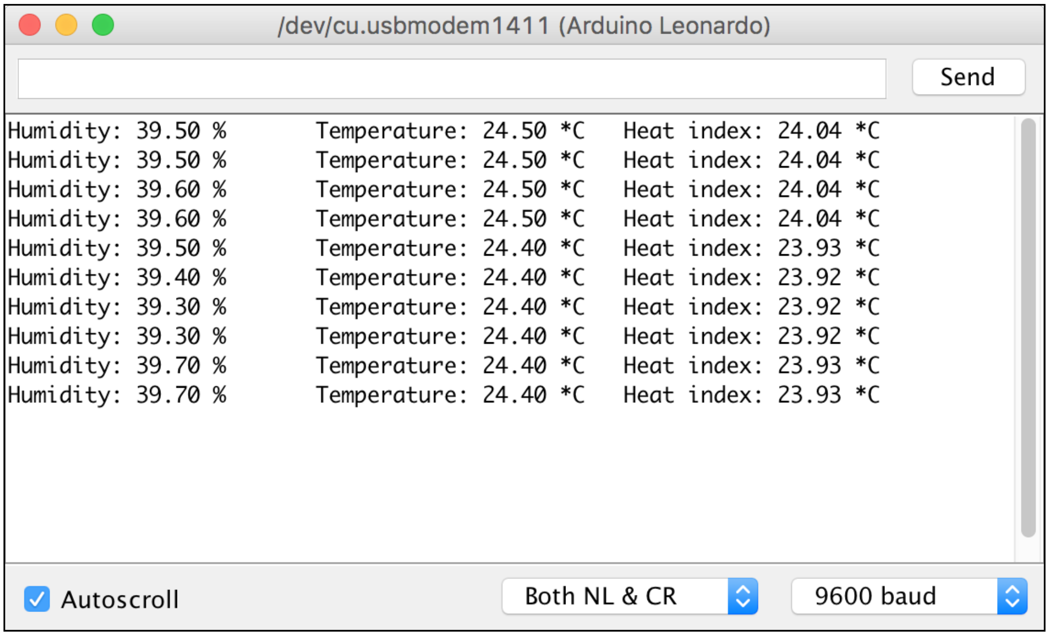


How does it work?

In the `setup()` function, we initialize the DHT module by calling `dht.begin()`. To read temperature and humidity, you can use `dht.readTemperature()` and `dht.readHumidity()`. You also can get a heat index using the `dht.computeHeatIndex()` function.

Sensing and actuating on Raspberry Pi devices

Raspberry Pi board is one of boards used for testing experiments in this book. In this section, we use Raspberry Pi to sense and actuate with external devices. I use a Raspberry Pi 3 board for testing.

Setting up

Before you use a Raspberry Pi board, you need to set up an OS on the board. OS software can be deployed on a microSD card. It's recommended to use an 8-GB microSD card . There's a lot of OS software you can use on a Raspberry Pi board. You can check it out at `https://www.raspberrypi.org/downloads/`.

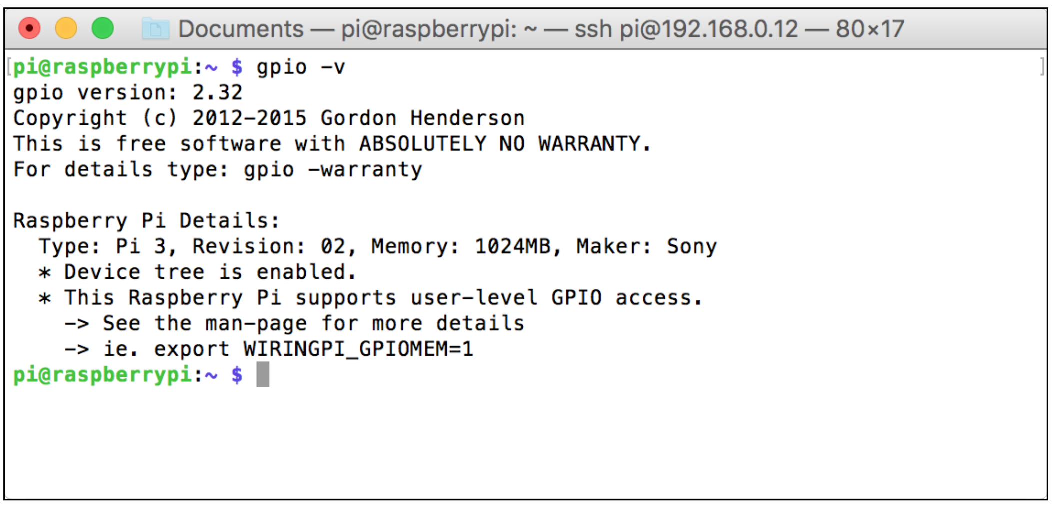
For testing purposes, I use Raspbian, `https://www.raspberrypi.org/downloads/raspbian/`, as the OS on my Raspberry Pi board. Raspbian is an operating system, based on Debian, optimized for Raspberry Pi. Follow the installation guidelines at `https://www.raspberrypi.org/documentation/installation/installing-images/README.md`. Raspbian is just one OS for Raspberry Pi OS. You can try other Raspberry Pi OSes at `https://www.raspberrypi.org/downloads/`.

Accessing Raspberry Pi GPIO

If you use the latest version of Raspbian (Jessie or later), wiringPi module, `http://wiringpi.com`, is already installed for you. You can verify your wiringPi version on Raspberry Pi Terminal using the following command:

```
$ gpio -v
```

You should see your wiringPi module version. A sample of the program output can be seen in the following screenshot:



Furthermore, you can verify the Raspberry GPIO layout using the following command:

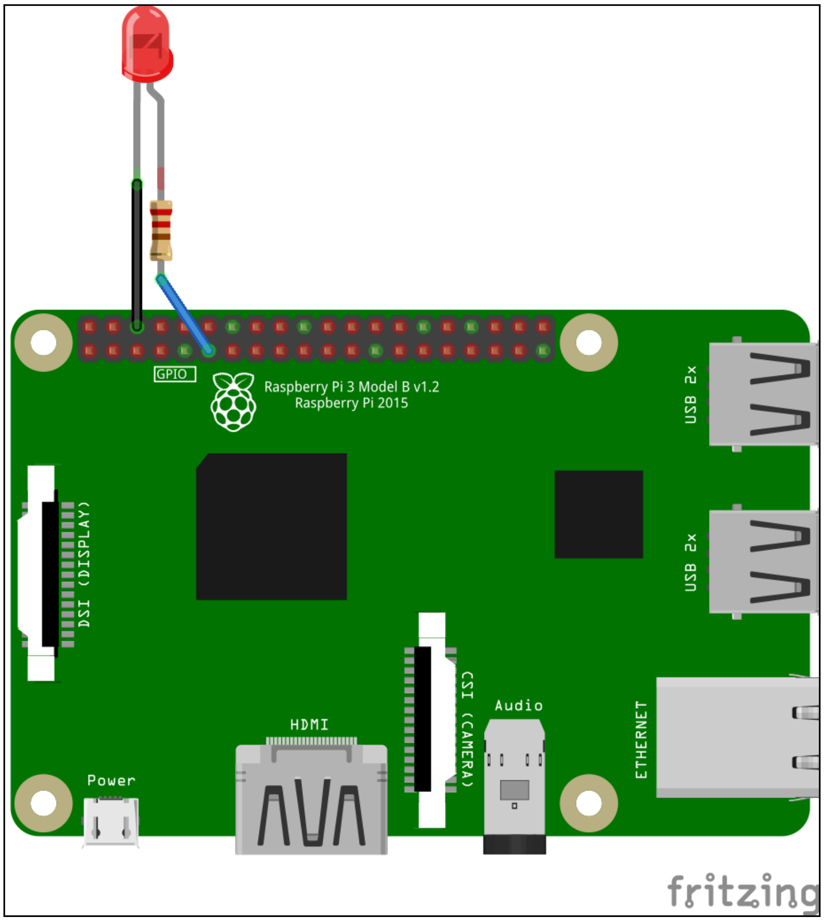
```
$ gpio - readall
```

This command will display the Raspberry Pi layout. It can detect your Raspberry Pi model. A sample of the program output for my board, Raspberry Pi 3, can be seen in the following screenshot:

```
Documents — pi@raspberrypi: ~ — ssh pi@192.168.0.12 — 80×28
pi@raspberrypi:~ $ gpio readall
 +-----+-----+---------+------+---+---Pi 3---+---+------+---------+-----+-----+
 | BCM | wPi |   Name  | Mode | V | Physical | V | Mode | Name    | wPi | BCM |
 +-----+-----+---------+------+---+----++----+---+------+---------+-----+-----+
 |     |     |    3.3v |      |   |  1 || 2  |   |      | 5v      |     |     |
 |   2 |   8 |   SDA.1 |   IN | 1 |  3 || 4  |   |      | 5V      |     |     |
 |   3 |   9 |   SCL.1 |   IN | 1 |  5 || 6  |   |      | 0v      |     |     |
 |   4 |   7 | GPIO. 7 |   IN | 1 |  7 || 8  | 1 | ALT5 | TxD     | 15  | 14  |
 |     |     |      0v |      |   |  9 || 10 | 1 | ALT5 | RxD     | 16  | 15  |
 |  17 |   0 | GPIO. 0 |   IN | 0 | 11 || 12 | 0 | IN   | GPIO. 1 | 1   | 18  |
 |  27 |   2 | GPIO. 2 |   IN | 0 | 13 || 14 |   |      | 0v      |     |     |
 |  22 |   3 | GPIO. 3 |   IN | 0 | 15 || 16 | 0 | IN   | GPIO. 4 | 4   | 23  |
 |     |     |    3.3v |      |   | 17 || 18 | 0 | IN   | GPIO. 5 | 5   | 24  |
 |  10 |  12 |    MOSI |   IN | 0 | 19 || 20 |   |      | 0v      |     |     |
 |   9 |  13 |    MISO |   IN | 0 | 21 || 22 | 0 | IN   | GPIO. 6 | 6   | 25  |
 |  11 |  14 |    SCLK |   IN | 0 | 23 || 24 | 1 | IN   | CE0     | 10  | 8   |
 |     |     |      0v |      |   | 25 || 26 | 1 | IN   | CE1     | 11  | 7   |
 |   0 |  30 |   SDA.0 |   IN | 1 | 27 || 28 | 1 | IN   | SCL.0   | 31  | 1   |
 |   5 |  21 | GPIO.21 |   IN | 1 | 29 || 30 |   |      | 0v      |     |     |
 |   6 |  22 | GPIO.22 |   IN | 1 | 31 || 32 | 0 | IN   | GPIO.26 | 26  | 12  |
 |  13 |  23 | GPIO.23 |   IN | 0 | 33 || 34 |   |      | 0v      |     |     |
 |  19 |  24 | GPIO.24 |   IN | 0 | 35 || 36 | 0 | IN   | GPIO.27 | 27  | 16  |
 |  26 |  25 | GPIO.25 |   IN | 0 | 37 || 38 | 0 | IN   | GPIO.28 | 28  | 20  |
 |     |     |      0v |      |   | 39 || 40 | 0 | IN   | GPIO.29 | 29  | 21  |
 +-----+-----+---------+------+---+----++----+---+------+---------+-----+-----+
 | BCM | wPi |   Name  | Mode | V | Physical | V | Mode | Name    | wPi | BCM |
 +-----+-----+---------+------+---+---Pi 3---+---+------+---------+-----+-----+
pi@raspberrypi:~ $
```

For Raspberry Pi GPIO development, the latest Raspbian also has the RPi.GPIO library already installed—`https://pypi.python.org/pypi/RPi.GPIO`, for Python, so we can use it directly now.

To test Raspberry Pi GPIO, we put an LED on GPIO11 (BCM 17). You can see the wiring in the following figure:



Now you can write a Python program with your own editor. Write the following program:

```
import RPi.GPIO as GPIO
import time


led_pin = 17
GPIO.setmode(GPIO.BCM)
GPIO.setup(led_pin, GPIO.OUT)
```

```
try:
    while 1:
        print("turn on led")
        GPIO.output(led_pin, GPIO.HIGH)
        time.sleep(2)
        print("turn off led")
        GPIO.output(led_pin, GPIO.LOW)
        time.sleep(2)

except KeyboardInterrupt:
    GPIO.output(led_pin, GPIO.LOW)
    GPIO.cleanup()


print("done")
```

The following is an explanation of the code:

- We set GPIO type using `GPIO.setmode(GPIO.BCM)`. I used the `GPIO.BCM` mode. In GPIO BCM, you should see GPIO values on the **BCM** column from the GPIO layout.
- We defined GPIO, which will be used by calling `GPIO.setup()` as the output mode.
- To set digital output, we can call `GPIO.output()`. `GPIO.HIGH` is used to send 1 to the digital output. Otherwise, `GPIO.LOW` is used for sending 0 to the digital output.

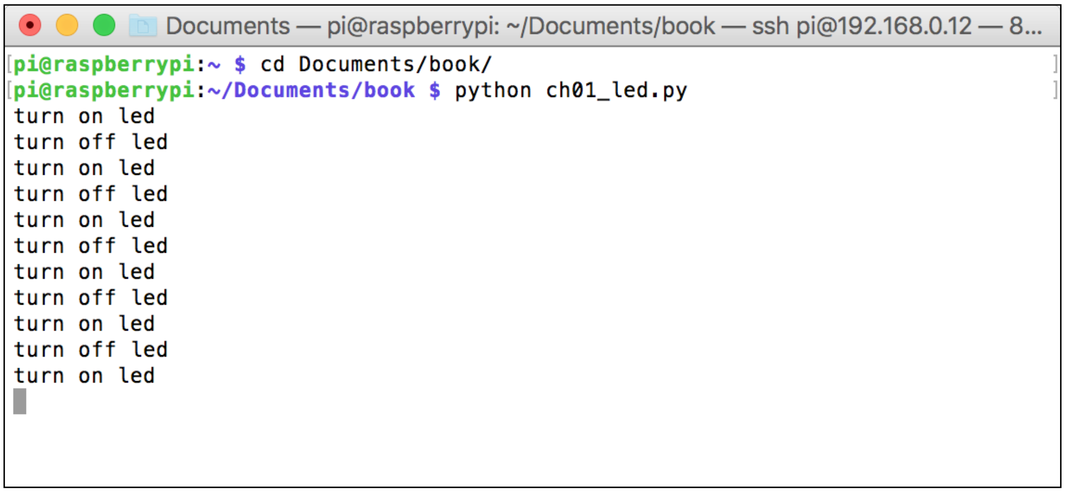
Save this program into a file called `ch01_led.py`.

Now you can run the program by typing the following command on your Raspberry Pi Terminal.

```
$ sudo python ch01_led.py
```

We execute the program using `sudo`, due to security permissions. To access the Raspberry Pi hardware I/O, we need local administrator privileges.

You should see a blinking LED and also get a response from the program. A sample of the program output can be seen in the following screenshot:



Sensing through sensor devices

In this section, we will explore how to sense from Raspberry Pi. We use DHT-22 to collect temperature and humidity readings on its environment.

To access DHT-22 using Python, we use the Adafruit Python DHT Sensor library. You can review this module at `https://github.com/adafruit/Adafruit_Python_DHT`.

You need required libraries to build Adafruit Python DHT Sensor library. Type the following commands in your Raspberry Pi Terminal:

```
$ sudo apt-get update
$ sudo apt-get install build-essential python-dev
```

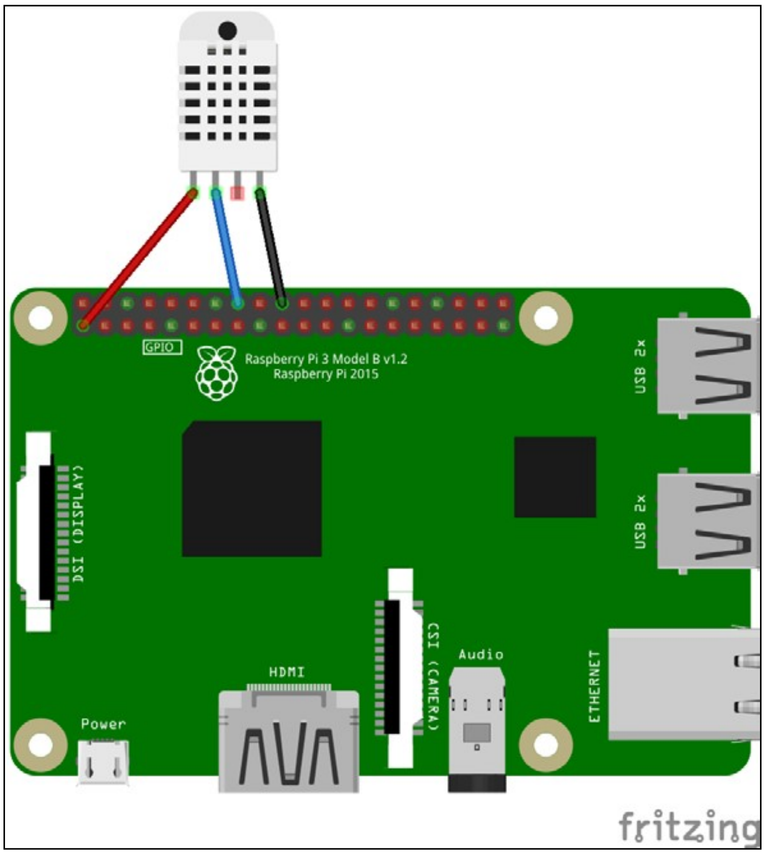
Now you can download and install the Adafruit Python DHT Sensor library:

```
$ git clone https://github.com/adafruit/Adafruit_Python_DHT
$ cd Adafruit_Python_DHT/
$ sudo python setup.py install
```

If finished, we can start to build our wiring. Connect the DHT-22 module to the following connections:

- DHT-22 pin 1 (VDD) is connected to the 3.3V pin on your Raspberry Pi
- DHT-22 pin 2 (SIG) is connected to the GPIO23 (see the **BCM** column) pin on your Raspberry Pi
- DHT-22 pin 4 (GND) is connected to the GND pin on your Raspberry Pi

The complete wiring is shown in the following figure:



The next step is to write a Python program. You can write the following code:

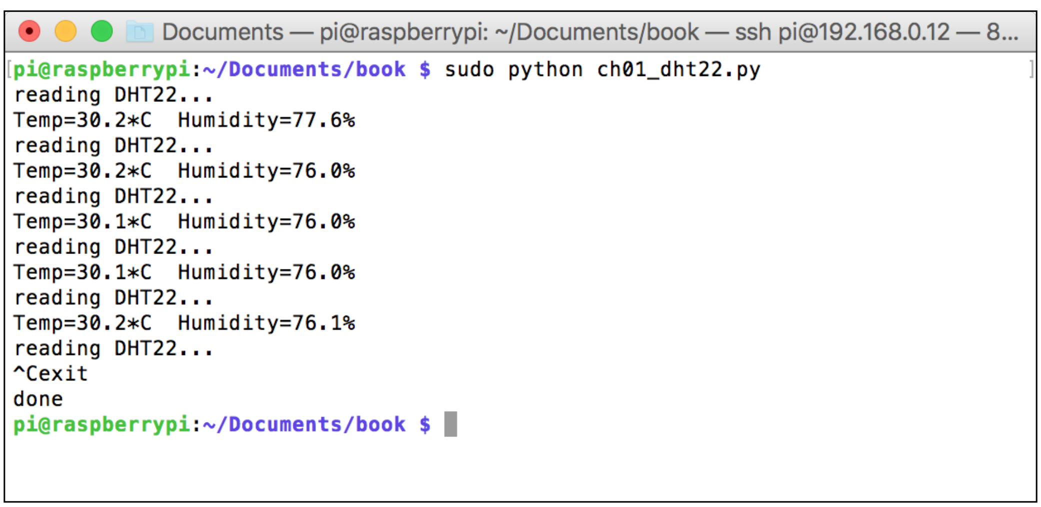
```
import Adafruit_DHT
import time

sensor = Adafruit_DHT.DHT22
```

```
# DHT22 pin on Raspberry Pi
pin = 23


try:
    while 1:
        print("reading DHT22...")
        humidity, temperature = Adafruit_DHT.read_retry(sensor, pin)

        if humidity is not None and temperature is not None:
            print('Temp={0:0.1f}*C  Humidity={1:0.1f}%'.
format(temperature, humidity))

        time.sleep(2)

except KeyboardInterrupt:
    print("exit")


print("done")
```

Save this program into a file called `ch01_dht22.py`. Then, you can run this file on your Raspberry Pi Terminal. Type the following command:

```
$ sudo python ch01_dht22.py
```

A sample of the program output can be seen in the following screenshot:



How does it work?

First, we set our DHT module type by calling the `Adafruit_DHT.DHT22` object. Set which DHT-22 pin is attached to your Raspberry Pi board. In this case, I use GPIO23 (BCM).

To obtain temperature and humidity sensor data, we call `Adafruit_DHT.read_retry(sensor, pin)`. To make sure the returning values are not `NULL`, we validate them using conditional-if.

Building a smart temperature controller for your room

To control your room's temperature, we can build a smart temperature controller. In this case, we use a **PID** (**proportional–integral–derivative**) controller. When you set a certain temperature, a PID controller will change the temperature by turning either cooler or hotter. A PID controller program is developed using Python, which runs on the Raspberry Pi board.

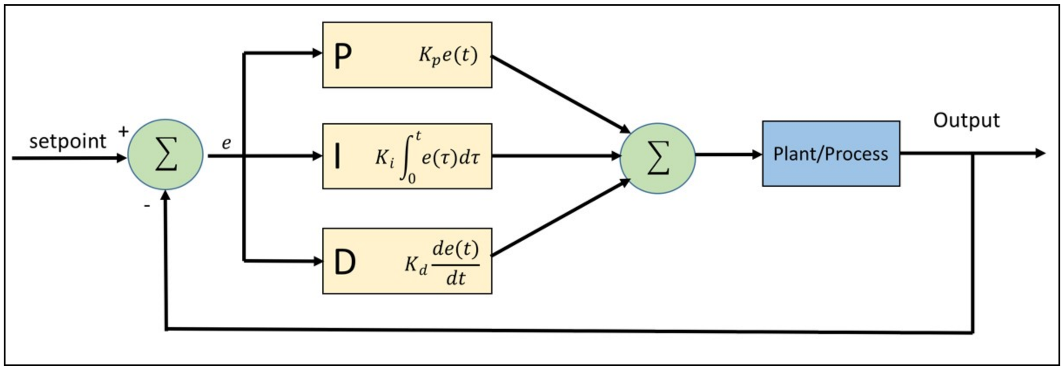
Assume cooler and heater machines are connected via a relay. We can activate cooler and heater machine by sending `HIGH` signal on a relay.

Let's build!

Introducing PID controller

PID control is the most common control algorithm widely used in industry, and has been universally accepted in industrial control. The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating proportional, integral, and derivative responses and summing those three components to compute the output.

An example design of a general PID controller is depicted in the following figure:



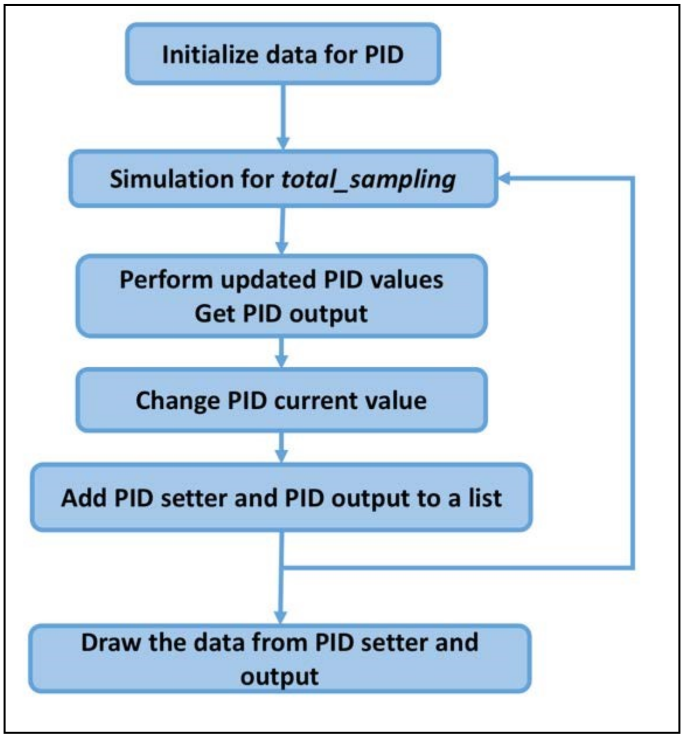
Furthermore, a PID controller formula can be defined as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

K_p, K_i, K_d represent the coefficients for the proportional, integral, and derivative. These parameters are non-negative values. The variable *e* represents the tracking error, the difference between the desired input value *i*, and the actual output *y*. This error signal *e* will be sent to the PID controller.

Implementing PID controller in Python

In this section, we will build a Python application to implement the PID controller. In general, our program flowchart can be described by the following figure:



We should not build a PID library from scratch. You can translate PID controller formula into Python code easily. For implementation, I use the PID class from `https://github.com/ivmech/ivPID`. The following is the content of the `PID.py` file:

```
import time

class PID:
    """PID Controller
    """

    def __init__(self, P=0.2, I=0.0, D=0.0):

        self.Kp = P
        self.Ki = I
        self.Kd = D

        self.sample_time = 0.00
        self.current_time = time.time()
```

```
        self.last_time = self.current_time

        self.clear()

    def clear(self):
        """Clears PID computations and coefficients"""
        self.SetPoint = 0.0

        self.PTerm = 0.0
        self.ITerm = 0.0
        self.DTerm = 0.0
        self.last_error = 0.0

        # Windup Guard
        self.int_error = 0.0
        self.windup_guard = 20.0

        self.output = 0.0

    def update(self, feedback_value):
        """Calculates PID value for given reference feedback

        .. math::
            u(t) = K_p e(t) + K_i \int_{0}^{t} e(t)dt + K_d {de}/{dt}

        .. figure:: images/pid_1.png
           :align:   center

           Test PID with Kp=1.2, Ki=1, Kd=0.001 (test_pid.py)

        """
        error = self.SetPoint - feedback_value

        self.current_time = time.time()
        delta_time = self.current_time - self.last_time
        delta_error = error - self.last_error

        if (delta_time >= self.sample_time):
            self.PTerm = self.Kp * error
            self.ITerm += error * delta_time

            if (self.ITerm < -self.windup_guard):
                self.ITerm = -self.windup_guard
            elif (self.ITerm > self.windup_guard):
```

```
                self.ITerm = self.windup_guard

            self.DTerm = 0.0
            if delta_time > 0:
                self.DTerm = delta_error / delta_time

            # Remember last time and last error for next calculation
            self.last_time = self.current_time
            self.last_error = error

            self.output = self.PTerm + (self.Ki * self.ITerm) + (self.
Kd * self.DTerm)

    def setKp(self, proportional_gain):
        """Determines how aggressively the PID reacts to the current
error with setting Proportional Gain"""
        self.Kp = proportional_gain

    def setKi(self, integral_gain):
        """Determines how aggressively the PID reacts to the current
error with setting Integral Gain"""
        self.Ki = integral_gain

    def setKd(self, derivative_gain):
        """Determines how aggressively the PID reacts to the current
error with setting Derivative Gain"""
        self.Kd = derivative_gain

    def setWindup(self, windup):
        """Integral windup, also known as integrator windup or reset
windup,
        refers to the situation in a PID feedback controller where
        a large change in setpoint occurs (say a positive change)
        and the integral terms accumulates a significant error
        during the rise (windup), thus overshooting and continuing
        to increase as this accumulated error is unwound
        (offset by errors in the other direction).
        The specific problem is the excess overshooting.
        """
        self.windup_guard = windup

    def setSampleTime(self, sample_time):
        """PID that should be updated at a regular interval.
        Based on a pre-determined sampe time, the PID decides if it
should compute or return immediately.
        """
        self.sample_time = sample_time
```

For testing purposes, we create a simple program for simulation. We need required libraries such as numpy, scipy, pandas, patsy, and matplotlib libraries. First, you should install python-dev for Python development. Type the following commands in your Raspberry Pi Terminal:

```
$ sudo apt-get update
$ sudo apt-get install python-dev
```

When done, you can install numpy, scipy, pandas, and patsy libraries. Open your Raspberry Pi Terminal and type the following commands:

```
$ sudo apt-get install python-scipy
$ pip install numpy scipy pandas patsy
```

The last step is to install the matplotlib library from source code. Type the following commands on your Raspberry Pi Terminal:

```
$ git clone https://github.com/matplotlib/matplotlib
$ cd matplotlib
$ python setup.py build
$ sudo python setup.py install
```

Once the required libraries are installed, we can test our `PID.py` file. Type the following program:

```
import matplotlib
matplotlib.use('Agg')

import PID
import time
import matplotlib.pyplot as plt
import numpy as np
from scipy.interpolate import spline


P = 1.4
I = 1
D = 0.001
pid = PID.PID(P, I, D)

pid.SetPoint = 0.0
pid.setSampleTime(0.01)
```

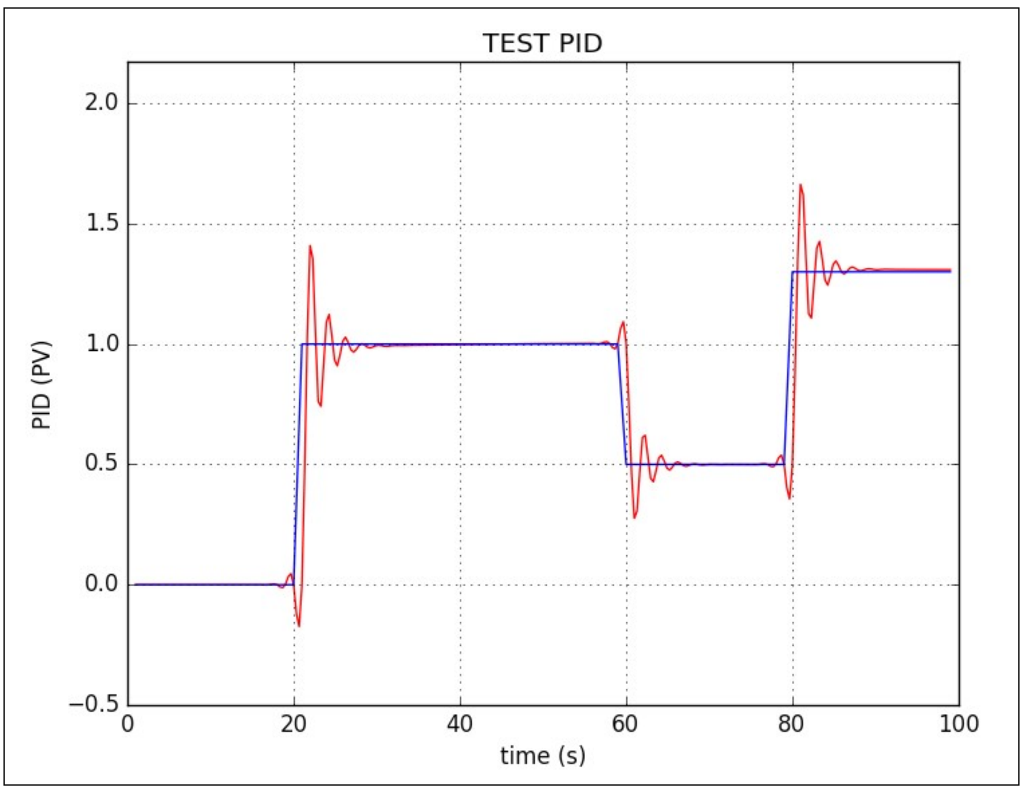
```
total_sampling = 100
feedback = 0

feedback_list = []
time_list = []
setpoint_list = []

print("simulating....")
for i in range(1, total_sampling):
    pid.update(feedback)
    output = pid.output
    if pid.SetPoint > 0:
        feedback += (output - (1 / i))

    if 20 < i < 60:
        pid.SetPoint = 1

    if 60 <= i < 80:
        pid.SetPoint = 0.5

    if i >= 80:
        pid.SetPoint = 1.3

    time.sleep(0.02)

    feedback_list.append(feedback)
    setpoint_list.append(pid.SetPoint)
    time_list.append(i)

time_sm = np.array(time_list)
time_smooth = np.linspace(time_sm.min(), time_sm.max(), 300)
feedback_smooth = spline(time_list, feedback_list, time_smooth)

fig1 = plt.gcf()
fig1.subplots_adjust(bottom=0.15)

plt.plot(time_smooth, feedback_smooth, color='red')
plt.plot(time_list, setpoint_list, color='blue')
plt.xlim((0, total_sampling))
plt.ylim((min(feedback_list) - 0.5, max(feedback_list) + 0.5))
plt.xlabel('time (s)')
plt.ylabel('PID (PV)')
```

```
plt.title('TEST PID')


plt.grid(True)
print("saving...")
fig1.savefig('result.png', dpi=100)
```

Save this program into a file called `test_pid.py`. Then, run this program.

```
$ python test_pid.py
```

This program will generate `result.png` as a result of the PID process. A sample of the output form, `result.png`, is shown in the following figure. You can see that the blue line represents desired values and the red line is an output of PID:



How does it work?

First, we define our PID parameters, as follows:

```
P = 1.4
I = 1
D = 0.001
pid = PID.PID(P, I, D)

pid.SetPoint = 0.0
pid.setSampleTime(0.01)

total_sampling = 100
feedback = 0

feedback_list = []
time_list = []
setpoint_list = []
```

After that, we compute the PID value during sampling time. In this case, we set the desired output value as follows:

- Desired output `1` for sampling from 20 to 60
- Desired output `0.5` for sampling from 60 to 80
- Desired output `1.3` for sampling more than 80

```
for i in range(1, total_sampling):
    pid.update(feedback)
    output = pid.output
    if pid.SetPoint > 0:
        feedback += (output - (1 / i))

    if 20 < i < 60:
        pid.SetPoint = 1

    if 60 <= i < 80:
        pid.SetPoint = 0.5

    if i >= 80:
        pid.SetPoint = 1.3

    time.sleep(0.02)

    feedback_list.append(feedback)
    setpoint_list.append(pid.SetPoint)
  time_list.append(i)
```

The last step is to generate a report and is saved to a file called `result.png`:

```
time_sm = np.array(time_list)
time_smooth = np.linspace(time_sm.min(), time_sm.max(), 300)
feedback_smooth = spline(time_list, feedback_list, time_smooth)

fig1 = plt.gcf()
fig1.subplots_adjust(bottom=0.15)

plt.plot(time_smooth, feedback_smooth, color='red')
plt.plot(time_list, setpoint_list, color='blue')
plt.xlim((0, total_sampling))
plt.ylim((min(feedback_list) - 0.5, max(feedback_list) + 0.5))
plt.xlabel('time (s)')
plt.ylabel('PID (PV)')
plt.title('TEST PID')


plt.grid(True)
print("saving...")
fig1.savefig('result.png', dpi=100)
```

Controlling room temperature using PID controller

Now we can change our PID controller simulation using the real application. We use DHT-22 to check a room temperature. The output of measurement is used as feedback input for the PID controller.

If the PID output positive value, then we turn on heater. Otherwise, we activate cooler machine. It may not good approach but this good point to show how PID controller work.

We attach DHT-22 to GPIO23 (BCM). Let's write the following program:

```
import matplotlib
matplotlib.use('Agg')

import PID
import Adafruit_DHT
import time
import matplotlib.pyplot as plt
import numpy as np
```

```
from scipy.interpolate import spline

sensor = Adafruit_DHT.DHT22

# DHT22 pin on Raspberry Pi
pin = 23

P = 1.4
I = 1
D = 0.001
pid = PID.PID(P, I, D)

pid.SetPoint = 0.0
pid.setSampleTime(0.25)  # a second

total_sampling = 100
sampling_i = 0
measurement = 0
feedback = 0

feedback_list = []
time_list = []
setpoint_list = []

print('PID controller is running..')
try:
    while 1:
        pid.update(feedback)
        output = pid.output

        humidity, temperature = Adafruit_DHT.read_retry(sensor, pin)
        if humidity is not None and temperature is not None:
            if pid.SetPoint > 0:
                feedback += temperature + output

            print('i={0} desired.temp={1:0.1f}*C temp={2:0.1f}*C pid.
out={3:0.1f} feedback={4:0.1f}'
                 .format(sampling_i, pid.SetPoint, temperature,
output, feedback))
            if output > 0:
                print('turn on heater')
            elif output < 0:
                print('turn on cooler')
```

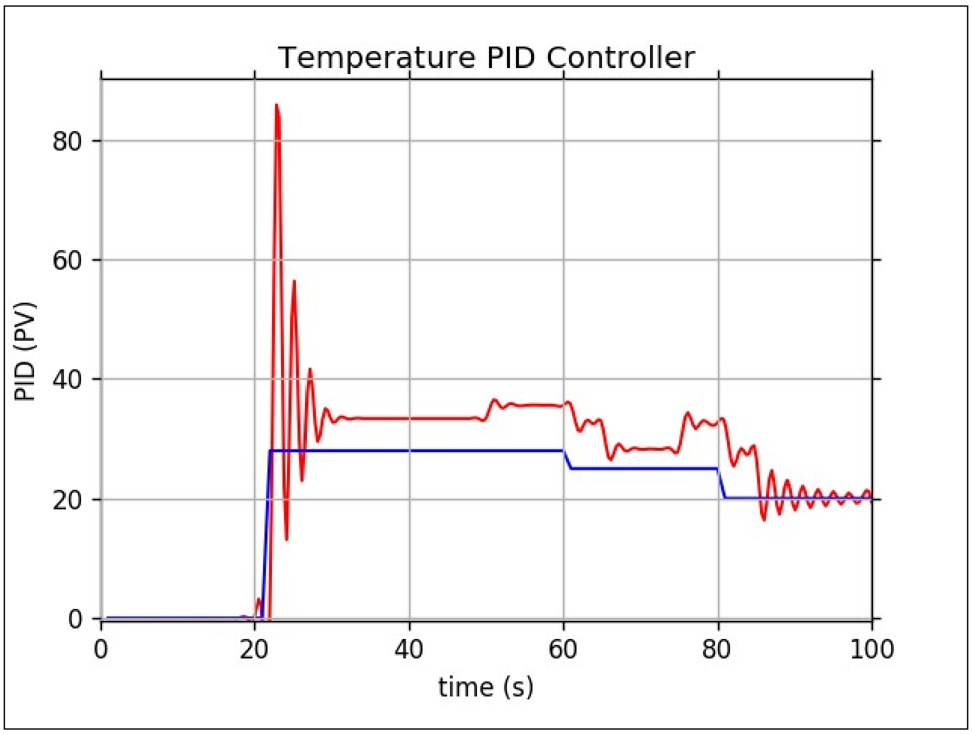
```
        if 20 < sampling_i < 60:
            pid.SetPoint = 28  # celsius

        if 60 <= sampling_i < 80:
            pid.SetPoint = 25  # celsius

        if sampling_i >= 80:
            pid.SetPoint = 20  # celsius

        time.sleep(0.5)
        sampling_i += 1

        feedback_list.append(feedback)
        setpoint_list.append(pid.SetPoint)
        time_list.append(sampling_i)

        if sampling_i >= total_sampling:
            break

except KeyboardInterrupt:
    print("exit")


print("pid controller done.")
print("generating a report...")
time_sm = np.array(time_list)
time_smooth = np.linspace(time_sm.min(), time_sm.max(), 300)
feedback_smooth = spline(time_list, feedback_list, time_smooth)

fig1 = plt.gcf()
fig1.subplots_adjust(bottom=0.15, left=0.1)

plt.plot(time_smooth, feedback_smooth, color='red')
plt.plot(time_list, setpoint_list, color='blue')
plt.xlim((0, total_sampling))
plt.ylim((min(feedback_list) - 0.5, max(feedback_list) + 0.5))
plt.xlabel('time (s)')
```

```
plt.ylabel('PID (PV)')
plt.title('Temperature PID Controller')


plt.grid(True)
fig1.savefig('pid_temperature.png', dpi=100)
print("finish")
```

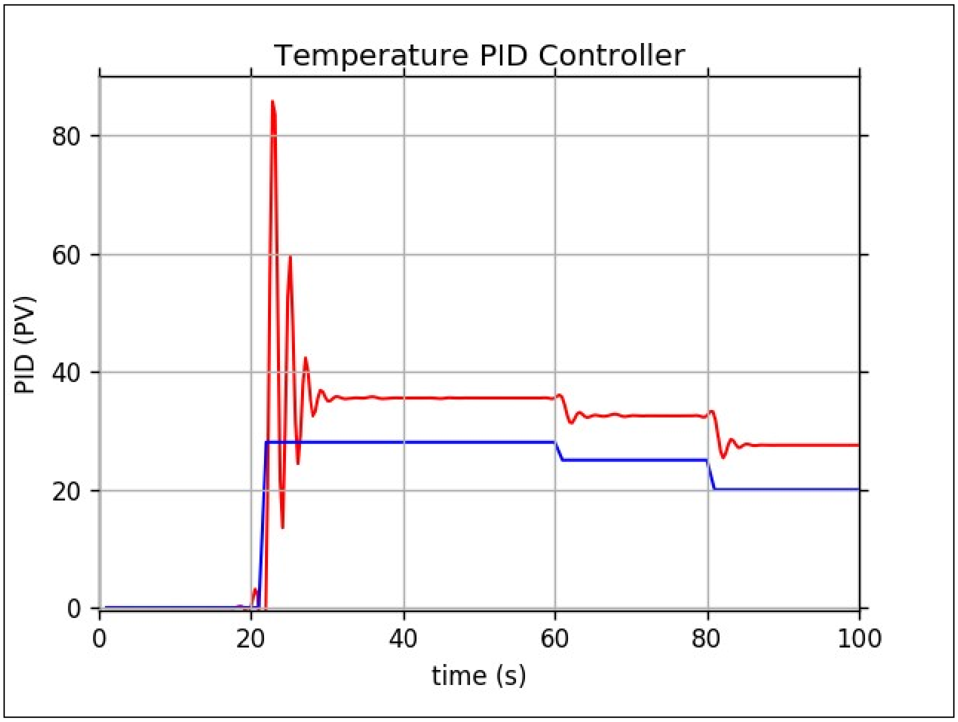
Save this program to a file called `ch01_pid.py`. Now you can this program:

```
$ sudo python ch01_pid.py
```

After executing the program, you should obtain a file called `pid_temperature.png`. A sample output of this file can be seen in the following figure:



If I don't take any action either turning on a cooler or turning on a heater, I obtain a result, shown in the following figure:



How does it work?

Generally speaking, this program combines our two topics: reading current temperature through DHT-22 and implementing a PID controller. After measuring the temperature, we send this value to the PID controller program. The output of PID will take a certain action. In this case, it will turn on cooler and heater machines.

Summary

In this chapter, we have reviewed some basic statistics and explored various Python libraries related to statistics and data science. We also learned about several IoT device platforms and how to sense and actuate.

For the last topic, we deployed a PID controller as a study sample how to integrate a controller system on an IoT project. In the following chapter, we will learn how to build a decision system for our IoT project.

References

The following is a list of recommended books from which you can learn more about the topics in this chapter:

1. Richard D. De Veaux, Paul F. Velleman, and David E. Bock, *Stats Data and Models*, 4th Edition, 2015, *Pearson Publishing*.
2. Sheldon M. Ross, *Introductory Statistics*, 3rd Edition, Academic Press, 2010.