Design and Technology

Year 12 Engineering Studies

ATAR Units 3 and 4

2018

MECHATRONICS

Booklet 3: Systems and control

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Teachers: Mr Čečins and Mr Tilley

1. Systems and control diagrams

Introduction

The descriptions for this section of study are largely, but not solely, based on the revised teacher's notes for **Standard Grade Technological Studies**: Introduction to Systems as used by schools in Scotland. The concepts are the same as for the **Engineering Studies** syllabus but some of the terminology is different.

Mechatronic devices and other engineered products and processes are often complex and difficult to describe to a third party without becoming too technical. One way of dealing with this problem is to use a systems approach where the concepts are presented as diagrams that communicate how the various aspects of the design are related to each other and integrated into a functioning whole. This also allows the designer to focus on the 'big picture'. This is sometimes referred to as a 'top-down' approach. The engineer can then apply specialist knowledge to sort out the details!

Universal system block diagram

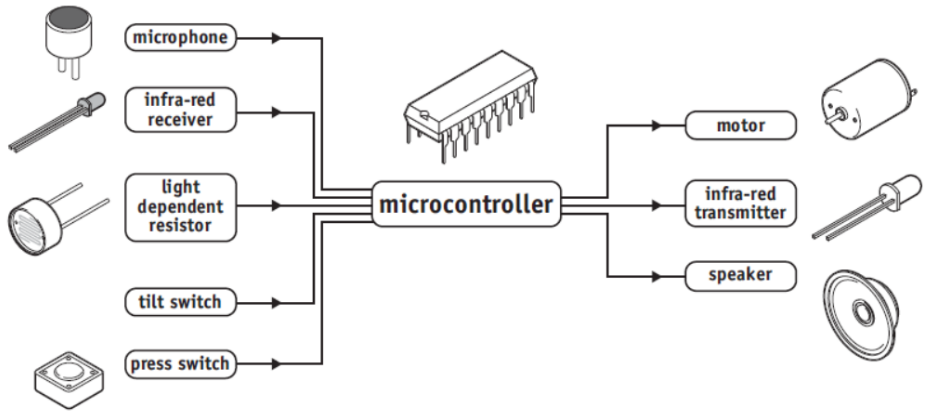
Block diagrams use a top-down approach to break down or analyse technology. All systems can be analysed in terms of input, process and output. A diagram called the universal system block diagram is the simplest form and consists of these three basic elements.

For example, the purpose of a kettle is to take cold water (input), heat it (process) and produce hot water (output), thus the universal block diagram becomes:

Thinking a little further, it becomes obvious that there may be more inputs required for the process to be undertaken and there may also be more outputs – desirable or not:

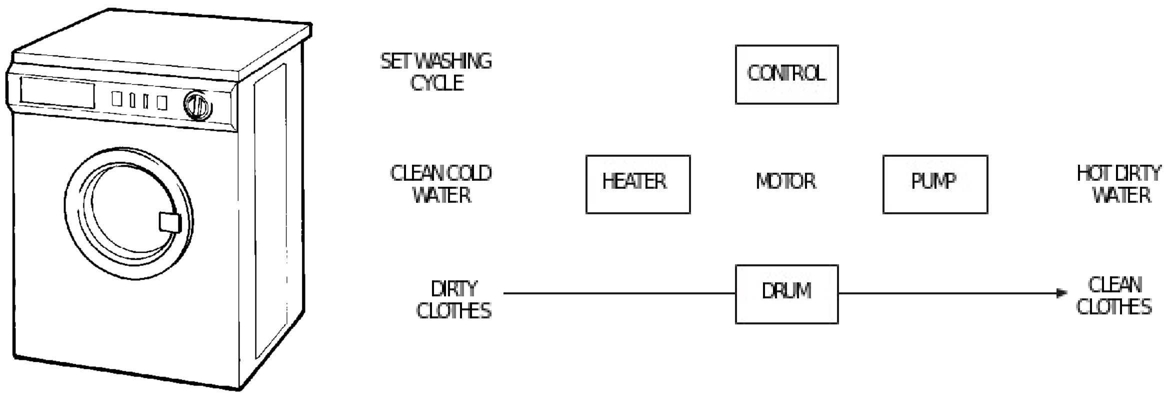
In Year 11 the marble machine could have been conceptualised as follows:

Illustrated below is a pictorial form of a universal system block diagram for specifying inputs and outputs to be connected to a microcontroller.



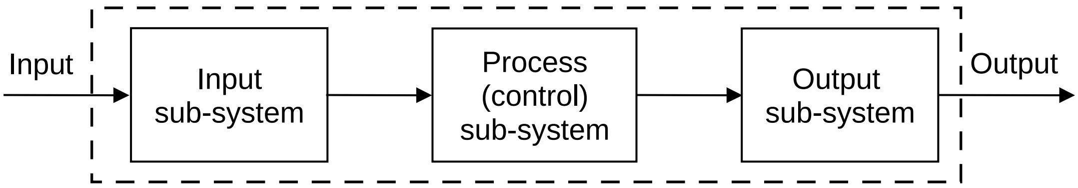
Sub-system diagram

The next step after developing a universal system block diagram would be to analyse the problem in greater detail and produce a *sub-systems diagram,* like that illustrated below for a washing machine. This communicates essential details that are still easily understood by both the expert and lay person alike.

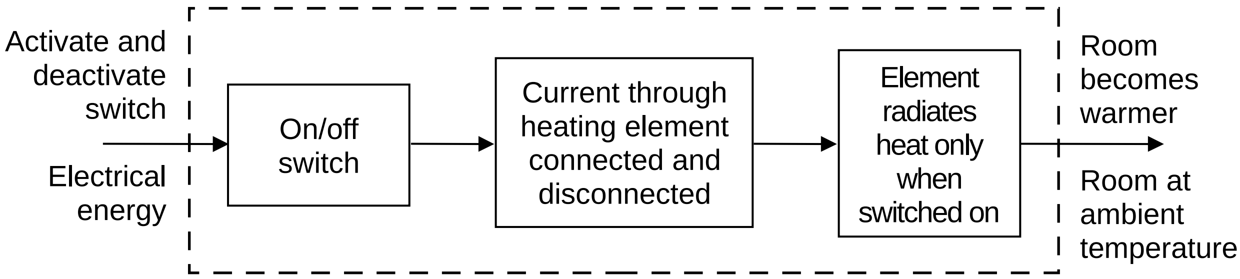


Open-loop control system

This form of diagram analyses the required system in even greater detail. The **input** and **output** are external to the functional elements of the system. These sub-systems are enclosed within the systems boundary. The latter is shown as a dashed box. An open loop system connects its blocks in a **linear** manner and the actual condition of the output has no influence on the process.

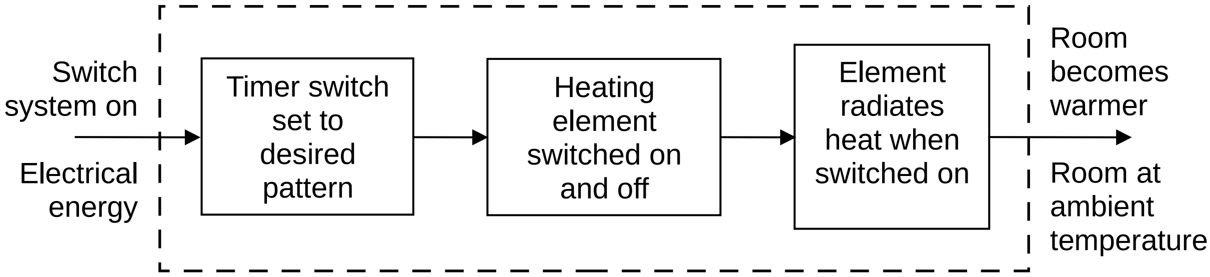


Using an electric heater as the example –



The above system is classified as a **manual open-loop control system** i.e. if a person activates or deactivates the system and leaves the room then the heating element remains on or off and regulation of the room temperature is likely to be very inaccurate.

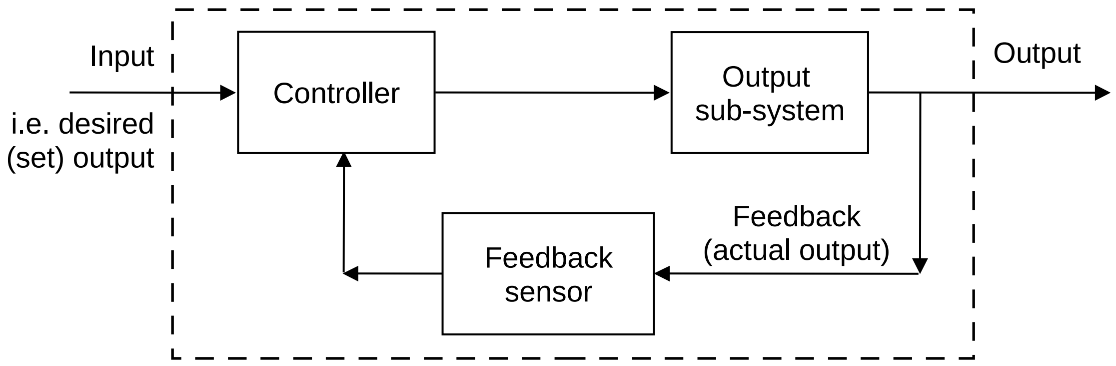
Suppose a timer is added to the system –



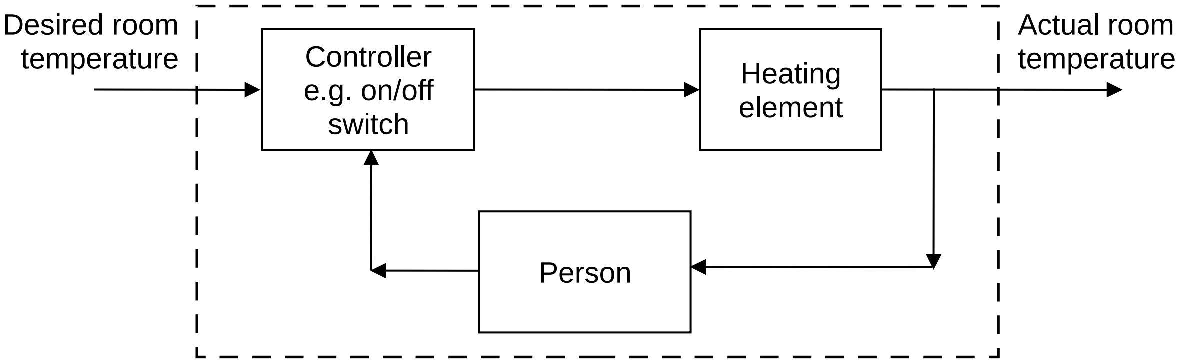
The above system is classified as an **automatic open-loop control system** i.e. a person **is not** required to be present to control the heating element. Although this does not require the direct intervention of a person the regulation of room temperature is likely to be an approximation at best and the heating element may be on when it should be off and vice-versa.

Closed-loop control system

The simplest form of this system consists of a controller that has two inputs (the desired or set output and the actual output), an output subsystem and a feedback loop that includes a feedback sensor. The significant difference between an open-loop and a closed-loop system is that the latter uses the **feedback loop** to continually correct any error between the desired (set) output and the actual output. Open loop systems do not incorporate a feedback loop.

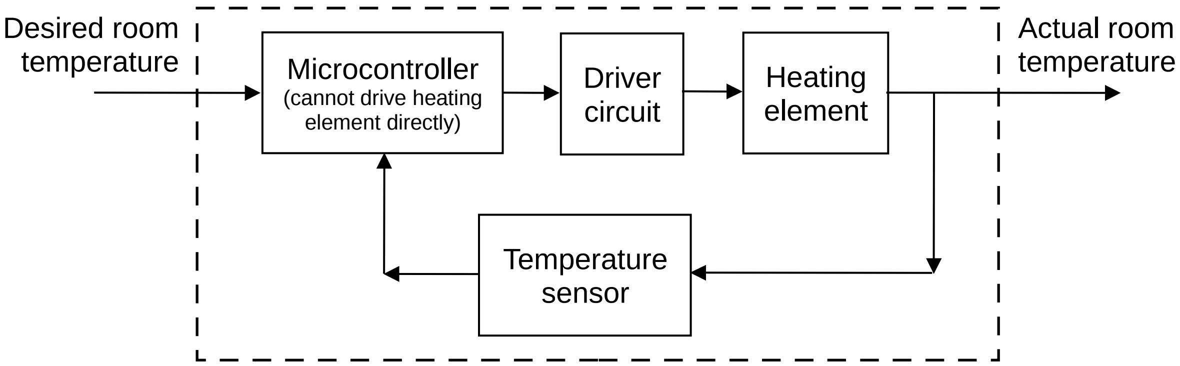


Returning to the electric room heater example. Suppose a person remains in the room -



This is an example of a **manual closed-loop control system**.

Suppose a temperature sensor takes the place of the person -

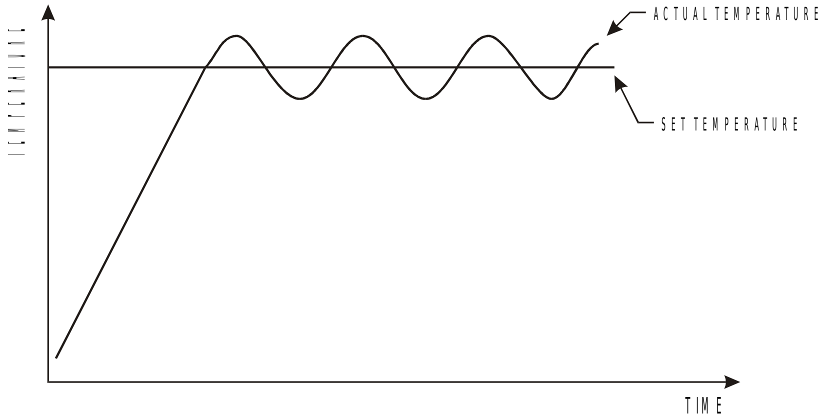


This is an example of an **automatic closed-loop control system**

Negative and Positive Feedback

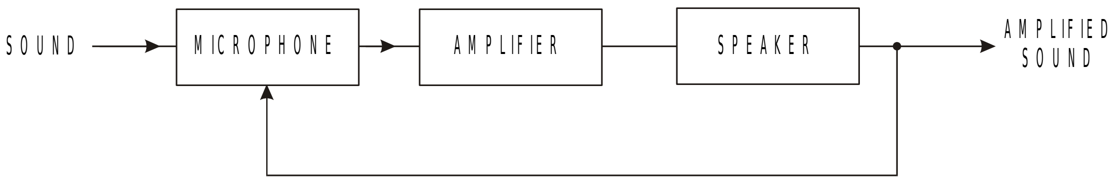
(Notes sourced from Technological Studies, Systems and Control, Students' Notes, Intermediate 2 1999, pages 17-18)

The purpose of closed loop control is to ensure that the output is maintained, as closely as possible, to the desired output level. In the case of an air conditioning system, a graph of the temperature in a room might appear as in the graph below.

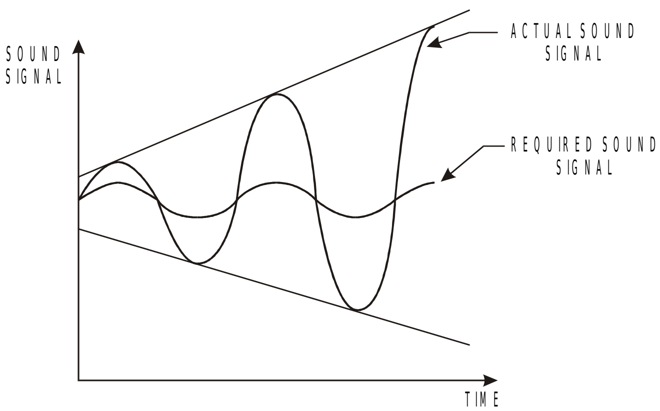


As can be seen from the graph, the control system is constantly trying to pull the temperature of the room back towards the set temperature level by reducing the error. This type of control uses **negative feedback** to reduce the error.

The opposite effect can be created by reinforcing the error, as can sometimes happen with public address systems when the microphone is held too close to the speakers.



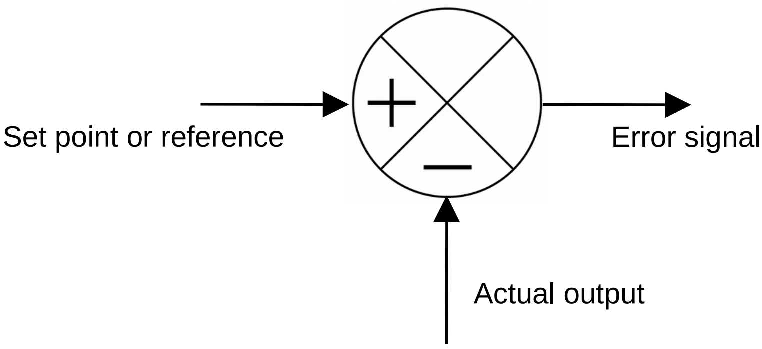
A sound is picked up by the microphone, amplified, and then output through the speaker. The amplified sound is then picked up, re-amplified and so on. The net result is a high pitch sound, which can be represented by the graph below.



This is an example of **positive feedback**. Although positive feedback does have some useful applications, negative feedback is far more widely used in control systems.

Control system: Error detection

Diagrams of sophisticated closed-loop control systems often incorporate an error detection symbol that utilize negative feedback in a more complex and subtle manner than the examples described previously. The error detector symbol is shown below.



Inside the error detector the actual value is subtracted from the set value and the resultant value is the error signal. The error signal changes the state of the input device in a way that tends to reduce the error.

The operating conditions of the error detector are summarised below.

Actual value Set value	Error signal	Input change
$V_a = V_s$	nil	none
$V_a < V_s$	+ve	increase
$V_a > V_s$	-ve	decrease

In a manual closed-loop control systems the brain is the error detector.

In automatic closed-loop control systems the error detection is usually performed electronically.

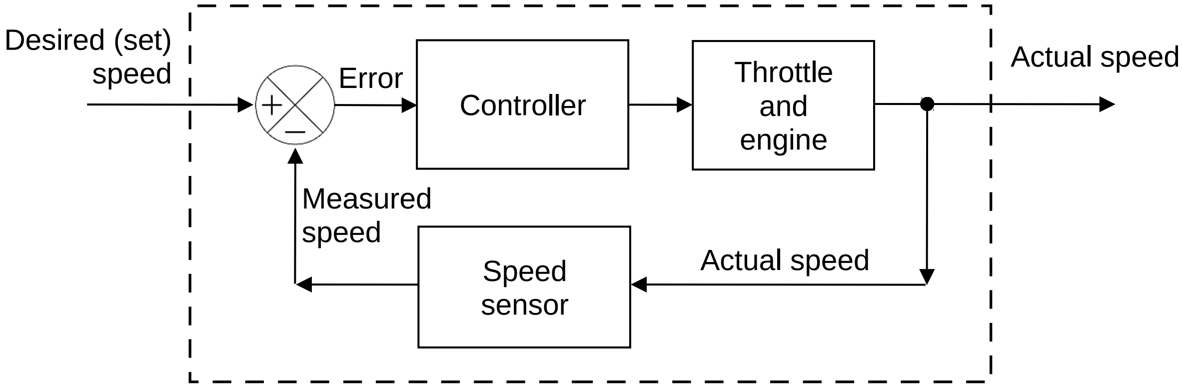
The following notes are sourced from Wikipedia:

‘An example of a control system is a car's cruise control, which is a device designed to maintain vehicle speed at a constant *desired* or *reference* speed provided by the driver. The *controller* is the cruise control, the *plant* is the car, and the *system* is the car and the cruise control. The system output is the car's speed, and the control itself is the engine's throttle position which determines how much power the engine delivers.

A primitive way to implement cruise control is simply to lock the throttle position when the driver engages cruise control. However, if the cruise control is engaged on a stretch of flat road, then the car will travel slower going uphill and faster when going downhill. This type of controller is called an *open-loop controller* because there is no feedback; no measurement of the system output (the car's speed) is used to alter the control (the throttle position.) As a result, the controller cannot compensate for changes acting on the car, like a change in the slope of the road.

In a *closed-loop control system*, data from a sensor monitoring the car's speed (the system output) enters a controller which continuously subtracts the quantity representing the speed from the reference quantity representing the desired speed. The difference, called the error, determines the throttle position (the control). The result is to match the car's speed to the reference speed (maintain the desired system output). Now, when the car goes uphill, the difference between the input (the sensed speed) and the reference continuously determines the throttle position. As the sensed speed drops below the reference, the difference increases, the throttle opens, and engine power increases, speeding up the vehicle. In this way, the controller dynamically counteracts changes to the car's speed. The central idea of these control systems is the *feedback loop*, the controller affects the system output, which in turn is measured and fed back to the controller.'

The system described above can be represented by the following **closed-loop control diagram**.



Revision questions

1. Classify the following as either open or closed loop systems. Circle your answer:

Timer based clothes drier	Open loop	Closed loop
Electric toaster	Open loop	Closed loop
Microwave oven	Open loop	Closed loop
Volume of radio	Open loop	Closed loop
Water level controller	Open loop	Closed loop
Engine cooling system	Open loop	Closed loop
Air conditioner	Open loop	Closed loop

2. Using an example, explain the difference between an open-loop and a closed-loop control system.

3. Using an example, explain the purpose of negative feedback in a closed-loop control system.

Study questions

(a) State three examples of open-loop control. Draw and label a block diagram for each one that includes its sub-systems and system boundary.

(b) State three examples of closed-loop control. Draw and label a block diagram that includes its sub-systems, feedback loop and system boundary.

(c) Draw a block diagram for a fridge with a thermostat, control unit, coolant pump, door switch and light.

More questions

WACE 2010 question 26 (a).

WACE 2013 multiple-choice question 20 and questions 25 (a) and 27 (d).

WACE 2014 multiple-choice question 16 and question 26 (a).

WACE 2015 multiple-choice question 16 and question 27 (a).

WACE 2016 question 46 (b)(i) and (b)(ii).

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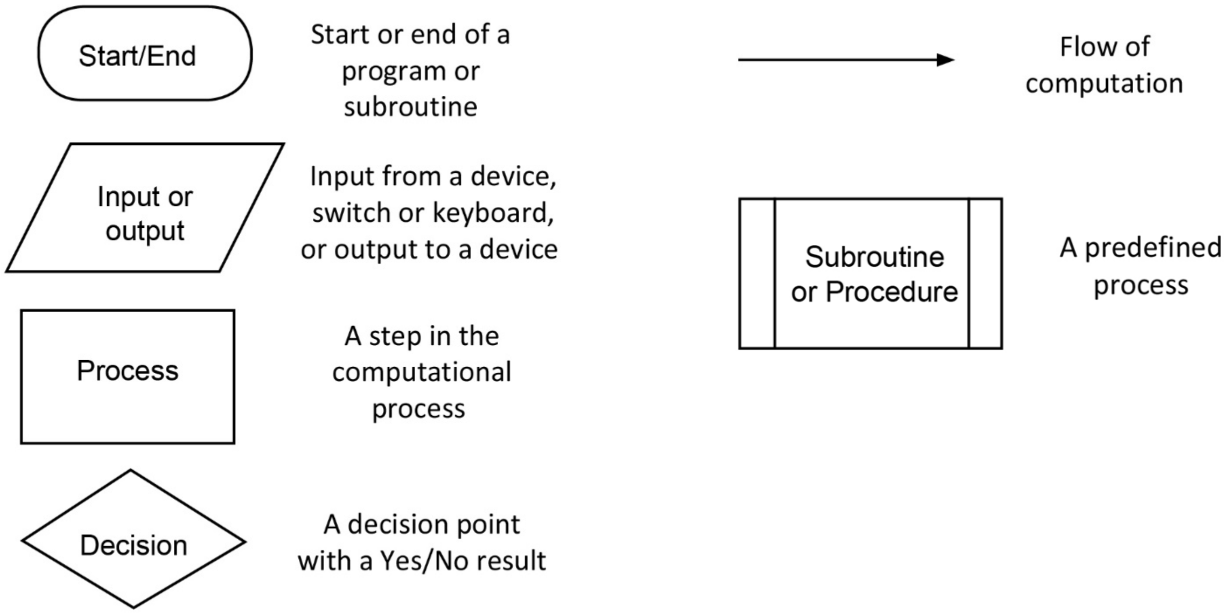
2. Flow charts

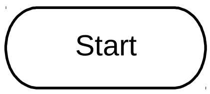
Flow chart symbols



1. A flow chart is required for a system that controls 2 (two) LEDs i.e. LED_{GREEN} and LED_{RED}. The specifications for the system are as follows:

   a. Immediately after starting, the two LEDs are off.
   b. Two switches are checked continuously and if neither is activated then the LEDs remain off.
   c. If the first switch, SW_1, is pressed then it turns LED_{GREEN} on. LED_{GREEN} will remain on only whilst SW_1 is being pressed. Once SW_1 is released then LED_{GREEN} will turn off and will remain off until SW_1 is pressed again.
   d. If the second switch, SW_2, is pressed then it turns LED_{RED} on. LED_{RED} will remain on only whilst SW_2 is being pressed. Once SW_2 is released then LED_{RED} will turn off and will remain off until SW_2 is pressed again.
   e. Only one LED at a time can be activated e.g. if SW_1 is being pressed then LED_{GREEN} will glow. If SW_2 is now pressed whilst SW_1 is still activated then LED_{GREEN} remains on and LED_{RED} cannot turn on until SW_1 is released.

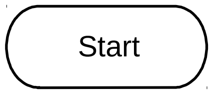
   Complete a drawing of the flow sheet in the space below. Label clearly the names of the commands and all Yes/No decisions. Use arrowed lines to show the flow of data. Standard symbols are given in the Data sheets.



2. An automated boom gate is illustrated below.

On the next page sketch a flow chart that could be used to control the boom gate such that:

a. The boom starts and finishes its cycle in the down position as shown in the picture.
b. In the down position the boom is pressing on a limit switch. The name of this switch is LIMIT DOWN. This causes the motor to be switched off i.e. MOTOR OFF.
d. A decision labelled UP must give a YES for the motor (i.e. MOTOR UP) to cause the boom to rise.
d. The boom will continue to rise until it contacts another limit switch i.e. LIMIT UP. This will cause the motor to switch off (i.e. MOTOR OFF) leaving the boom in its maximum upwards position.
e. After a time delay of 5 seconds the boom will begin to lower (MOTOR DOWN) until it contacts LIMIT DOWN.
f. The cycle is ready to begin again.


Start

More questions

WACE 2010 Multiple-choice question 24 and question 25 (c).

WACE 2011 question 25 (b).

WACE 2012 question 25 (e)* and 27 (d).

* This is an interesting problem but probably outside the intended scope of the syllabus

WACE 2013 question 24 (e).

WACE 2014 question 27 (b).

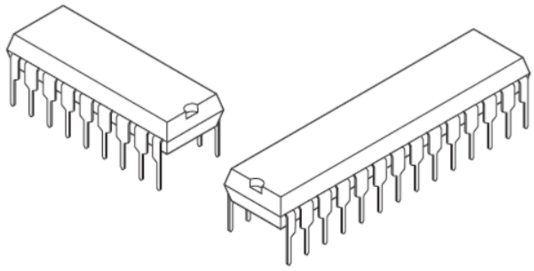
WACE 2015 question 24 (b) and question 27 (b).

WACE 2016 question 46 (a).

WACE 2017 question 43 (b).

3. Microcontroller

A microcontroller is a single integrated circuit that incorporates many of the features of a microprocessor that are normally separate integrated circuits. This means that a microcontroller is not as powerful as a microprocessor but this limitation does not exclude it from being used to control a huge range of automated devices. These include household appliances, security systems, cars, medical equipment and communication devices to name just a few.



Advantages of using microcontrollers

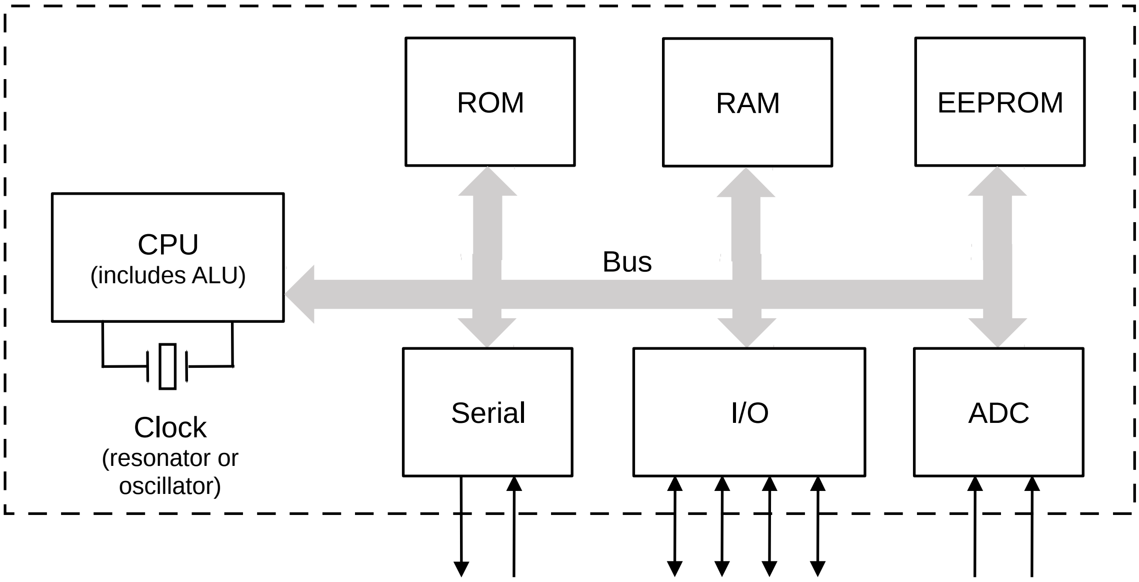
- Can replace several separate parts and/or a complex electronic circuit.
- More reliable and easier to trouble shoot due to having fewer parts.
- Simplifies assembly of the product in which it is incorporated and requires less space.
- Can be adapted for new operating parameters by changing the control program without having to change the electronic hardware.

Disadvantages of using microcontrollers

- Cannot directly drive high power devices

Operation of control sequences can be adversely affected by electrical ‘noise’

Architecture



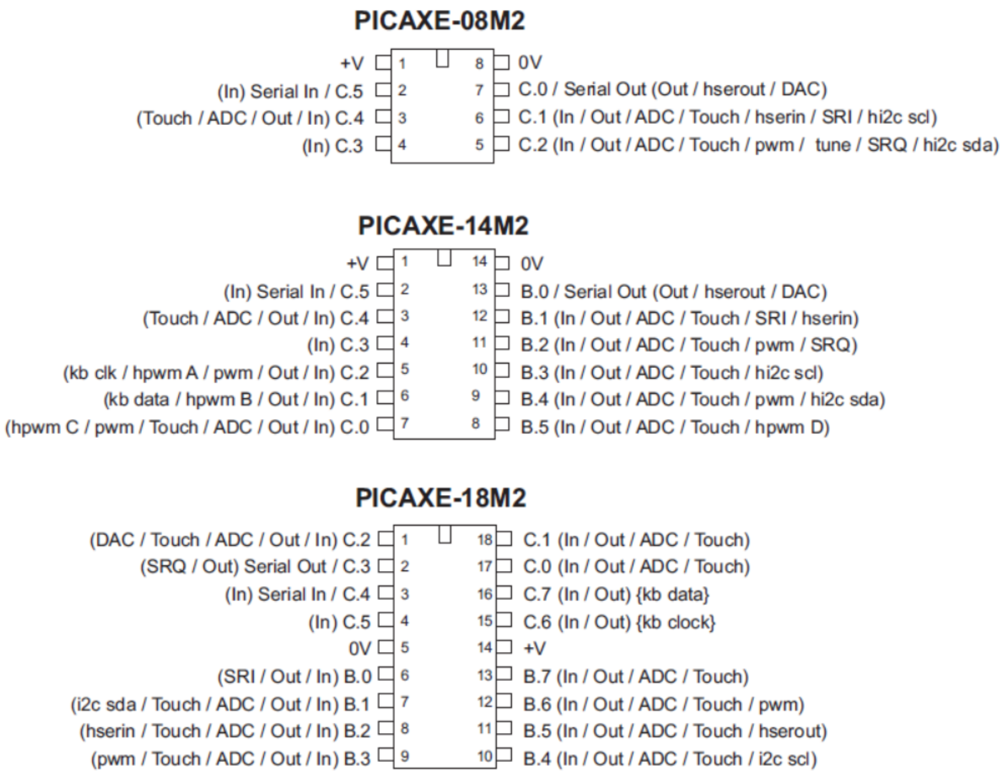
CPU	Central processing unit. The hardware within the microcontroller that carries out the instructions that have been written in a control programme. Incorporated in the CPU is the arithmetic logic unit (ALU) which performs mathematical and logic operations and the control unit (CU), which extracts instructions from memory which it decodes and executes.
ALU	Arithmetic logic unit. As mentioned above, this performs mathematical and logic operations.
ROM	Read only memory. Memory that can only be read from and is programmed only once.
RAM	Random access memory. Memory that can be accessed as required. Data is not held when power to the microcontroller is turned off.
EEPROM	Electronically erasable programmable read only memory. This type of memory can be programmed with data and read back. It is stored even if power is turned off. EEPROM makes up most of the memory used by a microcontroller.
I/O	Input/output port.
Serial	Serial input and output port.
ADC	Analogue to digital converter. Analogue sensors provide a signal in the form of varying voltages, usually in the range 0 – 5 V. The ADC converts this input voltage into 8 or 10 bit data depending on the microcontroller. The former will provide a resolution of 255 steps between the minimum and maximum voltage that is able to be detected at the analogue port. The latter is much more accurate and provides 1024 steps.
CLOCK	A resonator, sometimes incorporated in the microcontroller and sometimes fitted as an external component, is used to determine the speed at which information is processed. Typically this is at a frequency of 4 MHz or more.
Bus	Information is carried between the various blocks of the microcontroller along 'groups' of wires called **buses**. The 'data bus' carries the 8-bit data

between the ALU and RAM / Input-Output registers, and the 'program bus' carries the 13-bit program instructions from the ROM.

The size of the data bus provides a description for the microcontroller. Therefore an '8 bit microcontroller' has a data bus '8-bits' wide. Microcontrollers with 16-bit and 32-bit data buses are also available.

Pin-outs

In order to correctly connect a microcontroller to its power supply and peripheral systems it is necessary to know its pin-outs. The following pin-out diagrams are for 8, 14 and 18 pin PICAXE microcontrollers. These are commonly used by many schools but there are other systems that may also be used e.g. Audino. Nevertheless, the concept of what constitutes a pin-out diagram remains the same.



Power connection

When microcontrollers were first introduced into high school courses of study it was generally accepted that the supply voltage for these chips needed to be 5 V or very close to it. Newer generation microcontrollers like those used nowadays are designed to be more flexible in how these are powered e.g. The PICAXE 08M2 microcontroller can operate on 2.3 – 5.5 V and the 14M2 and 18M2 microcontrollers use the range 1.8 - 5.5 V.

Assuming that the microcontroller being used is a PICAXE or similar then the following power supplies are recommended -

3 V	2 × AA cell battery or 1 × lithium coin cell
4.5 V	3 × AA cell battery
5 V	7 – 12 V PSU with 7805 voltage regulator
≈ 5.4 V	4 × AA cell battery with a series diode

More questions

WACE 2011 multiple-choice question 16 and question 27 (d).

WACE 2012 multiple-choice question 17.

WACE 2015 multiple-choice question 15 24 (b) and question 27 (b).

WACE 2016 multiple-choice question 40.

WACE 2017 question 44 (a) and (b); and question 45 (b).

4. Interfacing circuits

Inputs

Microcontrollers can detect many different forms of input. These include digital and analogue inputs.

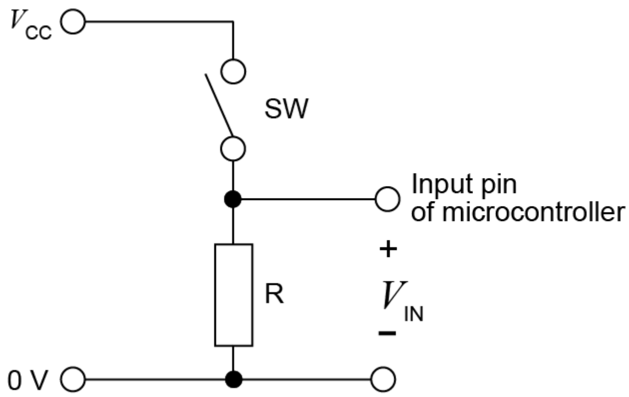
Digital

A digital input has two discrete states. These are commonly described as **0** or **1**, **high** or **low** and **off** or **on**. Essentially this means that the input pin detects 0 V (0 or low or off) or 5 V (1 or high or on). The reference to 5 V can vary depending on the microcontroller being used as there are low voltage versions and so it is more accurate to say that that the high state is the maximum operational voltage supplied to the microcontroller.

Note: In practice, high = 80% or more of V_{CC} and low = 20% or less of V_{CC}.

Normally low (tie down resistor)

This arrangement causes the input pin to detect a low input signal when a switch is open and a high input signal when the switch is closed.



For the questions that follow V_{CC} = 5 V, R = 10 kΩ and R_{SW} = 0 Ω for an ideal switch.

1. Using calculations demonstrate that V_{IN} = 0 V when the switch is open.

____

____

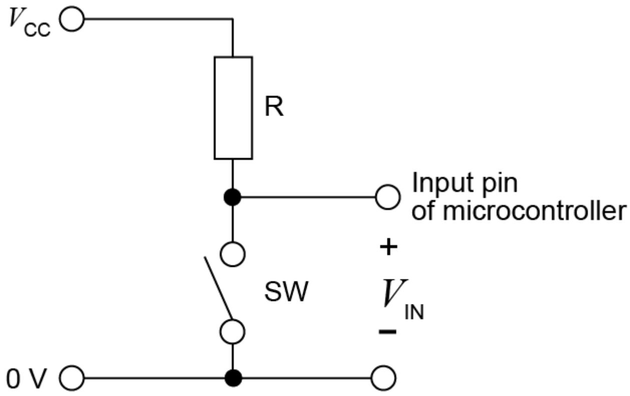
____

2. Using calculations demonstrate that V_{IN} = 5 V when the switch is closed.

____

Normally high (pull up resistor)

This arrangement causes the input pin to detect a high input signal when a switch is open and a low input signal when the switch is closed.



For the questions that follow V_{CC} = 5 V, R = 4k7 Ω and R_{SW} = 0 Ω for an ideal switch.

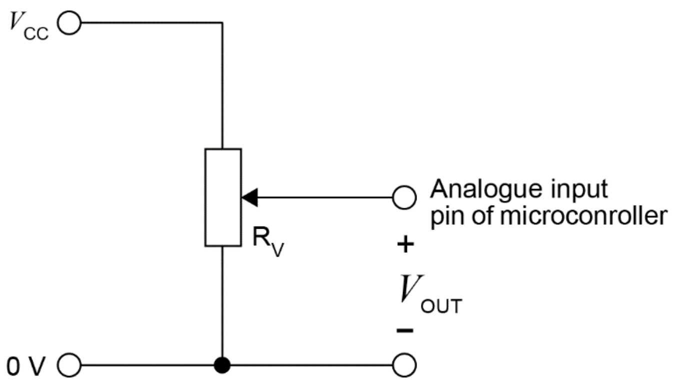
3. Using calculations demonstrate that V_{IN} = 5 V when the switch is open.

4. Using calculations demonstrate that V_{IN} = 0 V when the switch is closed.

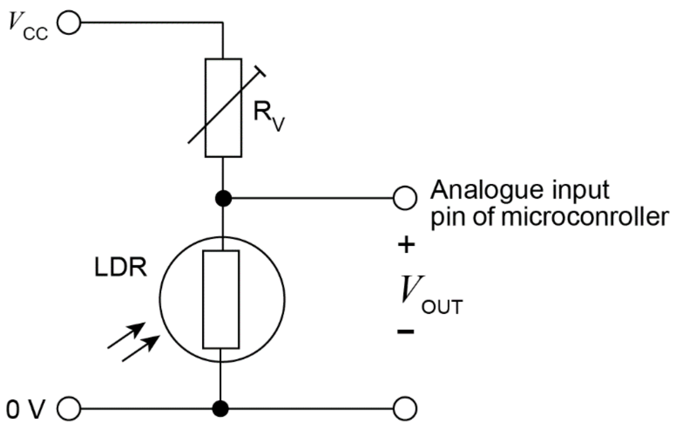
Analogue inputs

An analogue input can produce a signal anywhere between the minimum and maximum operational voltage being supplied to the microcontroller. This voltage is converted to a value on a scale using a feature on the microcontroller's internal circuitry known as and Analogue to Digital Converter (ADC). This will be discussed a little later.

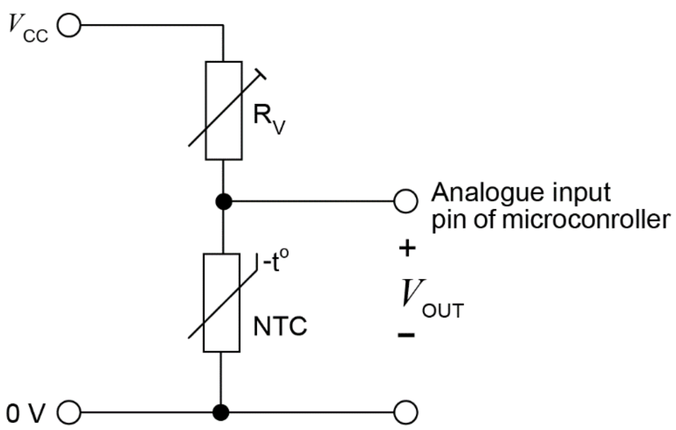
What follows are three common interfacing circuits that can be connected to an analogue pin of a microcontroller.



The spindle of a potentiometer can be linked to a rotating mechanism such that it also rotates. The resulting changes in output voltage can be used for detecting the position of the mechanism. This could be used to control the movement of a robotic arm or the opening and closing of windows.



A light detecting sensor can easily be made from a variable resistor and a light dependent resistor (LDR). The circuit as shown would increase its output voltage with a decrease in the level of light and vice versa. The opposite effect could be achieved by swapping the positions of the variable resistor and the LDR.



A temperature sensing circuit can be made from a variable resistor and a NTC thermistor. The circuit as shown would decrease its output voltage with an increase in temperature and vice versa. Again, the opposite effect could be achieved by swapping the positions of two components.

Analogue to digital conversion (ADC)

The output voltage of an analogue sensor of the type described earlier can be calculated using the voltage divider formula i.e.

$$V_O = V_{CC} \times \frac{R2}{R1 + R2}$$

However, a control strategy requires a digitized value and this can be achieved through a feature in the internal circuitry of a microcontroller known as analogue to digital conversion, ADC. Depending on the microcontroller, the ADC will convert the output voltage on either an 8-bit or 10-bit scale.

An 8-bit scale assigns an output of 0 V a value of 0 and the maximum output voltage a value of 255. The maximum output voltage can typically range from 1.8 – 5.5 V depending on the power supply and specific type of microcontroller. For the purposes of the descriptions that follow it will be assumed that the supply voltage is 5 V.

Here is how the scale works. Notice that it uses binary counting.

Bit	8	7	6	5	4	3	2	1
Low	0	0	0	0	0	0	0	0
High	128	64	32	16	8	4	2	1
2^n	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0

From the above table, if all bits are set low (00000000) then the sum of the values will be 0 and as mentioned before this will equate to 0 V. If all the bits are set high (11111111) then the sum of the values will be 255 and this equates to 5 V. It is possible to combine the highs and lows for each bit to create 256 values i.e. 2^8. These will range from 0 – 255 with the highest value being 2^{n-1}.

The ADC feature of a microcontroller will automatically make the calculation which can be represented mathematically as follows:

$$\text{8-bit value} = 255 \times \frac{VO}{VCC}$$ Round to nearest whole number

5. Using calculations demonstrate that if V_O = 3.7 V then the 8-bit value will be 189.

A 10-bit scale also assigns an output of 0 V a value of 0 but the maximum output voltage is now given a value of 1023. Again, the maximum output voltage can typically range from 1.8 – 5.5 V depending on the power supply and specific type of microcontroller. For the descriptions that follow it will be assumed that the supply voltage is 5 V.

Here is how the scale works. Notice that it continues to use binary counting.

Bit	10	9	8	7	6	5	4	3	2	1
Low	0	0	0	0	0	0	0	0	0	0
High	512	256	128	64	32	16	8	4	2	1
2^n	2^9	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0

From the above table, if all bits are set low (0000000000) then the sum of the values will be 0 and as mentioned before this will equate to 0 V. If all the bits are set high (1111111111) then the sum of the values will be 1023 and this equates to 5 V. It is possible to combine the highs and lows for each bit to create 1024 values i.e. 2^{10}. These will range from 0 – 1023 with the highest value being 2^{n-1}.

The ADC feature of a microcontroller will automatically make the calculation which can be represented mathematically as follows:

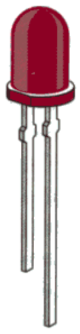
$$\text{10-bit value} = 1023 \times \frac{V\text{O}}{V\text{CC}} \qquad \text{Round to nearest whole number}$$

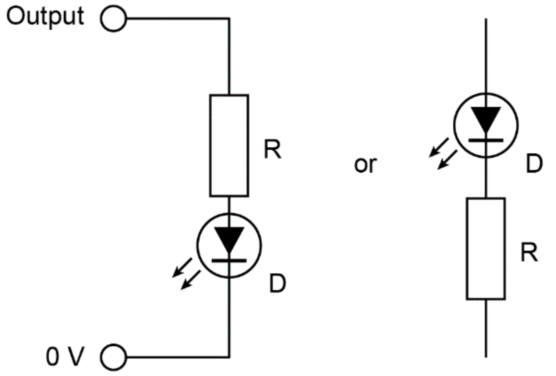
6. Using calculations demonstrate that if V_O = 1.8 V then the 10-bit value will be 368.

Outputs

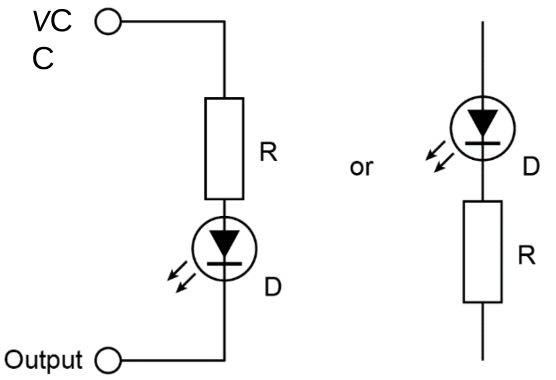
The digital output pins of a microcontroller generally cannot source or sink currents large currents. For example, the maximum current that the output pins of PICAXE ‘chips’ are able to deliver is 20 mA. This is sufficient for outputs like most LEDs and a piezo sounder but for many of the other outputs that usually need to be controlled it is not enough. For outputs that require high currents it is normal practice to use the microcontroller’s digital outputs as a signal to trigger some form of driver circuit.

LED





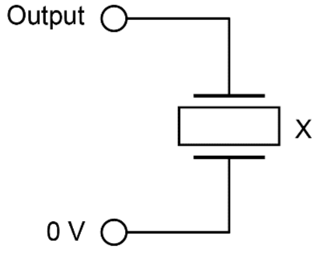
LED off when output is low and turns on when output goes high. Output pin is source of current.



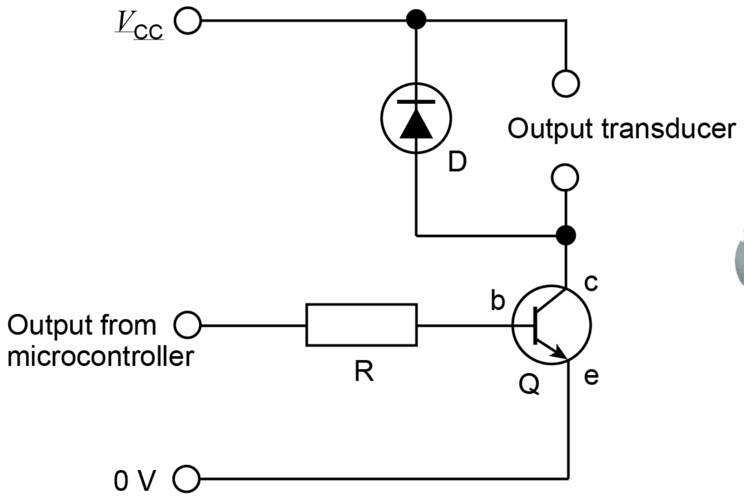
LED is on when output is low and turns off when output goes high. Output pin is sinking the current.

A 330 Ω resistor is recommended to limit current through the LED.

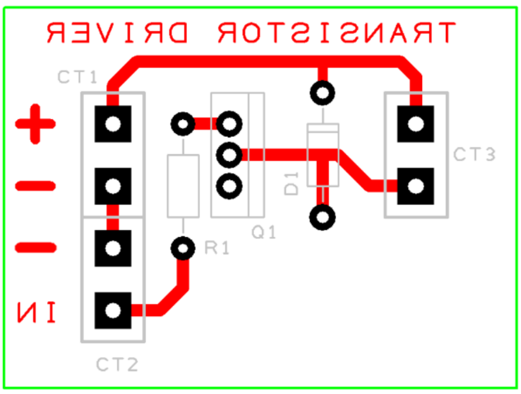
Piezo sounder



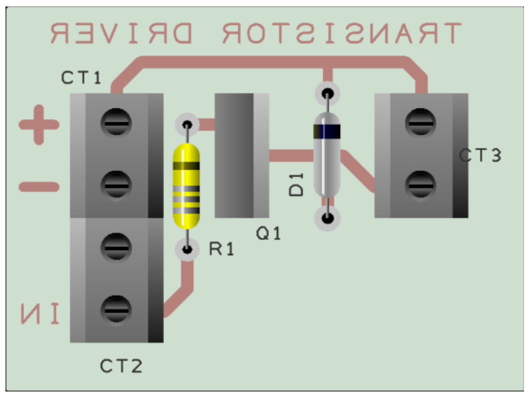
Transistor driver



The diode has been included to deal with back e.m.f. that would result if inductors are used as the output. Inductors are output transducers that use coils e.g. electromagnets, motors, solenoids and relays.



Mask with component outline



Component overlay

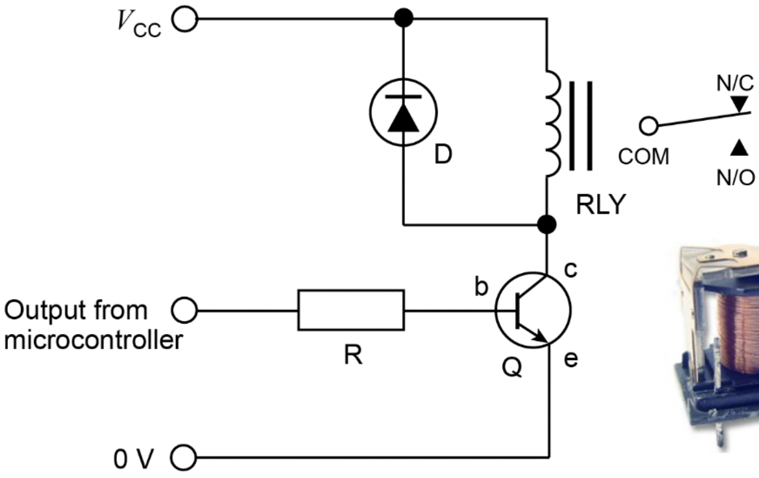
+ and **–** are the power supply required by the output.

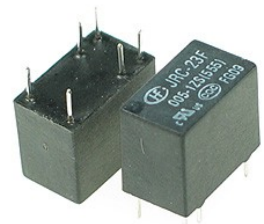
An extra **–** connection has been included for making a common 0 V rail with the microcontroller.

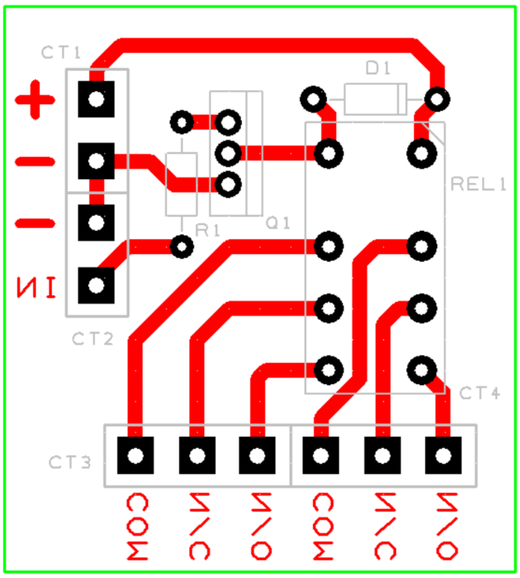
IN is connected to an output from the microcontroller.

Code	**Name**
CT$_1$ - CT$_3$	2 way connectors
R$_1$	1 kΩ resistor
Q$_1$	TIP 31C transistor or similar
D$_1$	1N4001 diode or similar

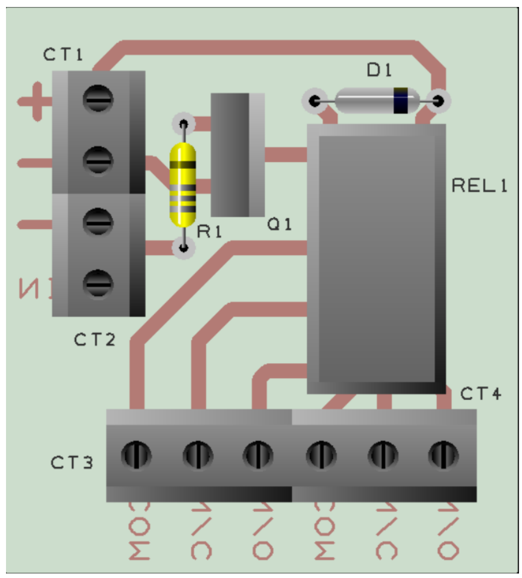
Relay







Mask with component outline



Component overlay

+ and **–** are the power supply required to operate the relay coil.

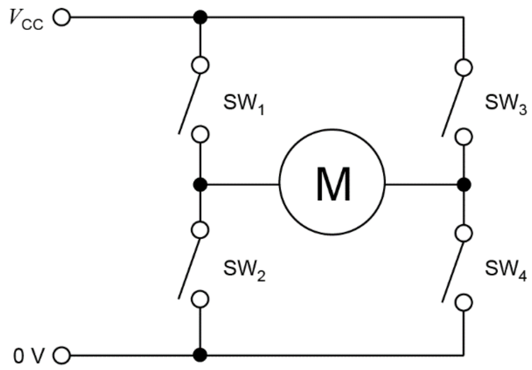
An extra **–** connection has been included for making a common 0 V rail with the microcontroller.

IN is connected to an output from the microcontroller.

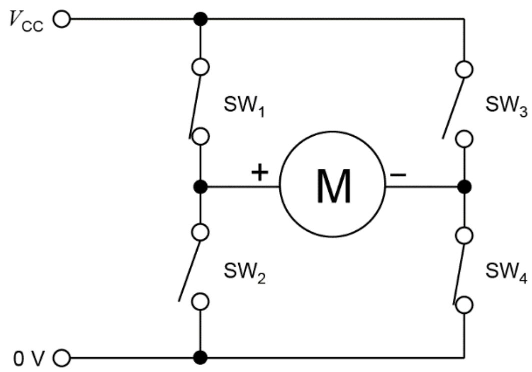
Code	**Name**
CT$_1$, CT$_2$	2 way connectors
CT$_3$, CT$_4$	3 way connectors
R$_1$	1 kΩ resistor
Q$_1$	TIP 31C transistor or similar
D$_1$	1N4001 diode or similar
RLY$_1$	DPDT relay

H-bridge

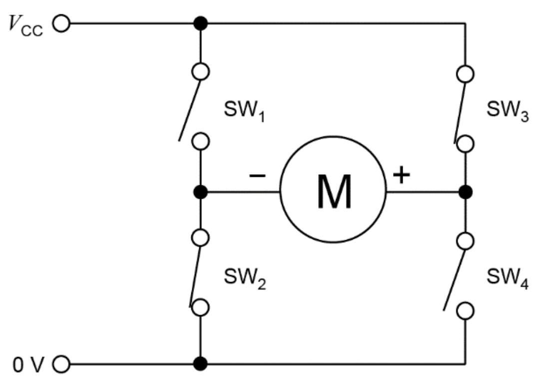
Bidirectional control of an electric motor is a common technique used in mechatronics. It involves using a system where the polarity of the connections to an electric motor can be reversed. In its simplest for it can be achieved using an electrical circuit. Examine the circuit diagrams that follow.



All switches open and motor is stopped.

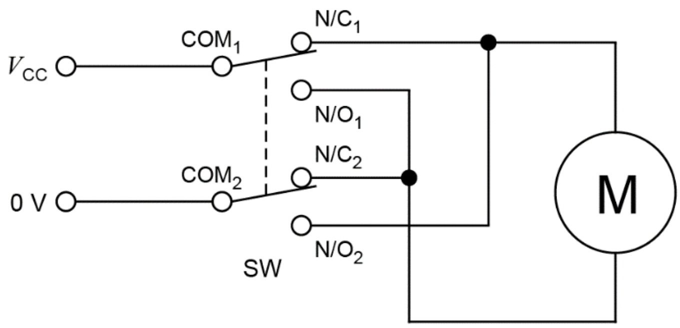


SW_1 and SW_4 closed. Motor is positive on left connection and negative on right connection.

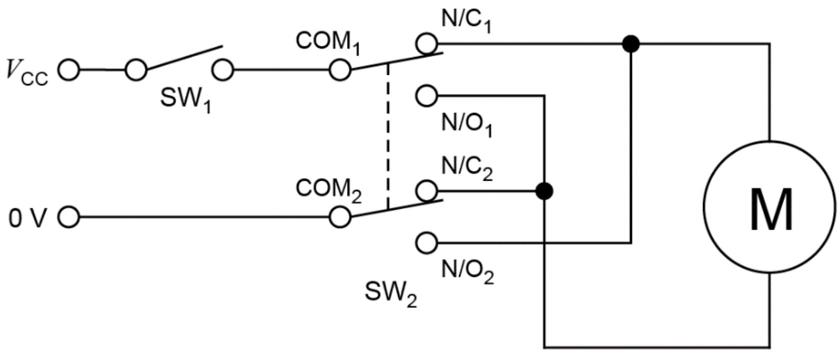


SW_3 and SW_2 closed. Motor is negative on left connection and positive on right connection.

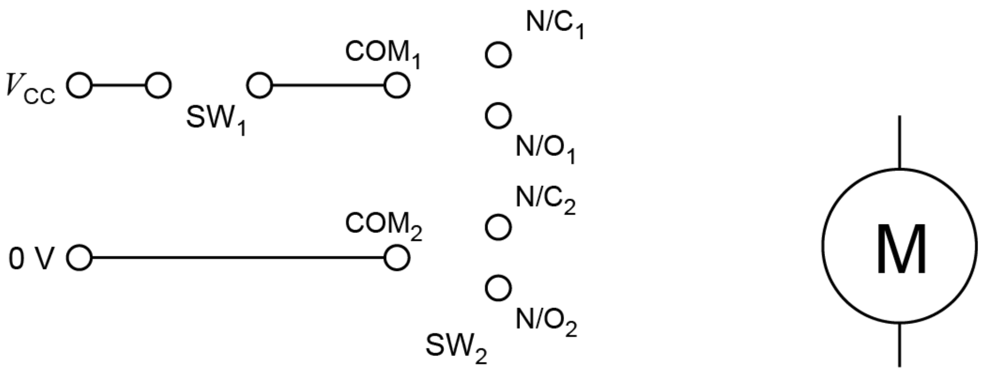
A more elegant electrical solution involves using a DPDT switch. This is shown below.



However, there is a problem with this circuit. It is not possible to stop the motor without removing the power supply. An improved circuit is shown below.



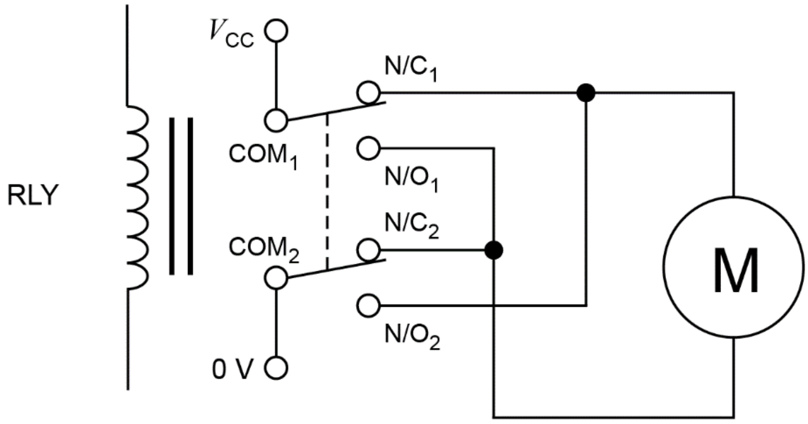
7. Complete the diagram given below such that the motor would be negative at its top connection and positive at its bottom connection when SW_2 is in its N/C position and vice versa when in its N/O position.



Would SW_1 need to be open or closed for the motor to run? open closed

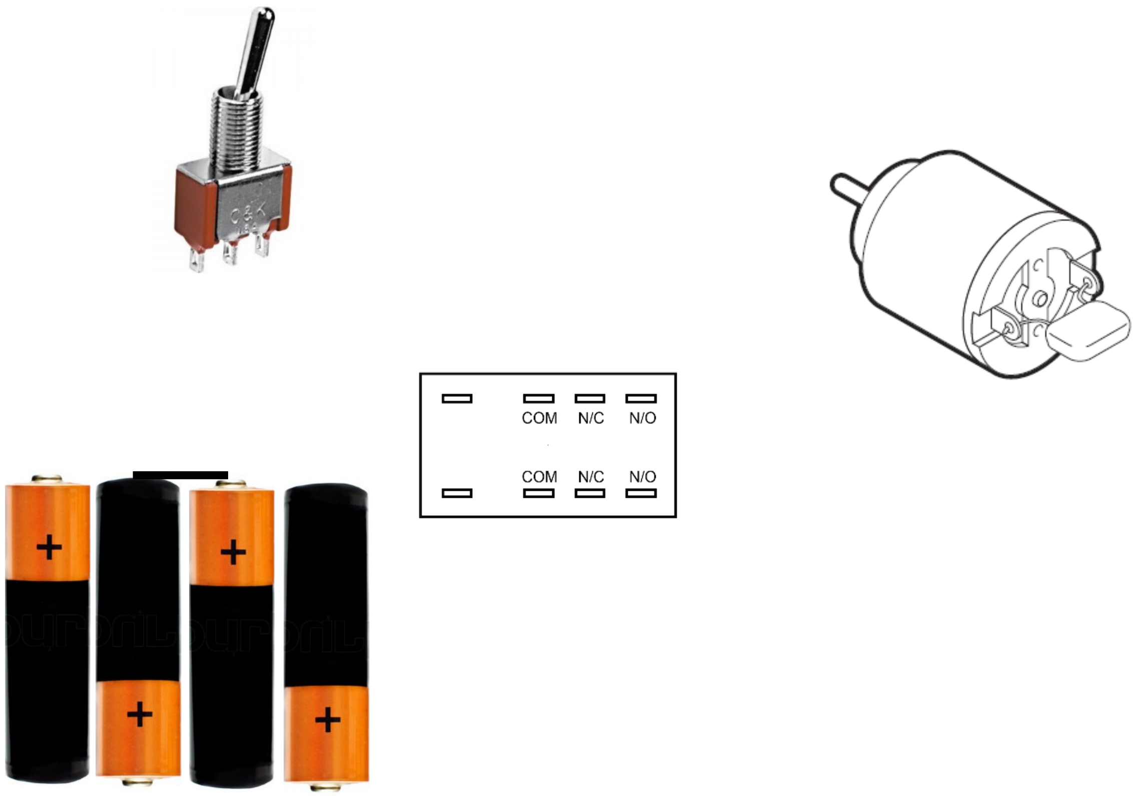
(circle your answer)

Another electrical solution would be to use a DPDT relay. This is illustrated below.

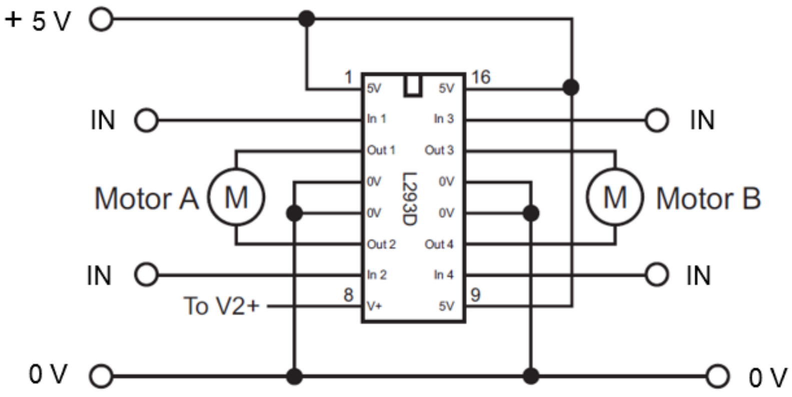


This circuit also has the inherit problem that the motor cannot be stopped. To resolve this it would be necessary to incorporate another switch to make and break the connection to the power supply – probably between V_S and COM_1.

8. On the diagram given below sketch how the motor and 9 V battery would be connected to the lugs on the bottom of a DPDT relay such that the relay would function as an H-bridge. Incorporate the SPDT toggle switch such that it will make and break the power supply connection to the positive terminal of the battery. Connections to the relay coil can be ignored.

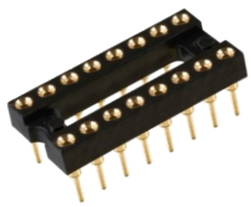


H-bridge L293D

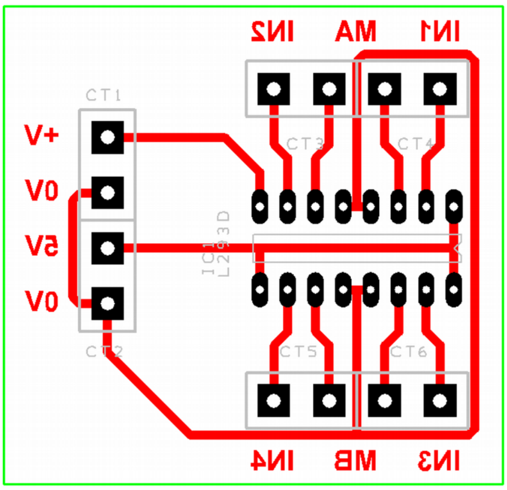


Note: It is also quite common for pins 1, 8, 9 and 16 to all be connected to V_2, the supply voltage for the motor(s).

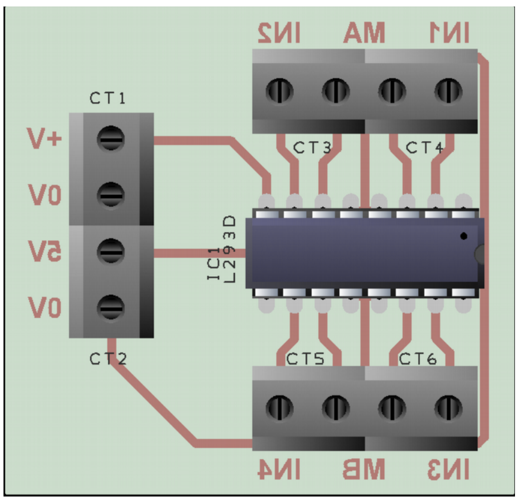
This differs from the arrangement shown in the circuit diagram where only pin 8 is connected to V_2 and pins 1, 9 and 16 are



The L293D motor controller is an 18 pin integrated circuit. It is usually inserted into an 18 pin DIL socket that is soldered on a printed circuit board. DIL is an acronym for *dual in line*.



Mask with component outline



Component overlay

+ V and **0 V** are the power supply required to
power the motor(s).

An extra **0 V** connection has been included for making a common 0 V rail with the microcontroller.

Code	Name
CT_1 – CT_6	2 way connectors
IC_1	L293D motor controller with 16 pin DIL socket

5 V operates the internal circuitry of the L293D motorcontroller (pin 16) and enables motors A and B to be driven (pins 1 and 9 respectively). This allows for more sophisticated motor control if these pins are supplied by outputs pins from a

Output 0 (IN 1)	Output 1 (IN 2)	M_A
0	0	Off
1	0	Clockwise
0	1	Anticlockwise
1	1	Not allowed

Output 2 (IN 3)	Output 3 (IN 4)	M_B
0	0	Off
1	0	Clockwise
0	1	Anticlockwise
1	1	Not allowed

microcontroller.

Pulse width modulation

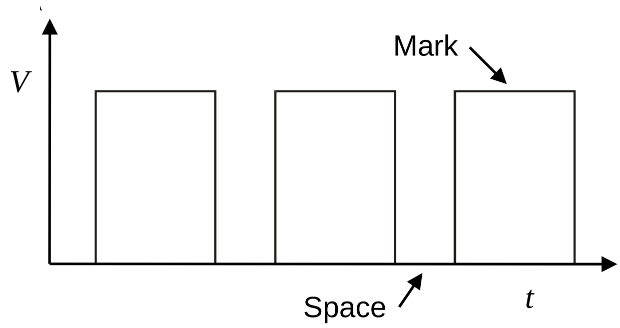
A Pulse Width Modulation (PWM) signal is a method for generating an analogue signal using a digital source. A PWM signal consists of two main components that define its behaviour: a duty cycle and a frequency. The duty cycle describes the amount of time the signal is in a high (on) state as a percentage of the total time of it takes to complete one cycle. The frequency determines how fast the PWM completes a cycle (i.e. 1000 Hz would be 1000 cycles per second), and therefore how fast it switches between high and low states. By cycling a digital signal off and on at a fast enough rate, and with a certain duty cycle, the output will appear to behave like a constant voltage analogue signal when providing power to devices.

Example: To create a 3 V signal given a digital source that can be either high (on) at 5 V or low (off) at 0 V, you can use PWM with a duty cycle of 60% which outputs 5 V 60% of the time. If the digital signal is cycled fast enough, then the voltage seen at the output appears to be the average voltage. If the digital low is 0 V (which is usually the case) then the average voltage can be calculated by taking the digital high voltage multiplied by the duty cycle, or 5 V x 0.6 = 3 V. Selecting a duty cycle of 80% would yield 4 V, 20% would yield 1 V, and so on.

DC Motor Speed Control

The simplest way to control the speed of a DC motor is to vary the voltage applied to the motor coils - the lower the voltage the slower the motor will spin (within the motor operating limits). However the current flowing through the motor coils also decreases as the voltage falls, and so the output torque (turning moment) of the motor also decreases.

Therefore this solution is often unsatisfactory for controlling DC motors due to the undesirable loss of motor torque. **Pulse Width Modulation (PWM)** is a digital method which can be used to vary the motor speed. In this method the full voltage is applied to the motor, but it is rapidly pulsed on and off. By varying the on and off ratio of the pulses the speed of the motor can be varied. As the full voltage is applied to the motor during the 'on' pulses the torque of the motor remains high.

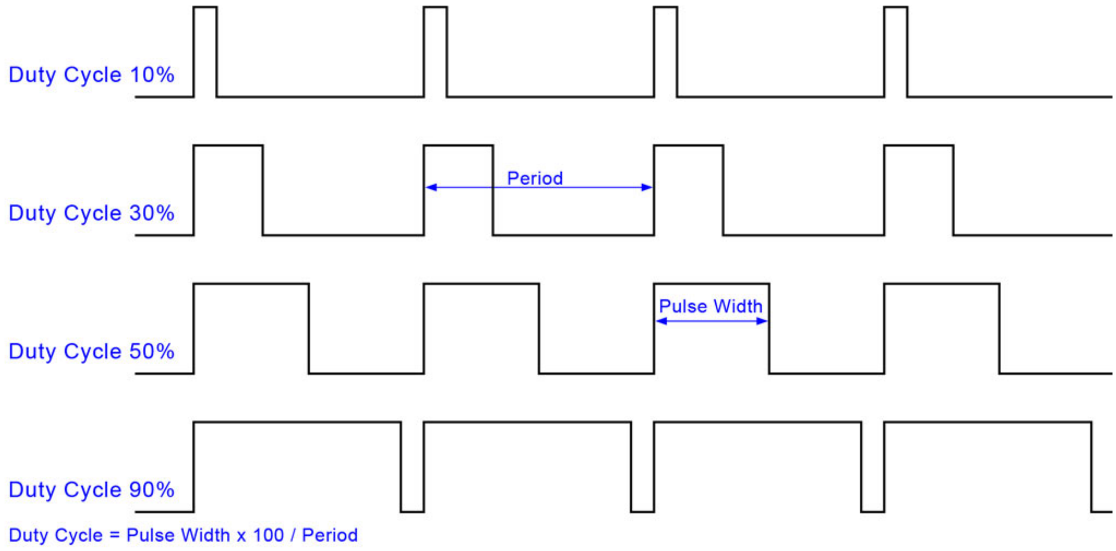


The graph shows how the technique is applied. The 'on' time for the motor is called the mark, the 'off' time is called the space. When the voltage is applied to the motor it accelerates to top speed. However before the top speed is reached the motor is switched off, thus slowing it down. By increasing the frequency of the pulses this acceleration/deceleration becomes negligible, and the motor rotates constantly at a slower speed.

Frequency and duty cycle

The PWM switching frequency has to be much higher than what would affect the load (the device that uses the power), which is to say that the resultant waveform perceived by the load must be as smooth as possible. Typically switching has to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

The term *duty cycle* describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on.



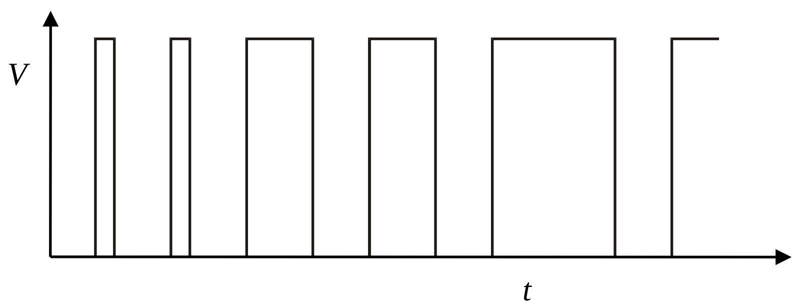
Disadvantages

The PWM technique does have certain limitations. It cannot be used with mechanical relays, as the rapid switching would damage the mechanical contacts. The frequency of the pulses must also be carefully selected e.g. if the frequency is too slow the motor will stall.

Advantages

The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM also works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle

Soft Start of DC Motors



In some devices, such as electric drills, it is desirable for the motor to start rotating slowly and then build up speed, rather than rapidly 'accelerating' up to full speed. This is called

'soft starting' the motor, and the use of PWM is often appropriate in these situations. The motor is started at a low speed and then gradually accelerated by varying the mark to space ratio over a period of time.

9. Explain the terms ‘mark’ and ‘space’ in relation to PWM control of a DC motor.

10. Describe the advantages and disadvantages of using PWM control.

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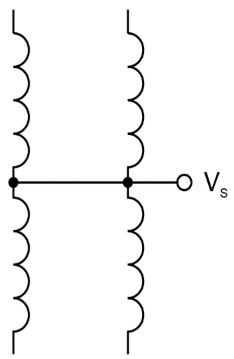
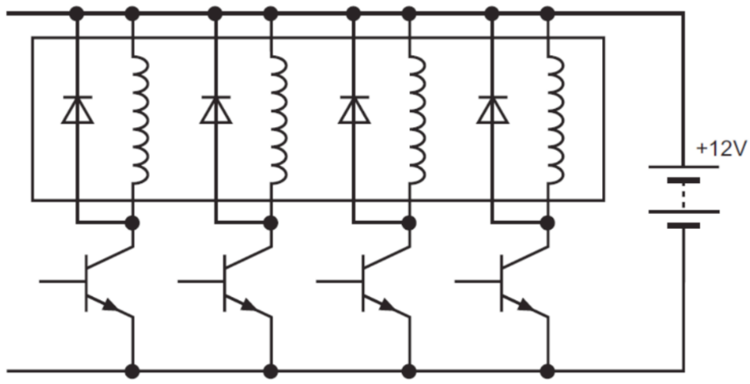
Unipolar stepper motor (4 input)

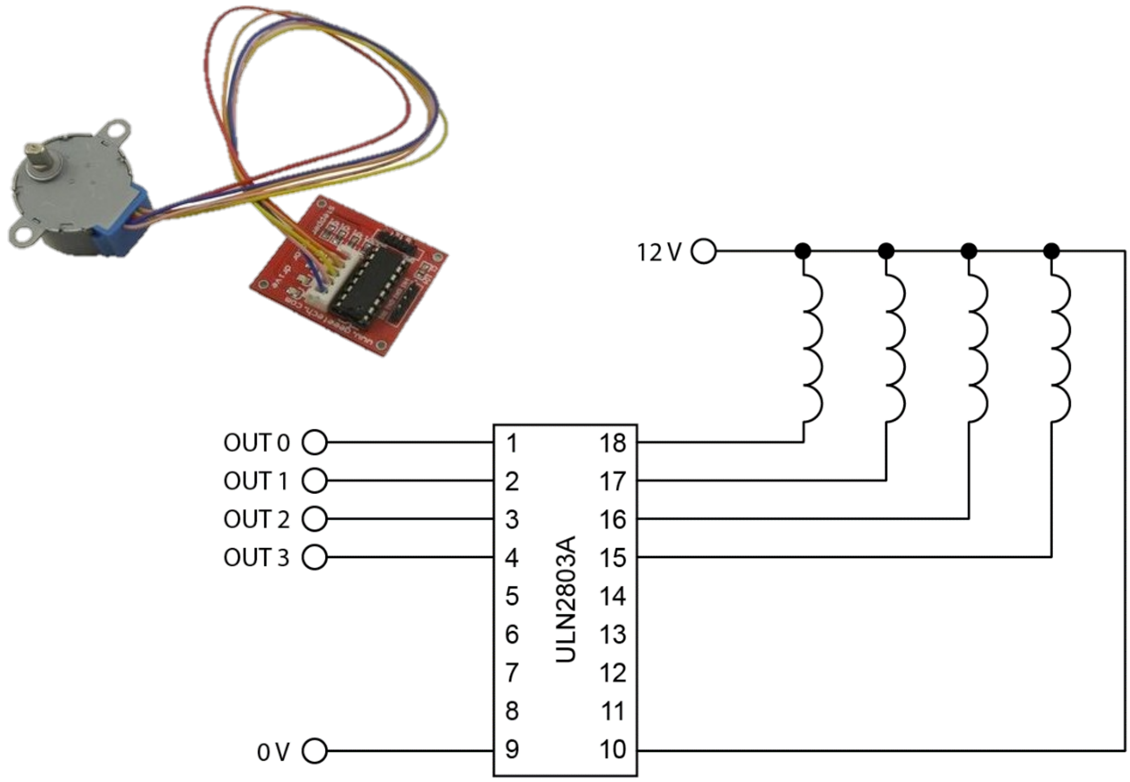
Unipolar stepper motors usually have 5 wires. These are the supply voltage (often 12 V) and the coils of which there are 4 sets. The coils can be independently controlled by 4 transistors which in turn are controlled by 4 outputs from the microcontroller. Rather than using 4 separate transistors a more convenient method is to use a Darlington driver like the ULN2803A which incorporate 8 transistor drivers, more than enough for the task.



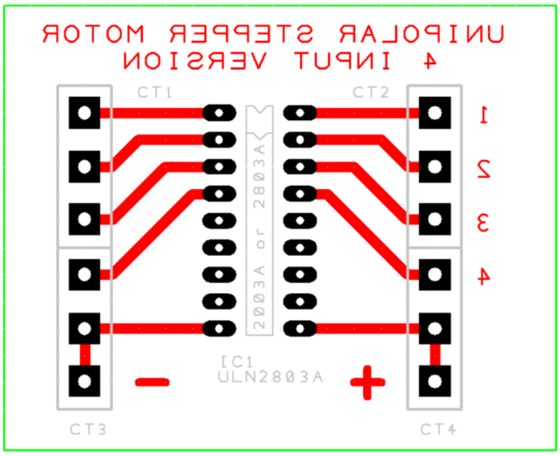
Circuit symbol for a unipolar stepper motor.



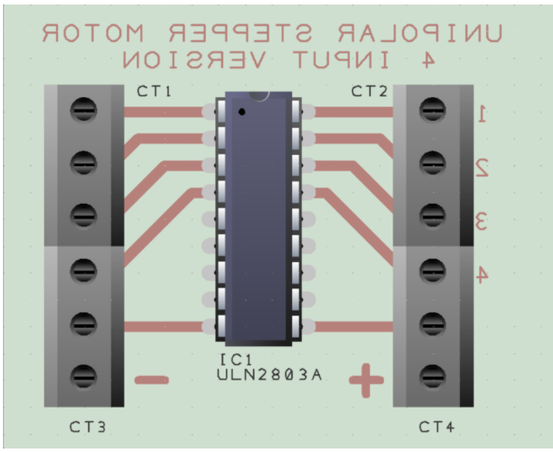
The 4 coils of a unipolar stepper motor being driven by 4 separate transistors.



Controlling a unipolar stepper motor using a ULN2803A Darlington driver.



Mask with component outline



Component overlay

+ and **–** are the power supply required to operate the stepper motor.

An extra **+** connection has been included connecting the red wire from the stepper motor.

An extra **–** connection has been included for making a common 0 V rail with the microcontroller.

Four outputs from the microcontroller are connected to CT_1 and the top pin of CT_3.

The wires from the coils of the stepper motor are connected to CT_2 and the top pin of CT_4.

Code	**Name**
$CT_1 – CT_4$	3 way connectors
IC_1	ULN2003A Darlington driver and 18 pin DIL socket

Step	**Coil 1** **OUT 0**	**Coil 2** **OUT 1**	**Coil 3** **OUT 2**	**Coil 4** **OUT 3**
1	1	0	1	0
2	1	0	0	1
3	0	1	0	1
4	0	1	1	0
1	1	0	1	0

The above table shows the combinations of outputs used by the ULN2803A to control the coils of the unipolar stepper motor. Unipolar stepper motors typically require 48 steps to complete one revolution i.e. 7.5^{o} per step.

11. On the next page sketch a flowchart that could be used to meet the following specifications:

There are 2 digital inputs. These are IN 0 and IN 1.

If both inputs are low the stepper motor is stationary (all coils off).

Only one of the inputs can be high at any one time.

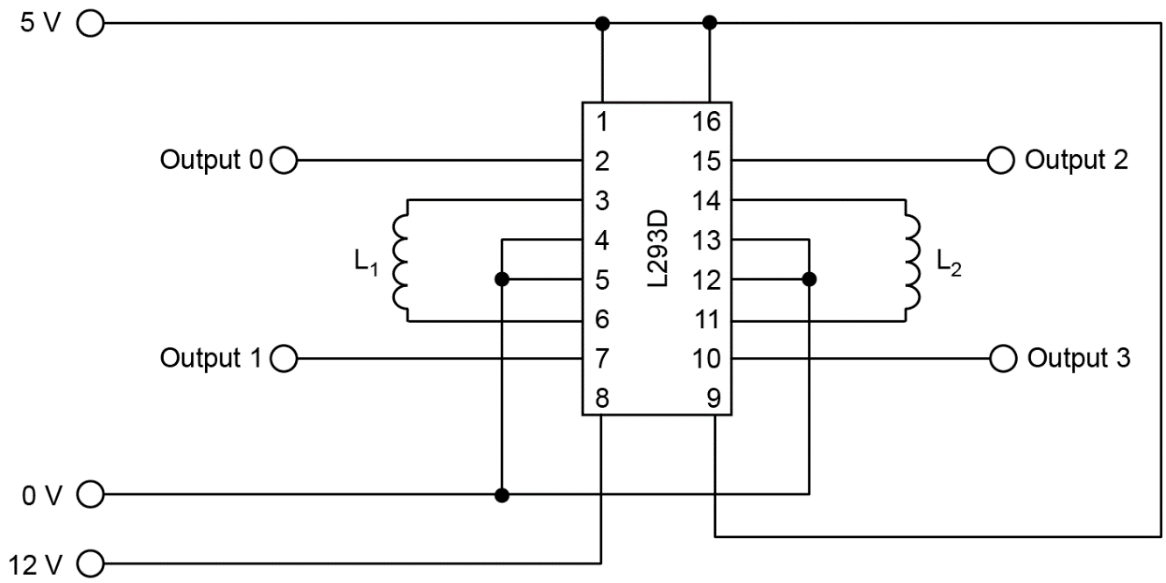
If IN 0 is high then the stepper motor coils are controlled in the sequence shown in the table i.e. Step 1 then Step 2 then Step 3 then Step 4 then repeat so long as IN 0 remains high. Each step has a timed duration of 1 ms. If IN 0 is released then the flow of data returns to the flowchart where the inputs are being monitored. This will occur after step 4 is completed.

If IN 1 is high then the stepper motor coils are controlled in the reverse to the sequence shown in the table i.e. Step 1 then Step 4 then Step 3 then Step 2 then repeat. Each step has a timed duration of 1 ms. If IN 1 is released then the flow of data returns to the flowchart where the inputs are being monitored. This will occur after step 4 is completed.

The use of Procedure (also called Sub-routine) commands that call up a Process is highly recommended.

Bipolar stepper Start

Note: the bipolar stepper motor is not specified in the syllabus but is a very useful actuator (probably more useful than a unipolar stepper motor).

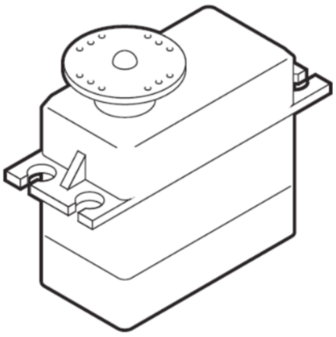


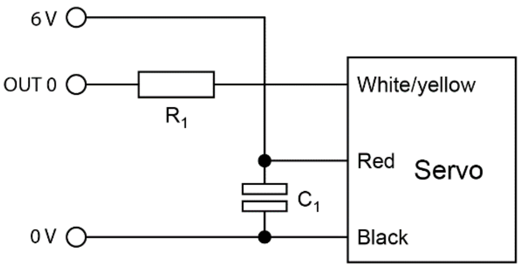
Bipolar stepper motors typically take 200 steps per rotation i.e. 1.8º per step. There are 4 wires. Two of these control one coil (L_1) and the other pair controls the second coil (L_2). An L293D motorcontroller is ideal for driving a bipolar stepper motor and will require 4 outputs from the microcontroller to sequence the steps.

Step	Coil 1		Coil 2	
	Out 0 Red	Out 1 Yellow	Out 2 Green	Out 3 Blue
1	1	0	1	0
2	1	0	0	1
3	0	1	0	1
4	0	1	1	0
1	1	0	1	0

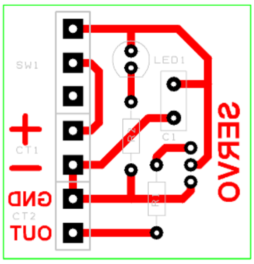
Sequencing the steps for a bipolar stepper motor

Servo



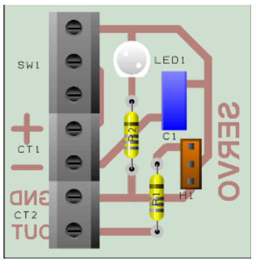


Left-hand end connects to 6 V and 0 V of power supply; and the output and 0 V of microcontroller



Right-hand end connects to white/yellow, red and black leads of servo.

Mask with component outline



Component overlay

Code	Name
R_1	330 Ω resistor
R_2	1k Ω resistor
C_1	100 nF capacitor
LED_1	5 mm LED
SW_1	SPDT toggle switch
H_1	3 pin header
$CT_{1\&2}$	2 way connectors

12. In the space below sketch a flowchart that could be used to meet the following specifications:

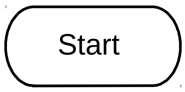
There are 2 digital inputs. These are IN 0 and IN 1.

If both inputs are low the servo is positioned at its midpoint (150).

Only one of the inputs can be high at any one time.

If IN 0 is high then the servo moves to its maximum travel in a clockwise direction (225) and holds this position only whilst IN 0 is still be pressed.

If IN 1 is high then the servo moves to its maximum travel in an anti- clockwise direction (75) and holds this position only whilst IN 1 is still be pressed.



More questions

WACE 2010 multiple-choice questions 15*, 16, 19 and 22 and questions 25 (a) and (b),

* Assume that the warning light is an LED

WACE 2011 multiple-choice questions 15, 19, 21, 22 and 23.

WACE 2012 multiple-choice questions 16, 17, 23 and 24 and questions 25 (a) and 27 (a), (b), (c), (e) and (f).

WACE 2013 multiple-choice questions 14, 18, 19 and 22 and questions 24 (a), (b), (c) and (d) and 28 (a), (b), (c) and (d).

WACE 2014 multiple-choice questions 15, 17, 18, 19 and 23 and questions 24 (a), (b) and (c), 26 (f) and 27 (d).

WACE 2015 multiple-choice questions 14, 17 and 18, and questions 25 (a), (b) and (c) and 27 (c).

WACE 2016 questions 42 (a)(i) and 44 (d).

WACE 2017 multiple-choice question 32; question 42 (a); question 43 (d); question 44 (d); question 45 (a) and (b).

5. Mechanisms

Mechanical formulae

Parameter	Formula	Terms
Mechanical advantage (MA)	$MA = \dfrac{\text{load}}{\text{effort}}$	
Velocity ratio (VR)	$VR = \dfrac{\text{distance moved by effort}}{\text{distance moved by load}}$	
Pulley belt ratio	$VR = \dfrac{\text{Ø follower pulley}}{\text{Ø driver pulley}}$	
Chain and sprocket ratio	$VR = \dfrac{\text{nº teeth follower gear}}{\text{nº teeth driver gear}}$	
Gear ratio	$VR = \dfrac{\text{nº teeth follower gear}}{\text{nº teeth driver gear}}$	
Compound gear ratio	$VR_T = VR_1 \times VR_2 \times \ldots..$	VR_T is the total velocity ratio VR_1, VR_2, … are the individual velocity ratios
Worm drive ratio	$VR = \dfrac{\text{nº teeth worm wheel}}{1}$	
Rack and pinion	$distance = \dfrac{\text{nº teeth pinion} \times \text{nº revolutions}}{\text{nº teeth per metre rack}}$	
Speed, velocity	$velocity = \dfrac{distance}{time} = \dfrac{(rpm)(2\pi r)}{60}$	
	$\text{output rpm} = \dfrac{\text{input rpm}}{VR}$	VR is the velocity ratio *rpm* is the revolutions per minute

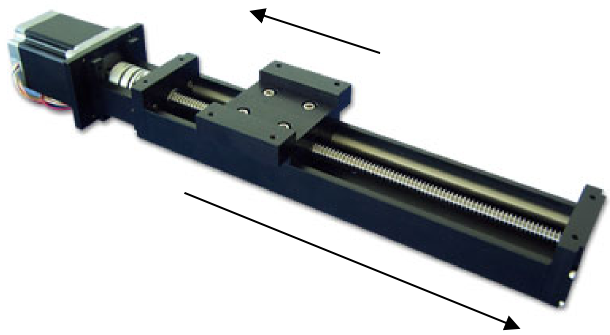
SI units

Quantity	SI unit	
	Name	Symbol
distance	metre	m
time	second	s
speed, velocity	metre per second	m s^{-1}

Types of motion

There are 4 simple types of motion used by mechanisms. These are linear, reciprocating, rotary and oscillating.

Linear: The motion is in a straight line.
Example: A sliding table as used by many machine tools like lathes and milling machines. This is also an example of converting rotary motion into linear motion.



Other examples: A sliding door and the useable part of a conveyor belt.

Reciprocating: Straight line motion back and forth between two points.
Example: A jig saw. This is also an example of converting rotary motion into reciprocating motion.

Other examples: A piston sliding up and down inside a cylinder in a lawn mower engine and the action of a sewing machine needle.

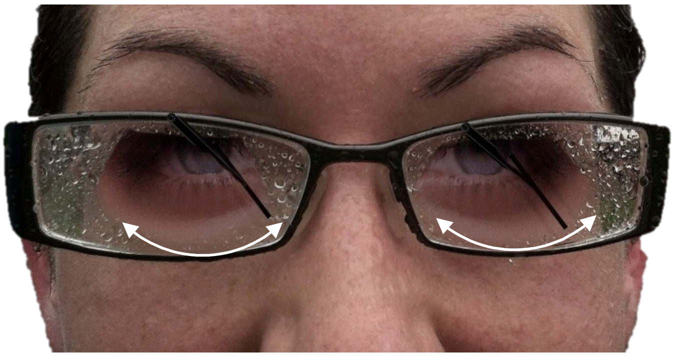
Rotary: A circular motion about a fixed point.

Examples: The spinning of a wheel, pulley or gear.

Other examples: The spinning of a wheel, pulley or gear.

Oscillating: Back and forth motion that follows an arc about a fixed point.

Example: Windscreen wipers.

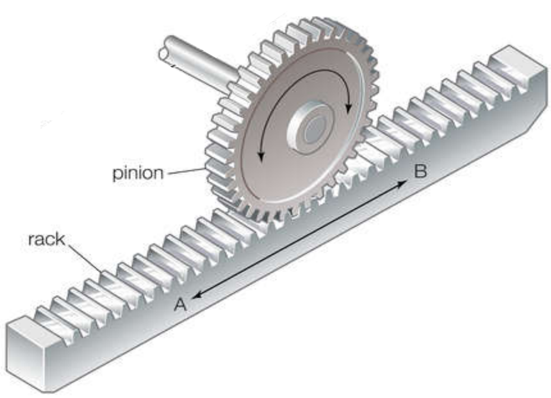


Other examples: A swing and scissors.

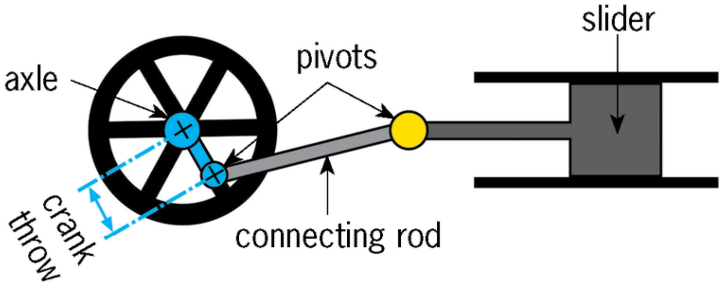
Transformations of motion

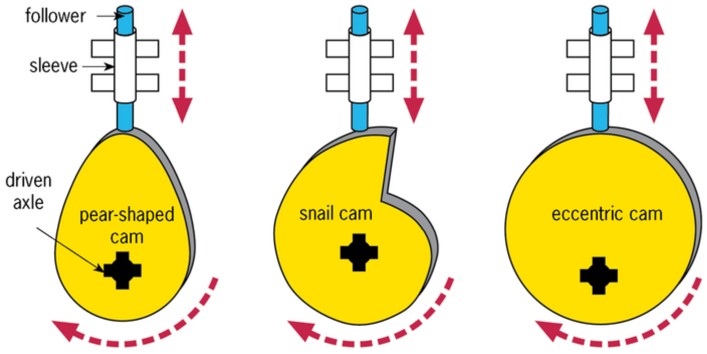
It is often the case that different types of motion need to be converted into another form to do useful work. Standard conversions include the following:

Rotary to linear e.g. winch and drum, conveyor belt or similar, rack and pinion

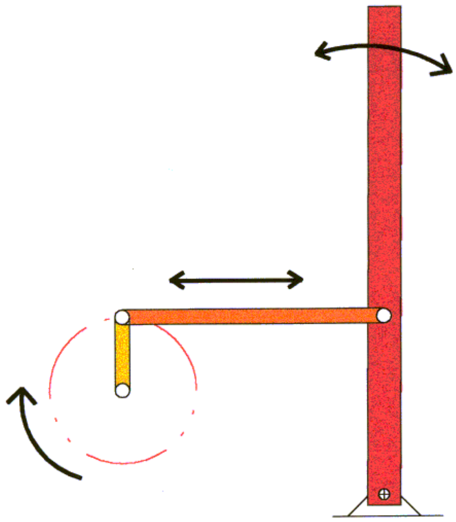


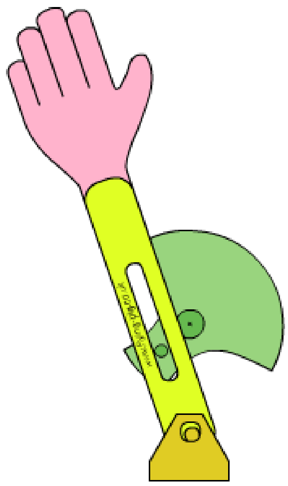
Rotary to reciprocating e.g. crank and slider, cam and follower





Rotary to oscillating e.g. linkage systems and pin in slot systems





Note: There are many other forms of transforming motion (e.g. reciprocating to rotatory, oscillating to reciprocating, and so on) and perhaps you may need to conduct research to discover more about these in order to undertake project work.

Mechanical drive systems

Mechanical drive systems are simple machines and these are a crucial aspect of mechatronic devices. There are many examples of these and what follows are those specified in the syllabus for this course of study i.e. pulleys, chain and sprocket, spur gears, compound gears, worm and worm wheel, and rack and pinion.

Before going further it is necessary to understand what is meant by the term *machine*.

*‘A machine is a means of overcoming a resistance (called the **load**) by the application of a force (called the **effort**).’*

The above definition is sourced from page 131 of *Engineering Mechanics by* R.K. Mullins, 1983.

Velocity ratio (VR)

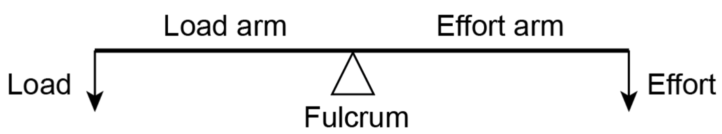
*‘The **velocity ratio** of a machine is the ratio of the distance through which the effort moves to the distance through which the load moves, at the same time.’*

The above definition is sourced from page 306 of *Engineering Mechanics by* R.K. Mullins, 1983.

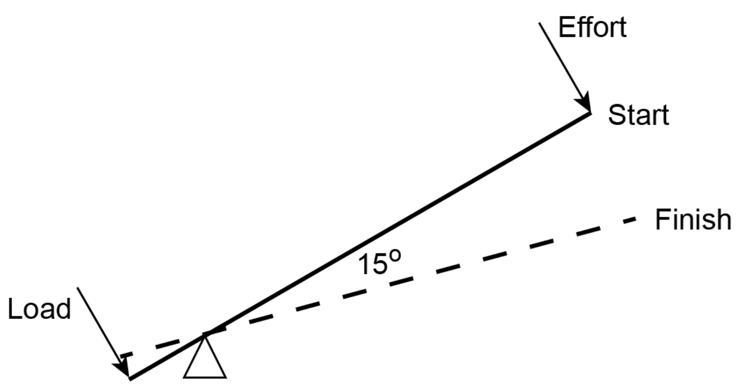
As a formula this is expressed as –

$$VR = \frac{\text{distance moved by effort}}{\text{distance moved by load}}$$

A Class 1 lever is a good example that illustrates this concept. A diagram of such a lever is shown below.



Suppose the lever is 1.8 m long and its effort arm is 1.5 m long. Assume it is used like a crowbar and moves from a starting position 30º to horizontal through to 15º to horizontal i.e. $^{1}/_{24}$ of a full rotation as shown below.



The distance moved by the effort, d_E, is as follows –

$$d_E = 2 \times 1.5 \times \pi \times {}^{1}/_{24} = 0.3927 \text{ m}$$ Note: Movement is in an arc.

The distance moved by the effort, d_L, is as follows –

$$d_L = 2 \times 0.3 \times \pi \times {}^{1}/_{24} = 0.07854 \text{ m}$$ Note: Movement is in an arc.

Using the formula for calculating velocity ratio

$$VR = \frac{0.3927}{0.07854}$$
$$= 5{:}1 = 5$$

Mechanical advantage (*MA*)

'*The mechanical advantage of a machine is defined as the ratio of the load to the effort.*'

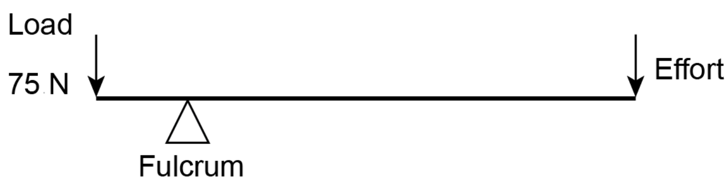
The above definition is sourced from page 132 of *Engineering Mechanics by* R.K. Mullins, 1983.

As a formula this is expressed as –

$$\text{Mechanical advantage} = \frac{\text{load}}{\text{effort}}$$

In most instances the mechanical advantage of a machine will be greater than one (1).

Again a Class 1 lever is a good example that illustrates this concept. Examine the following diagram. This is the same lever that was used before but now it is in its horizontal position. The lever is 1.8 m long and the effort arm is 1.5 m long.



Assuming the lever is in equilibrium, and ignoring its mass and any issues with friction, then the following conditions will apply –

$$\sum M = 0 = \sum CWM - \sum ACWM$$

$$\text{therefore } \sum CWM = \sum ACWM$$

$$\text{i.e. effort} \times \text{effort arm} = \text{load} \times \text{load arm}$$

Calculate effort -

$$\text{effort} \times 1.5 = 75 \times 0.3$$
$$\text{effort} = \frac{75 \;\; 0.3}{1.5}$$
$$= 15 \text{ N}$$

Now that the forces for load and effort are known the formula for mechanical advantage (MA) can be applied as follows –

$$MA = \frac{\text{load}}{\text{effort}}$$
$$= \frac{75}{15}$$
$$= 5{:}1 = 5$$

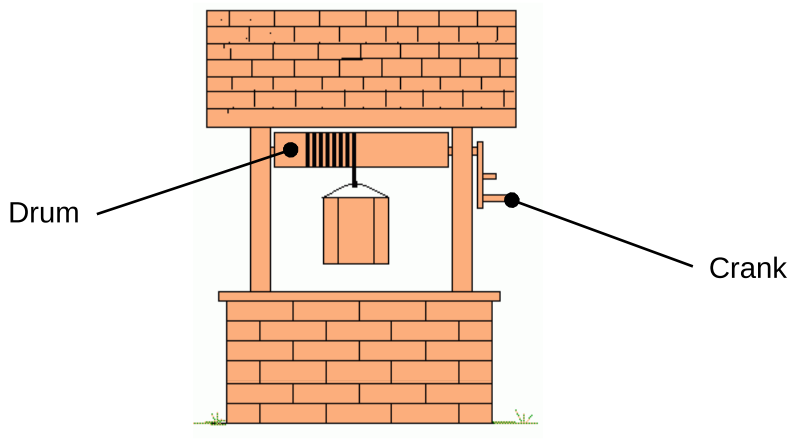
Assuming that no work is done in lifting any parts of the machine and that friction is ignored then for a simple machine –

velocity ratio = mechanical advantage

$$\frac{\text{distance moved by effort}}{\text{distance moved by load}} = \frac{\text{load}}{\text{effort}}$$

$$\text{effort} \times \text{distance moved by effort} = \text{load} \times \text{distance moved by load}$$

$$\text{work done by effort} = \text{work against load}$$



1. Examine the windlass illustrated above. For this example the windlass is used to lower and raise a bucket in a well. The radius of the crank is 350 mm and the radius of the drum is 125 mm.

   (a) Calculate the velocity ratio of this system.

   ____

   ____

   ____

   $VR =$ ______________

   (b) Assuming that the windlass is 100% efficient and that friction is ignored calculate the effort required to raise a 980 N load a distance of 1 metre.

   ____

   ____

   ____

   ____

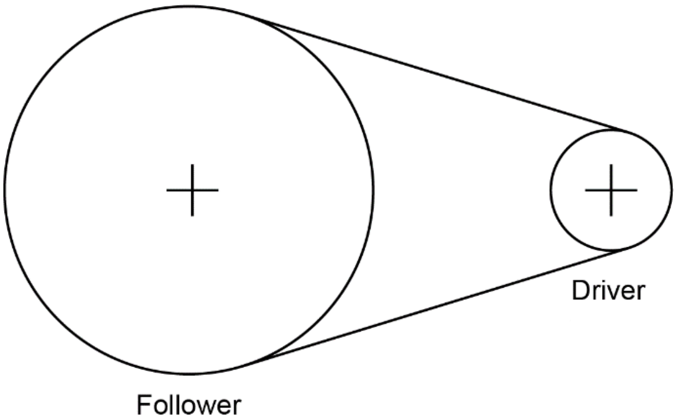
   ____

   ____

Effort = ___________

Pulley belt drive system

A pulley or belt drive is used to transmit rotary motion from one shaft to another when the distance between the centres of the shafts is large.



The velocity of the belt is the same throughout its path around the pulleys and, assuming that the belt does not slip, it follows that the linear velocities of the perimeter of each pulley must be the same. Although it is not prescribed in the syllabus for this subject it is useful to at least be aware of how linear velocity of the perimeter of a circular object is determined.

Velocity of a particle in a circular motion is determined using –

velocity = radius $\times$ angular velocity

velocity m s^{-1}
radius m
angular velocity rad s^{-1}

The term *rad* means **radian**. This refers to an angular displacement of 57.3º and one full rotation (360º) = 2π radians. For one radian the arc length is equal to the radius of the circular path.

For a pulley belt drive system –

velocity of perimeter of driver = velocity of perimeter of follower

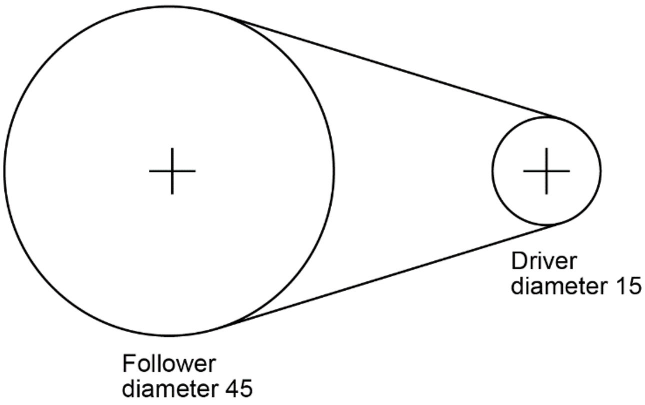
radius of driver $\times$ angular velocity of driver = radius of follower $\times$ angular velocity of follower

$$\text{therefore} \quad \frac{\text{angular velocity of driver}}{\text{angular velocity of follower}} = \frac{\text{radius of follower}}{\text{radius of driver}} = \frac{\text{Ø follower pulley}}{\text{Ø driver pulley}}$$

The formula used to calculate the velocity ratio of a pulley system is -

$$VR = \frac{\text{Ø follower pulley}}{\text{Ø driver pulley}}$$

= input revolutions: 1 output revolution



2. Calculate the velocity ratio (*VR*) for the pulley system illustrated above.

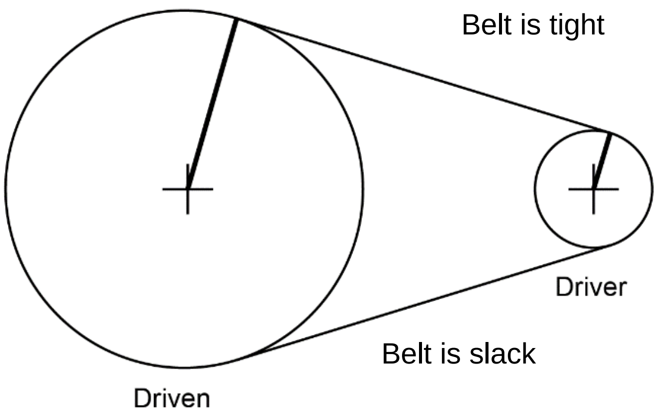
____

____

____

VR = ______________

Examine the diagram given below. Assume that the driver pulley is rotating in a clockwise direction.



The radial lines drawn on each pulley represent lever arms. The longer a lever arm is the greater the force it applies about its fulcrum. In the case of a pulley the fulcrum is its shaft. Each pulley can be treated as an infinite number of lever arms acting about a fulcrum. The shorter lever arms of the driver pulley are pulling the belt around the driven pulley. This acts on the longer lever arms of the driven pulley to give an increase in torque about its fulcrum at the cost of decreased angular velocity.

Note: In the above example the belt will be tight at the top and, in relative terms, slack at the bottom i.e. the belt can transmit a force when it is being pulled but not if it is being pushed.

3. What is the effect on output angular velocity and torque if –

(a) Two pulleys are of the same diameter?

Angular velocity:

Torque:

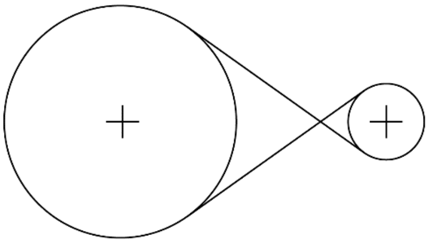
(b) A larger pulley is driving a smaller pulley?

Angular velocity:

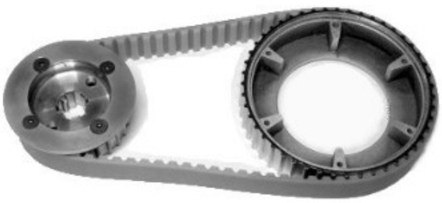
Torque:

Characteristics of pulley belt drive systems

- Used to transmit rotary motion when shafts are too far apart to use gears.
- Direction of rotation of the driver and the follower are normally the same. It is possible to have these rotating opposite directions of the drive belt is round and is twisted as shown in the following diagram.

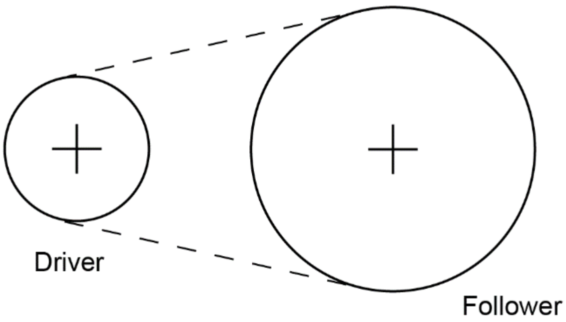


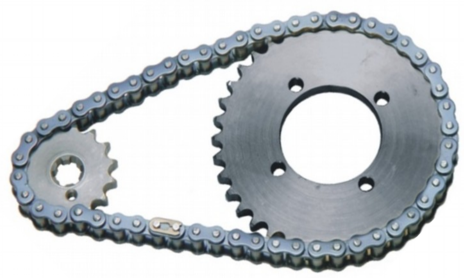
- Quiet running
- No need for lubrication
- Will slip if transmitting large forces (can be viewed both as an advantage and as a disadvantage)
- If it is vital that a belt drive does not slip then multiple belts can be used or a toothed belt can be used with a toothed pulley – the latter is very similar to a chain and sprocket system.



Chain and sprocket

A chain and sprocket is very similar to a pulley belt drive. The chain transmits rotary motion from the driver shaft to the follower shaft. Sprockets are toothed wheels that engage with the chain to produce a drive system that does not slip.





The formula used to calculate the velocity ratio of a chain and sprocket drive system is -

$$VR = \frac{\text{n° teeth follower gear}}{\text{n° teeth driver gear}}$$

= input revolutions: 1 output revolution

4. A chain and sprocket system has a driver gear with 18 teeth and a 72 tooth follower gear.

(a) Calculate the velocity ratio.

____

____

____

VR =______________

(b) This drive system will increase / decrease the torque of the follower gear shaft.

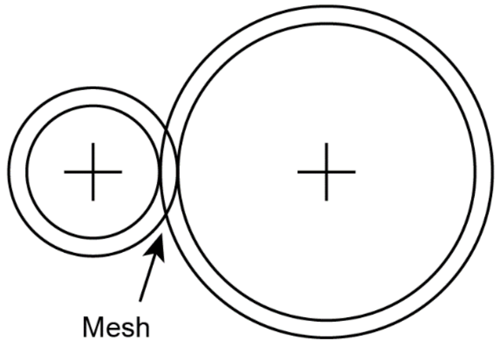
(circle your answer)

Characteristics of chain and sprocket drive systems

- Transmit large forces without slipping

- Usually require lubrication

Spur gear drive



To calculate the velocity ratio for a simple gear drive use -

$$VR = \frac{\text{nº teeth follower gear}}{\text{nº teeth driver gear}}$$

= input revolutions: 1 output revolution

5. A simple gear drive system has an 8 tooth driver gear and the 44 tooth follower gear.

   (a) Calculate the velocity ratio.

   ____

   ____

   ____

   VR =______________

   (b) This drive system will increase / decrease the torque of the follower gear shaft.

   (circle your answer)

Characteristics of gear drive systems

- Transmit large forces without slipping
- Usually require lubrication
- Are noisy compared to pulley systems

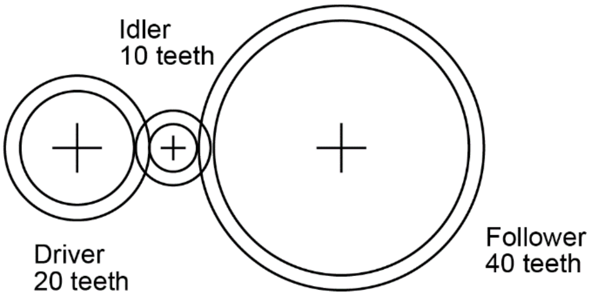
- The driven and follower gears rotate in opposite directions

Idler gear

If a third gear is added to a gear train the effect is to cause the follower gear to rotate in the same direction as the driver gear without affecting the velocity ratio. This extra gear is called an idler gear.

The velocity ratio for a gear system that includes an idler gear can be calculated using the following formula -

$$VR_{\text{TOTAL}} = VR_1 \times VR_2$$



For the above example -

$$VR_{\text{TOTAL}} = VR_1 \times VR_2$$

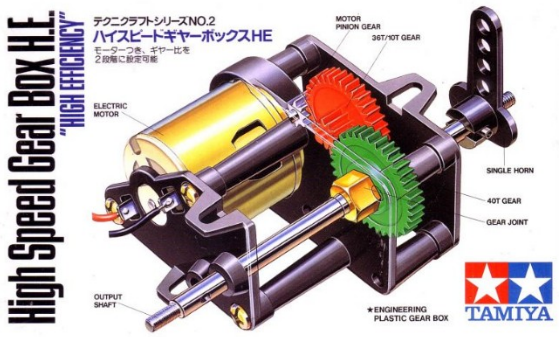
$$= \frac{10}{20} \times \frac{40}{10}$$

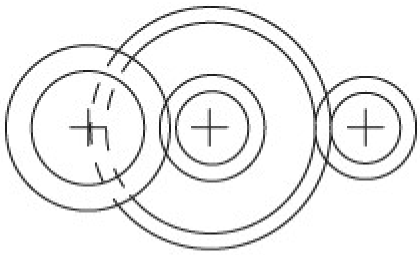
= 0.5 $\times$ 4 = 2 i.e. **2:1**

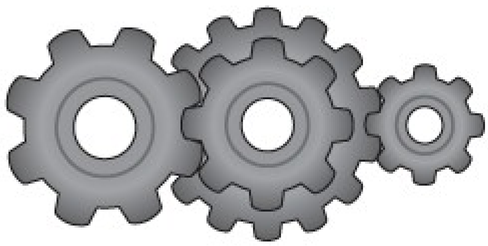
Note: This is the same *VR* that would have resulted if only the first and last gears had been used for a simple *VR* calculation.

Compound gear drive

Compound gears occur when two gears are joined together on the same shaft and these form a part of a gear drive system







To calculate the velocity ratio for a compound gear drive use -

$$VR_{\text{TOTAL}} = VR_1 \times VR_2 \times VR_3 \times \ldots$$

$$= \text{input revolutions: 1 output revolution}$$

The mathematical equivalent can be achieved using –

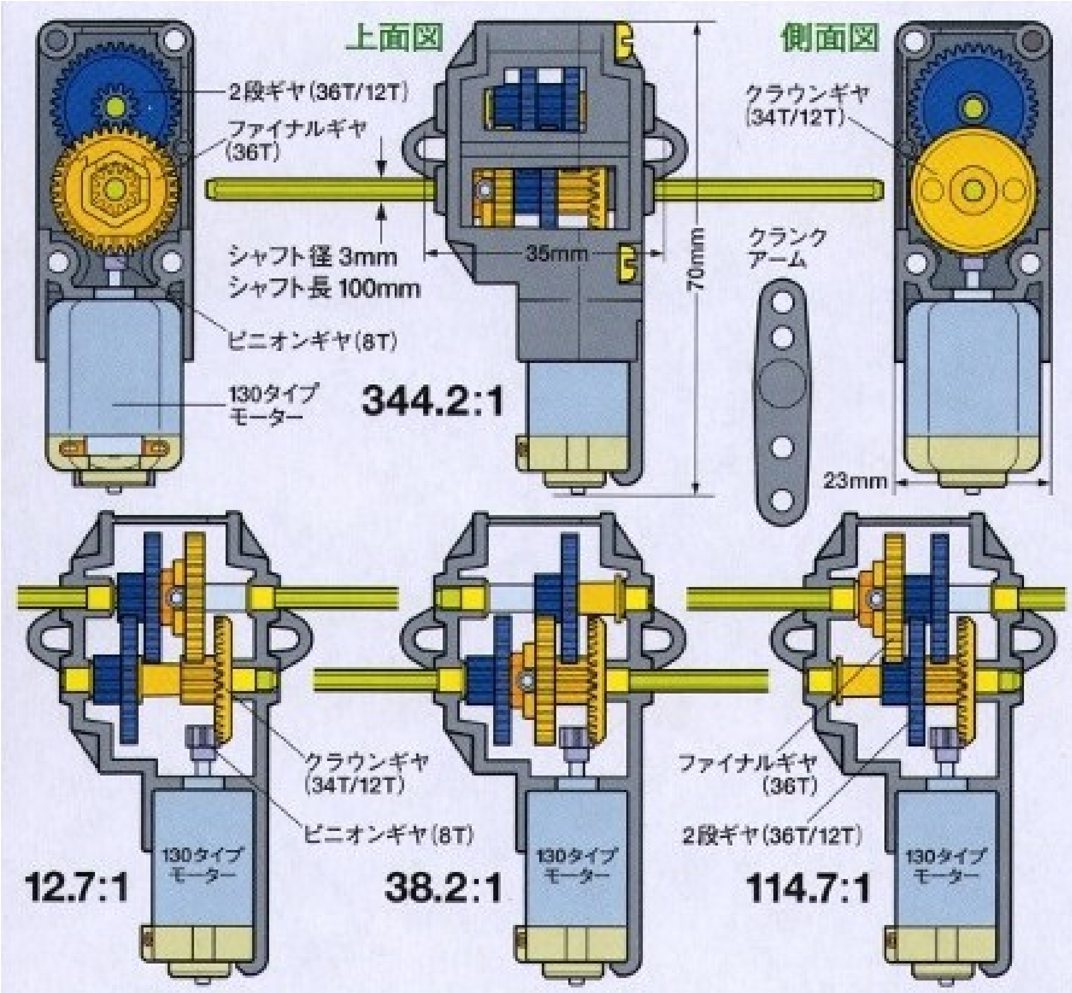
$$VR_{\text{TOTAL}} = \frac{(F1\ \ F2\ \ F3\ \ \ldots)}{(D1\ \ D2\ \ D3\ \ \ldots)}$$

where F = nº teeth on follower gears

and D = nº teeth on driver gears

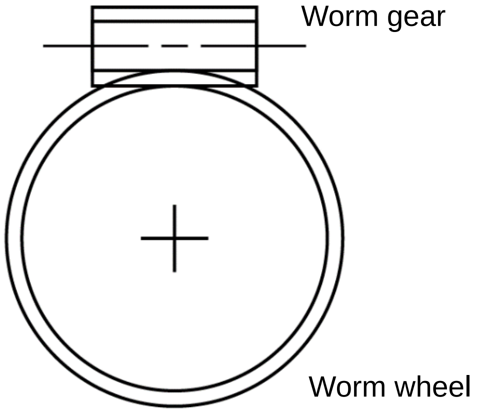
Characteristics of compound gear drive systems

- Very large increases in the velocity ratio are achieved in a compact space.



6. Use calculations to demonstrate that the velocity ratio of the compound gear drive illustrated in the bottom right corner is very close to 114.7:1 as shown on the diagram.

Worm and worm wheel



VR = worm & worm wheel ratio $= \dfrac{\text{nº teeth worm wheel}}{1}$

= input revolutions: 1 output revolution

7. Calculate the velocity ratio for a worm drive system that has a 72 tooth worm wheel.

____

____

____

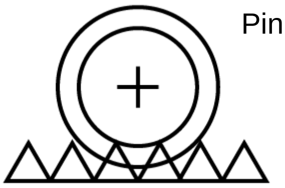
VR =____________

Characteristics of worm drive systems

- Large increases in the velocity ratio are achieved with only two gears.
- Only the worm gear can be used to drive the system and not the worm wheel.
- Due to very high inertia this system will essentially lock into place when power is switched off to the drive motor.

Rack and pinion

This drive system is used to convert rotary motion into linear motion and vice versa. Automated sliding gates are a good example of the former and a means for spinning the shafts of toys like a top or racing car for the latter.



$$\text{Distance moved (linear translation)} = \frac{\text{nº teeth pinion} \quad \text{nº revolutions}}{\text{nº teeth per metre of rack}}$$

8. Calculate the required number of revolutions of a 12 tooth pinion gear to result in a 600 mm linear translation of a rack that has 100 teeth per metre.

____

____

____

____

Revolution of pinion gear =______

Characteristics of rack and pinion drive system

- Rotary motion is converted into linear motion and vice versa.

Speed/velocity

Linear velocity is measured in m s^{-1} (metres per second) and the formulae for this are as follows -

$$\text{Velocity (v)} = \frac{\text{distance}}{\text{time}} = \frac{(\text{rpm})(2\pi r)}{60}$$

The first is used for a pathway that is in a straight line and the second for a circular pathway.

Output speed is measured in terms of angular velocity but rather than using units of radians it is more appropriate to use revolutions per minute (rpm) for this course of study. The formula for this is shown below.

$$\text{Output speed (rpm)} = \frac{\text{input speed (rpm)}}{VR}$$

9. Calculate the **output** speed of a pulley system that has a diameter 45 driver pulley, a diameter 60 follower pulley and an input speed of 720 rpm.

Output speed =________________

10. Calculate the **input** speed of a pulley system that has a diameter 30 driver pulley, a diameter 75 follower pulley and an output speed of 600 rpm.

Input speed =___________________

11. Calculate the **output** speed of a gear system that has an 8 tooth driver gear, a 48 tooth follower gear and input speed of 600 rpm.

Output speed =________________

12. Calculate the **input** speed of a gear system that has a 60 tooth driver gear, a 40 tooth follower gear and an output speed of 1050 rpm.

Input speed =________________

More questions

WACE 2010 multiple-choice questions 18 and 21.

WACE 2011 questions 26 (a), (b) and (c).

WACE 2012 multiple-choice question 18 and questions 26 (a), (b) and (c)*.

* Ignore (c) (iii)

WACE 2013 multiple-choice question 21 and questions 27 (a), (b), (c) and (e).

WACE 2014 multiple-choice question 20 and questions 26 (c) and (d).

WACE 2015 multiple-choice questions 21* and 23 and questions 26 (a), (e) and (f).

* The gearbox VR is 3:2.

WACE 2016 multiple-choice questions 33 and 38; questions 42 (b)(i), (b)(ii), (b)(iii) and(b)(iv) and 47 (e)(i), (e)(ii)* and (f).

* Non-syllabus but an interesting extension question.

WACE 2017 multiple-choice questions 30, 33, 36 and 38; question 41 (a), (b) and (c); question 43 (c)(i) – (vi); and question 45 (c), (d), (e), (f), (g) and (h).