Analog-to-Digital Conversion

Aliasing must be avoided.
It can only be avoided in the analog world!

To achieve a good result with an A/D conversion you need to assure three things:

1.) The anti-aliasing filter. . .
Make sure $f_{nyquist} > f_{max}$ so that all your signal makes it through the anti-aliasing filter.
Make $f_{nyquist}$ as low as is practical to reject as much noise as possible.
This step is harder than it looks. No filter is perfect, thus typically $f_{nyquist} > 1.1 f_{max}$ or more.
Typical error: Omit the anti-aliasing filter and try to average out or digitally filter out the noise later.
There is absolutely no hope for a good result if the anti-aliasing filter is not
an analog filter. . .
located in front of the sampler.

2.) Make sure $f_s > 2 f_{nyquist}$
Pretty easy with today's high-speed electronics.

To make the anti-aliasing filter simpler sometimes $f_s \gg 2 f_{nyquist}$, say 10 or even thousands of times more.
This is called *oversampling*.
Oversampling implies that you let some analog noise get converted to digital noise.
A digital filter can remove this kind of digital noise because it was at a digital frequency of less than one-half.
Any noise above $f_{nyquist}$ *cannot be removed with a digital filter*! It is indistinguishable from the desired signal.

3.) Your quantization range has to be a reasonable span of $f_{sa}(n)$'s signal amplitude's bound.

Is your digital frequency
greater than one-half? Oops!

1

We interrupt this program for a special message.

2

Time:
elusive and immediate…
limited yet infinite.
Because time is important to you…

https://www.ebay.com/itm/Hewlett-Packard-Very-Rare-HP-01-Calculator-Watch-with-Gold-Filled-FW-Perfect/254431757904?hash=item3b3d508650:g:0PoAAOSwzedd0dyQ

Honest scales and balances belong to the LORD;
all the weights in the bag are of his making.
Proverbs 16:11

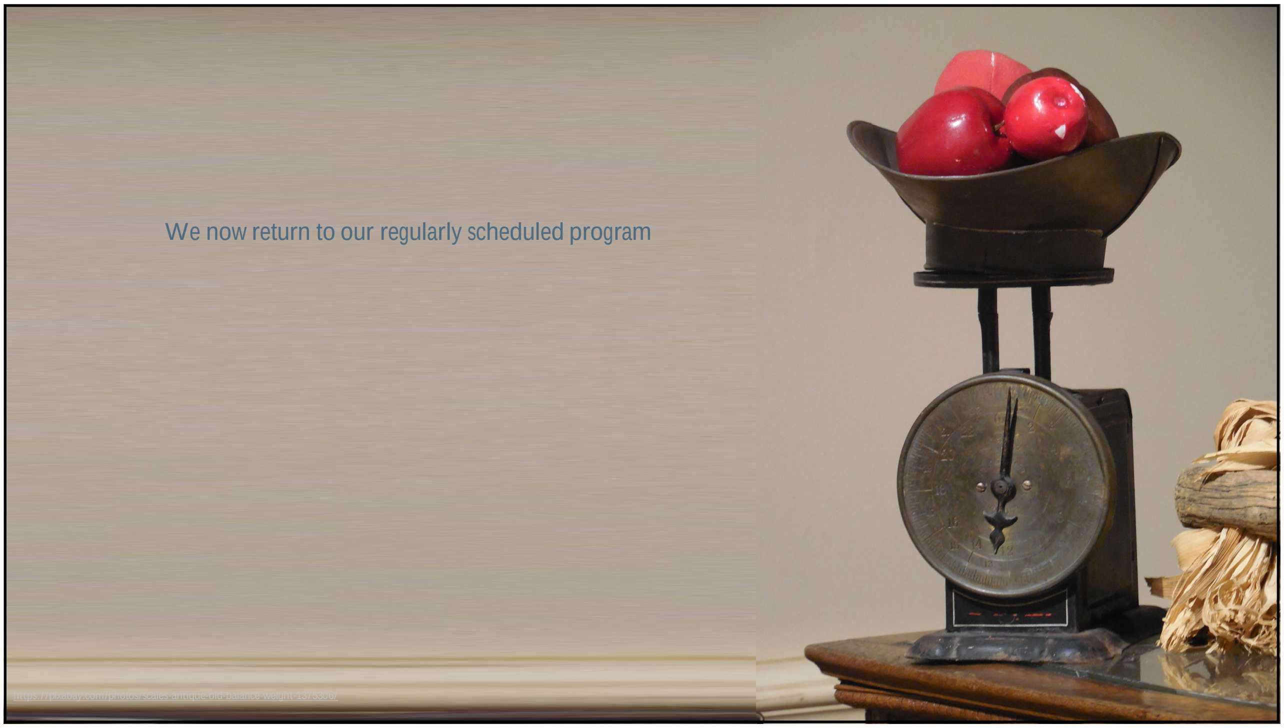
Thesis:

The Lord has an **unusual concern** for honest measures and correspondingly has provided a **generous benevolence** of **grace** to humanity in the form of **providential standards of measurement**.

Conference paper, page 119 or 125 at http://www.christianengineering.org/publications/cec-proceedings/CEC%202019%20Proceedings.pdf?attredirects=0&d=1

Conference slides in file http://www.christianengineering.org/publications/cec-proceedings/CEC%202019%20Presentations.zip?attredirects=0&d=1 in file “Session 5 – DeBoer. . .”

https://pixabay.com/photos/scales-antique-old-balance-weight-1375306/



We now return to our regularly scheduled program

https://pixabay.com/photos/scales-antique-old-balance-weight-1375306/

Tour of some of the more typical sensors used with embedded systems

Time (NIST time via WWV, via Internet; based on a crystal, based on resonance—pendulum. . .)
Temperature (Thermistor, RTD, "Precision Temperature Sensor," thermocouple, Infrared camera. . .)
Pressure (Bourdon tube, bellows, manometer, Piezoelectric crystal, resonance (for compressible fluids). . .,
Angle (absolute vs. relative using light, inductance, resistance, capacitance, . . .
Displacement (proximity) (similar to angle measurements except "unwrap" the circle into a line)
Force (weight) (spring deflection, strain gauge, buoyancy e.g. marks on side of a ship)
Fluid flow (hot wire, Pelton wheel, rotary piston or gear, oscillatory piston, inline-turbine, ultrasonic Doppler, var. orifice. . .)
Etcetera, etcetera. . .

The variety of sensors available is overwhelming.
Another approach: What are the "elements" of sensors that make them work?
If we understand how each of these work, then we understand how all the above sensors work.
This is what your basic physics and chemistry courses are about.

This course cannot possibly cover all of this.
Just be aware that getting to know the guts of how various sensors work at a fundamental level
pays dividends when you need to learn about a new sensor.

Techniques in time measurement.

NIST in the USA, NRC in Canada.
US time Canadian time

Or measure the period of a pendulum. (Subject to variations in gravitation.)
Or the count cycles of an LC tuned electrical circuit. (Subject to nearby metal, temperature, etc.)
Or count the oscillations of a temp compensated piezoelectric crystal. (Subject to acceleration)—about 3 ppm accuracy
piezoelectric crystal in a temperature-controlled stationary chamber—about 10 ppb accuracy

$$\left(60\,\frac{\text{sec}}{\text{min}}\right)\left(60\,\frac{\text{min}}{\text{hr}}\right)\left(24\,\frac{\text{hr}}{\text{day}}\right)\left(365\,\frac{\text{days}}{\text{year}}\right) = 31536000\ \text{sec}/\text{yr}$$

A good-quality wristwatch (crystal time base, not in a temperature-controlled environment) has about 3 ppm accuracy.
Divide by a million, multiply by three: one standard deviation of uncertainty is $\left(31536000\,\frac{\text{sec}}{\text{yr}}\right)(3\ \text{ppm}) \simeq 100\ \text{sec}/\text{yr}$
This level of accuracy, 100 sec/yr, can be achieved inexpensively.
Amazingly, often a dime or two is saved resulting in situations where the uncertainty is 10 or 100 times more (worse).
Hopefully, this kind of loss of accuracy happens only in contexts where it really does not matter much.

Arduino Uno's clock accuracy is not officially specified. It uses a ceramic resonator. These have accuracy of about 0.5 %.
That's about 7 min/day of uncertainty!

Raspberry Pi board clock accuracies are not specified. Experimenters report about 50 ppm.

https://pixabay.com/vectors/clock-time-face-hands-analog-34354/

Techniques in temperature measurement.

Thermistor

Portmanteau of "Thermal Resistor."

Definition: A ***thermistor*** is a resistor designed to have a calibrated temperature dependence.

A relationship between the temperature and the resistance is specified.
A simple linear relationship could be specified as. . .

$$\Delta R = k\Delta T$$

Where ΔR is the change in resistance from a specified nominal amount of resistance,
e.g. a "10 kΩ thermistor"
ΔT is the change in the temperature from a specified nominal temperature, e.g. "at 20 C"
k is the specified temperature coefficient, a constant. (in units such as Ω/C, ~20 Ω/C plausible at 20 C)

Other relationships may be specified, for example the Steinhart-Hart relationship or the "beta relationship."

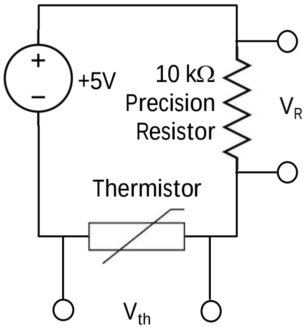
Two types: Positive and Negative temperature coefficient.
Positive: As temperature rises, resistance also rises. $k > 0$, also known as "PTC" thermistors
Negative: As temperature rises, resistance falls. $k < 0$, also known as "NTC" thermistors

Various materials are used to make thermistors, depending on the desired temperature range and environment.
PTC: doped ceramic, doped silicon, plastics with embedded carbon granules. NTC: sintered metal oxide—various metals.

https://www.alibaba.com/product-detail/All-Kinds-China-Supplier-High-Precision_62001754200.html Fair use.

Techniques in temperature measurement.

Thermistor—typical connections



Put the thermistor in series with its nominal resistance.
(Our thermistor is nominally 10 kΩ at 25 C.)
This resistance is called the *precision reference resistor*.

Measure the voltage across the precision reference resistor, V_R.
Measure the voltage across the thermistor, V_{th}.
The current through the precision reference resistor is the same as the current through the thermistor because the voltage sensing wires draw no measurable current.
Use the above measurements to calculate the resistance of the thermistor.

$$i = \frac{V_R}{R_P}$$

$$R_{th} = \frac{V_{th}}{i} = R_P \frac{V_{th}}{V_R}$$

Use the known mathematical relationship to find the temperature from the thermistor's resistance, R_{th}
The Steinhart-Hart relationship models most thermistors.

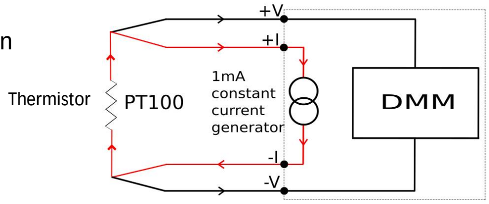
$$\frac{1}{T} = A + Bln(R_{th}) + C[\ln(R_{th})]^3$$

Where T = temp in K, R_{th} = thermistor resistance in Ω, and A, B, C are the Steinhart-Hart coefficients—from a datasheet.

Illustration by Prof. De Boer

Techniques in temperature measurement.

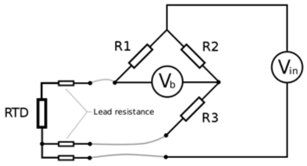
Thermistor—better connections



A *four-wire resistance measurement* would be better, but our NI equipment cannot do it. (But most mid-grade and up DMM's can do this and communicate the measurement back to the computer.)

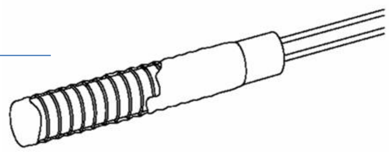
A Wheatstone bridge is also sometimes used, but is now rather archaic in the face of modern digital instrumentation. In older plants, these things still exist—very durable.

A particular issue with thermistors: The current you send through the thermistor in order to measure its resistance heats the thermistor! This current must remain insignificant.



https://commons.wikimedia.org/wiki/File:4wire2.svg
https://commons.wikimedia.org/wiki/File:RTD_3Wire.svg

Techniques in temperature measurement.



RTD

Resistance temperature-detector

Technically, this is a type of thermistor, but usually it is considered as a type of its own, not a subset of thermistors.
As for a thermistor, a linear model can be used over a limited temperature range.
The beta equation or the Steinhart-Hart give better results.
Wire it up and use it (electrically) just like a thermistor.

RTDs can be distinguished from thermistors by one important property:
An RTD is a (nearly) pure metal, not a semiconductor or alloyed metal.
(Carbon is counted as a metal, but not silicon for this application.)

Advantages: One of the most accurate technologies for temperatures below the melting point of the metal.
Stable over time, especially RTDs from noble metals such as platinum.

Disadvantage: Weak signal relative to a thermistor. (Typical thermistor, ~1 Ω/C change at room temperature.)

https://commons.wikimedia.org/wiki/File:Wire_Wound_PRT.png

Techniques in temperature measurement.

Precision temperature sensor
(also known as an integrated circuit temperature sensor or a silicon band-gap temperature sensor.)

One pin not used!

The base-current of a transistor is $I_B = I_S\left(e^{V_{BE}/V_T} - 1\right)$ where I_S is the reverse-saturation current.
V_T is the thermal voltage (hint, hint!)

This can be approximated as $I_B = I_S\left(e^{V_{BE}/V_T}\right)$

Solving for the base-emitter voltage of a silicon transistor gives $V_{BE} = V_T \ln(I_B/I_S) = V_T[\ln(I_B) - \ln(I_S)]$

The thermal voltage is given by $V_T = kT/Q$ where k = Boltzmann's constant
q = magnitude of the charge on an electron
r = the current density in the base of a transistor.

Operate two identical transistors which are in thermal contact with each other at different current levels

$$V_{BE1} - V_{BE2} = \frac{kT}{Q}[\ln(I_{B1}) - \ln(I_{B2})]$$

$$T = \Delta V_{BE}\left(\frac{Q}{k}\right)\ln(I_{B2}/I_{B1})$$

https://studylib.net/doc/18555550/ad590-temperature-sensors Fair use

Techniques in temperature measurement.

Precision temperature sensor
(also known as an integrated circuit temperature sensor or a silicon band-gap temperature sensor.)

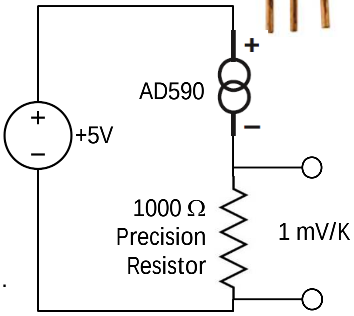
$$T = \Delta V_{BE}\left(\frac{Q}{k}\right)\ln(I_{B2}/I_{B1})$$

Thus, an integrated circuit that uses a basic property of silicon to sense temperature.

The sensor uses analog or digital electronics to “do the math” and calculate the temperature.
The temperature is then presented as some type of signal. The Analog Devices AD590 produces a current.

Output of the Analog Devices (brand) AD590 (part number) is. . .
At 25 C, 298.2 μA
For every degree C of deviation from there, 1 μA/C change in the output current.

Hook it up as shown at the right.



At 25 C the current through the 1 kΩ resistor will be 0.2982 mA
The voltage will be 0.2982 V and will vary 0.001 V/C.

The +5 V source does not have to be very accurate or stable (4 V to 30 V acceptable).
The typical power supply for a microcontroller will be good enough.

Techniques in temperature measurement.

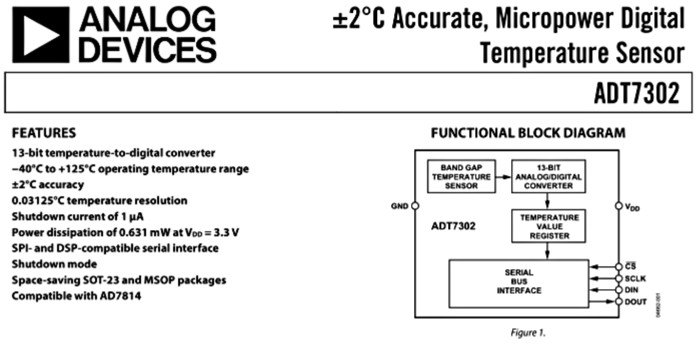
Precision temperature sensor
(also known as an integrated circuit temperature sensor or a silicon band-gap temperature sensor.)

$$T = \Delta V_{BE}\left(\frac{Q}{k}\right)\ln(I_{B2}/I_{B1})$$

Thus, an integrated circuit that uses a basic property of silicon to sense temperature.

The sensor uses analog or digital electronics to “do the math” and calculate the temperature.
The temperature is then presented as some type of signal.

Output of the ADT7302 is. . .
In digital form, on an SPI bus.
Connects directly to most microcontrollers
Examples: Connects directly to Arduino,
Raspberry PI, etc.
Can be found for <$1.00
±2 C accuracy with no calibration needed.



ANALOG DEVICES

±2°C Accurate, Micropower Digital Temperature Sensor

ADT7302

FEATURES

13-bit temperature-to-digital converter
−40°C to +125°C operating temperature range
±2°C accuracy
0.03125°C temperature resolution
Shutdown current of 1 μA
Power dissipation of 0.631 mW at V_{DD} = 3.3 V
SPI- and DSP-compatible serial interface
Shutdown mode
Space-saving SOT-23 and MSOP packages
Compatible with AD7814

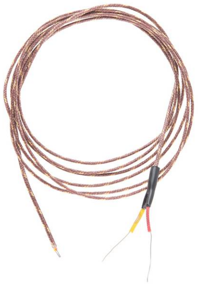
FUNCTIONAL BLOCK DIAGRAM

Figure 1.

https://www.analog.com/media/en/technical-documentation/data-sheets/ADT7302.pdf

Techniques in temperature measurement.

Thermocouple

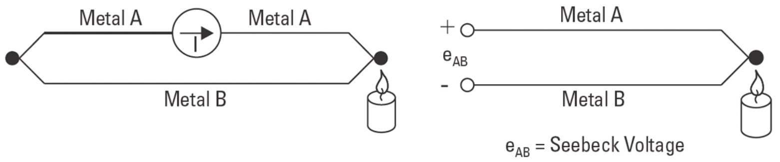


Definition: A ***thermocouple*** is a series connection of two dissimilar metals such that there are *two electrical junctions back-to-back* and located in two different places.

The metals produce a voltage that is mathematically related to the difference of the temperatures of the junctions.

In practice, one of the junctions is placed at the location where a temperature measurement is desired.

Operation is based on the Seebeck effect, $\Delta V = -S(T)\Delta T$ where S, a function of T is the Seebeck coefficient.



e_{AB} = Seebeck Voltage

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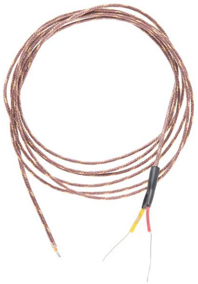
Techniques in temperature measurement.

Thermocouple



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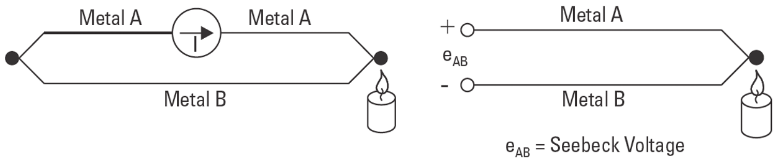

e_{AB} = Seebeck Voltage

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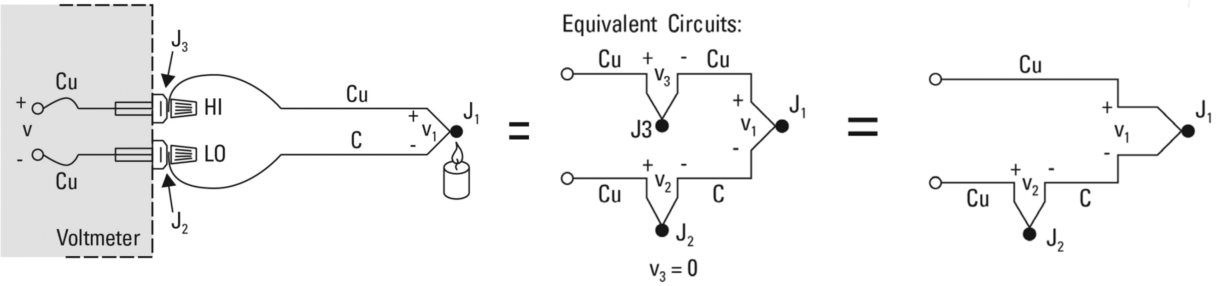
Techniques in temperature measurement.

Thermocouple

The Seebeck effect cannot be measured directly because we need to connect the metals of the thermocouple to a voltmeter, and that makes more junctions.



If we want to know the temperature of J_1 then we also need to know the temperature of J_2.
The classic technique of knowing the temperature of J_2 is to immerse it in a mixture of ice and water.
(The water must be pure, and the ice must be made from the pure water, so the mixture is at exactly 0 C.)

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Techniques in temperature measurement.

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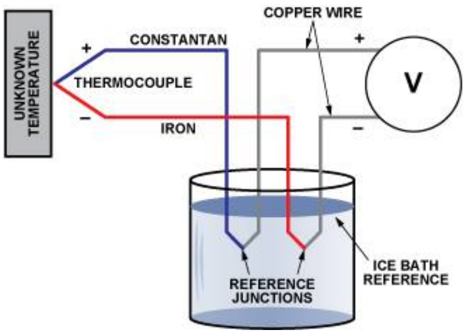

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Techniques in temperature measurement.

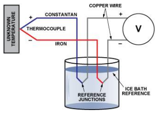
Thermocouple

The Seebeck effect cannot be measured directly because we need to connect the metals of the thermocouple to a voltmeter, and that makes more junctions.

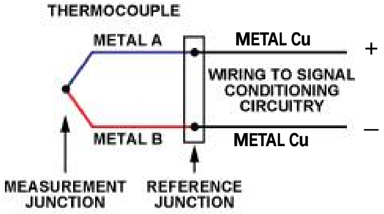
Well. . . That ice-bath stuff sounds messy, high maintenance, not portable. . .

Enter the electronic reference junction.

It is a block of metal alloyed to match the type of thermocouple you will be using. Its temperature is known. Often the temperature is measured via a precision temp sensor built into it. Instead of being an ice-bath, it is a "reference-junction-temperature bath." The measured temperature is now a difference from the reference junction temperature.



Too messy



Type T:
+ is Copper
– is Constantan

Electronic reference junctions are now almost universally used.
The electronic reference junction. . .
- Is made of specialized metals to match the thermocouple.
- Is made such that both of its terminals are at an equal and a known temperature.

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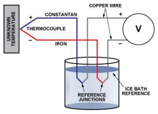
Techniques in temperature measurement.

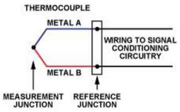
Thermocouple

Electronic reference junctions are now almost universally used.
The electronic reference junction. . .
- Is made of specialized metals to match the thermocouple.
- Is made such that both of its terminals are at an equal and a known temperature.

All of the above can be obtained in one instrument.
The instrument can be fitted with a multiplexer such that many thermocouples can be connected.
The instrument can be connected to a computer via Wi-Fi, Bluetooth, Xbee, Ethernet, USB, RS-232, etc.



Too messy



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Techniques in temperature measurement.

Observations about temperature measurement:

Measurements from about −50 C to about 150 C
with accuracy of about ±2 C
and precision of about ±0.1 C
are routine and inexpensive now. (ADT7302 is about $3.00 in single quantities, < $1.00 each in quantity)

Use a precision temperature sensor with a digital (SPI or I2C or Dallas One-Wire) output if possible.
Texas Instruments TMP102, Maxim DS18B20, Analog Devices ADT7302

Otherwise use a precision temperature sensor with a current output and a precision low-temperature coefficient reference resistor located near the analog input of your system to sample the signal.
Pay attention to range, precision, and digital resolution and make them as suitable as practically possible.

If you need more precision, it is going to get expensive fast. Question the need before taking it on!
(Sometimes people just specify things they "want" with little understanding of the trade-offs involved.)

If you need to work at higher temperatures, look to RTDs and thermocouples.
Consider using stand-alone processing equipment to do the A/D conversion.
Although a thermocouple can be purchased for $5.00, you will need expensive equipment to get accurate results.

Techniques in temperature measurement.

Thermistor—an example

Goal: Automotive engine coolant temperature is to be measured.
Desired range: -50 F to 300 F (-45 C to 150 C)
Desired accuracy: 3 F (1.67 C)
Desired precision: ~1 F (~0.5 C)
Search for a sensor: Decision for Texas Instruments LM34

The datasheet shows the schematic of "Figure 17" for this application:

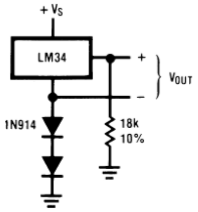
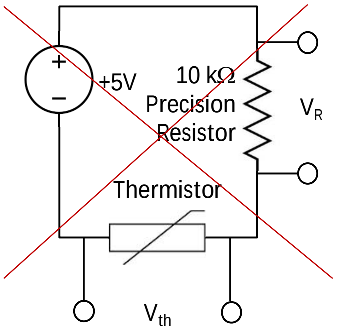


Figure 17. Full Range Farenheit Sensor (–50 °F to 300 °F)

This datasheet specifies an a-typical connection. (below left)



Two analog inputs are needed.
The − input will always be at nearly 1.4 V due to the diodes.

$$(-50\ \text{F})\left(10\frac{\text{mV}}{\text{F}}\right) = -500\ \text{mV} = -0.500\ \text{V wrt } - \text{terminal}$$

$$(300\ \text{F})\left(10\frac{\text{mV}}{\text{F}}\right) = 3000\ \text{mV} = 3.000\ \text{V}$$

At -50 F the + input will be at 1.4 V − 0.5 V = 0.9 V
At 300 F the + input will be at 1.4 V + 3.0 V = 4.4 V

Illustration by Prof. De Boer

Techniques in temperature measurement.

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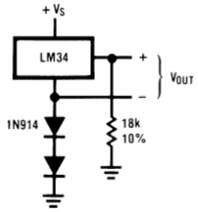

Figure 17. Full Range Farenheit Sensor (–50 °F to 300 °F)

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Two analog inputs are needed.
The – input will always be at nearly 1.4 V due to the diodes.
At -50 F the + input will be at 1.4 V – 0.5 V = 0.9 V
At 300 F the + input will be at 1.4 V + 3.0 V = 4.4 V

Arduino Uno has a 6-channel, 10-bit A/D converter. The range of the converter is 0 to 5 V. (There are a few other choices)
The voltage reference of the Arduino UNO is the +5 V power supply itself.
10 bits means the analogRead() command will return integers between 0 and 1023.
Each 1-bit change of the read value means the input voltage changed by (5 V)/1024 = 0.48828125 mV → ~0.5 F
(Precision is better than needed.)
I select channel A0 for the – input and channel A1 for the + input.
Read both, find the difference, multiply by 0.48828125. The result is the temperature in degrees F

Techniques in temperature measurement.

Thermistor—an example

Goal: Automotive engine coolant temperature is to be measured.
Desired range: -50 F to 300 F (-45 C to 150 C)
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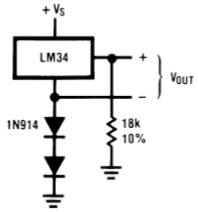
Desired precision: ~1 F (~0.5 C)
A search is done for a sensor: Decision for Texas Instruments LM34



The datasheet shows the schematic of "Figure 17" for this application

Arduino Uno has a 6-channel, 10-bit A/D converter. The range of the converter is 0 to 5 V. (There are a few other choices)
The voltage reference of the Arduino UNO is the +5 V power supply itself.
10 bits means the analogRead() command will return integers between 0 and 1023.
Each 1-bit change of the read value means the input voltage changed by (5 V)/1024 = 0.48828125 mV → ~0.5 F/count
(Precision is better than needed.)
I select channel A0 for the – input and channel A1 for the + input.
Read both, find the difference, multiply by 0.48828125. The result is the temperature in degrees F

Example of reading and computing the temperature;
`analogRead(A0);` gives 291
`analogRead(A1);` gives 814

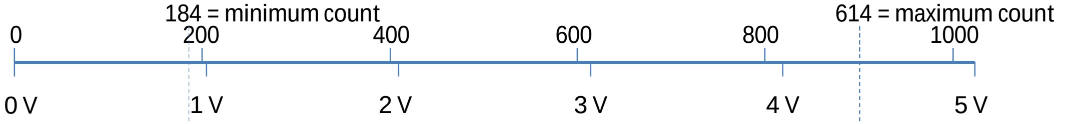
The voltage reference for the temperature sensor is 291 counts.
814 – 291 = 523 counts.
(523 counts)(0.48828125 F/count) = 255 F = engine cool. Temp.

Techniques in temperature measurement.

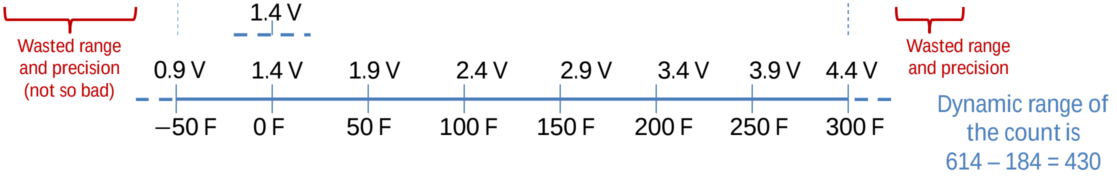
Thermistor—an example

Goal: Automotive engine coolant temperature is to be measured.
Desired range: -50 F to 300 F (-45 C to 150 C)
Desired accuracy: 3 F (1.67 C)
Desired precision: ~1 F (~0.5 C)
A search is done for a sensor: Decision for Texas Instruments LM34

The A/D conversion on the Arduino can be visualized along a number line labeled in counts or in volts.



The temperature sensor can be visualized as a number line labeled in either volts or degrees F.
The analog reference voltage also is a number line—quite short around 1.4 V.



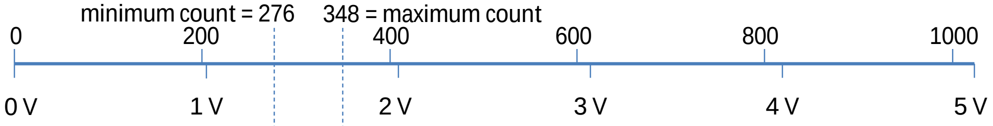
Dynamic range of the count is 614 – 184 = 430

Techniques in temperature measurement.

Thermistor—a bad example

We switch to a fictional sensor. It produces 1 mV/F.
To get the negative temperature range we add an offset of 1.4 just as before.
For simplicity we assume everything about this sensor it is perfectly accurate.

The A/D conversion on the Arduino can be visualized along a number line labeled in counts or in volts—no change



The temperature sensor can be visualized as a number line labeled in either volts or degrees F.
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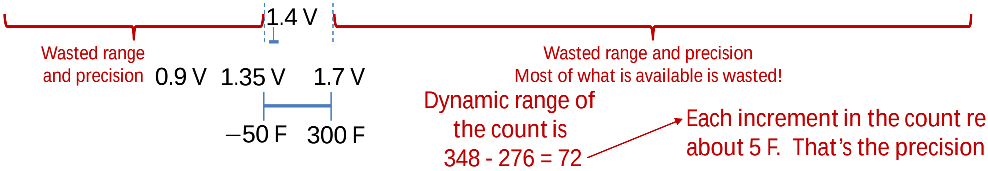

Dynamic range of the count is 348 - 276 = 72 → Each increment in the count represents about 5 F. That's the precision! (Awful.)

When this happens the typical cry from the <u>inexperienced</u> engineer is, "We need a better A/D converter. . . *Need More Bits*!"
A better solution: Reduce the scale of the A/D converter if possible. (e.g. 0 to 2.0 V) Could also reduce bias of signal.