Chapter 5: Semiconductor components

1. Diodes

Learning Objectives:

At the end of this topic you should be able to:

- recall the I–V characteristics of a silicon diode;
- describe the use of diodes for component protection in DC circuits;
- describe how to protect a LED from excessive current and reverse voltages;
- calculate the resistance and power rating of the series resistor used to protect a LED from excessive current.

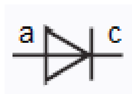
There are a number of different types of diodes. In this course we look at:

- silicon diodes, used in rectification;
- zener diodes, used as voltage regulators;
- light-emitting diodes, used as indicators.

The diode is a two-terminal device, having an anode and a cathode terminal.
The circuit symbols for the three types are shown below, along with identification information.

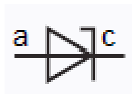
a = anode
c = cathode

Silicon diode

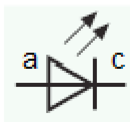


Cathode – stripe on body

Zener diode



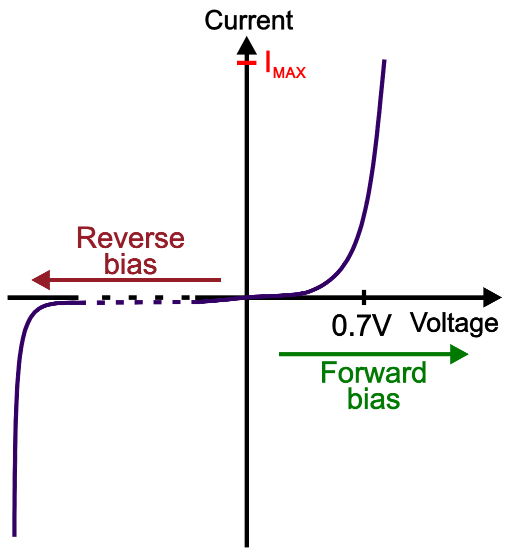
LED



Cathode – shorter lead

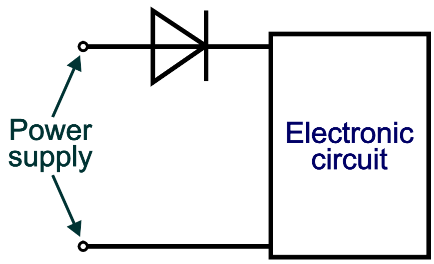
The diode is a 'one-way valve' for electric current, offering a very small resistance for current flowing from anode to cathode.
A diode offers a very large resistance (about 100,000 times bigger) for current trying to flow in the opposite direction, from cathode to anode.
The arrow in the symbols shows the direction in which the current can flow easily. It flows when the anode is more positive than the cathode. Under these conditions, the diode is 'forward biased'. When the diode is 'reverse biased', with the cathode more positive than the anode, the current flowing is negligibly small.

Silicon Power Diodes



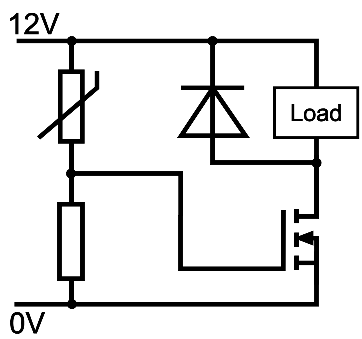
The behaviour of the diode as the applied voltage changes is shown in the graph.
When forward biased (anode more positive than cathode), the diode starts to conduct when the voltage reaches around 0.5 V. When it reaches around 0.7 V, the current increases rapidly, but the voltage drop across the diode stays around 0.7 V. With both a current flowing and a voltage drop across it, the diode dissipates power and heats up. Beyond a maximum current, 'I_{MAX}' in the graph, the diode will be permanently damaged.
Under reverse bias, the current is negligible until the voltage reaches a value, known as the reverse breakdown voltage, typically in excess of 100 V.

Diode Applications
Protection against reverse polarity



Diodes can prevent damage caused by a power supply connected the wrong way round. Current will flow to the circuit only if the power supply is connected with the upper terminal connected to the positive supply and the lower one to the negative (or 0 V) supply.

Protection against 'back emf'
When a voltage is applied to an inductor, a current begins to flow through it, generating a magnetic field in the inductor coil. When this current is suddenly switched off, the magnetic field collapses and, in the process, generates a high voltage in the opposite direction to the original voltage. This is known as 'back emf'.



Where a MOSFET or bipolar transistor is used to switch the current in an inductive load, such as a motor, solenoid or relay, the back emf that occurs when the device is switched off can damage the transistor.

The solution is to add a diode in parallel with the load, so that its cathode is connected to the positive power rail and its anode to the transistor.

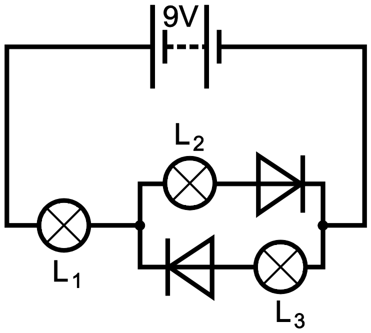
When the load is switched on, no current flows through the diode as it is reverse biased. When the transistor switches off, back emf is generated. Now, the diode is forward biased and conducts current. In the process, the voltage across the diode does not rise above 0.7 V, causing no problems for the controlling transistor.

Rectification
The mains electricity supply uses alternating current (AC). Many electronic circuits require a direct current (DC) supply. Rectification is the name of the process used to convert AC into DC.
Rectification is covered in Chapter 7 which looks at power supplies.

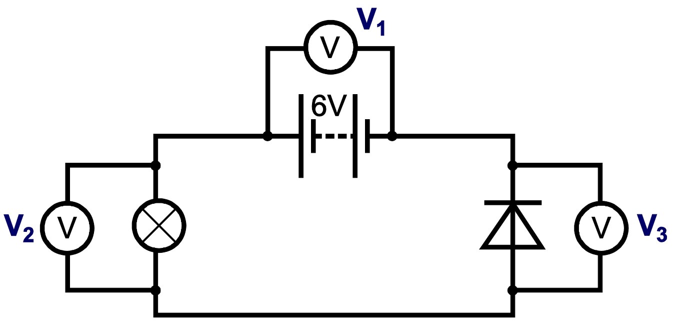
Exercise 5.1

1. The circuit contains a 9 V battery, three lamps and two diodes.
Complete the table to indicate the state of lamps $\mathbf{L_1}$, $\mathbf{L_2}$ and $\mathbf{L_3}$.

Lamp	State (On / Off)
L_1	
L_2	
L_3	



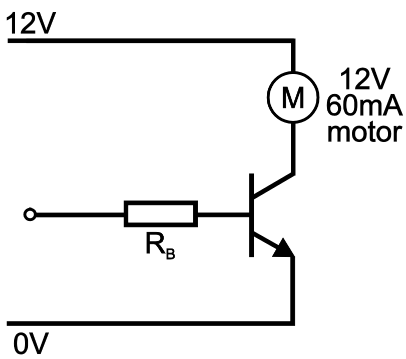
2. The circuit diagram shows a 6 V battery, connected to a diode, and a lamp.



Complete the table by adding the readings on the voltmeters.

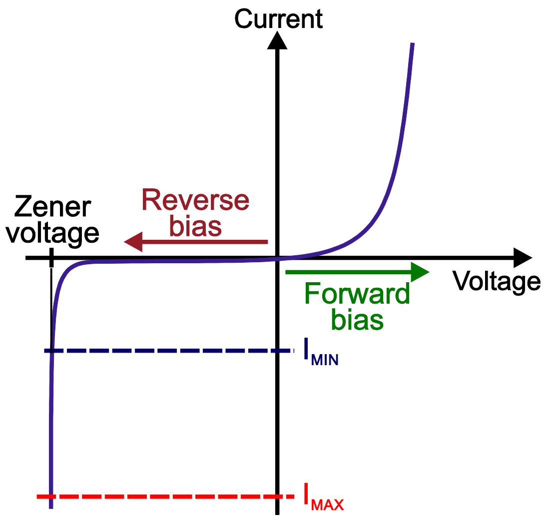
Voltmeter	Reading
V_1	
V_2	
V_3	

3. The circuit diagram shows part of a transistor circuit.
Add a component to the circuit diagram to protect the transistor when the motor turns off.



Zener Diodes

A diode made from a semiconducting material, such as silicon, 'breaks down' (begins to conduct,) when the reverse voltage across it rises too far.



The voltage at which this happens, known as the zener voltage, is usually high – hundreds of volts. Once the diode begins to conduct, the voltage across it remains remarkably constant no matter how great the current. This is ideal behaviour for a voltage regulator.

The voltage at which this breakdown occurs can be adjusted during the manufacturing process. The result is the availability of a wide range of zener diodes.

Zener voltage values mirror those in the E24 resistor series. The table shows some of the values available in the BZX55 series of zener diodes. The use of zener diodes to provide voltage regulation is covered in detail in Chapter 7.

BZX55 500mW Zener Diode Series					
2.4 V	2.7 V	3.0 V	3.3 V	3.6 V	3.9 V
4.3 V	4.7 V	5.1 V	5.6 V	6.2 V	6.6 V
7.5 V	8.2 V	9.1 V	10 V	11 V	12 V

Light-emitting Diodes

Like power diodes and zener diodes, light-emitting diodes (LEDs) are based on semiconductor p-n junctions, but use compound semiconductors based on elements such as gallium, indium and phosphorus. When they conduct a current, they emit light of a colour that depends on the exact composition of the compound semiconductor.

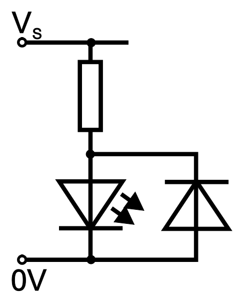
They are used as highly efficient indicator lamps. Used in forward-biased mode, the forward voltage drop across them also depends on their chemical composition. For example, for red LEDs, it is around 2.2 V, for yellow, slightly less, around 2 V and for blue it is around 3.2 V.

Their ability to dissipate power also depends on the type of LED. The 'standard' 5mm LED is limited to 100 mW or so, whereas the high-intensity LEDs can dissipate several watts.

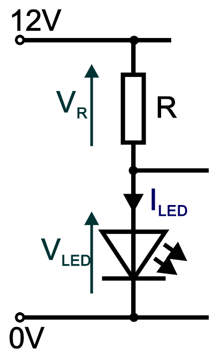
This is also reflected in the maximum forward currents they can handle. The 'standard' LED tolerates a maximum current around 20 mA, whereas for the high-powered version, this is closer to 1 A. Usually, they are used in conjunction with a series resistor, designed to reduce the current through the LED to a safe level.

LEDs are not tolerant to large reverse voltages. The 'standard' LED breaks down with a reverse voltage around 5 V. They can be protected by connecting another diode, even another LED, in inverse parallel with the LED.

Both of these features are shown in the circuit diagram.



Example 1:



A LED acts as a 'power-on' indicator for a system which operates on a 12 V DC power supply.
When lit, the LED should pass a maximum current of 10 mA.
It has a forward voltage drop of 2.2 V.

a) Calculate:

i) the voltage, $\mathbf{V_R}$, across resistor **R** when the LED is lit;

$$\begin{aligned} V_R &= V_S - V_{LED} \\ &= 12 - 2.2 \\ &= 9.8\text{ V} \end{aligned}$$

ii) the minimum value of resistance for **R** to protect the LED from excess current;
The LED and resistor are in series, so the same current flows through both.
This current is 10 mA ($\mathbf{I_Z}$).

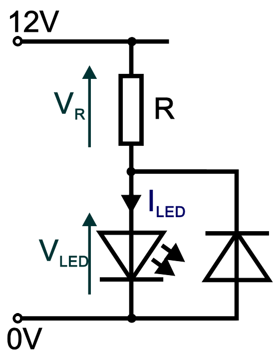
From Ohm's law
$$\begin{aligned} R &= \frac{V_R}{I_{LED}} \\ &= \frac{9.8}{10} \\ &= 0.98\text{ k}\Omega \end{aligned}$$

iii) the power dissipated in the resistor when the LED is lit.

$$\begin{aligned} \text{Using } P_R &= I_R \times V_R \\ &= 10 \times 9.8 \\ &= 98\text{ mW} \end{aligned}$$

b) Choose a suitable preferred value for **R** from the E24 series of resistors.
The next highest E24 resistor value is **R** = 1 kΩ.
(Choosing a lower value would increase the current past the 10 mA value.)

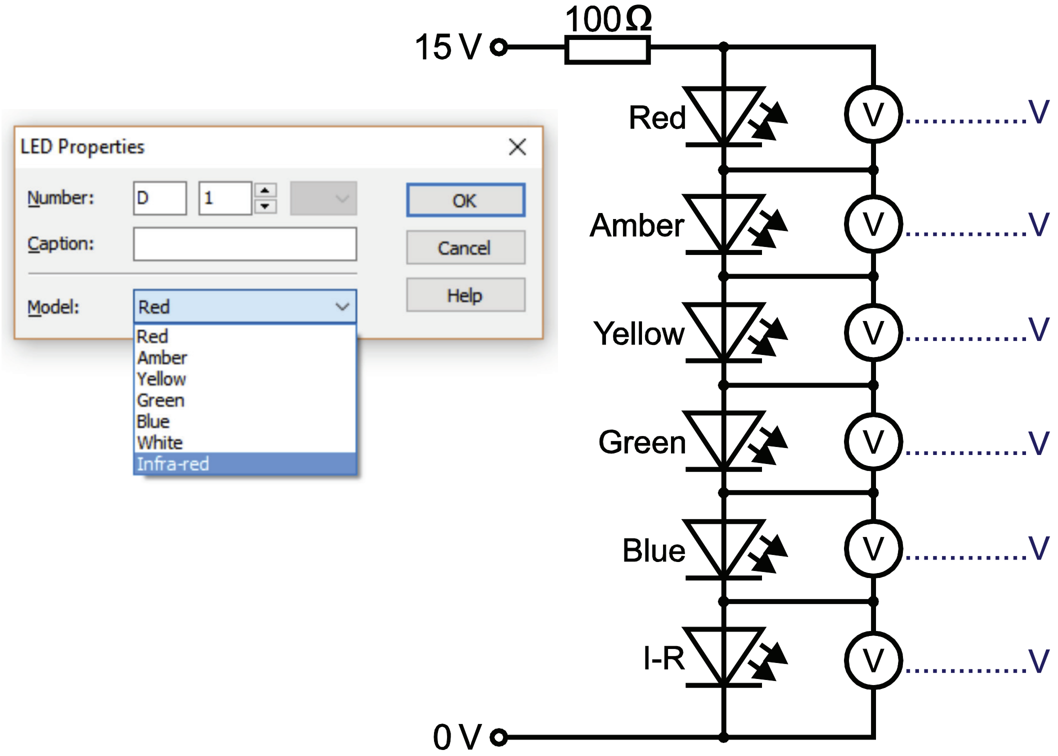
c) Modify the circuit diagram by adding a component which will protect the LED should the power supply be connected the wrong way round:



The component could be a different type of diode. A second LED would limit the reverse voltage to ~2 V. A zener diode could be used, providing its zener voltage is greater than 12 V. Whatever type is used, it must be 'normally' reverse biased.

Investigation 5.1

a) Set up the following circuit.
If you use a simulation program, right-click on each LED in turn to select the colour shown in the diagram.
Add the voltmeter readings to show the voltage drop across each LED.



b) Connect a diode across an infrared LED with the cathode connected to the 0 V rail.
Comment on:

- the change in the brightness of the LEDs that occurs;
- the voltage across the LEDs.

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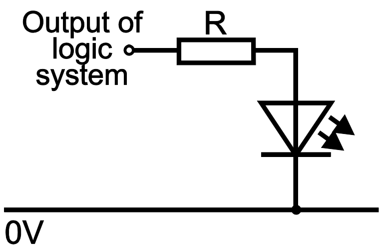
Exercise 5.2

A blue LED indicates when the output of a logic system is logic **1**. When lit, the LED passes a current of 25 mA and has a forward voltage drop of 3.2 V.



When at logic **1**, the logic system outputs a signal of 10.2 V.

a) Calculate:

i) the power dissipated in the LED when lit;

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ii) the minimum resistance of resistor **R** which limits the current through the LED to 25 mA;

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iii) the minimum power rating for resistor R used in this way.

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b) Select a suitable resistance value from the E24 series and the smallest suitable power rating from the following: ¼ W, ½ W, 1 W, 2 W or 5 W.

Resistance ....

Power rating ....

2. Switching Circuits

Learning Objectives:

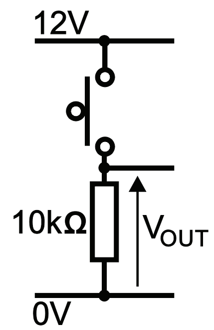
At the end of this topic you should be able to:

- describe the action of n-channel enhancement mode MOSFETs and npn transistors in switching circuits;
- describe the switching action of a npn transistor, by making reference to its voltage transfer characteristic;
- recall that the base-emitter voltage, V_{BE}, depends on the base current, I_B, and is approximately equal to 0.7 V when the transistor is conducting;
- select and apply the equation $I_C = h_{FE} \times I_B$ and recall the conditions necessary for it to be valid;.
- recall that MOSFETs have a very high input resistance;
- recall that r_{DS} decreases from a very high value to a very low value as V_{GS} is increased;
- recall that r_{DS} is at a minimum value, called r_{DSon}, at saturation;
- select and apply the MOSFET equation: $I_D = g_M(V_{GS} - 3)$;
- describe the need for diode protection for transistors and MOSFETs;
- compare the action of switching circuits based on MOSFETs and those based on npn transistors;
- use data sheets to design switching circuits using MOSFETs and npn transistors.

Introduction

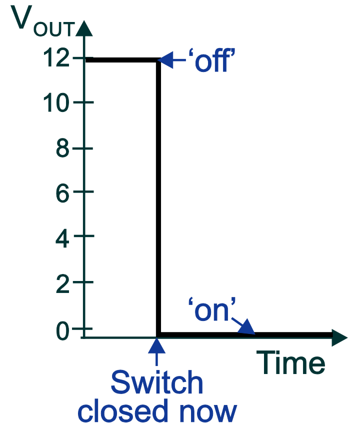
This section focuses on two devices, the npn transistor and the n-channel MOSFET, used in switching circuits.

What is a Switch?



A switch is a two-state device. It offers huge electrical resistance in one state and around zero in the other. The diagram shows the circuit for one form of switch unit.

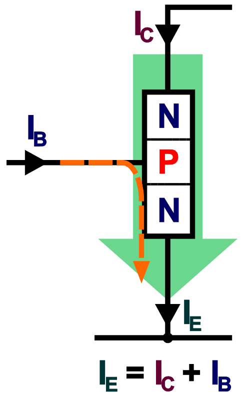
In one state ('off'), the air gap between the switch contacts has a resistance much bigger than the 10 kΩ resistor. It takes the vast majority of the supply voltage and so $\mathbf{V_{OUT}}$ ~ 0 V.
In the other state ('on'), the metal switch contacts touch, giving a resistance of ~ 0 Ω. Now the 10 kΩ resistor dominates, and $\mathbf{V_{OUT}}$ ~12 V.



This ideal switching characteristic is illustrated in the graph opposite:
The switch described above works when mechanical pressure is applied to its contacts. Electronic switches work on the principle that electrical 'pressure' or voltage at the input controls the current flowing in the output.
Electronic switching circuits are used to interface between low power sub-systems and higher power output devices.
We now consider two types of electronic switching circuit.

Bipolar Junction Transistors (BJTs)

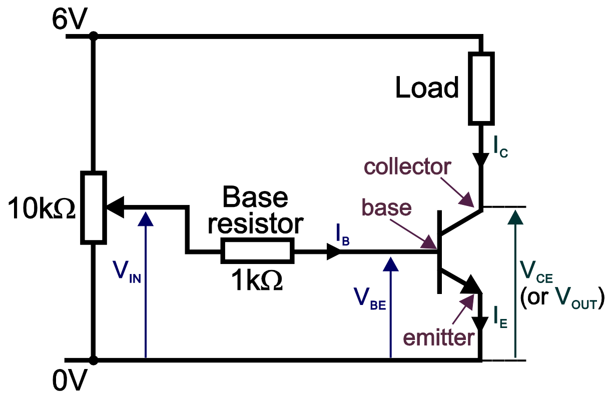
These come in two types, known as 'npn' or 'pnp', depending on the way in which impurities are added to the silicon from which the transistor is made. Each has two 'p-n' junctions, (n-p /p-n) for the npn and (p-n/ n-p) for the pnp. Each has three regions, called 'collector', 'base' and 'emitter'.



This course is concerned only with the npn transistor. The diagram shows the direction of current flow in the npn transistor.
The transistor is a current amplifier. The collector current, I_C, is typically around fifty times bigger than the base current, I_B.
Emitter current, I_E, is equal to the sum of base and collector currents.
Since the base current is much smaller than the collector current, the emitter current and collector currents are roughly equal.

NPN Transistor Behaviour

A circuit like that below can be used to investigate transistor behaviour.



The circuit diagram contains information about some common terms used when discussing transistors:

- the three terminals of the transistor are called:
  - collector;
  - base;
  - emitter.
- the three currents associated with transistor operation:
  - collector current, I_C;
  - base current, I_B;
  - emitter current, I_E.
- the two voltages associated with a transistor circuit of this type:
  - base-emitter voltage, V_{BE};
  - collector-emitter voltage, V_{CE}, also known as V_{OUT}.

The circuit includes:

- a base resistor – this protects the transistor from excessive currents;
- a load, shown as a resistor, connected between the positive supply rail and the collector (in switching circuits).

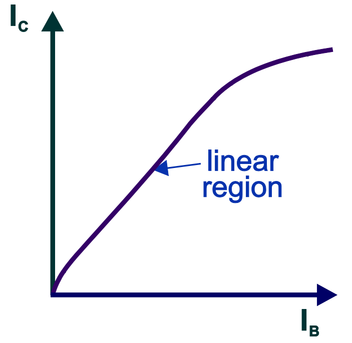
Transistor Action

The base current, I_B, controls the resistance between the collector and emitter and hence the collector current, I_C. The higher the base current, the lower the collector-emitter resistance and so the greater is the collector current, I_C.

The graph on the right shows the relationship between I_B and I_C.
The gradient of the graph in the linear region is known as the current gain, h_{FE}, of the transistor.
In other words:

$$I_C = h_{FE} \times I_B$$

Different types of transistor have different values of h_{FE}, ranging from 10 to over 800.

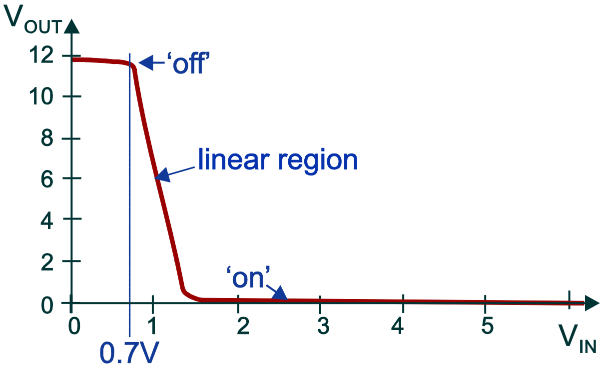


Note:
The current gain formula is valid **only** in the linear region. However, it can be used right up to the point where the transistor enters saturation. Examination questions are worded in the following or similar manner:

Determine the value of V_{IN} that will cause the transistor **just** to saturate.
or The transistor is **just** saturated when the input voltage V_{IN} = 2.5, etc.

This phraseology allows the equation to be used.

Voltage Transfer Characteristic for a Transistor
This shows the relationship between V_{OUT} and V_{IN} for the transistor. The graph that follows illustrates typical transistor behaviour.



There are three key sections:

- **'Off'** region:
  For V_{IN} between 0 and 0.7 V:
    - no base current flows;
    - no collector current flows;
    - the load voltage ~0 V;
    - V_{OUT} ~12 V.

  The transistor is switched off.
- **Linear** region:
  The linear region is so called because of a linear relationship between base current and collector current. When V_{IN} increases above 0.7 V:
    - base current starts to flow;
    - larger collector current flows through the load;
    - voltage across the load increases so V_{OUT} decreases.
- **'On'** region (or 'saturation'):
  As V_{IN} continues to increase, V_{OUT} continues to fall. Eventually, the collector current reaches a maximum value and further changes to V_{IN} have no effect. We say that the transistor is **saturated**. At this point, in practice, V_{OUT} is typically ~0.2 V and so the load voltage is just less than the power supply voltage.

Example 1:

Calculate the collector current for a transistor having a current gain, h_{FE}, of 120 and which is not in saturation.

Its base current, I_B, = 10 mA.

Using the formula: $I_C = h_{FE} \times I_B$

$I_C = 120 \times 10 = 1200 \text{ mA} = 1.2 \text{ A}$

The corresponding collector current is 1.2 A.

Example 2:

Calculate the base current for a transistor with a current gain, h_{FE}, of 250, when the collector current is 800 mA. The transistor output is not saturated.

Using the formula: $I_C = h_{FE} \times I_B$

$800 = 250 \times I_B$

$$I_B = \frac{800}{250} = 3.2 \text{ mA}$$

The corresponding base current is 3.2 mA.

Example 3:

Calculate the current gain, h_{FE}, when the collector current is 420 mA and the base current is 1.5 mA. The transistor output is not saturated.

Using the formula: $I_C = h_{FE} \times I_B$

$420 = h_{FE} \times 1.5$

$$h_{FE} = \frac{420}{1.5} = 280$$

Transistor Switching Circuit

When used as a switch, the transistor must operate only in the cut-off **and** saturation regions of the characteristic, avoiding the linear region.
The linear region is avoided because:

- the load will not have the full supply voltage across it;
- V_{CE} is not zero and neither is I_C, meaning that power is dissipated in the collector-emitter junction, which can cause the transistor to overheat.

To a good approximation, the following relationships are true and can be used in transistor calculations:

- for V_{IN} <0.7 V: $V_{BE} = V_{IN}$ and $V_{CE} = V_S$ (supply voltage);
- for V_{IN} >0.7 V: V_{BE} = 0.7 V and V_{CE} = 0 V.

Note:
The input resistance of the transistor, seen by a sub-system connected to it, is not very high when the transistor is switched **on**. Consequently, significant loading of the sub-system can occur due to a relatively high current flowing from the input sub-system into the transistor.

This causes V_{IN} to be less than the theoretical value calculated using the voltage divider rule. As a result, the transistor may not switch on fully.

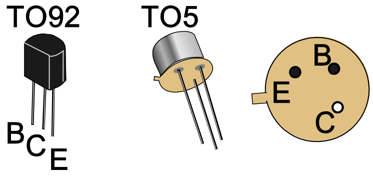
Selecting a Suitable Transistor

Key points to consider are:

- maximum collector current required;
- current gain, h_{FE}, required;
- cost.

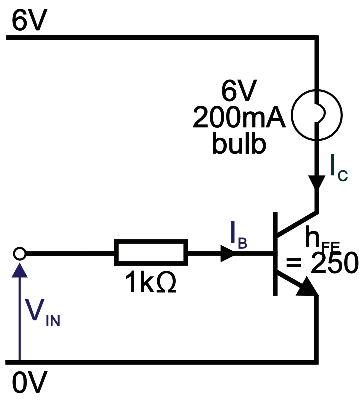
Power transistors, capable of delivering high collector current and of dissipating substantial power, tend to have low values of current gain, around 40. Small-signal transistors, where expected power dissipation is much smaller, have bigger values of current gain, around 500.

Transistor Packaging Types



Transistors come in a wide variety of encapsulations.
Some come encased in plastic, others in metal cans.
Part of the reason is the expected power dissipation.
Small plastic packages, like the TO92, can dissipate around a hundred milliwatts only. Metal-can types, like the TO5, can dissipate several watts.
(The prefix 'TO' stands for 'transistor outline'.)
Knowing the package type allows you to identify the collector, base and emitter.

Example 1:



The circuit opposite controls a warning lamp rated at 6 V, 200 mA.
It uses a transistor with a current gain, $\mathbf{h_{FE}}$, of 250.

The transistor is just saturated.
The lamp is working at its rated voltage and current.

Calculate:

a) the collector current, $\mathbf{I_C}$;

b) the base current, $\mathbf{I_B}$;

c) the voltage drop across the base resistor;

d) the value of $\mathbf{V_{IN}}$ that will just cause the transistor output to saturate.

a) When the lamp is fully lit and working at its rated voltage and current:

voltage across lamp = 6 V
collector current, $\mathbf{I_C}$ = 200 mA

b) Using the formula:

$$I_C = h_{FE} \times I_B$$
$$200 = 250 \times I_B$$
$$I_B = 0.8 \text{ mA}$$

When the lamp is working at its rated voltage and current, collector current, $\mathbf{I_B}$ = 0.8 mA.

c) Using Ohm's law: $V_B = I_B \times R_B$ where $\mathbf{V_B}$ = voltage drop across base resistor,

$\mathbf{R_B}$ = resistance of base resistor.

$$= 0.8 \times 1$$
$$= 0.8 \text{ V}$$

Voltage drop across base resistor = 0.8 V.

d) The transistor is just saturated.

Input voltage $V_{IN} = V_B + 0.7$
$= 0.8 + 0.7$
$= 1.5$ V

The value of $\mathbf{V_{IN}}$ that will just saturate the transistor output = 1.5 V.

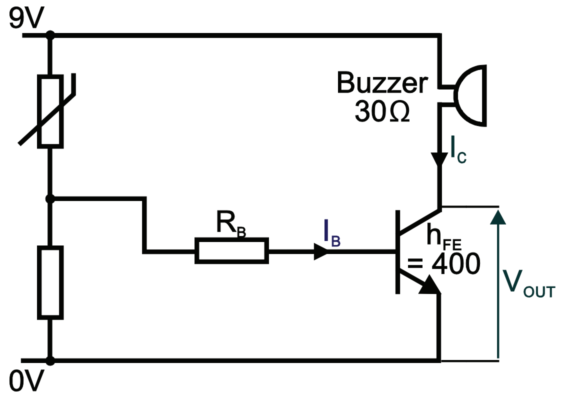
Example 2:

The temperature-sensing circuit switches on a warning buzzer when the temperature in the greenhouse gets too high. The circuit uses a transistor with a current gain, h_{FE} = 400.
The resistance of the buzzer is 30 Ω.

a) When the transistor is just saturated, calculate:
   i) the collector current, I_C;
   ii) the base current, I_B.

b) At a different temperature, the base current, I_B, is 0.5 mA. Calculate:
   i) the new value of collector current, I_C;
   ii) the new voltage across the buzzer.

c) When the base current, I_B , is 0.5 mA, the transistor becomes very hot. Suggest a reason for this.



a) i) When the transistor is just saturated, V_{OUT} will be 0 V.
Now, the full power supply voltage is dropped across the buzzer.
Assuming that Ohm's law applies to the buzzer:

$V_L = I_C \times R_L$ where V_L = voltage drop across the buzzer, R_L = resistance of buzzer.

$9 = I_C \times 30$

$I_C = 0.3$ A = 300 mA

When the transistor is just saturated, collector current, I_C = 200 mA.

ii) Using the formula: $I_C = h_{FE} \times I_B$

$300 = 400 \times I_B$

$I_B = 0.75$ mA

When the transistor is just saturated, base current, I_B = 0.75 mA.

b) The transistor was just saturated when the base current was 0.75 mA.
The base current has dropped to 0.5mA, so the transistor is no longer saturated.

i) Using the formula: $I_C = h_{FE} \times I_B$

$I_C = 400 \times 0.5$

= 200 mA = 0.2 A

With a base current, I_B, of 0.5 mA, collector current, I_C = 200 mA

ii) Using Ohm's law: $V_L = I_C \times R_L$ where V_L = voltage drop across the buzzer, R_L = resistance of buzzer.

= 0.2 × 30

= 6 V

With a base current, I_B, of 0.5 mA, voltage across buzzer = 6 V.

c) The transistor is now not saturated. The voltage across the buzzer is 6 V, so the voltage across the transistor, V_{CE} = (9 – 6) = 3 V.

The transistor is passing a current, I_C = 200 mA, and so power is dissipated in the transistor, resulting in it overheating.

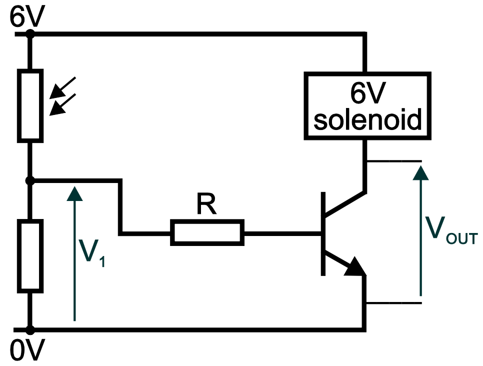
Example 3:

A light-sensing unit is connected to a transistor switch, to operate a solenoid when the light level gets too bright.

The solenoid is rated at 6 V, 800 mA and has a resistance of 7.5 Ω.

The transistor has a current gain (h_{FE}) of 200.

The transistor is **just** saturated and $\mathbf{V_1}$ = 4.2 V.



a) What is the voltage drop across resistor **R**?

b) Calculate the base current.

c) Calculate the ideal value of resistor **R**.

d) Choose a suitable preferred value for **R** from the E24 series of resistors.

e) Draw a graph to show how $\mathbf{V_{OUT}}$ changes as $\mathbf{V_1}$ increases from 0 to 5 V and use it to determine the value of $\mathbf{V_{OUT}}$ when $\mathbf{V_1}$ is 3 V.

f) The light level drops and $\mathbf{V_1}$ changes to 3 V. Calculate the value of the collector current and the power dissipated in the transistor.

a) Voltage drop across **R** = $\mathbf{V_1} - \mathbf{V_{BE}}$

$$= 4.2 - 0.7$$

$$= 3.5 \text{ V}$$

b) Base current:

$$I_B = \frac{I_C}{h_{FE}} = \frac{800}{200} = 4 \text{ mA}$$

(Here $\mathbf{I_C}$ = rated current of solenoid = 800 mA)

c) Ideal value of **R**:

$$R = \frac{V}{I_B} = \frac{3.5}{4} = 0.875 \text{ k}\Omega = 875\,\Omega$$

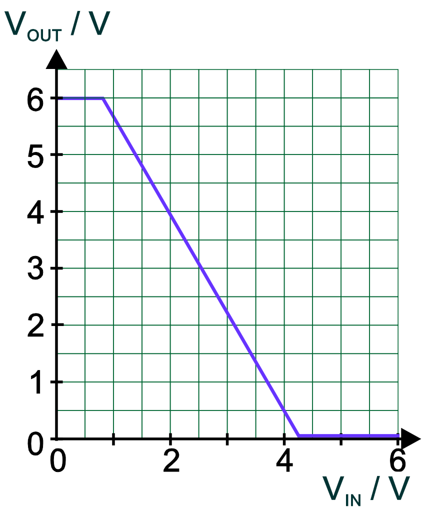
d) E24 preferred value for **R**:

The choice is either 820 Ω or 910 Ω.

For 910 Ω, the base current will be less than 4 mA and the transistor will not saturate.

Therefore choose 820 Ω.

e)



Note:

- initially, $\mathbf{V_1}$ = 0 V and $\mathbf{V_{OUT}}$ = 6 V;
- transistor starts to conduct when $\mathbf{V_1}$ ~ 0.7 V;
- $\mathbf{V_{OUT}}$ then decreases linearly until the transistor saturates at 4.2 V;
- after saturation, $\mathbf{V_{OUT}}$, remains constant at approximately 0 V.

From the graph, when $\mathbf{V_1}$ = 3 V, $\mathbf{V_{OUT}}$ = 2.4 V.

f) When $\mathbf{V_{OUT}}$ = 2 V, the voltage across the solenoid = 6 – 2 = 4 V.

Collector current

$$I_C = \frac{4}{7.5}$$
$$= 0.533\ \text{A} = 533\ \text{mA}$$

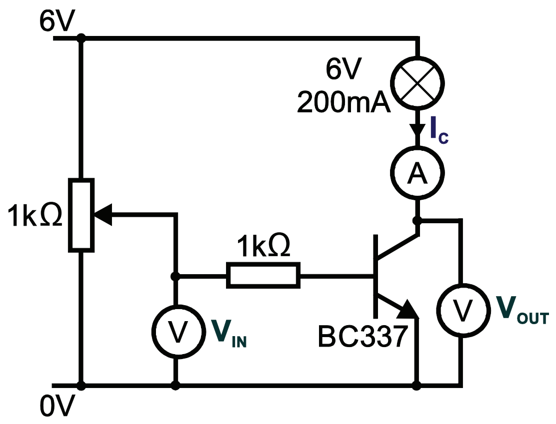
Power dissipated in transistor $= \mathbf{V_{OUT}} \times \mathbf{I_C}$
$= 2 \times 533$
$= 1066$ mW
$= 1.066$ W

Cautionary note:

Two issues result from working in the linear region:

- the solenoid is not working at its rated voltage and current;
- the transistor is dissipating more than 1 W of power.

Investigation 5.2

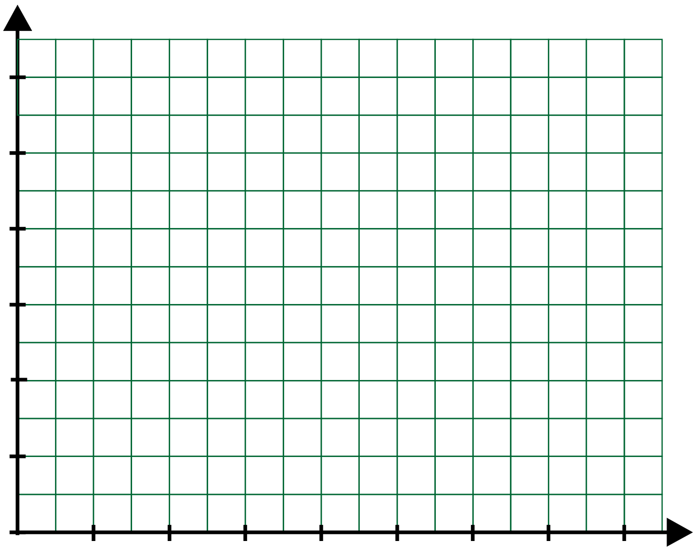


Set up the circuit shown on the right.

a) Adjust the potentiometer until V_{IN} = 0.5 V.
b) Measure the resulting collector current, I_C, and output voltage, V_{OUT}.
c) Complete the first row of the table with your results and comment on the brightness of the lamp.
d) Repeat this process for the other values of V_{IN}.

Input voltage V_{IN}	Output voltage V_{OUT}	Collector current I_C	Lamp brightness
0.5 V			
1.0 V			
2.5 V			
3.0 V			
3.5 V			

e) Plot a graph to show how V_{OUT} changes as the input voltage V_{IN} increases from 0 to 3.5 V. Label both axes clearly.



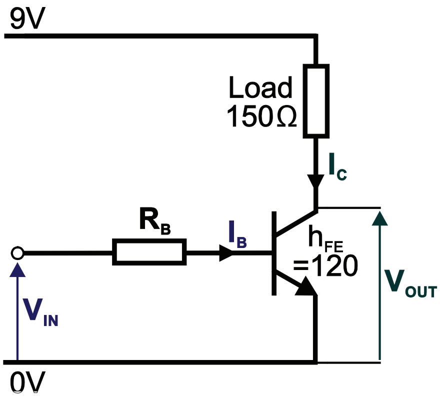
f) Estimate the value of input voltage at which the transistor just saturated. ………………

Exercise 5.3

1. The table gives information about three transistors.
Calculate the missing values and hence complete the table.

Transistor	Current gain h_{FE}	Base current I_B in mA	Collector current I_C in mA
1	50	4	
2	120		60
3		5	750

2. The transistor in the circuit opposite has a current gain, $\mathbf{h_{FE}}$, of 120.
When $\mathbf{V_{IN}}$ = 1.8 V, the transistor is **just** saturated.



a) When V_{IN} = 1.8 V calculate:

i) the collector current, $\mathbf{I_C}$

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ii) the base current, $\mathbf{I_B}$

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iii) the voltage drop across resistor $\mathbf{R_B}$

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iv) the value of resistor $\mathbf{R_B}$

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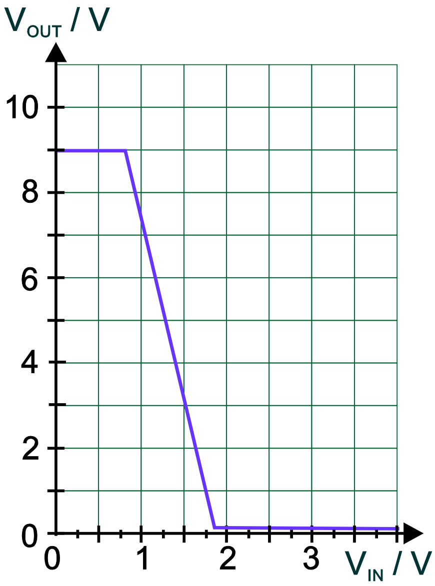
b) The graph shows how V_{OUT} changed as V_{IN} was increased from 0 to 3 V.



Use the graph to determine the value of V_{OUT} when V_{IN} is 1.3 V.

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f) Calculate the value of the collector current and the power dissipated in the transistor when V_{IN} is 1.3 V.

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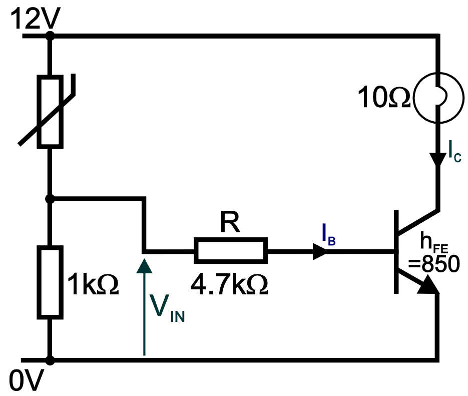
3. The diagram shows a temperature-sensing circuit which switches on a warning lamp when the temperature rises above a threshold value.



The transistor has a current gain (h_{FE}) of 850.
During testing, the base current, $\mathbf{I_B}$, was 0.8 mA when the temperature sat just above the threshold value.
However, the lamp, though lit, was only dim.
For a base current, $\mathbf{I_B}$, of 0.8 mA, calculate:

a) the value of the collector current;

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b) the voltage drop across the lamp which has a resistance of 10 Ω;

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c) the voltage V_{IN};

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d) the current through the 1 kΩ resistor;

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e) the resistance of the thermistor;
(Remember to include the base current in this calculation)

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f) Why is the lamp '…only dim…' under these conditions?

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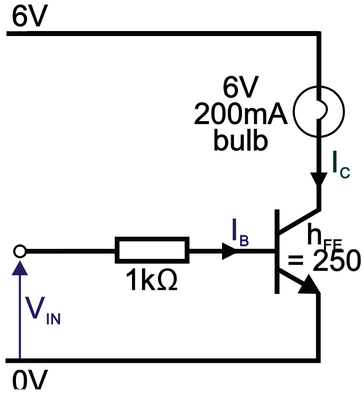
Loading a Voltage Divider Circuit

The loading of a voltage divider was mentioned earlier. We now consider how this affects the design of a transistor switching circuit.
Whenever a load is connected across the output of a voltage divider, the output voltage will drop. This **cannot** be avoided. The size of the voltage drop depends on the resistance of the load.
To illustrate this, we revisit the answers obtained earlier in Example 1.

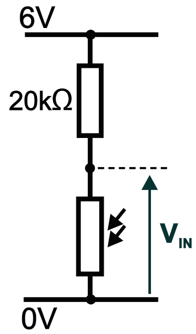


Example 1: (revisited)

The circuit opposite controls a warning lamp rated at 6 V, 200 mA.
It uses a transistor with a current gain, $\mathbf{h_{FE}}$, of 250.
The transistor is just saturated.
The lamp is working at its rated voltage and current.

Answers obtained

a) the collector current $\mathbf{I_C}$ = **200 mA**
b) the base current, $\mathbf{I_B}$ = **0.8 mA**
c) the voltage drop across the base resistor = **0.8 V**
d) the value of $\mathbf{V_{IN}}$ when the transistor output is just saturated = **1.5 V**



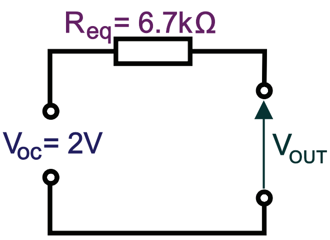
Assume that we want to use the system when the light level drops below 850 lux.
The light sensing sub-system is shown on the right..
At 850 lux the resistance of the LDR is 10 kΩ.
and so:

$$V_{IN} = \frac{R_2}{R_1 + R_2} V_S$$

$$= \frac{10}{20+10} \times 6$$

$$= 2\ \text{V}$$

This should be more than sufficient to saturate the transistor.
However, if you connect the light-sensing sub-system to the transistor switch, the bulb does not light up.
Thevenin's theorem helps us to understand what is happening:
The equivalent circuit for the light-sensing sub-system:



$$V_{OC} = \frac{R_2}{R_1 + R_2} V_S$$

$$= \frac{10}{20+10} \times 6$$

$$= 2\ \text{V}$$

$$I_{SC} = \frac{6}{20}$$

$$= 0.3\ \text{mA}$$

$$R_{EQ} = \frac{2}{0.3}$$

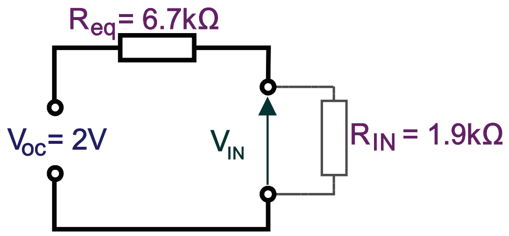
$$= 6.7\ \text{k}\Omega$$

We can use the answers to b) and d) provided earlier to work out the input resistance, $\mathbf{R_{IN}}$, of the transistor switch (at $\mathbf{I_B}$ = 0.8 mA):

$$R_{IN} = \frac{1.5}{0.8}$$
$$= 1.9\ k\Omega$$

Using the Thevenin equivalent circuit, the actual value of $\mathbf{V_{IN}}$ is:

$$V_{IN} = \frac{R_{IN}}{R_{EQ} + R_{IN}} V_{OC}$$
$$= \frac{1.9}{6.7 + 1.9} \times 2$$
$$= 0.4\ V$$



This value of V_{IN} is much smaller than the 1.5 V required to saturate the transistor.

Note:
$\mathbf{R_{IN}}$ is equal to the combined resistance of the base resistor and the resistance of the base-emitter junction. The value calculated for $\mathbf{R_{IN}}$ (1.9 kΩ) assumes that:

- the transistor is just saturating;
- the voltage across the base-emitter junction, $\mathbf{V_{BE}}$, is 0.7 V.

From our calculation for $\mathbf{V_{IN}}$, it is obvious that $\mathbf{V_{BE}}$ is much less than 0.7 V. Consequently, the value of $\mathbf{R_{IN}}$ will be more than 1.9 kΩ. This does not invalidate the analysis. It simply means that the situation is slightly worse than predicted, so that $\mathbf{V_{IN}}$ is actually slightly less than 0.4 V.

This example illustrates that care is needed when designing a transistor switch.
The analysis is time consuming and so engineers have developed a rule of thumb to provide a quick way to check the effect of loading voltage dividers:

Rule of thumb for voltage dividers

The current drawn by the load should be at least ten times smaller than the current flowing through the voltage divider.

Applying the rule to the above example:

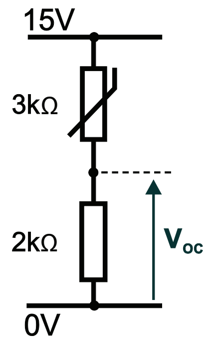
Base current required = 0.8 mA
so current through the voltage divider needs to be at least 8 mA

In fact, the current through voltage divider $I = \frac{6}{30}$
$= 0.2\ mA$

so the transistor cannot saturate.

Note:
Using a LDR to detect a low level of light will always be problematic because its resistance at low light levels could be well in excess of 100 kΩ, resulting in less than 1 mA flowing through the voltage divider.

Exercise 5.4



1. The temperature-sensing sub-system is used with a transistor switch that just saturates when the input voltage is 4 V.
At room temperature, the thermistor has a resistance of 3 kΩ.

a) Use Thevenin's theorem to calculate $\mathbf{V_{OC}}$ and $\mathbf{R_{EQ}}$ for the temperature-sensing sub-system at room temperature.

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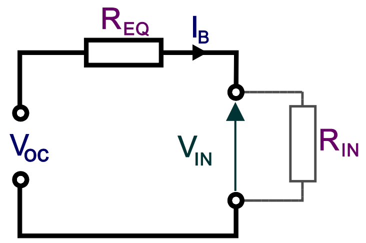
b) Use the equivalent circuit to determine the base current, $\mathbf{I_B}$, that will produce an input voltage, $\mathbf{V_{IN}}$, of 4 V to saturate the transistor.
$\mathbf{R_{IN}}$ represents the input resistance of the transistor base.



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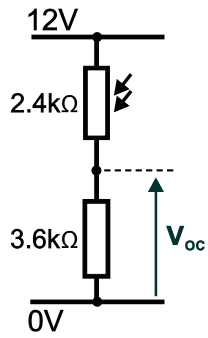

2. In the light-sensing sub-system shown opposite, the LDR has a resistance of 2.4 kΩ at a light level of 900 lux.

a) Use the voltage divider 'rule-of-thumb' to estimate the maximum output current that can be provided without loading the voltage divider.

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b) Use Thevenin's theorem to produce the equivalent circuit for the light-sensing sub-system. Label it with values of V_{OC} and R_{eq}.

c) The light-sensing sub-system is connected to a transistor switch.
Use the equivalent circuit to calculate the input voltage when the base current is equal to the answer in part a) above.

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d) Calculate the drop in its output voltage, as a percentage, when the light-sensing sub-system is connected to the transistor switch and comment on how well the 'rule-of-thumb' predicts the maximum acceptable output current available from the voltage divider.

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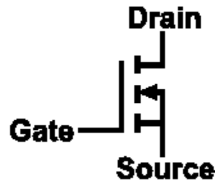
MOSFETs

These are part of a family of semiconductor devices called Field-effect transistors (FETs).
FETs can be subdivided in several ways:

- MOSFETs (Metal-Oxide-Silicon field effect transistors) and JFETs (Junction FETs)
- n-channel and p-channel devices
- depletion mode and enhancement mode devices.

This course focuses on only n-channel enhancement-mode MOSFETs.
The symbol for a MOSFET is shown opposite, along with labels identifying the terminals, called 'drain, 'gate' and 'source'.



BJT vs MOSFET

BJT:

- is a current amplifier – a small base current controls a much larger collector current;
- the input current flows through a forward-biased p-n junction, a small resistance, and so the resulting input current is relatively large;
- hence, the BJT has comparatively high input power requirements.

It is a **current**-controlled device – the collector current is controlled by the base **current**.

MOSFET:

- the gate is insulated from the remainder of the device, so the input current is negligible and can be assumed to be zero.

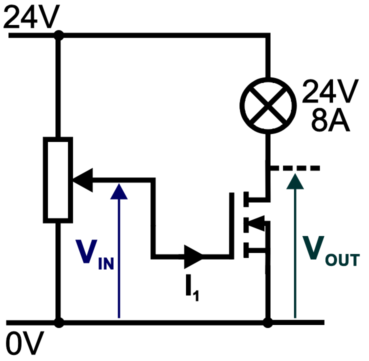
It is a **voltage**-controlled device – the drain current is controlled by the gate **voltage**.

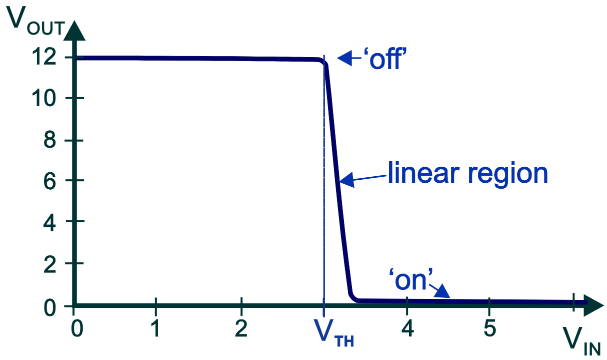
MOSFET Behaviour

The MOSFET is 'Off' when the gate voltage is zero.
A drain current starts when the gate-source voltage (V_{GS}) is just below the value of the gate-threshold voltage V_{TH}. This positive voltage reduces the overall resistance of the device allowing current to flow between drain (D) and source (S).
Increasing this positive gate voltage above V_{TH} increases the drain current, I_D. The MOSFET saturates when V_{GS} is increased sufficiently. At this point, the resistance between the drain and source, r_{DS}, reaches its lowest value, known as r_{DSon}, typically between 0.05 Ω and 1 Ω.

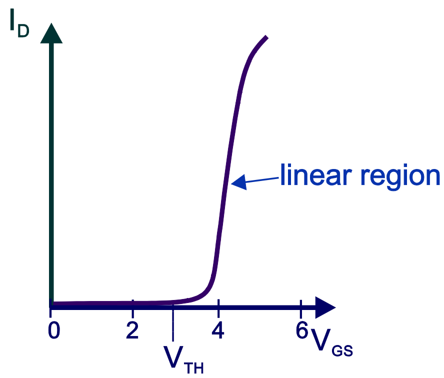
Voltage Transfer Characteristic for a MOSFET

This shows the relationship between $\mathbf{V_{OUT}}$ and $\mathbf{V_{IN}}$ for the MOSFET.





The graph illustrates typical MOSFET behaviour as V_{IN} is gradually increased from 0V
The MOSFET transfer characteristic is similar to that of the BJT transistor, but with one major difference – the linear region is very small, making it very unlikely that the MOSFET will operate in this region.
The exact voltages at which 'Off' ends and 'On' begins depend on the device itself.
The linear region is so called because of a linear relationship between drain current, $\mathbf{I_D}$, and gate-source voltage, $\mathbf{V_{GS}}$, for a range of values of $\mathbf{V_{GS}}$, above the threshold voltage, $\mathbf{V_{TH}}$, as the second graph illustrates.



The gradient of the graph in the linear region is known as the mutual conductance, $\mathbf{g_M}$, of the MOSFET.

To a good approximation: $g_M = \dfrac{I_D}{V_{GS} - V_{TH}}$

Using 3 V as a typical value for the threshold voltage, $\mathbf{V_{TH}}$ leads to the equation:

$$I_D = g_M\,(V_{GS} - 3)$$

Typical values for transconductance are 2 to 10 S (S = siemens = A/V).
Enhancement-mode MOSFETs make excellent electronics switches, because of their low 'ON' resistance, extremely high 'OFF' resistance and extremely high input resistance. (The input resistance is so high that the gate current is negligible and can be assumed to be **zero.)**
This means that they can be driven directly from sub-systems, such as logic gates, that can only provide a very small current or from sensing sub-systems. In other words, they do not 'load' the input sub-system.
The problem that can arise when a voltage divider is connected to a transistor switch is not an issue with a MOSFET switch.
Power MOSFETs can handle very large currents up to hundreds of amps.
However, the high input impedance of the MOSFET also means that static electricity can easily damage them by building up high voltages on the device.
Handle them carefully!

- Keep them in their anti-static conductive packaging as long as possible;
- Where possible, 'ground' yourself by touching a grounded metal object, such as a copper water pipe before handling them.

Switching – Power Considerations

Electrical power **P** is given by the formula: **P = I × V**
The danger for semiconducting, switching devices is that they can overheat during switching.
An ideal switch is either on or off. It dissipates no power in either state.

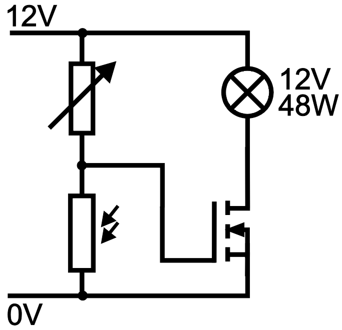
- When switched **off**, the current **I** is zero and so the power dissipated in them is zero.
- When switched **on**, the voltage **V** is zero and so the power dissipated is zero.

However, in practice, while the switching device is turning on or off (passing through the linear region), it is passing a current and so the voltage across it is **not** zero. It is dissipating power and getting hot. The power dissipated can be appreciable. The solution is very fast switching from one state to the other.

The BJT is not good at this. For high currents and voltages (i.e. high power loads), transistors do not make good switching devices. The smaller linear region and faster switching time of the MOSFET make it more suitable as a switch, though a heat-sink may be needed in high power applications.

Example 1:

The circuit diagram shows a light-sensing unit and MOSFET, controlling a high-powered lamp.
An extract from the data sheet for the MOSFET is shown below:



V_{DS}/V (max)	V_{GS} /V (max)	I_D /A (max)	r_{DSon}/W (typical)	P_{TOT} /W (max)	g_M /S (typical)
50	15	8	0.24	50	1.3

a) Calculate the minimum voltage from the light-sensing unit that allows the lamp to operate at its full power.

b) Calculate the power dissipated in the MOSFET when the lamp is operating at full power.

a) When the lamp is switched on at full power, using the power formula:

$$P = I \times V$$
$$48 = I \times 12$$
$$I = 4\ A$$

The current through the lamp = 4 A

Using the formula: $I_D = g_M (V_{GS} - 3)$

$$4 = 1.3\,(V_{GS} - 3)$$
$$\left(\frac{4}{1.3}\right) = (V_{GS} - 3)$$
$$V_{GS} = \left(\frac{4}{1.3}\right) + 3$$
$$= 6.1\ V$$

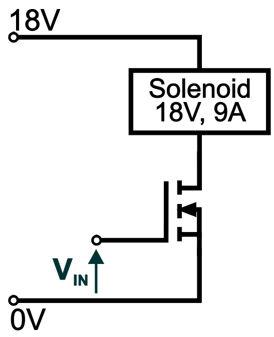
Voltage V_{GS} is the same as the output voltage of the light-sensing unit. Hence, to make the lamp operate at full power, the minimum voltage from the light-sensing unit is 6.1 V.

b) The power dissipated in the MOSFET is given by the formula:

$$P = I_D^2 \times r_{DSon}$$
$$= 4^2 \times 0.24$$
$$= 3.8\ W$$

The MOSFET dissipates 3.8 W when the lamp is operating at full power.

Example 2:



The circuit shows a MOSFET used to interface a logic system to a solenoid rated at 18 V, 9 A.
When activated, the logic system provides a signal V_{IN} of 5 V
Calculate the minimum value of mutual conductance, g_M, required to allow the solenoid to operate at its rated current.

Using the formula:

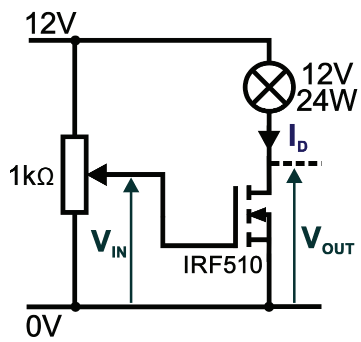
$$I_D = g_M (V_{GS} - 3)$$
$$9 = g_M (5 - 3)$$
$$g_M = \frac{9}{2}$$
$$g_M = 4.5\text{ S}$$

The minimum value of mutual conductance is 4.5 S.

Example 3:

A MOSFET has a mutual conductance, g_M, of 1.8 S. The input voltage is set to 7.5 V.
What is the maximum load current, I_D, possible with this value of input voltage?
Using the formula: $I_D = g_M (V_{GS} - 3)$
$= 1.8 \times (7.5 - 3)$
$= 8.1$ A.
The maximum load current is 8.1 A.

Investigation 5.3

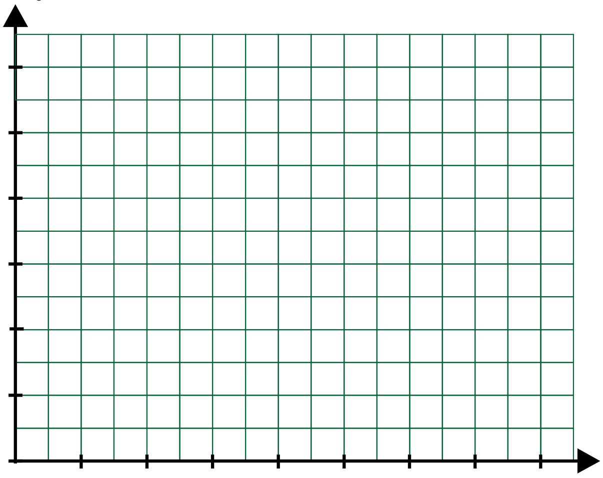


Set up the circuit shown on the right.

a) Adjust the potentiometer until the input voltage, V_{IN}, is 1.0 V.
b) Measure the output voltage, V_{OUT}, and drain current I_D and record them in the first row of the table.
Comment on the brightness of the lamp.
c) Complete the table for the other values of input voltage V_{IN}.

V_{IN} (V_{GS})	V_{OUT} (V_{DS})	I_D	Lamp brightness
1.0 V			
2.0 V			
3.0 V			
4.0 V			
5.0 V			
6.0 V			
7.0 V			
8.0 V			

d) Plot a graph to show how V_{DS} changes as V_{GS} increases from 0 to 8.0 V.
Label both axes clearly.



e) Use the graph to determine the value of V_{GS} at which the MOSFET is just saturated and hence estimate the value of r_{DSon}.

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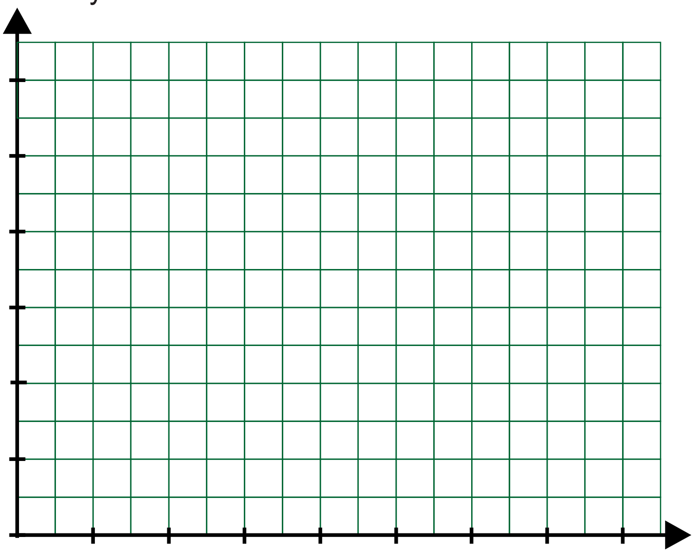
f) Plot a graph to show how I_D changes as V_{GS} increases from 0 to 8.0.
Label both axes clearly.



g) Use the graph to estimate:

i) the gate-threshold voltage V_{TH} …………………………………………………………….

ii) the value of g_M (by determining the gradient of the graph in the linear region).

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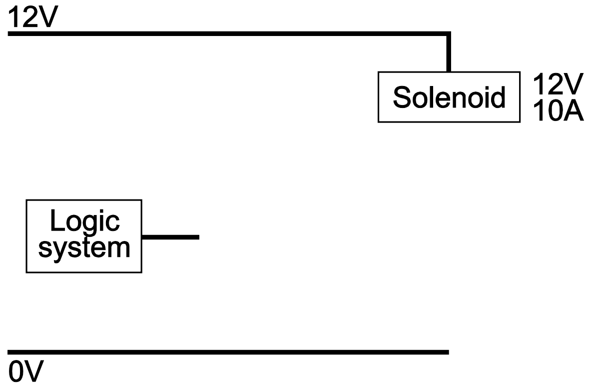
Exercise 5.5

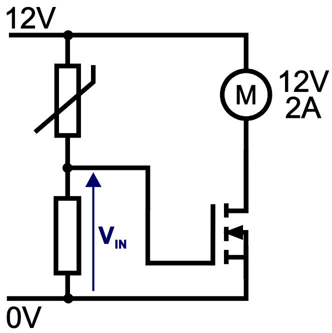
1. The output of a logic system controls a solenoid, which requires a current of 10 A.
Complete the diagram below by adding:

a) a suitable switching device and its connections;

b) a component to protect the switching device from back emf.



2. The circuit diagram shows a MOSFET used to control a fan motor.
The MOSFET has a transconductance, $\mathbf{g_M}$, of 3.0 S and on-resistance (minimum), $\mathbf{r_{DSon}}$, of = 0.35 Ω.



a) What is the minimum value of $\mathbf{V_{IN}}$ that allows the motor to run at its rated current?

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b) Calculate the power dissipated in the MOSFET when the motor is operating at full power.

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3. A light-sensing unit produces a maximum output voltage of 6.7 V.
A MOSFET connected to it has a transconductance, g_M, of 2.3 S.
Calculate the maximum load current, I_D, when the light-sensing unit outputs 6.7 V.

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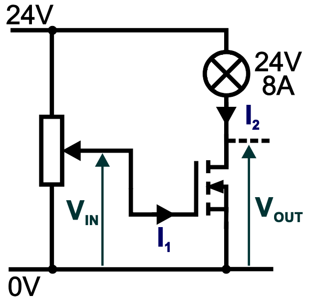
4. The following circuit is used to investigate a MOSFET.
The table lists some of the results obtained with the MOSFET just saturated:



V_{IN} /V	V_{OUT} / V	I_2 /A
4.8	0.45	7.96

a) **Estimate** the value of I_1 ....

b) Use the results to calculate the value of:

i) g_M;

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ii) r_{DSon}.

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c) Calculate the power dissipated in the MOSFET when the lamp is operating under the conditions shown in the table of results.

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