Industrial Control

Student Guide

Version 1.1

Note regarding the accuracy of this text:
Many efforts were taken to ensure the accuracy of this text and the experiments, but the potential for errors still exists. If you find errors or any subject requiring additional clarification, please report this to stampsinclass@parallaxinc.com so we can continue to improve the quality of our documentation.

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The Stamps in Class list is for students and educators who wish to share educational ideas. To subscribe to this list, go to http://www.stampsinclass.com and look for the E-groups list. This list generates about five messages per day.

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Preface

Industrial process control is a fascinating and challenging area of electronics technology and nothing has revolutionized this area like the microcontroller. The microcontroller has added a level of intelligence to the evaluation of data and a level of sophistication in the response to process disturbances. Microcontrollers are embedded as the "brains" in both manufacturing equipment and consumer electronic devices.

Process control involves applying technology to an operation that alters raw materials into a desired product. Virtually everything that you use or consume has undergone some type of automatic process control in its production. In a manufacturing environment, automatic process control also provides higher productivity and better product consistency while reducing production costs.

This text is intended to introduce you to the concepts and characteristics of microcontroller-based process control with the following experiment-based themes:

a) Writing a procedural program from a flowchart for sequential process-control.
b) Using pushbuttons, counting cycles and understanding simple I/O processes that form a system "under control".
c) Continuous process-control beginning with on-off control to more complex differential gap with multiple levels of control action.
d) Proportional-integral-derivative control of a small desktop heating system.
e) Time-based control of the above and introduction to data logging.

The hardware needed in the experiments to simulate the process has been kept to a bare minimum. While the microcontroller is the "brains" of the process, it is not the "muscle." Actual applications require the microcontroller to read and control a wide variety of input and output (I/O) devices. Simple breadboard mounted pushbutton switches are used to simulate the action of mechanical and electro-mechanical switches found in industry. Visible light emitting diodes, small fans, and low-wattage resistors simulate motor starters and HVAC equipment. Information included in the experiments will help you understand the electrical interfacing of "real world" I/O devices to the BASIC Stamp.

The physical nature of the elements in a system determines the most appropriate mode of control action. The dynamics of a process include a study of the relationship of input disturbances and output action on the measured variables. It is difficult to understand the dynamics of a process without being able to "see" this relationship. For the authors, this defined a need to develop a graphical interface for the BASIC Stamp; hence the creation and release of StampPlot Lite. This software allows digital and analog values to be plotted on graphs, and time-stamped data and messages to be stored. StampPlot Lite is used throughout the experiments, and is especially helpful as you investigate the various modes of process control. Typical screen shots from program runs are included.

This text is the first major revision and we have strived to make it better than the first. Some changes and additions include:

a) Addition of a 7^{th} section on Time-Based control.
b) A total rewrite of the PID section to better demonstrate and explain the theory.
c) The additions of FET and PWM sample-and-hold circuitry and theory.
d) The reworking of numerous example programs including more flowcharts and program explanations.

We thank our editors Ms. Cheri Barrall and Dale Kretzer, and of course Ken Gracey and Russ Miller of the Parallax staff for their review and improvement of this text. Further, we thank Dr. Clark Radcliffe of Michigan State University for his in-depth review. A variety of additional Parallax educational customers too numerous to list also provided valuable feedback for this second revision.

The authors are instructors at Southern Illinois University in Carbondale in the Electronic Systems Technologies program and also partners of a consulting and software company, SelmaWare Solutions. Visit the website to see examples of StampPlot Pro specifically tailored to users of this text.

We invite your comments and feedback. Please contact at us through our website, and copy all error changes to Parallax at stampsinclass@parallaxinc.com so the text may be revised.

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Electronic Systems Technologies http://www.selmaware.com
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Audience and Teacher's Guide

This text is aimed at an audience ages 17 and older. Effective during the first publication of this text in June, 2000, there is no Teacher's Guide edition planned. If a Teacher's Guide were to be published, it would likely be available the first part of year 2002. Solving these experiments presents no difficult technical hurdles, and can be done with a bit of patience.

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Experiment #1: Flowcharting and StampPlot Lite

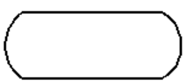
A flowchart is a detailed graphic representation illustrating the nature and sequencing of an operation on a step-by-step basis. A flowchart may be made of an everyday task such as driving to the store. How many steps are involved in this simple task? How many decisions are made in getting to the store? A formalized operation such as baking cookies can be flowcharted, whether on a small-scale process in your kitchen or on a very large scale in a commercial bakery. And, of course, a flowchart also may be made of the steps and decisions necessary for a computer or microcontroller to carry out a task.

A relatively simple process is usually easy to understand and flows logically from start to finish. In the case of baking cookies, the steps involved are fairly easy. A recipe typically requires mixing the required ingredients, forming the cookies and properly baking them. There are several decisions to make: Are the ingredients mixed enough? Is the oven pre-heated? Have the cookies baked for the recommended time?

As processes become more complex, however, it is equally more difficult to chart the order of events needed to reach a successful conclusion. A BASIC Stamp program may have several dozen steps and possibly a number of "if-then" branches. It can be difficult to grasp the flow of the program simply by reading the code.

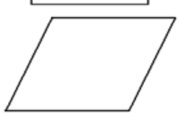
A flowchart is made up of a series of unique graphic symbols representing actions, functions, and equipment used to bring about a desired result. Table 1.1 summarizes the symbols and their uses.

Table 1.1: Flowchart Symbols

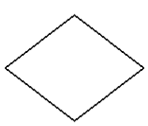


Start/Stop box indicates the beginning and end of a program or process.

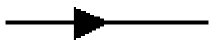
Process box indicates a step that needs to be accomplished.



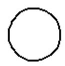
Input/Output box indicates the process requires an input or provides an output.



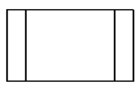
Decision box indicates the process has a choice of taking different directions based on a condition. Typically, it is in the form of a
yes-no question.



Flowline is used to show direction of flow between symbols.



Connector box is used to show a connection between points of a single flowchart, or different flowcharts.



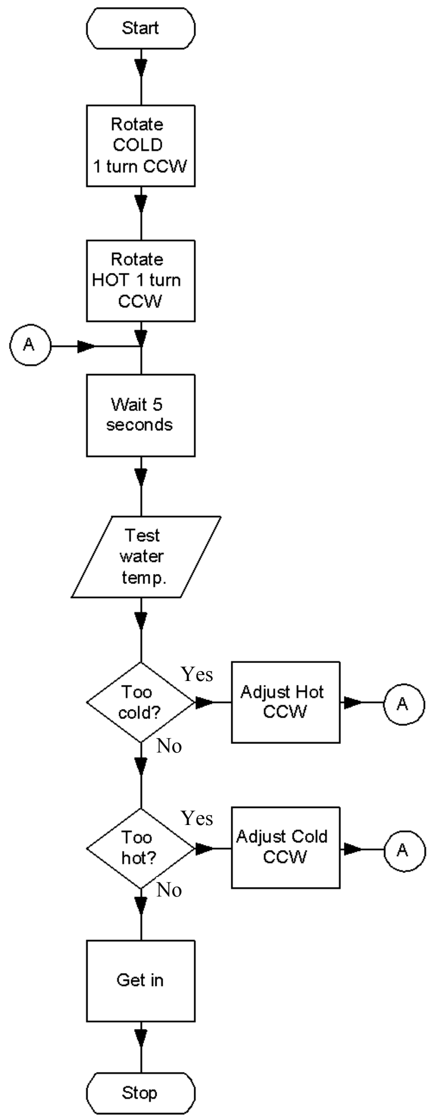
Sub-routine or sub-process box indicates the use of a defined routine or process.

Example #1: Adjusting the Temperature of a Shower

Let's take an example flowchart of an everyday task: adjusting the temperature for a shower. The process of adjusting the water temperature has several steps involved. The water valves are initially opened, we wait a while for the temperature to stabilize, test it, and make some decisions for adjustments accordingly. If the water temperature is too cold, the hot valve is opened more and we go back to test it again. If the water is too hot, the cold valve is opened more. Once we make this adjustment, we go back to the point where we wait for a few seconds before testing again. Of course this doesn't take into account whether the valves are fully opened. Steps may be inserted during the temperature adjustment procedure to correct for this condition. Figure 1.2 shows a flowchart of this process.

This example demonstrates a process that may be used in adjusting the temperature, but could it also be the steps in a microcontroller program? Sure! The valves may be adjusted by servos, and the water temperature determined with a sensor. In most cases, a simple process we go through can be quite complex for a microcontroller. Take the example of turning a corner in a car. Can you list all the various inputs we process in making the turn?

Figure 1.1: Shower Temperature Example

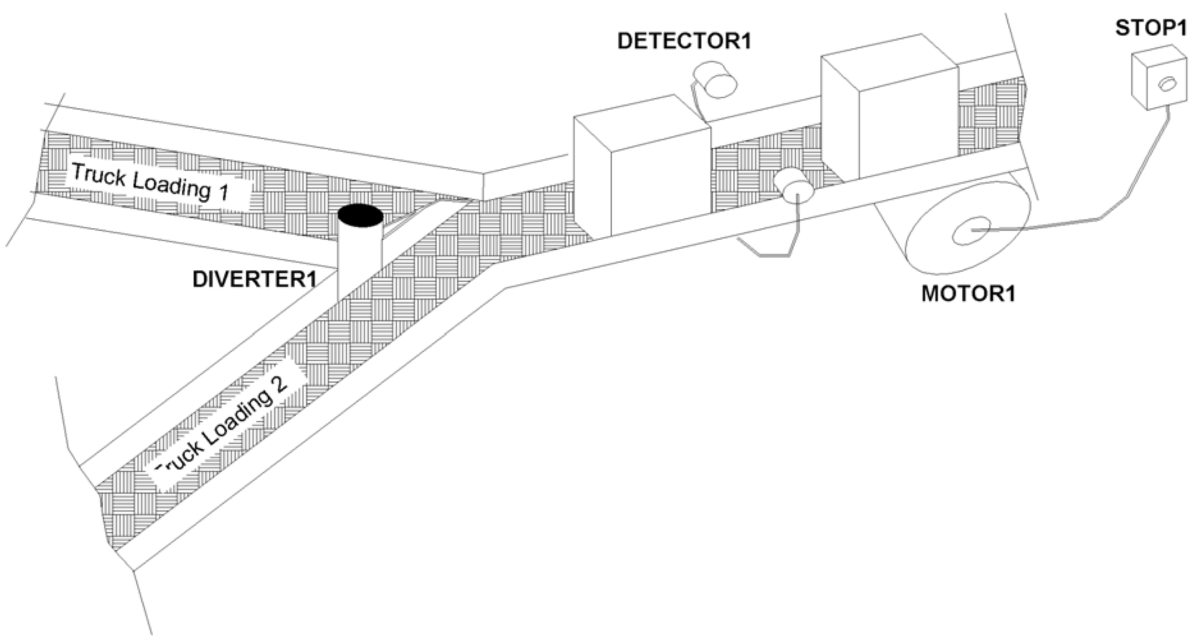


Example #2: Conveyor Counting Example

Let's look at a real scenario and develop a flowchart for it. In a manufacturing plant, items are boxed and sent down a conveyor belt to one of two loading bays with trucks waiting. Each truck can hold 100 boxes. As the boxes arrive, workers place them on the first truck. After that truck is full, the boxes must be diverted to the second truck so the loaded truck can be moved out and an empty one moved into position. Also, in the event of an emergency or problem, there must be a means of stopping the conveyor.

The physical aspects of the scenario are illustrated in Figure 1.2. The motor for the belt is labeled MOTOR1. The sensor to detect the boxes as they pass is labeled DETECTOR1. The lever to direct boxes to one truck conveyor or the other is labeled DIVERTER1. The emergency stop button is labeled STOP1.

Figure 1.2: Conveyor Counting Example



Let's list in order a brief description of what must occur:

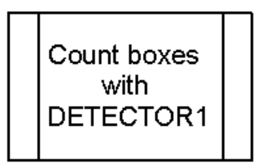
- Start the conveyor motor.
- Count the boxes as they pass.
- When 100 boxes have passed, switch the diverter to the opposite position.
- Whenever the emergency stop is pressed, stop the conveyor.

Now that we know the basic steps involved, let's develop a flowchart for the process. Let's begin by looking at the simple process flow in Figure 1.3 on the following page.

Notice the placement of the Input/Output box for checking the emergency stop button, STOP1. It ensures the button is tested during every cycle. What if we had placed it following the 100-count decision box? How long would it have taken from when the button was pushed until the conveyor stopped?

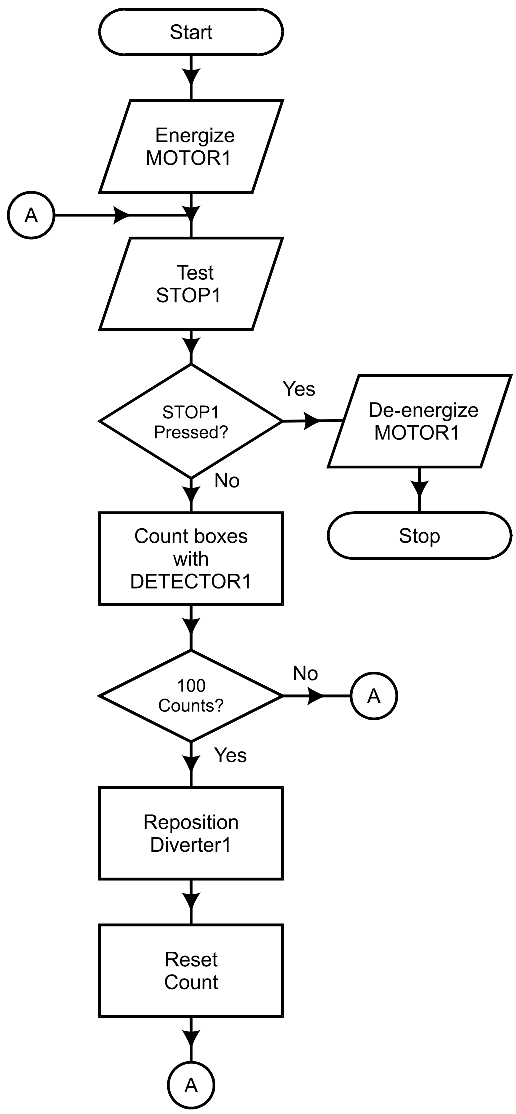
Does the flowchart describe everything our program needs to do? Definitely not, but it is a good start at determining the overall flow of the process. Look at the "Count Boxes with DETECTOR1" Process box. How exactly is this carried out? We may need to develop a flowchart to describe just this routine. If a process needs further detailing, we might replace the Process box with a Sub-Process box as shown in Figure 1.4.

Figure 1.4: Sub-Process Box



How involved is it to simply count a box passing by a detector? If DETECTOR1 is activated by "going low," do we count? When the detector stays low, how do we keep from recounting it again the next time our program passes that point? What if the box bounces on the conveyor as it enters our beam? How do we keep from performing multiple counts of the box? These answers may not be as simple as they seem. Even when performing a task as simple as counting a passing box, many variables must be taken into account.

Figure 1.3: Conveyor Counting Flowchart



Another consideration is the output of our detector. Can we directly measure the output using one of the BASIC Stamp inputs, or is there some circuitry needed to condition the signal first?

Let's consider an output in our conveyor counting example. How do we energize the motor? It is doubtful the 5-volt, milliamp-rated output of the BASIC Stamp will be able to drive a motor of sufficient horsepower to move a conveyor! How do we condition an output of the BASIC Stamp to control a higher voltage and current load?

These issues will be considered as you work through the chapters in this text. What may seem simple for us to do as humans may require some sophisticated algorithms for a microcontroller to mimic. We will use readily available electronic components, a BASIC Stamp module, and the Board of Education to simulate some complex industrial control processes.

Exercises

Exercise #1: Flowchart Design

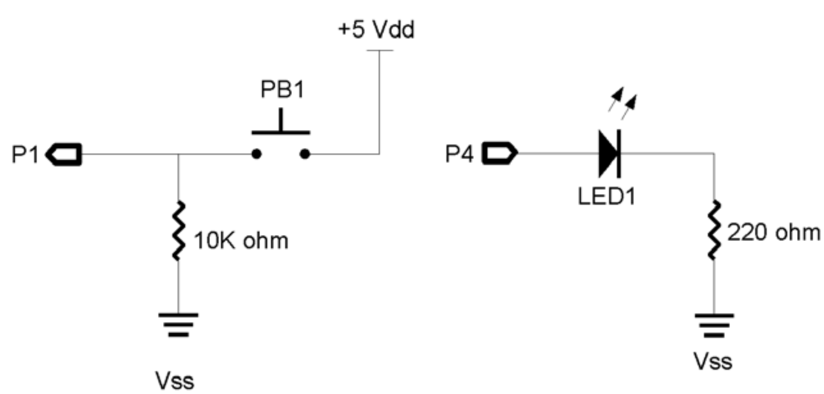
Develop a flowchart that will energize a heater below 100 degrees and de-energize it above 120 degrees.

Exercise #2: LED Blinking Circuit

We'll use a simple circuit to demonstrate a flowchart process and the program to perform the task. You'll need to build the circuit shown in Figure 1.5. The following parts will be required for this experiment:

(1) LED, green
(2) 220-ohm resistors
(1) 10K-ohm resistor
(1) Pushbutton
(1) 10K-ohm multi-turn potentiometer
(1) 1 uF capacitor
(Miscellaneous) jumper wires

Figure 1.5: Exercise #2 Blinking Circuit Schematic

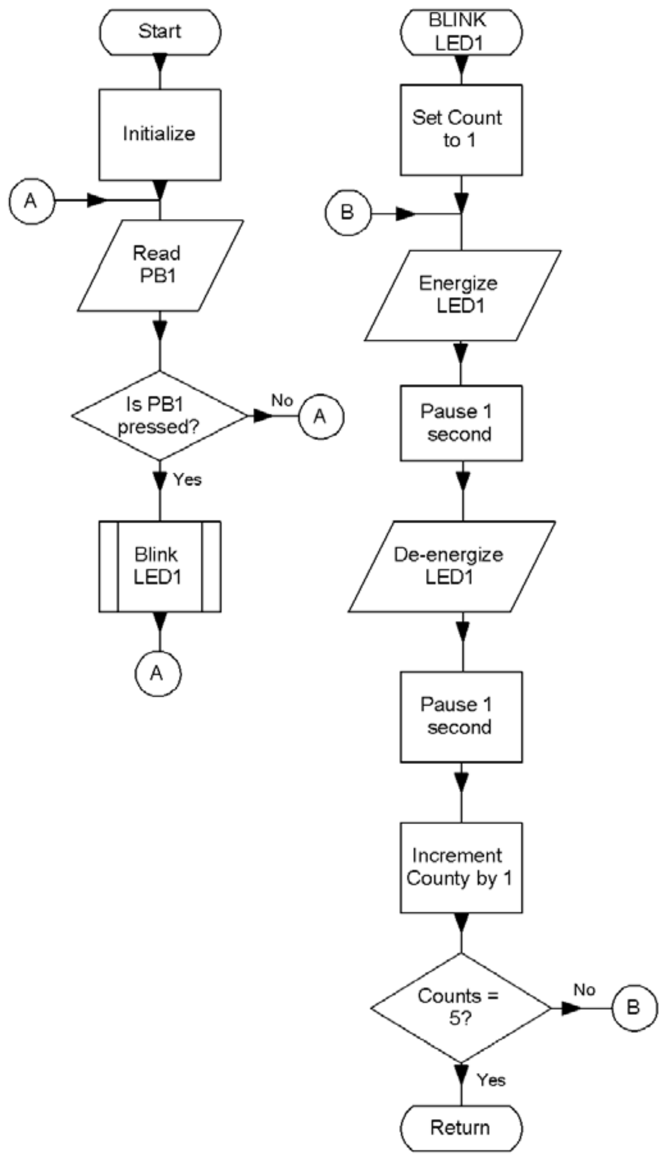


The circuit you are building consists of a single input button and a single output LED. Here is the process we want to perform: when the button (PB1) is pressed, blink the green LED (LED1) five times over 10 seconds. The flowchart for our process is shown in Figure 1.6.

Notice a few things about the flowchart. Our main loop is fairly simple. In the Initialize process box, we will define any variables needed and set initial outputs (LED off) and will loop unless PB1 is pressed, which calls our subroutine, **blink_led1**. Our subroutine doesn't begin with "Start," but the name of the process, so that we can identify it. The flowchart describes a process that we will repeat five times, alternately energizing and de-energizing our LED for one second each time.

Now that we have a flowchart to describe the process, how do we program it in PBASIC? Programmatically, we can sense PB1 using the **IN** statement. We have two ways we can call our subroutine. If the condition is true (1), then we can branch to our subroutine directly using an **IF-THEN** statement. This would be treated as a PBASIC **GOTO**. Once this completes, we would need to **GOTO** back to our main loop. Or, if the condition is false (0), we can branch back to our main loop from the **IF-THEN**, and use a **GOSUB** command to branch to our subroutine when true. We can then use a **RETURN** when our subroutine is complete.

Figure 1.6: Exercise #2 Blinking Circuit Flowchart



In our **`blink_led1`** subroutine, we need a loop to repeat five times. Choices for accomplishing this task may be to set up a variable we increment and check during each repetition, or use the **`FOR-NEXT`** statement to accomplish it for us.

The flowchart describes the general steps involved in accomplishing a process. The code required is flexible as long as it faithfully completes the process as described. The same flowchart may be used in multiple languages or systems and even for humans!

Program 1.1 is one way to write the code for our blinking LED process. Enter the text in the BASIC Stamp editor, download it to the BASIC Stamp, and press the pushbutton of the circuit you built. If it works properly, the LED will blink five times after the pushbutton is pressed.

```
'Program 1.1; Blinking LED Example
Cnt     VAR     BYTE                  'Variable for counting
PB1     VAR     IN1                   'Variable for PB1 input
LED1    CON     4                     'Variable for LED1 output

INPUT 1                               'Set PB1 as input
OUTPUT 4                              'Set LED1 as output

LOW LED1                              'Turn off LED

Start:
  IF PB1 = 0 then Start               'Not Pressed? Go back to loop
  GOSUB Blink_LED1                    'If it was pressed then perform subroutine
GOTO Start                            'After return, go back to start

Blink_LED1:                           'Subroutine to blink LED 5 repetitions
  For Cnt = 1 to 5                    'Setup loop for 5 counts
    HIGH LED1                         'Turn ON LED
    PAUSE 1000                        'Wait 1 second
    LOW LED1                          'Turn off LED
    PAUSE 1000                        'wait 1 second
  NEXT                                'Repeat loop until done

RETURN                                'return back to after gosub call
```

Programming Challenge

Flowchart and program a process where the LED will blink four times a second while the pushbutton is NOT pressed!

<u>Exercise #3: Analog Data</u>

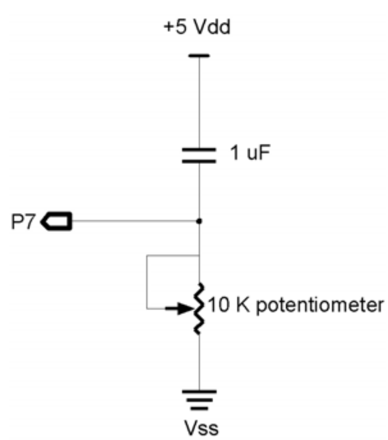
In many instances a process involves analyzing and responding to analog data. Digital data is simply on or off (1 or 0). This is comparable to the simple light switches in our homes. The light is on or it is off. Analog data on the other hand is a range of values. Some examples include the level of lighting if we use a dimmer switch instead of an on/off switch, or the temperature of the water coming out of our shower nozzle.

There are several methods to bring analog data into a microcontroller, such as using an analog-to-digital (A/D) converter that changes analog values into digital values that may be processed by the microcontroller. Another method used by the BASIC Stamp is a resistor/capacitor network to measure the discharge or charge time of the capacitor. By varying the amount of the resistance, we can affect and measure the time it takes the capacitor to discharge. In this experiment, resistance is set by manually adjusting a variable resistor. But the device may be more sophisticated, such as a photo-resistive cell that changes resistance depending on the amount of light shining on it, or a temperature sensor. More discussion on analog data is found in later sections, but for now let's perform a simple process-control experiment using an analog value.

Add the RC network shown in Figure 1.7 to your circuit from the previous experiment. It uses these parts:

(1) 1 uF capacitor
(1) 10K potentiometer

Figure 1.7: Schematic for Analog Data circuit added to Exercise #3



PBASIC Command Quick Reference: RCTime

`RCTIME pin, state, resultvariable`

- `Pin` is the I/O pin connected to the RC network.
- `State` is the input voltage of that pin.
- `Resultvariable` is normally a word-length variable containing the results of the command.

.

The PBASIC command we will use to read the analog value of the potentiometer is **`RCTIME`**. A typical block of code to read the potentiometer is as follow:

```
Pot     VAR WORD
HIGH 7
PAUSE 10
RCTIME 7, 1, Pot
```

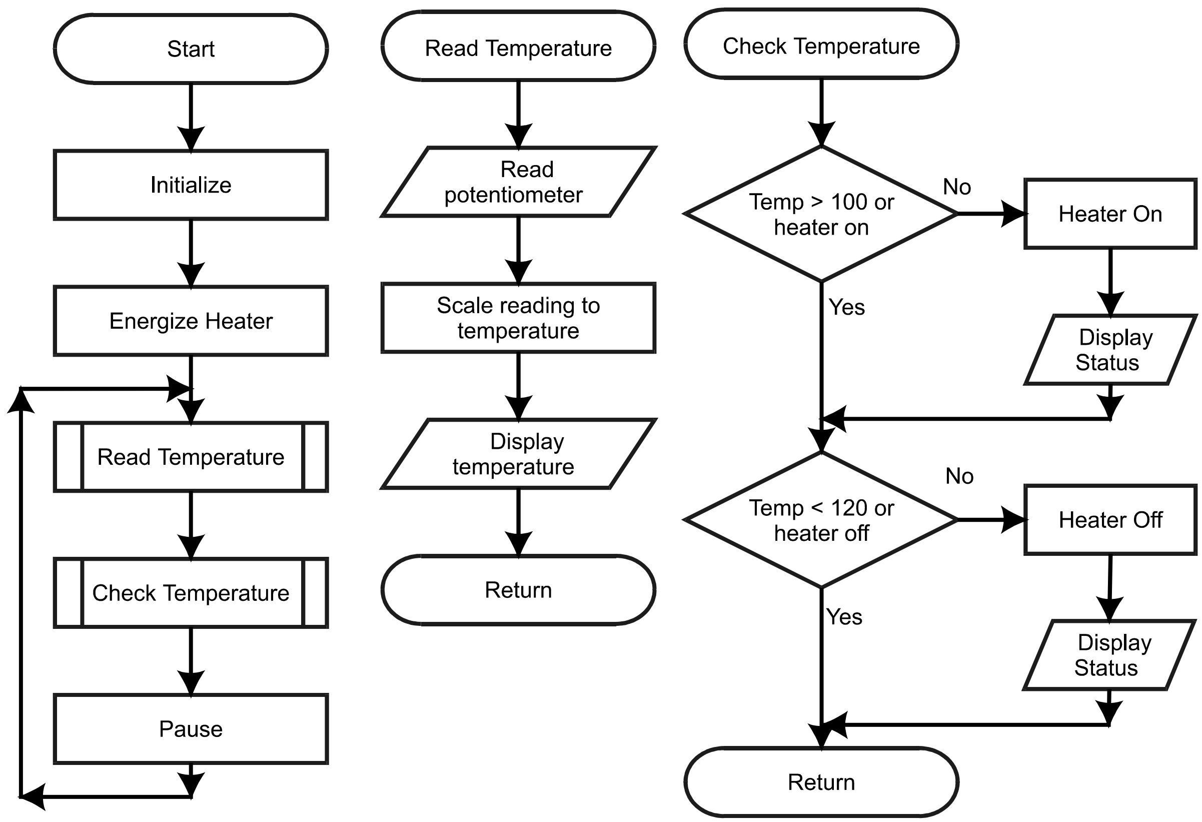
In order for the BS2 to read the potentiometer, the routine needs to take the following steps:

- +5V (HIGH) is applied to both sides of the capacitor to discharge it.
- The BASIC Stamp pauses long enough to ensure the capacitor is fully discharged.
- When **`RCTIME`** is executed, Pin 7 becomes an input. Pin 7 will initially read a high (1) because an uncharged capacitor acts as short.
- As the capacitor charges through the resistor, the voltage at Pin 7 will fall.
- When the voltage at Pin 7 reaches 1.4 V (falling), the input state is read as low (0), stopping the process and storing a value in **`Pot`** proportional to the time required for the capacitor to charge.

The greater the resistance, the longer the time required for a capacitor to discharge; therefore, the higher the value of **`Pot`**. In this manner, we can acquire an analog value from a simple input device.

Let's write a process-control program to make use of this input. Our process will be one where temperature is monitored and a heater energizes below 100 degrees and de-energized above 120 degrees. The potentiometer will represent a temperature sensor and the LED will represent the heater being energized. We will use the debug window to display our temperature and the status of the heater. The maximum potentiometer value, with this combination of resistor and capacitor, may reach 5000, so we will divide it by 30 to scale it to a more reasonable range. Figure 1.8 is the flowchart of the process.

Figure 1.8: Exercise 3 - Simple Heater Flowchart



Enter and run Program 1.2. Monitor the value in debug window while adjusting the potentiometer and note what occurs as the value rises above 120 and below 100.

```
'Program 1.2, Simple Heater
LED1    VAR     OUT4                    'LED1 is on P4
RC      CON     7                       'RC network is on Pin 7
Temp    VAR     WORD                    'Pot is a variable to hold results

OUTPUT 4                                'Setup LED as output
LED1 = 1                                'Energize initially

Main:
  GOSUB ReadTemp                        'Read pot value as temperature
  GOSUB CheckTemp                       'check temp to setpoint
  PAUSE 250
GOTO Main

ReadTemp
  HIGH RC                               'Read Potentiometer
  PAUSE 10
  RCTIME RC, 1, Temp
  Temp = Temp/30                        'Scale the results down,
                                        'store as temperature
  DEBUG "Temp = ",dec Temp, CR
RETURN

CheckTemp:                              'If Temp > 100, or heat already on,
                                        'check if should be off
  IF (Temp > 100) OR (LED1 = 1) THEN CheckOff
  LED1 = 1                              'If not, then energize and display
  DEBUG "The heater energized",CR

CheckOff:                               'If Temp < 120 or heat is off already, all done
  IF (Temp < 120) OR (LED1 = 0) THEN CheckDone
  LED1 = 0                              'if not, then energize and display
  DEBUG "The heater de-energized", CR
CheckDone:
RETURN
```

Programming Challenge

Modify the process flowchart and program so the LED indicates an air conditioner cycling between 70 and 75 degrees.

Exercise #4: Using StampPlot Lite

While the debug window for the BASIC Stamp is very useful for obtaining data and information from the BASIC Stamp, it can be difficult to visualize the data without careful scrutiny. Is the temperature increasing or decreasing? How quickly is it changing? At what point did the output change? What temperature is it cycling around?

Enter StampPlot Lite! StampPlot Lite (SPL) was specifically developed for this text. SPL accepts data from the BS2 in the same fashion the debug window does, only SPL interprets the data and performs on of 4 actions based on the structure of the data:

- A value is plotted on an analog scale in real time.
- A binary value starting with % is plotted as digital traces in real time.
- Strings beginning with ! are interpreted as instructions to control and configure SPL.
- Any other string is listed as a message at the bottom of SPL and optionally time-stamped.

A main rule of SPL is that each line must end in a carriage return (13 or CR).

Please review Appendix A for a more in-depth discussion of StampPlot Lite.

If you have not yet installed StampPlot Lite, install it on your computer by downloading it from http://www.stampsinclass.com. Double-click the setup button and install it in your designated directory.

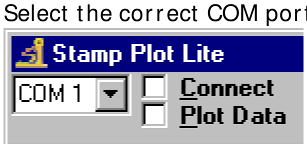
Let's take another look at Program 1.2, our simple heater, but this time using StampPlot Lite to help visualize the process. Program 1.2 has been rewritten as Program 1.3 to utilize StampPlot Lite (bold lines are added/modified from program 1.2).

```
'Program 1.3; Simple Heater using StampPlot Lite
'Configure StampPlot Lite
PAUSE 500
DEBUG "!SPAN 50,150",CR                     'Set span for 50-150
DEBUG "!TMAX 60",CR                         'Set for 60 seconds
DEBUG "!PNTS 500",CR                        '500 data points per plot
DEBUG "!TITL Simple Heater Control",CR      'Title the form
DEBUG "!SHFT ON",CR                         'Allow plot to shift at max
DEBUG "!TSMP ON",CR
DEBUG "!PLOT ON",CR                         'Enable plotting
DEBUG "!RSET",CR                            'Reset Plot

LED1    VAR     OUT4                        'LED1 is on P4
RC      CON     7                           'RC network is on Pin 7
Temp    VAR     WORD                        'Pot is a variable to hold results

OUTPUT 4                                    'Setup LED as output
LED1 = 1                                    'Energize initially
```

```
Main:
  GOSUB ReadTemp                             'Read pot value as temperature
  GOSUB CheckTemp                            'check temp. to setpoint
  PAUSE 250
GOTO Main

ReadTemp
  HIGH RC                                    'Read Potentiometer
  PAUSE 10
  RCTIME RC, 1, Temp
  Temp = Temp/30                             'Scale the results down,
                                             'store as temperature
  DEBUG DEC Temp, CR                         'Send temperature value
  DEBUG IBIN LED1,CR                         'Send LED Status
RETURN

CheckTemp:                                   'If Temp > 100, or heat already on,
                                             'check if should be off
  IF (Temp > 100) OR (LED1 = 1) THEN CheckOff
  LED1 = 1                                   'If not, then energize and display
  DEBUG "The heater energized",CR
  DEBUG "!USRS The heater is energized!",CR  'Update SPL status bar

CheckOff:                                    'If Temp < 120 or heat is off, all done
  IF (Temp < 120) OR (LED1 = 0) THEN CheckDone
  LED1 = 0                                   'if not, then energize and display
  DEBUG "The heater de-energized", CR
  DEBUG "!USRS The heater is de-energized!",CR 'Update SPL Status Bar
CheckDone:
RETURN
```

Download this program to your BASIC Stamp, and follow these instructions to use StampPlot Lite.

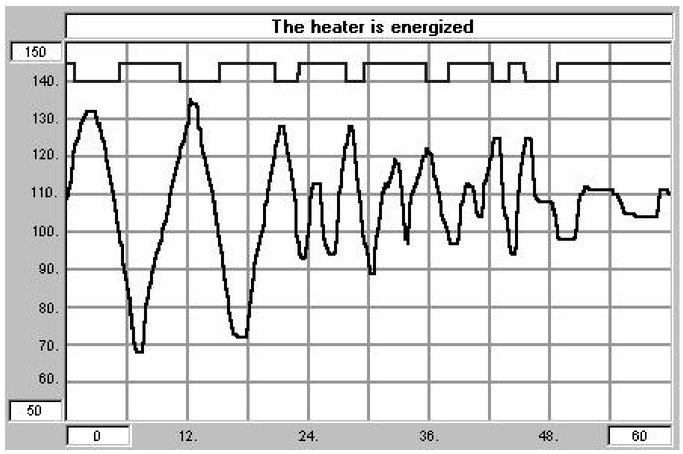
- Start StampPlot Lite by using your Windows Start button and going to Programs/StampPlot/StampPlot Lite.
- Enter and run Program 1.3 on your BASIC Stamp.
- Close the BASIC Stamp editor's blue debug window.
- Select the correct COM port in StampPlot Lite and click 'Connect.'



-
- Reset the BASIC Stamp by pushing the button on the Board of Education. Now you're ready to use this unique software utility.

At this point you should see data being plotted. Adjust the 10K-ohm potentiometer with your fingers or a small screwdriver. The analog line displays the value of the potentiometer. The digital trace at the top displays the status of the LED indicator. Figure 1.9 is a sample capture of the plot from our circuit.

Figure 1.9: StampPlot Lite Graph of Exercise #4



Note the correlation between the analog value and the switching of the digital output. Use the various controls on StampPlot Lite to become familiar with the functions and features. Analyze Program 1.3 and note the various configuration settings and data sent to the application. Refer to Appendix A for additional information on StampPlot Lite if you are having problems understanding the basics of the software utility.

Programming Challenge

Modify your air conditioner challenge from Exercise #2 to use StampPlot Lite. Configure your program to transmit data approximately every 0.5 seconds. Calculate the number of data points needed to fill the screen within a maximum of 60 seconds, and test.

Just for fun!

Enter and run the following program. The potentiometer simulates a single-handle shower (mixer) valve with adjustment delay. Adjust the shower temperature for a constant 110 degrees. See how fast you can stabilize the temperature at the set point! Press the reset button on the Board of Education and try again. We'll leave it up to you to figure out the program.