<u>The *range* of a sensor—Two numbers: max input and min input</u>.

Think about your vision. What is the darkest scene that you might be able to see something of?

The darkest scenes that we can perceive have darkest elements that are not black of about 10^{-6} cd/m^2 (candelas per meter squared)
Our eyes have poor color sensitivity at this brightness, but if you want to count black-and-white as good enough, then this is the dark limit.

If you want good color rendition to be perceived, the scene's elements should stay in the range of 10^0 cd/m^2 to 10^5 cd/m^2

The brightest scenes that we can perceive have brightest elements that are not white of a brightness of about 10^6 cd/m^2.

The *range* of human vision is from $L = 10^{-6}$ cd/m^2 to $H = 10^6$ cd/m^2

Notice: The output of the sensor will also have a range which is related to the range of the input. From an applications point of view, you need to match the *input* range of your sensor to your *physical environment*.

Various manufacturers of sensors specify all kinds of stuff. Look to be sure the *input* range of the sensor is appropriate.

1

<u>The *precision* of a sensor—the smallest change that can be sensed</u>.

Think about your vision. What is the smallest change in brightness that your eye can perceive?

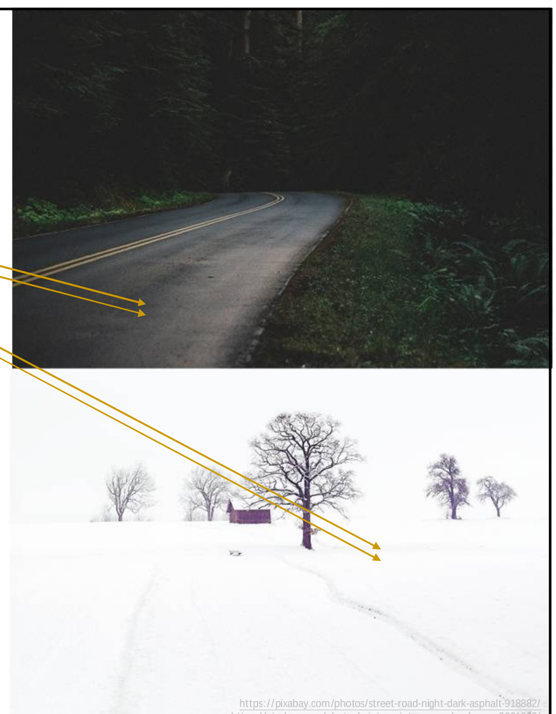
It varies, but many people can detect about a 0.02 cd/m^2 change in brightness, or luminance. This is the precision of your eye.

Changes in the phenomenon to be sensed (light in this case) that are smaller than the precision of the sensor will not be reliably detected.

This small change will by definition, produce a change in the output of the sensor of one unit of significance.

0.02 cd/m^2 change in brightness?

0.02 cd/m^2 change in brightness?



Let $x(t)$ be the light input to one pixel of a camera's image sensor.
Let $f\big(x(t)\big)$ be the resulting voltage output of the sensor.

Let the pixel's brightness precision be $p = 0.02$ cd/m^2.

Then by definition of precision

$$f\left(x(t) + 0.02\ \text{cd/m}^2\right) - f\big(x(t)\big) = 1 \text{ unit of significance}$$

2

The *precisoin* of a sensor—the smallest change that can be sensed.

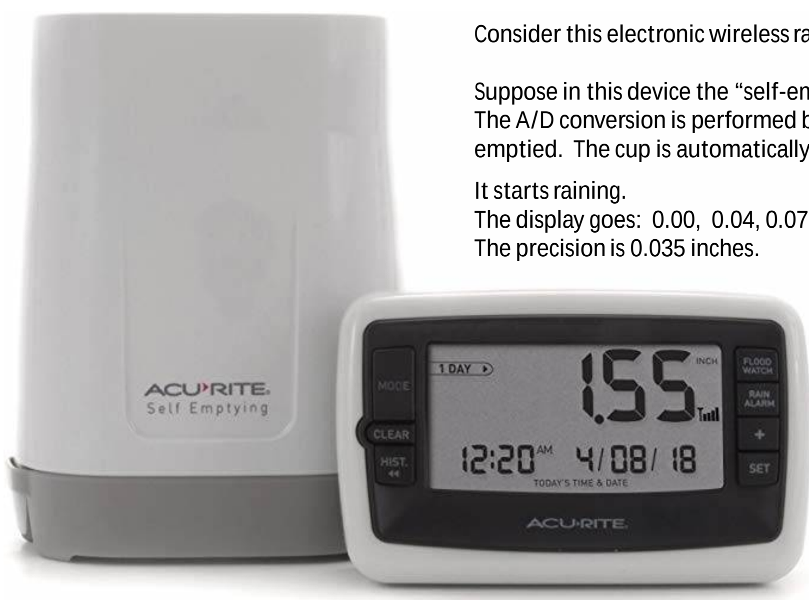
Many analog sensors do not specify precision.
That does not mean they have perfect precision, but usually the precision of the sensor is then so good (such a small amount) that it does not matter what it is numerically speaking. (Assuming the analog signal is being properly handled and noise is not being added to it.)

But practically, the precision of these sensors is usually determined (limited) in the quantization of the analog-to-digital converter that must be in the signal path in order to get the signal into an embedded system. More on quantization and how it limits the precision of an analog sensor later.

https://pixabay.com/photos/street-road-night-dark-asphalt-918882/
https://pixabay.com/photos/winter-winter-scene-landscape-3031382/

3

Precison ≠ smallest possible non-zero display.
Precision is defined prior to conversion to digital!



Consider this electronic wireless rain gauge.

Suppose in this device the "self-emptying cup" holds 0.035 inches of water. The A/D conversion is performed by counting the number of times the cup is emptied. The cup is automatically emptied when it is full.

It starts raining.
The display goes: 0.00, 0.04, 0.07, 0.11, 0.14, 0.18, 0.21, 0.25, 0.28, . . .
The precision is 0.035 inches.

Don't get fooled by sensors that have lots of digits in the display. Often it is not quite as good as it seems!

https://www.amazon.com/AcuRite-00899-Wireless-Self-Emptying-Collector/dp/B004V1XJW0

4

<u>The *dynamic range* of a sensor—number of distinguishable levels</u>.

That So far we have noted that for the human eye,
$L = 10^{-6}$ cd/m^2 (darkest item that is not black in a dark scene)
$H = 10^{6}$ cd/m^2 (brightest item that is not white in a bright scene)
$p = 0.02$ cd/m^2 (precision of the human eye)

Dynamic range is defined from the above as

$$D = \frac{H - L}{p}$$

Dynamic range is dimensionless.
Dynamic range is the number of distinguishable levels (minus 1 or 2).

IF the eye was as simple as so far described. . .

$$D_{eye} = (10^6 - 10^{-6})/0.02 = 50\,000\,000$$

The trouble is, the eye takes 15 or more minutes to adapt to brightness or darkness. Furthermore, the detectable range of brightness to darkness in one scene is limited to about 1000:1. So the above specification is not that valuable—it is here for illustration.

(The human ear has similar issues—a very wide dynamic overall range, but much more limited within a given sound-scape.)

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https://pixabay.com/photos/winter-winter-scene-landscape-3031382/

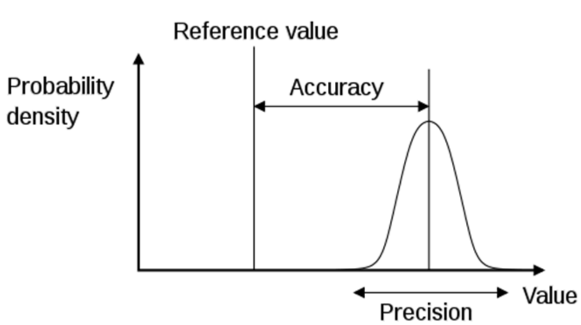
5

<u>The *accuracy* of a sensor—relative to NIST standards</u>.

Suppose I use a light meter to measure the amount of light coming from a scene I wish to photograph.

The accuracy of the meter tells me how close the measurement is likely to be to some type of standard. Each country has government-specified standards. In the USA it is NIST. In Canada it is Measurement Canada (Mesures Canada).

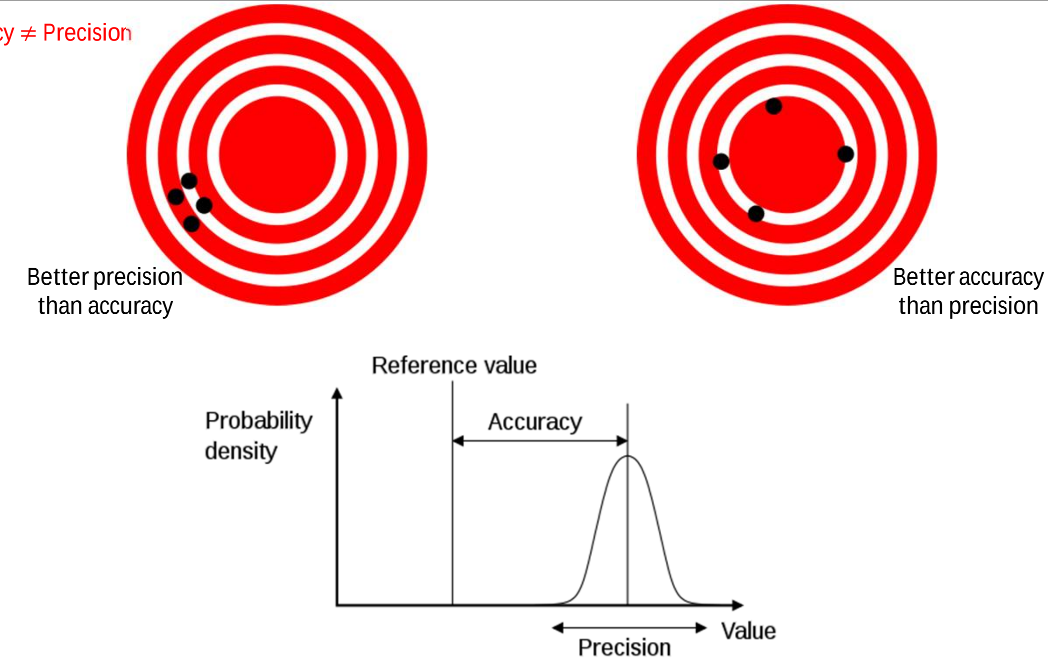
Accuracy refers to the degree of closeness of the average measurement result to the reference standard as defined in your context.
Accuracy has units.



https://pixabay.com/photos/street-road-night-dark-asphalt-918882/
https://pixabay.com/photos/winter-winter-scene-landscape-30313820/
https://helpwiki.evergreen.edu/wiki/index.php/Light_Meters_Quick_Guide
https://commons.wikimedia.org/wiki/File:Accuracy_and_precision.svg

6

Accuracy ≠ Precision



https://commons.wikimedia.org/wiki/File:High_precision_Low_accuracy.svg
https://commons.wikimedia.org/wiki/File:High_accuracy_Low_precision.svg
https://commons.wikimedia.org/wiki/File:Accuracy_(trueness_and_precision).svg

7

Sensors produce electrical signals. The signal must traverse some wiring to get to the A/D converter.
Let's talk about analog signals.

Defn: A ***analog signal*** is. . .
continuous with respect to the independent variable (in the mathematical sense of a continuous function).
It is a continuum of unquantized values chosen from an infinitely dense set of possible values that have a bounded magnitude.
(e.g. if real-number valued the finite set customarily is represented as a range of real numbers, V_{min} to V_{max})

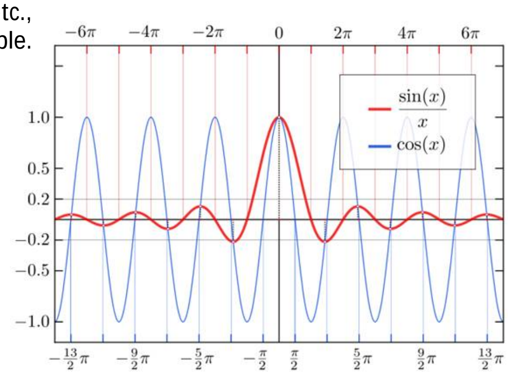
Notice that an analog signal has an independent variable,
typically expressed as a *time* (e.g. in seconds) or distance, or angle, etc.,
typically when plotted, the ordinate (horizontal axis) is the ind. variable.

and the signal has a dependent variable—the signal's value
typically expressed in units of volts or amps,
typically when plotted, the abscissa (vert. axis) is the dep. variable.

Examples,

$\cos(x)$ is an analog signal.

$sinc(x) = \frac{\sin(x)}{x}$ is an analog signal.



https://commons.wikimedia.org/wiki/File:Si_cos.svg

8

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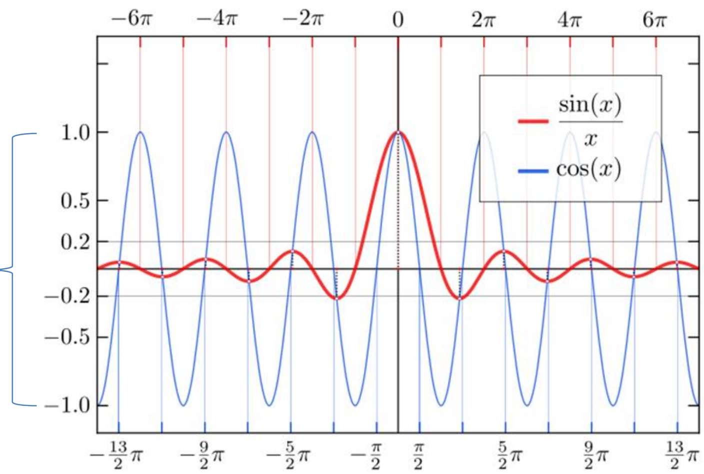

Continuous

Defined for any time-value within the range of the signal—no gaps.

https://commons.wikimedia.org/wiki/File:Si_cos.svg

9

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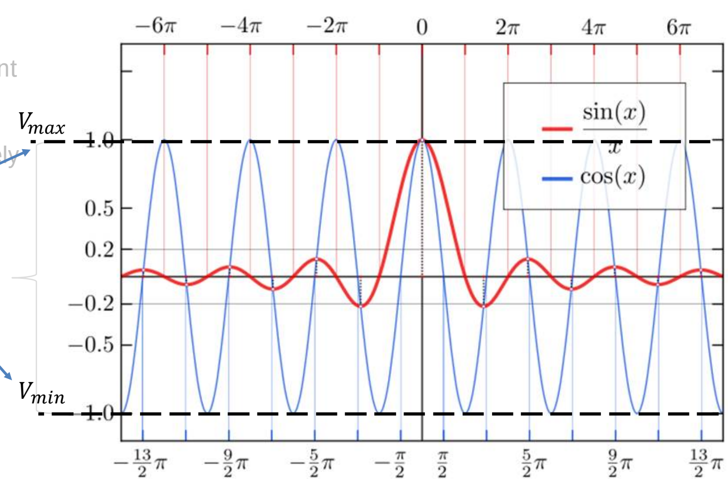

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https://commons.wikimedia.org/wiki/File:Si_cos.svg

10

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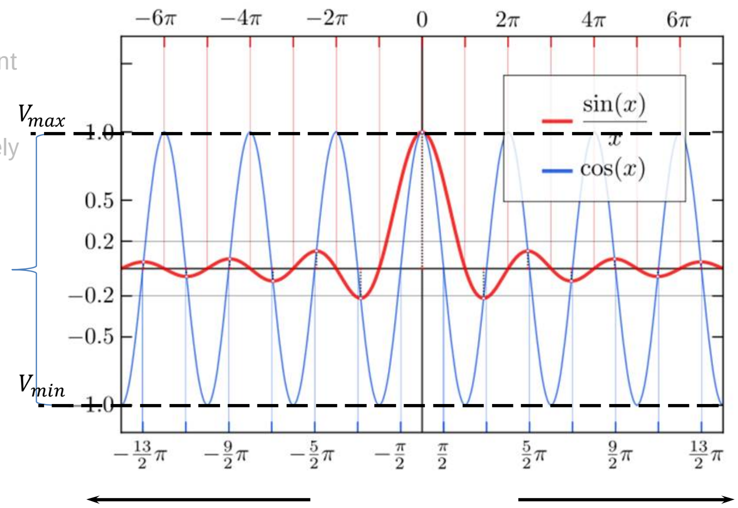

If it is not all these things
it is either a digital signal
or possibly neither analog nor digital!

11

An analog electrical signal may be thought of as. . .

Defn: A ***voltage signal*** is a signal that bears its information in the voltage-level of the signal.
The current that flows in association with the signal is merely incidental to the transmission of the signal.
The current bears no information by definition, but may be related to the voltage.
(For instance, if the signal is connected to a resistor, then $i(t) = v(t)/R$.)

Voltage signals are the most common type of electrical signals we encounter.

12

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Defn: A ***current signal*** is a signal that bears its information in the current-flow of the signal.
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Because an electrical signal must have both current and voltage present in order for it to move across a wire, power is needed to transmit the signal. Power costs money. Nothing in life is free.

14

An analog electromagnetic (radio) signal may be thought of as. . .

Defn: An ***electromagnetic signal*** is a signal that is radiating in free space or another medium as a coupling of an electric and a magnetic wave. It bears its information in both the electric and the magnetic portions of the signal since these are coupled in a process described by Maxwell's equations.

Because an electromagnetic signal must have both an electric and a magnetic field present in order for it to move through a medium, power is needed to transmit the signal. Power costs money. Nothing in life is free.

Radio, microwave, radar, light, x-ray, and more can be used as electromagnetic signals.

15

Electric signals are transmitted in wires. (Duh. . . !)

16

~~Electric signals are transmitted on wires. (Duh. . . !)~~ Say what? Signals are NOT in wires?

Wires are not as simple as you might think. (Why are there so many kinds of wire?)

- Romex
- zip cord
- coaxial cable
- outdoor power transmission line, e.g. 750 kV
- wire-wrap wire
- pc-board trace
- interconnect on an integrated circuit
- etc.

And. . . In all cases, the signal is traveling in the electromagnetic waves induced by the voltage and current.

If you could block that E&M wave, then the signal would not go past the barrier even through the conductors!

The whole point of coaxial cable is to confine the electric and the magnetic fields to the insulation between the shield and the inner conductor. This way the cable can be passed through walls and other spaces with no signal loss due to the structure around the cable. (But the plastic insulation inside the cable takes a toll. And don't bend coax too much—sharp bends take pretty serious tolls.)

Other wires let the E&M waves pass through the air around them. This results in codes and rules for the proper placement of the wires. Ignoring proper placement causes trouble.

(Hint: will your senior project have wires?)

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The signal is in an E&M field related to the conductors.
The wire is a waveguide.

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18

Defn: A ***single-ended*** electrical source has. . .
two conductors, not necessarily of symmetric design.
One conductor is said to be the ground reference (if a voltage signal) or the ground return (if a current signal).
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19

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Upon reception of a current signal the current-flow is measured by completing the circuit through the ground return.

20

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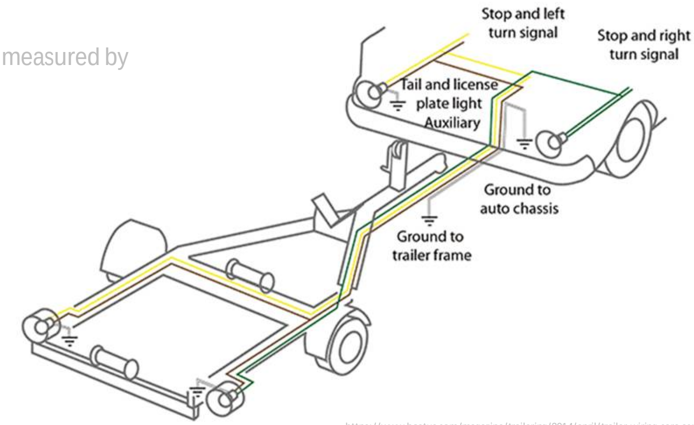
Example: An automotive trailer turn-signal wiring.



https://www.boatus.com/magazine/trailering/2014/april/trailer-wiring-care.asp

21

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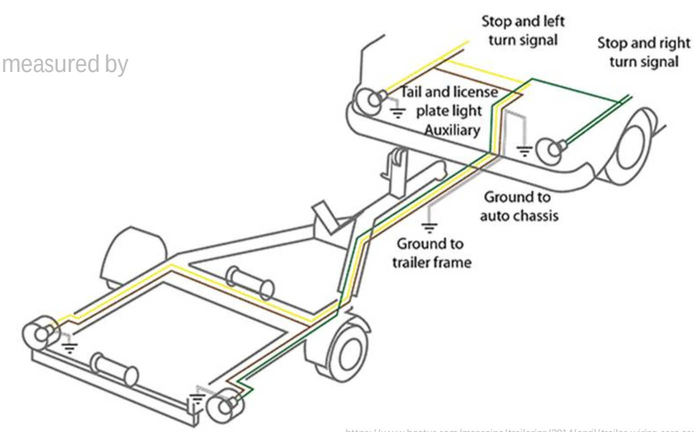
Example: An automotive trailer turn-signal wiring.

Single-ended wiring is prone to radiate its signal
Single-ended wiring is prone to act like an antenna.

Single-ended wiring requires "strong" signals.
(A combination of voltage and power.)
Typical rule-of-thumb: > 1 V and < 10 ft.
But this is R.O.T.



https://www.boatus.com/magazine/trailering/2014/april/trailer-wiring-care.asp

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