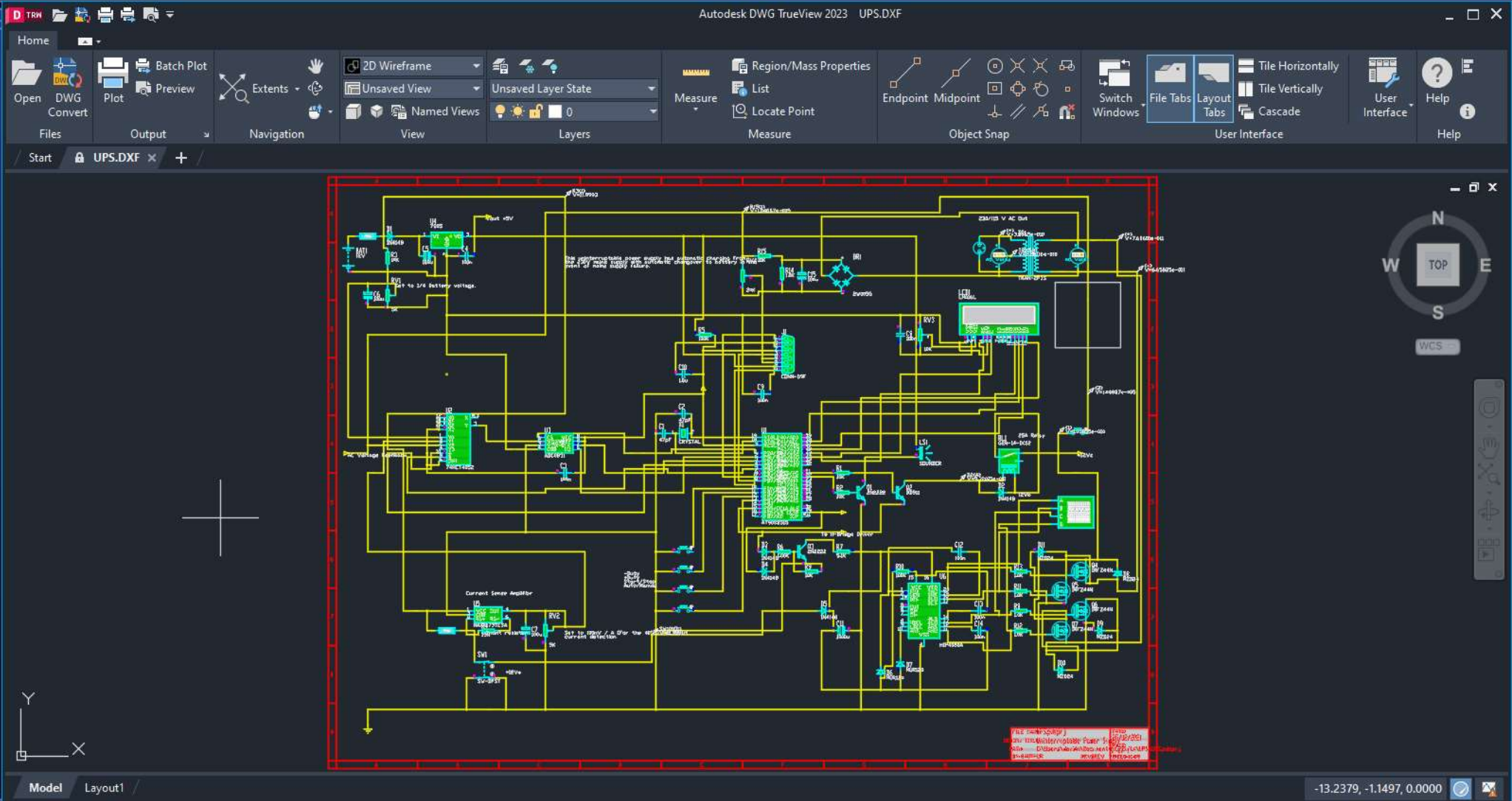
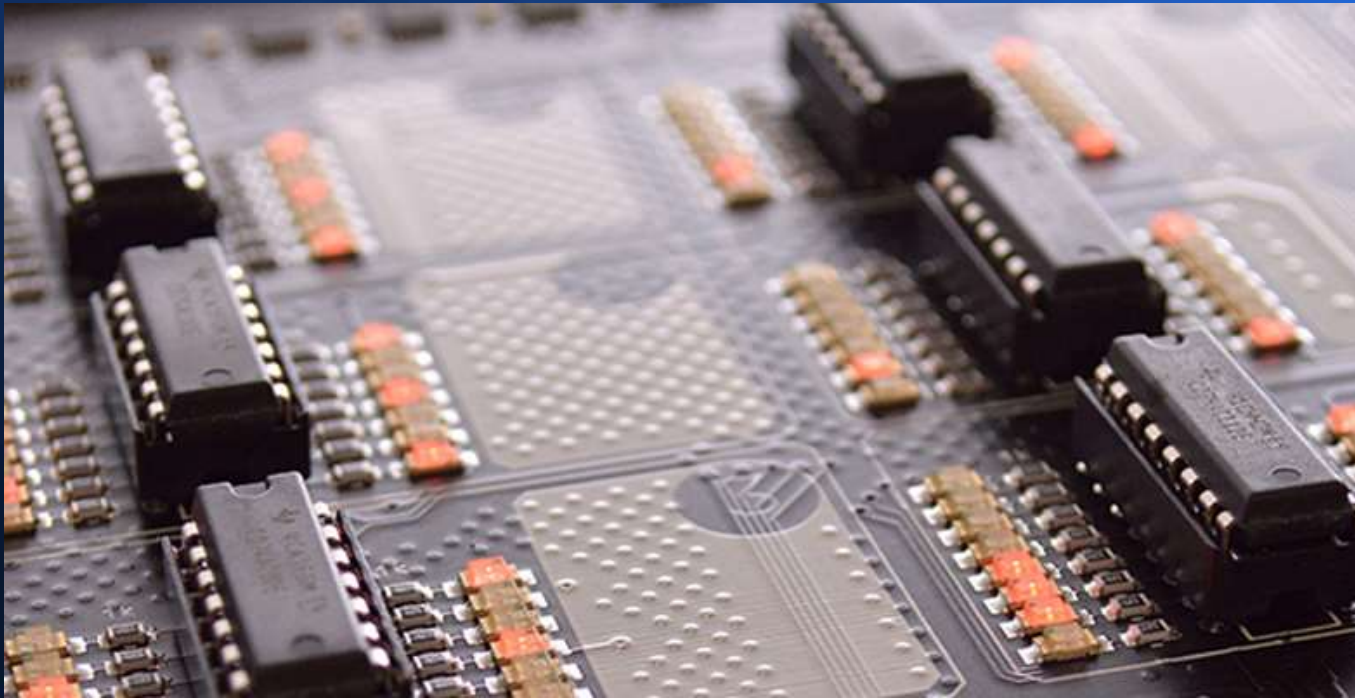


# The previous design as a CAD (Computer Aided Design) schematic. Copyright © David Norris, 2022



# Introduction to Electronics

- “Electronics is about manipulating electricity to accomplish a particular task and is very much a hands-on endeavor. Since the result of building electronic circuits is usually a device that performs a task, this hands-on aspect should be self-evident.”



# Electronics is fundamental to 21<sup>st</sup> century life!

- Electronic devices and systems are fundamental to modern life. In this introductory course, I will show you how central electronic devices and systems are to modern life, pervade everything we do, and explain some of ideas which are fundamental in explaining their operation.
- Advanced modern electronic devices are often said to be autonomous.
- Any autonomous system has three fundamental aspects: sensing the environment using sensors, reasoning through logic and information processing, and then interacting with the environment through actuators. Together, these are known as the sensing–logic–actuation cycle.

# An Important Safety Warning!

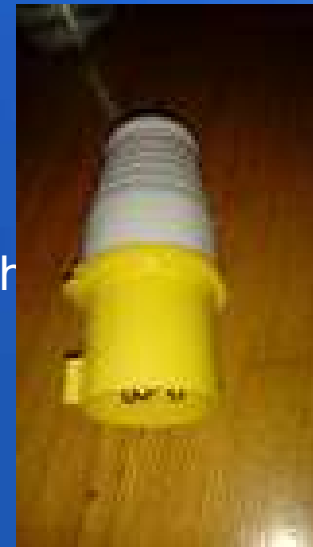
- Although I might mention devices operating at higher voltages (for example a mains powered benchtop supply) all circuits presented operate at a maximum of 24 volts – **most operate at 12 volts or less.**
- Details of how to power circuits will be given. **However – under no circumstances is the mains power in your home to be used in ANY demonstration. The mains supplies around the world include 100 volts (Japan), 110 volts (USA), 220 volts (China), 230 volts UK/EU and 240 volts (Australia). These are ALL very dangerous both in terms of their voltage and the current they are capable of delivering. Never be tempted to use the mains supply to power your circuits. I cannot overstress this point.**
- Suitable power supplies include batteries – (details will be given), and approved benchtop supplies (Generally integrated circuits need a regulated 5 volt supply, details will be given).

# Electricity & Electronics: The difference

- Electricity is all about making electromagnetic energy flow around a circuit so that it will drive something like an electric motor or a heating element, powering appliances such as electric cookers, kettles, vehicles, and machines. Generally, electrical appliances need a great deal of energy to make them work so they use quite large (and often quite dangerous) electric currents. The 2300-watt heating element inside an electric kettle (operated on the EU voltage of 230 volts) operates on a current of 10 amps. By contrast, electronic components use currents measured in milliamps (mA) or even microamps (µA) (which are thousandths and millionths of amps, respectively)! Put another way, a typical electric appliance is likely to be using currents tens, hundreds, or even thousands of times bigger than a typical electronic one – in addition, mains supplies have a relatively high AC voltage, for example: 100V(Japan), 110V (USA), 220V (China) 230V (UK/EU) and 240V (Australia).

# Electricity & Electronics: The difference

- Take a microwave oven as an example. An Electrical circuit provides the power that generates high-energy radio waves at 2.4GHz that cook your food; an electronic circuit however controls the operation and timing functions.
- Unlike the high voltage AC mains, electronic circuits operate at low DC voltages. For example, TTL (transistor-transistor logic) circuits operate only at 5 volts DC – the voltage of a standard US charger.
- Left: a specialist charger I designed to charge USB devices in the construction industry in the UK and Irish Republic. The supply is a reduced low voltage supply (55-0-55 volts AC, centre tapped to earth). This is considerably safer than a 230 volt mains supply in the construction industry.



# Analogue and digital electronics: the difference

- There are two very different ways of storing information—known as analogue and digital. Most of the things we wish to express are analogue quantities- sound intensity, temperature, light intensity - and of course voltage are all examples. Conventional methods of sound recording such as vinyl records and cassette tapes are analogue. The recording is an 'analogy' of the sound.
- However, modern recording stores sound in a totally different way. Instead of saving a recognisable pattern of sound which will play directly, it converts the amplitude and frequency components into binary numbers and stores those instead. Storing a numerical, coded version of something is known as digital.

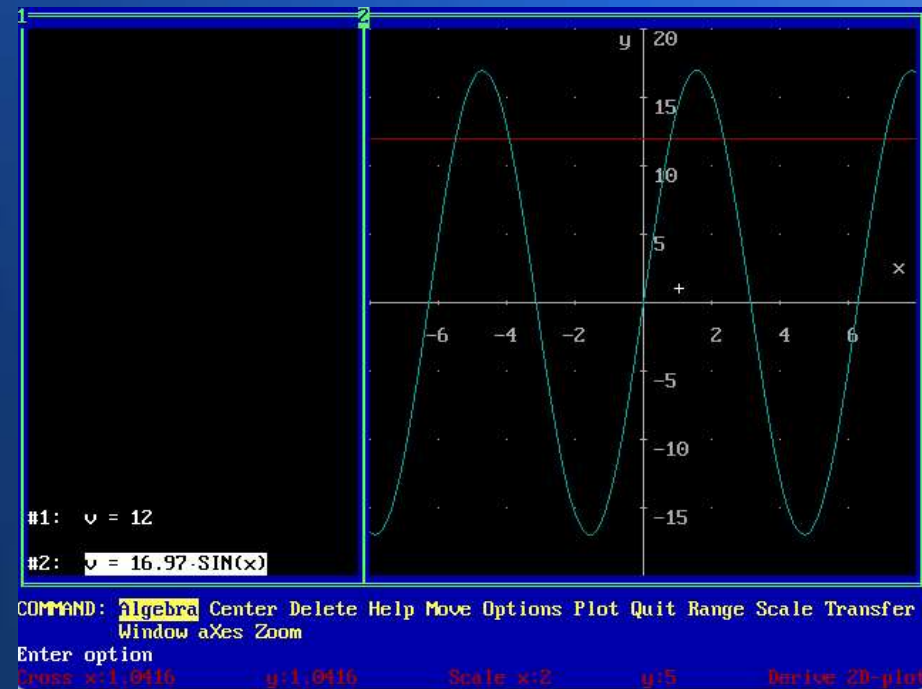
# Direct and alternating current

- There are actually two basic “types” of electricity, direct and alternating current.
- Direct current flows in one constant direction only. Examples of sources include batteries, dynamos, and photovoltaic (solar) panels.
- Alternating current has cyclical changes on voltage and polarity. The number of changes per second is called its frequency, measured in Hertz. Main supplies in North and South America has 60 cycles per second (60Hz) and in the rest of the world 50 cycles per second (50Hz).
- The voltage of a DC supply is easy to measure! But what about AC? Here the RMS (which stands for root mean square) – the 'average' voltage.
- For a sinewave, RMS voltage = peak voltage /  $\sqrt{2}$ .



# AC & DC

- DC, shown in red, has a constant voltage and direction. This is 12 volts, as from a car battery. AC, shown in blue, has a frequency and RMS voltage.
  - The AC has a RMS (root mean Square) voltage of 12 volts, and the Peak voltage is  $12 \times \sqrt{2} \approx 16.97V$ .
- The software is Derive, from Texas Instruments.



# Electronic Components

- The circuits inside pieces of electronic equipment seem baffling at first glance: they're packed with components that all have different functions and the components are linked together by wires or printed metal connections .Electronic circuits are built up from a relatively small number of standard component types. But just as you can build a variety of structures from a relatively small number of materials, you can make endless circuits designs to serve a given purpose.
- This is in a similar fashion to everything in existence, including our own bodies, being constructed of 92 naturally occurring chemical elements.

# Resistors

These are the simplest components in any circuit. Their job is to restrict the flow of electrons and reduce the current or voltage flowing by converting electrical energy into heat. Resistors come in many different types and material constructions. Variable resistors can have a variable value of resistance so they change the amount of resistance when you adjust them. Volume controls in audio equipment, for example, often use variable resistors like these. Current flowing in a resistor = voltage (V) / resistance ( $\Omega$ ). For example,  $12\text{ V} / 4\Omega = 3\text{ amps (A)}$ .

Power can be found by voltage X current. In the above example,  $12\text{V} \times 3\text{A} = 36\text{W} = \text{watts}$ . This is about the power of a soldering iron.

# Capacitors

- These relatively simple components consist of two pieces of conducting material (normally metallic) separated by a non-conducting (insulating) material called a dielectric. They are often used as timing devices, but they can separate AC and DC electrical currents and also signals of different frequencies in other ways too. In a radio, one of the most important jobs, tuning into the station you want to listen to, is done by a variable capacitor. The unit of capacitance is the Farad, F. As the Farad is an extremely large unit, an example of a circuit value might be 3.3  $\mu\text{F}$  or microfarads.

# Diodes

- The electronic equivalents of a valve in fluid dynamics, diodes allow an electric current to flow through them in only one direction. Diodes can be used to change alternating currents (ones flowing back and forth round a circuit, constantly reversing direction) into direct currents (ones that always flow in the same direction). Four diodes form a basic bridge rectifier.

# Inductors

- Inductors exploit the electromagnetic characteristics of current flow. A basic inductor is a coil of wire, although inductance can be increased using a ferrite core. A transformer is a double wound inductor. The unit of inductance is the henry, H. The henry is an extremely large unit, so typical values may be in microhenries,  $\mu\text{H}$ .

# Transistors

- The most well known components in electronic devices, transistors can switch tiny electric currents on and off or amplify them. Transistors that work as switches act, at a fundamental level as the memories in computers, while transistors working as amplifiers boost the volume of sounds in audio devices. When transistors are connected together, they make devices called logic gates (AND, OR, NOT and so on) that can carry out very basic forms of decision making. (Thyristors are a little bit like transistors, but function in a very different way.)

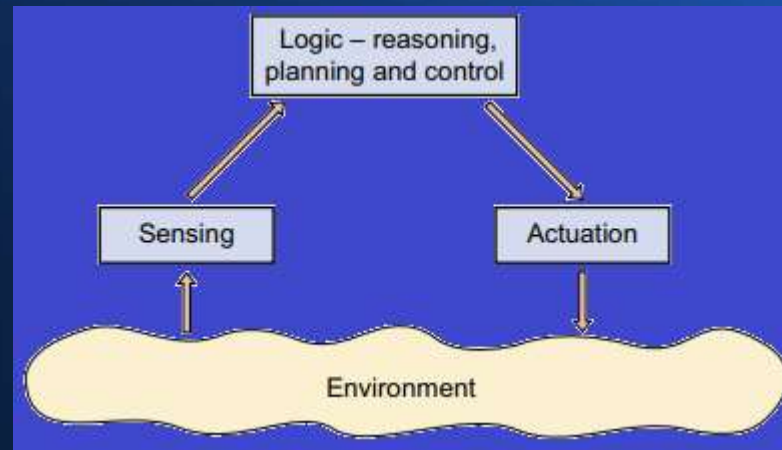
# Opto-electronic (optical electronic) components

- There are various components that can turn light into electricity or vice-versa. Photovoltaic cells (also known as photoelectric cells) generate electric currents when light falls on them and they're used in various types of sensing equipment, including some type of smoke detector. Light-emitting diodes (LEDs) work in the opposite direction, converting small electric currents into light, and are typically used on the instrument panels of audio equipment. Liquid crystal displays (LCDs), such as those used in flatscreen televisions and laptop computers, are more sophisticated examples of opto-electronics.
- On the large scale, photovoltaic cells convert solar energy into electrical energy. I plan to establish a solar powered electronic business in Western Africa.
- And as we are about to see, the sensing/logic/actuation cycle depends heavily on sensors, including optoelectronic devices.



# What is the sensing-logic-actuation cycle?

- Electronic devices can sense the world around them, converting a wide variety of physical phenomena into electrical signals that communicate useful information. Such devices (called transducers) have capabilities similar to our own human senses: hearing (microphones), seeing (cameras, including visible light and infrared, and proximity sensors), touch (piezoelectric transducers), and smell and/or taste (chemical sensors).



# Sensing – a simple example

- A light dependent resistor used as a daylight sensor in a Proteus Simulation. As the sensor is virtual, the torch stands in for actual daylight. A UA741 is configured as a comparator in the following circuit.

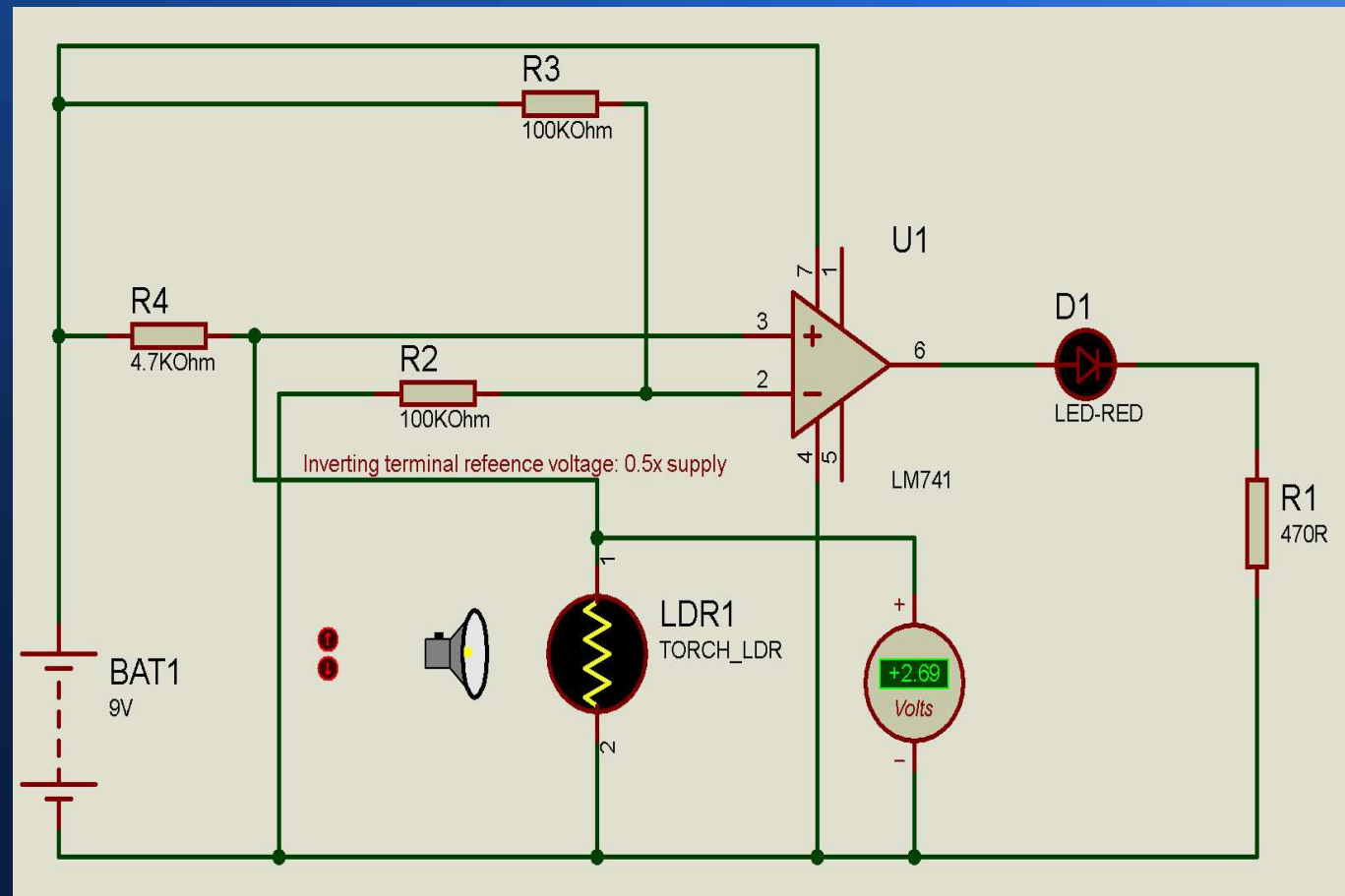
**This is a simple demonstration of how lighting can be controlled using a light dependent resistor. The LDR serves as a daylight detector.**

**The idea is that the lighting is triggered automatically when the light falls below a given level. The torch in this demonstration stands in for daylight in this demonstration circuit. And the UA741 operational amplifier here is used as a comparator. The reference voltage is half the supply voltage.**

# Sensing – Daytime (torch off) – note D1 light emitting diode is OFF.

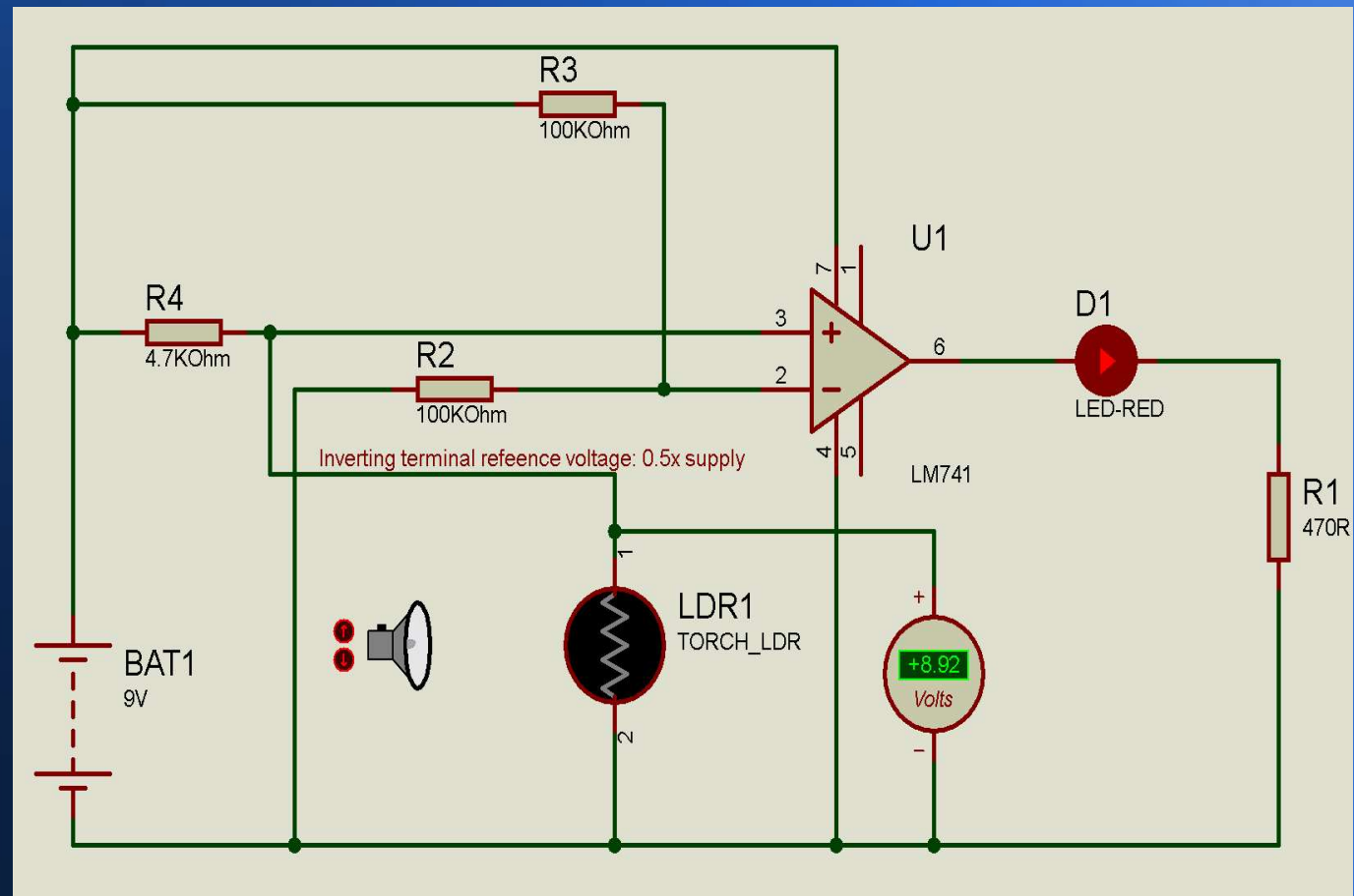
Once light level reduces the voltage below the reference value of 4.5v, D1 turns off.

An easy way to automate illumination.



# Sensing – Nighttime (torch off) – note D1 light emitting diode is ON.

8.92v is above  
the Reference  
Voltage.

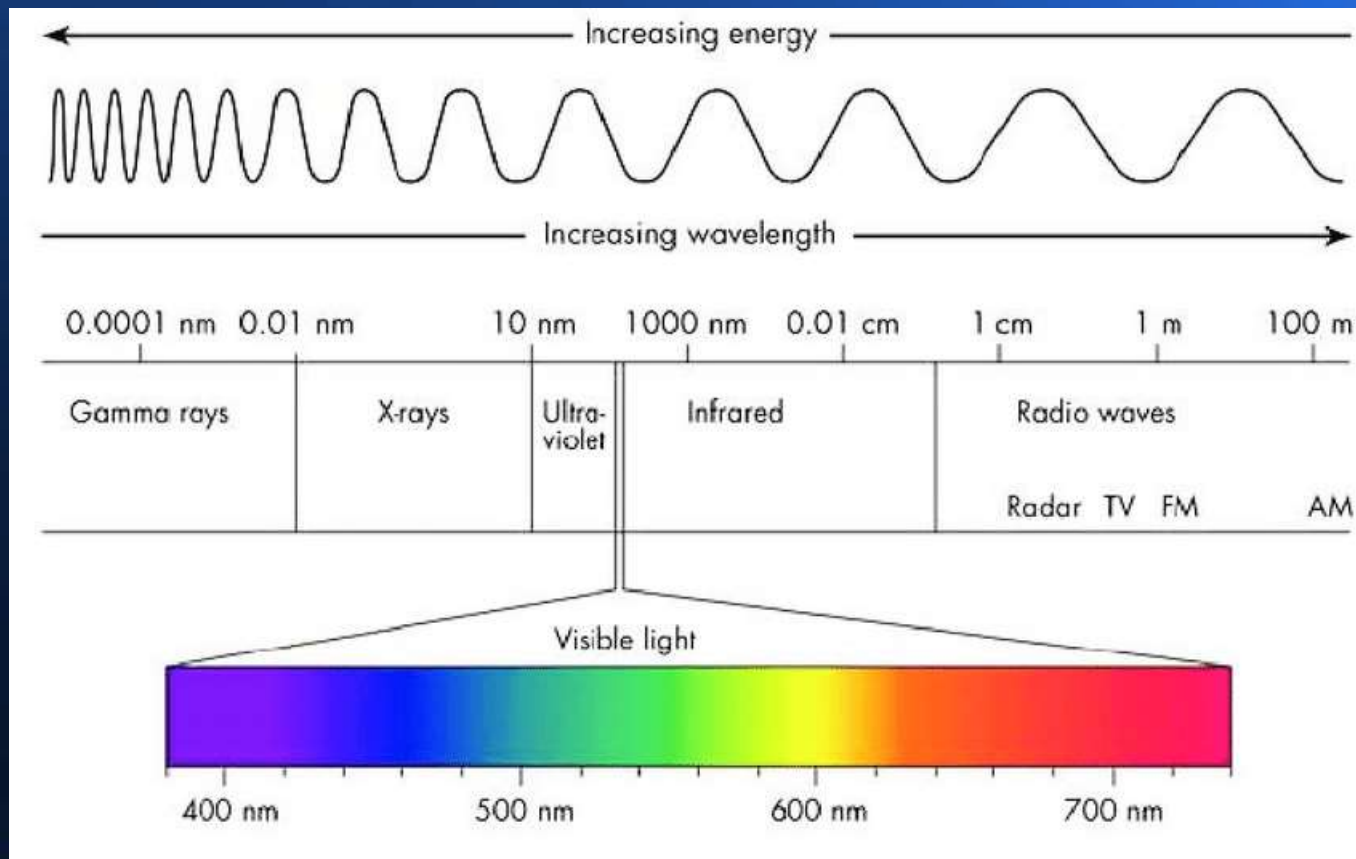


# Sensing beyond human senses

- It is possible to design electronic devices which can sense things which we cannot sense directly. For a few examples:
- Ultrasound allows us to 'see' inside our bodies;
- Infrared camera images allow us to 'see' pictures of radiated heat;
- terahertz (micrometric) images allow us to see through opaque materials
- Our eyes are only sensitive to a tiny 'window' in the electromagnetic spectrum....

# The electromagnetic spectrum

- Our eyes sense only wavelengths from 0.4 – 0.7  $\mu\text{m}$ .



# Logic – what is it?

- Sometimes the information from sensors is fed directly to a human being to act on, as in a visual display. However, in many cases that information is used to control systems automatically. To do this requires the functions of logic, which are carried out by logic circuits or programmable microprocessors or microcontrollers.

# Actuation

- Actuators are components that control the movement in an autonomous system. In many systems, actuators of various kinds are automatically controlled to give the desired behaviour. Examples include electric motors (including stepper motors), and pneumatic actuators.
- Robotics are possible through clever use of actuation!

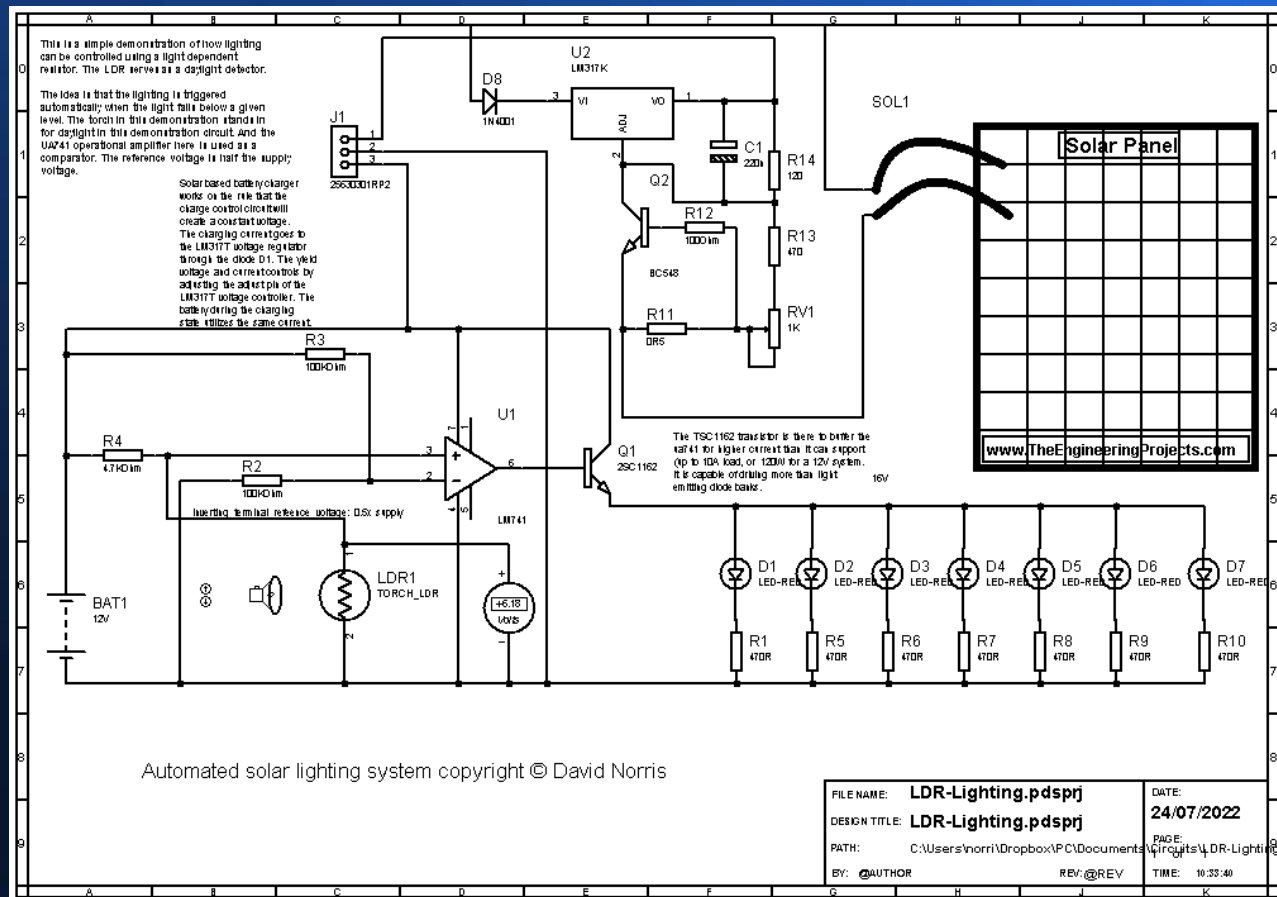


# Actuation

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# A fully automated, solar powered lighting system. Sensing uses light dependent resistors, the operational amplifier is a comparator in this application. Copyright © David Norris, 2022



# Relationships Between Voltage, Current, Resistance & Power

- For a DC circuit, the relationships are straightforward...
- Power (W) = voltage (V) x current (in amps, symbol I)
- Resistance ( $\Omega$ ) =  $V/I$
- So power is the product of voltage and current, and current is proportional to current in most materials, said to be 'ohmic'
- Please note however that some materials do not have an ohmic relationship – (see diodes and transistors later!) These are said to be non-ohmic.
- And for AC circuits, please note that its more involved! We talk about resistance and capacitance later also.

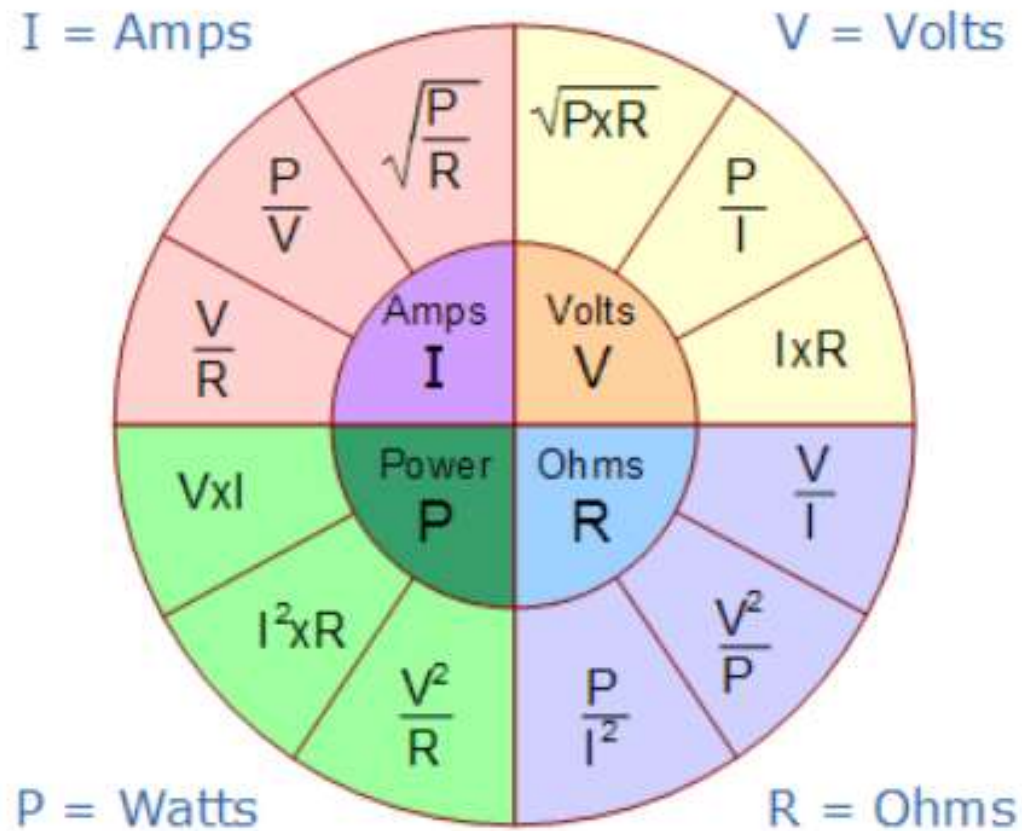
# Prefixes – for large and small quantities

- There are larger and smaller prefixes too!
- But there will be enough to get started.
- These are all SI units.

Prefix	Symbol	Multiple of standard unit		Example
micro	$\mu$	one millionth	$10^{-6}$	microamp, $\mu\text{A}$
milli	m	one thousandth	$10^{-3}$	millivolt, mV
kilo	k	one thousand	$10^3$	kilo-ohm, $\text{k}\Omega$
mega	M	one million	$10^6$	megawatt, MW

# An easy way to remember Ohm's law...

Ohms Law Pie Chart



# Some Basic Components

- **Function of the most Basic Electronic Components**
- **Terminals and Connectors:** Components to make electrical connection.
- **Resistors:** Components used to resist current.
- **Switches:** Components that may be made to either conduct (closed) or not (open).
- **Capacitors:** Components that store electrical charge in an electrical field.
- **Magnetic or Inductive Components:** These are Electrical components that use magnetism such as inductors..
- **Network Components:** Components that use more than 1 type of Passive Component.
- **Piezoelectric devices, crystals, resonators:** Passive components that use piezoelectric. effect.
- **Semiconductors:** Electronic control parts with no moving parts.
- **Diodes:** Components that conduct electricity in only one direction.
- **Transistors:** A semiconductor device capable of amplification.
- **Integrated Circuits or ICs:** A microelectronic computer circuit incorporated into a chip or semiconductor; a whole system rather than a single component.

# Introduction to electrical circuits

- Units of measurement – a more complete list

Quantity	Quantity Symbol	Unit	Unit Symbol	Quantity	Quantity Symbol	Unit	Unit Symbol
Length	l	metre	m	Resistance	R	ohm	$\Omega$
Mass	m	kilogram	kg	Conductance	G	siemen	S
Time	t	second	s	Electromotive force	E	volt	V
Velocity	v	metres per second	m/s or $\text{ms}^{-1}$	Potential difference	V	volt	V
Acceleration	a	metres per second squared	$\text{m/s}^2$ or $\text{ms}^{-2}$	Work	W	joule	J
Force	F	newton	N	Energy	E (or W)	joule	J
Electrical charge or quantity	Q	coulomb	C	Power	P	watt	W
Electric current	I	ampere	A	These are the units we need in our discussion of electrical machines. Please use these symbols to prevent confusion.			
				All of these are S.I units.			



# Electrical characteristics

- Electrical characteristics often have physical equivalents in the mechanical world...

Pressure	G/m <sup>2</sup>	Electrical pressure	Voltage (V)
Current	Litres/second	Electric current	Amps (I)
Friction	Newtons	Resistance	Ohms ( $\Omega$ )
Capacity	Litres	Charge	Coulombs (C)
-	-	Power	Watts (W)
Thermal conductance	W/M <sup>2</sup> .K	Conductance	Siemens (s)
-	-	Inductance	Henries (L)

# Some Basic Components



# Ohms Law – in more detail

- Ohm's law
- Ohm's law states that the current  $I$  flowing in a circuit:
- is directly proportional to the applied voltage  $V$  and
- inversely proportional to the resistance  $R$ , provided the
- temperature remains constant. Thus,
- $I = V/R$  or  $V = IR$  or  $R = V/I$
- This is analogous to current flow in a water pipe. Current flow is proportional to the pressure, and inversely proportional to the force of friction.
- Conductance is the reciprocal of resistance. It is measured in Seimens (S) as  $1/R$ .

# Example of a calculation

- A light emitting diode, I.e.d needs a current limiting resistor to ensure that no more than 20mA flows through the I.e.d (or it will burn out). And the voltage is 9V from a PP3 battery. What is the lowest resistor value we can use? (Note that the I.e.d does not have an ohmic resistance, it introduces a voltage drop in a circuit. It is an example of a non-ohmic device. With no limiting resistor the current flow would be:  $9V / 0\Omega = \infty!$ . In practice, the maximum current the battery can deliver. This will burn the I.e.d out).
- Referring to ohms law,  $R = V/I = 9 \times 0.002 = 4500\Omega$  or 4.5k $\Omega$ . As 4.5k $\Omega$  is not a preferred value, in practice I would use a 4.7k $\Omega$  or 4k7 resistor.
- But - how can you tell the value of a resistor?

# Resistor Colour code

- Our 4k7 resistor will have bands: yellow, purple, brown (the tolerance is not too critical here).

Color	Value	Multiplier	Tolerance
Black	0	$\times 10^0$	$\pm 20\%$
Brown	1	$\times 10^1$	$\pm 1\%$
Red	2	$\times 10^2$	$\pm 2\%$
Orange	3	$\times 10^3$	$\pm 3\%$
Yellow	4	$\times 10^4$	- 0, + 100%
Green	5	$\times 10^5$	$\pm 0.5\%$
Blue	6	$\times 10^6$	$\pm 0.25\%$
Violet	7	$\times 10^7$	$\pm 0.10\%$
Gray	8	$\times 10^8$	$\pm 0.05\%$
White	9	$\times 10^9$	$\pm 10\%$
Gold	-	$\times 10^{-1}$	$\pm 5\%$
Silver	-	$\times 10^{-2}$	$\pm 10\%$

**4-band resistor**



**270 ohms  $\pm 5\%$**

**5-band resistor**



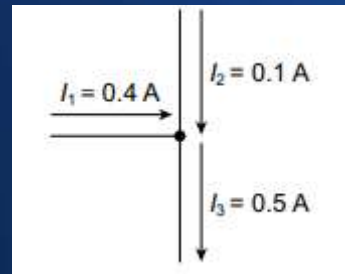
**100k ohms  $\pm 1\%$**

# Ohms law exercise

- A kettle element is designed to draw 10A of current from the 230V mains supply. Find: the resistance of the element and the power rating of the kettle?
- $R(\Omega) = V/I = 230/10 = 23\Omega$
- Power (W) =  $VI = 230V \times 10A = 2300W$  or 2.3KW.

# Kirchhoff's first law (the current law)

- At any junction, or node, in a circuit, the sum of the currents flowing into the node is equal to the sum of the currents flowing out of the node. This is the same as saying that charge can neither be stored at, nor dispensed from, these nodes. This is a useful rule to remember – it helps when thinking about problems to be able to distinguish between places where energy can be stored (inductors and capacitors, about which more later) and and cannot be stored (such as connectors, resistors and transducers).



# Kirchhoff's Laws | KCL & KVL

- Kirchhoff's Voltage Law (KVL)
- The second law is also called Kirchhoff's voltage law (KVL). It states that the sum of the voltage rises and voltage drops over all elements in a closed loop is equal to zero. In formula form:
- $\sum_{i=1}^n V_i = 0$

Kirchov's Voltage Law:

$$\sum_k V_k = 0 \quad \text{where } k = 1, 2, 3, 4, \dots$$
$$V_1 + V_2 + V_3 + V_4 + \dots = 0$$

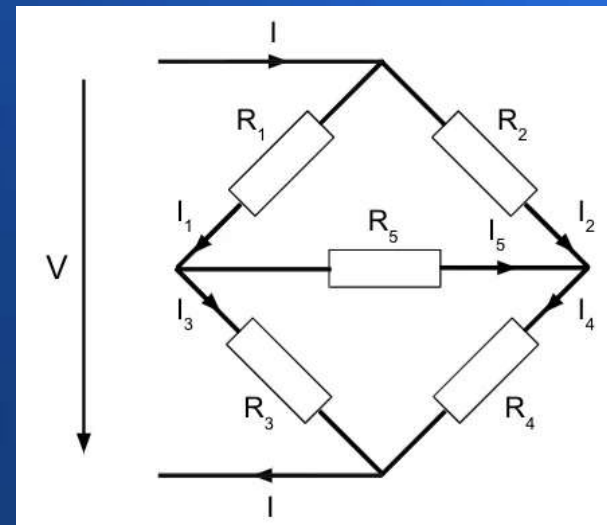
Kirchov's Current Law:

$$\sum_k i_k = 0 \quad \text{where } k = 1, 2, 3, 4, \dots$$
$$i_1 + i_2 + i_3 + i_4 + \dots = 0$$



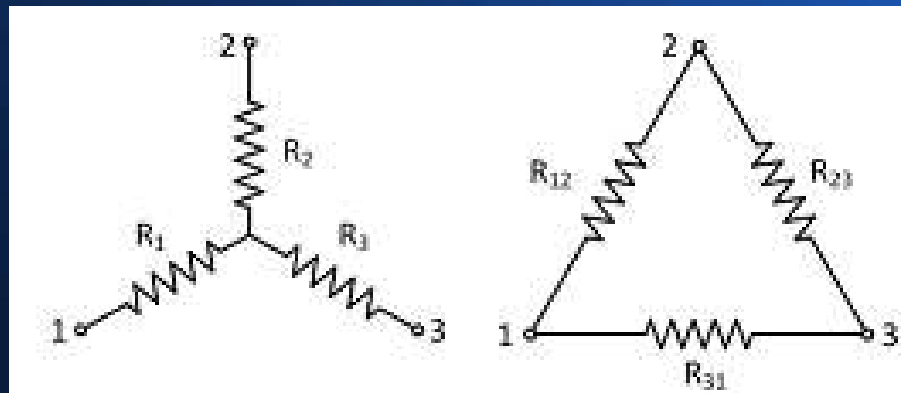
# Kirchoff's Law Example: the Wheatstone Bridge

- Bridge circuits are a very common tool in electronics. They are used in measurements, transducers and switching circuits. I had an assignment involving one as an undergraduate. In this example, we will show how to use Kirchoff's laws to determine the current  $I_5$ . The circuit has four bridge sections with resistors  $R_1 - R_4$ . There is one cross bridge connection with resistor  $R_5$ . The bridge is subject to a constant voltage  $V$  and current  $I$ .
- The first Kirchoff law (KCL) states that the sum of all currents in one node is zero. So the total current entering must equal the total current leaving – electrons and energy cannot be made or destroyed.



# Kirchoff's Law Example: the star-delta (or Y- $\Delta$ ) conversion

- Kirchoff's laws can be used to convert a star (also known as a Y) connection to a delta connection. For example, this connection is often seen in three phase AC systems, (for example the 400/230V mains supply in the European Union). A widely used application for star delta connections other than three phase transformers, is to limit the starting current of electric motors. The high starting current causes high voltage drops in the power system. As a solution, the motor windings are connected in the star configuration during starting and then change to the delta connection.



# Capacitance

- Capacitance is the ratio of the amount of electric charge stored on a conductor to a difference in electric potential.
- Typically, two conductors are used to separate electric charge, with one conductor being positively charged and the other negatively charged, but the system having a total charge of zero. The ratio in this case is the magnitude of the electric charge on either conductor and the potential difference measured between the two conductors.
- The capacitance is a function only of the geometry of the design (the area of the plates and the distance between them) and the permittivity of the dielectric material between the plates of the capacitor. For many dielectric materials, the permittivity and thus the capacitance, is independent of the potential difference between the conductors and the total charge on them.
- The unit of capacitance is the Farad (F). A 1 farad capacitor, when charged with 1 coulomb of electrical charge, has a potential difference of 1 volt between its plates. The reciprocal of capacitance is called elastance. The formula for calculating capacitive reactance is:  $X_c = 1 / (2\pi f C)$  where  $f$  is in hertz,  $C$  in farads.
- The Farad is, in practice, a very large unit, so most values are in  $\mu\text{F}$ ,  $\text{nF}$  and even  $\text{pF}$ .

# Capacitive Reactance Example

$$X_c = \frac{1}{(2\pi FC)}$$

- Find the reactance of a 1uF capacitance at the mains frequency of 50Hz.
- $X_c = 1/(2\pi FC) = 1/(2\pi(50)(0.000001)) = 3.183k\Omega$
- On a DC supply, a capacitor simply charges to the supply voltage and then no further current flows. For AC, the polarity is constantly reversing, so the capacitor never catches up with the voltage – allowing a 'flow' of current!




# Inductive Reactance Example

$$X_L = 2\pi FL$$

- For example, take a  $10000\mu\text{H}$  inductor at the mains frequency of  $50\text{Hz}$ :
- $X_L = 2\pi FL = 2\pi((50)(0.0001)) = 3.14\Omega$
- Remember that  $10000\mu\text{H} = 10\text{mH}$ !
- When DC is applied to an inductor, a brief high voltage spike appears (known as a back EMF) and then the constant current flowing induces no further voltage in the inductor. For AC, the current is constantly changing! So, a reverse voltage is induced which tries to oppose the flow of current.

# Resistors, capacitors & inductors in series and parallel

- Memorise!

Elements Symbol	<b>RESISTOR</b> 	<b>CAPACITOR</b> 	<b>INDUCTOR</b> 
Denoted by	<b>R</b>	<b>C</b>	<b>L</b>
Equation	$R = \frac{V}{I}$	$C = \frac{Q}{V}$	$L = \frac{V_L}{(di/dt)}$
Series	$R_T = R_1 + R_2$	$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$	$L_T = L_1 + L_2$
Parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$	$C_T = C_1 + C_2$	$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2}$

# Electrical Resistivity – a brief introduction

- Electrical resistivity is a measure of a material's property to oppose the flow of electric current. This is expressed in Ohm-meters ( $\Omega \cdot m$ ). The symbol of resistivity is usually the Greek letter  $\rho$  (rho). A high resistivity means that a material does not conduct electric charge well. A low resistivity means a good conductor!
- Electrical resistivity is defined as the relation between the electric field inside a material, and the electric current through it as a consequence:
- $\rho = E/J$  where:
- in which  $\rho$  is the resistivity of the material ( $\Omega \cdot m$ ),
- $E$  is the magnitude of the electrical field in the material ( $V/m$ ),
- $J$  is the magnitude of the electric current density in the material ( $A/m^2$ )
- If the electric field ( $E$ ) through a material is very large and the flow of current ( $J$ ) is very small, it means that the material has a high resistivity.
- As an example, copper wire has a lower resistivity than nichrome wire (used to make heating elements).

# Wire Resistance

- What is the actual resistance of a piece of wire? The resistance value of a wire depends on all three of the following parameters: resistivity, length and diameter. The formula to calculate wire resistance is as follows:
- $R = \rho (l / A)$
- in which R is the resistance in ( $\Omega$ ),
- $\rho$  is the resistivity of the material ( $\Omega \cdot m$ ),
- l is the length of the material (m),
- A is the cross-sectional area of the material ( $m^2$ ).
- It follows that a long thin wire has a much higher resistance than a short length of thick cable of the same material.
- In practice performance and economic considerations determine the type of cable used in a given application.

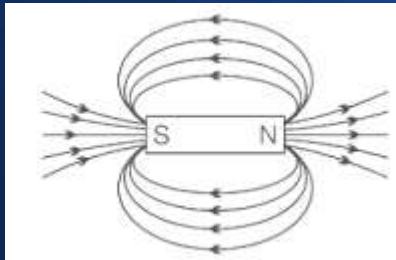


# Examples of Resistivity

Material	$\rho$ ( $\Omega \cdot m$ ) at 20°C	$\sigma$ (S/m) at 20°C	Temperature coefficient (1/°C) $\times 10^{-3}$
Silver	$1.59 \times 10^{-8}$	$6.30 \times 10^7$	3.8
Copper	$1.68 \times 10^{-8}$	$5.96 \times 10^7$	3.9
Gold	$2.44 \times 10^{-8}$	$4.10 \times 10^7$	3.4
Aluminum	$2.82 \times 10^{-8}$	$3.5 \times 10^7$	3.9
Tungsten	$5.60 \times 10^{-8}$	$1.79 \times 10^7$	4.5
Zinc	$5.90 \times 10^{-8}$	$1.69 \times 10^7$	3.7
Nickel	$6.99 \times 10^{-8}$	$1.43 \times 10^7$	6
Lithium	$9.28 \times 10^{-8}$	$1.08 \times 10^7$	6
Iron	$1.0 \times 10^{-7}$	$1.00 \times 10^7$	5
Platinum	$1.06 \times 10^{-7}$	$9.43 \times 10^6$	3.9
Tin	$1.09 \times 10^{-7}$	$9.17 \times 10^6$	4.5
Lead	$2.2 \times 10^{-7}$	$4.55 \times 10^6$	3.9
Manganin	$4.82 \times 10^{-7}$	$2.07 \times 10^6$	0.002
Constantan	$4.9 \times 10^{-7}$	$2.04 \times 10^6$	0.008
Mercury	$9.8 \times 10^{-7}$	$1.02 \times 10^6$	0.9
Nichrome	$1.10 \times 10^{-6}$	$9.09 \times 10^5$	0.4
Carbon (amorphous)	$5 \times 10^{-4}$ to $8 \times 10^{-4}$	1.25 to $2 \times 10^3$	-0.5

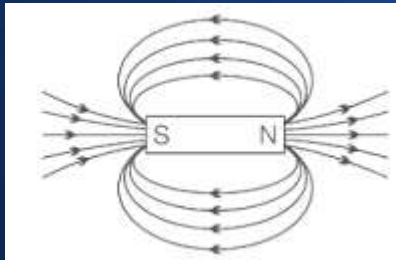
# Electromagnetism

- A magnet is a material or object that creates a magnetic field. While the magnetic field is completely invisible, it creates a force that pulls on other ferromagnetic materials, such as iron, steel, nickel, and cobalt. It can also attract or repel other magnets (like poles repel, unlike poles attract). While a magnet attracts these examples of magnetic materials, non-magnetic materials, such as rubber, coins, feather and leather, are not attracted. This is a diagram of the field around a simple bar magnet:



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# Electromagnetism

- Electric currents typically consist of huge numbers of electric charges that move in a coordinated, overall motion. However, unless you see it heat up and start glowing, it is not easy to tell from the outside whether a wire is carrying a current or not.
- This is because a conductor remains electrically neutral while electrons move through it. Any excess electrons that enter a segment of the wire on one end will simultaneously be made up for by electrons leaving that segment on the other end. Remember, the conductor contains equally many positive charges in the nuclei of its atoms, as there are electrons in it.
- Electromagnetism is the best way to detect and quantify how many amperes of current is going through a circuit. It is created by the motion of the negatively-charged electrons that make up the current, whereas the positively-charged nuclei have no magnetic effect because they are not moving! So while the electric influences of electrons and nuclei cancel out as seen from the outside, their magnetic effects do not.

# Electromagnetism

- How are electromagnetic fields created in the first place, and what determines their strength?
- An electromagnet uses an electric current to create the same magnetic forces we have just discussed. We use electromagnets for everything from a crane in a scrapyard which lifts scrapped cars, to controlling the beam of a particle accelerator. But if you look at an electromagnet closely, it is nothing but a loop coil of wire, just like the coils we just mentioned in motors and metres.
- How can we use the same device (a coil) for two different purposes: creating a force on a current, as in a motor, and turning a current into a magnetic field?
- Recall Newton's Third Law: every action creates an equal and opposite reaction. In a motor, a magnet created a force on the current-carrying coil via the magnetic field. By Newton's Third Law, the current-carrying coil must simultaneously be exerting a force on the magnet. That is the magnetic field created by the coil, and it makes the coil into an electromagnet.

# Electromagnetism and Ampere's Law

- To quantify the strength and direction of the magnetic field created by flowing currents, it is best to start with the simplest case of a straight wire.
- In all cases, the magnetic field is proportional to the current. But the way the magnetic field behaviour depends on your position relative to the wires is very much affected by the geometry of the wires.
- The simplest behaviour is found for a straight wire: the magnetic field in this case decreases inversely with the distance measured perpendicular to the wire.
- Ampère's Law is a discovery André-Marie Ampère made - it is as an example of Newton's Third Law in action, because it puts the "source" and "recipient" of a magnetic force on equal terms -they must be (as action and reaction are equal!).

# Electromagnetism – time for some numbers!

- A Tesla is equal to a Newton per meter and ampere. An exemplary example illustrates this: It corresponds exactly to the flux density of a Tesla, which exerts on a 1 meter long electrical conductor, which in turn conducts a current of 1 ampere, exactly 1 Newton attraction.
- The unit Tesla (T) in magnetism: The Tesla was named after the engineer and inventor Nikola Tesla. The definition of the magnetic flux density does not correspond directly to that of the magnetic field. However, it can ultimately be specified in the two quantities (units) Gauss and Tesla. The following relationship applies to convert the Tesla unit:
  - 1 Tesla = 10,000 Gauss
  - 1 T = 1000 mT )
  - 1KG (outside) = 0.1T

# Fundamentals of the Tesla Unit and Calculation

- The definition of the magnetic flux density does not correspond to that of the magnetic field. However, it can ultimately be specified in the two quantities (units) Gauss and Tesla. The following relationship applies to convert the Tesla unit:
- 1 Tesla = 10,000 Gauss
- 1 T = 1000 mT (esla)
- 1KG (outside) = 0.1T (esla)
- In physics, the magnetic flux density is abbreviated by the letter B. A magnet is ferromagnetic magnetized material. The strength of the magnet is described by remanence. The units of remanence of a permanent magnet are thus also the units Gauss and Tesla.

The Tesla Unit and Calculation:

- The magnetic flux density can finally be calculated from the force of moving charges. The following relationship applies:
- $1/T = 1(N/Am)$ .
- A Tesla is equal to a Newton per meter and ampere. An exemplary example illustrates this: It corresponds exactly to the flux density of a Tesla, which exerts on a 1 meter long electrical conductor, which in turn conducts a current of 1 ampere, exactly 1 Newton attraction. The necessary magnetic field is created by the current flow in the conductor or by the moving electrons.



# Fundamentals of the Tesla Unit and Calculation

- From the magnetic flux density  $B$  one can determine the magnetic field strength  $H$ . The magnetic flux density must be divided by the permeability of the vacuum  $\mu_0$  and that of the material  $\mu$  - for example, the core material of a coil (usually iron in a transformer):
- $H = 1/(\mu * \mu_0) B$

# Fundamentals of the Tesla Unit and Calculation

- Definition
- A particle, carrying a charge of one coulomb, and moving perpendicularly through a magnetic field of one tesla, at a speed of one metre per second, experiences a force with magnitude one newton, according to the Lorentz force law. The Tesla, like any S.I unit, can be expressed as:

$$T = \frac{V \cdot s}{m^2} = \frac{N}{A \cdot m} = \frac{J}{A \cdot m^2} = \frac{H \cdot A}{m^2} = \frac{Wb}{m^2} = \frac{kg}{C \cdot s} = \frac{N \cdot s}{C \cdot m} = \frac{kg}{A \cdot s^2}$$

# Thermal Characteristics of Materials: chemical and mechanical design

- Many machines which are electrically powered are designed to transfer heat (and/or prevent heat transfer) and this makes thermal design a consideration. Furthermore, waste heat can build up in any machine - as no form of energy conversion is 100% efficient, some energy is lost as heat. Motors, transformers and even electronic components create heat, so thermal design becomes a consideration. For example, your computer requires a cooling fan, and some electronic components – notably power transistors – may need a heatsink to avoid undue heating.
- There are 3 laws of thermodynamics.
- 1st Law of Thermodynamics - Energy cannot be created or destroyed, but can be converted from one form to another;
- 2nd Law of Thermodynamics - For a spontaneous process, the entropy of the universe increases.
- 3rd Law of Thermodynamics - A perfect crystal at zero Kelvin has zero entropy.

# Heat transfer mechanisms

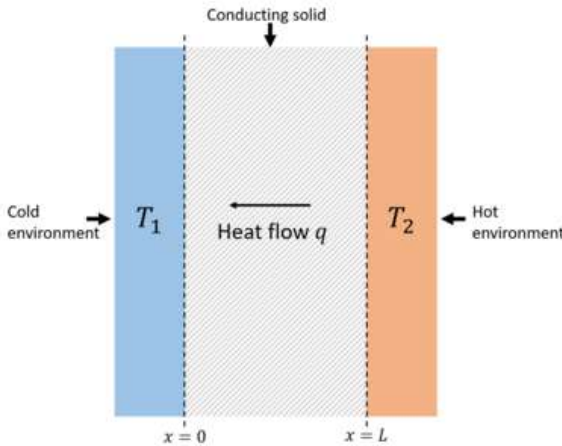
- There are broadly four heat transfer mechanisms. The mechanisms of heat transfer are as follows:
- Conduction: This is the transfer of heat (normally through a solid; trapped liquids and gasses conduct poorly). For example, heat generated inside an enclosure is transferred to the outer surface by means of conduction.
- Convection is the transfer of heat from a surface by means of a fluid (liquid or gas). Convection occurs as liquids or gasses are heated: they expand, rise, and are replaced by cooler fluid. The amount of convection may be increased by using a fan to increase the flow.
- Radiation: This is a process where energy is radiated away by means of electromagnetic radiation where an object has a temperature  $>$  absolute zero ( $-273.16^{\circ}\text{C}$  or  $0^{\circ}\text{K}$ ). Although effective for high temperature sources such as the sun, it's less effective for small temperature differences.
- Evaporative cooling: The latent heat of a liquid can be used to transfer heat by absorbing the energy required to evaporate that liquid. The heat absorbed is released by allowing the fluid to condense outside the enclosure – this is how your refrigerator works.

# Heat transfer prevention

- In some situations heat transfer is not desirable. As the previous slide shows, heat is transferred in many ways. It has both advantages and disadvantages. Heat transfer can be controlled and prevented by insulation so that it minimises transfer to the environment. The purpose of insulation is to prevent heat transfer from a higher temperature to a lower temperature and therefore all means of heat transfer must be taken into account when designing the insulation. The most important property of insulation is poor thermal conductivity, -a material with poor thermal conductivity acts as a good thermal insulator.
- Because heat transfer can occur in many ways and at the same time in the same object or space, some expertise is needed to ensure that the insulation is done correctly!

# Thermal Conductivity in practice...

- A good insulator will exhibit poor thermal conductance...



$$q = -k \cdot \frac{T_2 - T_1}{L}$$

$q$  = thermal conductivity

$T_2 - T_1$  is the temperature differential

$L$  is the thickness of the conductor.

$A$  is the surface area.

Thermal conductance is defined as  $kA/L$  and is measured in watts per degree Kelvin.

Thermal resistance is the inverse of thermal conductance,  $L / (kA)$  and is measured in  $\text{k.W}^{-1}$ .

The heat transfer coefficient =  $k/L$ , measured in watts per kelvin,  $\text{W.K.A}^{-1}$  - i.e watts per kelvin per square metre.

# Thermal Conductivity Example

- Consider what happens when a layer of ice builds up in a freezer. When this happens, the freezer is much less efficient at keeping food frozen. Under normal operation, a freezer keeps food frozen by transferring heat through the aluminum walls of the freezer. The inside of the freezer is kept at  $-10\text{ }^{\circ}\text{C}$ ; this temperature is maintained by having the other side of the aluminum at a temperature of  $-25\text{ }^{\circ}\text{C}$ .
- 
- The aluminum is 1.5 mm thick. The thermal conductivity of aluminum is  $240\text{ J / (s m }^{\circ}\text{C)}$ . With a temperature difference of  $15^{\circ}$ , the amount of heat conducted through the aluminum per second per square meter can be calculated from the conductivity equation:
- $q = k\Delta t/l = 240(15)/0.0015 = 2.4 \times 10^6\text{ J / s m}^2$ .
- This is a good heat-transfer rate.

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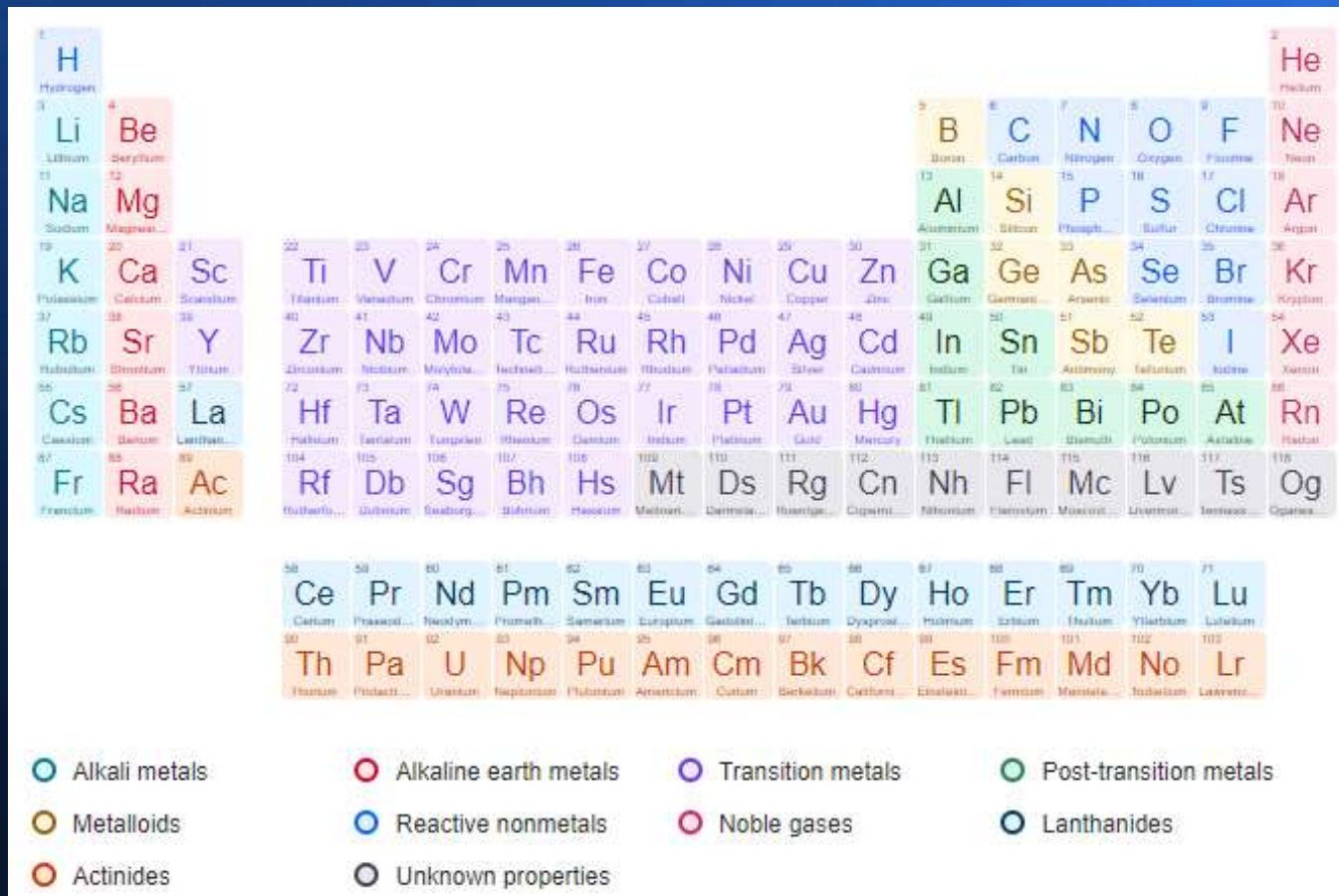


# Thermal Conductivity Example

- What happens if 5 mm of ice builds up inside the freezer? The heat must now be transferred from the freezer, at  $-10\text{ }^{\circ}\text{C}$ , through 5 mm of ice, then through 1.5 mm of aluminum, to the outside of the aluminum at  $-25\text{ }^{\circ}\text{C}$ . The rate of heat transfer must be the same through the ice and the aluminum (as the heat has to pass through both); this allows the temperature at the ice-aluminum interface to be calculated.
- Setting the heat-transfer rates equal gives:
- $k_{\text{ice}} (-10 - T)/l_{\text{ice}} = k_{\text{al}} (T - 25)/l_{\text{al}}$
- The thermal conductivity of ice is  $2.2\text{ J / (s m }^{\circ}\text{C)}$ .
- Solving for T gives:  $T = (-10k_{\text{ice}} / l_{\text{ice}} - 25k_{\text{al}} / l_{\text{al}}) / (k_{\text{ice}} / l_{\text{ice}} + k_{\text{al}} / l_{\text{al}}) = -24.959^{\circ}\text{C}$
- Now, instead of heat being transferred through the aluminum with a temperature difference of  $15^{\circ}$ , the difference is only  $0.041^{\circ}$ . This gives a heat transfer rate of:
- $J = kDt/l = 240(0.041) / (0.0015) = 6.6 \times 10^3\text{ J / (s m}^2\text{)}$ .
- So with just 5mm of ice covering the walls, the rate of heat transfer is reduced by a factor of more than 300! The freezer has to use much more energy to keep the food cold. This is why manufacturers recommend defrosting regularly!

# Periodic Table of the elements

(For reference, Silicon and Germanium are Metalloids).



# Errors and Uncertainties

- PRECISION AND ACCURACY:
- Accuracy is the closeness of agreement between a measured value and a true or accepted value (measurement error reveals the amount of inaccuracy).
- Precision is a measure of the degree of consistency and agreement among independent measurements of the same quantity (also the reliability or reproducibility of the result).
- A voltmeter which gives readings of 10, 10, 10, 10 and 10 volts on five measurements of a known voltage of 10 volts is both precise and accurate;
- A meter registering 8,8,8,8, and 8 volts on five measurements at a known voltage of 10 volts is precise, but not accurate
- A meter which reads 11, 10, 8, 9 and 12 volts on five measurements of a known source of 10 volts is neither precise nor accurate.

# Errors and Uncertainties

- RANDOM AND SYSTEMATIC ERRORS

- There are 2 types of errors in measured data. It is important to understand which you are dealing with, and how to handle them.
- **RANDOM ERRORS** refer to random fluctuations in the measured data due to:
  - The readability of the instrument
  - The effects of something changing in the surroundings between measurements
  - The observer being less than perfect (yes that's you!)
- Random errors can be reduced by averaging. A precise experiment has small random error.
- **SYSTEMATIC ERRORS** refer to reproducible fluctuations consistently in the same direction due to:
  - An instrument being wrongly calibrated
  - An instrument with zero error (it does not read zero when it should – to correct for this, the value should be subtracted from every reading)
  - The observer being less than perfect in the same way during each measurement.  $\Xi$
- Systematic errors cannot be detected or reduced by taking more measurements. Even an accurate experiment has small systematic error.
- When graphing experimental data, you can see immediately if you are dealing with random or systematic errors (if you can compare with theoretical or expected results).

# Errors and Uncertainties

- REPORTING A SINGLE MEASUREMENT
- You would be surprised at how few people actually know how to take a proper reading of something!
- Most people try to report a measured value with a degree of certainty that is too generous – expressing more certainty in a reported value than really exists. You should avoid this! It is bad practice.
- Generally we report the measured value of something with the decimal place or precision going not beyond the smallest graduation (called the ‘least count’) on the instrument. In cases where the least counts are wide enough to estimate beyond them with certainty, you may do so. It is ultimately up to the experimenter to determine how to report a measured value, but be conservative and do not overestimate the precision of the instrument.
- Sometimes you hear that uncertainties should generally be reported as  $\frac{1}{2}$  the least count; this is technically correct. But since they should be reported with the same number of decimal places as the instrument, in practice this amounts to stating them as  $\pm$  the least count.

# Errors and Uncertainties

- Uncertainty in calculated results: absolute and percentage uncertainties
- Absolute uncertainties are expressed as  $\pm$  the number of units in the measurement ( $\pm \Delta x$ ).
- Length =  $234 \pm 2$  mm Period =  $1.6 \pm 0.3$  s
- This tells you immediately the maximum and minimum experimental values of a measurement.
- Absolute uncertainties have the same units as the stated measurement. All uncertainties begin as an absolute uncertainty, stated according to the uncertainty in the precision of the instrument.
- Percentage uncertainties are expressed as  $\pm$  [the fractional uncertainty in the measurement  $\times 100$ ] ( $\pm [(\Delta x/x)100]\%$ ).
- Length =  $234 \pm 2$  mm or  $234 \pm (2/234)\times 100 = 234 (\pm 8.5 \%)$  mm
- Period =  $1.6 \pm 0.3$  s or  $1.6 \pm (0.3/1.6)\times 100 = 1.6 (\pm 18.8 \%)$  mm
- Percentage uncertainties are unitless and can save lots of time when making calculations, even though it seems cumbersome to express uncertainty this way.

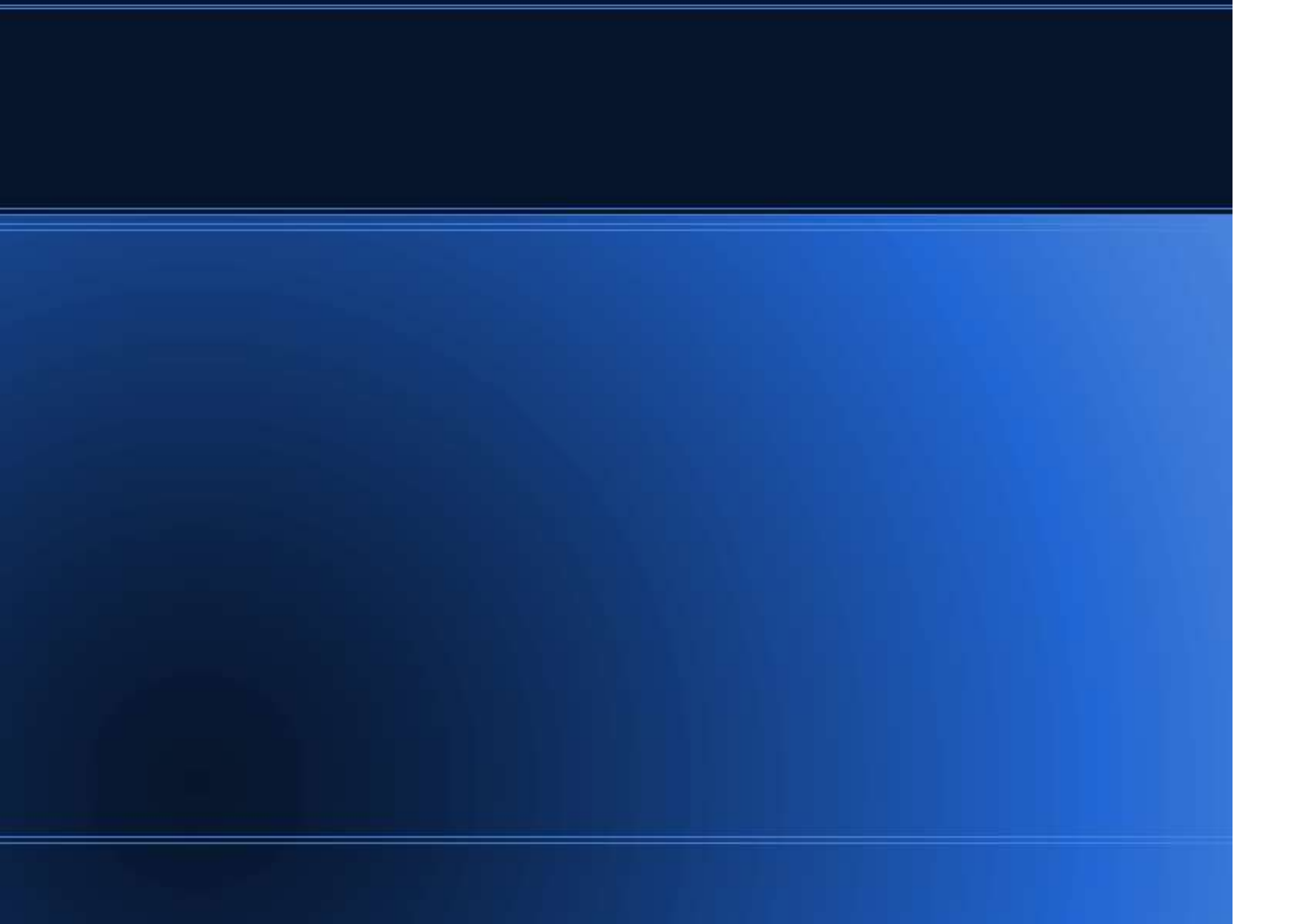
# Errors and Uncertainties

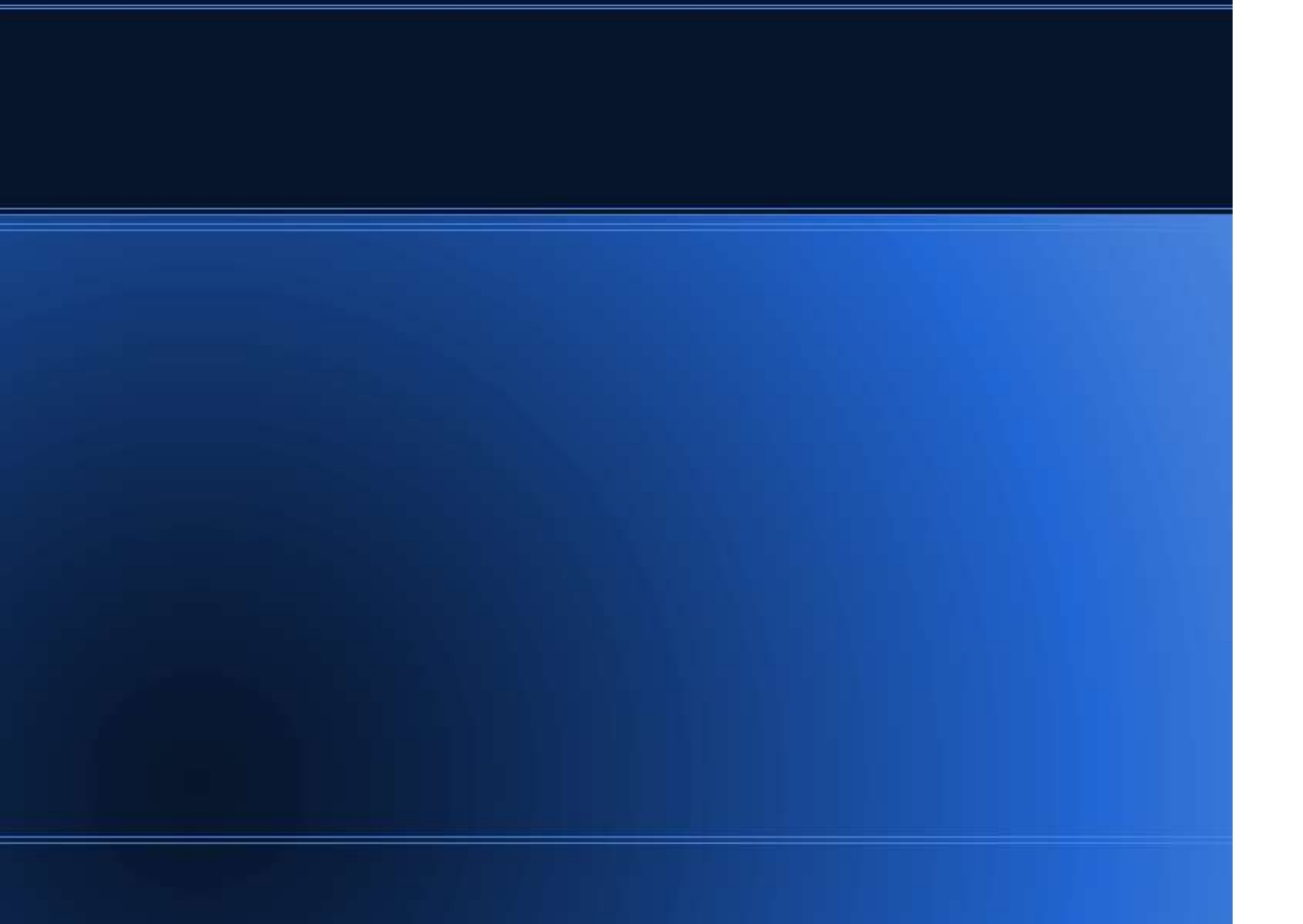
- It is good form to leave all final calculated answers with an absolute uncertainty. Therefore, you need to be able to convert from absolute uncertainties to percentage and back again. Constants such as  $\pi$  do not affect the uncertainty calculation.
- When doing calculations involving percentage uncertainties, it is easier to leave out the ( $\times 100$ ) step and simply multiply using the decimal form.
- Uncertainties when making graphs:
- In many cases, the best way to present and analyse data is to make a graph. A graph is a visual representation of 2 things and shows nicely how they are related. A graph is the visual display of quantitative information and allows us to recognise trends in data. Graphs also let you display uncertainties nicely.

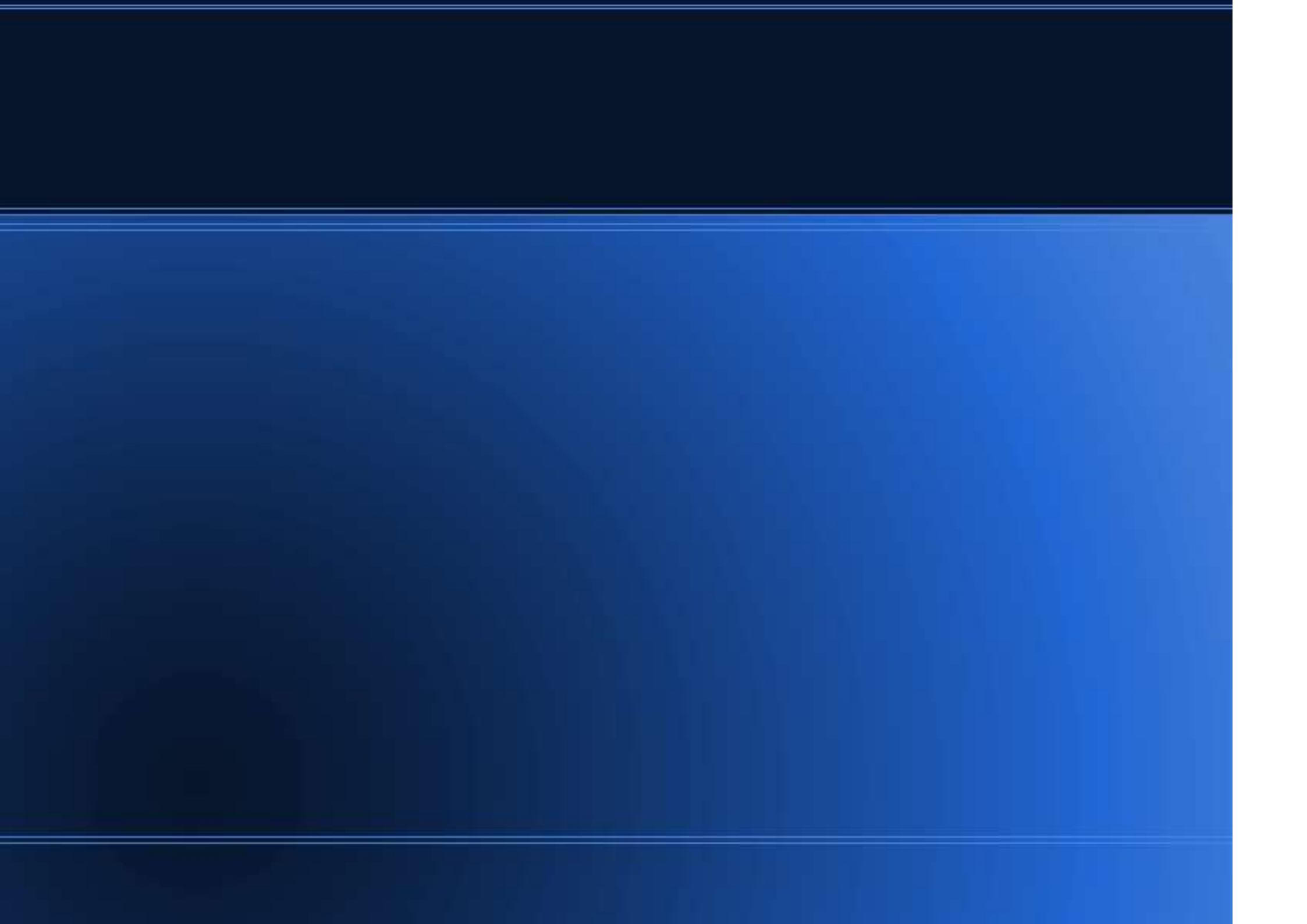
# Errors and Uncertainties

- A nice way to show uncertainty in data is with error bars. These are bars in the x and y directions around each data point that show immediately how big or small the uncertainty is for that value. Uncertainties can be constant values for every data point or percentage values (in which case the length will vary).
- Either way, an error box is created when there are error bars in both x and y directions around a data point. It is usually a rectangle and often varies in size around every point.









**Let's get building!!!**