9.9 Option- The Age of Silicon: 1. Electronics, silica, the microchip and society

Syllabus reference (October 2002 version)		

1. Electronics has undergone rapid development due to greater knowledge of the properties of materials and increasingly complex manufacturing techniques	*Students learn to*:
	
	• identify that early computers each employed hundreds of thousands of single transistors
	• explain that the invention of the integrated circuit using a silicon chip was related to the need to develop lightweight computers and compact guidance systems
	• explain the impact of the development of the silicon chip on the development of electronics
	• outline the similarities and differences between an integrated circuit and a transistor
		Students:
		
		• identify data sources, gather, process and analyse information to outline the rapid development of electronics and, using examples, relate this to the impact of electronics on society
		• gather secondary information to identify the desirable optical properties of silica, including:
		  ○ refractive index
		  ○ ability to form fibres
		  ○ optical non-linearity

[Edit: 2 July 09]

Prior knowledge: Preliminary modules: 8.2 (particularly part 5), 8.3 and HSC module 9.4, particularly part 3.

NOTE that past HSC papers have asked questions in this module that require you to use information from the HSC core module 9.4: *From ideas to implementation* in particular section 3 about transistors. Questions have assumed that you will know transistor and diode structure, function and principles of operation as well as how environmental factors, such as light and heat, impact on their electrical properties when they are used as transducers in circuits.

identify data sources, gather, process and analyse information to outline the rapid development of electronics and, using examples, relate this to the impact of electronics on society

- Locate reliable, authoritative and recent sources that fill out to your satisfaction the story of the development of electronics. The bare bones of that story are provided below, but remember that it is only the syllabus point details that will be examined.

- Sources you might access include:
    - **KIDS.NET.AU** is the site of an interactive encyclopedia.

- The Nobel prize site has a history of **semiconductors** and **vacuum tubes** (thermionic emission) in its Educational section.
- The US **Public Broadcasting Service** provides some background information on the invention of transistors and integrated circuits.
- **Jack Kilby (Texas Instruments)** and **Robert Noyce (Fairchild)** are both credited with the discovery of the integrated circuit at the end of the 1950s.
- Intel is a company that manufactures ICs and they have information modules on their website about the electronics that drive today's modern communication systems. Their online exhibit, **From Sand to Circuits** tells how Intel makes integrated circuit chips.

Background

To tell the story of electronics from the mid-twentieth century to the present time, you will need to know the physical structure and operating principles for the following devices:

- thermionic valves
- diodes
- transistors
- integrated circuits (ICs)
- active and passive transducers
- the difference between linear and non-linear devices
- the similarities and differences between analogue and digital signals
- systems for handling analogue and digital signals.

Some of that information can be found in HSC module 9.4, *From ideas to implementation*, in section 3 about semiconductors and transistors.

The key phases in the story of electronics are related to:

1. the thermionic valve
2. the transistor and its successor, the integrated circuit
3. the replacement of analogue with digital coding of information.

You should identify the key events and the time span when each was/is the dominant technology and provide a summary of significant refinements made and their advantages and disadvantages. Their disadvantages will assist you to understand why they were replaced with the next technology…and thus provide the beginnings of a list of advantages for the succeeding technology. Relevant features of each technology are outlined in the following snapshots about the thermionic valve, transistor and IC.

The thermionic valve is a relatively large, evacuated glass tube containing metal electrodes in a carefully organised but delicate structure. To do useful things, a valve needs external components such as capacitors, resistors and inductors and two power supplies. One is a low voltage, high current supply to produce the heat for thermionic emission of electrons (5 -15 volts). The other is a high voltage, low current supply to control the movement of electrons in the valve (100+ volts). An individual valve cannot be reduced in size much below half of an index finger on an adult hand. Useful equipment (radio, tape recorders, amplifiers and computers) requires multiple valves and related circuits containing large resistors, capacitors and inductors. The components need to be well spaced to allow for heat dissipation and to ensure that the high operating voltages do not cause short-circuits. Thus valve-based electronic equipment takes up a lot of space, is relatively heavy and needs to be kept in situ for long-term, reliable operation.

Transistors are relatively small, solid state devices (packaged into about 5 mm^3 for low power applications) and physically robust. They do not require high voltages or currents and thus produce little heat. Initially they were made from a Germanium base, but Silicon became the preferred base because it could better handle higher currents and consequent higher temperatures than Germanium. Transistors, like valves, require external resistors, capacitors and inductors in their circuits to perform useful tasks. In low power applications, the size of resistors and capacitors can be reduced (less heat is produced to be dissipated) and they can be packed closer together in circuits without overheating or risking a short-circuit. The use of printed circuit boards and automated soldering processes (to fix all the components to a circuit board without human intervention) means that the same functionality as valve based electronics can be provided at a fraction of the cost (both in terms of material and labour) and in a greatly reduced package size. Transistor based equipment uses much less energy, is truly portable (lighter and smaller in size), more reliable (not so prone to physical damage) and can do much more (size for size) than valve based electronics. Battery technology was sufficiently advanced to provide practical amounts of energy to run transistorised equipment at a reasonable cost.

The first integrated circuits (ICs) contained a few transistors, resistors and capacitors all fabricated on what started out as a single, very pure, wafer of silicon crystal. Today, a single silicon crystal can have up to 10^8+ transistors and related resistors and capacitors (as well as other devices and circuitry) all fitted onto an area covered by a five cent piece. Manufacture of ICs today is very complex and requires highly advanced technology to:

- produce ultra clean environments
- maintain high vacuum spaces where very small doses of metal vapour can be delivered to precisely identified regions of the substrate crystal
- provide very precise measurements down to 10^{-9} m (nanometers)
- refine very pure sources of rare metal elements
- support laser etching tools and computer-aided design.

These latest ICs, when compared to earlier ICs:

- require little electrical energy to operate
- are very robust
- are extraordinarily fast
- are relatively cheap to produce
- are versatile
- have massive calculating capacity.

It is interesting to note the social forces that drove the development of electronics from the 1940s and it's growing impact on our daily lives.

- The main impetus for the development of electronics from the mid-twentieth century was military conflict, eg World War 2, the Korean War and the Cold War. The need for better electronics to support the development of missile guidance and control systems and the space race to the moon led to the development and production of the first ICs in the US by the early 1960s.

- Since the collapse of the Soviet Union and the end of the Cold War (by 1990), commercial and military interests have continued to fund research and development of bigger, more powerful and faster silicon-based very large scale integrated (VLSI) and ultra large scale integrated (ULSI) circuits.

NOTE: The above information about social forces is interesting but should not be included in an answer in the HSC.

- Both military and commercial interests continue to build sophisticated global communication networks. These networks utilise computers, massive data storage banks, satellites, very high frequency radio (microwave) links on the ground and optical fibre networks (which are rapidly replacing copper wire-based networks) in the ground and under oceans to transfer digitised data around the Earth.
- Faster and faster circuits are needed in the computers that manage the growing volume of data being moved around those networks. To achieve higher speeds, silicon-based ICs will need to be replaced soon (this will be explained in later material for this module).
- After you have **gathered** and **analysed** the information you need to use the examples you have found to relate this to the impact of electronics on society.

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identify that early computers each employed hundreds of thousands of single transistors

- The first transistor based computers appeared in the second half of the 1950s and replaced those with valves. Transistors replaced valves because they took up less space (more transistors per unit area could be included in a computer than valves), used much less power and were more reliable. Large numbers of transistors were needed to perform the operations required to make computers practical tools.

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explain that the invention of the integrated circuit using a silicon chip was related to the need to develop lightweight computers and compact guidance systems

- Transistors were replaced by ICs in the late 1960s to make minicomputers. The first desktop or personal computer was the Altair 8800 produced for the mass market by Micro Instrumentation Telemetry Systems (MITS) in December 1974. Different integrated circuits to perform a variety of different functions were developed. By packaging a number of different integrated circuits into a single package, a set of useful functions could be achieved. This was the way the 8080 8-bit microprocessor that was made by Intel and then used by MITS in the Altair. In this way useful computing power was achieved as was miniaturisation, thus paving the way for portable computers and effective and practical missile guidance systems.

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outline the similarities and differences between an integrated circuit and a transistor

- Similarities
    - Both use pure silicon as the starting point for their manufacture.
    - Both are encased in a protective, heat dissipating electrical insulator.
    - Both need to have conductors attached to the internal devices that pass through the casing for attachment to external circuits
    - Both use low voltage direct current energy supplies.

- Differences
    - An IC contains the resistors and capacitors needed to make the transistors work as required as part of its internal structure (hence the term integrated circuits).
    - An IC can have millions of transistors located on the same piece of silicon.
    - An IC can perform much faster the same task as a separate transistor equivalent circuit.
    - An IC is inherently more reliable than a separate transistor equivalent circuit.
    - An IC is a much more efficient user of its externally supplied electrical energy than a separate transistor equivalent circuit.

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explain the impact of the development of the silicon chip on the development of electronics

- The impact of the silicon chip on the development of electronics can be demonstrated by refering to the differences between separate transistors and ICs. The use of ICs has enabled computers to become portable (laptops and notebooks); telephones once connected to a fixed network can become mobile; and, once separate devices are now available in a single package (convergence). By taking once separate ICs performing different functions and combining them into one package, we now have home entertainment systems (multimedia players, Sony Playstation and X Box) that provide video, TV and games capability along with related stereo or surround sound. Mobile phones can be purchased that are personal digital organisers (PDAs), computers and digital cameras that can capture and store single and video images for later sending to another phone or computer as needed..

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gather secondary information to identify the desirable optical properties of silica, including: refractive index, ability to form fibres and optical non-linearity

- The syllabus itself defines optical fibres (see p. 85) as:

  Consisting of a core where light rays travel and the cladding which is made of a similar material with a slightly lower refractive index to cause total internal reflection. Two types of material are used to manufacture fibres – glass (silica) and plastic.

- Try these sources below and organise the information collected in a way that is accessible to you (such as in a table) and helps you to understand why silica (pure glass) is used to make optical fibres.

- **How stuff works** has a series of pages that contain information relevant to the topic and a collection of other sites you can go to for more information.
- The following site explains how **optical fibres are made** Network Cabling Help, UK.

The information you gather should support the outline provided below:

- Glass has the same refractive index throughout. Light can be transmitted down a glass fibre using the property of total internal reflection. A ray of light moves through that glass in a straight line until it hits the boundary between the glass and another medium. If a light ray enters the glass fibre almost perpendicular to the end of the fibre, it will be totally internally reflected from the internal boundary of the glass and the other medium to eventually emerge from the other end of the fibre, even if the fibre turns back on itself.

- Scientists have discovered that you can improve the efficiency of this internal reflection process if the refractive index (RI) of the glass is highest at its core and progressively reduced as you move to the outer edge. This change in RI as you move from the fibre core to the outer cladding (as it is called) can be achieved by deliberately introducing chemicals, such as germanium and boron, into ultra-pure glass in a process called doping.

- A lump of doped glass is then physically manipulated into thin fibres in a way that locates the high RI glass at the core of the fibre. The change in RI as you move from core to cladding is also referred to as 'optical non-linearity'. Optical non-linearity is deliberately created in optic fibres to improve the efficiency of light transmission.

9.9 Option - The Age of Silicon: 2. Analogue verses digital circuits

Syllabus reference (October 2002 version)		
2. Electronics use analogue and digital systems, the basic circuit elements of which are potential dividers and transistors	*Students learn to*: • describe the difference between an electronic circuit and an electric circuit and the advantages and disadvantages of each • distinguish between digital and analogue systems in terms of their ability to respond to or process continuous or discrete information • identify systems that are digital and systems that are analogue in a range of devices • identify potential dividers and transducers as common elements in both analogue and digital	*Students*: • identify and analyse data and perform an investigation to demonstrate the difference between digital and analogue voltage outputs over time • gather, process and present information to identify electronic systems that use analogue systems, including television and radio sets and those that use digital systems, including CD players • solve problems and analyse information involving resistances, voltages and currents in potential

	systems • explain how the ratio of resistances in a potential divider allows a range of voltages to be obtained • describe the role of transducers as an interface between the environment and an electronic system	dividers

[Edit: 21 Aug 08]

distinguish between digital and analogue systems in terms of their ability to respond to or process continuous or discrete information

- Analogue systems produce or respond to continuously changing voltages and currents. Digital circuits work with binary states such as off or on or with two distinct voltages that switch individual circuit elements off or on as needed.

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describe the role of transducers as an interface between the environment and an electronic system

- Transducers are devices that accept an input of energy in one form and output it in another form, with a fixed relationship between the input and the output. In electronics, we are interested in transducers that produce an electrical output signal or that change the voltage or current flow in the circuit where they are located. Some transducers accept an electrical signal as an input from electronic systems and produce effects (outputs) in the environment. See sections 3 & 4 below for more details.

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describe the difference between an electronic circuit and an electric circuit and the advantages and disadvantages of each

- An electric circuit contains only devices such as switches, resistors, capacitors, inductors and transducers (see below for a definition) such as lights, motors, solenoids or combinations of these. An electronic circuit can contain all or any of the above plus one or more semiconductor-based devices such as a diode, light emitting diode, transistor, IC, light dependent resistor (LDR), thermistor or photodiode.

Electric circuits	Electronic circuits
Advantages: can handle higher voltages and current than electronic circuits	Advantages: are more efficient than electric circuits, the use of semiconductor based devices in them

Disadvantages: less efficient than electronic circuits	enable them to perform many different functions, can detect and work with tiny voltages and currents when compared to electric circuits, take up less space than equivalent electric circuits. Disadvantages: there are limits to the voltages and currents they can handle.

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identify potential dividers and transducers as common elements in both analogue and digital systems

- Both digital and analogue systems may use potential (voltage) dividers in their circuits. A transducer (see section 3 below for different kinds of transducers that you must know about for the HSC) may take the place of one of the resistors in a voltage divider circuit. The resistance of the transducer is changed as it is affected by the environment which in turn changes the current and voltage in the circuit of which it is a part. Those changes in voltage and current can then be detected by electronic circuits (see some examples below).

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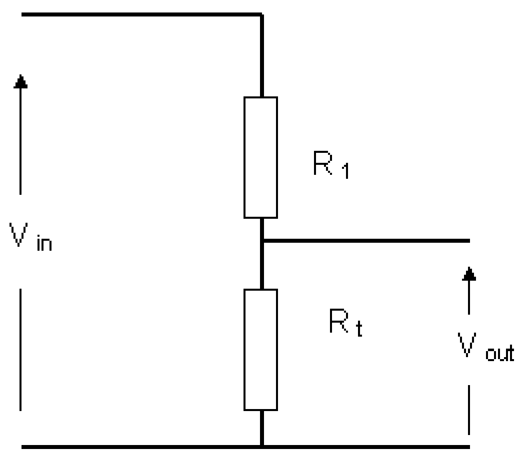
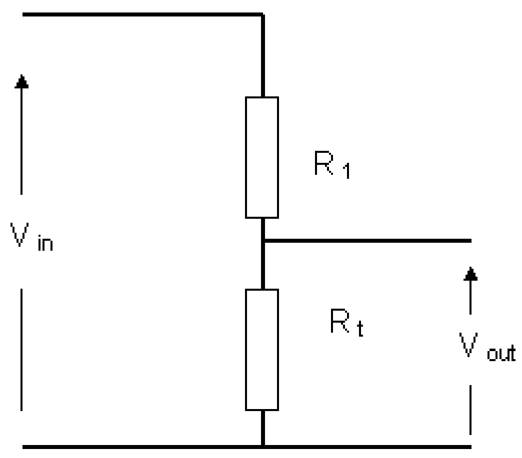
explain how the ratio of resistances in a potential divider allows a range of voltages to be obtained

Potential divider circuit that produces a linear relationship between the input and the output	Potential divider circuit that produces a non-linear relationship between the input and the output
 $V_{out} =$ $\frac{R_t}{R_1 + R_t} \times V_{in}$	 $V_{out} =$ $\frac{R_t}{R_1 + R_t} \times V_{in}$ Where R t is replaced by a transistor or other type of transducer

- If V_{in} is 5 volts and R_1 is 1000 ohms and we vary R_t from 500 to 1000 ohms in increments of 100 ohms, V_{out} varies from 1.7 (to 1.9 to 2.1 to 2.2 to 2.4) to 2.5 volts. R_t could well be an LDR, thermistor or phototransistor (see sections 3 and 4 on transducers below)

- If we keep R_1 (say 500 ohms) and R_t constant (say 1000 ohms) and vary V_{in}, then V_{out} is a fixed proportion of V_{in} ; in this case V_{out} = 0.67 V_{in}

  Note that V_{out} must always be less than V_{in}

  An internet resource with information about circuits that use resistive transducers in voltage divider circuits is the doctronics site in the UK: http://www.doctronics.co.uk/voltage.htm

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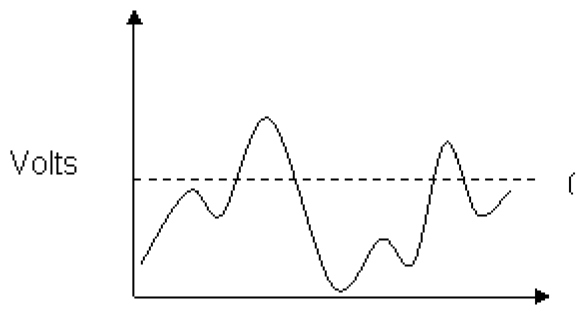
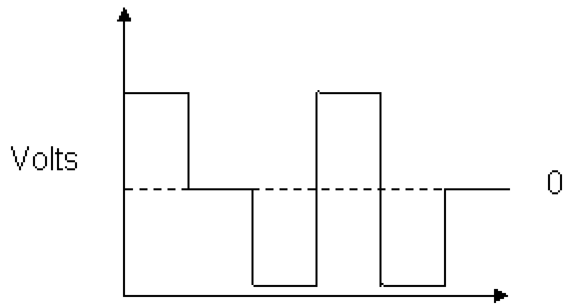
identify and analyse data and perform an investigation to demonstrate the difference between digital and analogue voltage outputs over time

- Analogue voltage outputs vary continuously between preset limits over time. Digital voltage outputs also vary over time between preset limits, but they will be pulses whose amplitude varies in multiples of a basic voltage.

Analogue voltage	**Digital voltage**
	

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identify systems that are digital and systems that are analogue in a range of devices

- A compact disc (CD) or digital versatile (or video) disc (DVD) player uses digital processes to extract information from the disc and an analogue system to produce sound. If an image is involved, then the systems that make them may be digital or analogue or a combination of the two.

- Mainstream radio stations in Australia, whether AM or FM, are analogue systems. Some are broadcasting digitally coded signals as part of a planned move to digital broadcasting in the future.

- TV stations transmit both analogue and digitally coded signals to your TV antennae. Again, there is a plan to move exclusively to digitally coded broadcasting in the future.

- Mobile phone systems are a combination of digital and analogue systems.

- The central processing unit (CPU) in a computer is a digital device, that convert inputs to digital codes that are transferred, processed, stored and retrieved as needed.

- An iPod uses digital systems to store and manage the music pieces and an analogue system to produce the sound in your ear piece.

- A cassette tape recorder/player or video tape recorder/player is an analogue storage system.

- A cathode ray tube (used to produce the images on many television sets and computer monitors) is an analogue system.

- The video screens and monitors on portable computers, liquid crystal display (LCD) screens and plasma screen TVs are driven by digital devices called video graphic arrays (VGAs).

- Camera film (analogue) is being replaced in digital cameras. The heart of the digital camera is a digital device called a charge coupled device (CCD). It contains an array of light detecting elements (pixels) that digitally code information about intensity and colour of the light falling on it. That information is stored on a digital device for transfer to a computer or digital decoder on a printer.
- Camera lenses are analogue systems.

- Computer hard drives (HD) and Random Access Memory (RAM) use digital systems to store information.

- Thermionic valves and transistors can be used in digital systems as switches and in analogue systems as amplifiers (see section 6 below).

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gather, process and present information to identify electronic systems that use analogue systems, including television and radio sets and those that use digital systems, including CD players

- This point is related to the one above. Use the sources listed below to gather information about, at least, television and radio sets and CD players.

  How stuff works has a series of pages that contain information relevant to the topic and a collection of other sites you can go to for more information

  KIDS.NET.AU is the site of an interactive encyclopedia.

  Infoplease site also has explanations of how CD players and other devices work.

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solve problems and analyse information involving resistances, voltages and currents in potential dividers

- You should try to work out relevant problems from previous HSC exams. The formula related to potential (voltage) dividers is provided above and you can use the Ohms Law formula R = V/I (or rearranged as needed: I = V/R & V = IR) to calculate the current flow in a series circuit (note that in a series circuit, the current is the same in each element of the circuit).

Q 32 (b) from the 2002 HSC paper

The resistance of the LDR is found from the graph. Light intensity of 2 lux produces an LDR resistance of 800 ohms

V =" " I X R_{total} and R_{total}

= LDR resistance (800 ohms) + resistance of coil in the relay (R_c)

12 =" " $4.8 \times 10^{-3} \times (800 + R_c)$
$R_c = 12/4.8 \times 10^{-3}$ 800

=" " 2500 - 800
=" " 1700 ohms or 1.7 kΩ

Q 32 (d) (i) from the 2003 HSC paper

At 15^0C, from the graph provided, the thermister resistance is 1.4 kΩ

V_{out} =" " $\dfrac{R_t}{R_1 + R_t} \times V_{in}$

=" " {15000 Ω/ (22000Ω + 15000Ω)} x 12 Volts
=" " 4.9V

9.9 Option - The Age of Silicon: 3. Transducers and other non-linear devices

Syllabus reference (October 2002 version)		
3. Sensors and other devices allow the input of information in electronic systems	*Students learn to*: • define a transducer as a device that can be affected by or affect the environment • explain the relationship in a light-dependent resistor (LDR) between resistance and the amount of light falling on it • describe the role of LDRs in cameras • explain why thermistors are transducers and describe the relationship between temperature and resistance in different types of thermistors • distinguish between positive and negative	*Students*: • gather, process and present graphically information on the relationship between resistance and the amount of light falling on a light-dependent resistor • solve problems and analyse information involving circuit diagrams of LDRs and thermistors • gather and analyse information and use available evidence to explain why solar cells, switches and the light meter in a camera may be considered input

	temperature coefficient thermistors • explain the function of thermistors in fire alarms and thermostats that control temperature	transducers

Extract from *Physics Stage 6 Syllabus (Amended October 2002)*. © Board of Studies, NSW.

[Edit: 21 Aug 08]

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define a transducer as a device that can be affected by or affect the environment

- Aspects of the environment that people might want to monitor for a range of purposes include: temperature, light intensity, air pressure, humidity, chemicals present in water needed for drinking and chemical pollutants in air, to name some. Transducers are specially made devices that respond to a chosen energy source in the environment and transform it into a continuously varying electrical signal, usually detected as a voltage, that is an analogue of the environmental condition that produced it. Transducers of various types are often used in the probes we attach to data loggers.

Background

The relationship between the environmental variable (say temperature) and the amount of voltage it induces in the transducer is found, usually by experimental methods. When we graph the independent variable (the environmental aspect of interest, say, temperature) against the electrical output (voltage or resistance), the relationship between the two is not usually linear. Thus we cannot say that when the temperature doubles, the voltage from the transducer output doubles or the resistance doubles. In some cases the relationship is an inverse oneincreasing the light intensity decreases the resistance. Again that relationship is not usually linear.

Some transducers accept an electrical signal as an input from electronic systems and produce an effect (output) in the environment. These output transducers will be dealt with in section 4.

Transducers may be passive or active. Passive transducers require only an energy input to produce an electrical output. Active transducers require a separate source of electrical energy to produce an electrical output when they are exposed to the environmental energy source of interest.

Examples of input transducers include:

- microphones (convert sound to electric current). They can be made to respond to sounds well outside the range of human hearing which ranges from 20 20 000 Hz. Microphones can be made of moving coils and fixed magnets (or the reverse) or they use a piezoelectric crystal or piece of piezoelectric film to convert sound into a voltage analogue.

- photovoltaic cells (solar cells) made from semiconductor material convert light energy into an electric current. They can also be made to respond to electromagnetic radiation wavelengths outside of the range (400-700 nm) our eye can respond to.
- thermistors made of semiconductor material (heat decreases their resistance, thus increasing the current flow in a circuit in which they are located)
- light dependent resistors or LDRs made from Cadmium Sulfide (the greater the light intensity, the lower the resistance)
- phototransistors react to incident light (the greater the light intensity, the lower the resistance)
- piezoelectric crystals or film (physical stress from sound or heat results in the production of a voltage between two different surfaces)
- the LM35 is an IC that responds to temperature changes in a very predictable way (it produces, or drops, 10mV for every one degree C change in temperature)
- aerials in a number of devices such as radios, TVs and specialized equipment used to search for metallic ores (large scale exploration) or even coins lost on the beach (electromagnetic radiation induces an electric current in the circuit containing the aerial).

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gather, process and present graphically information on the relationship between resistance and the amount of light falling on a light-dependent resistor

- It is important to recognise that the relationship between light intensity and resistance is not linear. All the syllabus requires for this point is that you are able to present the relationship graphically. A typical graph can be seen at **Resistive Input Transducers** Antoine Education, UK. Scroll down until you see the graph.
- If you are really keen, use Google and do an advanced search using the names of major manufacturers (if you know any) or use light dependent resistors (exact phrase) and English (Language)
- When you have gathered enough information, **process** it by deciding which information presents the graph best and is the clearest.
- **Present** the information in graphical form with notes of explanation.

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explain the relationship in a light-dependent resistor (LDR) between resistance and the amount of light falling on it

- A light dependent resistor (LDR) is made of a high resistance semiconductor material (such as Cadmium Sulfide). When exposed to electromagnetic radiation (emr) of a particular frequency, the electrical resistance falls. The brighter the radiation (more photons per second), the lower the resistance. Resistance falls because photons eject electrons from the semiconductor into the conduction band. The more electrons ejected, the lower the resistance.

- Cadmium Sulfide is sensitive to emr from 515 nm to 730 nm (which almost covers the range of frequencies our eye can detectbut is most sensitive at 515 nm which corresponds to green, the colour our eyesight is most sensitive to).

- LDRs are analogue devices because the change in electrical characteristic is as continuously variable as the light falling on the device.

  Some more **information about LDRs** can be found at Technology Student.com by V Ryan, UK and **some more** at Chemistry Daily, USA.

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describe the role of LDRs in cameras

- LDRs are used in the light metering circuits in typical cameras to control the total amount of light that falls on the film. The LDR converts the light intensity it records into a voltage. That voltage is interpreted by the electronics in the shutter and/or aperture control circuits. Those circuits set an appropriate shutter speed and/or aperture to ensure that the amount of light falling on the film (or charge coupled device in a digital camera) will reproduce an image of the scene just photographed, usually as the eye would see it.

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gather and analyse information and use available evidence to explain why solar cells, switches and the light meter in a camera may be considered input transducers

- **Gather** information from websites, journals, CD ROMs or digital or hard copy encyclopedias

- You could analyse the information by drawing together information from different parts of this material. You then may arrive at the following conclusions:
  - Solar cells convert sunlight (electromagnetic radiation input) into electrical energy in output circuits to which they are connected.
  - Switches convert mechanical energy (the act of manipulating the switch) into electrical energy (when the circuit is completed, electrical energy flows in the output circuit.
  - The light meter in a camera is usually an LDR that varies the electric current flow in a circuit according to the amount of light falling on it. That output variable current is linked to shutter and/or aperture control circuits in the camera.

- All three have in common the production of electrical energy as output. This satisfies the definition of an input transducer.

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explain why thermistors are transducers and describe the relationship between temperature and resistance in different types of thermistors

- Thermistors (from thermal resistors) are semiconductor based devices that respond to heat by changing their resistance in predictable ways. Thus an environmental input to the device produces a corresponding electrical output which satisfies the criteria for an (input) transducer.

- There are two types of thermistors. One type responds to heat by increasing its resistance (a positive thermal coefficient or PTC devices) the other responds by decreasing its resistance (a negative thermal coefficient or NTC devices). Thermistors are analogue devices.

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distinguish between positive and negative temperature coefficient thermistors

- The capacity to respond to heat by increasing or decreasing resistance is a function of the way thermistors are made.

- NTC thermistors may be made from crystallised silicon and germanium (semiconductor material). The resistance of NTC thermistors decreases proportionally with increases in temperature and their resistance changes gradually as the temperature changes.

- PTC thermistors are made by adding small quantities of semiconductor material to polycrystalline ceramic. Their resistance rises rapidly over a narrow range of increased temperatures which means that they can operate like an on-off switch. The critical temperature range over which the resistance rapidly increases is determined by the composition of the thermistor at the time of manufacture.

- Some NTC and PTC thermistors are made using other than semiconductor materials.

  For additional information about **thermistors** see the wiseGEEK, USA site.

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explain the function of thermistors in fire alarms and thermostats that control temperature

- A fire alarm needs to respond to a rapid rise in temperature. An NTC thermistor in a fire alarm circuit can be used in an electronic circuit to trigger a siren once the temperature in a room rises above a predetermined level.

- Thermostats that control temperature (in say a hot water system or in a room) may use NTC thermistors in electronic circuits to switch on heating devices when the temperature falls below a certain point or switch on cooling devices when the temperature rises above a certain point.

Background information

PTC thermistors are useful in protecting devices from overheating such as windings that may be overheating in transformers, coils in loudspeakers or electric motors. The thermistor can be linked to a circuit that cuts off the power once a predetermined temperature is reached or exceeded.

NTC thermistors are also used to limit current flow in situations where a current surge might be experienced, such as at the switch-on of an electric motor. An NTC thermistor in the input circuit of an electric motor has a high resistance at room temperature. This restricts the initial current flow to the motor at switch on, thus preventing it being overloaded. As the motor begins to work, the temperature rises and the resistance of the thermistor decreases thus allowing the current flowing to the motor to increase to an optimum amount.

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solve problems and analyse information involving circuit diagrams of LDRs and thermistors

- Because phototransistors, LDRs and thermistors are resistive transducers, the examples worked in the above section involving potential (voltage) dividers are appropriate here too.

- As the resistance changes in response to input from the environmental aspect affecting the phototransistor, LDR or thermistor, the voltage across that device in the circuit changes in proportion to the current flowing through it. Thus circuits containing LDRs and thermistors are used to provide input voltages to other circuits designed to respond once the output voltage reaches or exceeds (or falls below) a predetermined level.

9.9 Option - The Age of Silicon: 4. Output transducers

Syllabus reference (October 2002 version)		
4.Some devices use output transducers to make connections between the device and the environment	*Students learn to*: • explain the need for a relay when a large current is used in a device • describe the role of the electromagnet, pivot, switch contacts and insulator in a relay • describe the structure of light-emitting diodes (LEDs) in terms of p-type and n-type semiconductors • explain why voltmeters, ammeters, CROs and other electronic meters are considered output transducers	*Students*: • process information to explain the way in which a relay works using a circuit diagram • solve problems and analyse information using circuit diagrams involving LEDs and relays • analyse information to assess situations where an LED would be preferable to an ordinary light source

[Edit: 21 Aug 08]

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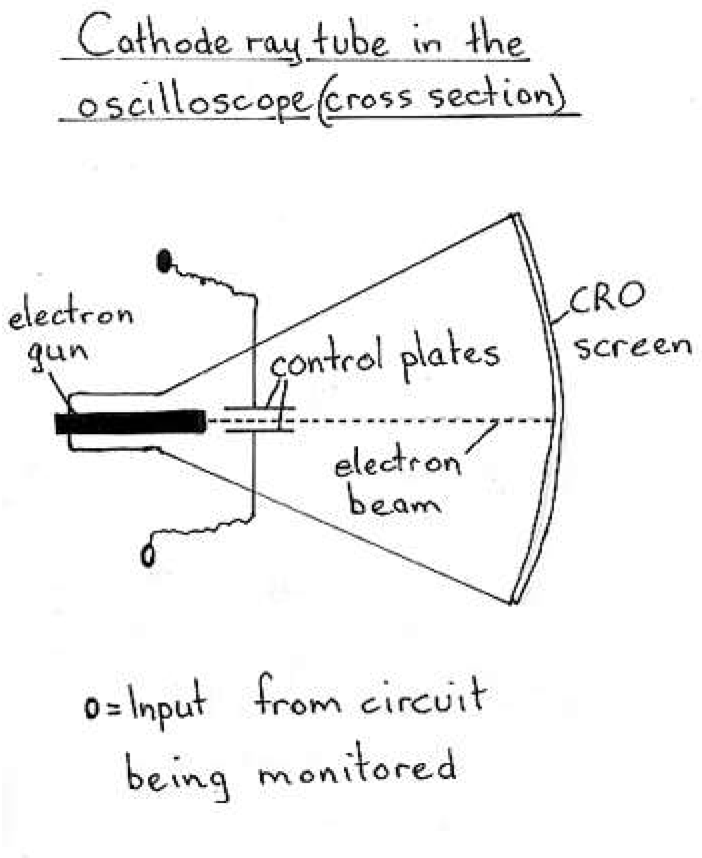
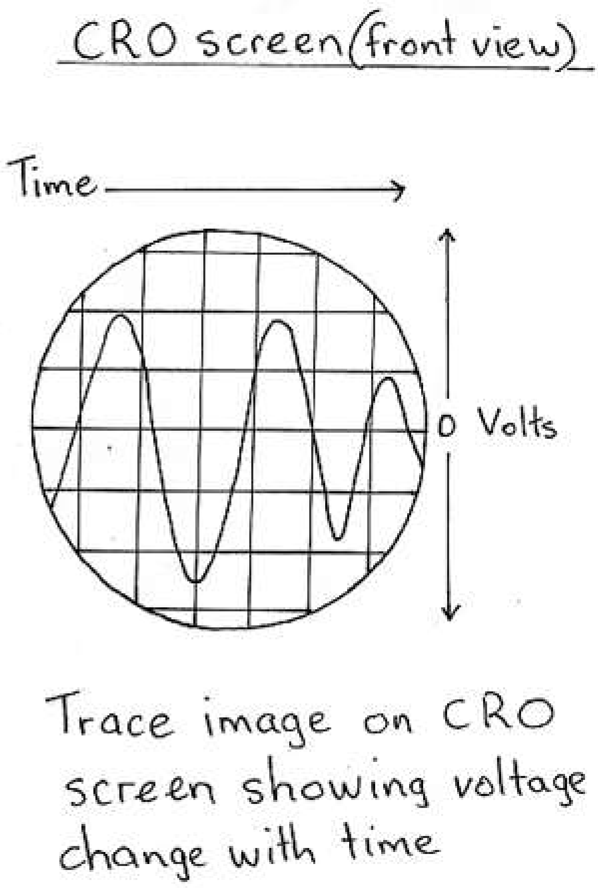
[explain](#) why voltmeters, ammeters, CROs and other electronic meters are considered output transducers

- Voltmeters and ammeters convert electric currents (electrical energy) to mechanical energy (of a needle moving over a scale) or images of numbers (light) on the display of an electronic digital multimeter. The amount of movement of the needle or numbers in the display correspond to the aspect of electrical energy being measured (voltage, current, resistance, watts).
- The inputs to Cathode Ray Oscilloscopes (CROs) transfer electrical energy from the circuit being monitored to control plates inside the picture tube of the CRO. The control plates deflect a very finely focused electron beam traveling from the electron gun to the front of the tube in a way that corresponds to the voltage in the circuit being monitored. The electron beam hits a screen coated with tiny particles (phosphors) that emit light when hit by electrons. The greater the deflection of the beam from the centre of the screen the higher the voltage being measured. The screen also has a visible grid printed on it. The grid is calibrated to show the voltage of the circuit being monitored. Because the electron beam sweeps across the screen, changes in the voltage against time can be observed as a visible trace on the screen.





A diagram and more information is available at **DOCTRONICS Educational Publications** by WD Phillips, UK.

Additional background information listing a number of output transducers:

- loudspeakers (convert electrical energy into sound)
- light emitting diodes or LEDs made of semiconductor material that convert electrical energy into light (the opposite of photovoltaic cells), but, unlike light bulbs they do it efficiently and produce almost no heat
- electric motors (convert electrical energy into motion)
- analogue galvanometers, ammeters and voltmeters (a special type of electric motor)
- solenoids (convert electrical energy into movement to physically switch on or off another circuit. A solenoid is a useful way to couple a low power electronic circuit to a high energy (high currents and voltages) electric circuit containing, for example, a powerful electric motor or flood lights
- aerials linked to radio and TV stations convert coded electric currents into coded electromagnetic signals that are broadcast into the atmosphere and space; magnetrons do that in microwave ovens

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explain the need for a relay when a large current is used in a device

- Semiconductor devices in electronic circuits have strict limits on the amount of current they can carry without being destroyed. A relay allows a small current in an electronic circuit to mechanically switch on a high current-carrying circuit.

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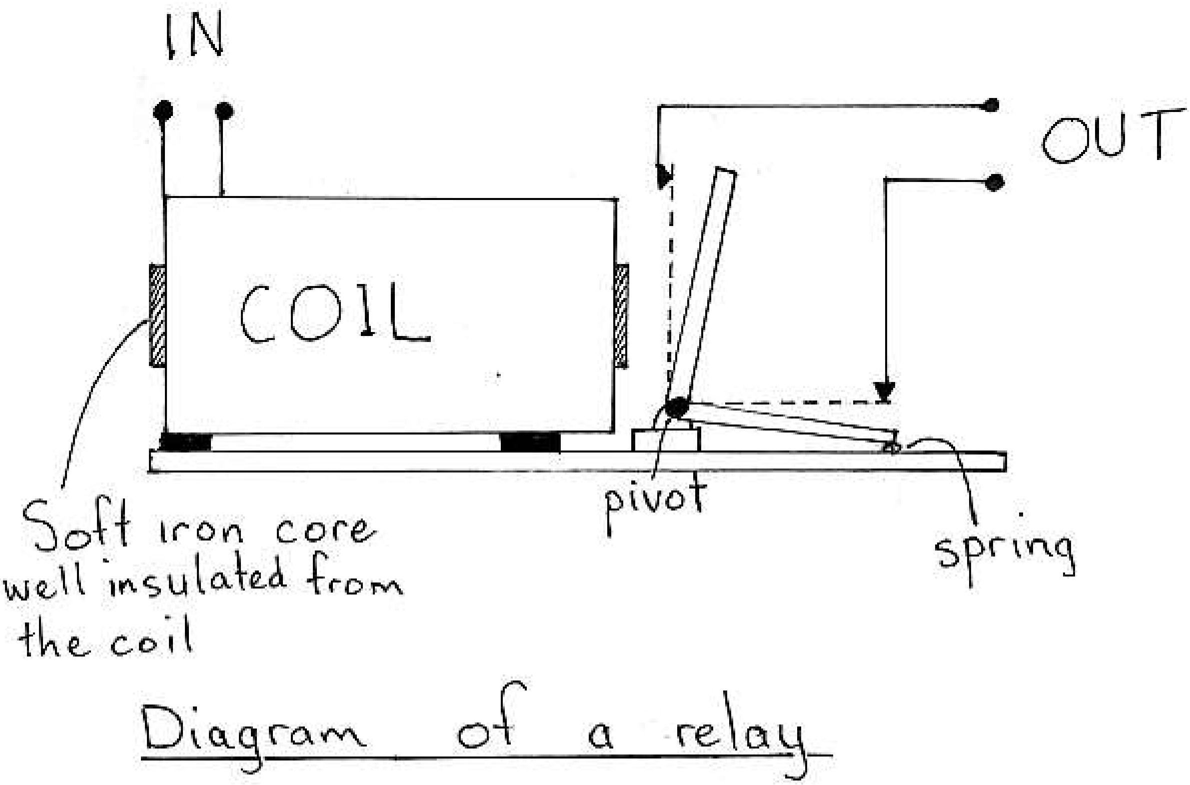
describe the role of the electromagnet, pivot, switch contacts and insulator in a relay

- The coil is well insulated from the soft iron core, armature and contacts linked to the other circuit (labeled OUT). When the current flows into the coil (IN) or solenoid, as it is sometimes called, it becomes an electromagnet. The soft iron core inside the coil concentrates the magnetic field. This magnetic field pulls the metal armature towards it (see dotted lines showing new position of armature) and brings it against the switch contacts (arrowheads) to complete another circuit (OUT). The pivot holds the armature in place and ensures a reliable connection with the switch contacts as long as the current flows in the coil. When the current in the coil is shut off, the spring pulls the armature back off the switch contacts, thus breaking the other circuit.

- The other circuit (connected to OUT) may have a high voltage & high current (250 V and 10 A) to run an electric motor. Relays like this are also used to turn on the headlights in a car (12V, 15A circuits).



Some more information and diagrams of relays can be found at the **Jag Lovers, USA** website.

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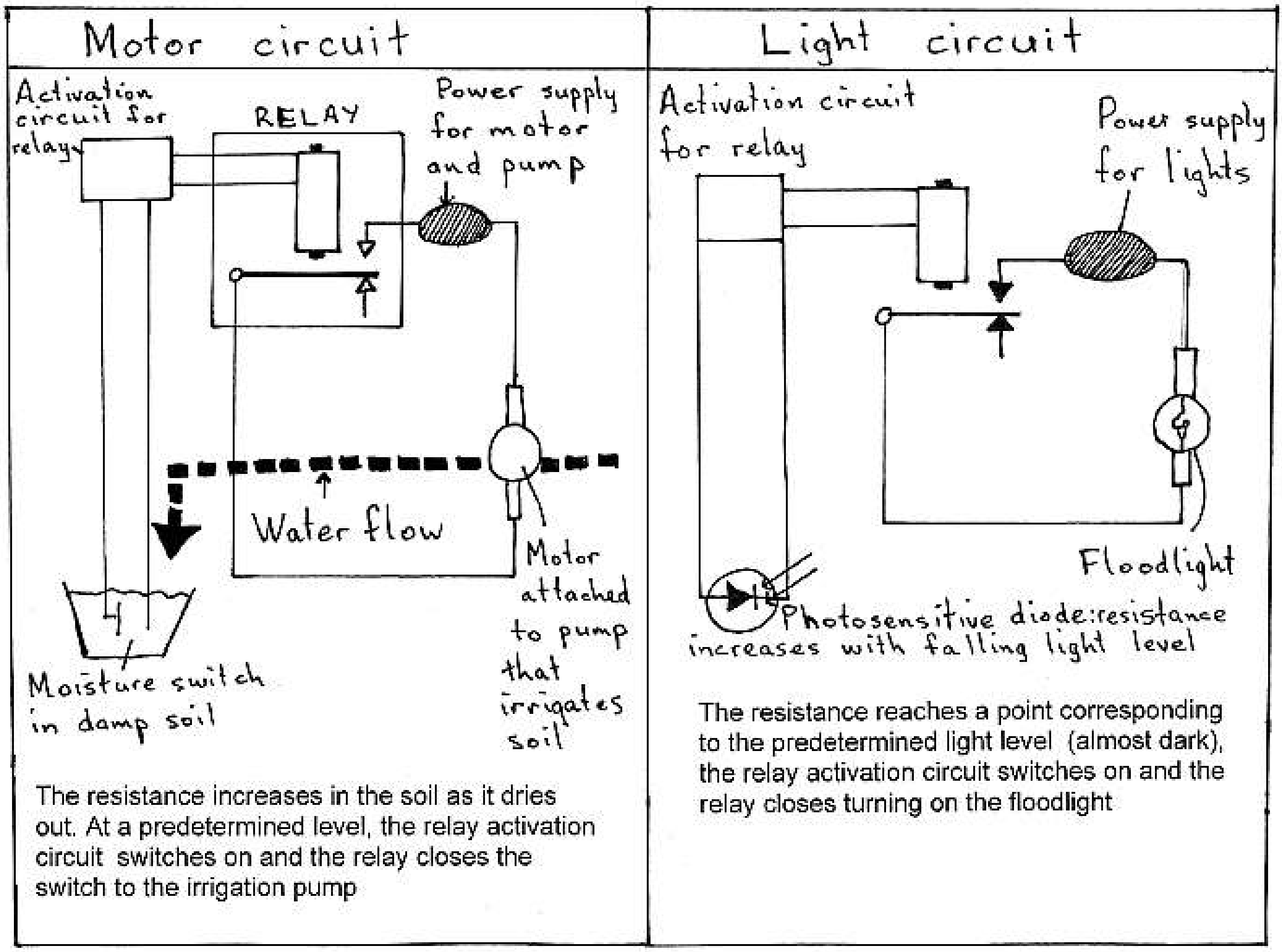
process information to explain the way in which a relay works using a circuit diagram

- Two examples follow. You can work in reverse. Use the circuit diagram to tell the story of the two circuits.



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describe the structure of light-emitting diodes (LEDs) in terms of p-type and n-type semiconductors

- Light emitting diodes (LEDs) are solid state devices that emit light when forward-biased. A layer of P-type and a layer of N-type semiconductors are made adjacent to each other by doping a suitable substrate semiconductor material. The diode with its connection leads is packaged in a plastic capsule which is transparent to the light frequency it is designed to produce.

- Forward-biasing the diode pushes charge carriers across the P-N junction. The P-N junction emits energy in the form of light in a process called electroluminescence as they do so. The colour of the LED depends on the substrate semiconductor material and the doping chemicals used to make the P & N type semiconductor material.

- **Background information:** A range of LED colours (frequencies), bias voltages and the composition of some semiconductors producing those colours is provided at **EF Schubert, Cambridge University Press, UK**

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solve problems and analyse information using circuit diagrams involving LEDs and relays

- These problems are similar to ones seen in the potential (voltage) divider section. LEDs and the coil in the electromagnet behave as simple resistances in DC circuits. The LED resistance is finite and may vary slightly depending on the amount of forward bias.

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analyse information to assess situations where an LED would be preferable to an ordinary light source

- LEDs are very efficient (all light and no heat) and reliable producers of light at a single frequency and they are virtually indestructible. They are used when using as little energy as possible is important and where reliability is paramount. Light output is being increased all the time and they are now used in traffic control signals and in car lighting systems to replace incandescent globes (the filaments burn out in these).

9.9 Option - The Age of Silicon: 5. Circuits and information processing

Syllabus reference (October 2002 version)		
5.Information can be processed using electronic circuits	*Students learn to*: • describe the behaviour of AND, OR and inverter logic gates in terms of high and low voltages and relate these to input and outputs • identify that gates can be used in combination with each other to make half or full adders	*Students*: • identify data sources, plan, choose equipment or resources for, and perform first-hand investigations to construct truth tables for logic gates • solve problems and analyse information using circuit diagrams involving logic gates

[Edit: 18 June 10]

describe the behaviour of AND, OR and inverter logic gates in terms of high and low voltages and relate these to input and outputs

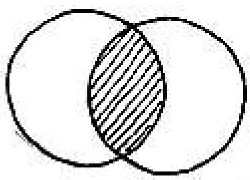
- **Logic is a form of human reasoning that tells us a certain** proposition is true if certain preconditions are true.

- In 1854 George Boole developed a mathematical system for formulating logic statements with symbols, so the problems could be written and solved in a similar manner to ordinary algebra. His system is called Boolean Algebra and it is used in the analysis and design of digital systems.

- The basic building blocks of digital circuits are called logic gates. A gate is a circuit that performs a simple logic operation. Gates can have one, two, three or more inputs and the basic gates have a single output dependent on the inputs. Each output is also called a digital 'bit' of information (or 'bit' for short).

- The behavior of a gate can be shown in a truth table which systematically lists all the possible input states for a gate and the corresponding output states. Gates can be represented in five ways.

Consider the AND gate:



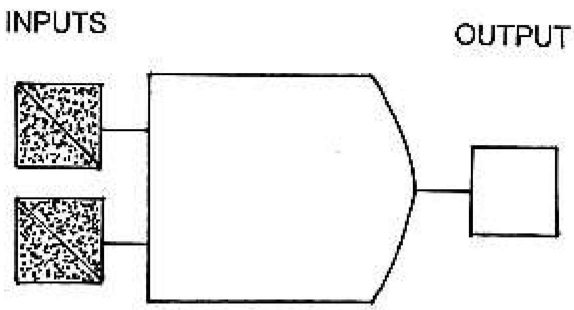
Venn diagram

A	B	f
0	0	0
0	1	0
1	0	0
1	1	1

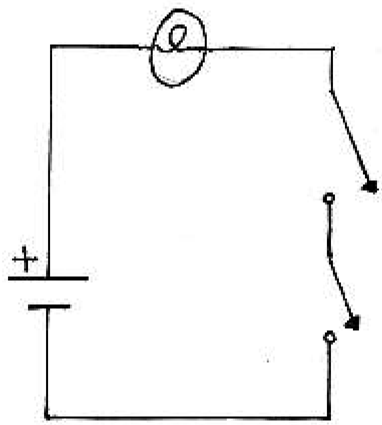
Truth table

$f = A \cdot B$

Boolean expression



Circuit symbol for a logic gate

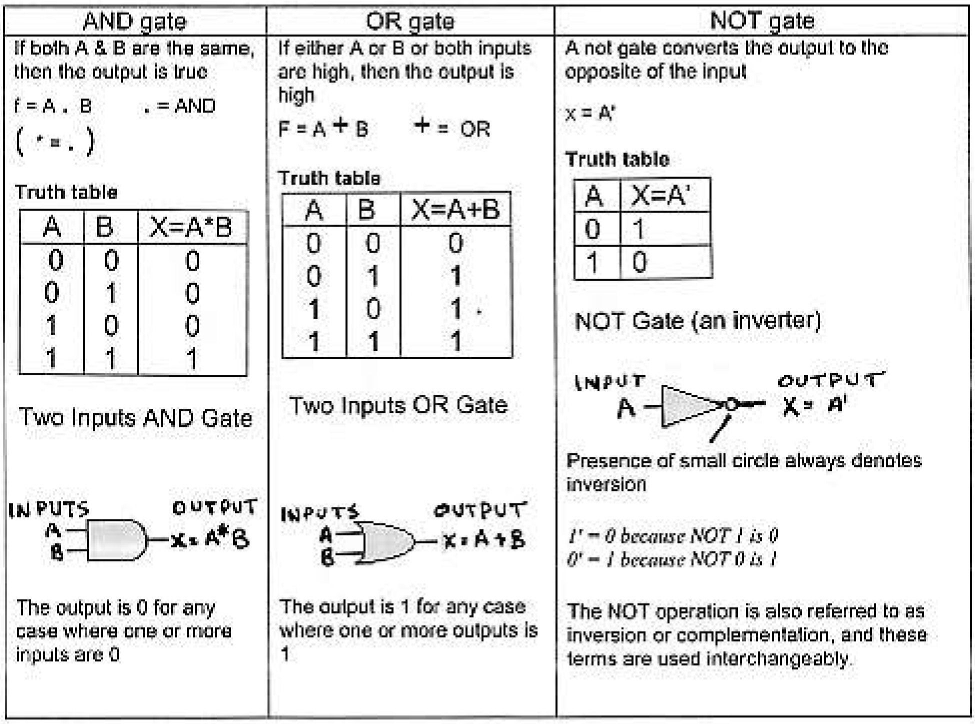


Switch circuit

- A zero (0) corresponds to a low voltage. A one (1) corresponds to a high voltage. An inverter logic gates converts a low voltage (0) to a high voltage (1) or vice versa. Some alternative meanings for 0 and 1 are as follows:

Logic 0	**Logic 1**
False	True
Off	On
Low	High
Open switch	Closed switch

- Digital circuits can be put together using diodes, transistors and resistors and connected together to provide a circuit output that corresponds to the logic operations OR, AND, NOT performed on the inputs to those circuits.



- NOR and **NAND** gates are used extensively in digital circuitry. These gates combine the basic operations **AND** **OR** and **NOT** which make it relatively easy to describe them using Boolean Algebra. EELAB Student Pages, Electrical and Information Engineering, The University of Sydney, NSW.

NAND gate

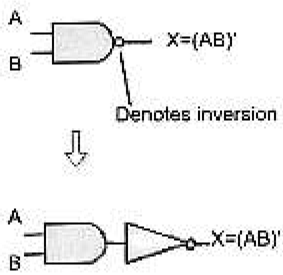
NAND is the same as the AND gate symbol *except* that it has a small circle on the output. This small circle represents the inversion operation. Therefore the output expression of the two input NAND gate is: X = (AB)'

Truth table

INPUTS		AND	NAND
A	B	X= AB	X= (A B)'
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

Two Inputs NAND Gate

INPUTS OUTPUT



NOR gate

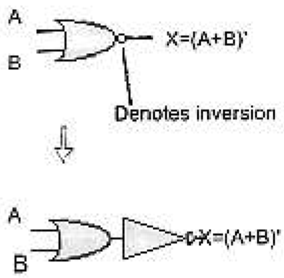
NOR is the same as the OR gate symbol *except* that it has a small circle on the output. This small circle represents the inversion operation. Therefore the output expression of the two input NOR gate is: X = (A + B)'

Truth table

INPUTS		OR	NOR
A	B	X= A+B	X= (A +B)'
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

Two Inputs NOR Gate

INPUTS OUTPUT



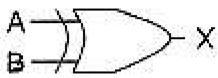
XOR gate

Can be formed by a combination of other gates.

Truth table

INPUTS		OUTPUT (X)
A	B	$A \oplus B$
0	0	0
0	1	1
1	0	1
1	1	0

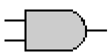
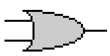
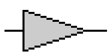
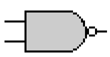
Two input XOR Gate

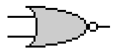
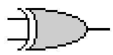


The XOR gate output is HIGH if one (and only one) of the inputs is HIGH; otherwise it is LOW

- Negative logic circuits can also be used where the positive logic gate is equivalent to the complement when acting in a negative logic circuit, for example +OR is equivalent to -AND and -AND is equivalent to +OR.
- In working through the above information about logic gates, you will have noticed that each logic gate is represented uniquely. This is useful when drawing and interpreting diagrams of logic circuits.

  The set of symbols is as follows:

Name	Symbol	Input	Output
AND		Two signals	One signal
OR		Two signals	One signal
NOT		One signal	One signal
NAND		Two signals	One signal

NOR		Two signals	One signal
XOR		Two signals	One signal

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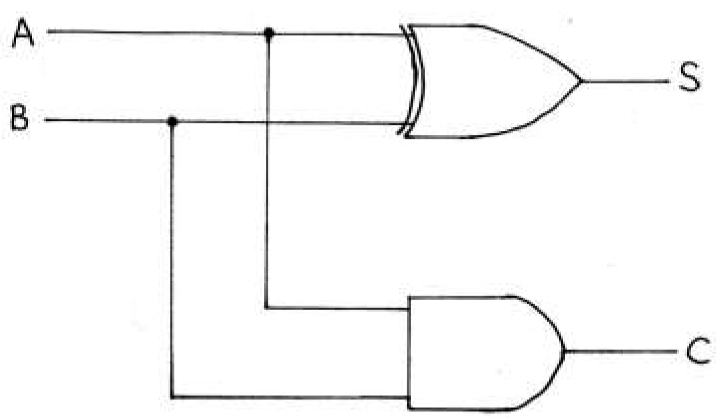
identify that gates can be used in combination with each other to make half or full adders

- Practical circuits to perform arithmetic operations, such as addition, combine two or more gates in a circuit to provide a result.
- Two such circuits are the half-adder and full-adder. In the examples below, a bit represents the binary digits 1 or 0.

A half-adder

A and B are the inputs
S represents the output *sum* and
C represents the output *carry*.



The relevant truth table for this circuit is:

A	B	C	S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

The need for two outputs to represent the sum of two binary 1s is obvious:

1 + 1 = 1 0

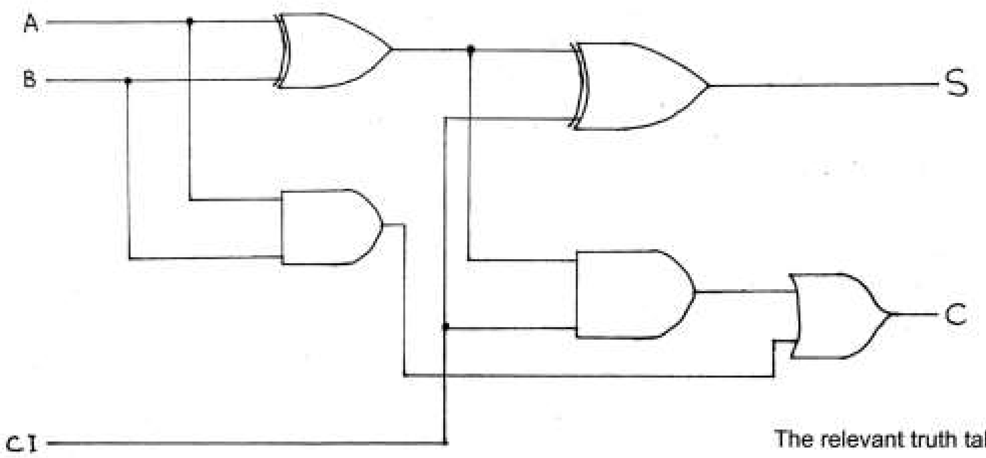
This is **not** ten, but two. The two digits are distinguished by their place or position relative to each other. The left-most digit is the significant bit (and is assigned the C for carry label); the right-most digit is the least significant bit (and is assigned the S for sum label).

A combination of gates in a circuit that adds two bits is called a **half-adder**. In the above case, this is achieved by combining an exclusive-OR and an AND gate.

A combination of gates in a circuit to add three bits is called a **full-adder**. The circuit below shows a combination of gates to produce a full-adder. A and B are the two inputs for this operation. CI (the third input digit) is the least significant bit from the two outputs of a separate half-adder circuit.

The term significant or least significant in front of 'bit' is necessary in order to correctly sequence the digits that represent the sum from the operation of the gates in the circuit. If all three inputs are carrying a 1, then the sum is 3 (the 1 from CI is the least significant bit from the other circuit). This is represented in binary code as 11 (see the truth table for the full-adder).

A full-adder



The relevant truth table for this circuit is:

A	B	CI	C	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

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identify data sources, plan, choose equipment or resources for, and perform first-hand investigations to construct truth tables for logic gates

1. Use your own resources to draw circuit diagrams and truth tables to represent a three input OR gate (can you use a NOR gate and another gate to achieve the same result?).

Solution

2. Use your own resources to draw circuit diagrams and truth tables to represent a three input AND gate.

Solution

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solve problems and analyse information using circuit diagrams involving logic gates

3. Do this question from the **2003 HSC paper** (Q 32. Scroll down to p 41 to find the question.)

Solution

4. Do this question from the **2004 HSC paper** (Q 32 (b). Scroll down to p 37.)

Solution

Truth table

A	B	C	D	E	What is X	Output
1	1	?	?	?	?	1

Is there only one answer to X? Explain your answer.

9.9 Option - The Age of Silicon: 6. Amplifiers

Syllabus reference (October 2002 version)		
6. Amplifiers are used in different ways in current technologies	*Students learn to*: • describe the functions and the properties of an ideal amplifier • explain that the gain of an ideal amplifier is the ratio of its output voltage to its input voltage: $Ao=\frac{V_{out}}{V_{in}}$ • identify that an operational amplifier is a component of a typical amplifier • describe the characteristics of an operational amplifier • distinguish between open-loop gain and closed-loop gain • identify the voltage range over which an operational amplifier circuit acts as a linear device • describe how an operational amplifier can be used as an inverting amplifier • explain that the gain of an inverting amplifier is given by:	*Students*: • solve problems and analyse information to show the transfer characteristics of an amplifier • gather and present graphical information to show the transfer characteristics of an inverting amplifier • solve problems and analyse information about setting the gain of an inverting amplifier by calculating the values of external resistors using: $\frac{V_{out}}{V_{in}}=-\frac{R_f}{R_i}$ • perform a first-hand investigation of a summing amplifier by adding voltages from two separate sources • gather information to identify the different ways in which amplifiers are used in current technologies

	$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$ • explain the difference between the non-inverting input and the inverting input • discuss how feedback can be used in a control system • explain the use of two input resistors to produce a summing amplifier	

[Edit: 21 Aug 08]

describe the functions and the properties of an ideal amplifier

- An ideal amplifier has:
    - infinite input impedance, $Z_{in} \rightarrow \infty$ (any signal can be supplied to the op-amp without loading problems)
    - zero output impedance, $Z_{out} \rightarrow 0$ (the power supplied by the op-amp is not limited)
    - infinite bandwidth
    - infinite (open loop) gain, $A_o \rightarrow \infty$
    - infinite bandwidth (another way of saying this is to refer to slew rate which is a measure of the rate at which the output voltage can change. Slew rate is measured in V/s which would be ∞ for an ideal amp)

- In an ideal amplifier the output voltage signal is an exact copy of the input signal, only amplified

- In an ideal amplifier impedance is measured in ohms. Input impedance refers to how the circuit inputing to the amplifier sees its input. The output impedance refers to the ohm value of the device into which the amplifier will deliver its maximum output.

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describe the characteristics of an operational amplifier

- An operational amplifier (op amp) is typically constructed as an integrated circuit (IC). They come very close to the ideal performance of an amplifier (see above).

$$Ao = \frac{V_{out}}{V_{in}}$$

  Op amps are represented in circuits by the following symbol:
- Ideal op amps have the following characteristics:
    - infinite input impedance
    - zero output impedance

    - infinite voltage gain
    - infinite bandwidth
    - zero input offset voltage.

- By way of comparison the characteristics of the 741 which is a real op amp are:
    - the input impedance is about 2 Megohms
    - the output impedance is about 75 ohms
    - the voltage gain rolls off 6dB per octave starting at 100kHz
    - the slew rate is 0.5V/microsecond
    - there is a finite input offset voltage which must be zeroed by a resistor between pins 1 and 5. the input offset is typically 2mV to <6mV.

- Note that op amps have two inputs, which can be selected for particular purposes in real circuits. There are two consequences of these characteristics for ideal op amps that use external feedback. They are:
    - the output does whatever is necessary to make the voltage difference between the inputs zero
    - the inputs draw no current.

  These consequences (called golden rules in the literature) allow us to design real op amp circuits (see summing amplifier described below).

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explain that the gain of an ideal amplifier is the ratio of its output voltage to its input voltage: $Ao=\frac{V_{out}}{V_{in}}$

- An amplifiers job is to amplify voltage, current or power. In this case the gain (or measure of the amplification) of a voltage amplifier is defined as the ratio of output voltage over the input voltage.

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identify that an operational amplifier is a component of a typical amplifier

- Many typical amplifiers in use today have operational amplifiers as a component within their circuits.

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distinguish between open-loop gain and closed-loop gain

- The gain of an amplifier can be specified in two ways. Open-loop gain is the gain of the amplifier without a feedback loop in the circuit and is the quoted gain from manufacturers for the op amps they make.

- Many practical amplifiers use an external feedback loop to ensure a stable operating environment for the amplifier over the range of frequencies for which it is designed to operate.

- The closed loop gain is usually much less than the open loop gain.

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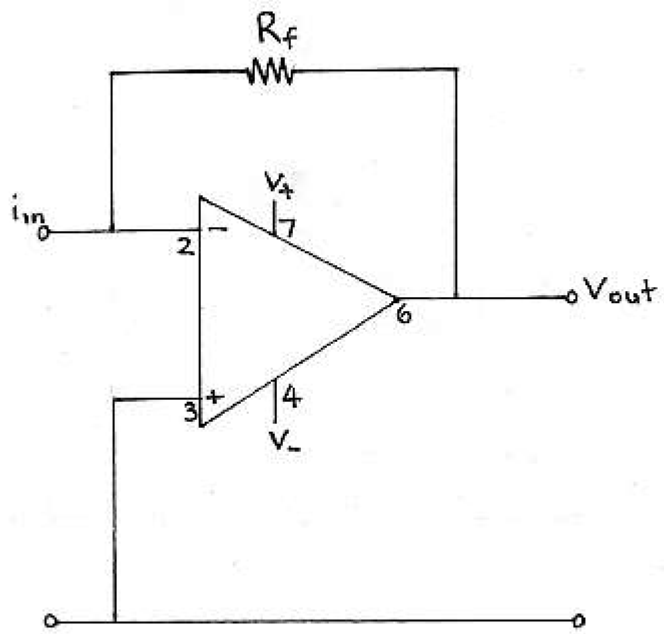
identify the voltage range over which an operational amplifier circuit acts as a linear device



R_f = feedback resistor

V_+ = external supply to IC amp (in this case a 741)

V_- = external supply to IC amp

1-8 = pin numbers on IC package

- By linear is meant that the output voltage is exactly proportional to the input voltage. To achieve this, the power supply voltages to the IC and output voltage it delivers need to be keep within this range: $V_- \leq V_{out} \leq V_+$

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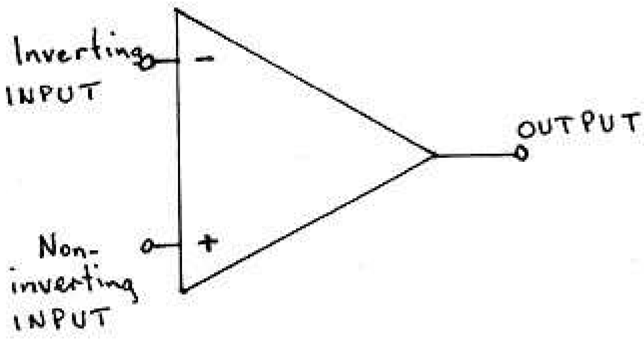
explain the difference between the non-inverting input and the inverting input

- The non-inverting input produces an output signal that is in phase with the input signal. The inverting input produces an output signal that is 180^0 out of phase with the input. The inverting input is marked with a **-** on the IC circuit above and the non-inverting output is marked with a**+**.



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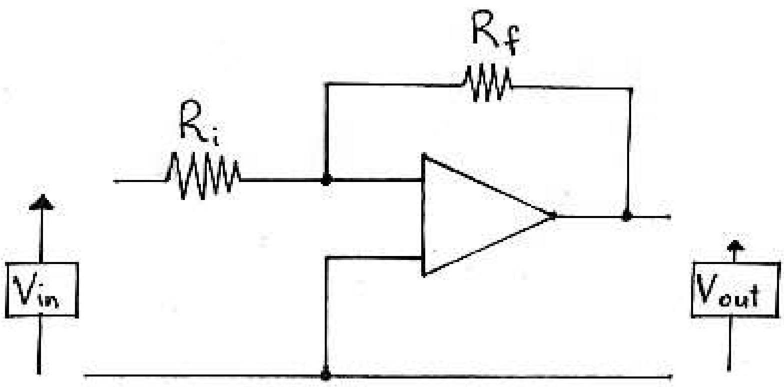
describe how an operational amplifier can be used as an inverting amplifier

- An inverting amplifier produces an output voltage that is the inverse of the input voltage (if the input is positive, the output is negative). To be an inverting amplifier, the feedback loop needs to be connected to the inverting input (as shown in the diagram below).



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explain that the gain of an inverting amplifier is given by: $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$

- In the circuit above, R = R*i*. This is the closed loop gain for the amplifier and the values of the two resistors are chosen to ensure that the output voltage keeps the IC within its linear operating region.

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discuss how feedback can be used in a control system

- Feedback is used to ensure that op amps remain stable and do what they are designed to do.

- Negative feedback can be provided (as shown above) by connecting a resistor between the output and inverting input. The choice of feedback resistor controls the gain of the amplifier so that it cant overload the next stage in the circuit and it will keep the amplifier within its linear operating range. Examples include:

    - amplifiers (usually designed to operate within a set range of frequencies, such as the audio spectrum or one of the range of radio frequencies used to transmit radio, television and mobile phone signals)
    - current to voltage converters as in a light detector circuit
    - summing amplifier to make an audio mixer or a digital-to-analogue converter (see below)
    - integrator
    - differentiator

- Positive feedback can be provided by connecting a resistor between the output and non-inverting output. Examples include:
    - voltage follower circuit to buffer logic circuits
    - oscillator circuits to make radio transmitters

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gather information to identify the different ways in which amplifiers are used in current technologies

- Consult your own sources to identify specific examples of technologies that use amplifers in the ways listed above. Feed the search terms *op amp amplifiers* and *uses* into an appropriate Internet search engine and identify the ways amplifiers are used in a range of current technologies.

- Record the results of your research in an appropriate way.

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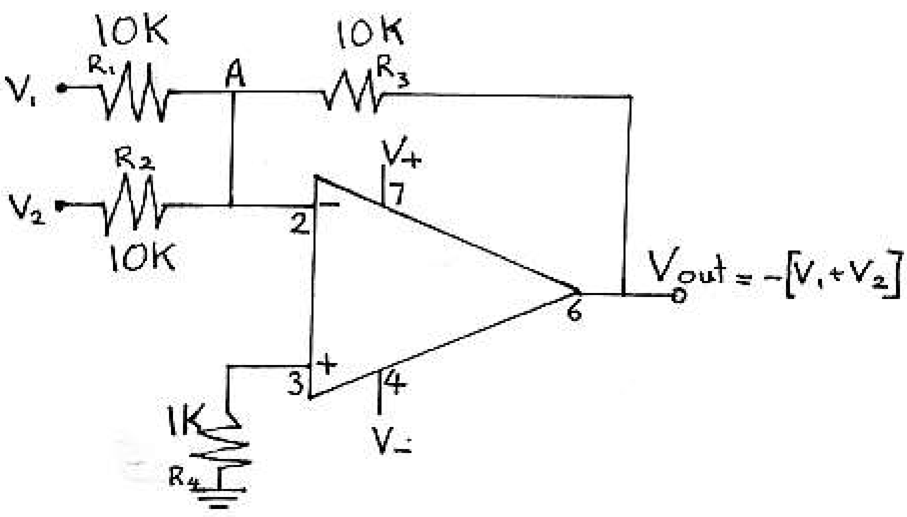
explain the use of two input resistors to produce a summing amplifier



- The input resistors are chosen to provide a combined input current that matches and cancels the current in the feedback resistor (at point A) thus preserving the first of the golden rules for ideal op amps using external feedback. (I = V / R)

  $V_1 / R_1 + V_2 / R_2 = - V_{out} / R_3$

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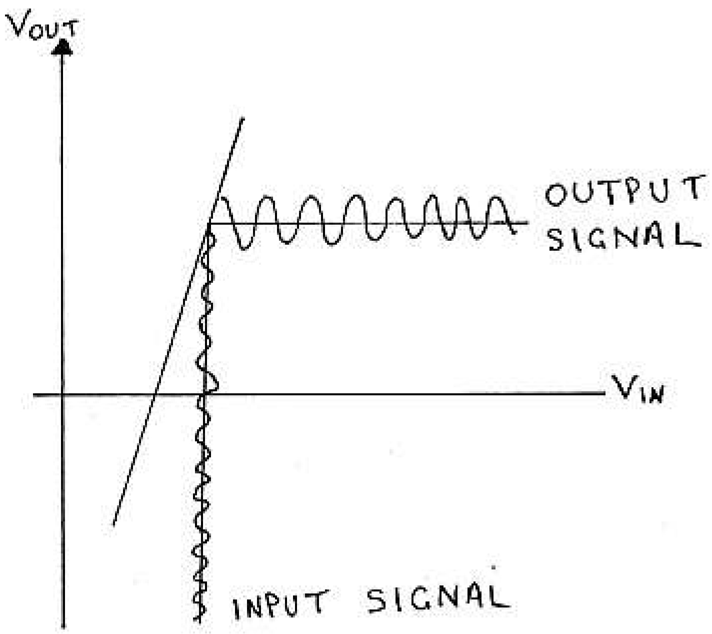
gather and present graphical information to show the transfer characteristics of an inverting amplifier

- The transfer characteristics of amplifiers are determined from data gathered by monitoring and recording data from operating amplifier circuits. The goal is to optimise the circuit performance so that the output signal is an exact copy of the input signal shape (ie the amplifier is operating in its linear region for the input and output voltages you want to use).
- Below is a graph showing the relationship between the output voltage of an inverting amplifier and its corresponding input signal when it is operating in its linear region.



- You might like to see if you can find data from manufacturers of op amps from which to construct graphs like that above.
- See notes related to the next two syllabus points

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solve problems and analyse to show the transfer characteristics of an amplifier

- See notes related to the next syllabus point

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solve problems and analyse information about setting the gain of an inverting amplifier by calculating the values of external resistors using: $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$

1. **Q 32 (c) parts (i), (ii) and (iii)** from the 2002 HSC Physics exam. Scroll down to p 37 (the last page)

Answer

2. **Q32 (d) part (i) and (ii)** from the 2003 HSC Physics exam. Scroll down to p 42.

Answer

3. **Q32 (d) parts (i), (ii) and (iii)** from the 2004 HSC Physics exam. Scroll down to p 38.

Answer

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perform a first-hand investigation of a summing amplifier by adding voltages from two separate sources

- You will need to do this first hand investigation but it is important that you discuss it with your teacher to make sure it is done properly and safely and that your school has the equipment needed.
- You could record your results in a table.

9.9 Option - The Age of Silicon: 7. Limits to current devices

Syllabus reference (October 2002 version)		
7.There are physics limits that may impact on the future uses of computers	*Students learn to*: • identify that the increased speed of computers has been accompanied by a decrease in size of circuit elements • explain that as circuit component size is decreasing, quantum effects become increasingly important	*Students*: • gather, process and analyse information and use available evidence to discuss the possibility that there may be a limit on the growth of computer power and this may require a reconceptualisation of the way computers are designed

[Edit: 9 Jul 09]

gather, process and analyse information and use available evidence to discuss the possibility that there may be a limit on the growth of computer power and this may require a reconceptualisation of the way computers are designed

- There is a physical limit to how small you can make a transistor before it fails as a binary switch (about 4 nm). Thus, making smaller and smaller transistors on silicon-based substrates will eventually hit this limitation. If we want faster, more powerful computers, other kinds of computers will need to be made.

- A good starting point is **Moore's law** from Wikipedia's free web-based encyclopedia.

  Moore's law (so called) provides a context for discussing the change in computing power or complexity. Gordon Moore (he worked for Intel and Intel make ICs) had an article published in Electronics Magazine, 19 April 1965 titled "Cramming more components onto integrated circuits". In that article he said:

  The complexity for minimum component costs has increased at a rate of roughly a factor of two per year ... Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000. I believe that such a large circuit can be built on a single wafer.

- The initial observation proved remarkably accurate and in 1975 he projected that the complexity would double every two years into the future. The original observation was dubbed "Moore's Law" by Caltech professor, Carver Mead. Since then a popular form of the law (complexity will double every eighteen months) has become the goal that IC and memory (hard disk and random access) manufacturers have set themselves.

- It is predicted that the limitation (4 nm) to the size of silicon-based transistors will be reached in less than twenty years. By then, it is predicted that new technology will be ready to replace silicon-based transistors and that Moore's Law will continue into the foreseeable future on the back of this new technology.

- Speculation based on information from Intel and AMD (two of the biggest chip manufacturers) has it that using nickel gates in their silicon-based transistors will allow smaller transistors to be made but they still be bigger than the 4 nm limit mentioned above. This is just a refinement on current technology. Gallium Arsenide is already replacing silicon, but transitors made on that substrate are not able to be made smaller than the 4 nm limit.

- The ABC's *News in Science* website carried a story (28 August 2000) about a **successful test of molecular-sized switches** that worked hundreds of times. This represents a first step toward the goal of molecular computers. This article reports on a chip using molecular switches **Densest IC ever made** Andre Kesteloot, **Amateur Radio Research and Development Corporation** Jan 27, 2007. Another possibility is to implant computer-technology into humans (cyborg technology). The combined power of the two may provide advantages to humans, but is it really the next generation of computers or another way of using what we already have?

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identify that the increased speed of computers has been accompanied by a decrease in size of circuit elements

- The increase in speed since the first personal computers (PCs) generally appeared (1980s) is due to the increased sophistication of manufacturing processes making silicon based ICs. These processes have allowed the switching transistors to be reduced in size and placed closer together on the silicon substrate.

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explain that as circuit component size is decreasing, quantum effects become increasingly important

- This dot point is covered by the video clip of Playing Pool with Electronics Dr Adam Micolich, University of NSW. Dr Micolich presented this talk as part of the Tall Poppies program in partnership with DET, NSW and the Tall Poppy Campaign.