.

```
h = Historian(lab)
p = Plotter(h, tfinal)
```

where `lab` is a `TCLab` instance as before and the optional parameter `tfinal` provides an initial scaling of the time axes. Each call to `p.update()` will automatically update both the historian and the plot.

```
In [1]: %matplotlib notebook
        from tclab import TCLab, clock, Historian, Plotter, setup

        TCLab = setup(connected=False, speedup=10)

        with TCLab() as lab:
            h = Historian(lab.sources)
            p = Plotter(h, twindow=200)
            for t in clock(200):
                lab.Q1(100 if t < 100 else 0)
                p.update(t)
```

```
Simulated TCLab
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

```
TCLab Model disconnected successfully.
```

8.1 Specifying layout

The layout of values can be speficied when creating a `Plotter`. Layout is given as a tuple of tuples. Each of the first level tuples creates a new axis, and each of the elements in the tuple is plotted on that same axis.

```
In [2]: %matplotlib notebook
        from tclab import setup
```

```
        from tclab import Historian, Plotter, clock
        import time

        tic = time.time()
        TCLab = setup(connected=False, speedup=10)

        with TCLab() as lab:
            h = Historian(lab.sources)
            p = Plotter(h, 200, layout=(('T1', 'T2'), ('Q1', 'Q2')))
            for t in clock(200):
                lab.U1 = 80
                p.update(t)
        toc = time.time()

        print(toc-tic, 'seconds')
```

```
Simulated TCLab
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

```
TCLab Model disconnected successfully.
20.255380153656006 seconds
```

CHAPTER 9

NotebookUI

The `tclab.gui` module supplies a graphical interface to the Temperature Control Laboratory.

```
In [1]: from tclab.gui import NotebookUI
        %matplotlib notebook
        interface = NotebookUI()
```

```
In [2]: interface.gui
```

```
A Jupyter Widget
```

```
Simulated TCLab
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

CHAPTER 10

Experiment Class

The `Experiment` class provides an all-in-one interface for running simple experiments. It combines the effect of instantiating a `TCLab`, a `Historian` and optionally a `Plotter`.

```
In [3]: %matplotlib notebook
```

```
In [8]: import tclab

        with tclab.Experiment(connected=False, plot=True, speedup=10) as experiment:
            for t in experiment.clock():
                experiment.lab.Q1(0 if experiment.lab.T1 > 40 else 100)
```

```
Simulated TCLab
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

```
TCLab Model disconnected successfully.
```

10.1 Accessing results

`experiment.historian` contains the historian instance which was created by `Experiment`:

```
In [14]: experiment.historian.log[:5]
```

```
Out[14]: [(0, 20.812700940382776, 20.788384634613717, 0, 0),
          (1.0, 20.905995814379526, 20.978928790222188, 100, 0),
          (2.0, 21.245346825807175, 21.23492347886724, 100, 0),
          (3.0, 21.071910253650344, 21.17195991571187, 100, 0),
          (4.0, 21.11707641600787, 20.841145497515168, 100, 0)]
```

10.2 Even simpler experiments

Sometimes you can use a simple function to describe the experiment you are running. In this case, it is simpler to use `runexperiment`. `Experiment` and `runexperiment` share arguments.

```
In [9]: from tclab import runexperiment
```

```
In [10]: %matplotlib notebook
```

```
In [11]: def onoffcontroller(t, lab):
             lab.Q1(0 if lab.T1 > 40 else 100)
```

```
In [12]: experiment = runexperiment(onoffcontroller, connected=False, time=100, speedup=10)
```

```
Simulated TCLab
```

```
<IPython.core.display.Javascript object>
```

```
<IPython.core.display.HTML object>
```

```
TCLab Model disconnected successfully.
```

CHAPTER 11

The Labtime Class

The `Labtime` class is a tool for speeding up the simulation of process control experiments. With this tool you can more quickly develop control algorithms through simulation, then apply the algorithms to the Temperature Control Lab device with minimal changes to your code.

In most cases you do not need to directly invoke `Labtime`. For example, `setup` with the optional parameter `speedup` (described in the chapter *TCLab Simulation for Offline Use*) uses `Labtime` to adjust the operation of the `clock` iterator. This is sufficient for many applications.

11.1 Basic Usage

11.1.1 .time()

`Labtime` provides a replacement for the `time.time()` function from the Python standard library. The basic usage is demonstrated in the following cell. Note that `import` brings in an instance of `Labtime`. `labtime.time()` returns the *lab time* elapsed since first imported into the Python kernal.

```
In [1]: from tclab import labtime

        tic = labtime.time()
        labtime.sleep(2)
        toc = labtime.time()

        print("Time since first imported = ", round(tic, 2), " labtime seconds.")
        print("Time since first imported = ", round(toc, 2), " labtime seconds.")
```

```
Time since first imported =  0.0  labtime seconds.
Time since first imported =  2.01  labtime seconds.
```

By default, `labtime.time()` progresses at the same rate at real time as measured by the Python `time` package. The following cell demonstrates the default correspondence of labtime and real time.

```
In [2]: from tclab import labtime
        import time
```

```
        time_start = time.time()
        labtime_start = labtime.time()

        def do(n):
            for k in range(0,n):
                t_real = time.time() - time_start
                t_lab  = labtime.time() - labtime_start
                print("real time = {0:4.2f}    lab time = {1:4.2f}".format(t_real, t_lab))
                time.sleep(1)

        do(5)
```

```
real time = 0.00    lab time = 0.00
real time = 1.00    lab time = 1.00
real time = 2.01    lab time = 2.01
real time = 3.01    lab time = 3.01
real time = 4.01    lab time = 4.01
```

11.1.2 .set_rate(rate) and .get_rate(rate)

Lab time can proceed at a rate faster or slower than real time. The relative rate of lab time to real time is set with the `labtime.set_rate(rate)`. The default value is one. The current value of the rate is returned by the `get_rate()`.

```
In [3]: from tclab import labtime
        import time

        time_start = time.time()
        labtime_start = labtime.time()

        labtime.set_rate(2)
        print("Ratio of lab time to real time = ", labtime.get_rate())

        do(5)

        labtime.set_rate()
        print("\nRatio of lab time to real time = ", labtime.get_rate())

        do(5)
```

```
Ratio of lab time to real time =  2
real time = 0.00    lab time = 0.00
real time = 1.00    lab time = 2.00
real time = 2.01    lab time = 4.01
real time = 3.01    lab time = 6.02
real time = 4.01    lab time = 8.03

Ratio of lab time to real time =  1
real time = 5.02    lab time = 10.04
real time = 6.02    lab time = 11.04
real time = 7.02    lab time = 12.04
real time = 8.03    lab time = 13.05
real time = 9.03    lab time = 14.05
```

As demonstrated, conceptually you can thinkg of lab time as a piecewise linear function of real time with the following properties

- monotonically increasing
- continuous

- shared by all functions using `labtime`.

11.1.3 .sleep(delay)

The `labtime.sleep()` function suspends execution for a period `delay` in lab time units. This is used, for example, in the `clock` iterator to speed up execution of a control loop when used in simulation mode.

11.2 Advanced Usage

An additional set of functions are available in `Labtime` to facilitate construction of GUI's, and for programmatically creating code to simulate the behavior of more complex control systems.

11.2.1 .reset(t)

The `labtime.reset(t)` method resets lab time to `t` (default 0). The function `setnow(t)` provides an equivalent service, and is included to provide backward compatibility early versions of `tclab`. This function is typically used within a GUI for repeated testing and tuning of a control algorithm.

```
In [4]: from tclab import labtime

        print("Resetting lab time to zero.")
        labtime.reset(0)
        print("labtime =", labtime.time(),"\n")

        print("Resetting lab time to ten.")
        labtime.reset(10)
        print("labtime =", labtime.time(),"\n")
```

```
Resetting lab time to zero.
labtime = 3.2901763916015625e-05

Resetting lab time to ten.
labtime = 10.000032901763916
```

11.2.2 .stop() / .start() /.running

`labtime.stop()` freezes the labtime clock at its current value. A Runtime warning is generated if there is an attempt to sleep while the labtime is stopped.

`labtime.start()` restarts the labtime clock following a stoppage.

`labtime.running` is a Boolean value that is `True` if the labtime clock is running, otherwise it is `False`.

```
In [5]: from tclab import labtime
        import time

        print("Is labtime running?", labtime.running)
        print("labtime =", labtime.time(), "\n")

        print("Now we'll stop the labtime.")
        labtime.stop()
        print("Is labtime running?", labtime.running, "\n")
```

```
        print("We'll pause for 2 seconds in real time.\n")
        time.sleep(2)

        print("We'll restart labtime and pick up where we left off.")
        labtime.start()
        print("labtime =", labtime.time())
```

```
Is labtime running? True
labtime = 10.015635967254639

Now we'll stop the labtime.
Is labtime running? False

We'll pause for 2 seconds in real time.

We'll restart labtime and pick up where we left off.
labtime = 10.015910148620605
```

11.3 Auxiliary Functions

11.3.1 clock(tperiod, tstep)

The `clock` iterator was introduced in an earlier section on synchronizing `tclab` with real time. In fact, `clock` uses the `Labtime` class to cooridinate with real time, and to provide faster than real time operation in simulation mode.

```
In [6]: from tclab import labtime, clock
        import time

        time_start = time.time()
        labtime_start = labtime.time()

        def do(n):
            print("\nRate =", labtime.get_rate())
            for t in clock(n):
                t_real = time.time() - time_start
                t_lab  = labtime.time() - labtime_start
                print("real time = {0:4.1f}    lab time = {1:4.1f}".format(t_real, t_lab))

        labtime.set_rate(1)
        do(5)

        labtime.set_rate(10)
        do(5)
```

```
Rate = 1
real time =  0.0    lab time =  0.0
real time =  1.0    lab time =  1.0
real time =  2.0    lab time =  2.0
real time =  3.0    lab time =  3.0
real time =  4.0    lab time =  4.0
real time =  5.0    lab time =  5.0

Rate = 10
real time =  5.0    lab time =  5.0
real time =  5.1    lab time =  6.0
real time =  5.2    lab time =  7.1
```

```
real time =  5.3    lab time =  8.0
real time =  5.4    lab time =  9.1
real time =  5.5    lab time = 10.0
```

11.3.2 setnow(t)

`setnow(t)` performs the same function as `labtime.reset(t)`. This function appeared in an early version of `tclab`, and is included here for backwards compatibility.

CHAPTER 12

Search Page

- search