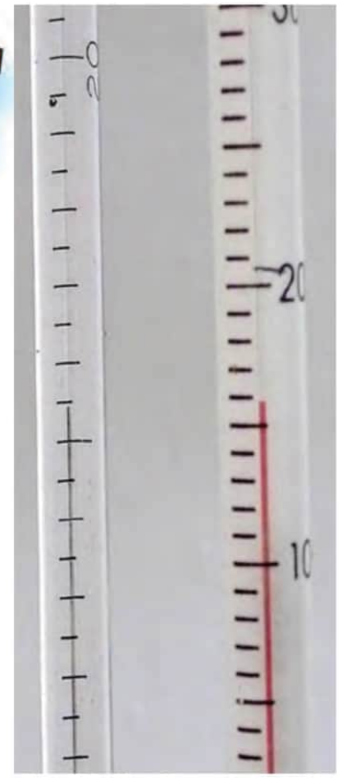
Low-cost, high-precision

Thermometer Calibrator



By Allan Linton-Smith

Many digital thermometers have readouts with a 0.1°C resolution but rarely are they accurate to within ±0.1°C. Despite their claims, some can be several degrees out, giving a false sense of accuracy. This simple, low-cost thermometer checker will tell you just how accurate your thermometer is. In some cases, you may even be able to adjust the thermometer to be more accurate.

There are many reasons why you might need an accurate thermometer. Checking to see if someone (especially a child) has a fever is an everyday use case. This requires pretty good accuracy, as the difference between a normal-but-elevated temperature (as can happen when someone has been exercising, crying etc) and a fever is just fractions of a degree.

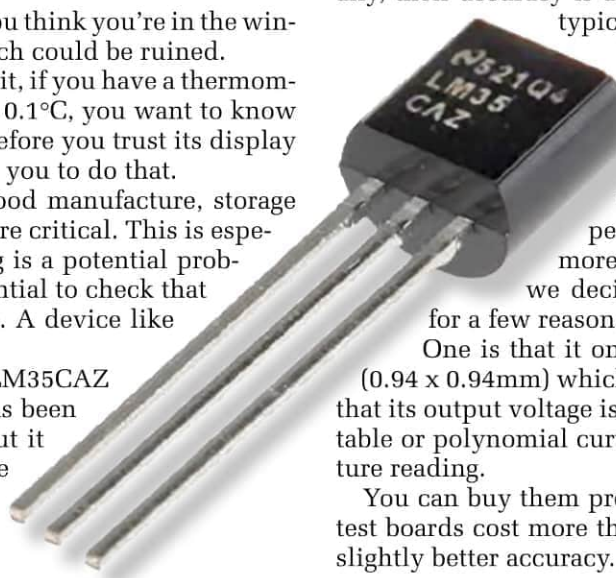
Or maybe you're a keen chef, and you want to use processes like tempering chocolate, where you need to heat the chocolate to a temperature within a fairly small window, eg, 31-33°C.

A 1°C error could mean that you think you're in the window, but you aren't, and the batch could be ruined.

Whatever the reason for using it, if you have a thermometer that will read out to within 0.1°C, you want to know if it's at least "in the ballpark" before you trust its display fully. This simple device allows you to do that.

In some industries such as food manufacture, storage and distribution, temperatures are critical. This is especially true when food poisoning is a potential problem. So in these cases, it is essential to check that your thermometers are accurate. A device like this is therefore invaluable.

This design is based on the LM35CAZ IC, a temperature sensor that has been available for some time now. But it has really come down in price lately. If managed correctly, it can be expected to give readings within ±0.2°C at 25°C.



It works over a -40°C to +110°C range, but its accuracy is not as good when reading temperatures further away from room temperature.

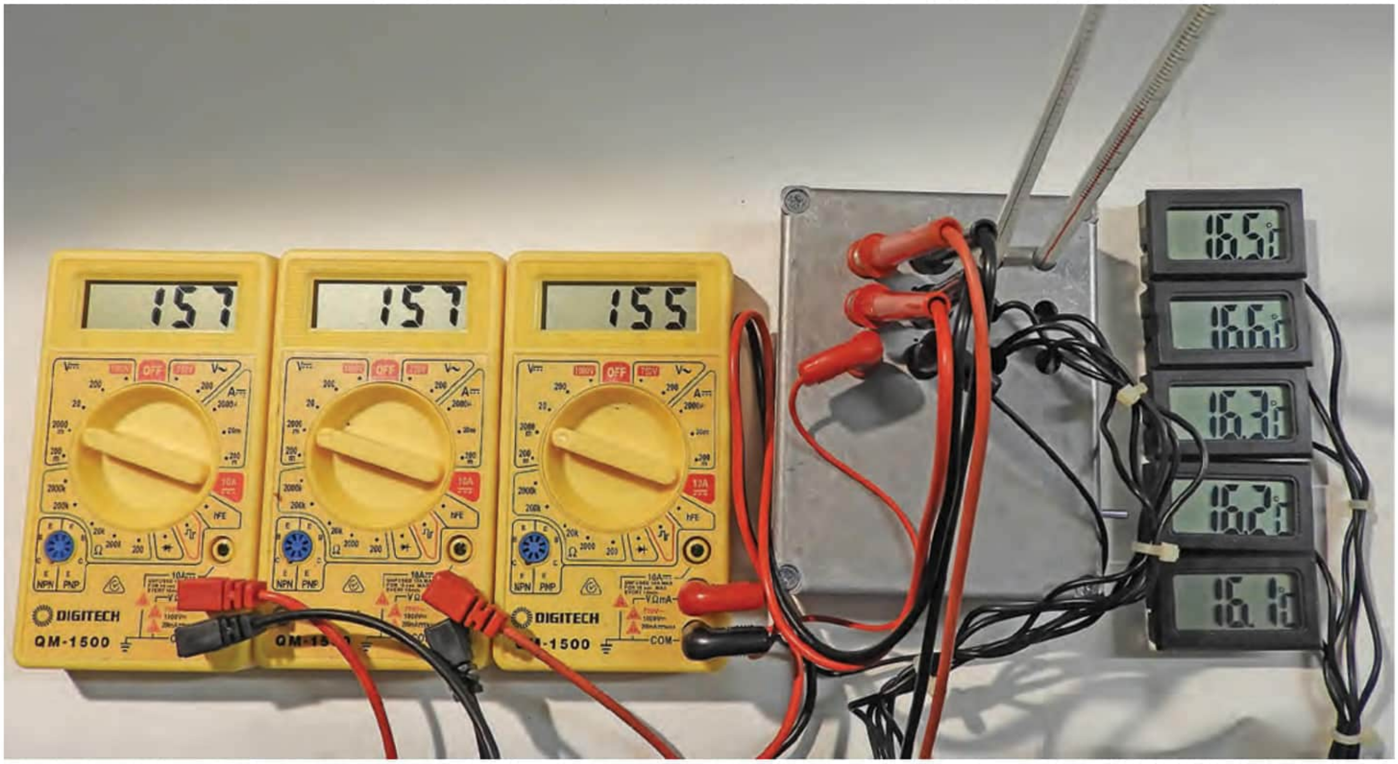
It's worth building this yourself because other devices with precise temperature readings, eg, ±0.1°C, are not commonly available and are very expensive. For example, the Fluke 9142 and 9143 are excellent calibrating instruments with a display accuracy of ±0.2°C over their full range, but we recently spotted a *used* one for sale for over $5,000!

Some say that glass thermometers are very accurate. Usually, their accuracy is accepted as ±0.5 divisions, which typically translates to ±1°F or ±0.5°C, but they are becoming quite rare. And they are still susceptible to reading errors, some of which are described in the side panel.

When designing this device, we found that there are a few temperature sensor ICs that are even more accurate, such as the LMT70, but we decided against using this (for now) for a few reasons.

One is that it only comes in a tiny SMD package (0.94 x 0.94mm) which is hard to work with. Another is that its output voltage is non-linear and requires a lookup table or polynomial curve-fitting to convert to a temperature reading.

You can buy them pre-soldered to a module, but these test boards cost more than $50, which is not worth it for slightly better accuracy.



The three DMMs are reading the outputs of the LM35s but we have also inserted the probes of five cheap digital thermometers and two lab-grade glass thermometers into the device. The cheap thermometers have a 0.5°C spread, quite a bit larger than the 0.2°C difference between the LM35s.

To give you an idea of how hard it is to measure temperature precisely with a digital sensor, here is a passage from the LMT70 data sheet:

"Although the LMT70 package has a protective backside coating that reduces the amount of light exposure on the die, unless it is fully shielded, ambient light will still reach the active region of the device from the side of the package. Depending on the amount of light exposure in a given application, an increase in temperature error should be expected."

"In circuit board tests under ambient light conditions, a typical increase in error may not be observed and is dependent on the angle that the light approaches the package. The LMT70 is most sensitive to IR radiation. Best practice should include end-product packaging that provides shielding from possible light sources during operation."

Circuit details

The LM35CAZ is a precision integrated-circuit temperature sensor with an output voltage linearly proportional to the temperature in degrees Celsius.

It requires no external calibration or trimming. It is low in cost, can operate on a wide variety of single supply voltages and has low self-heating.

There's little to the circuit besides three of these devices, and a battery to power them, as shown in Fig.1. IC1-IC3 can run from a wide supply range of 4-20V, so they are very well suited to be powered from a 9V battery.

The output of each device can be measured by a multimeter connected across one of CON1-CON3, set to its 1V range or thereabouts (ideally, with 1mV resolution). IC1-IC3 have a nominal 0V output at 0°C, rising by 10mV/°C.

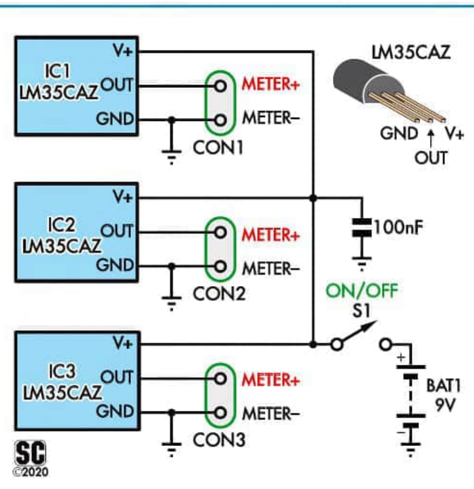
So, for example, in the photo above showing a 155mV reading on the multimeter display means that the temperature is 15.5±0.2°C.

Note that the LM35CA is only guaranteed to be within ±0.5°C at 25°C, but in reality, a typical sample of the device is within ±0.2°C from around -25°C to 50°C.

The reason for using three different devices is threefold. First, it increases your confidence that you have an accurate reading when they are all giving similar results. Second, it also lets you get an idea of which sensors read a little higher or lower than the others. And third, it also lets you check that the case is at an even temperature before making your readings.

In the photo above, with all three giving readings within 0.2°C of each other, note how the cheap digital thermometers with their probes inserted into the same metal case, and presumably reading the same temperature, are

Fig.1: the circuit couldn't be much simpler; it's just the three LM35s with a shared 100nF bypass capacitor, power switch S1 and a 9V battery for power.



Accurate temperature measurement is not easy . . .

Making precise temperature readings (say to within ±0.1°C) is difficult. Devices to do this are not commonly available and are very expensive!

For example, if your backyard weather thermometer is showing 40°C, it could actually be 38°C or 42°C.

It could even be much higher or lower than this if your thermometer is poorly sited (eg, near an air conditioner or road) or in a poorly designed enclosure or bad position, which allows its reading to be affected by direct sunlight.

Assuming you have a linear sensor, you can calibrate it using a stirred ice bath (to determine its reading at 0°C) and vigorously boiling pure water (100°C), both at sea level. But unless you do this correctly, your readings could still be out considerably.

For example, at around 300m elevation, the boiling point of water is about 98.9°C. Normal day-to-day atmospheric pressure variations can have a small effect on the boiling point, too.

Any salt in the water or ice can have a dramatic effect on both the boiling and freezing points.

According to the CRC Handbook of Chemistry and Physics, 2.92% sodium chloride in solution reduces the melting point of ice by 0.19°C and increases the boiling point by 0.05°C.

A practical thermometer calibration method is given at www.nfsmi.org/documentlibraryfiles/PDF/20130806025735.pdf

Even if your calibration method is flawless, you also need to know that the sensor response is perfectly linear to have confidence in readings between the two extremes.

Even IC-based temperature sensors like the LM35 suffer from some level of non-linearity, even though they are designed to be as linear as possible.

It isn't just electronic sensors that suffer from accuracy problems, either. As one meteorologist pointed out, even the meniscus (bulge in the top of a column of liquid in a tube) in a mercury or alcohol thermometer can lead to significant inaccuracies in the readings.

He also mentions:

"… mercury freezes at -38.8°C. It becomes increasingly less malleable as it approaches that temperature and makes low temperatures with mercury thermometers of no value. The 18th century observers of the Hudson's Bay Company using thermometers provided by the Royal Society were unaware of the problem ..."

Because of problems like this, interpreting historical air and sea temperature data is quite tricky!

all reading high (by about 0.5-1°C) and also have a considerably greater spread than the LM35CA devices.

You **must** use the LM35CA version for accuracy, as the LM35/LM35A/LM35C/LM35D cannot achieve the same accuracy. (Note: the "Z" suffix indicates a TO-92 package).

Note though that the LM35CA is limited to measuring in the range of -40°C to +110°C, while the less accurate LM35 and LM35A versions can measure from -55°C to +150°C.

The three multimeters we've used here are low-cost devices that you can get for a few dollars from Jaycar, and we've found that they are very accurate. They have a voltage accuracy rating of ±0.5%, which equates to an additional error of just ±0.1°C in the temperature readings.

To demonstrate the accuracy of the LM35CAs, we also have two laboratory-grade analog thermometers measuring the same temperature. As shown in the separate photo, they are both reading just under 16°C, just slightly higher than the figures shown on the DMMs.

Do not buy cheap LM35 sensors online if you are expecting accuracy, or even for them to function. We also purchased several LM35Ds cheaply on the internet to compare, but NONE of them worked at all!

So it is essential to obtain them from a reputable supplier (eg, the ones mentioned in the parts list).

Parts list – Thermometer Calibrator

- 1 diecast aluminium box, approx. 115 x 90 x 55m *[eg, Jaycar Cat HB5042]*
- 3 LM35CAZ temperature sensors *[eg Mouser LM35CAZ/NOPB, Digi-key LM35CAZ/NOPB-ND, RS Cat 5335878]*
- 3 voltmeters *[eg, Jaycar Cat QM1500]*
- 3 red banana plug-banana plug leads
- 3 black banana plug-banana plug leads
- 3 black chassis-mounting banana sockets
- 3 red chassis-mounting banana sockets
- 1 chassis-mounting 9V battery holder
- 1 9V battery clip with flying leads
- 1 9V battery (alkaline recommended)]
- 1 100nF ceramic, MKT or greencap capacitor
- 1 SPST toggle switch
- 1 small piece of protoboard
- 1 3mm ID solder lug
- 1 M3 x 10mm machine screw and nut
- 1 adhesive TO-3P or TO-247 insulating washer
- 1 small tube adhesive heatsink compound *[eg Jaycar NM2014]*
- various lengths of ribbon cable or hookup wire

Construction

We recommend that you build this into a diecast aluminium box. This will not only provide some shielding, it allow you to check glass thermometers and to help maintain a uniform and stable temperature, without any thermal gradients. The sensors have very little self-heating, but it is still present; the large thermal mass of the case helps to mitigate this.

The LM35s also detect temperature variations through their pigtails. If these are exposed to small amounts of heat variations, such as human breath or wind, it can disturb the measurements and give false readings. By placing the ICs inside a metal box, we can eliminate these errors.

Solder the three LM35s to a small piece of protoboard, veroboard or similar. Join their V+ and GND leads together,

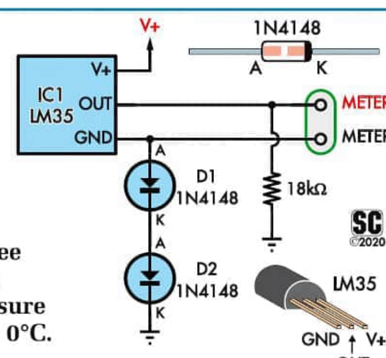


Fig.2: by adding three components to each LM35, you can measure temperatures below 0°C.

	Thermistor	RTD	Thermocouple	LM35CAZ
Range	-100 to +325°C	-200 to +650°C	+200 to +1750°C	-40 to +150°C
Accuracy	±0.05 to ±1.5°C	±0.1 to ±1°C	±0.5 to ±5°C	±0.2°C at 25°C
Stability @ 100°C	0.2°C/year	0.05°C/year	Variable	0.2°C/year
Linearity	Exponential	Fairly linear	Non-linear	Linear
Power	Small current	Small current	Self-powered	4-20V DC
Response	0.1-10s	1-50s	0.1-10s	2-15s
Interference	Rarely	Rarely	Susceptible	Susceptible
Cost	Low to moderate	High	High	Moderate

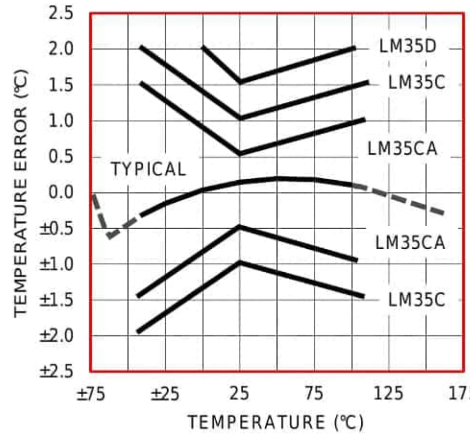


Table 1 shows the typical parameters of various temperature sensors, while the graphs at right show the errors in the different iterations of the LM35.

and solder the 100nF capacitor across these rails. Also connect pairs of wires to the GND and OUT terminals of each device, plus one pair of wires between the V+ and GND rails.

Ideally, the pairs of wires should be figure-8 cable (eg, stripped from ribbon cable). If you are using individual wires, it's best to twist them together so that any interference is mostly cancelled out between the two conductors.

Now glue the three TO-92 plastic packages to the inside of the diecast box using thermally conductive adhesive. We used Jaycar NM2014 adhesive thermal paste.

Drill holes in the case for the power on/off switch and 9V battery holder, plus holes for the three pairs of banana sockets in the lid. Also drill a 3mm hole for the chassis grounding screw, near the battery holder, and one or two extra holes in the lid for analog thermometer calibration, if desired.

Deburr all the holes and mount these parts. Then solder the pairs of wires from the LM35 GND and OUT terminals to the banana sockets, with the OUT terminals going to the red sockets.

The remaining pair of wires then goes to the switch (V+) and case (GND). Solder the other switch terminal to the red lead from the 9V battery, so that V+ is connected to the battery when the switch is in the on position (usually down).

Join the remaining GND wire to the black wire of the 9V battery to the solder lug and attach it to the inside of the case using an M3 machine screw and nut (not shown below).

Stick the insulating washer on the inside of the case directly below the analog thermometer insertion holes in the lid. This will provide the thermometers with a bit of a 'cushion' so that they do not break when inserted.

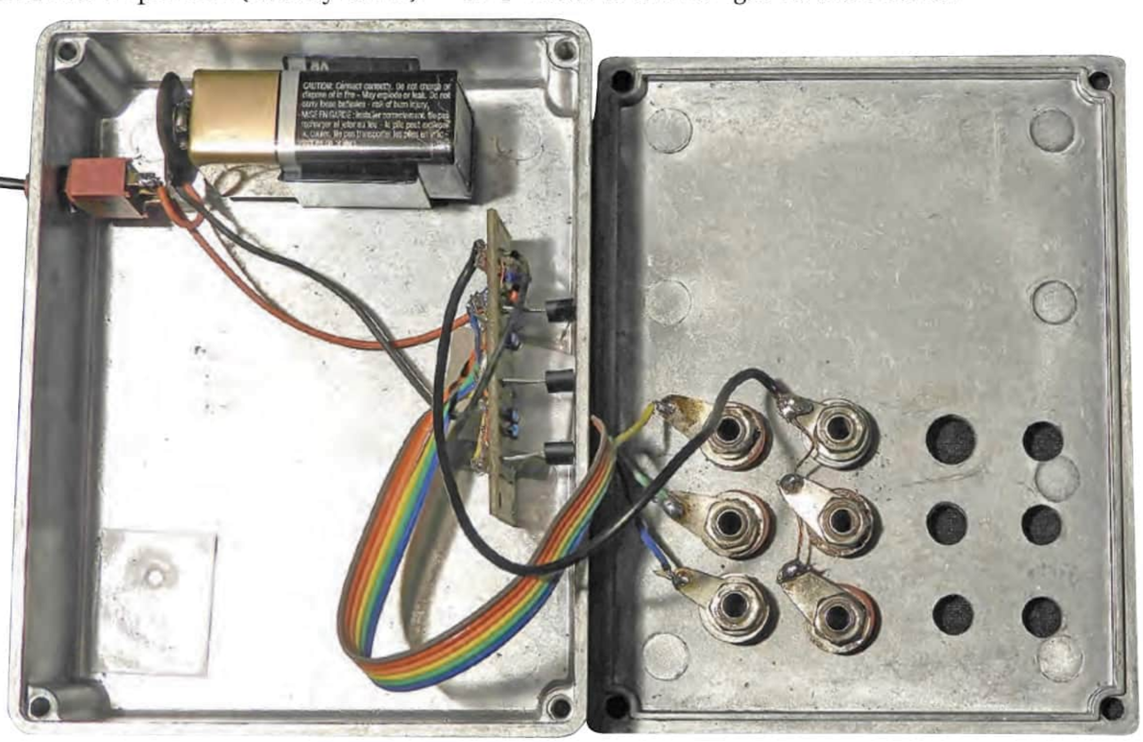
Now connect the battery clip to the battery, slot it into its holder and switch on the power. Use a red and black pair of banana plug leads to connect one of the DMMs to one of the pairs of binding posts, and check that you get a reading that's fairly close to ambient temperature.

For example, if it's around 25°C where you are, you should get a reading around 250mV. Verify that all the outputs are similar values.

Using it

Avoid using this device in a windy environment or one with rapidly changing temperatures, such as near a window that's exposed to full sun where clouds may pass by. Ideally, it should be used indoors with still air in an environment with a stable temperature.

Switch it on and allow everything to stabilise for around 20 minutes before using it for best results. **SC**



While it might seem like overkill, placing the project in a diecast case has several benefits – it's shielded, of course, and the thick aluminium provides some thermal inertia. Placing the LM35CAZs inside the box also means they will be less affected by external variants. Of course, a smaller diecast case could be used, providing the various components will fit.