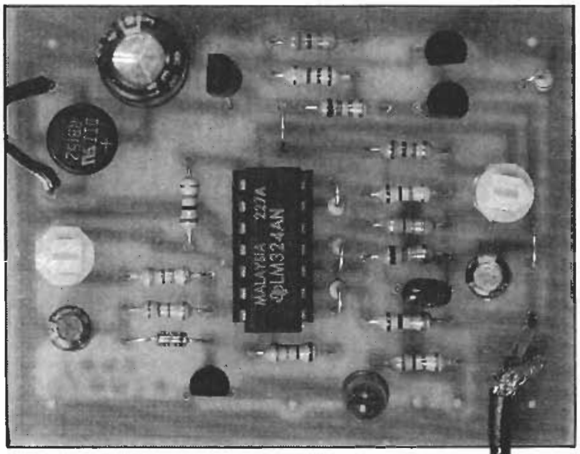
electronic THERMOSTAT



This solid-state thermostat can replace those old mechanical units—at a cost of less than twenty dollars!

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THE MEASUREMENT AND CONTROL of temperature is one area in which electronics has had a great impact. From "set back" home thermostats to laboratory controllers with ±0.001-degree accuracy and digital fever thermometers, the use of electronics has all but eliminated mechanical systems.

Many methods are used for measuring and controlling temperature, including the expansion of mercury or alcohol, bimetallic strips, thermistors, silicon sensors, and thermocouples. Each has its advantages and disadvantages.

The author was recently asked to design an inexpensive thermostat to replace some old bi-metallic-type thermostats. The new thermostat had to meet the ±5°C accuracy of the bi-metallic strips, have a −50 to +150°C range, and cost less than twenty dollars. A simple solid-state thermostat was the only solution.

Whether you're trying to keep a fish-tank temperature to within 1°C, maintain working temperature for PC-board etchant, shut down an overheated amplifier, or turn on cooling fans, you'll find that this simple solid-state thermostat will do the job. Note that this project is *only* a controller, so you must supply the heater (or cooler), a suitable relay, and a temperature-measuring device for calibration.

Looking around

Before anyone decides to design and build something, it pays to have a look around to see what's available on the market. First there's the Radio-Shack Thermometer/Controller. Total cost (with switches, etc.) is about twenty eight dollars. The temperature range is −40 to +50°C (−40 to +122°F), and it has a digital readout and temperature memory. So far so good—if the temperature range suits your needs. Maximum measurement speed is once per second. However, the real drawback is that if the temperature limit is exceeded, the output goes high for one minute; during that time period the temperature is not measured!

National Semiconductor has been making a number of temperature sensor/controllers for at least 15 years. The LM3911 (−25 to +85°C) and the LM35 (−55 to +150°C) are two examples. They are easy to work with, but they are more difficult to find and ones with a large temperature range aren't exactly cheap.

Sensors are also made by Linear Technology (the LM134 with a −55 to +125°C range) and Analog Devices (the AD590 with a −55 to +150°C range) as well as dozens of others. The only catch, besides availability, is that they are precision sensors meant to measure as well as control temperature. They are also quite expensive.

Complete controllers are also made by other companies such as Omega, but the cost is about the same as a cheap personal computer. That is due partly to super accuracy and digital temperature readout.

Rollin' your own

When so many people are making temperature sensor/controllers, why build one from scratch? There are two basic reasons:

- Commonly available parts can be used.
- You can control such parameters as accuracy and temperature measurement bandwidth.

Theory of operation

If a constant current is passed through an ordinary silicon diode, the voltage across the diode will be a function of temperature. There are more accurate ways to measure and control temperature, but at twenty for a dollar you can't beat the price, and control accuracy of ±0.5°C is typical.

The actual voltage across the diode with 1 milliamp of current passing through it is about 0.75 volt at −50°C and 0.35 volt at 150°C. That works out to about 2 millivolts per °C. Although a controller could be made to work at that level, a little amplification makes things much simpler.

The schematic of the controller is shown in Fig. 1. Transistors Q1 and Q2 make up the 1-milliamp constant-current source for the temperature-sensing diode, D1. The base-emitter junction of Q1 is used to temperature-compensate the base-emitter drop of Q2. The 1.25-volt reference of the LM317 regulator appears across resistor R4, keeping the emitter current (and therefore the collector current) of Q2 constant at about 1 milliamp. The actual amount of current isn't nearly as critical as the fact that the current remains constant.

Differential amplifier IC1-a serves two purposes. The first is to subtract a DC voltage from the temperature-sensing diode D1. That's necessary so that a DC amplifier can be used to amplify the signal from D1 without saturating. The signal is also inverted by IC1-a so that an increase in temperature produces an increase in voltage.

Op-amp IC1-b is configured with a gain of 11 (1+R11/R10). That makes the job of comparator IC1-d easier.

The temperature set point is controlled by resistor R15 and buffered by IC1-c. Note that by changing the values of R14 and R16 you can restrict the control range, making it easy to vary the set point in very fine steps. Using the values shown, control is adjustable from about −50 to

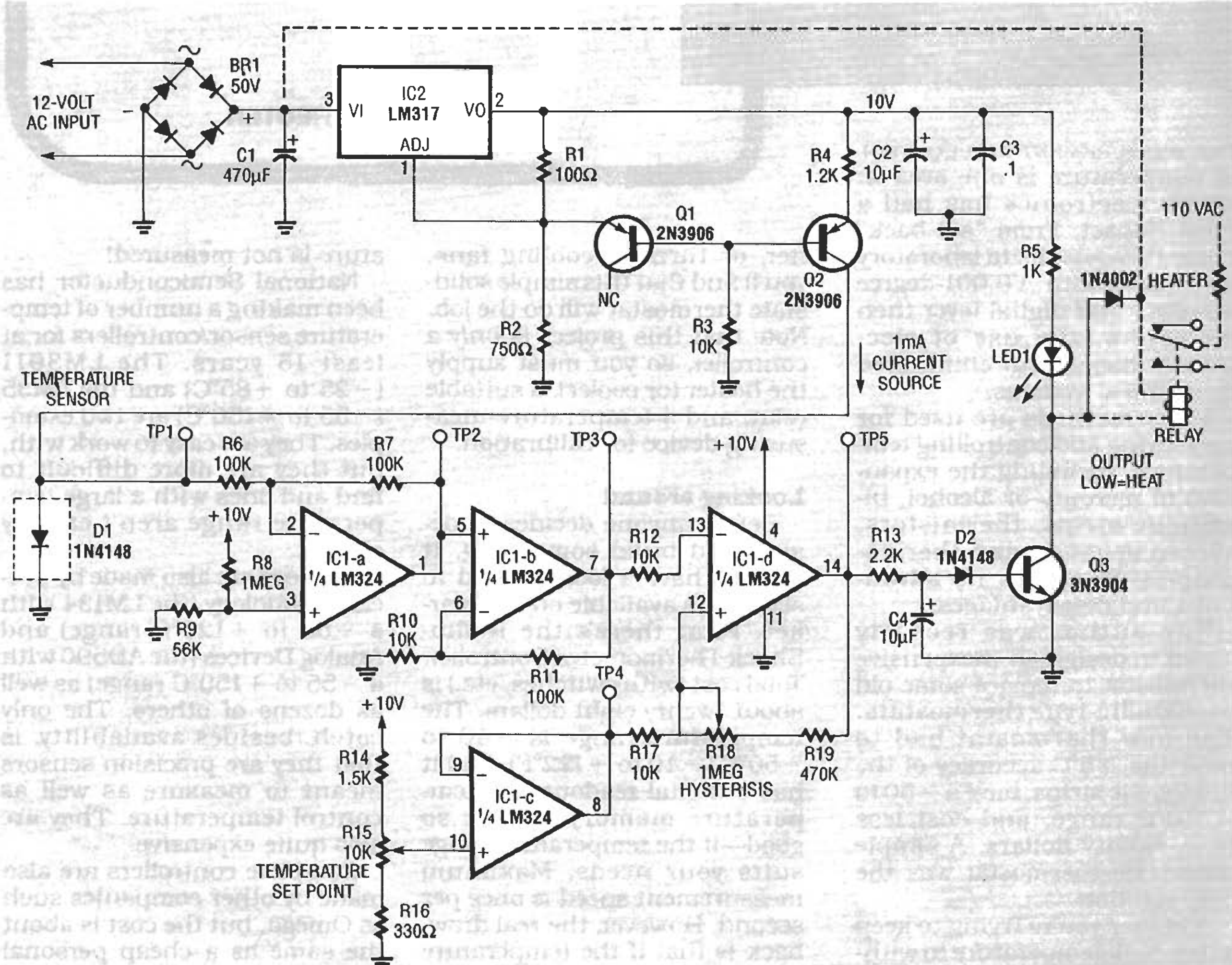


FIG. 1—CONTROLLER SCHEMATIC. If a constant-current is applied to a diode (D1 in this case), the voltage across the diode will be a function of temperature.

+150°C. With that much range, a small movement of a single-turn potentiometer will produce a large change in the set point. A ten-turn potentiometer would be a better choice for a large-range thermostat. Table 1 shows recommended values for R14, R15, and R16 for smaller temperature ranges.

Comparator IC1-d compares the set-point voltage with the output voltage of IC1-c. If the voltage at TP3 is greater than TP4, the output of the comparator will be low, thus shutting off transistor Q3. If more heat is needed, the voltage at TP3 will be less than TP4 and the comparator output will go high, turning on Q3.

Resistors R18 and R19 provide some hysteresis. Providing a small amount of hysteresis in a comparator ensures a smooth transition from one state to the other. Although it limits the accuracy somewhat, the benefits far outweigh the disadvantages. Without hysteresis, the output of the comparator would dither, or oscillate from one state to the other when the inputs are about equal. Imagine ordering an oil-burning furnace to turn on and off a thousand times a second!

The amount of hysteresis can be controlled by resistors R18 and R19. Decreasing R18 will increase the hysteresis and cause a greater temperature variation in the controller. For example, using the highest resistance, the temperature window might be 0.5°C. At the lowest, it might be 3°C.

The output of the controller can control a conventional or solid-state relay. A solid-state relay is preferable since its reliability is much greater than that of a conventional relay. (If you'd like to build your own solid-state relay, see **Radio-Electronics**, May 1992.) Any relay rated from five to twelve volts will work if you connect it to the positive side of C1 through the appropriate resistor. That resistor value can be obtained by dividing the voltage drop required by the current consumed by the relay. If a conventional relay is used, a snubbing diode such as a 1N4002 should be used to protect Q3 when the relay turns off.

Construction

Any method of construction can be used since there is nothing critical about the circuit layout, but it will be easier using a PC board made from the foil pattern we've provided or one purchased from the source mentioned in the Parts List. *Do not* substitute another regulator for the LM317. In addition to providing a regulated voltage, the LM317's 1.25-volt reference is used to operate the constant-current source for diode D1. Figure 2 shows the parts-placement diagram.

Twelve-volts AC can be supplied from just about any transformer since only a few milliamps are required—not counting the relay current. Relay current of up to 100 milliamps can be handled by Q3.

The temperature probe can be made of metal or glass. The diode is so small that it can be put into standard glass tubing and sealed with RTV (room-temperature vulcanizing) silicone. Coating the diode with RTV sil-

TABLE 1—RESISTOR VALUES

Temperature Range (Degrees C)	R14	R15	R16
−50 to −30	10K	1K	330Ω
−30 to −10	9.1K	1K	1.2K
−10 to 15	8.2K	1K	2.2K
15 to 35	7.5K	1K	3.3K
35 to 55	6.2K	1K	4.3K
55 to 75	5.1K	1K	5.1K
75 to 95	4.3K	1K	6.2K
95 to 115	3.3K	1K	6.8K
115 to 135	2.2K	1K	8.2K
135 to 155	1.2K	1K	9.1K

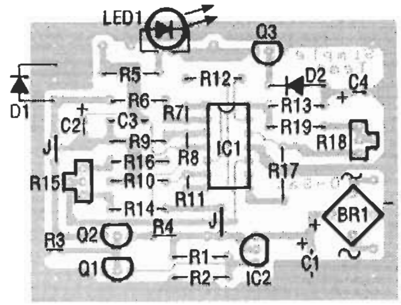
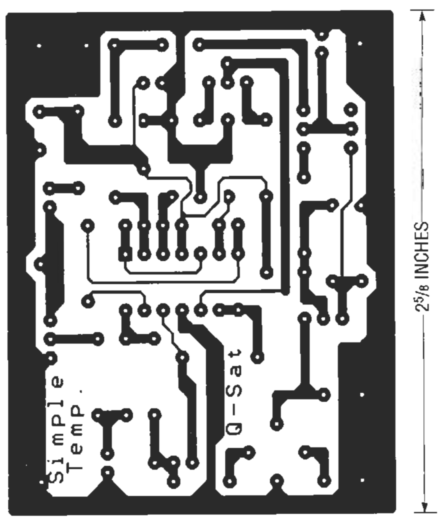


FIG. 2—PARTS-PLACEMENT DIAGRAM. Any method of construction can be used, but it's best to use a PC board. You can make one from the foil pattern we've provided or buy one from the source mentioned in the Parts List.

FIG. 3—THE TEMPERATURE-SENSING diode can be sealed in a length of glass tubing and sealed with RTV silicone. You must use a shielded cable between the probe and the measuring circuit.



FOIL PATTERN for the solid-state thermostat shown actual size.

icone might also work although the thermal time constant would probably increase using that method. You must use a shielded cable between the probe and the measuring circuit. Figure 3 is a close-up view of the probe assembly with the diode installed in a length of glass-tubing.

The printed circuit board is designed to accept two different trim potentiometers, hence the four holes instead of three. If you must adjust the temperature often, you might opt to run wires from the PCB to standard-type potentiometers. Figure 4 shows the author's completed prototype.

Testing

You should first test the 1-milliamp current source. If the voltage across R4 measures about 1.2, you're in business. Placing a milliammeter in series with D1 can confirm that.

For the purposes of testing, it's handy to replace D1 with a 1K potentiometer. Since a constant current of 1 milliamp is flowing through the resistor, a voltage from 0 to 1 volt can be obtained depending on its setting. Of course that range is too much since the diode voltage varies only from about 0.8 volt at −50°C to about 0.3 volt at +150°C.

First measure the voltage from pin 3 of IC1 to ground. It should be about 0.55 volt. Using the 1K potentiometer, adjust TP1 for the voltages shown in Table 2, and make sure the TP2 and TP3 voltages agree with Table 2 for each voltage at TP1. Next check the temperature setpoint range. Measure the voltage from TP4 to ground; with the potentiometer set at the extreme counterclockwise position, TP4 should be about 0.31 volt. Clockwise, it should be about 8.88 volts.

If the testing works out, you're ready for the real test. With R15 set counterclockwise and the temperature-sensing diode at room temperature, LED1 (and Q3) should be off. Turn R15 slowly clockwise until the LED comes on. Now heat the diode with a soldering iron or match; the LED should go off. If everything is allright, the final step is to calibrate the controller with an accurate temperature-measuring device. **R-E**

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise noted.
R1—100 ohms
R2—750 ohms
R3, R10, R12, R17—10,000 ohms
R4—1200 ohms
R5—1000 ohms
R6, R7, R11—100,000 ohms
R8—1 megohm
R9—56,000 ohms
R13—2200 ohms
R14—1500 ohms (see text)
R15—10,000-ohm potentiometer (see text)
R16—330 ohms (see text)
R18—1-megohm potentiometer
R19—470,000 ohms
Capacitors
C1—470 µF, 25 volts, electrolytic
C2, C4—10 µF, 16 volts, electrolytic
C3—0.1 µF, Mylar
Semiconductors
IC1—LM324 quad op-amp
IC2—LM317L voltage regulator
D1, D2—1N4148 diode
LED1—light-emitting diode, any color
Q1, Q2—2N3906 PNP transistor
Q3—3N3904 NPN transistor
BR1—50-volt bridge rectifier
Miscellaneous: 12-volt AC power supply, PC board, glass or other similar tube for temperature probe, RTV cement, wire, solder, etc.
Note: The following items are available from Q-Sat, PO Box 110, Boalsburg, PA 16827:
• PC board (Temp-PCB)—$7.00 postpaid
• All parts (including PC board) except 12-volt transformer (Temp-KIT)—$18.00 postpaid
Pennsylvania residents please add 6% sales tax.

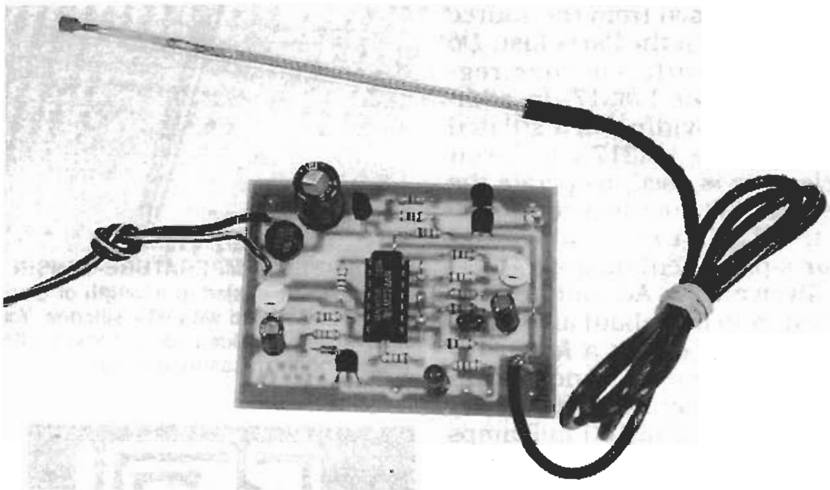


FIG. 4—THE AUTHOR'S PROTOTYPE. If you will need to adjust the temperature often, run wires from the PCB to standard-type potentiometers.

TABLE 2—TEST-POINT VOLTAGES

Approximate Temperature (°C)	TP1	TP2	TP3
	0.300	0.766	8.38
150	0.350	0.717	7.84
	0.400	0.665	7.28
	0.450	0.616	6.74
	0.500	0.566	6.81
50	0.550	0.515	5.63
	0.600	0.465	5.08
	0.650	0.415	4.54
	0.700	0.364	3.97
	0.750	0.315	3.43
−50	0.800	0.263	2.87
	0.850	0.212	2.31