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Simplifying Electricity

## Battery and high voltage systems

Contents

Worksheet 1

Testing Sealed Lead-Acid batteries

There are number of ways to test a battery, but, ultimately, the only sure way is to test its energy-storage capacity. This involves charging it and then discharging it, making measurements of energy intake and output as you do so.

The Sealed Lead-Acid battery (SLA) provided is a small one but it behaves just like the larger lead- acid batteries you find in vehicles.

The photograph shows a Voltcraft battery tester.
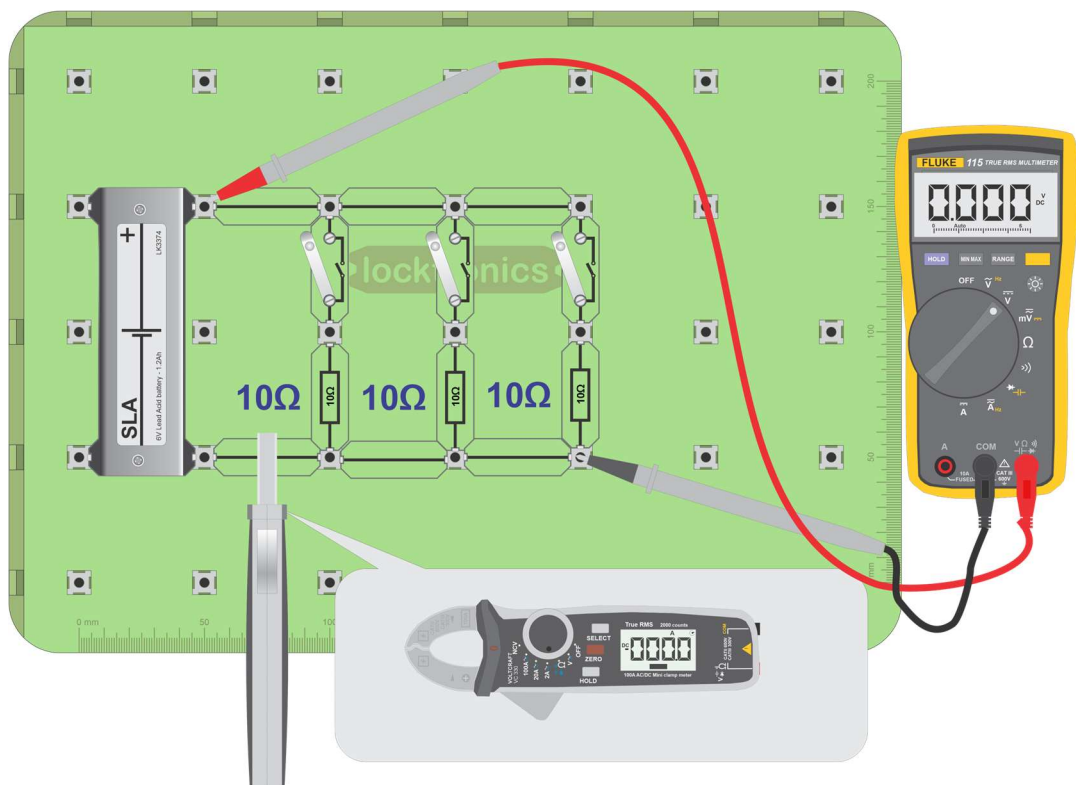
Over to you:

- Build the circuit shown above but leave the switches open for now.
- Configure the multimeter to measure DC volts.
- Configure the current clamp to measure DC amps and 'zero' it.
- Connected as shown, the meters measure the output voltage and current of the battery.

Worksheet 1

Testing Sealed Lead Acid batteries

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Over to you continued ...

- Measure these and record them in the table in the Student Handout.
- Close the first switch briefly and measure output voltage and current again.
- Close the second and then third switch, briefly, and repeat the process.
- Note down all readings in the Student Handout.

So what?

- You made a battery tester and used it to measure elements of the performance of the SLA battery. The circuit diagram for this tester is shown opposite.
- Batteries are more complex than they may appear. To understand their behaviour, it helps to think of them as a combination of a battery and a series resistor, **R**.
  R is called the 'internal resistance'.

- For lead-acid cells the internal resistance of a battery becomes higher when the battery *'state of charge'* (SOC) is low and as the battery ages.
- Many simple lead-acid battery testers show you the effects of this internal resistance.
- As the internal resistance increases, more of the voltage is dropped across it and the battery output voltage falls eventually to below an acceptable level.
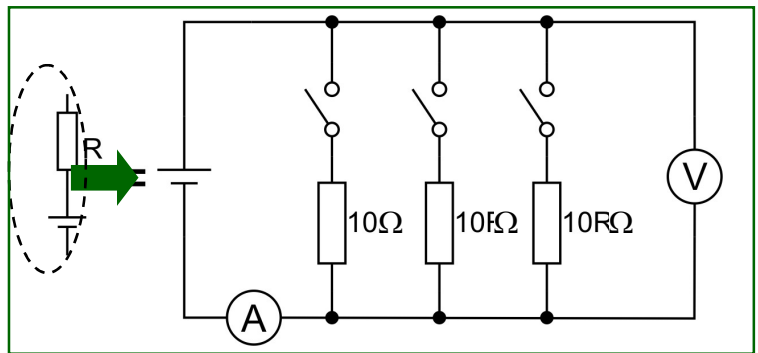
Over to you again:

- Using the same circuit with all switches open, measure the initial output voltage.
- Close two switches and measure battery output voltage and current.
- Repeat this process after five minutes and then after ten minutes.
- Record your results in the table in the Student Handbook.

So what?

- The energy capacity of the battery, C, indicates how much energy it can store. It is measured in units called 'amp.hours, (Ah). This battery is rated at '6V 1.2Ah', meaning that, when fully charged, it should deliver a current of approximately 1.2A at 6V for 1 hour.
- As a rule of thumb, if this battery is fully charged, when you draw 1.2A for 10 minutes (i.e. two switches closed) the battery is probably satisfactory if the voltage stays above 5.5V under this load.
- Simply measuring the output under no load is not a good enough test for lead-acid batteries.
- Using a quick and simple load test, like the one above, allows you to say with some degree of certainty that a battery is satisfactory.
- The only real way to test a battery with 100% certainty is to discharge it, charge it fully, and then discharge it whilst making sure that it supplies the rated current for the rated time.

Worthsheet 2

Charging Sealed Lead Acid batteries

The car alternator is continually charging the lead-acid battery whilst, at the same time, its output is also used by the car's electrical system.

Just like when testing lead-acid batteries, the proper charging process is more complex than it may at first seem. The current needed and charging time depend on the battery's initial SOC.

For this SLA battery, one recommended method is to charge it at 10% of its amp.hour rating for 24 hours. The amp.hour rating for the SLA used here is 1.2Ah, implying a charging current of 0.12A for 24 hours.

The photograph shows a garage-based battery charger.
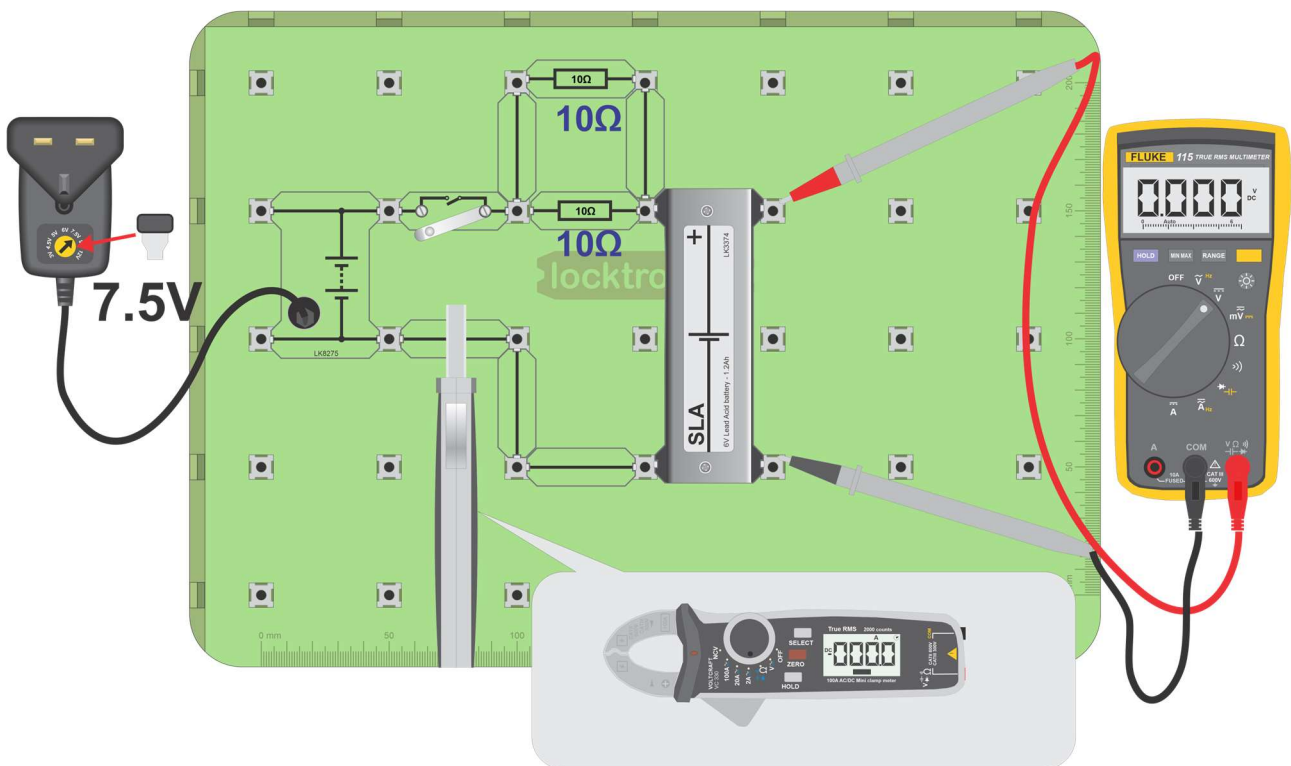
Over to you:

- Construct the circuit shown above.

Woruksheet 2

Charging Sealed Lead Acid batteries

Over to you continued...

- Measure the initial battery voltage with the switch open.
- Close the switch.
- Measure the charging current from the power supply and battery voltage.
- After five minutes, note the battery voltage and charging current again.
- Briefly, open the switch and measure the open-circuit voltage again.
- Close the switch and continue charging the battery.
- Repeat this process after 10 minutes.
- Complete the table in the Student Handout with your measurements.

So what?

- As the *State of Charge (SOC)* increases, the open-circuit battery voltage rises.
  (It may be difficult to see much of a change in such a short time.)
  This voltage will also change as the battery settles once charging is finished.
- With a simple voltage source power supply, like the one used here, the current reduces as the SOC increases. (SLA batteries are quite robust and withstand erratic charging like this.)

- The graph gives typical SOC voltages for 6V and 12V SLA batteries.
- It shows how SOC changes with battery voltage and can be used to predict SOC from battery voltage.
- In practice, a 12V SLA battery usually reads an output voltage of around 12.7V and a 6V SLA battery around 6.4V.
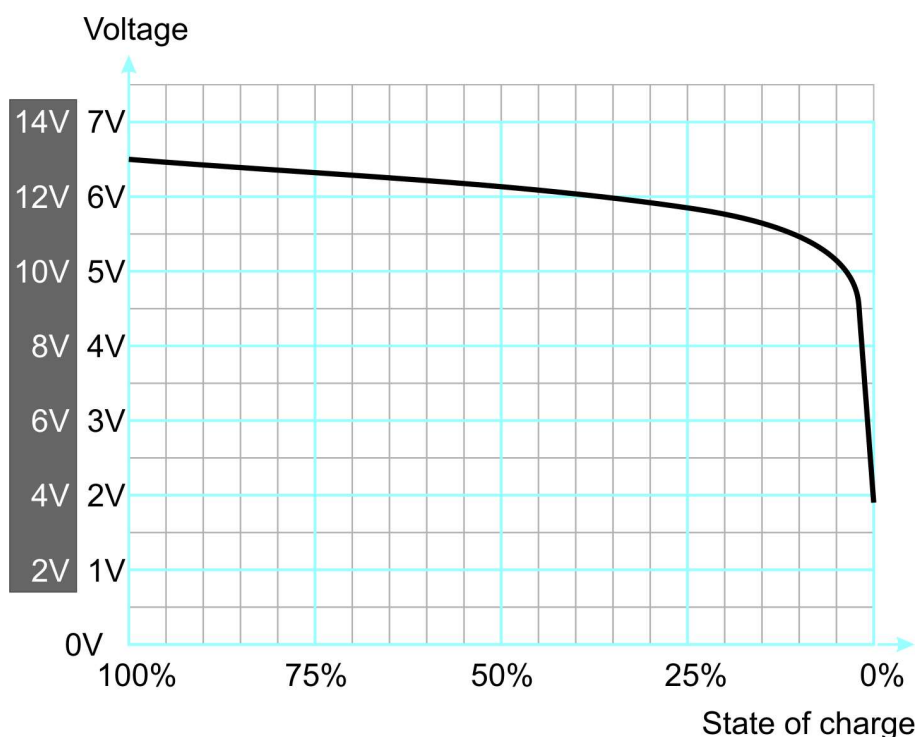
Worksheet 3

Testing Li-ion cells

In practice, lithium-ion (Li-ion) battery packs are made up of a large number of 'cells'. Testing the whole battery is difficult and so each cell, or group of cells, is monitored separately by the battery management system.

The photograph shows the interior of a Tesla battery with hundreds of small Li-ion cells identical to those in your kit. They are known as '18650' cells. In the kit, they are housed in a metal case because they can catch fire or explode if mistreated.
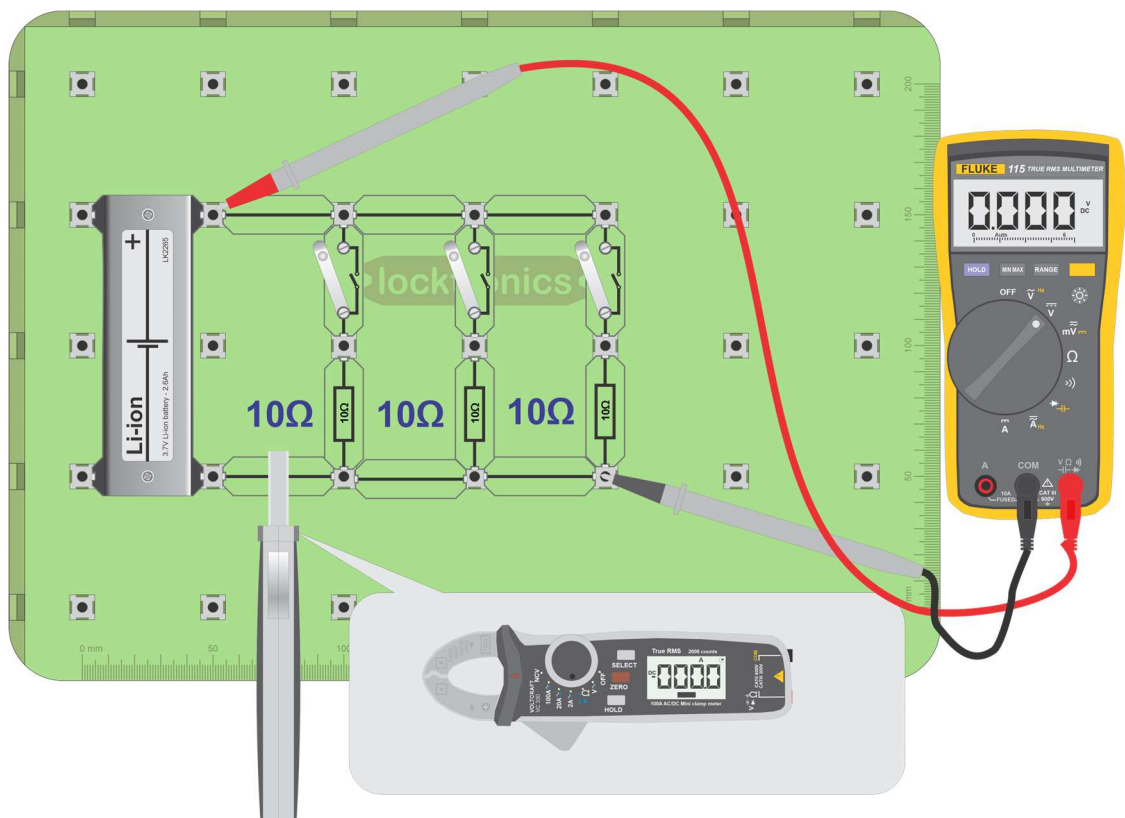
Do not discharge the batteries below 3.2V

Over to you:

- Construct the circuit shown above but leave the switches open for now.

Worknsheet 3

Testing Li-ion cells

Over to you:

- Configure the multimeter to measure DC volts.

- Configure the current clamp to measure DC amps and 'zero' it.

- Measure the battery output voltage and current as shown.

- Close the first switch briefly and measure output voltage and current again.

- Close the second and then third switch, briefly, and repeat the process.

- Note down all readings in the Student Handout.

So what?

You should have noticed two obvious differences between the Li-ion and SLA batteries:

- their output voltage is very different - around 3.7V for the Li-ion cell compared to around 6.3V for the SLA battery;

- Li-ion cells have a much smaller internal resistance than the SLA batteries, allowing them to deliver huge power for their small volume.

Worksheet 4

Charging Li-ion cells

Batteries convert chemical energy into electrical energy and vice-versa. They can be charged in a number of ways - slowly with a low current 'trickle' charge or quickly with a high current charge.

Charging time is becoming more important as the need to recharge cars mid-journey becomes a necessity.

The photograph shows a Tesla 18650 battery cell.

4.5V
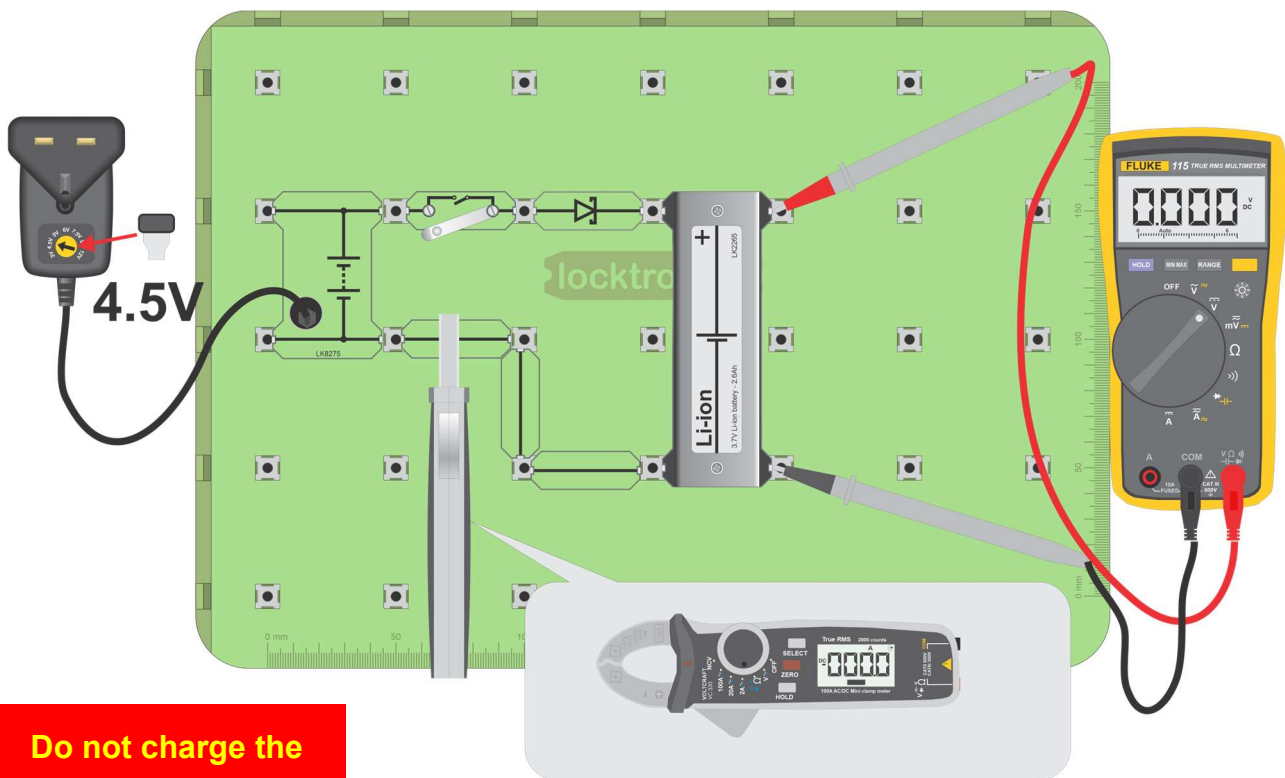
Do not charge the batteries above 4.2V

Over to you:

- Construct the circuit shown above.
- The circuit above delivers around 4.1V to the Li-ion battery. Check the voltage with your meter.

Caution: if you mistreat Li-ion batteries they can catch fire. Do not use any other charger than the one supplied with this kit and make sure you use the correct voltage and the Schottky diode in series.

Worksheet 4

Charging Li-ion cells

Over to you continued...

- Measure the initial output voltage with the switch open.
- Close the switch.
- Measure the charging current from the power supply and battery voltage.
- After five minutes, note the output voltage and charging current again.
- Briefly, open the switch and measure the open-circuit voltage again.
- Close the switch and continue charging the battery.
- After ten minutes, and then after 15 minutes, repeat this process.
- Complete the table in the Student Handout with your measurements.

So what?

- The results depend on the state of charge of the cell.
- In general, the output voltage of a Li-ion cell varies less with SOC than it does for a SLA battery.
- The graph shows typical output voltage variation with SOC for Li-ion cells.
- At high SOC, the output voltage can be up to 4.5V.
- In the middle section, the curve is very flat at around 3.7V.
  This makes it impossible to deduce the state of charge from voltage alone.
- The voltage really tails off in the last 10% of SOC.
  In practice, we should not let Li-ion cells fall to below 20% of SOC.
- Note that the shottky diode in the circuit drops the power supply voltage from 4.5V to 4.3V.
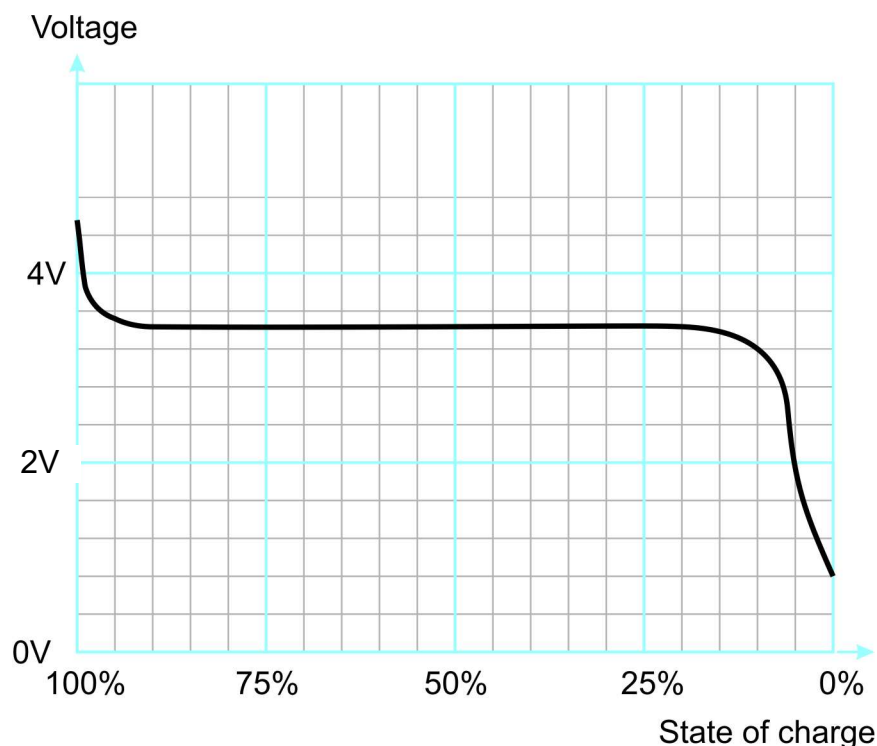
Worksheet 5

Building larger batteries

Larger batteries are made by connecting smaller batteries in series and / or parallel.

For example, a Tesla car battery is made up of 7,000 of the 18650 batteries like the one in your pack.

The photograph shows a Metal-nickel hydride cell from a Toyota Prius. These 7.2V packs are made up
of six 1.2V cells.
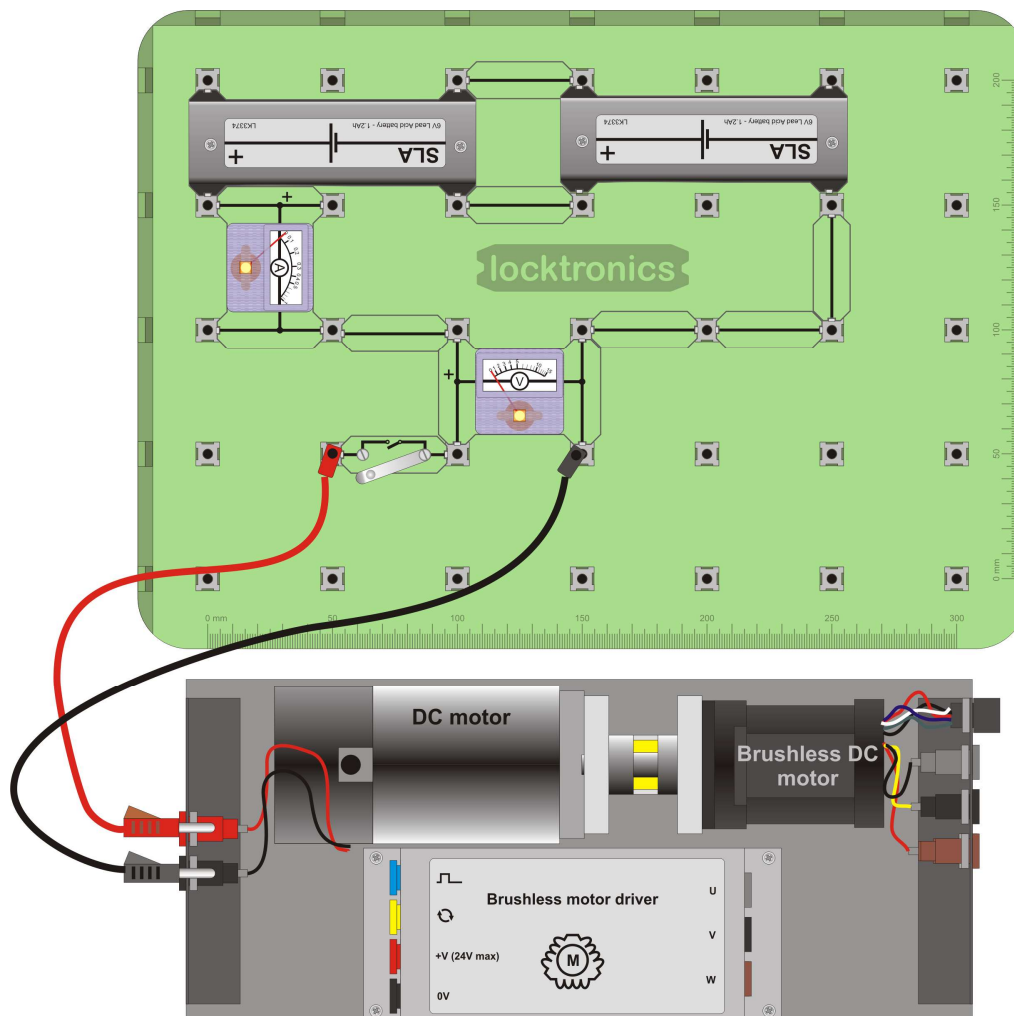
Over to you:

- Using two 6V SLA batteries, build the layout shown above.
- Close the switch - the DC motor/Brushless motor coupled pair should rotate.
- Measure the battery output voltage and current and record them in the Student Handout.
- Calculate the power delivered to the motor.

Worksheet 5

Building larger batteries
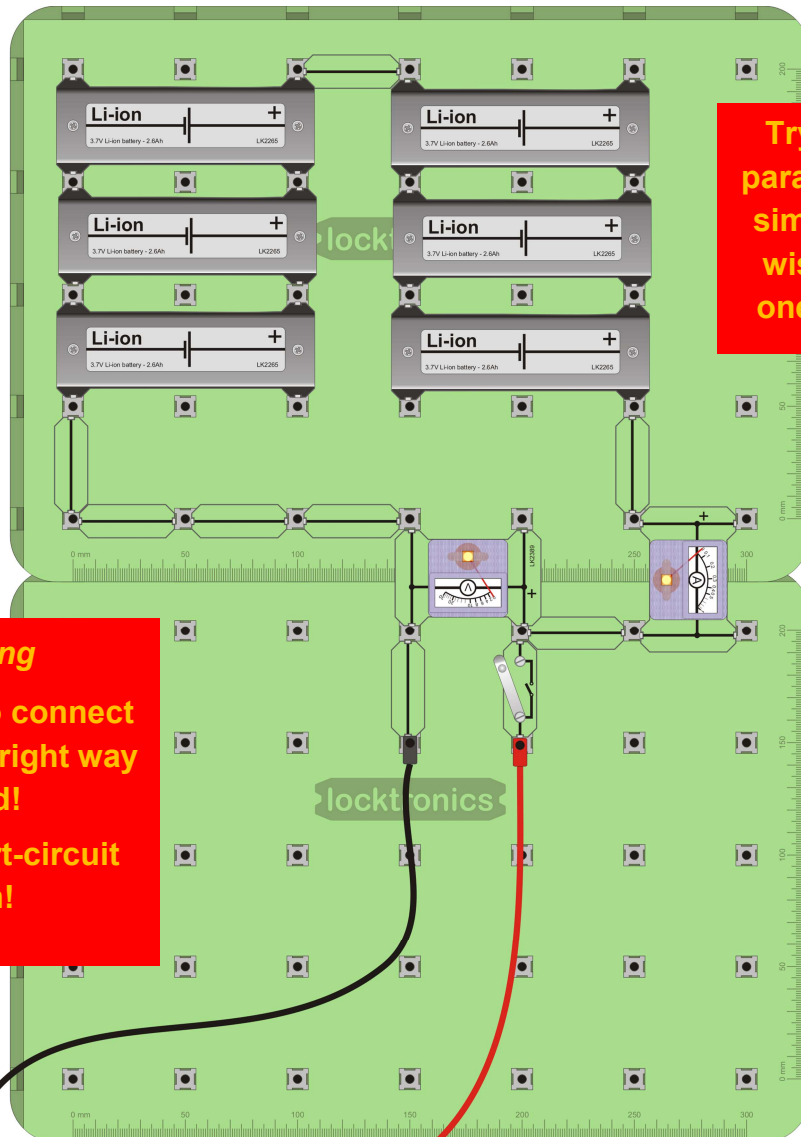
Try to match cells in parallel with others of a similar voltage: otherwise you just charge one cell with another.

Warning

Be careful to connect the cells the right way round!

Do not short-circuit them!
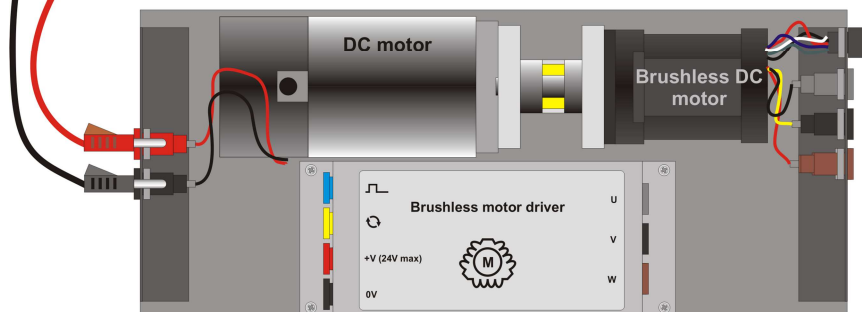
Over to you continued ...

- Use six Li-ion cells, two sets of three, or 2,3, to build the battery shown above.
- Measure battery output voltage and current and calculate the power output: V x I.
- Record all your results in the Student Handout.

Worksheet 5

Building larger batteries

So what?

- The circuit you built is shown in the circuit diagram below. It is known as a '2 by 3' battery or, simply, a 2,3 battery, meaning that it is made up of two sets of three parallel cells, connected in series. The output voltage is twice the cell voltage, i.e. 2 x 3.7V = 7.4V.
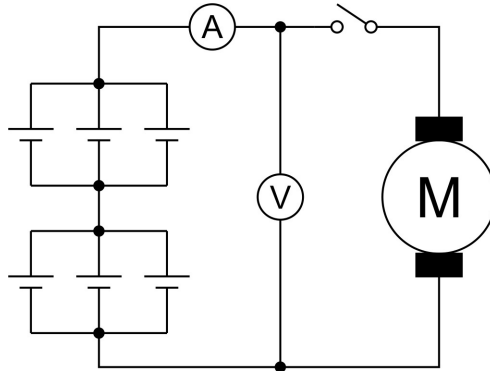
- The following table shows you how to calculate the power rating of the larger battery:

Cell voltage	A	3.7	V
Individual cell current rating	B	2.6	Ah
Cells in parallel	C	3	
Groups of cells in series	D	2	
Combined power rating	A x B x C x D	57.72	Wh

So what?

- Battery voltage and current capability can be changed by simply changing the number of batteries in series and parallel

- The Power rating of a battery is the voltage multiplied by the one hour current rating.

- Batteries are scalable. We can refer to a 2,3 battery as a 'module'. Then we can add other modules in series and parallel to build an even larger battery.

> ***Warning* - Be careful to connect the cells the right way round!**

Worksheet 5

Building larger batteries

Challenge 1:

- Build the 3,2 battery module shown in the circuit below. You can use the diagram to help you.
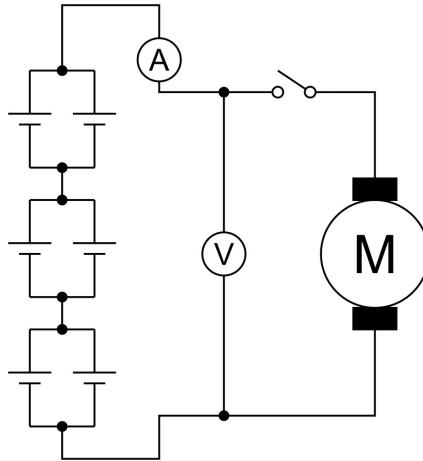
- Measure the battery module output voltage and current and calculate the power delivered to the motor.
- Use the current clamp meter and multimeter to improve accuracy.
- Record all your results in the Student Handout.
- Calculate the power rating for the 3,2 battery using the table in the 2,3 calculation above.
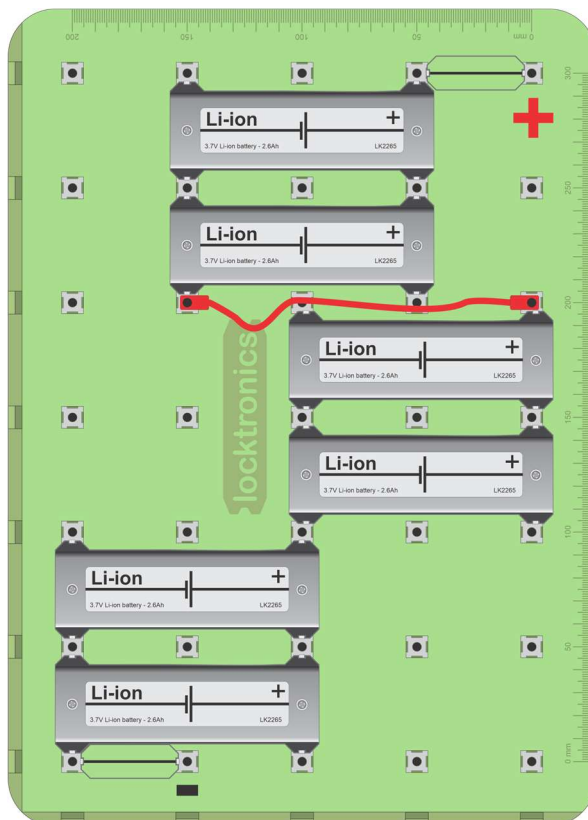
A 3,2 battery module

Worksheet 5

Building larger batteries

Challenge 2:

- Build the 6,1 battery module shown in the circuit below.

<div style="background-color:red; color:white;">

Warning **- Be careful to connect the cells the right way round!**

</div>

- Measure the battery output voltage and current and calculate the power delivered to the motor.
- Again, use the current clamp meter and multimeter to improve accuracy.
- Record all your results in the Student Handout.
- Calculate the power rating for the 6,1 battery
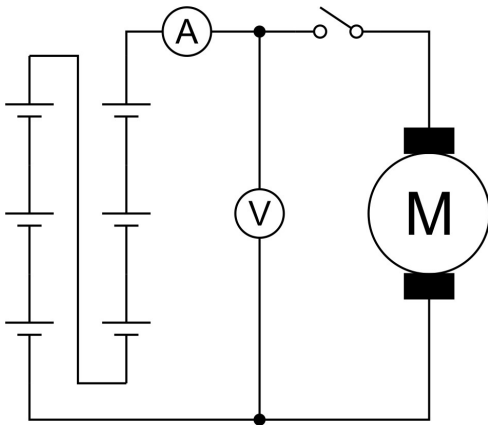
So what?

- You can build batteries with different output voltages, current and power capacities by varying the number of cells and their series / parallel configuration.

- You can keep the assembly in place as you will be using this for the next few experiments.
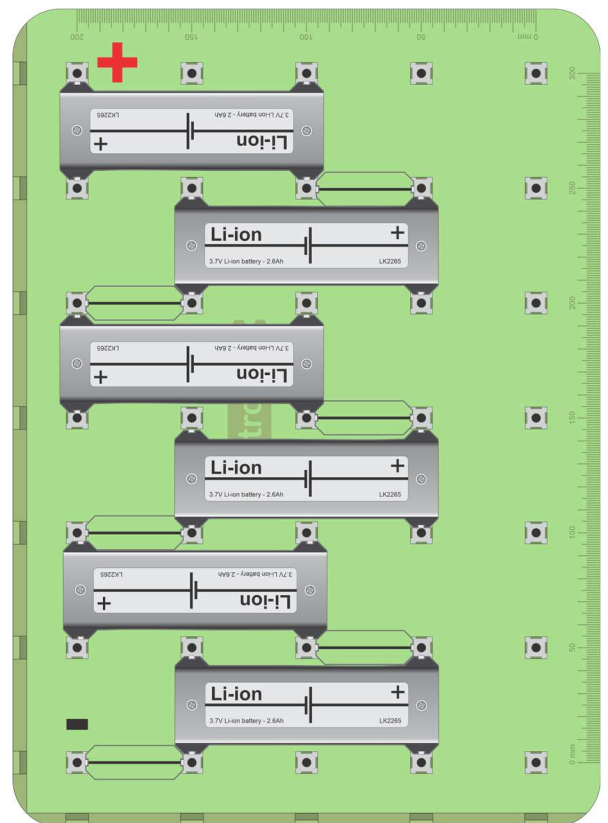
Challenge 3:

A Tesla model S battery pack contains 6,912 '18650' cells.
These are arranged in sixteen modules, or bricks, each containing 432 cells arranged with 72 cells in parallel, 6 groups of 72 batteries in series.

- What is the voltage of each brick?
- What is the total battery output voltage?
- What is the theoretical total power rating, in watt.hours, of the whole battery?
- Record your answers in the Student Handout.

Worksheet 6

Li-ion battery faults

Resolving faults in battery packs is made easier by the reports (or clues) that on-board computers give.

There are two main causes of failure in a battery pack:
- bad cells;
- bad links between cells.

The photograph shows corrosion on the battery links in a Toyota Prius.
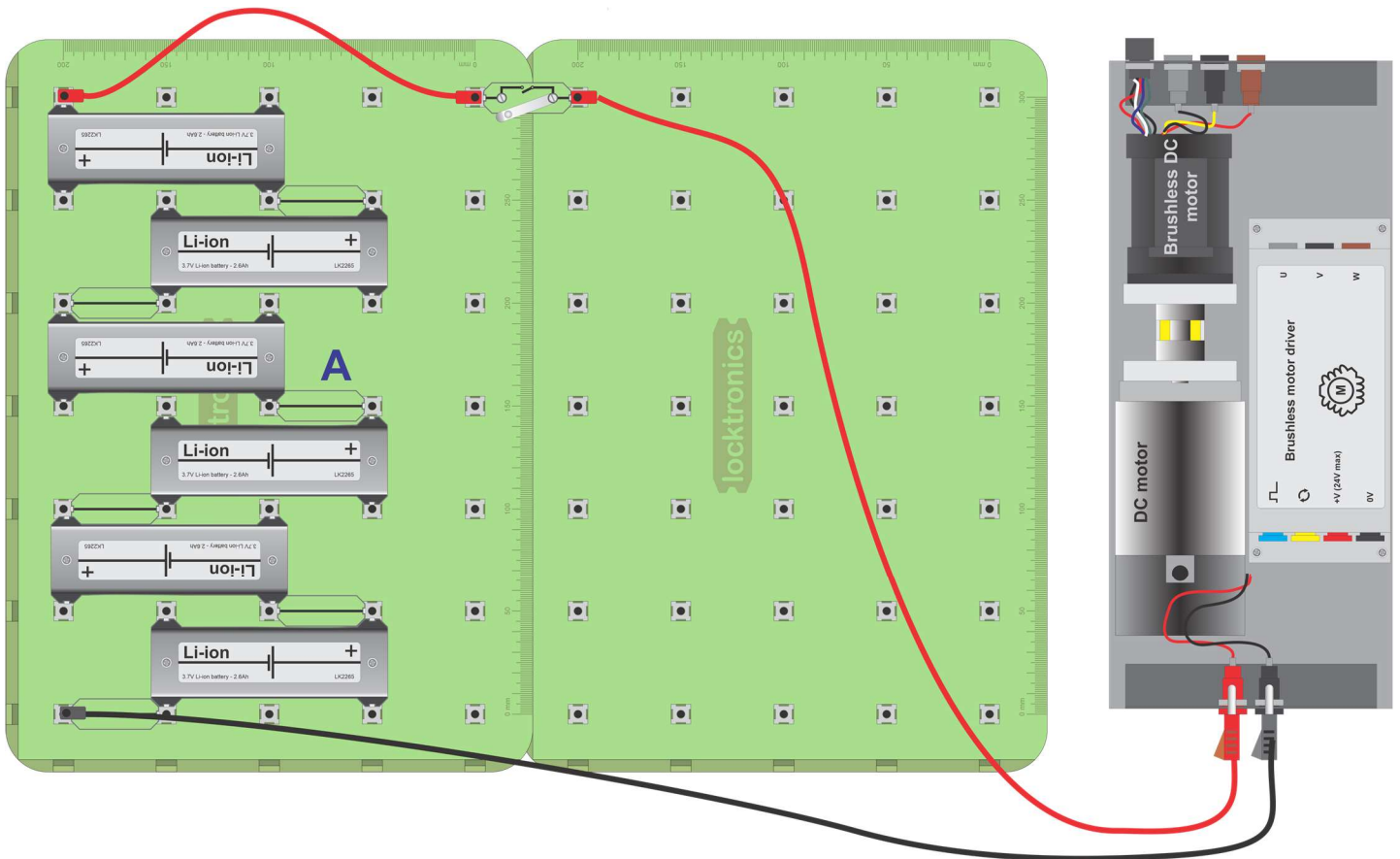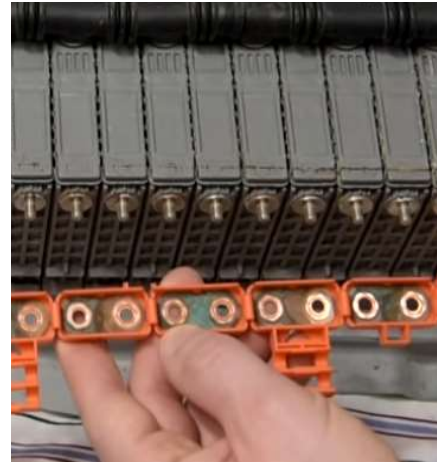
Over to you:

- Build the 6,1 battery as shown above but with the switch open for now.

> *Warning -* **Be careful to connect the cells the right way round!**

- Measure the battery output voltage.
- Turn on the switch to power the motor.
- Measure the battery output voltage again.

Worksheet 6

Li-ion battery faults

Over to you continued ...

- Open the switch.
- Change the central link **A** for the fault component 'corrosion'.
- Measure the battery output voltage again - no load.
- Turn on the switch to power the motor.
- Measure the battery output voltage again.
- Measure the voltage across the corrosion component.
- Record all your results in the Student Handout.

So what?

- The 'corrosion' component was used to simulate a fault. Corrosion on contact terminals adds resistance to the circuit. Bad or loose contacts can also behave like added resistance.
- Testing for corrosion or bad contacts is difficult in isolation. Battery voltages appear normal when tested with a multimeter. The effects are noticed only when a large current is drawn.
- In an electric vehicle, the battery management system constantly tests the voltage from battery cells.

Over to you:

- There are six Li-ion cells in your kit. The nominal output voltage for each is around 3.7V for SOC values between 15% and 90%.
- Measure the output voltage of each with a multimeter and record your results in the table in the Student Handout.
- If you see a voltage above 3.85V then the cell is likely to be in the top 5% of SOC. Discharge it for 10% of its SOC (see Appendix 3) and remeasure it.

So what?

- Battery voltages vary a great deal. In the case of the '18650' battery, the output voltage for a good cell can vary from 3.5 to 4V.
- An output voltage of below 3.5V for a charged Li-ion cell means that it is defective.

Worksheet 7

SLA battery faults

When chemicals from the battery leak onto the terminals, they can cause corrosion.

Corrosion on the negative terminal is often a sign of undercharging.

Corrosion on the positive side is often a sign of overcharging.

The photo shows a car battery with bad corrosion on one terminal.
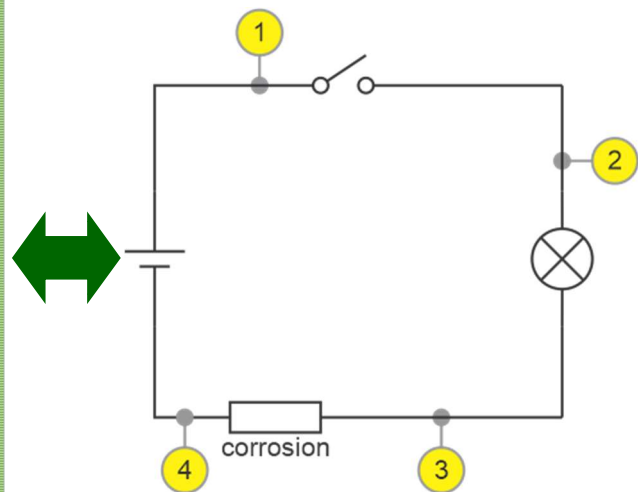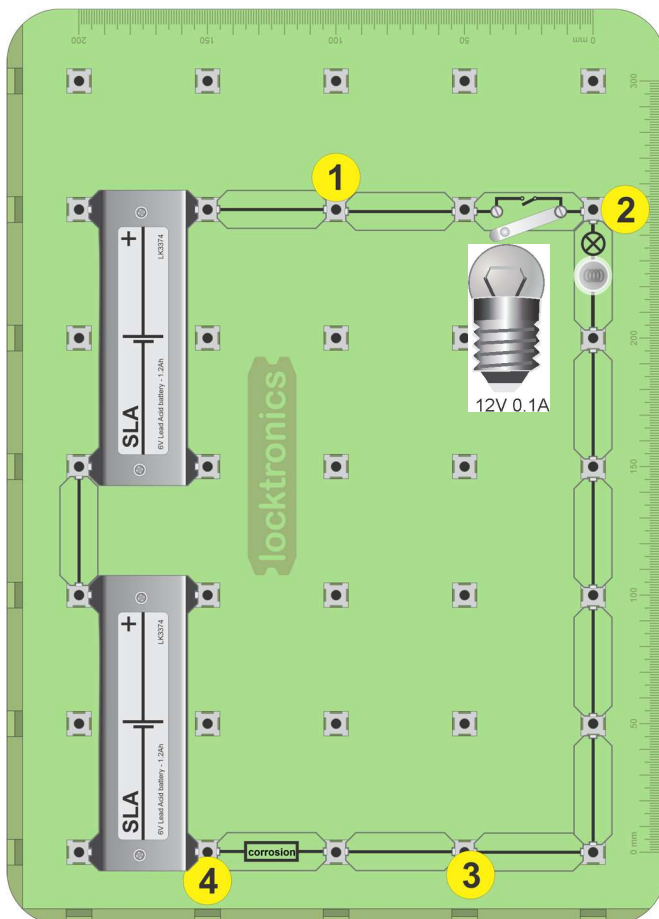
Over to you:

- Build the layout shown above. It includes a 12V 0.1A filament lamp.
  The circuit diagram for this is shown alongside.
  The effect of corrosion is simulated by adding the 'corrosion' component in the earth path of the battery.

Worksheet 7

SLA battery faults

Over to you:

- Set up a multimeter to measure DC voltages.

Part 1:

- Connect the multimeter COMmon terminal to node 4.
- Measure the voltage across the battery, between nodes 4 and 1, with the switch open and then closed.
- Record the readings in the table in the Student Handout.

Part 2:

- Move the COMmon connection to node 3 .
- Measure the voltage across the battery between nodes 3 and 1, with the switch open and then closed again.
- Record the readings in the table in the Student Handout.
- Now answer questions 1 and 2.

Part 3:

- With the switch closed, measure the voltage dropped across the bulb.
- Open the switch and replace the 'corrosion' link with a normal link.
- With the switch closed, measure the voltage dropped across the bulb again.
- Record the readings in the table in the Student Handout and answer question 3.

So what?

- Corrosion is the equivalent to a resistor in the circuit.
- You need to be careful about what you assume is the 0V line or earth.
- Always make sure you know what the exact battery voltage is.
  If you know that the battery voltage is 12.7V and you see under 12V in a circuit then it could be a sign of problems.

Challenge:

- Build the circuit opposite, which has corrosion in the 6V line.
- Use a multimeter to investigate the effect of the corrosion component.
- Record the results of your investigation in the Student Handout.
  Describe how you would check whether there is corrosion on the battery?
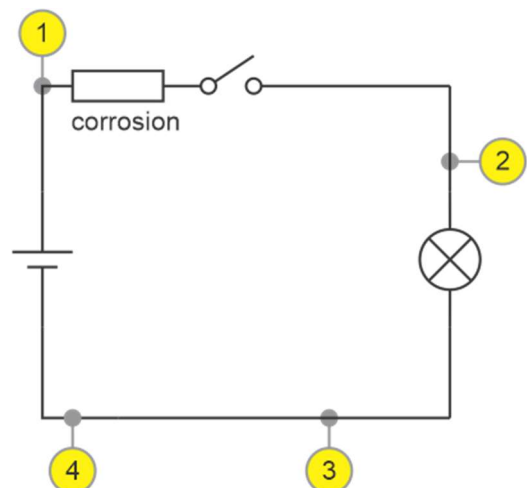
Worksheet 8

Voltage converters

Voltage converters are crucial to all modern electric vehicles. They may:

- convert 200V DC to 12V DC;
- convert 240VAC to a battery voltage of perhaps 200VDC;
- convert the low voltage three-phase AC, alternator output to 200V DC for the battery.

The photograph shows a voltage converter and management system from a Toyota Prius.

Step-up converter

Measuring output voltage

Measuring input current

7.5V

1kΩ **1kΩ**
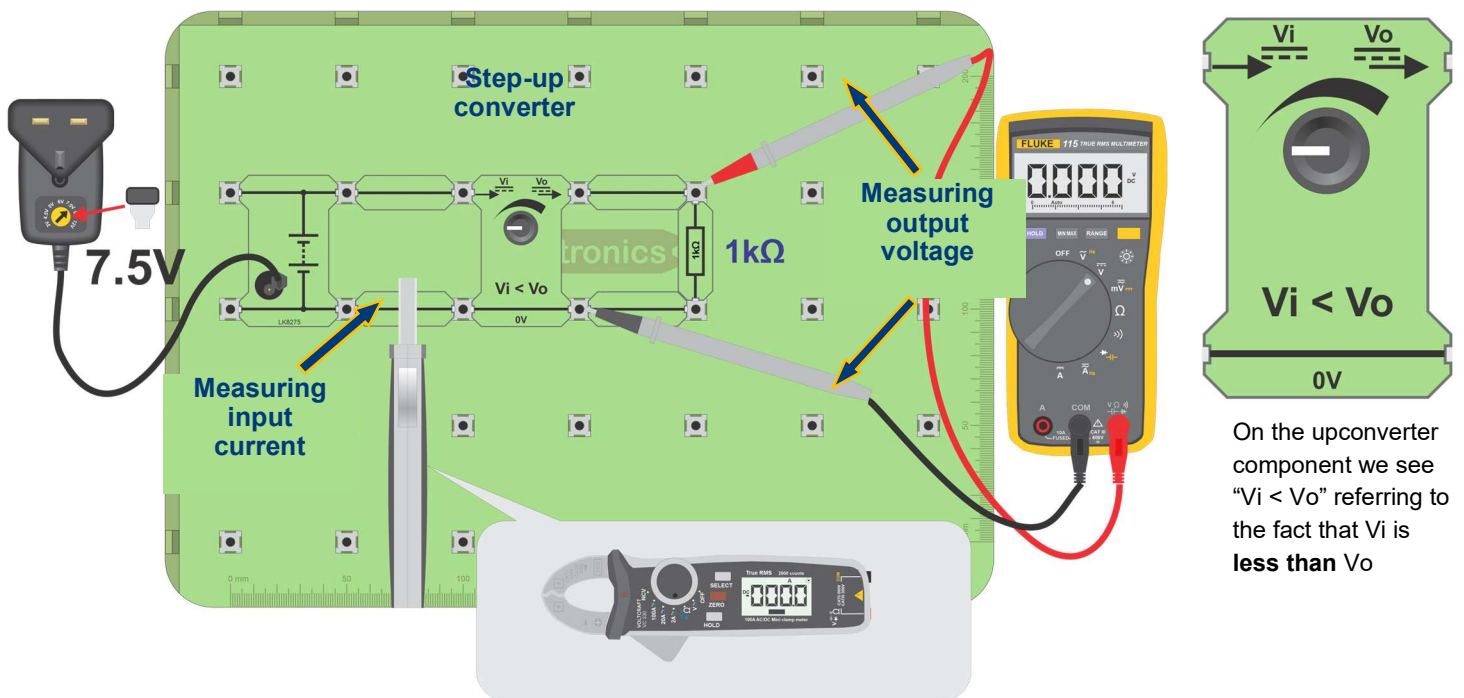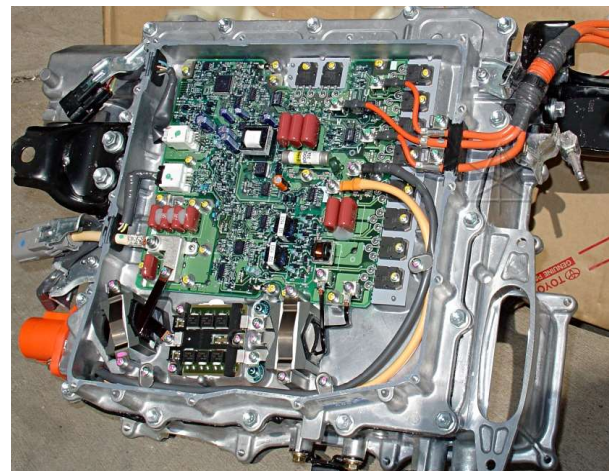
Vi < Vo

On the upconverter component we see "Vi < Vo" referring to the fact that Vi is **less than** Vo

Over to you:

- Build the layout shown above.
  The circuit converts the 7.5V output of the power supply to a voltage between 12V and 20V, depending on the position of the step-up converter potentiometer.
- Rotate the potentiometer fully anti-clockwise.
- Use the multimeter to measure the input and output voltages of the step-up converter.
- Use the current clamp-meter to measure input and output currents of the step-up converter.
- Rotate the potentiometer half way round and measure the same quantities again.
- Then do the same when the potentiometer is rotated fully clockwise.
- Calculate the power in and out of the step-up converter for all three positions.

Worksheet 8

Voltage converters

So what?

A 'DC-to-DC converter' or 'inverter' converts one DC voltage to another and can reverse its polarity. The voltage conversion inevitably includes a loss of energy, i.e. an efficiency of less than 1. This circuit has high losses. In electric vehicles, the loss would be less than 5%.
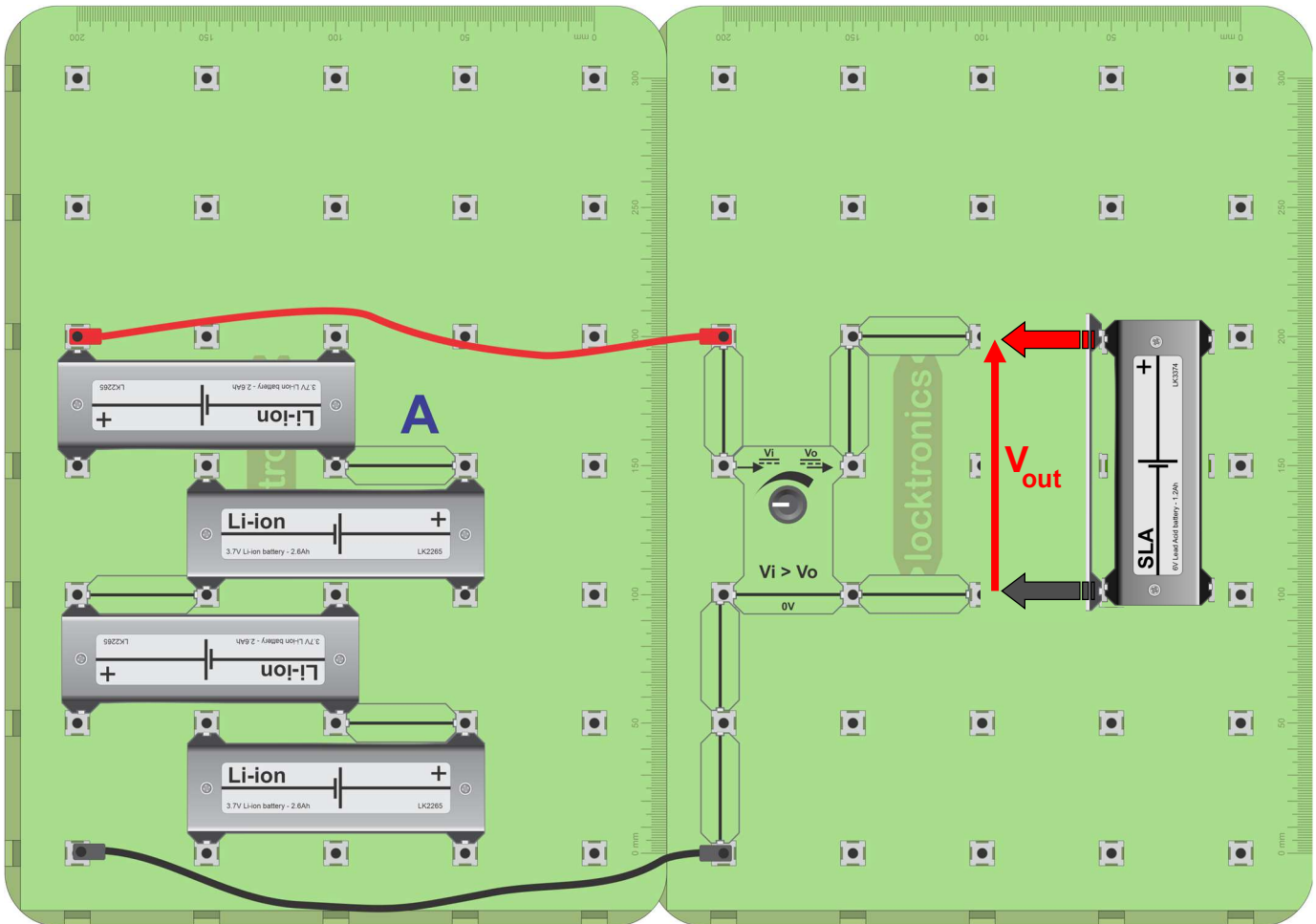
Over to you:

- Build the circuit shown above using four Li-ion cells in series and the Downconverter component (Vi > Vo).
- Adjust the potentiometer in the step down-converter so that its output voltage, V_{OUT}, is 7V.
- Now connect a single SLA battery to the output.
- This circuit converts the 15V or so output of the Li-ion battery to a voltage suitable for charging the SLA battery. In the same way as before, take measurements to allow you to calculate the power in and out of the step-down converter.
- Hence, calculate the efficiency of the step-down converter.

So what?

- Modern electric vehicles may have more than one inverter and more than one battery.
- Inverters are a key technology at the heart of every electric vehicle.

***Warning** - Be careful to connect the cells the right way round!*

Worksheet 9

Powering DC motors

Traditionally, DC motors are the most common type found in vehicles, used for fans, windscreen wipers electric seats, etc. They are rapidly being replaced by brushless DC motors which weigh less and are more efficient.

The photograph shows a VW DC motor with an integrated gearbox.
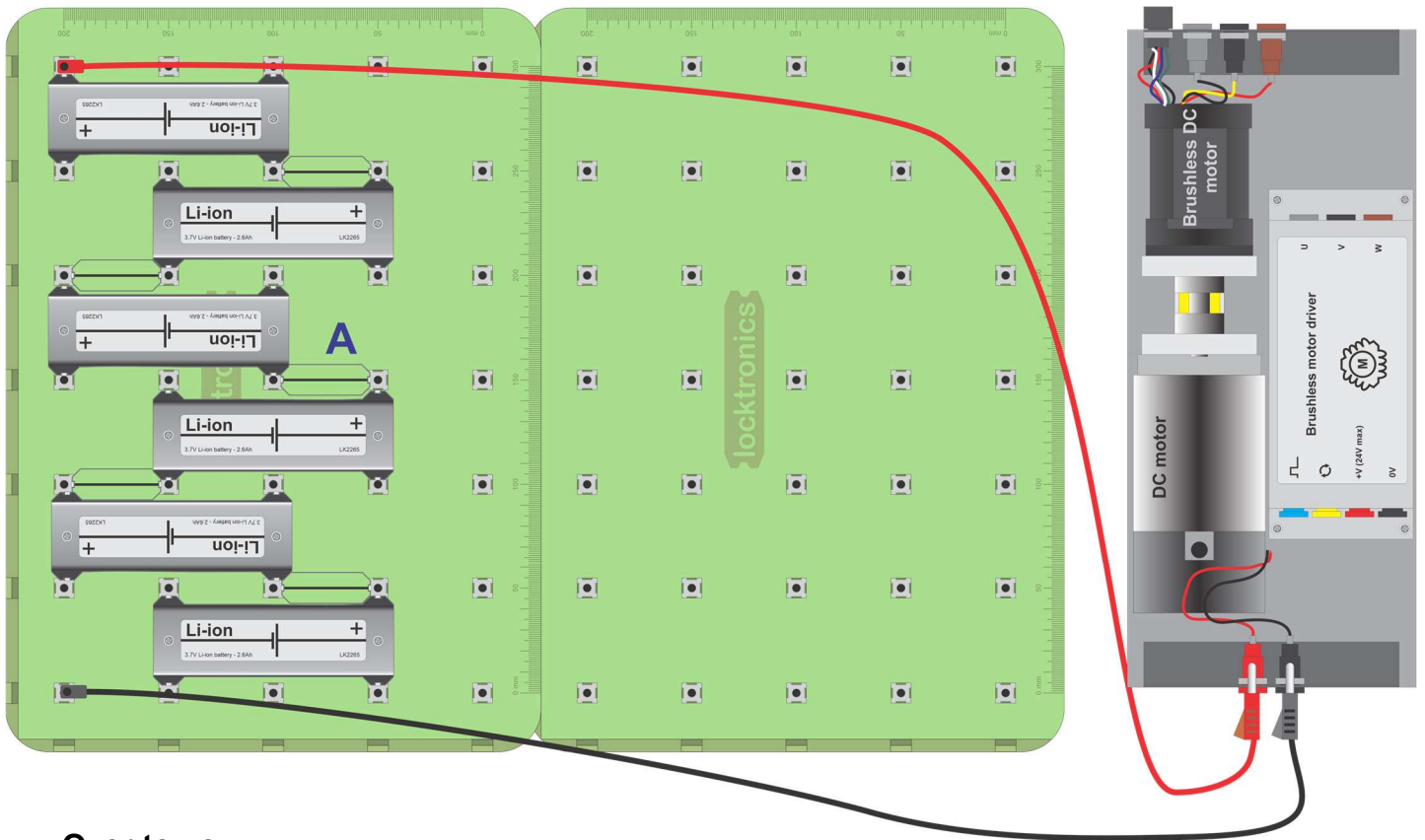
Over to you:

- Build the circuit shown above.

Warning - Be careful to connect the cells the right way round!

- Start with all six Li-ion cells. Then use five in series, then four etc.
  What happens to motor speed as you reduce the number of batteries in series?
  Answer the question in the Student handout.

So what?

- The motor speed is dependent on the voltage supplied to it and the current available.

Worshseet 9
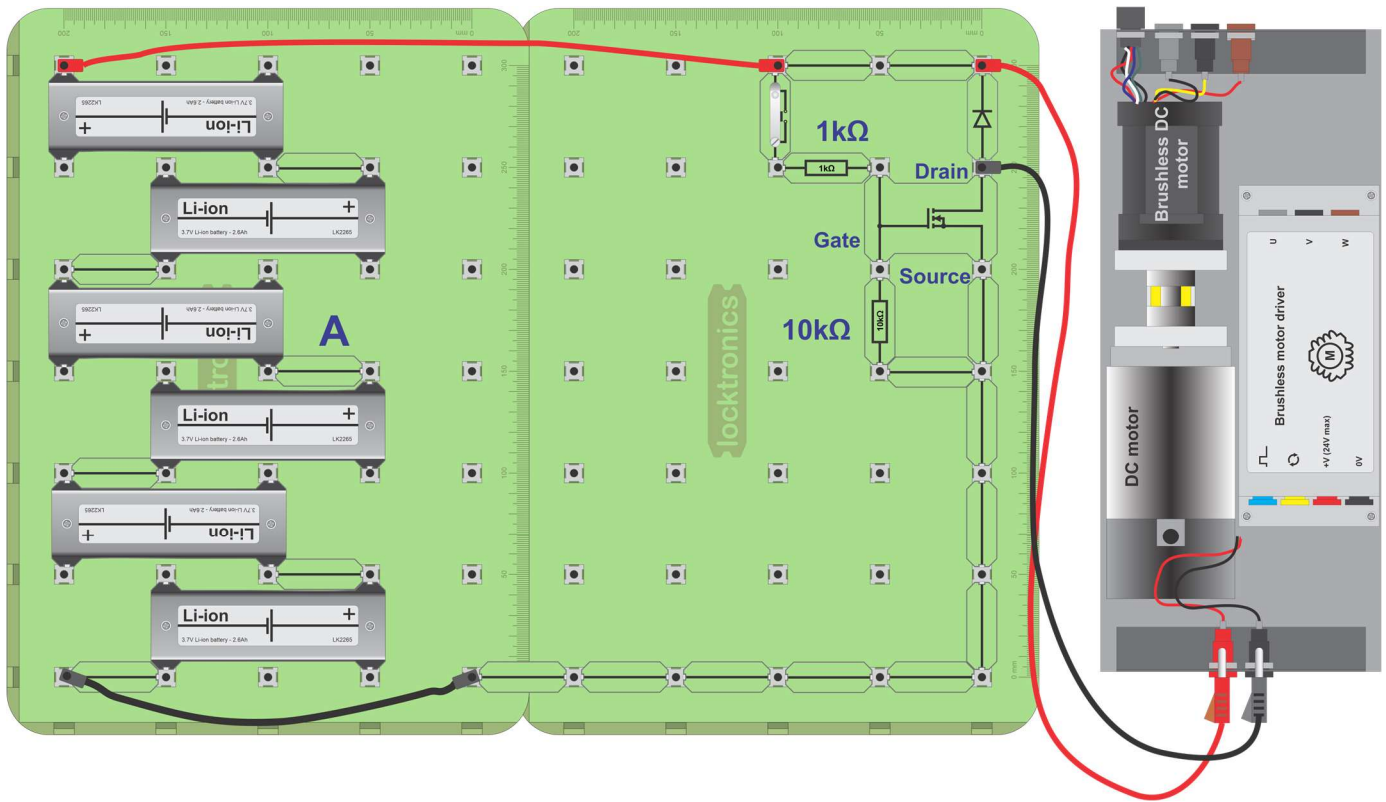
Powering DC motors

Over to you:

- Build the circuit shown above.

> **Warning - Be careful to connect the cells the right way round!**

- Use the switch to control the DC motor. This is on / off control.
  There is no mechanism in this circuit for controlling motor speed.

So what?

- The transistor is just like an electronic switch. A small current flowing in the 'gate' controls a large current flowing between the 'source' and the 'drain'.
- When the DC motor is turned off, it produces a high voltage spike, due to the 'back EMF' ('electro-motive force') produced. The diode is used to suppress this spike and protect the circuitry around the transistor.

Challenge:

The transistor we are using is quite rugged. If you have access to an oscilloscope, remove the diode and capture the back EMF spike. *(You may have to use the 'x10' setting on the oscilloscope probe.)*

Over to you continued...

- The circuit is modified, as shown on the next page, to use an ECU (electronic control unit) to control the motor speed. Modify the layout as shown.
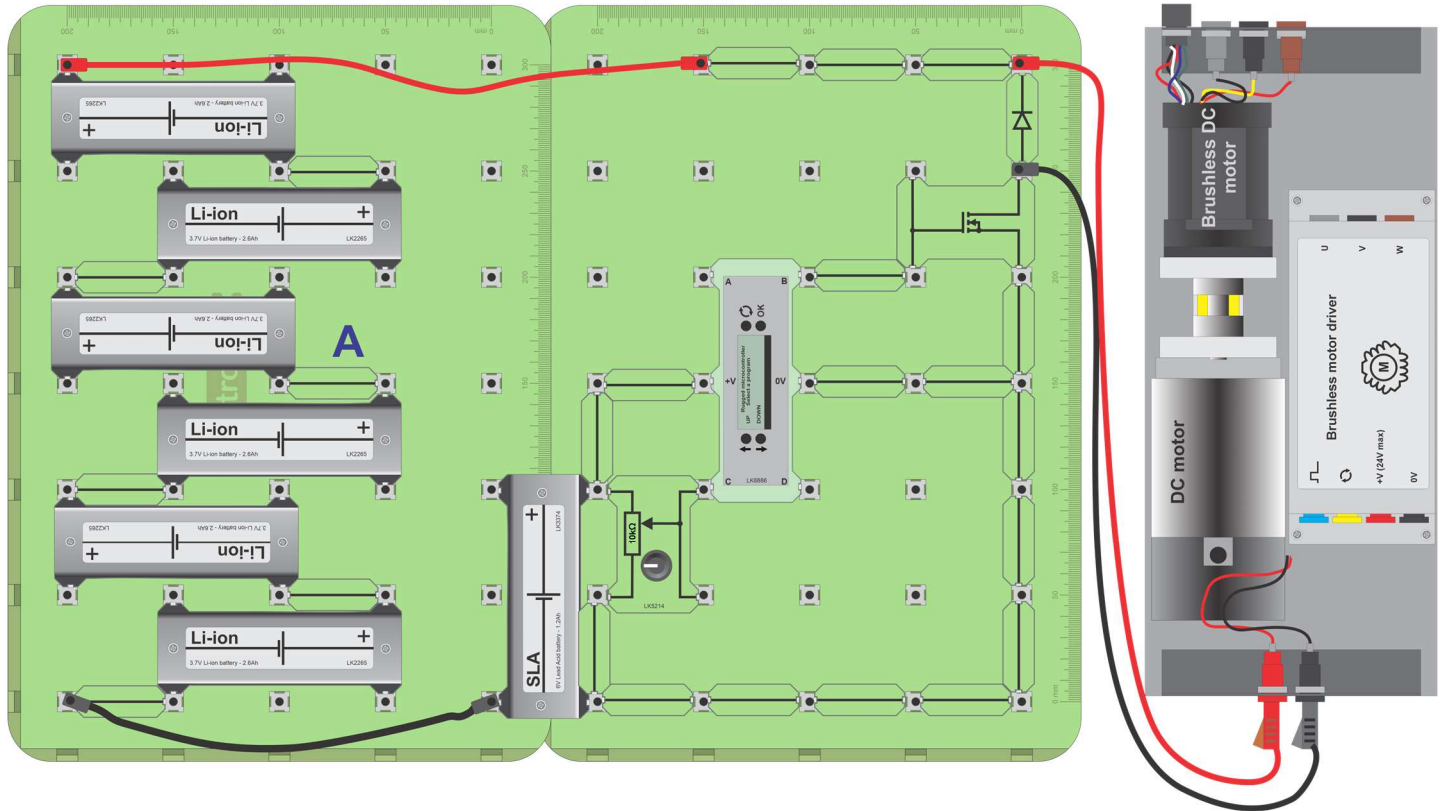
Oscilloscope settings:

Timebase -100µs/div	**Voltage range -** ±5V DC	**Trigger mode** - Auto
Trigger channel - ch A	**Trigger direction** - Rising	**Trigger threshold** - 5V

Over to you:

- Press the reset button on the Micro ECU: 🔄

- Use the 'UP' and 'DOWN' arrows to select program 14 - DC motor control - and press '**OK**'.

- The potentiometer controls the voltage at the input of the ECU.

  This, in turn, controls the speed of the DC motor.

  Turn the knob fully anticlockwise to run the motor at minimum speed.

  The ECU display shows an output of 0% motor drive.

- Next, turn the knob until the display shows a drive of 30%.

- Use an oscilloscope to view the signal at the output (terminal **B**) of the microcontroller.

  Using the axes provided in the Student Handout, sketch this output signal.

  Suitable oscilloscope settings are given above.

- Then, turn the knob to give a drive of 70%. Again, view the output signal and sketch it.

Worksheet 9

Powering DC motors

So what?

- This control technique is called PWM (pulse-width modulation.) It is illustrated in the diagram opposite.

  - The 'mark' (*on* time) lasts for three units of time whereas the 'space' (*off* time) lasts for only one.

  - This is known as a mark-to-space ratio (m:s) of 3:1. This can also be described using the term 'duty cycle' - the fraction of the signal for which the output is 'on'. A m:s of 3:1 is the same as a duty cycle of 75%.
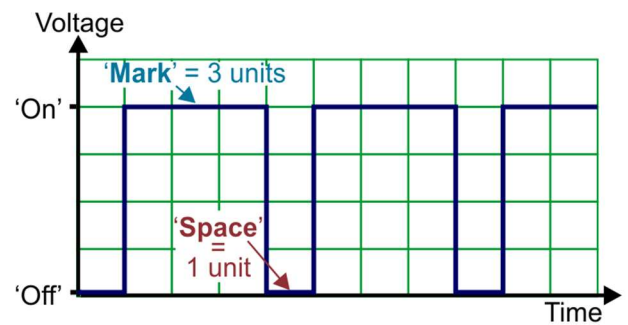
- Varying the mark:space ratio has the same effect as varying the DC voltage. It alters the average power supplied to the motor and the resulting speed.

- In vehicles, microcontrollers inside ECU's use PWM to control devices such as motors, heaters, lamps etc. The current for these devices comes from transistors, controlled by the ECU's.

  Usually, these transistors are connected to 'sink' current rather than 'source' it, i.e. used in the ground path not the V+ path of the control circuit. When sinking, current flows 'into' the transistor. When sourcing, current flows 'out of' the transistor.

  The meaning of 'sinking' and 'sourcing current is illustrated in the diagram below.
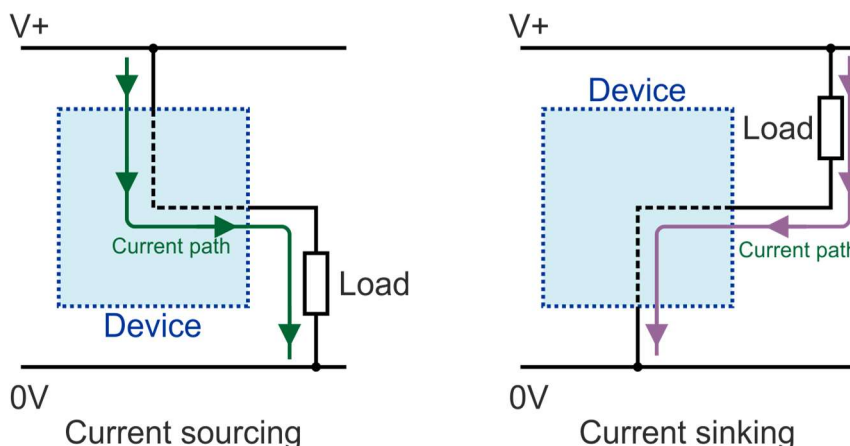
Worksheet 10

Powering three-phase motors

Three-phase systems - generators, electric motors, power transmission lines - are more energy efficient than their two-phase or single-phase equivalent.

In vehicle electrical systems, nearly all alternators and most motors are three-phase devices.

The photograph shows part of a Toyota Prius electric motor.
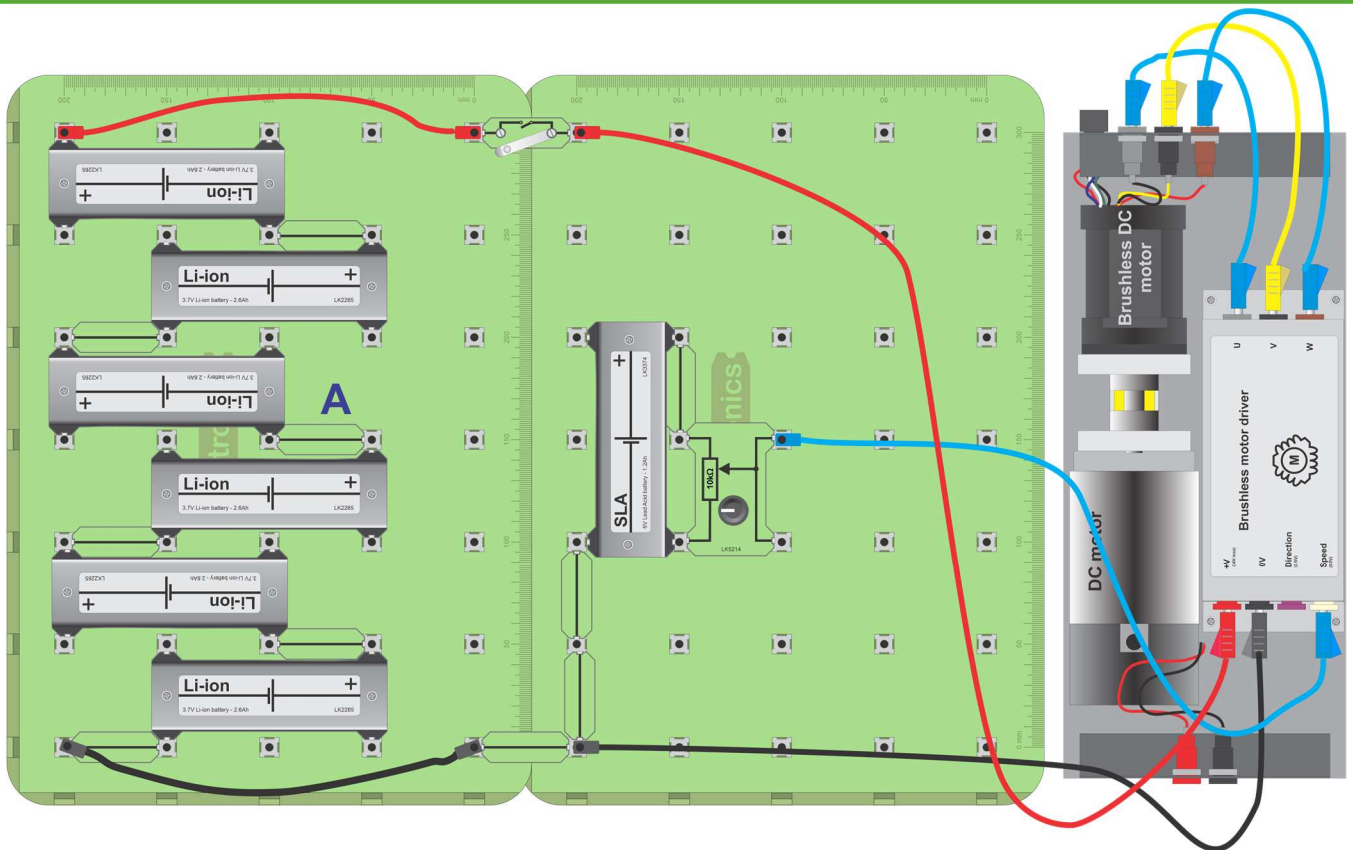
Over to you:

- Set up the circuit shown in the diagram above. It uses six Li-ion cells for the motor supply.

> *Warning - Be careful to connect the cells the right way round!*

The single SLA battery and 10kΩ potentiometer provide a varying voltage between 0 and 6V for the 'Brushless motor driver' module to control motor speed.

- Turn the knob on the potentiometer fully anticlockwise to output minimum voltage.
- Close the power switch.
- Increase the potentiometer output slowly to start the brushless motor rotating.

Worksheet 10

Powering three-phase motors

So what?

- Three-phase motors require a special power circuit to operate them. This is housed in a steel casing in the HP2001 DC motor / Brushless motor module.

- In a three phase motor the voltages across all three phases would ideally look like this:
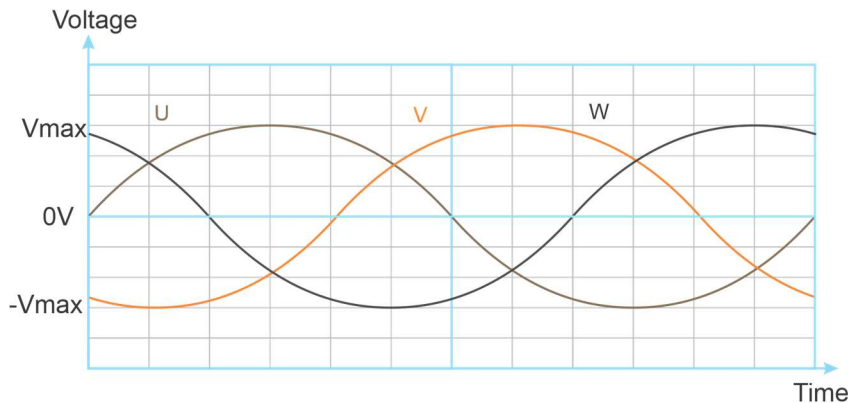
- The signals are identical but 120 degrees apart. This is a hard signal to reproduce with power electronics. Something easy to produce might be like this:
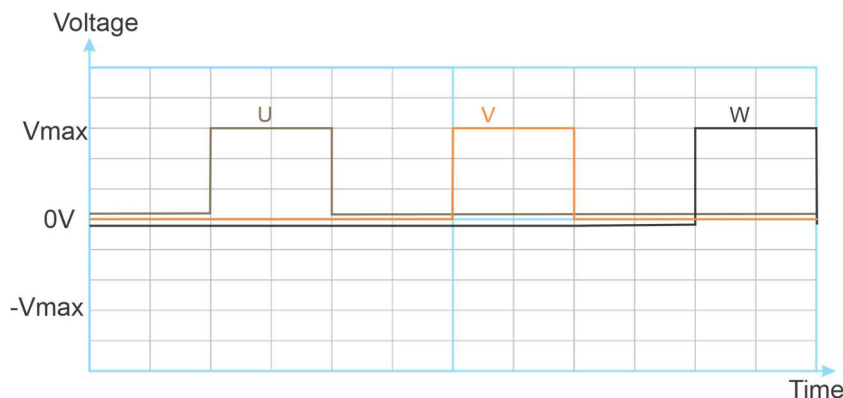
- Here the power supplied to each of the three phases is still 120 degrees apart.

- However this signal would produce very jerky motion, would be inefficient.

- What we can do easily with Power electronics is create a signal made up of pulses that vary in mark space ratio and amplitude. For one phase its something like this:

locktronics®
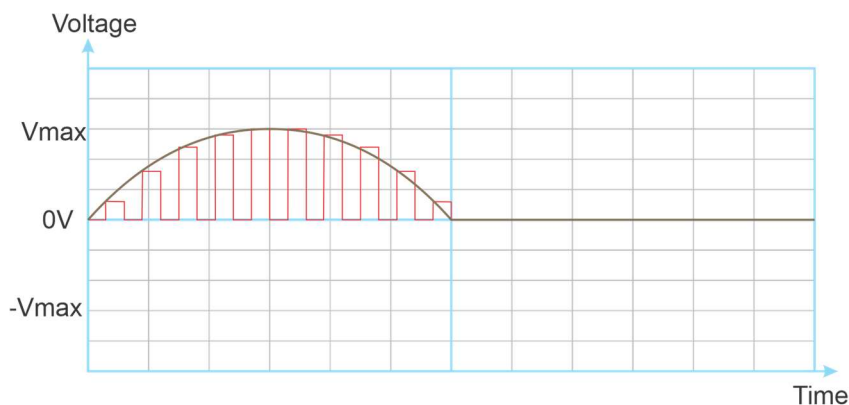
Oscilloscope settings:		
Timebase -2ms/div	**Voltage range -** ±20V DC	**Trigger mode** - Single
Trigger channel - ch A	**Trigger direction** - Rising	**Trigger threshold** - 1V

Over to you:

- With the ground lead on the 0V line take an oscilloscope and connect each channel to sockets **U** and **V** on the 'Brushless motor driver' .
- You will not be able to trigger the oscilloscope easily - use the Single trigger mode to capture and freeze a single trace.
- Run the motor fast and slow. Confirm that:
    - the PWM varies according to motor speed
    - The signals of U, V, W are 120 degrees apart
    - The signal approximates a sinusoid

Worksheet 11

Three-phase generators

Car alternators are actually three-phase AC generators. Their output signal is rectified to DC by a single block of electronics that contains six power diodes.

The drive motors in electric vehicles are also three-phase.

The photograph shows part of a Toyota Prius drive train with both a three-phase generator and a three-phase motor.
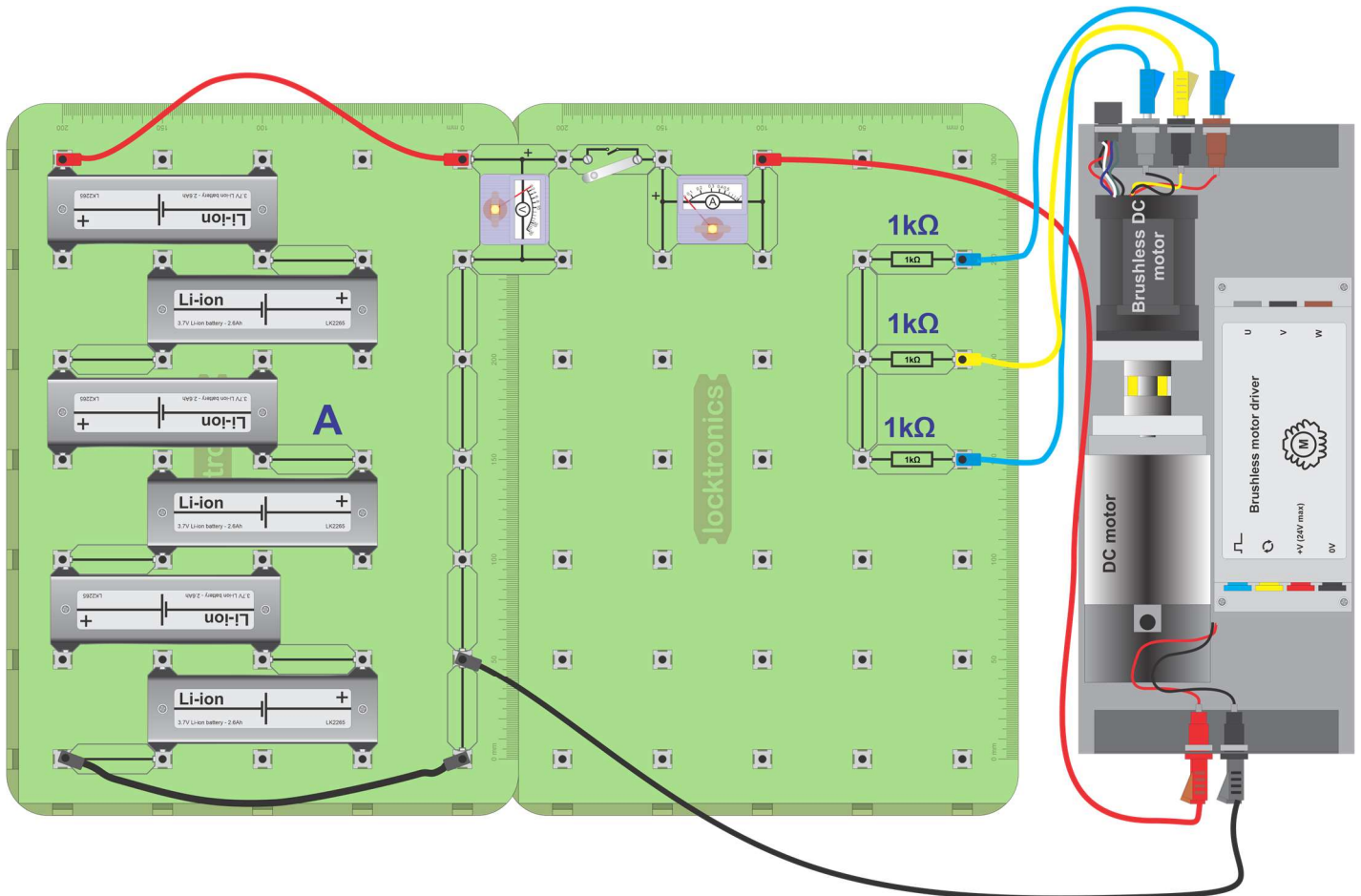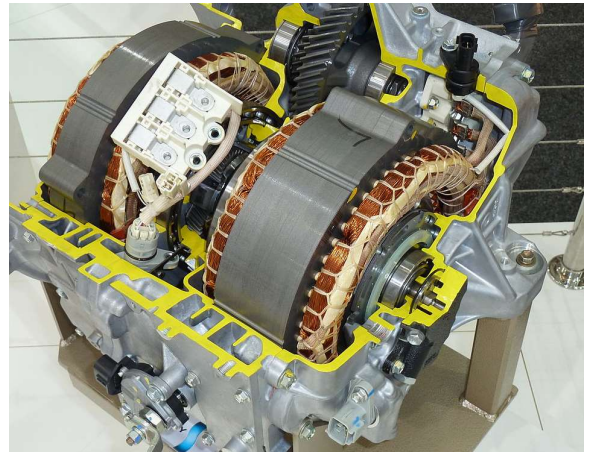
Over to you:

- Build the circuit shown above.

Warning - Be careful to connect the cells the right way round!

Worksheet 11

Three-phase generators

Over to you continued ...

- Use an oscilloscope to look at the waveforms coming from the three-phase generator.

  Your oscilloscope probably has only two inputs. To see the relative timing of the three waveforms, keep one waveform on channel 1 all the time and use channel 2 to examine the other two waveforms, in turn.

  Connect the oscilloscope probe across one of the 1kΩ resistors with the ground connection of the oscilloscope attached to the connecting links.

Oscilloscope settings:		
Timebase -10ms/div	**Voltage range -** ±10V DC	**Trigger mode** - Auto
Trigger channel - ch A	**Trigger direction** - Rising	**Trigger threshold** - 5V

- Use the axes provided in the Student Handout to sketch the waveforms across the three resistors.
- Reduce the supply voltage to the DC motor by using just three Li-ion batteries in series rather than six..
- Sketch one of the waveforms again.

So what?

- The three-phase outputs all have different timings on the oscilloscope. The windings in the three-phase generator are spaced 120^0 apart. The peaks of the waveforms occur spaced at 33% of the time period of the waveform. Hence we say that "the waveforms are 120^0 apart".

- The output of the three-phase generator depends on the speed of the DC motor.
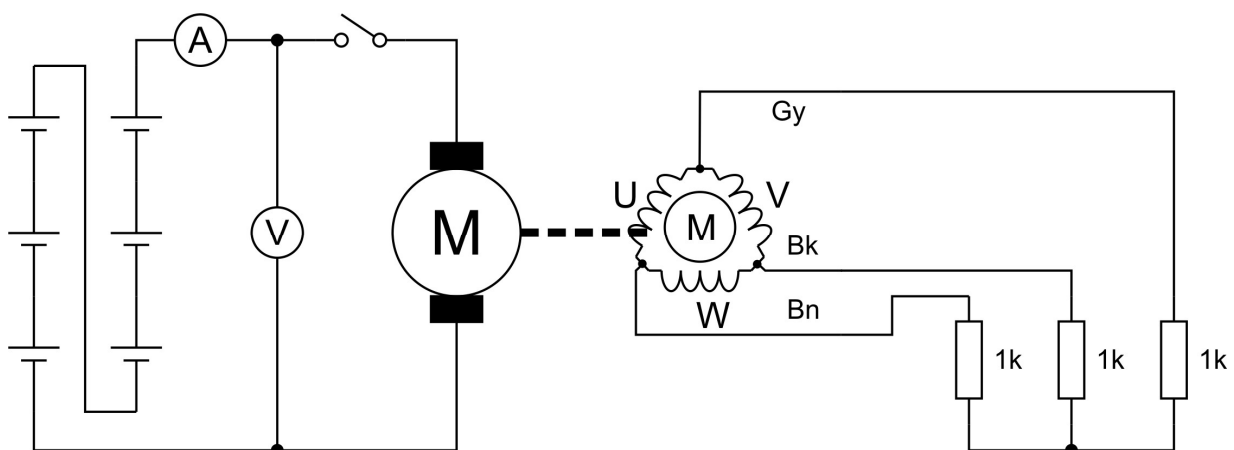
You built the circuit shown in the diagram above. In reality, it is two separate circuits. Each has its own earth or ground. They are not connected and can be at different voltages.

Worksheet 11

Three-phase generators
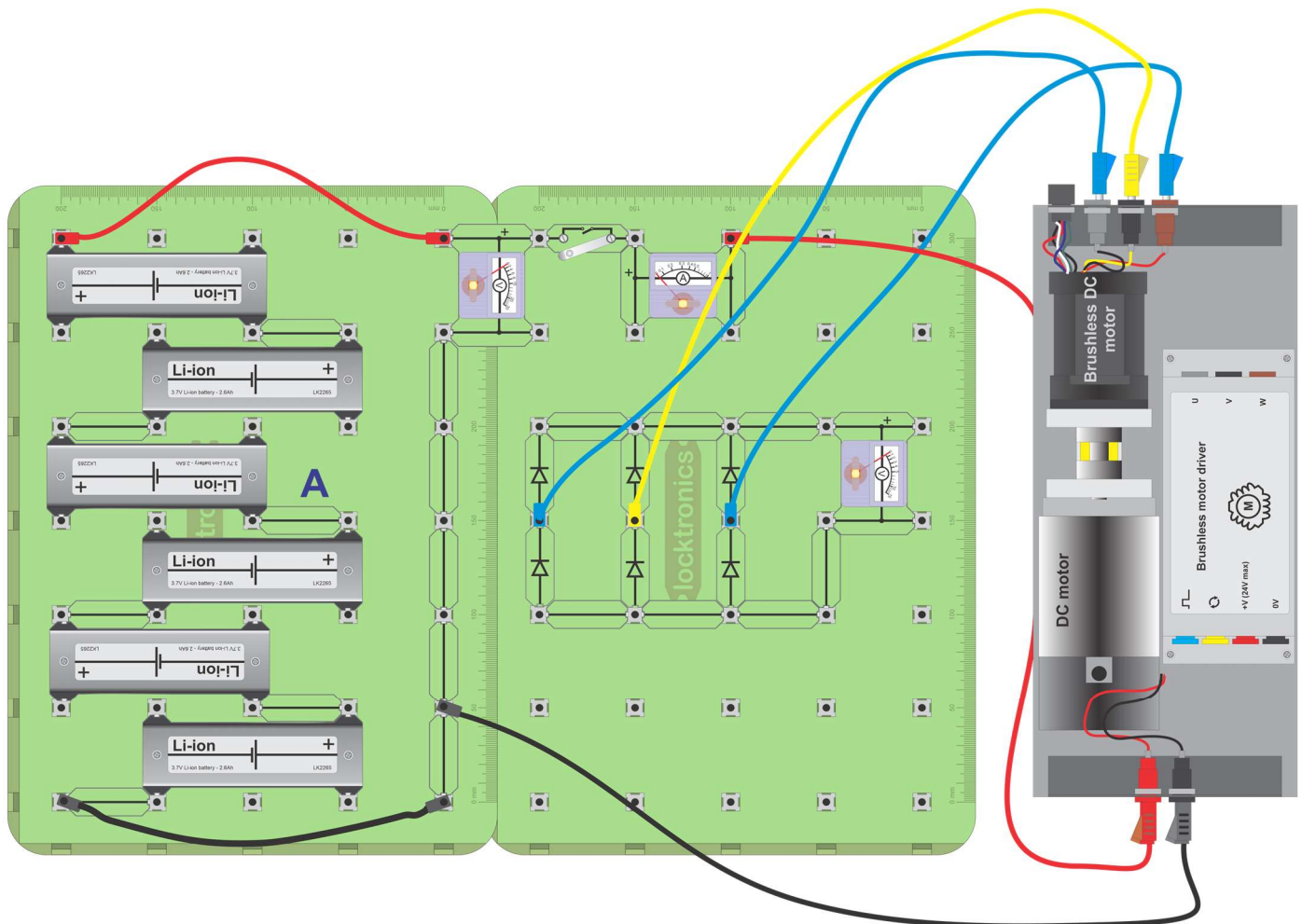
Over to you:

- Build the circuit shown above.

> **Warning - Be careful to connect the cells the right way round!**

- Use an oscilloscope to look at the waveforms coming from the three-phase generator.

Oscilloscope settings:		
Timebase -10ms/div	**Voltage range -** ±10V DC	**Trigger mode** - Auto
Trigger channel - ch A	**Trigger direction** - Rising	**Trigger threshold** - 5V

- Use the axes provided in the Student Handout to sketch the waveforms across the banks of diodes.

Worksheet 11

Three-phase generators

So what?

- The diodes rectify the three phase voltage signal into a single DC waveform.
- The DC waveform has some ripple on it. When the output of a bridge like this is connected to a battery, the battery removes the ripple.

Over to you:

- Add a large 2200µF capacitor to the rectifier output.
- Connect a LED bulb across the rectifier output.
- The circuit looks like the one below.
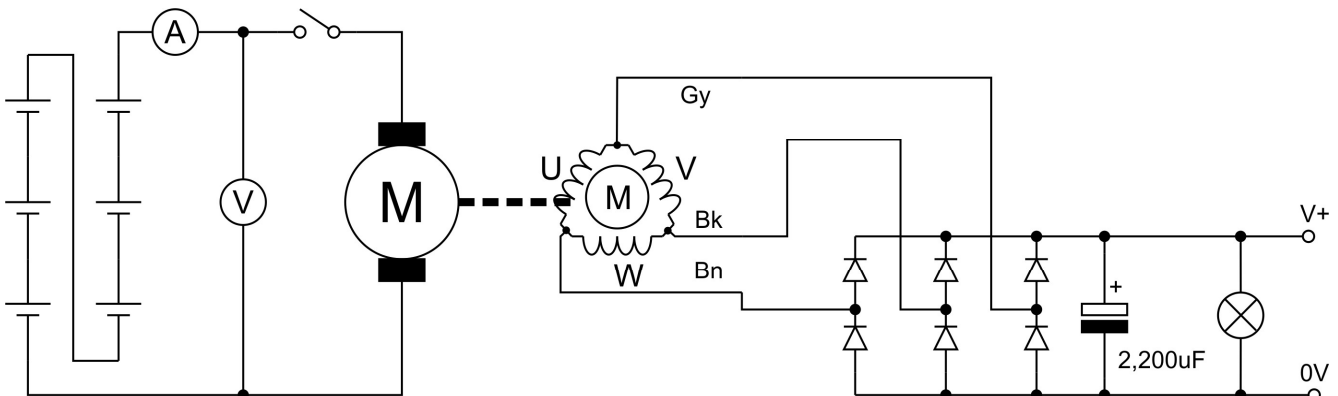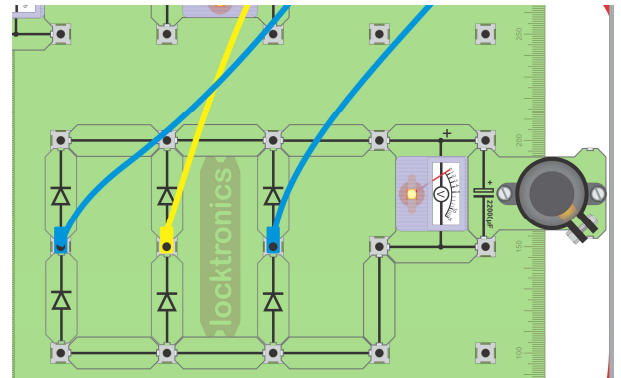
- Close the switch and run the DC motor.
- Open the switch to stop the DC motor.
- How long does the bulb stay lit?
- With a multimeter on DC voltage setting, measure the **initial** voltage between the two earths - this voltage will decline rapidly.

So what?

- The capacitor is discharging because of only one LED bulb. Without that in place it would stay charged for much longer.
- You need to be very careful of capacitors in the high voltage side of electric vehicles - even when batteries are removed they may still contain enough charge to kill.
- There is no electrical link between the ground of each side of the circuit. That means there could be a significant voltage between the two grounds.

Worksheet 12

Isolation relays

In electric vehicles the battery voltage can be over 400V DC. This is a very high voltage which presents hazards to humans when servicing a vehicle or when a vehicle crashes and the crash team need to get access. It is important that the high voltage can be isolated from the rest of the vehicle.

Photograph shows a selection of isolation relays.
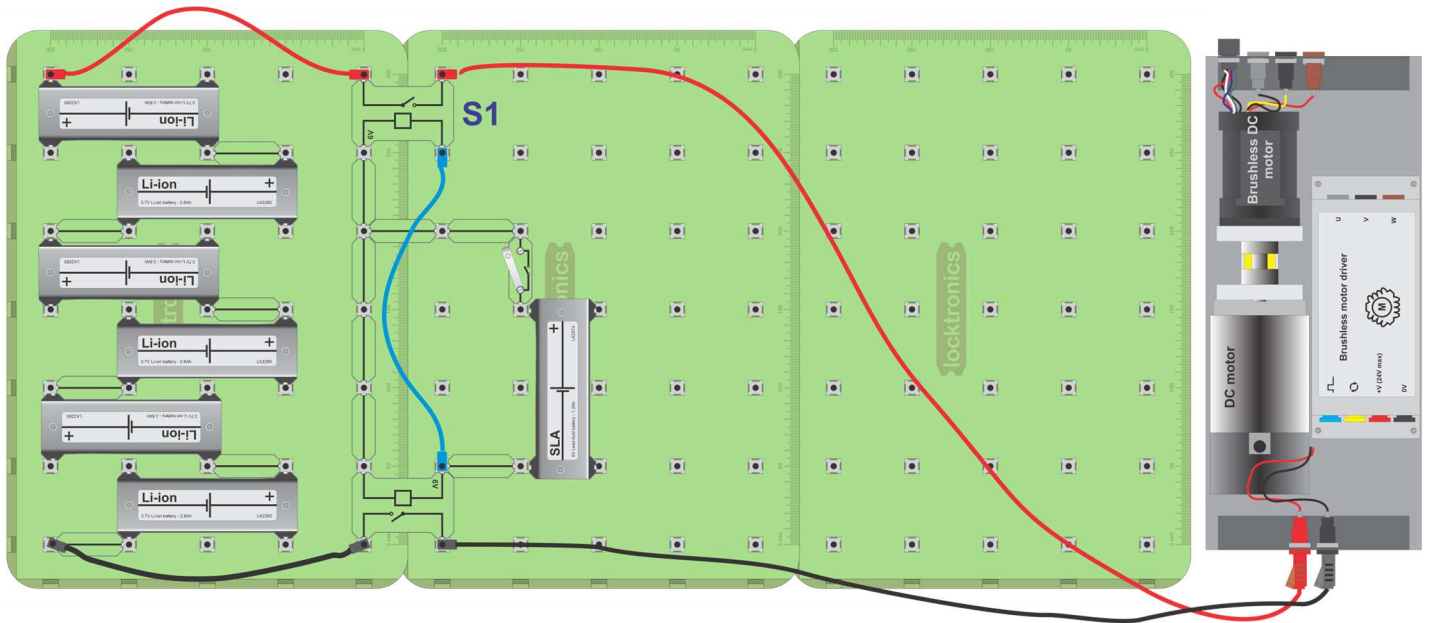
Over to you:

- Build the circuit shown above.

So what?

- The two relays are switched on and off from the Sealed Lead Acid battery. This is a 6 V source.

- The Li-ion batteries form a 24V battery. The relays use 6V to switch 24V.

- There are two separate circuits which do not connect together as the relays provide electrical isolation of one circuit to the other.

Worksheet 13

Electric vehicle project

There is no single design for hybrid or electric vehicles.

Initially, vehicles used energy reclaimed while braking to assist a petrol engine via the drive train.

Later models use the electricity mains supply to recharge a battery with a small 'assist' motor as back-up.

More recent designs are purely electric.

In modern electric vehicles using high-voltage batteries, residual charge brings additional electrical hazards even when the power seems to be off.

The photograph shows a Volvo hybrid car.

Over to you:

- Expand the layout built in the previous worksheet by adding the circuit shown on the next page. The result is the system shown in the circuit diagram below.
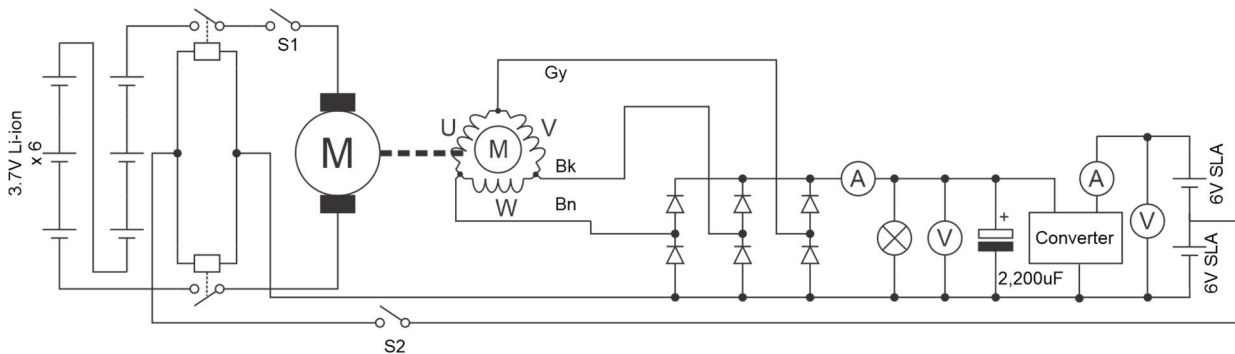
- Two relays separate the DC motor from the Li-ion batteries. They are controlled by switch **S2**, which applies 6V to the relays. The bulb represents the load applied to the output of the rectifier. A step-up converter is used to charge two SLA batteries connected in series.
- Turn the step-up converter potentiometer fully anticlockwise to give minimum output.
- Close switches **S1** and **S2**. Initially, no current flows into the SLA batteries because the step-up converter output is too low. Rotate the step-up converter potentiometer until current flows to charge the SLAs . Comment on what you notice in the Student Handout.

So what?

- As soon as the SLAs draw current, the motor slows. As more electrical energy is drawn from the generator, less mechanical energy is available for the motor.
- The voltage without the SLAs in place rises to around 16V. With them in place, it does not get much beyond 13V as the SLAs clamp the output at their voltage.
- In practice, every type of vehicle has a different arrangement of batteries, relays, inverters, motors, generators and other components. Some include two batteries - a high-voltage   Li -ion battery and a conventional SLA battery.
- In electric vehicles, relays separate the high-voltage battery from the rest of the vehicle, isolating both the positive and the negative sides of the battery.
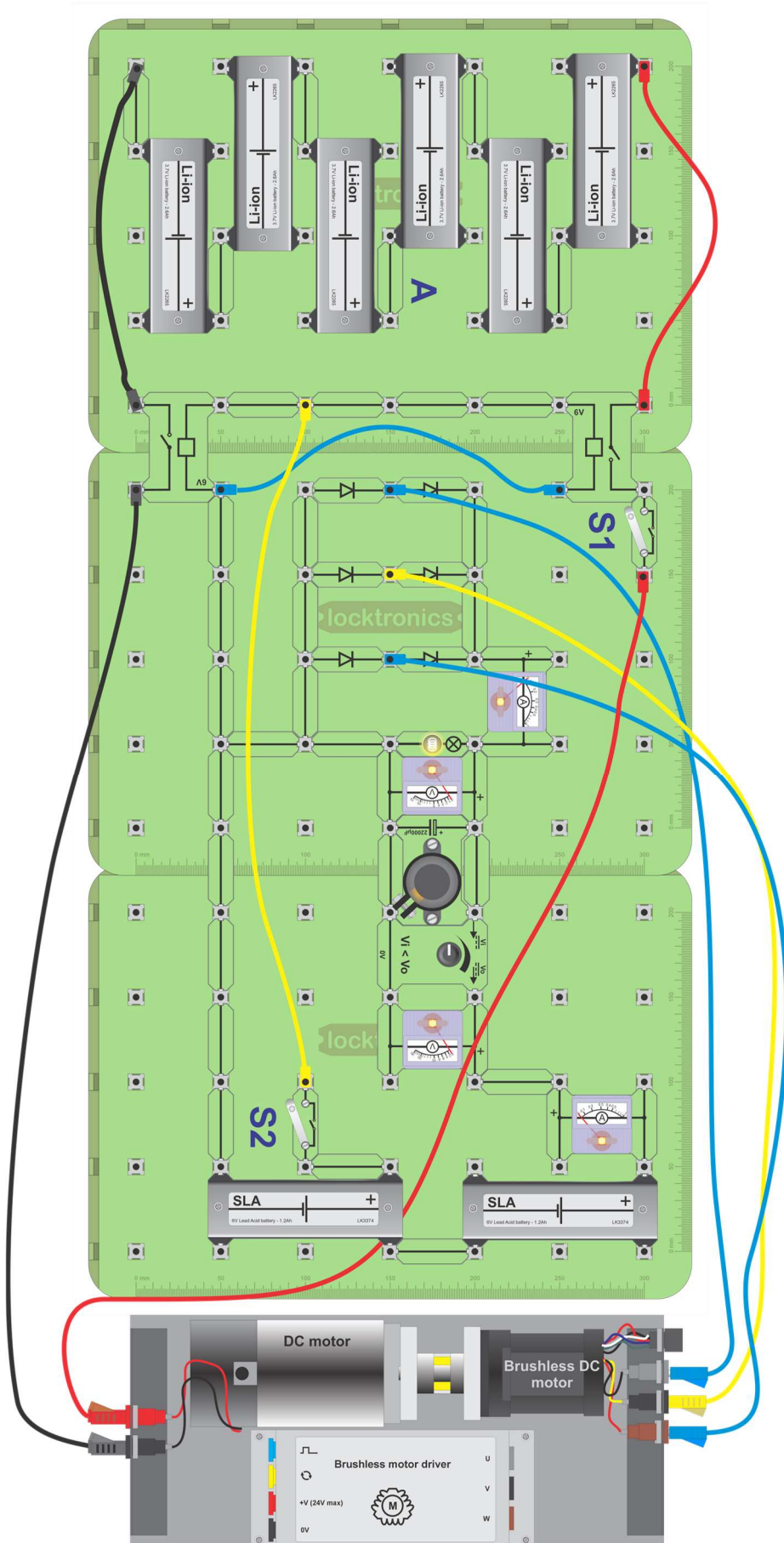
On the upconverter component we see "Vi < Vo" referring to the fact that Vi is **less than** Vo

Note - if the State Of Charge of your SLAs is low then current will always be drawn independent of the setting on the upconverter.

Worksheet 14

Charging system faults

The technology used in the charging posts for electric vehicles is the same as that used in the cars themselves:

- AC energy is converted to DC;
- this is converted to battery voltage;
- then stored in the battery.

The photograph shows a charging facility incorporated into a lamp post.

Over to you:

- Use the system you built for the previous worksheet, shown on the previous page, to test the effects of:

1 - Diode failure - open circuit:

A. Minimum output
- Set the step-up converter to give minimum output, so that no current is supplied to the battery.
  - Measure and record the output voltage of the rectifier (across the bulb).
- Remove the top left diode.
  - Measure and record the output voltage of the rectifier.
- Remove the bottom left diode.
  - Measure and record the output voltage of the rectifier.
- Remove the middle bottom diode.
  - Measure and record the output voltage of the rectifier.
- Replace all diodes.

B. Increased output
- With the inverter turned up to the point where it is charging the SLA batteries, repeat the exercise.
- Removal of the diodes mimics the case where diodes fail and go open circuit.

2 - Diode failure - short circuit:
- Repeat **A** and **B** but this time replacing the diodes with connecting links.
- Rebuild the circuit as it should be.

So what?
- The three phase rectifier is a very robust circuit. Partial failure is relatively hard to detect and may only be noticed by the vehicle user as a partial loss of charging/battery capability.

3 - Effect of corrosion:

- Set the step-up converter to minimum output, so that no current is supplied to the battery.
- Measure and record the output voltage of the rectifier (across the bulb).
- Replace the earth link between rectifier block and meter with a 'Corrosion' component as shown in the diagram below.
- Measure and record the output voltage of the rectifier (across the bulb).
- Now turn the potentiometer until the step-up converter starts supplying current to the SLA batteries.
- Measure and record the output voltage of the rectifier (across the bulb).
- Remove the corrosion. Measure the voltage again.
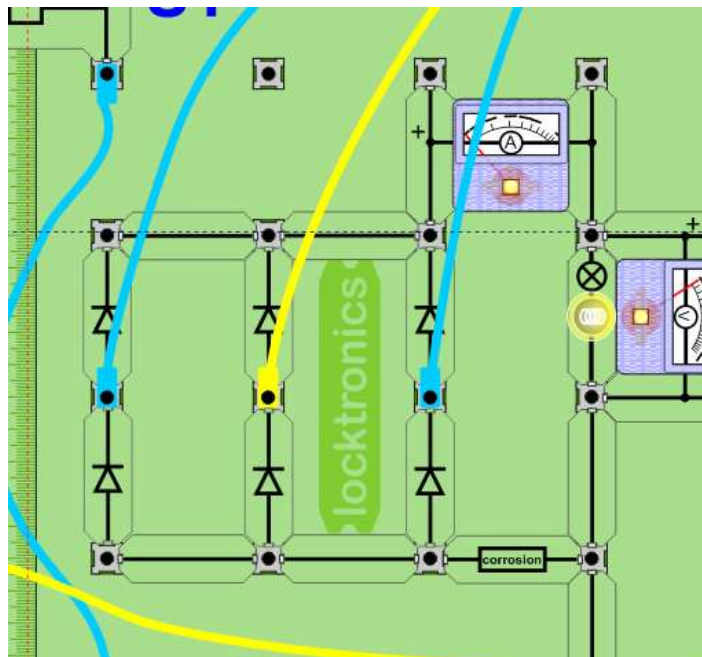
So what?

- Corrosion faults produce a measurable voltage drop when current is flowing.
- These faults are harder to detect when there is not much current flowing - when the battery is well charged.

Batteries are all different, physically and therefore electrically. That's the result of a manufacturing process which is not exact.

This raises problems that need managing by the electronics systems that supervise charging.

The photograph shows the battery from a Ford Escape hybrid SUV .

Over to you:

There are six Li-ion cells in your kit. The nominal voltage is around 3.7V for each, provided that the SOC is between 15% and 95%.

- Measure the output voltage of each with a multimeter and record your answers in the table in the Student Handout.
- Choose two batteries with different voltages.

So what?

- The actual output voltage of a Li-ion '18650' cell will vary between 3.5 and 3.9V.
- Providing that it is properly charged, with a SOC between 5% and 95%, any cell with an output voltage outside this range can be assumed to be out of specification.
- One bad cell in a battery pack can affect the performance of the entire battery pack.
- Where it is necessary to charge many batteries connected in parallel, batteries of similar output voltages are chosen.

Over to you:

- Select two cells from your collection, one with high voltage and one with low voltage.
- Note their voltages in the Student Handout.
- Build the circuit shown on the next page. The analogue meters give an approximate value of current.
- Using the potentiometers adjust the current in the transistors so that the meter reads 1A flowing into each battery. If the State of Charge of your batteries is low the current may be more than this - if so choose a current of 1.2A.
- Measure the bypass voltage across each of the 10 ohm resistors.
- Calculate the bypass current using Ohm's law.
- Make a note of the starting voltage of each cell and the bypass current.
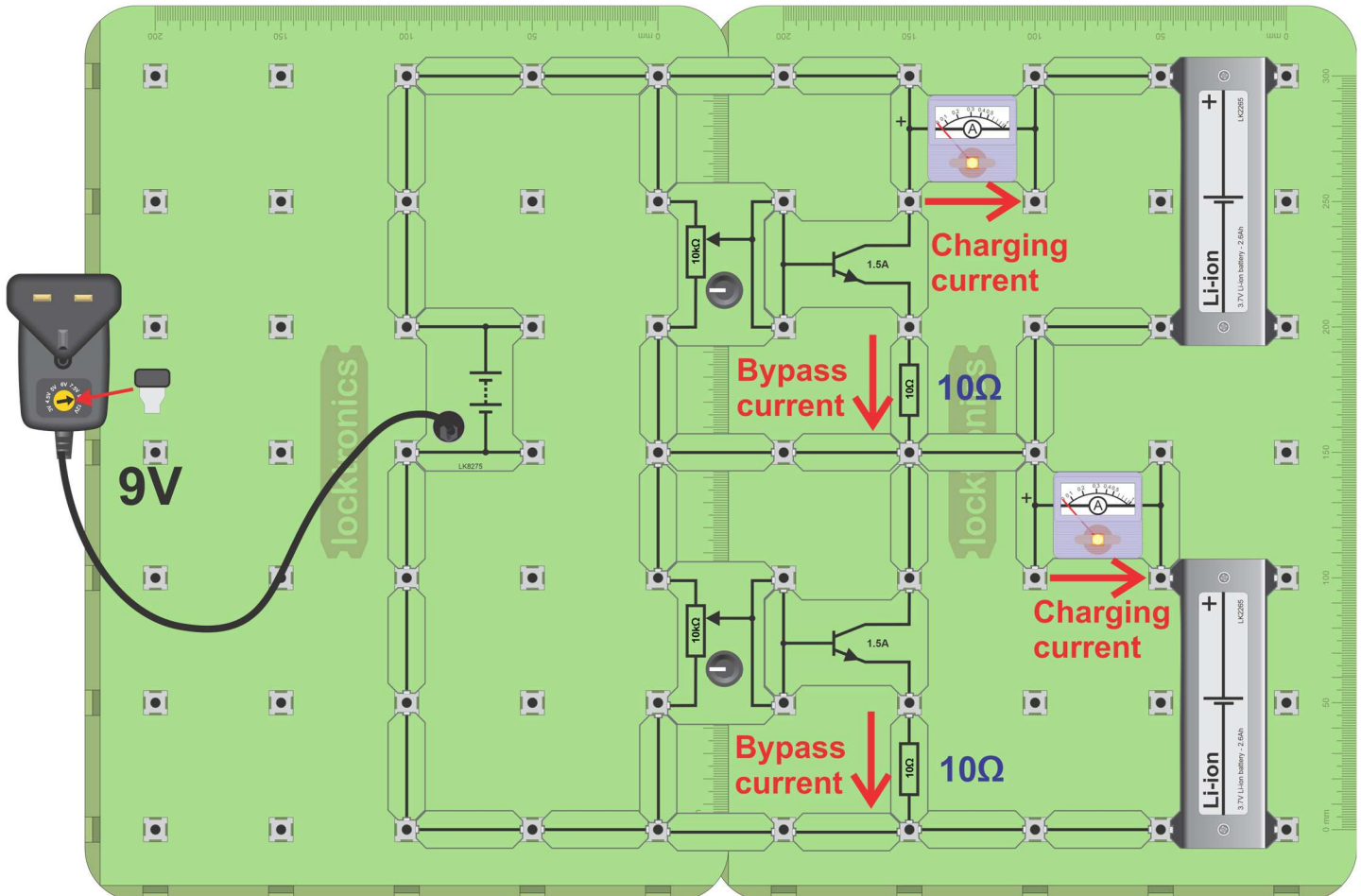
So what?

- This circuit allows you to vary the charging current for each cell.

- Effectively we are charging two Li-ion batteries in series. The two circuits made up of the potentiometer, transistor and 10 ohm resistor act as current bypass circuits reducing the current through each battery.

- In a full battery management system, a computer measures the voltage and current for each battery - or for each set of batteries in parallel.

- The computer then uses similar transistor circuits to bypass current for batteries that are fully charged so that they do not overcharge and this prolongs the battery life.

- You should see that the bypass current is larger for the cell with the higher starting voltage.

Worksheet 15

Battery management
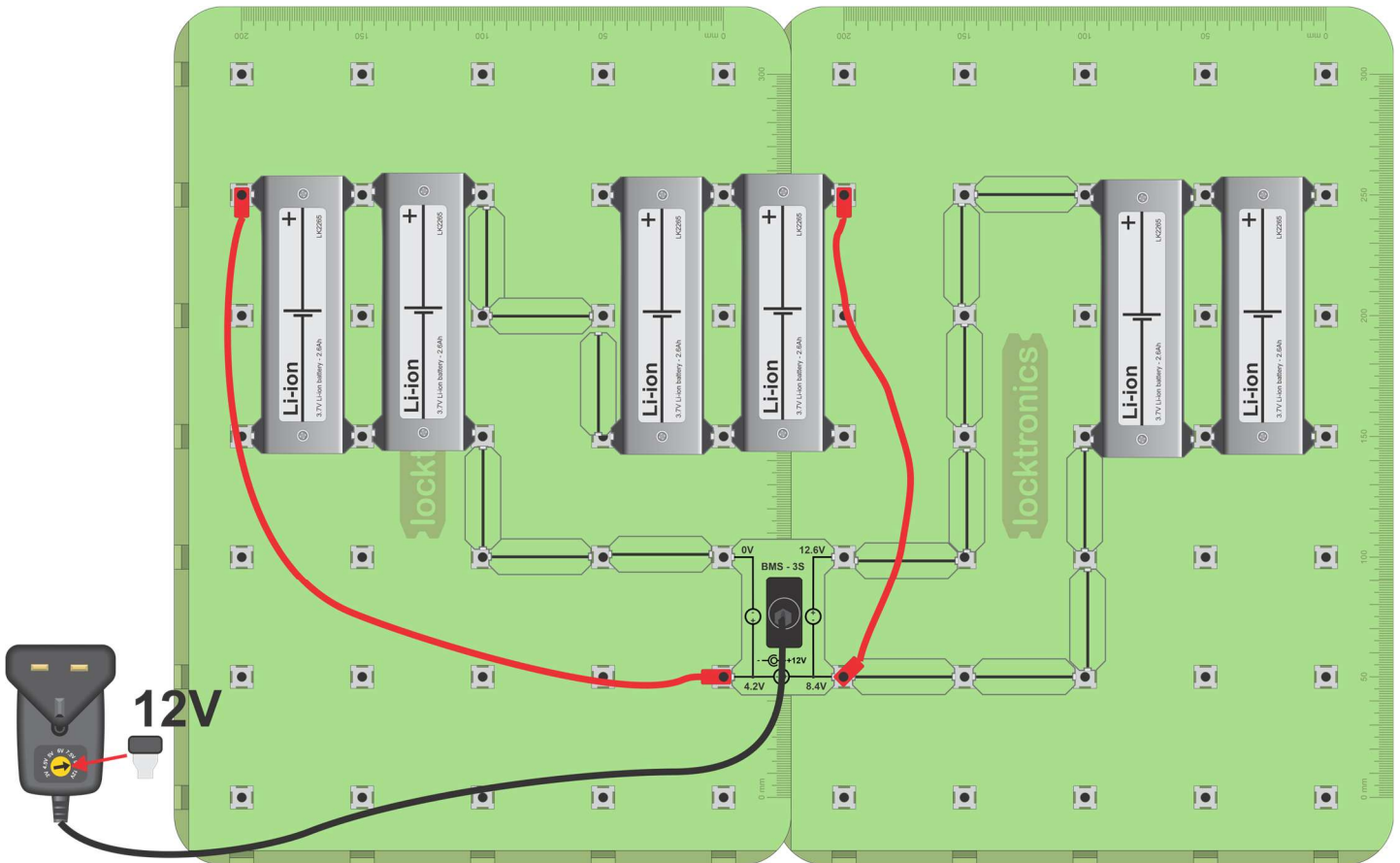
Over to you:

- Build the circuit shown above. The Battery Management System (BMS) allows you to charge three pairs of batteries together.
- Measure the voltage and current of each pair of batteries and make a note in the handout.

So what?

- Battery Management Systems vary in their complexity. The Locktronics BMS charges all batteries at the same rate until the voltage across one pair of batteries reaches 4.2V. Then it stops charging all batteries.

- This unsophisticated system is safe, but it does not allow all batteries to reach their maximum capacity.

Student

Handout

Worksheet 1 - Testing Sealed Lead-Acid batteries

Effect of load on output voltage:

Switches closed	None	1st only	1st and 2nd	1st, 2nd and 3rd
Battery voltage				
Total current	0			

Effect of discharge time on output voltage:

Time in mins	0	5	10
Battery voltage			
Battery current			

Worksheet 2 - Charging SLA batteries

Time in mins	0	5	10
Battery voltage while on charger			
Battery current			
Battery voltage open-circuit			

Worksheet 3 - Testing Li-ion batteries

Effect of load on output voltage:

Switches closed	None	1st only	1st and 2nd	1st, 2nd and 3rd
Battery voltage				
Total current	0			

Worksheet 4 - Charging Li-ion batteries

Time in mins	0	5	10
Battery voltage			
Battery current			
Battery voltage open-circuit			

Student Handbook

Worksheet 5 - Building larger batteries

Two 6V SLA batteries in series:

Voltage (V)	Current (A)	Power delivered (W)

Six Li-ion cells in a 2,3 battery:

Voltage (V)	Current (A)	Power delivered (W)

Challenge 1: six Li-ion cells in a 3,2 battery:

Voltage (V)	Current (A)	Power delivered (W)

Cell voltage	A	3.7	V
Individual cell current rating	B		Ah
Cells in parallel	C		
Groups of cells in series	D		
Combined power rating	A x B x C x D		Wh

Challenge 2: six Li-ion cells in a 6,1 battery:

Voltage (V)	Current (A)	Power delivered (W)

Cell voltage	A	3.7	V
Individual cell current rating	B		Ah
Cells in parallel	C		
Groups of cells in series	D		
Combined power rating	A x B x C x D		Wh

Challenge 3: Tesla model S battery

For one brick:

Cell voltage	A		V
Individual cell current rating	B		Ah
Cells in parallel	C		
Cells in series	D		
Combined power rating	A x B x C x D		Wh

For 16 bricks the total power rating is 16 times this number or 66.5kWh.

Worksheet 6 - Li-ion battery faults

No load output voltage: _____

Output voltage when connected to motor: _____

Output voltage with corrosion at point A _____

Output voltage with corrosion at point A - with load _____

Voltage across the corrosion component _____

Battery 1 (V)	Battery 2 (V)	Battery 3 (V)	Battery 4 (V)	Battery 5 (V)	Battery 6 (V)
(V)					

Student Handbook

Worksheet 7 - SLA battery faults

Part 1 - COMmon connected to node 4:

Switch	Voltage across battery (between nodes 1 and 4)
Open	
Closed	

Part 2 - COMmon connected to node 3:

Switch	Voltage across battery (between nodes 1 and 3)
Open	
Closed	

Question 1: Why are both readings the same when the switch is open?

....

....

Question 2: In part 1, why does the reading change when the switch is closed?

....

....

Part 3 - Effect of corrosion on load voltage:

Switch	Voltage across bulb (between nodes 2 and 3)
With corrosion in	
Without corrosion	

Question 3: What is the effect of corrosion in the cables and connectors on the brightness of the bulb?

....

Challenge:

Results of the investigation:

....

....

....

....

....

Describe how you would check whether there is corrosion on the battery.

....

....

....

....

....

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Worksheet 9 - Voltage converters

Pot position	Fully anti-clockwise	Half way	Fully clockwise
Input current			
Input voltage			
Input power			
Output current			
Output voltage			
Output power			
Efficiency			

	Reading
Input current	
Input voltage	
Input power	
Output current	
Output voltage	
Output power	
Efficiency	

Worksheet 10 - Powering DC motors:

What happens to motor speed as you reduce the number of batteries in series?

....

....

PWM signals:

Voltage

24V

0V

24V

0V

70%PWM

30%PWM

Time

Student Handbook
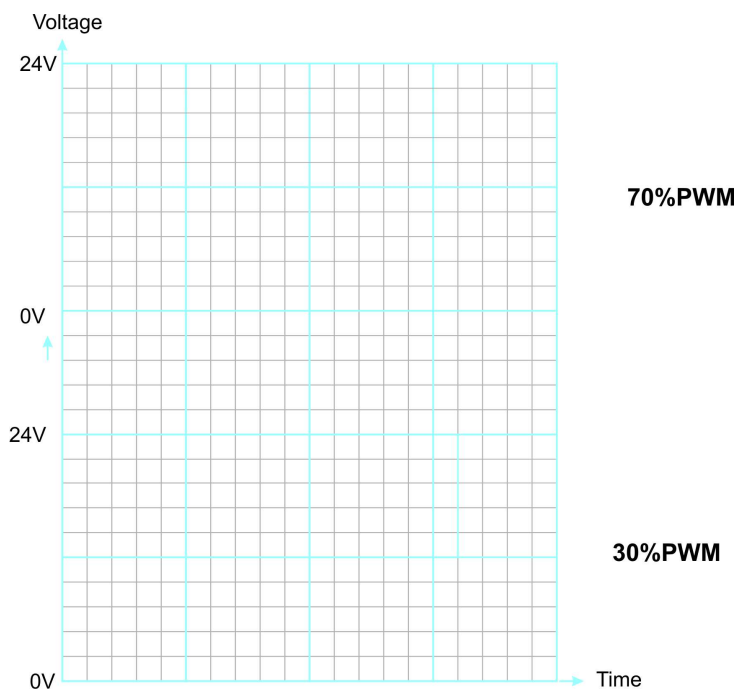
Worksheet 10 - Powering three-phase motors

Phase 1:

Voltage

10V

0V   Time

Phase 2:

Voltage

10V

0V   Time

Phase 3:

Voltage

10V

0V   Time

Student Handbook
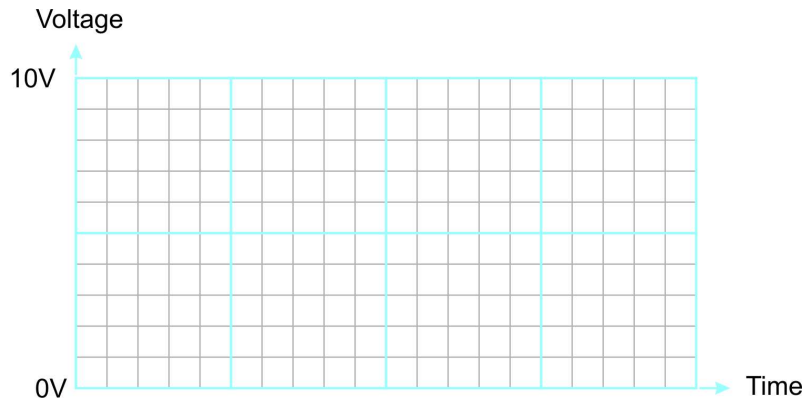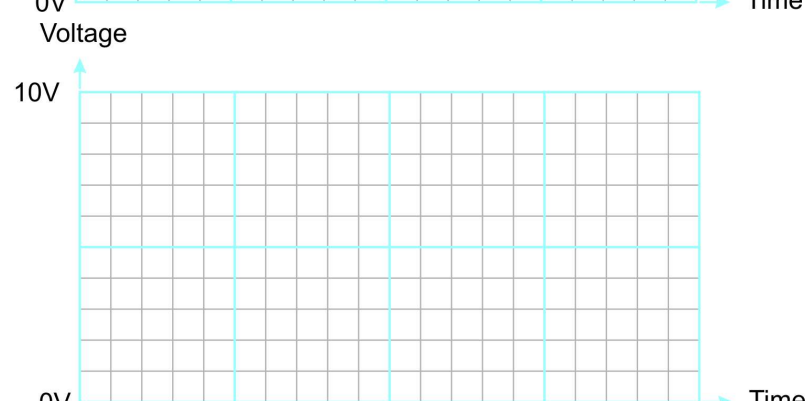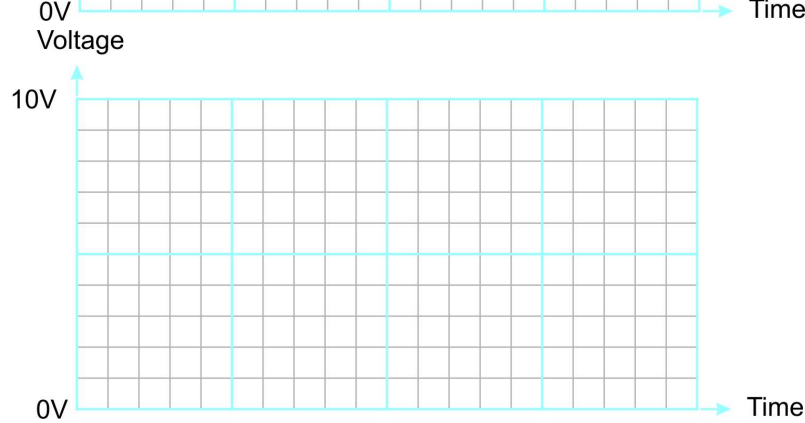
Worksheet 11 - Three-phase generators

Motor powered by 6 batteries:

Voltage

+5V

0V

-5V

Time
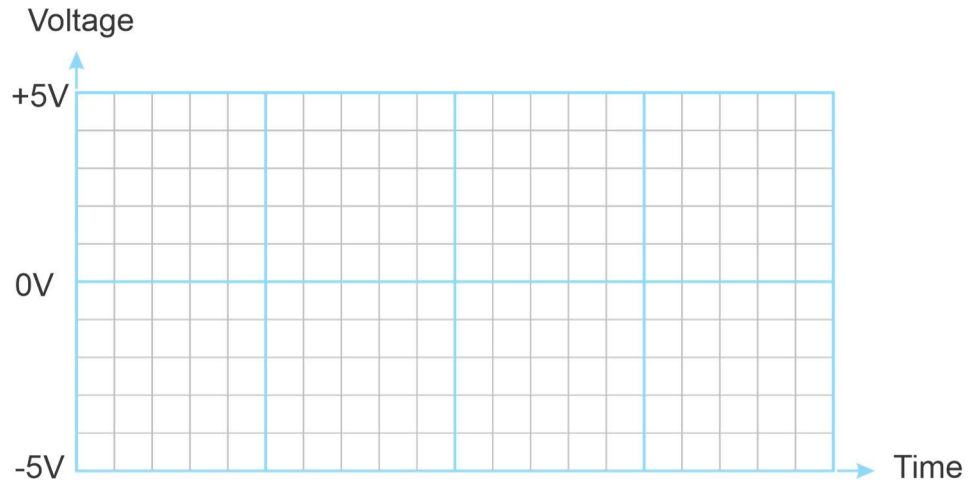
Motor powered by 3 batteries:

Voltage

+5V

0V

-5V

Time
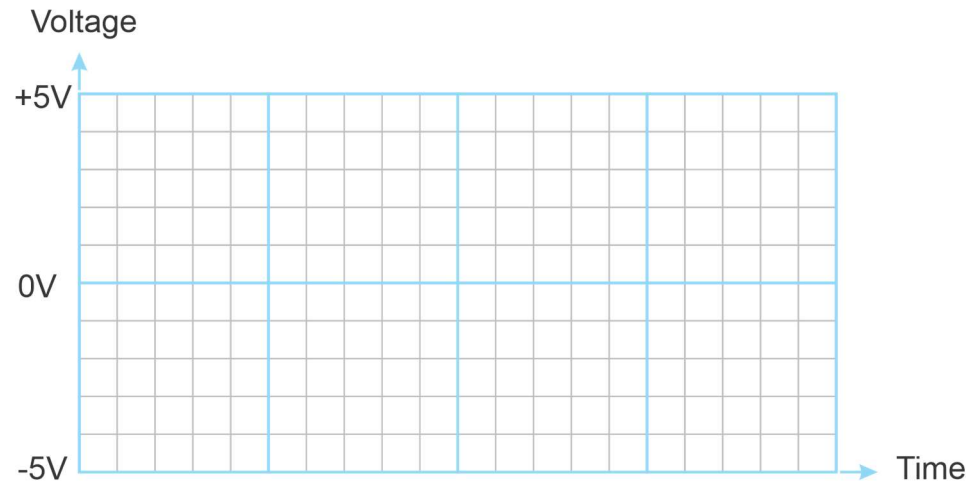
Full wave rectified:

Voltage

10V

0V

Time
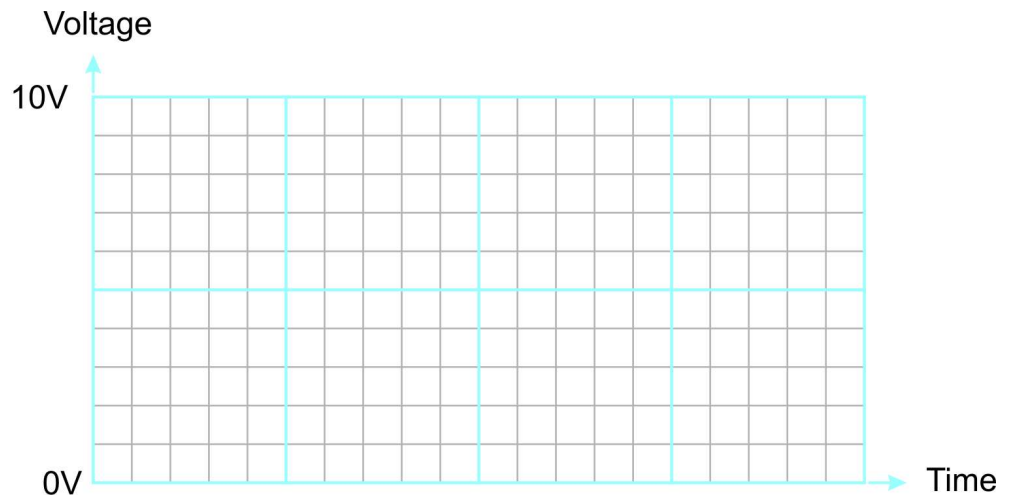
Worksheet 13 - Electric vehicle project:

What do you notice when current starts to flow to charge the SLAs?

....

....

....

Worksheet 14 - Charging system faults

Minimal current flowing:
All diodes in place: Voltage across the LED bulb: _____
Remove any diode: Voltage across the LED bulb: _____

Max current flowing:
All diodes in place: Voltage across the LED bulb: _____
Remove any diode: Voltage across the LED bulb: _____

Corrosion
LED voltage with minimal current, no corrosion: _____
LED voltage with corrosion in place: _____

LED voltage with max current, no corrosion: _____
LED voltage with corrosion in place: _____

Student Handbook

Worksheet 14 - Charging system faults

1 - Diode failure - open circuit (OC):

A. Minimum output

	No fault	1 diode 'OC'	2 diodes 'OC'	3 diodes 'OC'
Rectifier output				

B. Increased output

	No fault	1 diode 'OC'	2 diodes 'OC'	3 diodes 'OC'
Rectifier output				

2 - Diode failure - short circuit (SC):

A. Minimum output

	No fault	1 diode 'SC'	2 diodes 'SC'	3 diodes 'SC'
Rectifier output				

B. Increased output

	No fault	1 diode 'SC'	2 diodes 'SC'	3 diodes 'SC'
Rectifier output				

3 - Effect of corrosion:

A. Minimum output

	No fault	Corrosion
Rectifier output		

B. Increased output

	No fault	Corrosion
Rectifier output		

Worksheet 15 - Battery management

Battery 1 (V)	Battery 2 (V)	Battery 3 (V)	Battery 4 (V)	Battery 5 (V)	Battery 6 (V)
(V)					

Battery	Initial voltage (V)	Charge current (A)	Resistor voltage	Bypass current (A)

BMS system

	Pair 1	Pair 2	Pair 3
Voltage V			
Current I			

Notes for the Instructor

Please make sure that you read the section on Battery care in the Reference section to make sure your batteries are well kept.

About this course

Introduction

This module allows students to develop an understanding of high-voltage electrical systems in modern vehicles. The course is essentially a practical one. Using Locktronics equipment, students set up and test circuits that simulate the behaviour of these high-voltage electrical systems.

Measurements use multimeters, clamp meters and oscilloscopes, following guidelines set out in each worksheet. The significance of the results is examined.

The course includes elements of fault-finding in two key areas, charging systems and HT systems.

Aims

The course gives students an overview of modern high-voltage and conventional electrical systems in motor vehicles.
In addition, it introduces techniques used to troubleshoot these areas.

Prior Knowledge

It is recommended that students have followed the 'Automotive Electrics' course, or have equivalent knowledge and experience of building and testing simple circuits, including the use of multimeters and clamp meters to measure voltage and current, and oscilloscopes to analyse AC signals.

Using this course:

There are two main parts to the workbook: the worksheets and the Student Handout.
We envisage that you print (and bind) one copy of the worksheets, to stay with each set of Locktronics equipment. You will need print a copy of the Student Handout for each student.

The worksheets are written in a student-centred way. The plan is that you give each pair of students a set of equipment, the bound workbook and a Student Handout each. You then allow them to work through the topics in the workbook, offering help and assistance where needed. Students record their measurements in the Student Handout.

This approach encourages self-study, with students working at a rate that suits their ability. It is for the instructor to monitor that their understanding is keeping pace with progress through the worksheets. The Student Handout is one element of this monitoring. The instructor can assess progress by looking at the quality of their entries. This can form the basis for the feedback given to the students.

Knowing that multidisciplinary teaching teams are increasingly popular, the 'Notes for the instructor' aims to help instructors for whom this topic is not their principal area of experience.

Time:
It will take from ten to fifteen hours to complete the module.

Learning Objectives

On successful completion of this course the student will be able to:

- state that batteries convert energy between chemical and electrical forms;
- recall that a battery can be thought of as containing an internal resistor in series with the battery;
- state that the internal resistance of a lead-acid cell increases as the cell discharges;
- explain the significance of battery energy capacity and recall that it is measured in units called amp.hours (A.h);
- compare SLA and Li-ion cells in terms of their output voltage and internal resistance;
- hence appreciate the need to avoid short-circuiting a Li-ion battery;
- describe the meaning of 'state of charge (SOC)' and explain its significance;
- use a battery voltage/SOC curve to predict the state of charge of a battery;
- explain why the SOC of a Li-ion battery cannot be predicted from its output voltage;
- given data on voltage and current, calculate the power delivered by a battery;
- given the battery type and its energy capacity, C, estimate a suitable charging current for 'normal' and 'fast' charging;
- given the energy capacity of each cell and its rated voltage, calculate the energy, in watt.hours, deliverable in a given time;
- describe the effect of combining a number of cells or batteries to make a larger battery;
- interpret the meaning of the term '2,3' battery;
- describe the effects of corrosion on the electrical devices in a vehicle;
- describe how to use a multimeter to check for the presence of corrosion;
- explain why it may be necessary to select individual cells for a battery pack;
- describe the function of a DC-to-DC step-up converter, giving examples of its use in vehicles;
- describe the function of a DC-to-DC step-down converter, giving examples of its use in vehicles;
- recall that DC motor speed increases as the applied voltage increases;
- describe how a diode can be used to prevent damage from 'back-em.f.' from a motor;
- draw a graph to illustrate the meaning of 'pulse-width modulation';
- explain the meaning of mark:space ratio for a PWM signal;
- explain what is meant by 'duty cycle' and convert it to mark:space ratio;
- explain the meaning of 'sourcing' and 'sinking' current in the output of a transistor;
- sketch a voltage / time graph to illustrate the meaning of 'three-phase supply';
- state an advantage of a three-phase motor over a single-phase motor;
- draw a circuit diagram for a three-phase rectifier, using six diodes;
- distinguish between the effects of an open-circuit fault in a diode and a short-circuit fault in a three-phase rectifier.

Appendix 4

Bill Of Materials

To deliver this course you will need the following components in a Locktronics kit:

1	HP2666	Adjustable DC power supply
4	HP4039	Tray lid
3	HP5540	Deep tray
1	HP5540	Shallow tray
3	HP7750	Daughter tray foam cutout
3	HP8600	Crash foam
3	HP9564	62mm daughter tray
1	LAS9556	SLA cut out foam
1	LAS7551	LI-ion cut out foam
1	LK3662-V2	2200uF 25V capacitor.
6	LK2265	3.7V Lithium-ion battery
1	LK2346	12V incendescent MES bulb
1	LK2389	Voltmeter, 0V to 30V
2	LK3374	6V Sealed Lead Acid battery
2	LK3982	Voltmeter, 0V to 15V
3	LK4025	10 ohm resistor
3	LK5202	1Kohm ressitor
1	LK5203	10Kohm ressitor
2	LK5214	Potentiometer, 10K ohm (DIN)
6	LK5243	Diode, power, 1A, 50V
31	LK5250	Connecting Link
2	LK5403	6V relay
2	LK5291	Lampholder, MES
2	LK5620	Yellow 4mm to 4mm lead, 1m
3	LK5625	Red 4mm to 4mm lead, 1m
2	LK5640	Blue 4mm to 4mm lead, 1m
3	LK5660	Black 4mm to 4mm lead, 1m
1	LK5894	BMS 3S Li-ion battery charger
1	LK6152	Corrosion component
3	LK6209	Switch, on/off, metal strip
2	LK6705	Power transistor
1	LK6716	Downconverter
1	LK6841	12V LED bulb white
1	LK8000	Shottky diode
1	LK8011	Power MOSFET
1	LK8275	Power supply carrier with battery symbol
2	LK8397	Ammeter 0A to 1A
1	LK8886	Locktronics PIC II
3	LK8900	7 x 5 metric baseboard with 4mm pillars
1	LK9593	Upconverter

You will also need the HP2001 Brushless DC motor / DC motor pair.

Updated 14 11 23

Notes for the instructor

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Preliminary issue

Some groups may need initial guidance / revision on using an oscilloscope, including an explanation of the significance of the various settings and help with interpreting and taking measurements from the oscilloscope trace. In some investigations, it will be necessary to use the 'x10' setting on the probes to reduce the voltage sensitivity. Students may need guidance on how to use this and interpret the results.

Similarly, some will need an overview of the uses of multimeters and current-clamp meters.

General checks

- Is the correct type of plug-top power supply (AC or DC) being used?

- Is it on the correct voltage setting?

- Are cells connected with the correct polarities in multiple-cell configurations?

- Is the layout correct (including connections to potentiometer carriers)?

- Are all components, including the power supply carrier, connected with the correct polarity?

Multimeter and current clamp-meter checks:

- Is the meter connected to the circuit correctly?
  If not, the '-' sign will appear in the wrong place.

- Are the leads connected to the correct sockets on the multimeter?

- Is the meter set on the correct range?

- Some voltage readings are negative.
  The meter leads are the wrong way round.

- The current clamp meter keeps flipping out the connecting link.
  It may be easier to remove the connecting link and replace it with a 'flying lead' to make the current measurement. It may also be an advantage to use the 'Hold' button to retain the reading.

Oscilloscope checks:

- Is the oscilloscope connected to the circuit properly?

- Are the oscilloscope settings correct?
  If not, the correct trace will not be created. (Try the 'Auto' trigger mode / 'AC' coupling)

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Worksheet	Notes
1 Testing Sealed Lead-Acid batteries	Specific problem: • Resistors may heat up. Do not leave switched on. • Unexpected meter readings - see Multimeter and current clamp-meter checks on previous page. Points for discussion: • Distinction between cells and batteries. • Significance of internal resistance of a cell. • Significance of 'State of Charge' (SOC). • Meaning and significance of energy capacity, C, of a battery. • Amp.hour (A.h) as a unit of energy capacity.

2
Charging
Sealed
Lead-Acid batteries
	Specific problem:
	• In the event of difficulty using the current clamp meter, swap the connecting link for a wire.
	• Unexpected meter readings -
	    see Multimeter and current clamp-meter checks and General Checks on previous page.
	    check polarity of SLA and plug-top power supply.
	Points for discussion:
	• Link between energy capacity, charging current and charging time.
	• Significance of 'Output voltage / SOC' graph for SLA batteries.

3 Testing Li-ion cells	Specific problem: See above for worksheets 1 and 2. Points for discussion: • Comparison of Li-ion and SLA cells.
4 Charging Li-ion cells	Specific problem: See above for worksheet 2. Points for discussion: • Significance of 'Output voltage / SOC' graph for Li-ion cells (c.f. SLA batteries).
5 Building larger batteries	Specific problem: See above for worksheet 2. Points for discussion: • Calculating power delivered by a battery. • Benefits of combining cells in series and in parallel. • Health and safety when handling Li-ion batteries. • Nomenclature such as '2,3' battery. • Calculating amp.hour rating, current capability and power capability of a battery.

Notes for the instructor

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Worksheet	Notes
6 Li-ion battery faults	Specific problem: See above for worksheet 2. Points for discussion: • Corrosion - causes and effects. • Issues when charging cells in parallel.
7 SLA battery faults	Specific problem: See above for worksheet 2. Points for discussion: • How to detect corrosion problems.
8 Voltage converters	Specific problem: See above for worksheet 2. Points for discussion: • Roles for voltage converters in modern vehicles. • Significance of, and how to calculate, energy efficiency.
9 Powering DC motors	Specific problem: See above for worksheet 2. Points for discussion: • Advantage of using a transistor driver. • Cause and perils of back-e.m.f and how to suppress it. • P.W.M. and its advantage over analogue voltage control. • Sourcing and sinking current. • Use of ECU's in modern vehicles.
10 Powering three-phase motors	Specific problem: Complicated circuit needs checking, especially speed circuit. Points for discussion: • Meaning of three-phase supply and reasons for its importance. • Significance of 'U', 'V' and 'W' outputs.
11 Three-phase generators	Specific problem: Students may need help in viewing the separate phases on the oscilloscope. Check the orientation of the diodes in the circuit on p.32. Points for discussion: • Phase relationships and their significance. • Three-phase rectifier. • Interpreting the circuit diagrams on p.31 and p.33

Notes for the instructor

Worksheet	Notes
12 Isolation relays	Specific problem: None really - just awareness Points for discussion: • Isolation • Voltage in one circuit with reference to the other.
13 Electric vehicle project	Specific problem: Complicated circuit needs checking, especially polarity of components. Points for discussion: • Types of hybrid / electric vehicles. • Energy flow through the vehicle. • Need to isolate both terminals of the power supply. • High-voltage safety issues.
14 Charging system faults	Specific problem: See above for worksheet 13. Points for discussion: • Significance of diode failure and how to detect it. • Detecting corrosion.
15 Battery management	Specific problem: See above for worksheet 2. Points for discussion: • The need for battery management. • The operation of the circuit

Caution: if you mistreat Li-ion batteries they can catch fire. Do not use any other charger than the one supplied with this kit and make sure you use the correct voltage.

Do not discharge the batteries below 3.2V

We have taked considerable precautions against any mishap here: the batteries are all encased in stainless steel casings to protect the students and the equipment. However students using batteries should be supervised at all times, and batteries should not be left on charge for more than 2 hours.

Reference

Battery care

Li-Ion Battery

Long Term Storage Voltage: 3.85V

Short Term Storage Voltage: 3.7V – 4.0V

Absolute Max Voltage: 4.2V

Absolute Min Voltage: 3.0V

Recommendations

At the end of each session we highly recommend checking the voltage of each battery. Batteries with a voltage of 3V and below should be topped up to around 3.8V or they risk becoming permanently damaged and will need replacing. Batteries with a voltage higher than 4V should be discharged to around 4V or they risk losing both capacity and current capability. Checking the voltage of the batteries after each session also allows students to be held accountable for any misuse or abuse.

The battery voltage is very important when storing the battery for any mid to long period of time. The storage voltage should be around 3.85V and should be checked and topped up at least once every 6 months to prevent the battery becoming damaged. The batteries should be stored in a cool and dry environment for maximum life expectancy.

Lead Acid Battery

Long Term Storage Voltage: > 6.4V
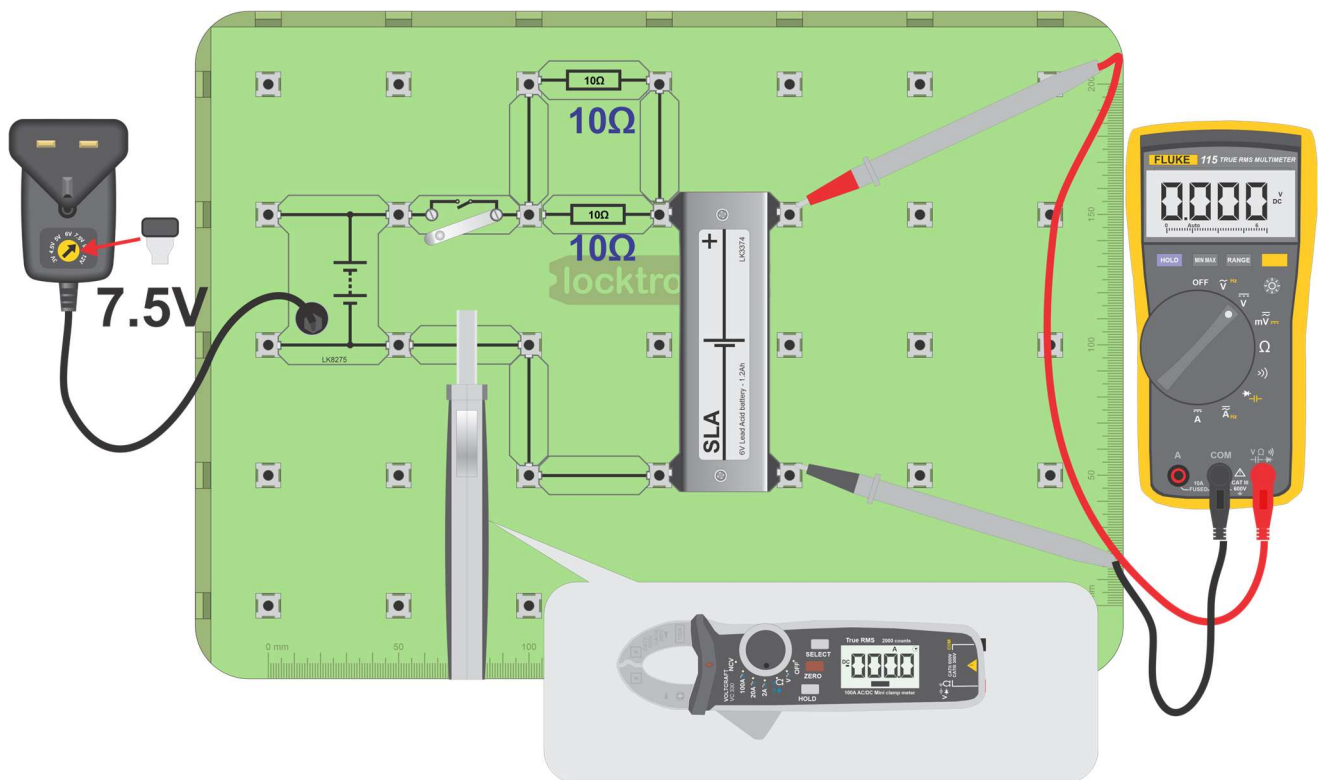
Short Term Storage Voltage: > 6.0V

Absolute Max Voltage: 6.7V

Absolute Min Voltage: 5.3V

Recommendations

At the end of each session we highly recommend checking the voltage of each battery. Batteries with a voltage of less than 6.2V should be topped up to around 6.4V or higher or they risk losing capacity and current capability. Checking the voltage of the batteries after each session also allows students to be held accountable for any misuse or abuse.

The battery voltage is very important when storing the battery for any mid to long period of time. The storage voltage should be around 6.4V and should be checked locked topped up at least once every 6 months to prevent the battery becoming damaged. The batteries should be stored in a cool and dry environment for maximum life expectancy.

Charging the SLA batteries

Information:

- The charge time and current your battery needs depends on the State of Charge (**SOC**) of the battery. However, you are unlikely to know the battery **SOC** when you open the kit.

- The battery we are using is RS Pro part number 727-0388. For this Sealed Lead Acid (**SLA**) battery, a recommended method is to charge it at a constant current of (0.1x **C**) for up to twenty-four hours, where **C** is the battery energy capacity.
  For this battery, **C** is 1.2A.h, which implies a constant current of 0.12A.

- The kit does not include a constant-current generator circuit. The circuit shown above is a near equivalent. The plug-top power supply outputs 7.5V. The resistors drop between 1V and 1.5V so that the current varies between 0.15A and 0.3A as the battery charges up.

Method:

- Construct the circuit shown above.

- Measure the charge current with your clamp meter, positioned as shown.

- Charge the battery in this way for two hours.

  Assuming that the battery has a reasonably high **SOC**, then that will probably be enough. As the battery charges the battery voltage rises and the charge current falls. When the charge current falls to below 0.05A then replace the diode with a link and carry on charging for a further hour.

Charging the Li-ion batteries
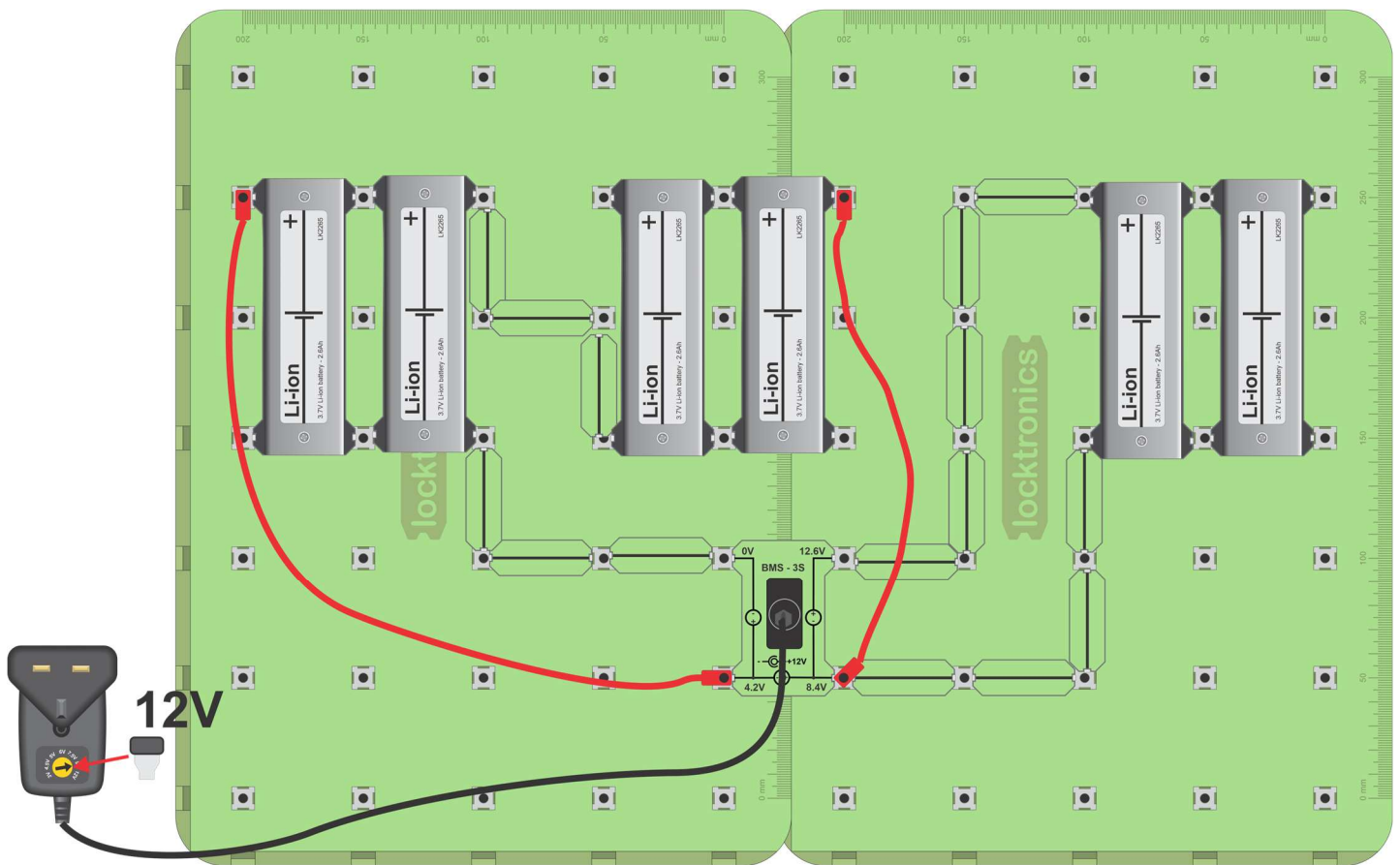
Information:

- Before each lesson you will need to make sure that there is enough energy in your batteries. That's hard to measure. Most of the time you will not need to charge the batteries as they will not fully discharge much over a single lesson.
- To charge the batteries use the BMS supplied with the kit and set up the circuit above. You can get students to do this for you at the end of a lesson.
- The BMS will cut out when one set of batteries reaches 4.2V. That will not ensure that all batteries are charged to the maximum, but it will be more than good enough for your students.

Discharging the Li-ion batteries
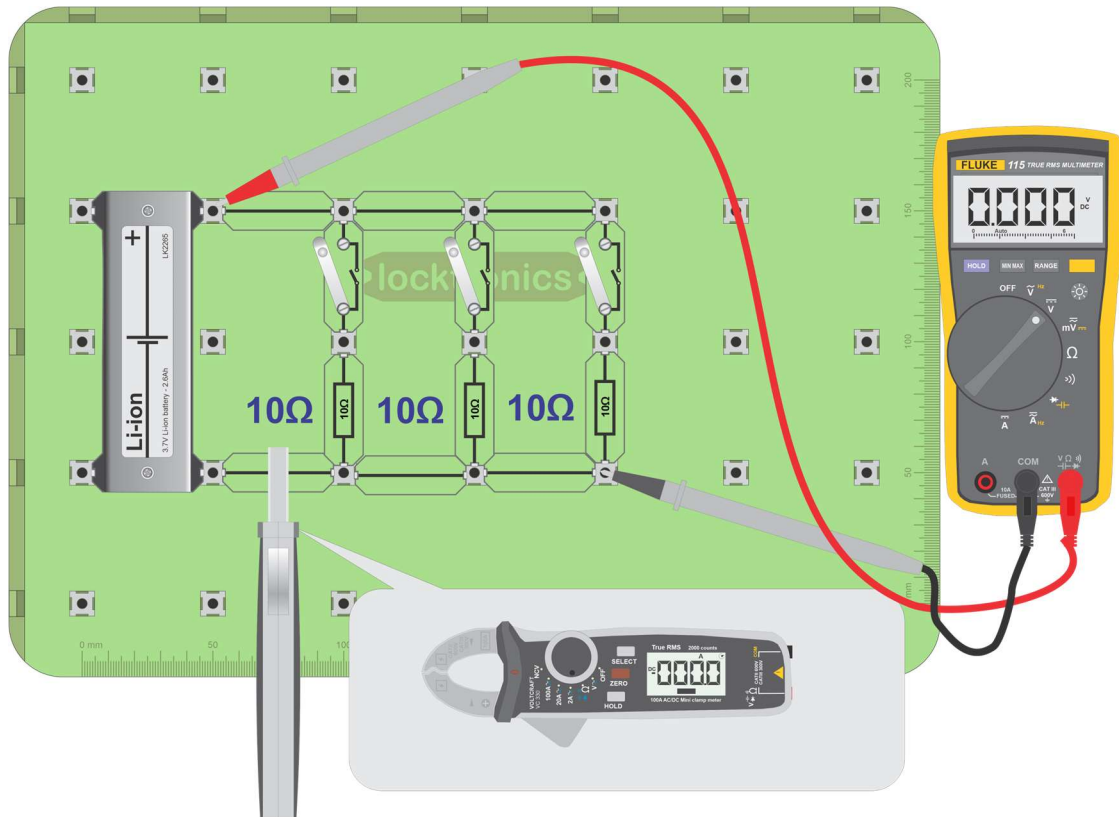
Do not discharge the batteries below 3.2V

Over to you:

- Discharge your Li-ion cells slightly if you feel that they are overcharged.
- To discharge a Li-ion cell or a SLA battery, you can use the same circuit used to test them, using up to three 10 ohm resistors in parallel.

  For the SLA, this should give a discharge current of around 1.5A.

  For the Li-ion, this should give a current of around 1A.

- 10% discharge:
    - for the SLA will take around 10 minutes;
    - for the Li-ion battery will take around 15 minutes.
- 50% discharge:
    - for the SLA will take around 40 minutes;
    - for the Li-ion battery will take around 50 minutes.
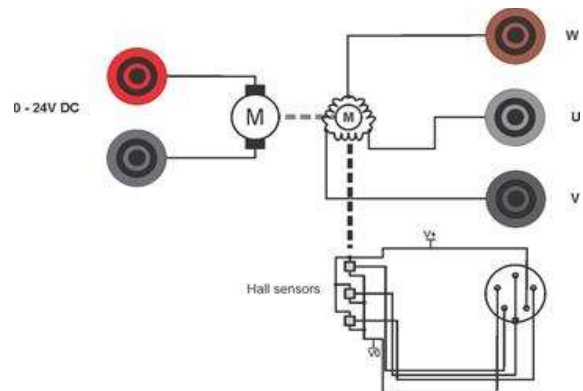
DC motor / brushless DC motor pair
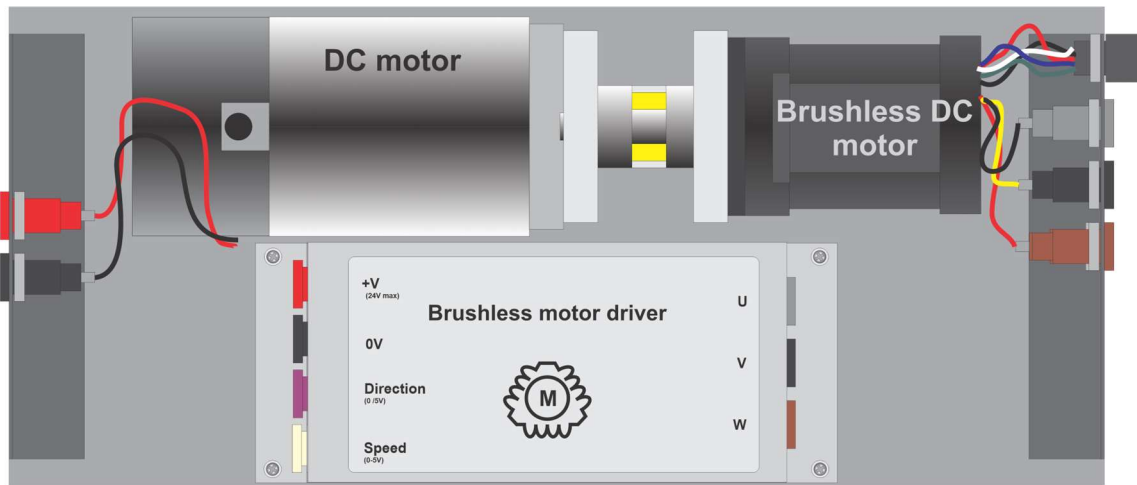
The HP2001 DC motor/brushless motor pair consists of two parts: the motors themselves, coupled together, and a brushless DC motor driver.

The coupled DC motor / brushless motor pair can be driven in two ways:

- the DC motor drives the brushless DC motor;
- the brushless DC motor drives the DC motor.

The DC motor supply voltage can be up to 24V.

With the Brushless DC motor unloaded the approximate speeds are:

Volt-	RPM
2.4	0
4.8	180
7.2	390
9.6	600
12.0	800
14.4	1000
16.8	1210
19.2	1410
21.6	1680
24.0	2010

Unloaded, the brushless DC motor will generate $6V_{RMS}$ between two phases at 2000 rpm.

When driving the DC motor with the brushless DC motor at 2000 rpm, the DC motor acts as a generator and generates 25VDC.

The polarity of the voltage generated on the terminals will depend on the direction of rotation. When driven clockwise with respect to the face of the motor the red terminal will be positive.

DC motor / brushless DC motor pair

When driven at full speed (speed input 5V) and unloaded, the DC motor speed of rotation is approximately 2000rpm.

The following table shows the relationship (approximate) between speed and generated voltage for the brushless DC motor for varying speed input voltages when a 24V DC power supply is used and no load:

Speed rpm	Output V(DC)
1199	14
1795	21.5
2292	27
2565	29
2522	28
2631	30
3099	35

Brushless DC motor driver

The brushless DC motor driver board is housed in a rugged stainless steel casing. It should be supplied from a 24V power supply. This is included with HP2001.

The HP2001 has two additional inputs: a direction input and a speed input.
- The direction input should be 0V or +5V.
- The speed input should vary from 0V to 5V.

Micro ECU - User instructions
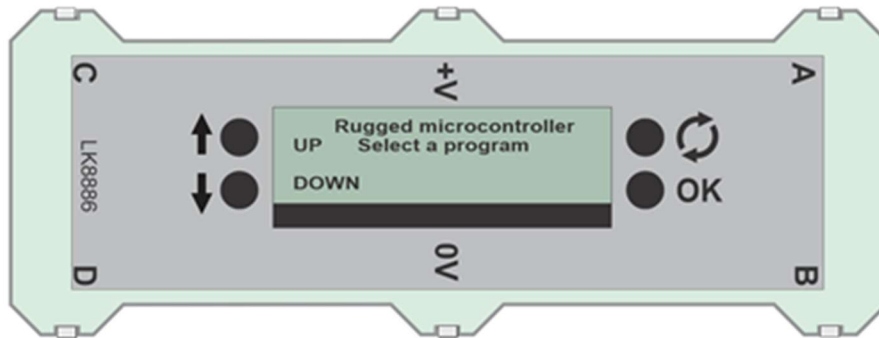
The LK8886 Micro ECU has six standard Locktronics legs that allow it to be inserted into the Locktronics base board.

The controls on the Micro ECU are:

UP: allows program selection and control from within a program.

DOWN: allows program selection and control from within a program.

RESET: resets the Micro ECU into program selection mode.

OK: confirms program selection; may also be used in a program.

To select a program: press the **RESET** switch and use the **UP** and **DOWN** buttons to navigate to the programme you want. Select the **OK** button to start the program.

Terminals **A**, **B**, **C**, **D** are input / output connections. Their function is dictated by the programme selected.

Each is fitted with series 220Ω resistors between the microcontroller and the output pin and will sink or source 20mA.

Terminals **B** and **D** can be programmed to deliver PWM output.

Max voltage at V+ is 12VDC.

The list of programs at date of publishing is as follows:

1. Logic NOT
2. Logic AND
3.
4. Logic OR
5. Slow PWM
6. Fast PWM
7. Temperature alarm B
8. Reverse alarm
9. Temperature alarm A
10. Heater fan control
11.
12. Auto headlights
13. Brake light alarm
14. DC motor drive
15.
16. Alternator feedback loop
17. Spark creator

Version control

27 08 20   **First prototype release**

10 02 21   **First version released**

16 02 21   **2 x cct diagrams changed slightly**

24 11 21   **included Schottky diode in Li-ion charging circuit, removed series charging on Li-ion**

08 12 21   **included section on battery care**

24 01 22   **Layout errors in ws12, ws13 fixed**

08 02 22   **10k added to FET circuit, new worksheet on isolation**

24 02 22   **BMS added to the kit and minor BOM changes.**

06 04 22   **Changed BMS to be at end of programme**

23 11 22   **reinserted suppression diode in PWM worksheets**

05 12 22   **Misprint on page 15 corrected**

16 02 23   **small changes**

09 08 23   **Reformatted to new style**

14 11 23   **updated BOM spreadsheet on page 55**