Signal Characteristics and Conditioning

Starting from the sensors, and working up into the system:

1. What characterizes the sensor signal types
2. Accuracy and Precision with respect to these signals
3. General noise model with respect to these signals
4. The impact of the processing model

Reading from the book: Mancini, R. “Op Amps for Everyone”:

1) Instrumentation: Sensors to A/D Converters, especially section 12.3

The entire book can be found out on:

http://www.ee.nmt.edu/~thomas/data_sheets/op-amp-slod006a.pdf

Sensor Signal Types

Because sensors respond to some physical phenomena, they tend to exploit the properties of material that change as a function of the phenomena. These can be things like:

- Resistance/conductance
- Capacitance
- Inductance
- Permeability to something
- Geometry/Structure/Appearance
- Motion/Displacement

Or, they convert the phenomena into something that can be more easily directly measured, such as:

- Voltage
- Charge
- Current
- Frequency
- Phase
- Color or shape

Many analog sensors in the Mentorspace are members of the first examples (resistance and capacitance).

Currently, we have some sensors you can use

Humidity: similar to Shinyei Kaisha model C5-M3
Temperature: similar to NTC thermistors, accuracy line 2322 640 3/4/6....
Resistive light sensors: similar to Fuji & Co MPY series
Barometric pressure: Freescale MPL115A (we only have 1 of these)
Optical dust sensor: Sharp GP2Y1010AU0F (we only have 1 or 2 of these)
Gyroscope: Maxim Semiconductor MAX21000 (we only have a few)
Color sensors: Maxim Semiconductor MAX44006/MAX44008
Alcohol sensor: HanWei Electronics MQ-3
Carbon Monoxide sensor: HanWei Electronics MQ-7
Distance/proximity: Sharp GP2D12
Microphone: Panasonic WM-60A

Basic characteristics of sensors

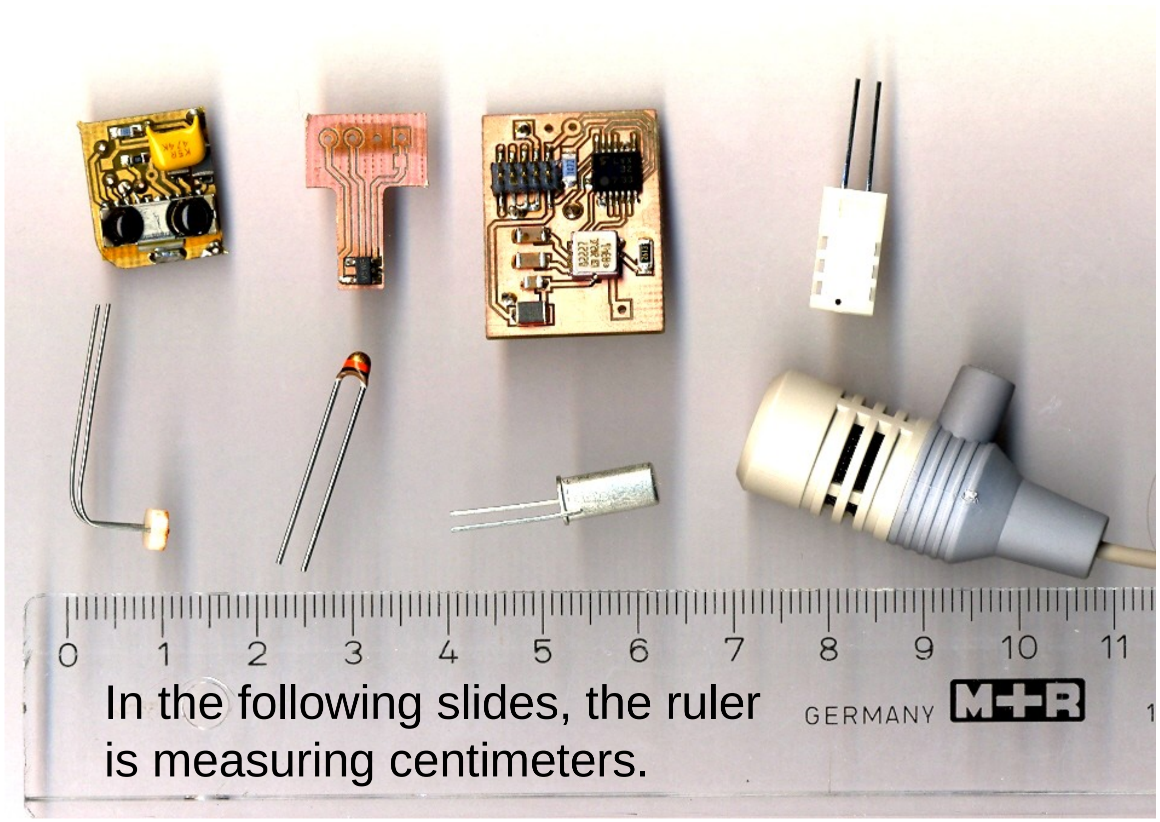
Sensors are available from a wide variety of sources.

- When choosing one, there are a number of considerations that you need to take into account. Here are some:

1. How it works. How it measures what you want. *Performance*.
2. Physical form factor
3. Some sensors are active, some passive.
4. *Power* requirements
5. *Cost*
6. Interface. How easy it will be to read what the sensor is saying.
7. Resolution and dynamic range. Sensitivity over what range.
8. Accuracy and precision. Quality of the signals you want to see.
9. Noise. Things the sensor may output that you don't want to see.

Real sensors

There are a zillion sensors that you can get to measure basic physical phenomenon. Here are some examples that show this.

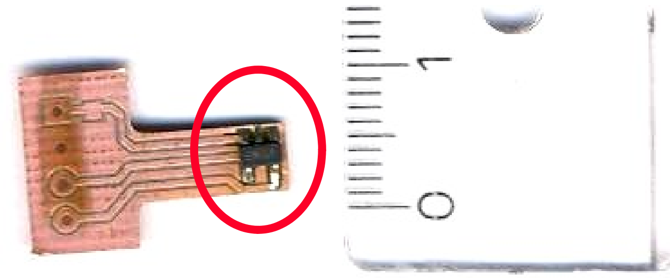


In the following slides, the ruler is measuring centimeters.

Often you will need to use your imagination to select a sensor (or to make you own).

Temperature

Lots of uses for temperature measurements. Two examples are shown. One is passive, and the other is active.



- Passive
- Resistance changes as a function of temperature.
- You have to map resistance to temperature. Not automatic.
- Doesn’t consume any power itself, but will dissipate power
- Very cheap
- No interface. Forms part of an analog circuit.

- Active
- Temperature causes changes to a semiconductor structure.
- Output is a digital number directly giving temperature to +-1 degree C.
- Consumes power (660 uW).
- Not as cheap as the thermistor.
- Digital interface. Complete circuit and interface all in one.

Using resistance to detect chemical vapor

HANWEI ELETRONICS CO.,LTD MQ-3 http://www.hwsensor.com

TECHNICAL DATA MQ-3 GAS SENSOR

FEATURES

* High sensitivity to alcohol and small sensitivity to Benzine .
* Fast response and High sensitivity
* Stable and long life
* Simple drive circuit

APPLICATION

They are suitable for alcohol checker, Breathalyser.

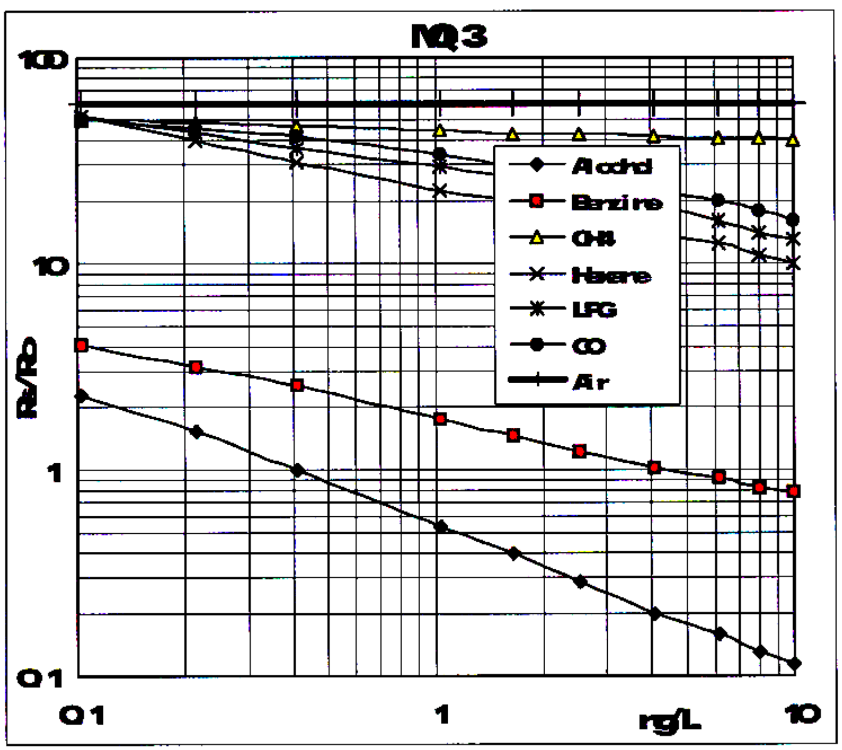


Fig.3 is shows the typical sensitivity characteristics of the MQ-3 for several gases.

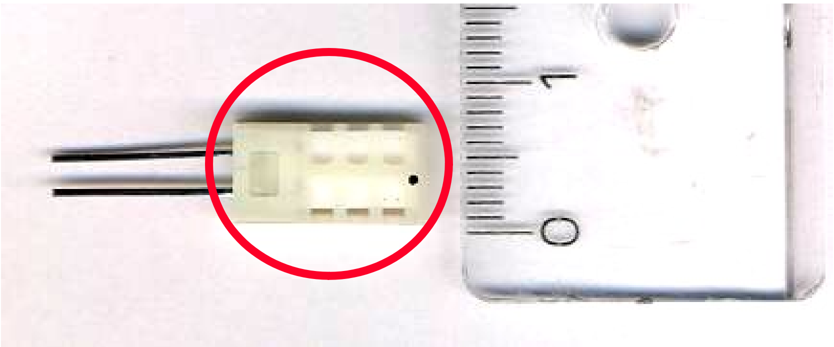
in their: Temp: 20℃、
Humidity: 65%、
O_2 concentration 21%
RL=200kΩ

Ro: sensor resistance at 0.4mg/L of Alcohol in the clean air.

Rs:sensor resistance at various concentrations of gases.

What if you wanted to detect if someone is breathing?

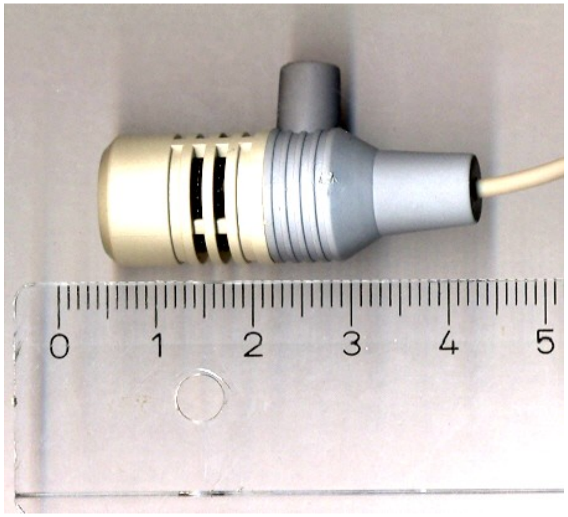
There are many ways, but one way is to measure Humidity.



- Passive. Useful for detecting moisture in air (rh).
- Moisture causes molecular changes to a capacitive structure.
- Humidity is reported as a change in resistance, so you need to put it in an alternating current circuit to see it.
- You then map AC resistance to humidity. Not automatic.
- Consumes no power itself, but will dissipate power
- Very cheap
- No interface. Forms part of an analog circuit.

Acoustic pressure, sound or vibration

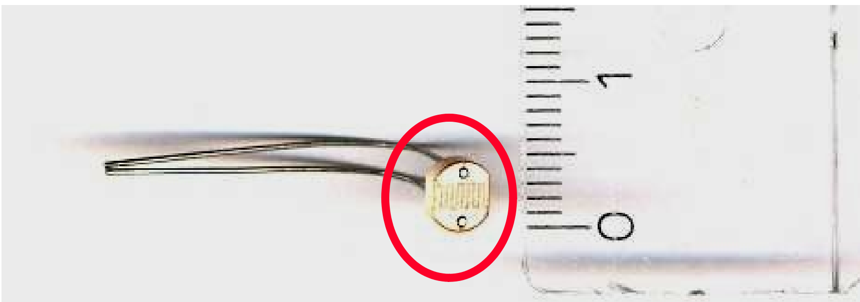
Microphones make great sensors for a variety of measurements.

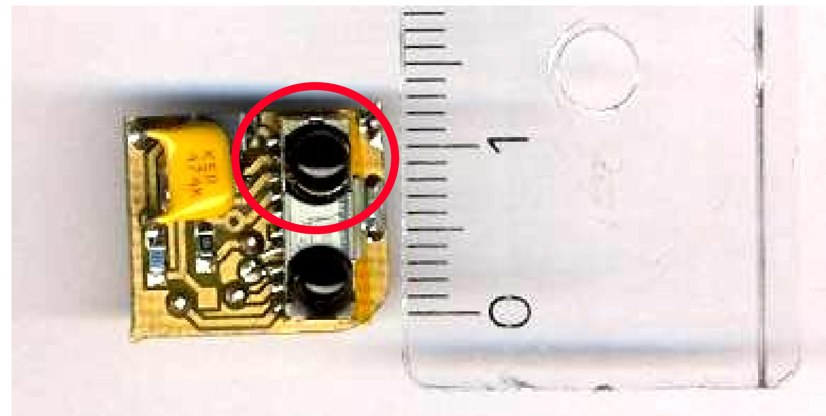


- They are effectively a pressure or vibration sensor.
- This one is active. Sounds causes changes to a capacitor.
- This microphone dissipates power, but not much. A few uW.
- There are passive varieties based on resistance or inductance.
- Not very cheap, but this one has good audio quality (ie good *dynamic range*)
- Analog interface. Forms part of an analog circuit.

Light intensity

Two examples are shown. One is generic, and the other is special.



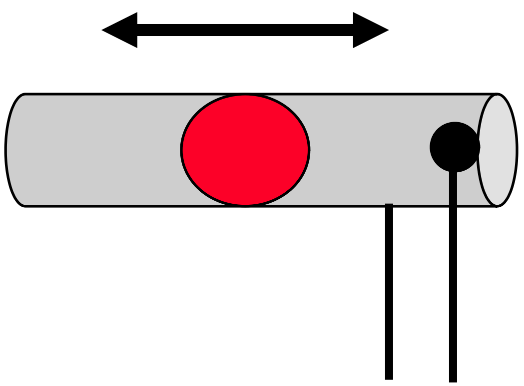


- Passive
- Resistance changes as a function of light intensity.
- You have to map resistance to light intensity. Not automatic.
- Doesn’t consume any power itself, but will dissipate power
- Cheap
- No interface. Forms part of an analog circuit.

- Active
- Used to detect infrared light. The infrared light is used to communicate.
- The sensor is part of a complete circuit
- Consumes significant power
- Not cheap, but OK for what it does.
- Digital interface. This device also has an infrared light emitter to send data as well

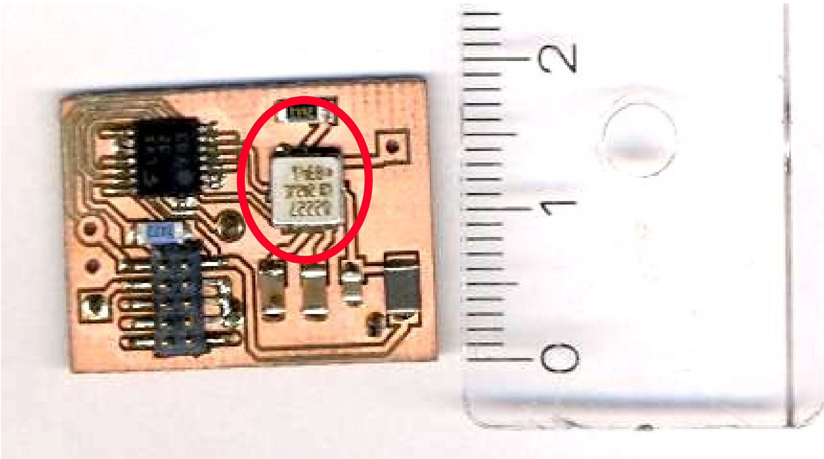
What if you wanted to detect orientation?
For example, is something upside down.

You can use a tilt sensor to do this. This tilt sensor is nothing more than a switch activated by a metal ball.



- Passive. Useful to detect binary position
- Rolling metal ball completes a switch connection
- Consumes and dissipates no power itself
- Very cheap
- You can treat this as either an analog or digital device
- Switches in various forms are among the most useful sensors

Acceleration



- Active
- Acceleration displaces a micromachined weight inside the device
- The weight is part of a capacitor. So acceleration results in a change in capacitance. There are lots of ways to read this out.
- One way measures the capacitance change and uses it to pulse width modulate a digital waveform.

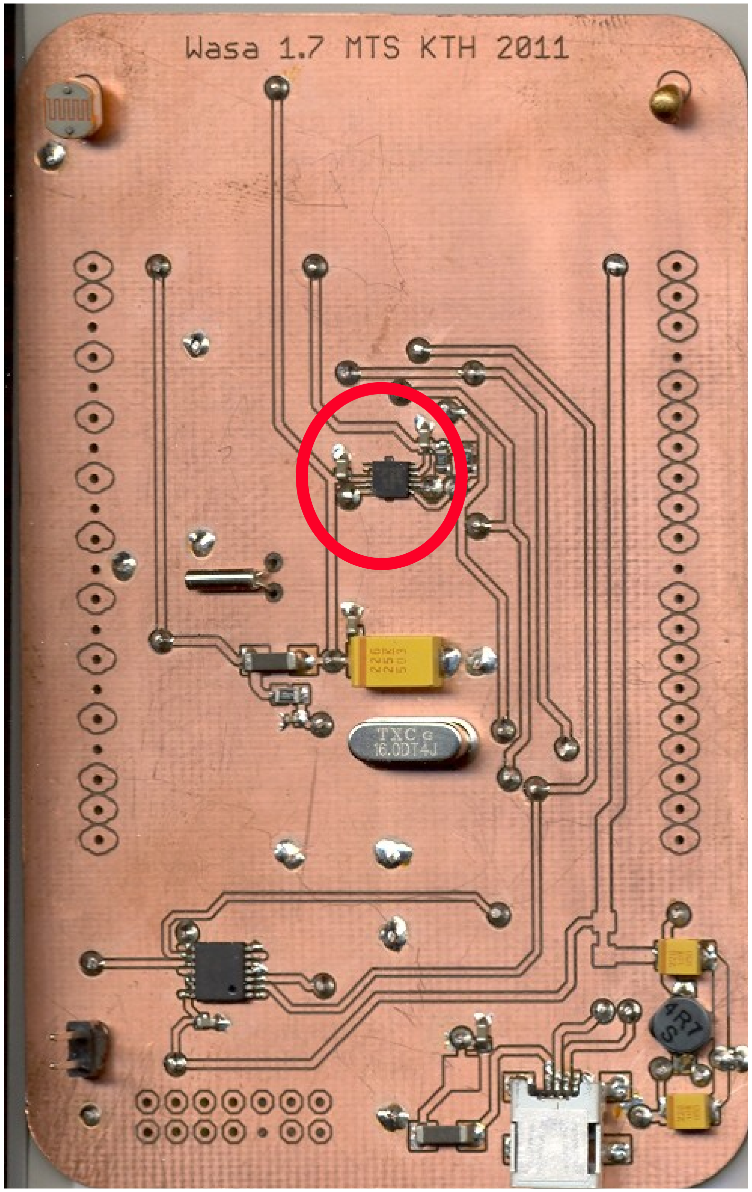
The position of this edge moves.

- Consumes power, a few mW.
- Not cheap, but relatively cheap for motion measurements.
- The interface is electrically digital, but requires special techniques to read. You need an accurate timer.

Acceleration

Example of a 3 axis accelerometer

- Active
- Uses micro-machined capacitors.
- The sensor is part of a complete circuit that measures the change in capacitance.
- Consumes very low power (155 uA)
- About 2 Euros
- Digital interface (I2C).
- It has it’s own Analog to Digital converter internal to the part.



Motion

- Motion is about measuring position, velocity and acceleration.
- There are lots of ways to do this. Several lectures could be given to how to measure motion.
- Position, velocity and acceleration are related by time.

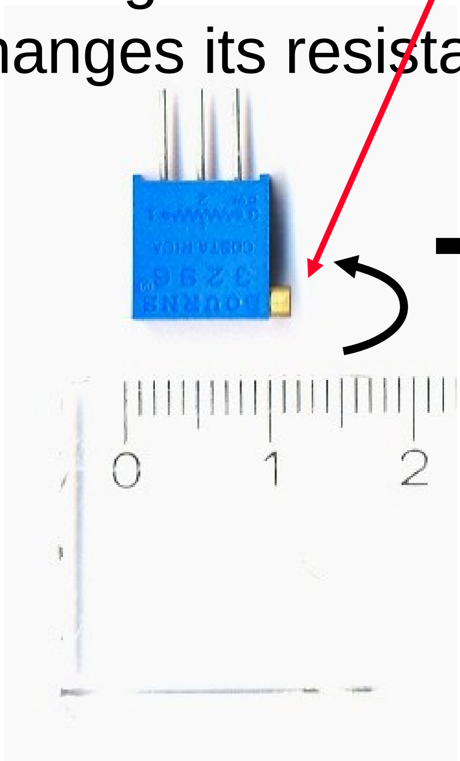
$$p = \int v \, \mathrm{dt} = \int \int a \, \mathrm{dt}$$

Where *p* is position, *v* is velocity and *a* is acceleration.

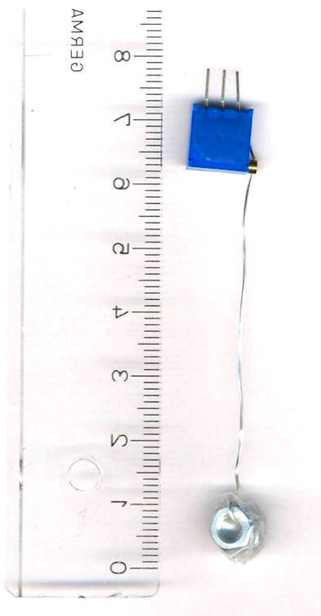
Make your own accelerometer

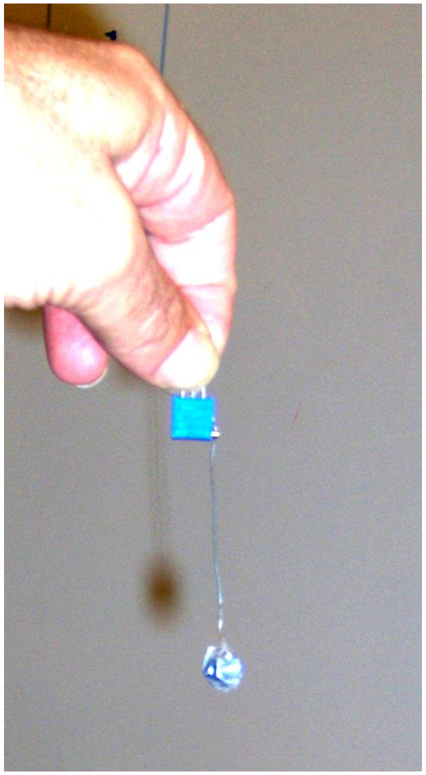
Sometimes it makes sense to make your own sensors.
Here’s an easy, very cheap, but somewhat big accelerometer.

A potentiometer
Turning the shaft
changes its resistance



Add a stiff rod
and a weight

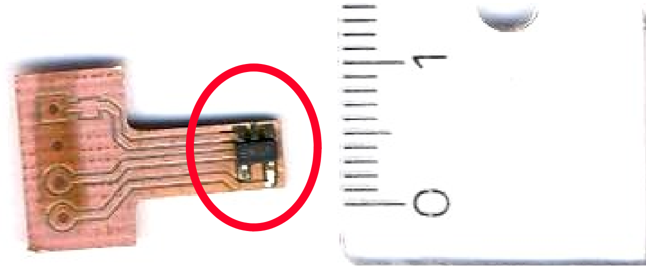




and let gravity help!

Analog or Digital outputs

- Although the phenomena being sensed is usually considered to be analog in nature, the outputs of a sensor could be an analog representation or a digital one.
- Digital output sensors are really just analog sensors with built in signal conditioning.
  - You still have to deal with noise, accuracy, precision, resolution and everything else.
- They come in all common I/O formats
  - Parallel / GPIO
  - Bit serial / I2C, RS-232, SPI, ‘1 wire’, USB and more
  - Different number of resolution bits
- Factors that influence your choice.
  - + Time to market
  - + Retrofit existing platforms. No redesign
  - + Physical constraints/size, higher levels of integration
  - – Cost; digital ones often cost more.
  - – Processing limitations. Digital ones distribute the processing, although your system might be able to do that too.



MICROCHIP

TC74

Tiny Serial Digital Thermal Sensor

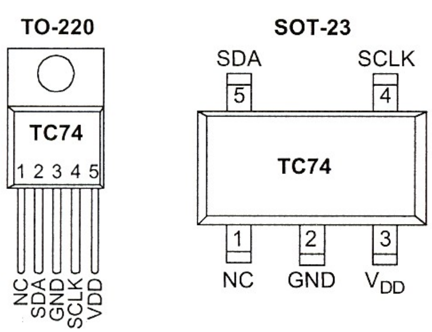
Features

- Digital Temperature Sensing in SOT-23-5 or TO-220 Packages
- Outputs Temperature as an 8-Bit Digital Word
- Simple SMBus/I^{2}C™ Serial Port Interface
- Solid-State Temperature Sensing:
  - ±2°C (max.) Accuracy from +25°C to +85°C
  - ±3°C (max.) Accuracy from 0°C to +125°C
- Supply Voltage of 2.7V to 5.5V
- Low Power:
  - 200 µA (typ.) Operating Current
  - 5 µA (typ.) Standby Mode Current

Applications

- Thermal Protection for Hard Disk Drives and other PC Peripherals
- PC Card Devices for Notebook Computers
- Low Cost Thermostat Controls
- Power Supplies
- Thermistor Replacement

Package Types



Note: The TO-220 tab is connected to pin 3 (GND)

General Description

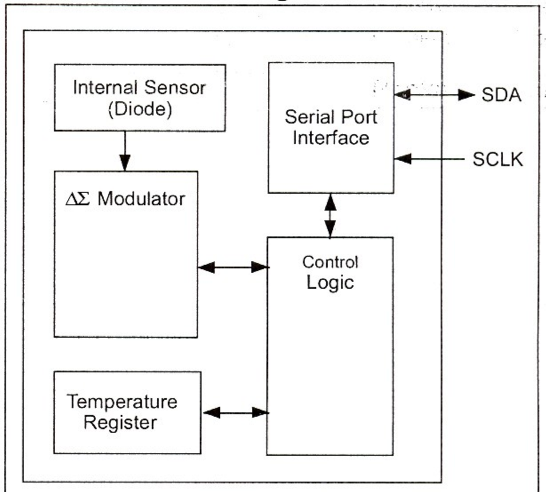
The TC74 is a serially accessible, digital temperature sensor particularly suited for low cost and small form-factor applications. Temperature data is converted from the onboard thermal sensing element and made available as an 8-bit digital word.

Communication with the TC74 is accomplished via a 2-wire SMBus/I^{2}C compatible serial port. This bus also can be used to implement multi-drop/multi-zone monitoring. The SHDN bit in the CONFIG register can be used to activate the low power Standby mode.

Temperature resolution is 1°C. Conversion rate is a nominal 8 samples/sec. During normal operation, the quiescent current is 200 µA (typ). During standby operation, the quiescent current is 5 µA (typ).

Small size, low installed cost and ease of use make the TC74 an ideal choice for implementing thermal management in a variety of systems.

Functional Block Diagram



Analog Sensor Signal Characterization

- Sensor response
  - Linear sometimes. It's often non-linear.
  - Lots of methods to deal with non-linear response.

$$R(T) = R_{ref} \times e^{A + B/T + C/T^2 + D/T^3} \qquad (1)$$

$$T(R) = \left(A_1 + B_1 \ln\frac{R}{R_{ref}} + C_1 \ln^2\frac{R}{R_{ref}} + D_1 \ln^3\frac{R}{R_{ref}}\right)^{-1} \qquad (2)$$

where:

A, B, C, D, A_1, B_1, C_1 and D_1 are constant values depending on the material concerned

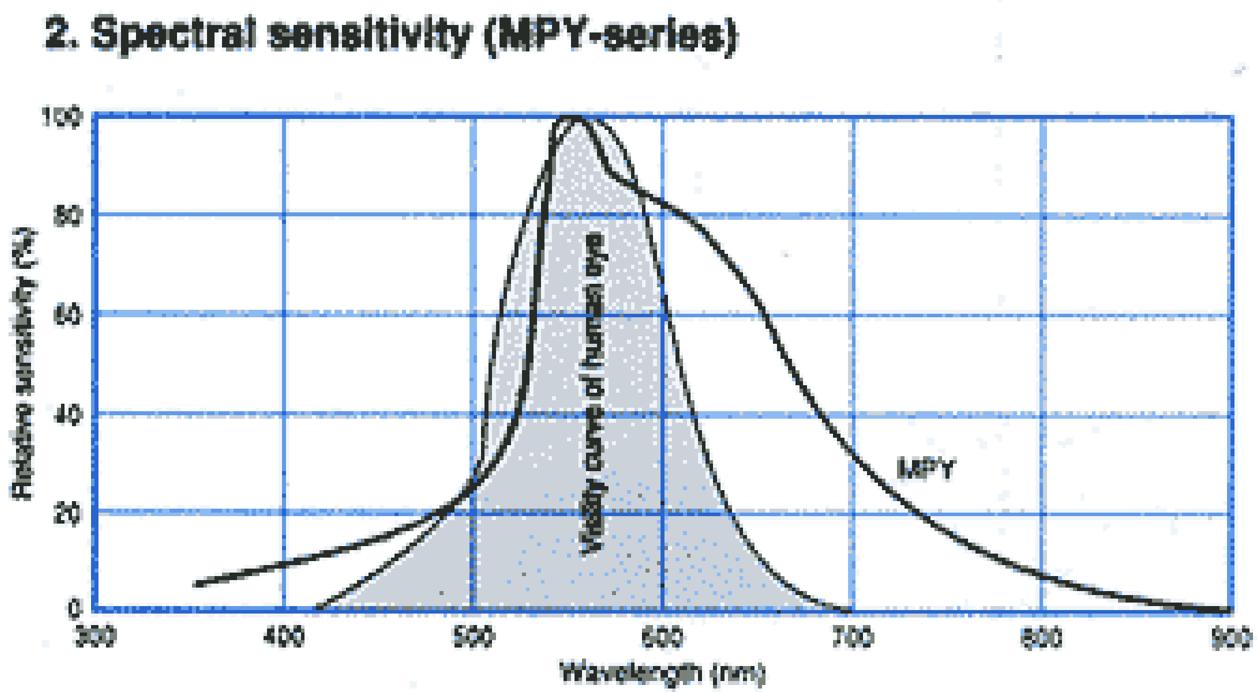
R_{ref} is the resistance value at a reference temperature (in this event 25 °C).

T is the temperature in K.

This is a typical thermistor response. To determine the actual temperature, you might want to use a lookup table, or a collection of piecewise linear segments. Depends on your application requirements.

Analog Sensor Signal Characterization

- Sensor sensitivity
  - Does it respond to the phenomena range you want?



This is a typical resistive light detector response.
It isn't very good for UV.

Analog Sensor Signal Characterization

- Dynamic range
  - Does the sensor respond across all values in the range of phenomena you want?
  - This applies to digital sensors as well.

Dynamic Range: The ratio of a specified maximum level to the minimum detectable value; sometimes expressed in dB.

Or considering noise:
The largest signal that can be measured, divided by the inherent noise of the device (sensor).

It isn't just the noise of the sensor which will determine the dynamic range of your Measurement system. There are many other contributing elements.

Analog Sensor Signal Characterization

- The “output” of an analog sensor may be just a DC level.
- Or, it can be a modulated AC signal.
  - Amplitude modulated, for example some humidity sensors
  - Pulse Width modulated, for example some accelerometers
  - Frequency Modulated
  - Phase Modulated
- You could have a combination of several of these, ie amplitude and phase.
  - Sensing and detecting radio signals are an example.
  - This is often done to measure the location of something.

Accuracy, Precision and Resolution

Good to review these, as they are directly affected by noise

Given a "true" value to measure:

Accuracy relates to the difference between your measurement and the "true" value. It helps to assume you have perfect repeatability when thinking about what accuracy is.

Precision relates to how repeatable your measurements are. It's possible to be very precise, but not very accurate. It's also possible for a group of measurements taken together to be quite accurate, but not very precise.

Resolution relates to the smallest difference in "true" value that a sensor can measure. For example, a temperature sensor that can at best resolve 1 degree vs a sensor that can resolve 0.001 degree. Note, this is NOT the same as dynamic range!

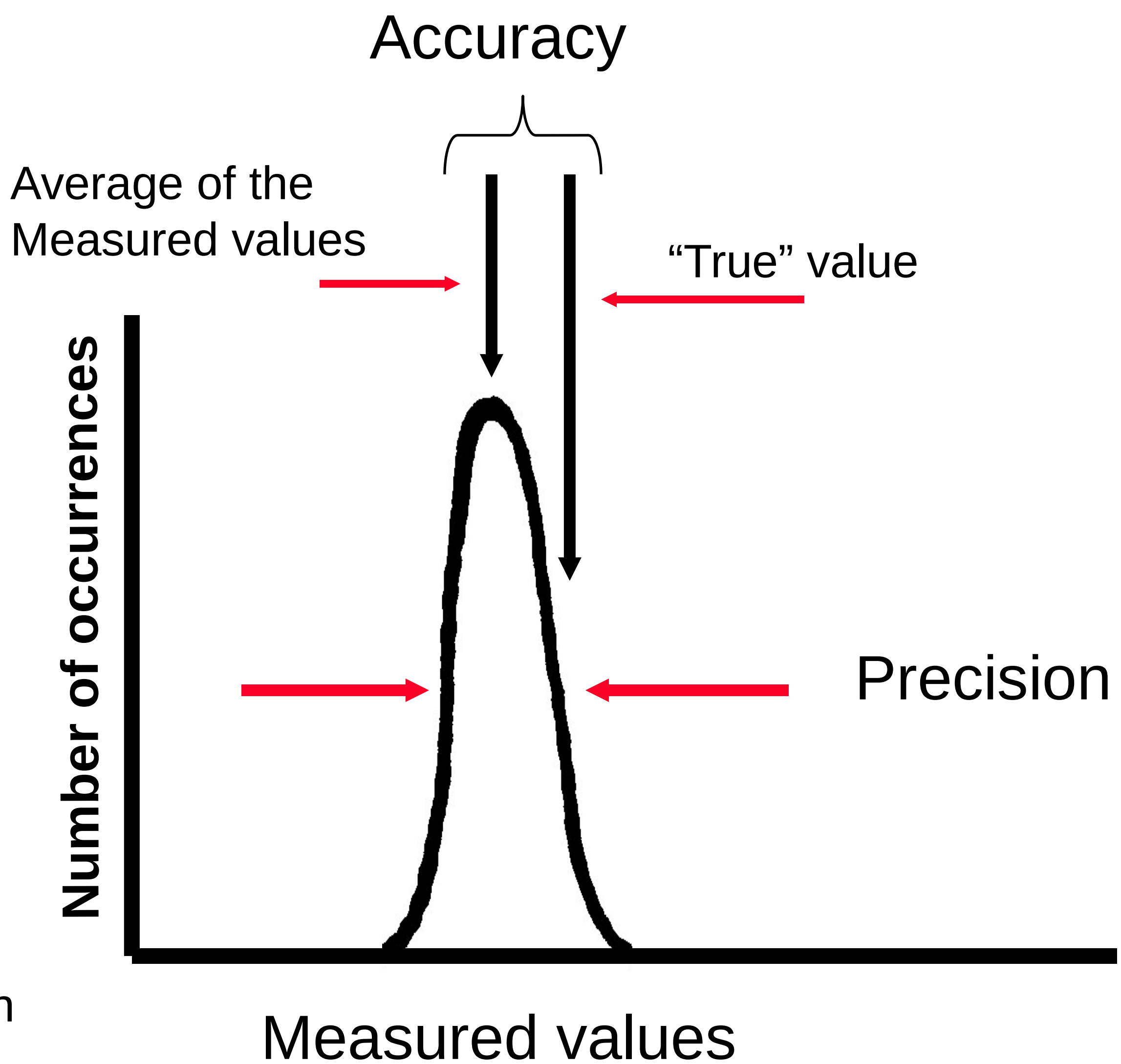
As we look at noise in the system, we will see how accuracy, precision and resolution are affected.

Example: Accuracy and Precision

Accuracy: Is the difference between the “true” value and the average of your actual measurements of the “true” value. Perfect accuracy would result in the average of the actual measurements of the “true” value being exactly the same as the “true” value.

Precision: A measure of the value spread of your actual measurements of the “true” value. Perfect precision would have a spread of zero. The wider the spread, the worse the precision.

Note that it is possible to have perfect accuracy with non-perfect precision. Also it is possible to have *near* perfect precision with non-perfect accuracy.



Resolution

What resolution can a sensor have? It depends.

- Both analog and digital sensors have intrinsic noise sources.
- The amount and nature of the noise will affect resolution.

All sensors start out as analog. Noise in these are due to:

- Charge and conduction phenomena, such as thermal or shot noise
- Material phenomena. What the sensor is made out of.
- Environmental effects on the sensor material, ie moisture.
- Packaging and other constructional details can induce noise.

If the sensor is digital, further noise is introduced.

- For us, quantization effects (A to D conversion) are the biggest factors. The ADC greatly affects the resolution obtainable.
- Anything that touches the signal before it is digitized will also produce noise

Example: Analog to Digital Resolution

Suppose you have an 8 bit ADC, and suppose:

- The lowest voltage it can accept is 0 volts.
- The highest voltage it can accept is 1 volt.

Then, its resolution in the absence of any other noise is:

$$(1-0)\big/2^8 = 1\big/256 = 0.0039 \text{ volts/LSB}$$

This means that in this case an applied voltage must change by at least 0.0039 volts for the ADC to show any output change (a *change* of 1 LSB).

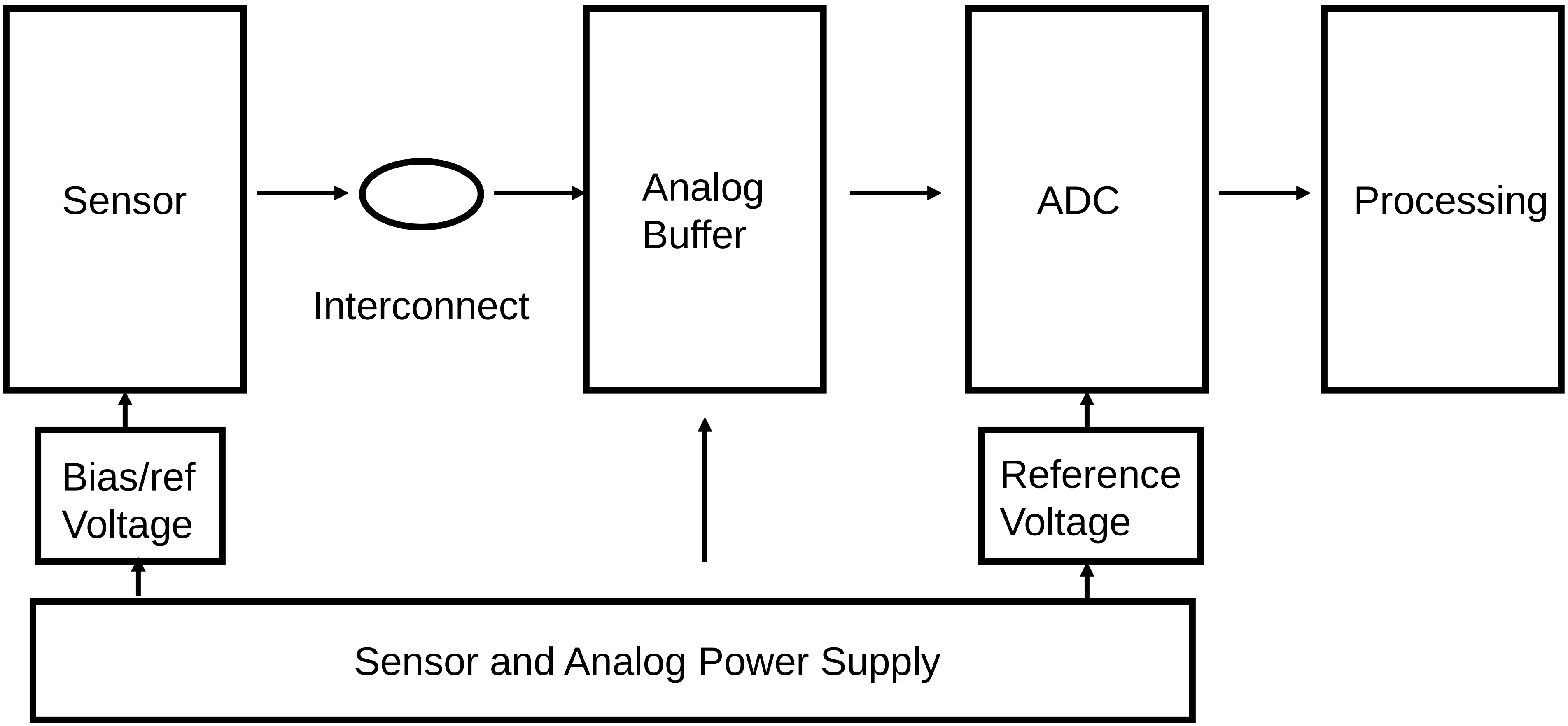
Note that as the dynamic range goes up, the resolution goes down!

A circuit using this example can not resolve less than 0.0039 volts. If you need better resolution, then you need an ADC with more bits.

Generalized Noise Model for Sensor Systems

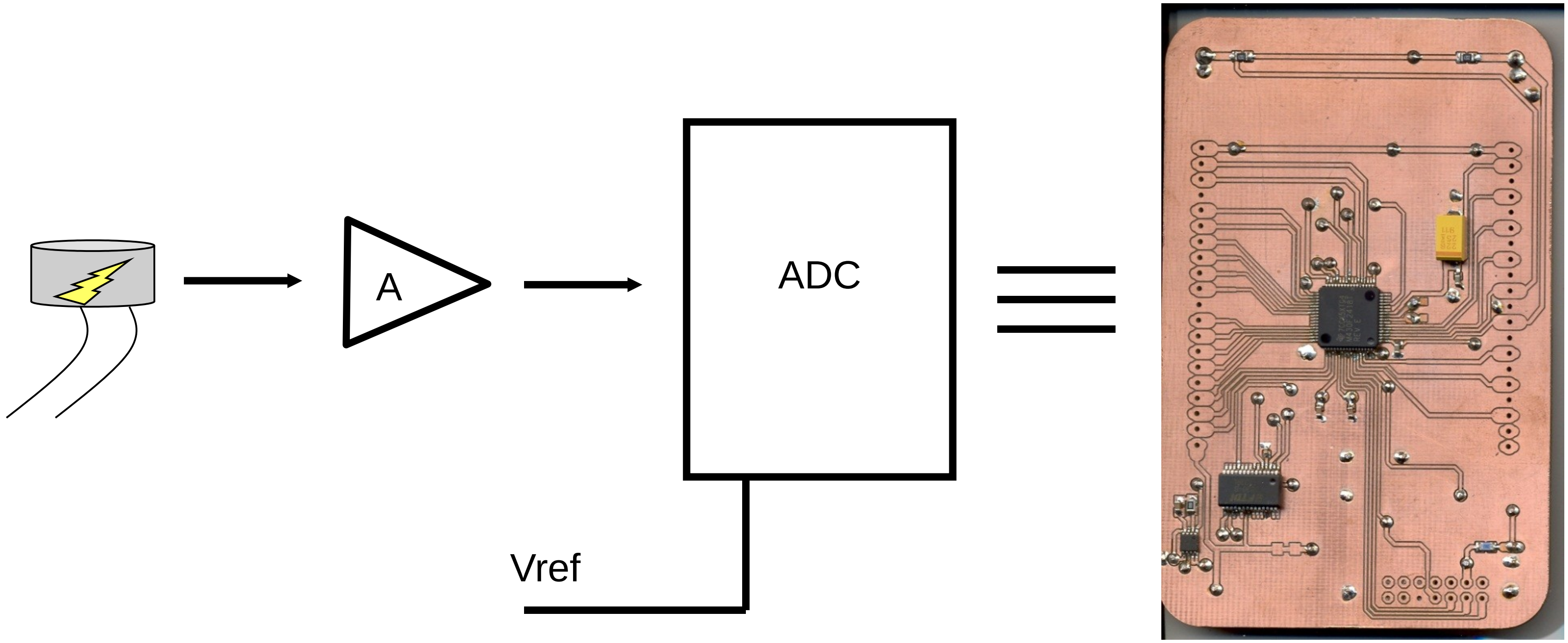
- Want a *simple*, *general* framework noise model that we can use
  - Useful for generic platforms and examples
  - One that we can add to as necessary
- Use it to determine:
  - If an existing design will perform according to what we want
  - To help design new systems
- Applies both to analog and digital sensor sets
  - You can decompose a digital sensor back into this model.
- Start with static noise, and then take into account time varying noise

Noise Model



Assume that in this example, everything will be operating over a range of ambient temperatures from 15 to 35 degrees C. Average room temperature is assumed to be 25 degrees C.

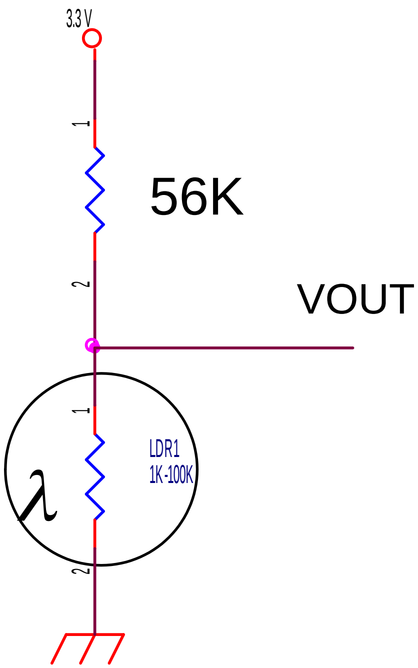
Example using a light sensor application

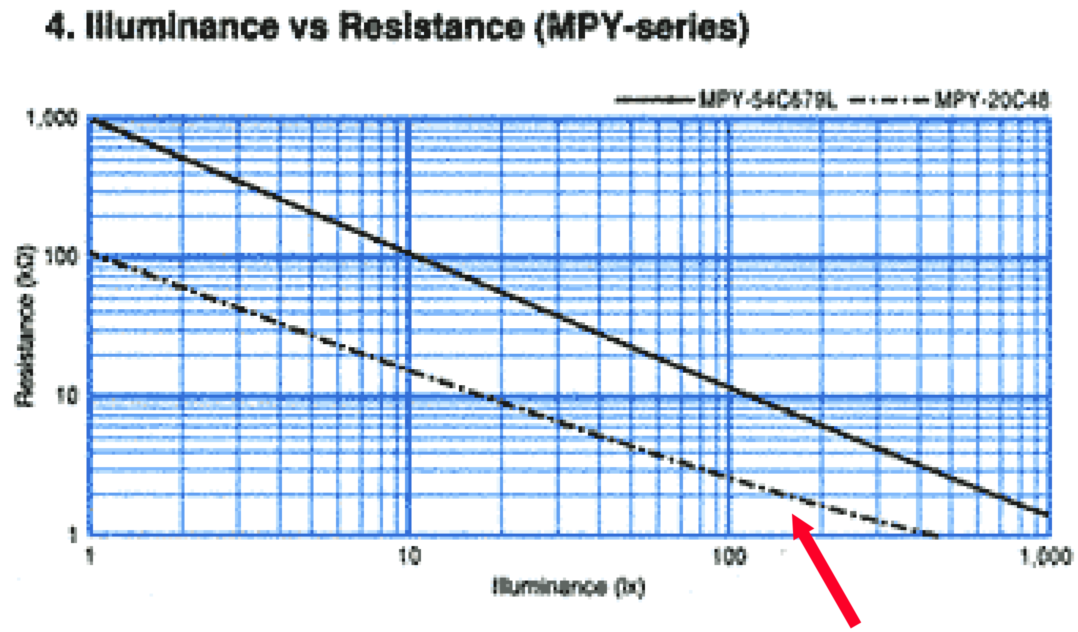


This board has a 12 bit ADC on it. In this example, how many (bits of) resolution do we really get with the light sensor circuit? Also, what affects accuracy and precision? Where is the noise, and how much noise do we have?

1. Light Sensor and bias circuit
2. Buffer (amplifier) Stage
3. ADC and voltage reference

Light sensor and bias circuit





We use the curve for the MPY20C48

- Specified output at 25 degrees C:
  - Full illumination: VOUT = 57.9 mv
  - Least illumination: VOUT = 2.115 volts
- Error sources:
  - LDR1 device tolerance: 5%
  - R1 resistor tolerance: 0.1%
  - LDR1 temperature coefficient: +-2% drift over 20 degrees C.
  - R1 temperature coefficient: negligible over 20 degrees C.

Light sensor non-correctable error

- The device tolerance for both LDR1 and R1 will be adjusted out in the buffer stage. They are fixed errors that don't change for the same part.
- The temperature drift for LDR1 is significant and cannot be adjusted out. Calculate resulting voltage output drift for worst case.

Worst case is at lowest illumination:

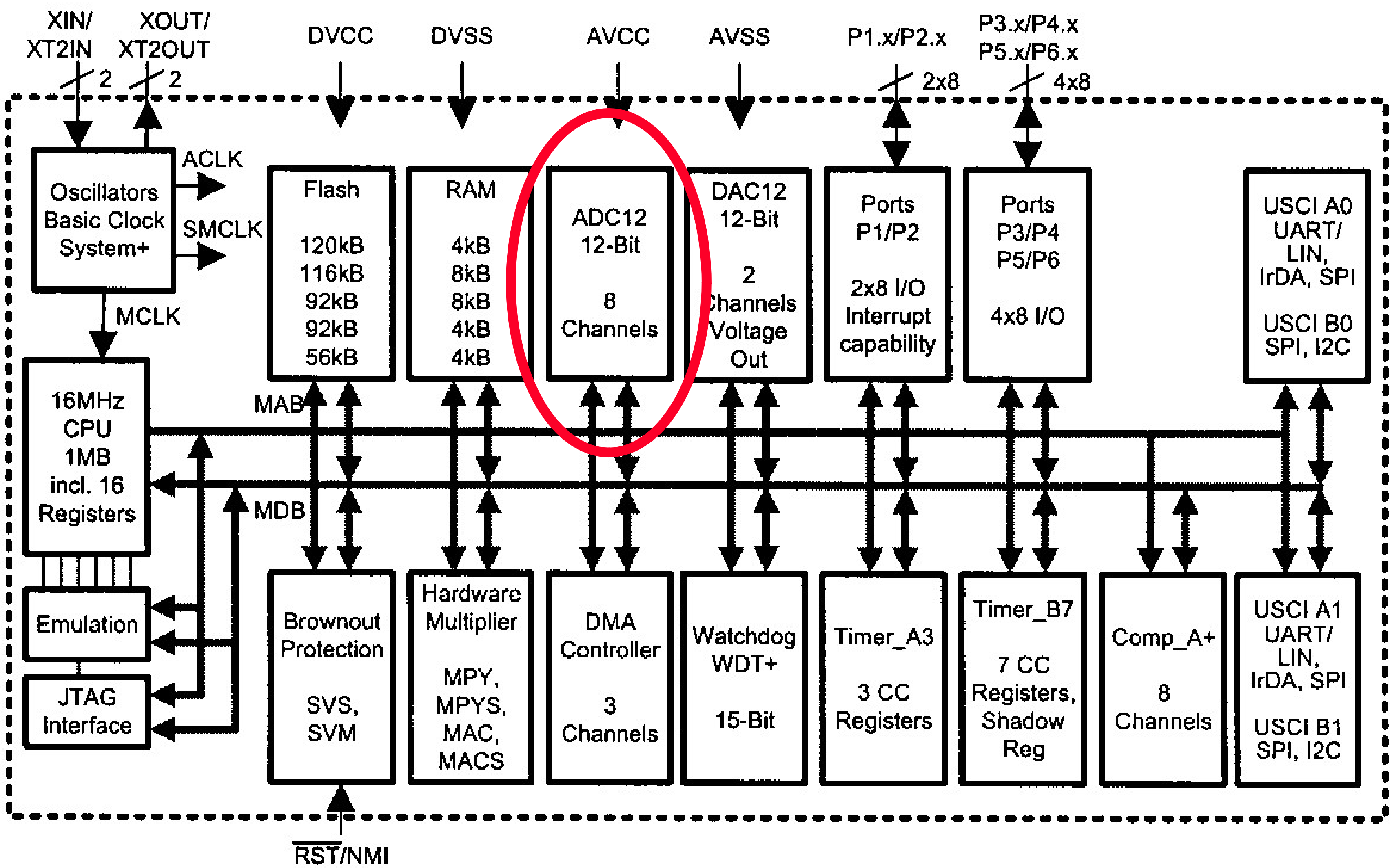
100K + 2%, VOUT = 2.130 volts
100K – 2%, VOUT = 2.100 volts

Thermal drift = 30mv over 20 ^{o}C, or 1.50mv/^{o}C

This noise will be multiplied by the amplifier stage.
We will remember this number for later.

Analog to Digital Converter and reference voltage error

functional block diagram, MSP430F261x, 64-pin package



Analog to Digital Converter and reference voltage error

The light sensor design uses the internal microcontroller ADC

- Has built in analog MUX for sensors (there is only 1 ADC, not 8)

- 12 bit output
- Internal reference set to 2.5V

1LSB = $2.5/2^{12}$ = 0.61mV
(Our ADC can resolve 0.61mV)

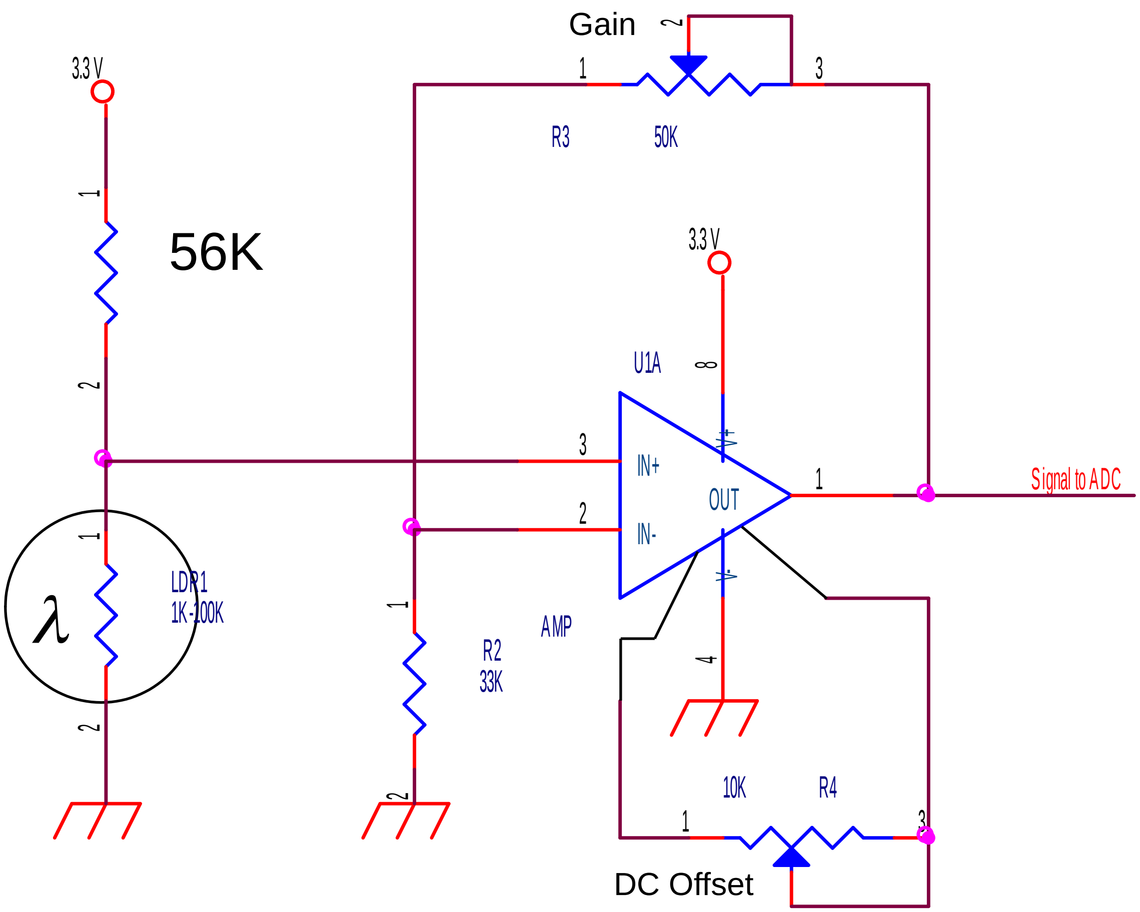
Input offset error = 2.44mV (4LSB)
Gain error = 1.22mV (2LSB)
Reference voltage error = 100PPM/^{o}C

To convert PPM to error in LSBs:
$1\times10^{6}/2^{12}$ = 244 PPM/LSB
20^{o}C * 100PPM/^{o}C = 2000 PPM
2000/244 = 8LSB

Amplifier Error

- Often a signal from a sensor will need to be amplified before sending the signal to an Analog to Digital Converter.
- Usually this is done in order to take advantage of the full resolution of the ADC with respect to the range over which the sensor is intended to operate.
- A very commonly chosen amplifier for such applications is an Operational Amplifier.
- Some versions of microcontrollers have internal OP Amps.

Amplifier Circuit and Parameters related to noise



R_{IN}	10^{12} ohms
R_{OUT}	150 ohms
V_{OS}	3.8mv
I_B	10 pA
TCV_{OS}	2uV/^{o}C
V_N	$37\mathrm{nv}/\sqrt{\mathrm{Hz}}$
I_N	$100\mathrm{pA}/\sqrt{\mathrm{Hz}}$

V_{OS} (input offset voltage) and I_B (input bias current) are calibrated out.

Mark Smith KTH School of ICT

Remember the light sensor error

Light sensor non-correctable error

- The device tolerance for both LDR1 and R1 will be adjusted out in the buffer stage. They are fixed errors that don't vary for the same part.
- The temperature drift for LDR1 is significant and cannot be adjusted out. Calculate resulting voltage output drift for worst case.

Worst case is at least illumination:

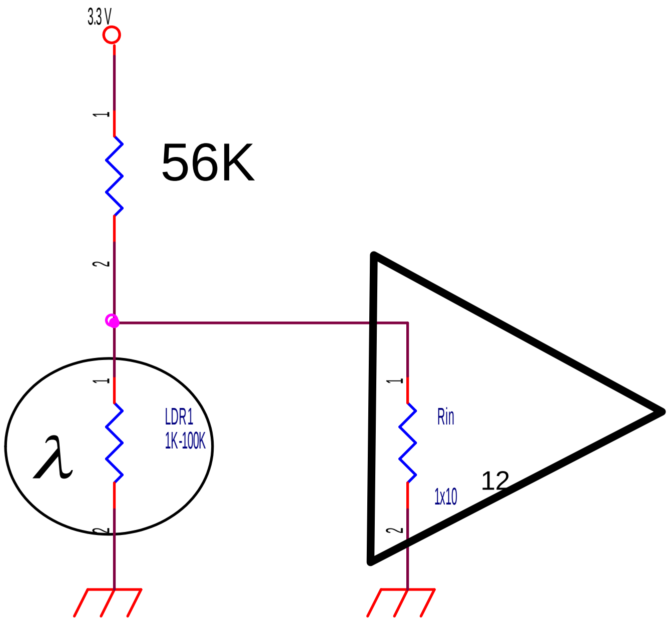
100K + 2%, VOUT = 2.130 volts
100K – 2%, VOUT = 2.100 volts

Thermal drift = 30mv over 20 ^{o}C, or 1.50mv/^{o}C

This noise will be multiplied by the amplifier stage.

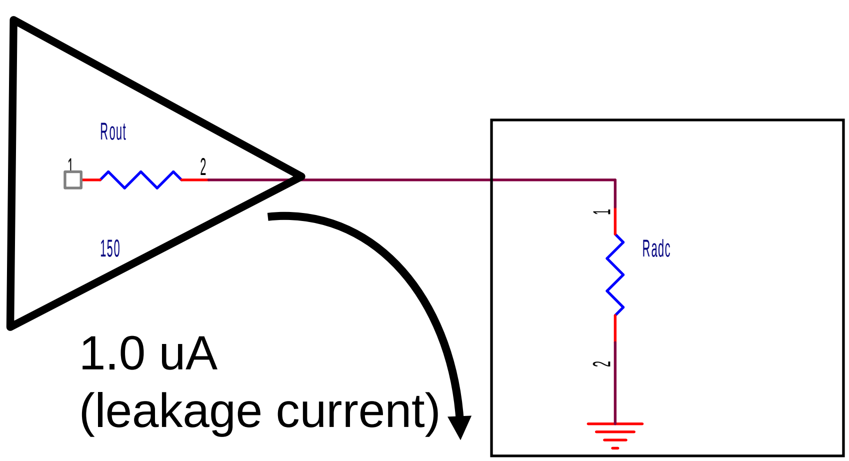
Suppose our Op Amp gain will be 1.17
This gives 2.13V * 1.17 = 2.5 volts (max ADC input)
This works out to: 30mV * 1.17 / 0.61(mV/LSB) = 57 LSB

Effect of R_{IN} and R_{OUT}



R_{IN} is the input resistance of the Op Amp. It forms a voltage divider with the output resistance of the sensor.

R_{IN} in this case is extremely high compared to what is driving it (7 orders of magnitude). Not significant.

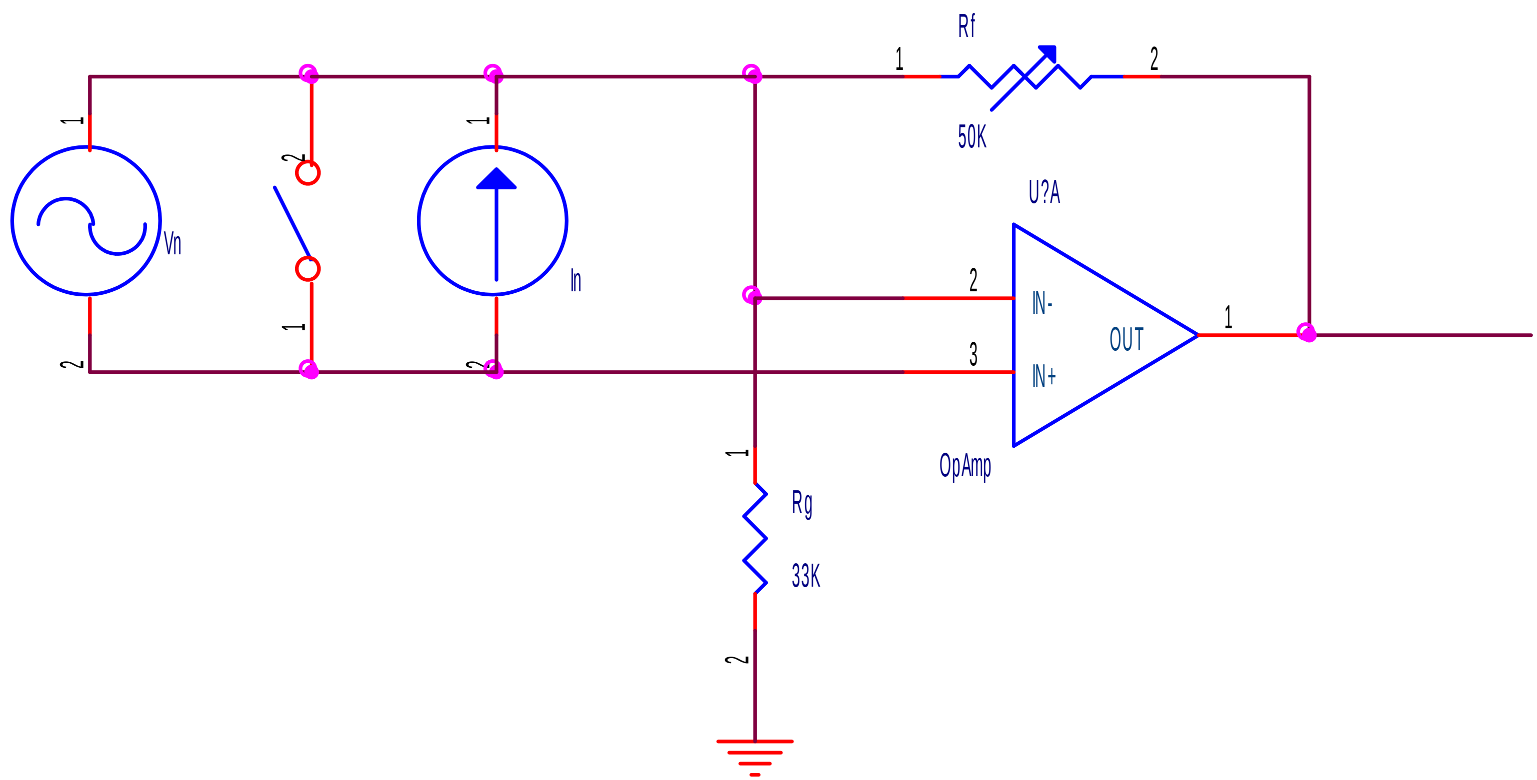


R_{OUT} is the output resistance of the Op Amp. It forms a voltage divider with the input resistance of the ADC.

1uA * 150 ohms = 150uV
150uV / 0.61(mV/LSB) = 0.245 LSB

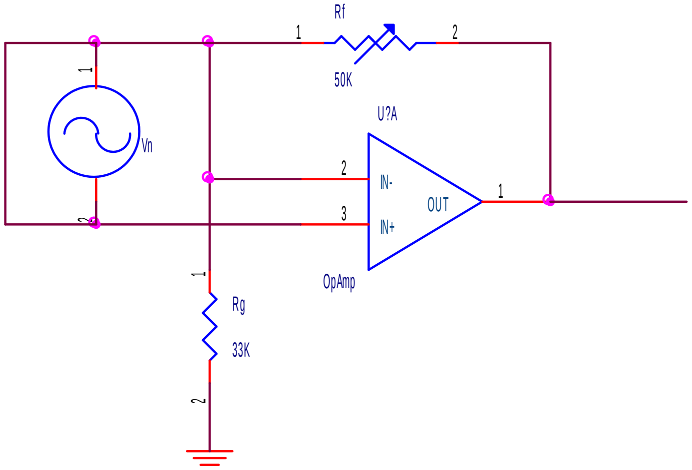
Effect of V_N and I_N

V_N is the noise voltage that appears to exist at the input of the Op Amp with the inputs shorted. I_N is the noise current that appears to flow at the inputs when open. When measured across a Rf and Rg it produces an extra input voltage.



For more details on V_N and I_N see:
National Semiconductor, Application Note AN-104, *Noise Specs Confusing?*
http://electro.fisica.unlp.edu.ar/temas/pnolo/p1_AN-104.pdf
http://www.ti.com/lit/an/snva515c/snva515c.pdf

Effect of V_N and I_N

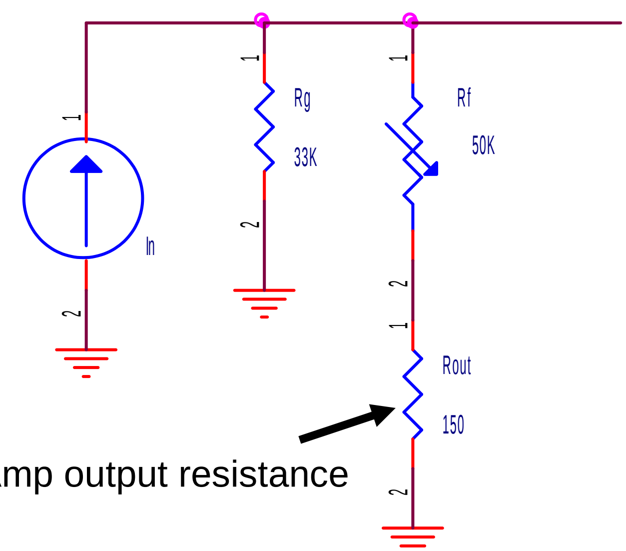


$$V_N = (37nv/\sqrt{Hz}) \times \text{closed loop gain}$$

$$\mathrm{V_N} = (37\ \mathrm{nV}/\sqrt{Hz}) \times 1.17 = 43\ \mathrm{nV}/\sqrt{Hz}$$

$$43n(V/\sqrt{Hz})/0.61(mV/LSB) = 7.05x10^{-5}\,LSB/\sqrt{Hz}$$

Not significant in our case at 1 hz.



Op Amp output resistance

$$I_N = 100\,pA/\sqrt{Hz}$$

Resulting voltage across resistor network is :

$$V(I_N) = 100\,pA/\sqrt{Hz} \times 16.5Kohms \times \text{closed loop gain}$$

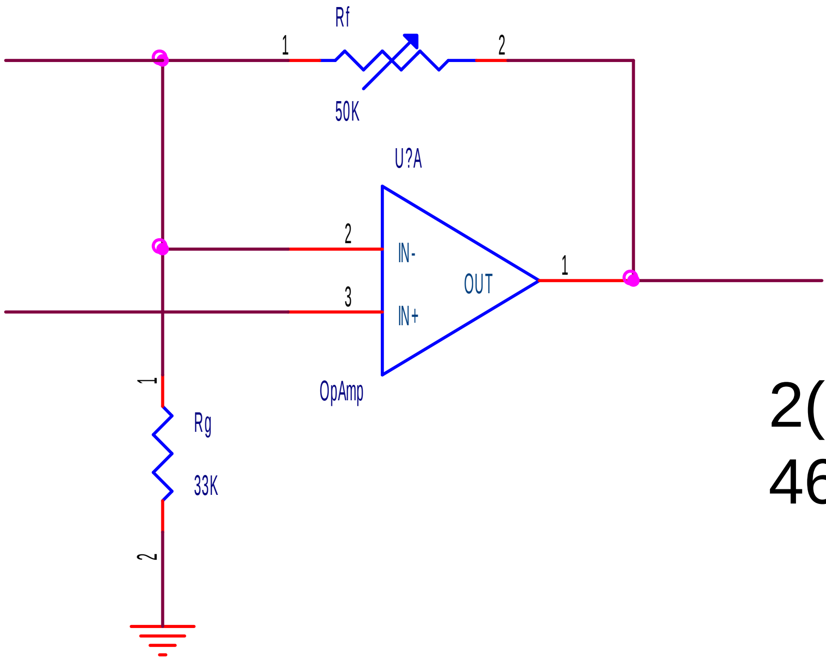
$$\mathrm{V(I_N)} = 100(\mathrm{pA}/\sqrt{Hz}) \times 16.5\mathrm{K} \times 1.17 = 1.9\ \mathrm{uV}/\sqrt{Hz}$$

$$1.9(uV/\sqrt{Hz})/0.61(mV/LSB) = 3.11x10^{-3}\,LSB/\sqrt{Hz}$$

Not significant in our case at 1 hz.

Effect of TCV_{OS}

TCV_{OS} is input offset voltage temperature drift of the Op Amp



$2(uV/^{O}C) * 20^{O}C * 1.17 = 46uV$

$46uV / 0.61(mV/LSB) \rightarrow 7.5x10^{-2}$ LSB

Noise error summary

Error Parameter	Calibrate out	Error in mV	Error in LSBs
Sensor device tolerance	yes	41	[67]
Sensor thermal drift	no	35	57
Op Amp Vos	yes	3.8	[6.2]
Op Amp Ib	yes	0	[0]
Op Amp Rin	no	0	0
Op Amp Rout	no	0.15	0.24
Op Amp Vn	no	0	0
Op Amp In	no	0.003	0
Op Amp TCVos	no	0.047	0.07
ADC input offset	no	2.4	4
ADC gain error	no	1.2	2
Reference voltage error	no	4.8	8
Total worst case	no	40	71.31

71.3 LSBs represent the following loss :

$$2^x = 71.3$$

$$x = \frac{\log(71.3)}{\log(2)} = 6.1\,\text{bits}$$

Overall, the light sensor is accurate to 12 – 6.1 = 5.9 bits.