S'Cool LAB

Quadrupole Ion Trap

DO-IT-YOURSELF-MANUAL

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Contents

1. Introduction

It is possible to observe isolated electrically charged particles or even antiparticles for a long time, when they are confined in "traps without material walls" (Paul, 1990). Wolfgang Paul and Hans Georg Dehmelt developed two types of these traps in the 1960s and shared one half of the Nobel Prize 1989 for their work. While Penning traps, developed by Dehmelt and Penning, use static electric and magnetic fields, Paul traps, developed by Wolfgang Paul, are operated with alternating electric fields (Major, Gheorghe, & Werth, 2006).

Today, particle traps are used in many fields: In mass spectrometry, in atomic frequency and time standards and in trapped ion quantum computing research. At CERN, particle traps are used in the antimatter factory to trap and study, for example, anti-protons and to allow the formation and study of anti-hydrogen atoms. Physicists are thereby seeking to solve the matter-antimatter asymmetry problem. One of the experiments in the antimatter factory, GBAR, seeks to study the gravitational effect on antihydrogen atoms (Grabowski, 2014).

Although the Paul traps used in mass spectrometry and other physics experiments are operated in vacuum with atomic ions, macroscopic particles such as lycopodium spores can be trapped in a similar way in air. In the following we present how this hands-on particle physics experiment can be built and studied by high-school students. We have developed activities which allow students to learn about electric quadrupole fields while discussing the fascinating world of antimatter research.

2. Classroom Recommendations

This activity was designed for physics students who are between 16 and 19 years old. In the classroom, we recommend that students perform the quadrupole ion trap experiments in groups of 3-4 students. Each group will require a quadrupole ion trap, an AC power source with transformer (capable of reaching 2-3 kV) and lycopodium spores. Once the trap is constructed and connected, students typically set up and perform an experiment with the trap within 30 minutes.

Constructing the quadrupole ion traps can serve as a potential STEM project for enthusiastic students as it incorporates mechanical construction, 3D printing and electronics. After collecting all components, a small group of students will need approximately 10-15 hours to build and observe a trap. A standard 3D printer will run for approx. 48 hours to print all components.

2.1. Learning Outcomes

Performing an experiment with the ion trap is an opportunity for students to explore the following topics in more depth:

- Electric Fields (in particular quadrupole fields) around charge distributions
- AC and DC current, transformers if applicable
- Frequency

It is also an opportunity to introduce the students to the stroboscopic effect.

Building the quadrupole ion trap as an extended project enables students to develop:

- Circuit construction and electronics skills
- 3D printing skills
- Basic mechanical assembly skills

3. Required Materials

The Table 3.1 below presents all the required materials to build the quadrupole ion trap. Note that the components highlighted in blue are sufficient if you do not intent to build the blinking circuit.

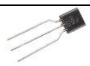
Description	Picture	Price	Online Shop	Stock Number
2 x Resistor (10 $M\Omega$)		8 €		2960572
Multi Contact 4mm Banana plug sockets		6 € for 2 pieces		404-200
1 × Toggle Switch On-Off-On*		25 € for 5 pieces		448-0753
Male to Male Leads (9 required) Male to Female Leads (6 required)		5 € for packs of 10 (20 € total)		791-6463 791-6454
Electric Paint (Bare Conductive)		20 € for 50 ml	RS Components http://www.rs-components.com	835-2693
Breadboard		18 €	*Note any on-off switch will work for the non-strobing circuit however an on-off-on switch is required for flasher circuit.	102-9147
Capacitors 1 × 1 µF 1 × 10 µF		Come in packs of 4 for 2 € (4E)		374-910 0571256
Diode		Packs of 10 for 5 €		251-3025
2 × NPN Transistor		Packs of 10 for 3 €		739-0442
Resistors 2 × 10 Ω 1 × 100 Ω 1 × 8.2 kΩ 1 × 10 kΩ		Come in packs of 10 for 3 € (total 12 €)		707-8063 707-8827 707-8902 707-8300
10 kΩ Potentiometer		3 €		468-8705
Battery Strap (Clip)		5 for 4 €		489-021
9V Battery		8 €		841-7002 (or 386-9997)
2 x High power LED		0.12 € per piece	Reichelt Elektronik https://www.reichelt.de	LED 3-6000L GN

Table 3.1) List of required materials

Three M2.5x7 (ISO metric screw thread), and three M2.5 Washer are also required.

To build the trap you will also need a paintbrush, scissors, duct tape, screwdrivers and soldering equipment.

3.1. Other materials required to perform experiment

In addition to the materials required to build the trap, there are materials that are required to carry out the experiment.

Spores (Lycopodium Powder) – These are the dry spores of clubmoss plants that will be levitated in the experiment. These can be purchased here (approx. 10 €): https://www.phywe.com/en/lycopodium-powder-10-g.html or here: https://www.amazon.com/s/ref=nb_sb_ss_i_8_11?url=search-alias%3Daps&field-keywords=lycopodium+powder&sprefix=lycopodium+%2Caps%2C274&crid=27VGW5VZOMRBN&rh=i%3Aaps%2Ck%3Alycopodium+powder

Wooden Skewers – Ordinary wooden skewers are used to collect lycopodium powder and deposit them it the trap.

Power Source/Transformer – The experiment requires a 2-3 kV power source of frequency 50 Hz. We produce this using a standard variable 20 V AC power source and a transformer with voltage transformation ratio of 200 (coils with N_1 = 50, N_2 = 10000).

Perspex tube/Overhead slide sheet – The spores can be blown out of the trap by the airflow in the room or by breathing students, so we recommend placing a clear plastic barrier around the electrodes. It is possible to use a Perspex tube of diameter approximately 120 mm or a clear sheet of plastic (for example the slides used on overhead projectors).

4. Building Instructions

This section contains instructions for building a quadrupole ion trap. The instructions are broken into four sections. The first three sections (4.1.1-0) describe how to build a basic quadrupole ion trap without the strobing circuit. The final section (4.2) contains instructions for building the strobing circuit.

The original trap design uses three electrodes (two end caps and one ring). However, we have discovered that using two electrodes, the bottom end cap and the ring works better as the top electrode blocks the LED light and can obscure the view of the Lycopodium spores.

4.1. Basic Quadrupole Ion Trap

4.1.1. 3D printing

The first step to building the trap is to use a 3D printer to print all of the components. All components can be downloaded as STL files from zenodo with the following DOI: 10.5281/zenodo.1251787

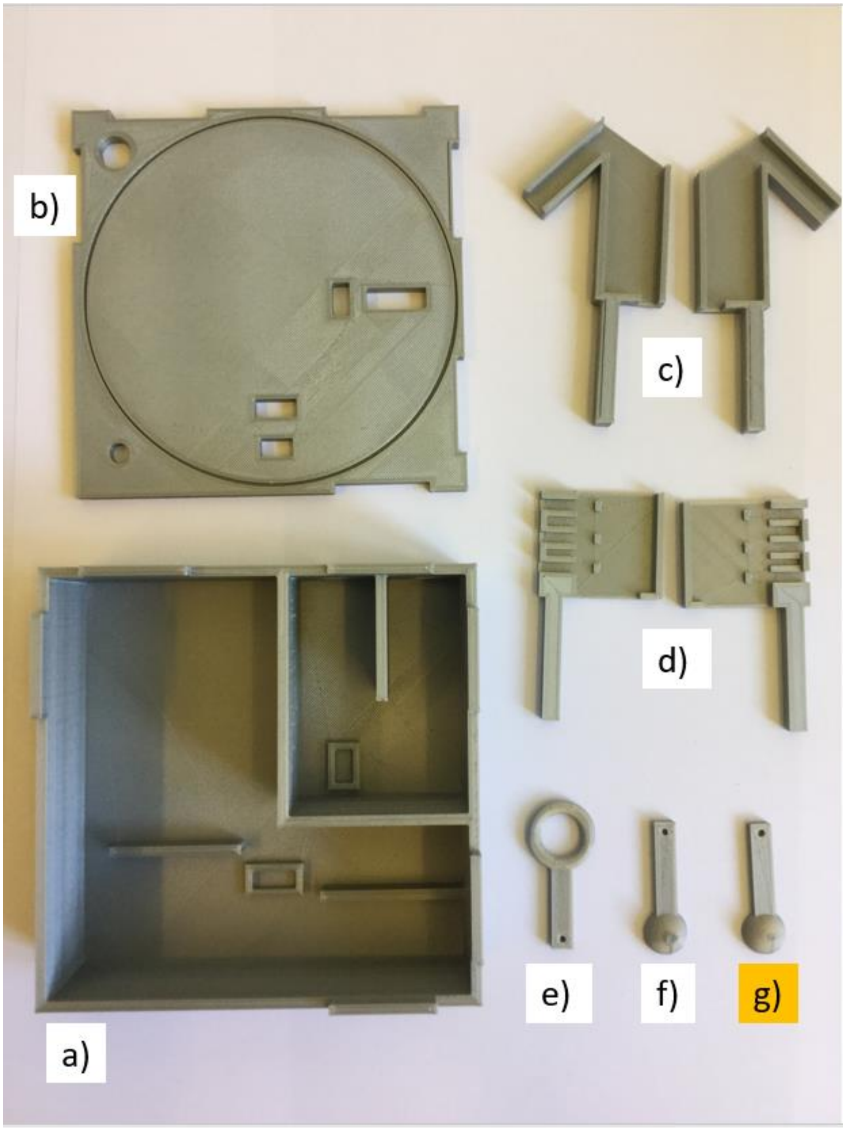


Figure 1: Image of 3D printed components
Image of all 3D printed components needed to build the quadrupole ion trap. Please note that the second endcap (g) electrode is optional.

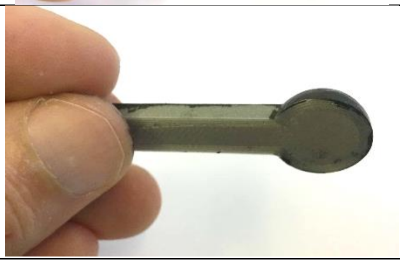
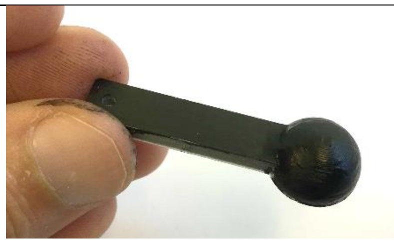
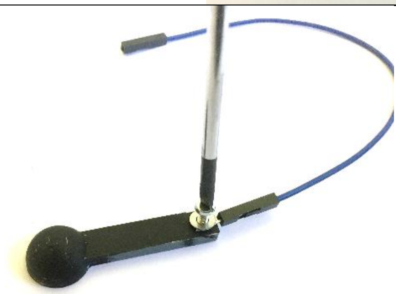
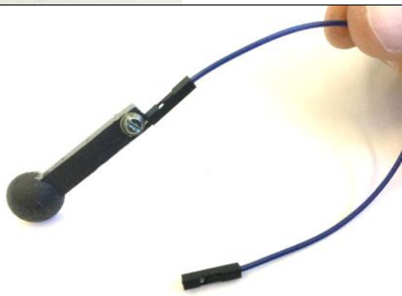
The following components need to be printed. For contrast with the spores, we recommend printing the trap using PLA and printing the trap in any dark colour, but not green. To print we used a 0.4 mm print core and a layer height of 0.1 mm. We have printed these structures with infill of 20% without the use of build plates or supports.

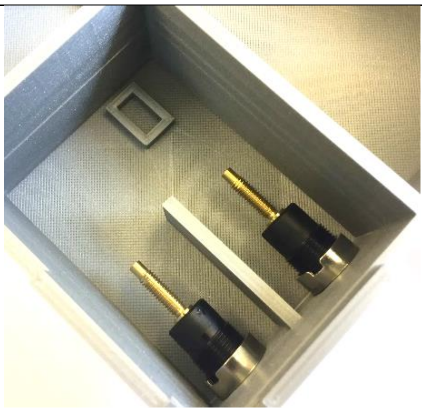
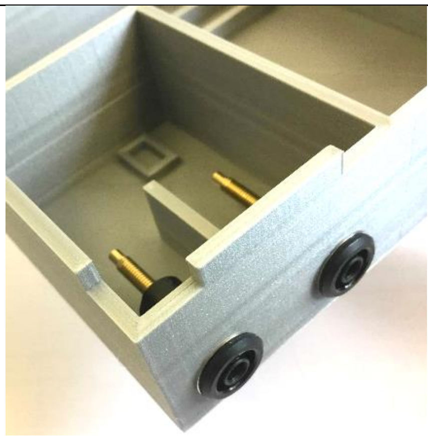
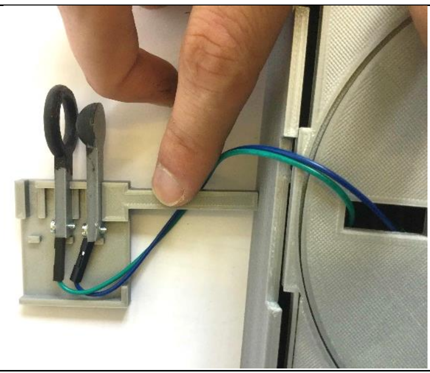
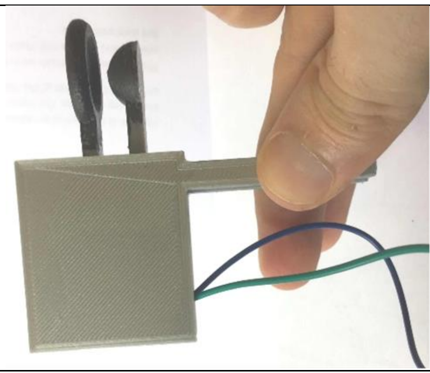
a) Base – approximate mass 110 g
b) Lid – approximate mass 55 g
c) LED holder – approximate mass 15 g
d) Electrode Stand – approximate mass 12 g
e) Ring Electrode – approximate mass 2 g
f) Spherical Electrode – approximate mass 2 g
g) Second Spherical Electrode (optional) – approximate mass 2 g

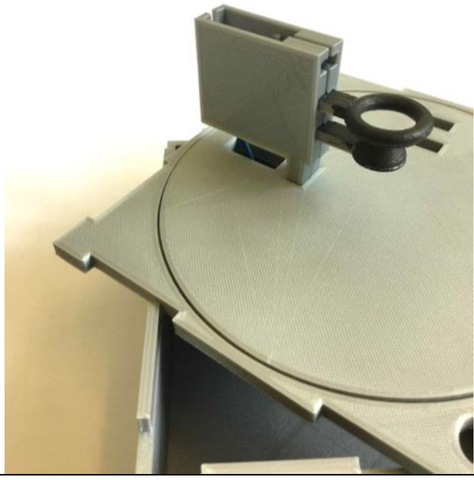
We recommend printing the spherical and ring electrodes in the highest possible resolution as these have small holes designed for screws.

4.1.2. Electrodes, Conductive Paint and sockets

To build the electrodes you will need conductive electric paint, two 4mm banana plug sockets, two 10 MΩ resistors, the 3D printed electrodes and two male to female leads. The instructions for building the electrode circuit are shown step by step in the table below:

Description	Picture
Paint electrodes with conductive paint. Note: Conductive paint can be more difficult to apply than regular paint.	
Paint the ring on both sides. The paint is only required on one side of the shaft.	 
Paint only the top side of the endcap electrodes.	 
After the conductive paint has dried, attach the male end of the male-to-female leads to the electrodes. Do this by using M2.5x6 bolts and a washer. Note: Depending on how well the electrode is 3D printed, it may be difficult to screw the bolt. Note: you may not need all the supplied bolts.	  

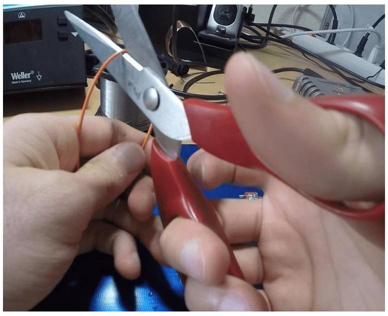
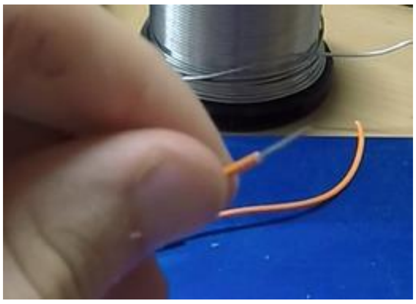
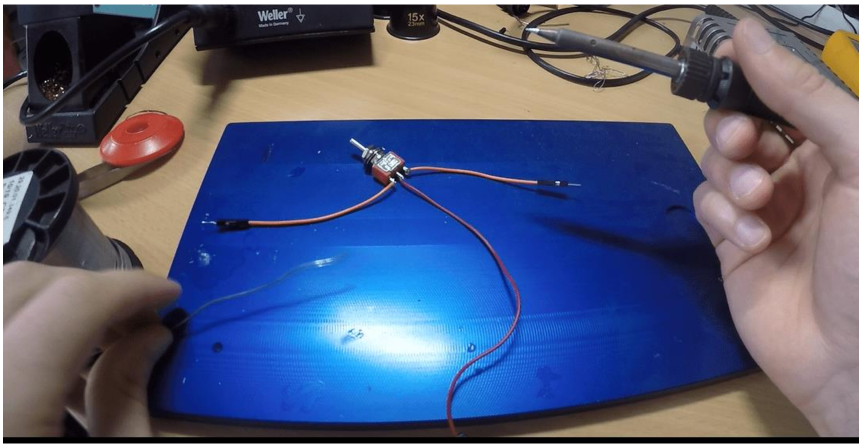
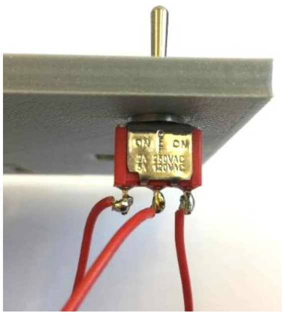
Next install the 4 mm plugs into the base of the quadrupole ion trap. Place the (black) plug in the holes on the side of the quadrupole ion trap and then screw this into place using the silver ring. Note: you may not need to use all the supplied bolts. Note: This can be difficult; it may help if you use a screwdriver or pliers to turn the ring.		
Solder or bolt the 10 MΩ resistors onto the sockets. In order to bolt, wrap one of the legs of the resistor around the metal thread between washers and bolts. Ensure the bolts are tightened so the resistor is held firmly in place. Alternatively, you can simply solder one of the legs on to the end of the socket.	 Bolting of 10 MΩ resistors onto the sockets	 Soldering of 10 MΩ resistors onto the sockets
Place the electrodes in the electrode holder.		

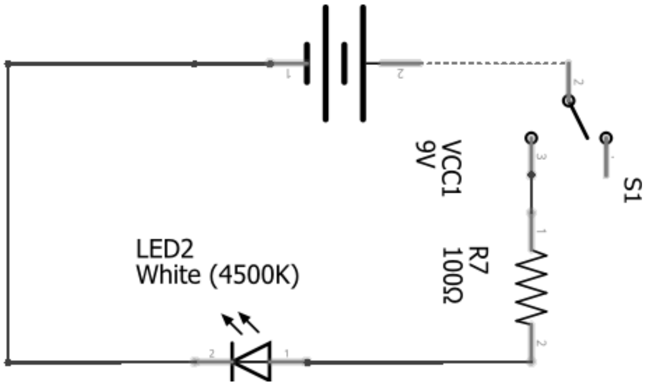
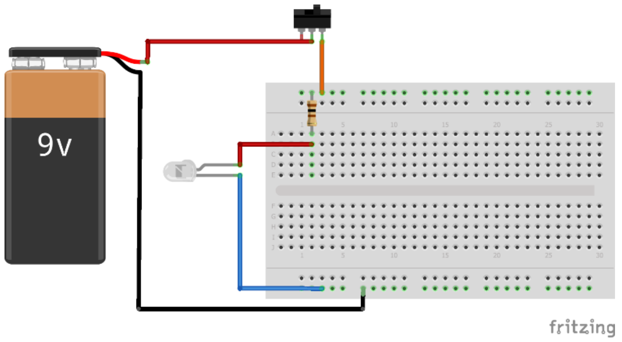
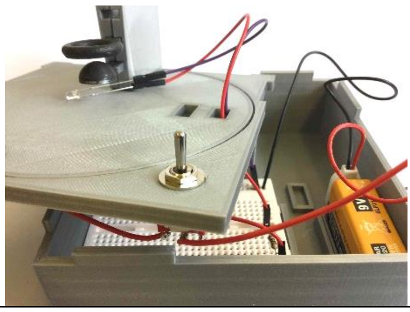
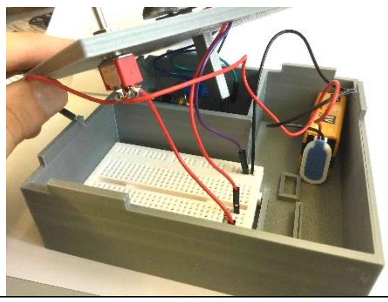
Thread the electrode leads through the hole in the lid and then connect them to the 10MΩ resistors.	
Place the electrode holder in the corresponding hole in the lid. If you have difficulties, getting the electrode holder to fit in the hole try using a file to sand down the corners.	

LED circuit

To build the LED circuit circuit you need one male to male jumper lead, batter clips, one 9V battery, one 60 mm × 80 mm breadboard one LED and one switch.

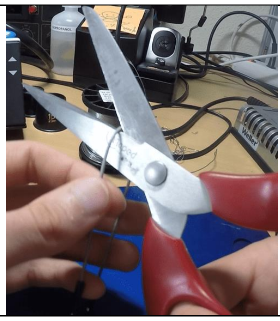
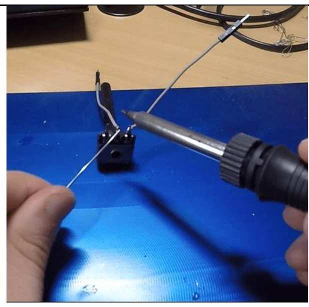
The instructions for building the simple LED circuit are shown step by step in the table below:

Description	Picture	
This first step is to attach wires to the switch. Take a male-to-male wire (shown in orange) and cut it in half. Then using scissors or a wire stripper, strip the ends where you cut the wire.		
Solder the two cut ends of the male-to-male wires to the outside legs of the switch. Solder the positive (red) lead of the battery clip to the centre leg of the switch. *Note: If you are not constructing the astable multivibrator circuit (see section 4.2 below) then you only need to solder one of the orange wires (it does not matter which).*		
Attach the switch to the lid using one of the provided nuts. Note: You may not need all of the supplied nuts.		

Construct the LED circuit following the circuit diagram and/or breadboard schematic. Attach male to female leads to the LED's before placing on the breadboard. *The diagrams were created using the Fritzing software.* For help identifying resistors please see Section 10: Appendix A – Resistor Bands.	 
Place the circuit inside the base. To complete the circuit insert the LED holder and attach the LEDs. Seen final instruction in section 4.2 Strobing Circuit	 

4.2. Strobing Circuit

A good extension of the quadrupole ion trap is to observe the charged particles under a strobing light. This section contains instructions for building an 'astable multivibrator', a circuit that causes an LED to turn on and off multiple times per second. This astable multivibrator contains a switch to switch between strobing and continuous LED's and a potentiometer to change the frequency of strobing. The frequency should range between 30Hz and 70Hz.

Description	Picture	
Attach leads to the potentiometer. To do this cut a male-to-male (grey in diagrams below) lead in half and strip the ends. Then solder one lead to the middle pin of the potentiometer and solder the second lead to either of the side pins.		

Construct the astable multivibrator circuit following the circuit diagram and/or breadboard schematic.

If leads/jumper wires of different lengths are available we recommend using short wires for all the wires except the LEDs. Leads to the LED's need to beabout 15cm long so they can reach the required position in the LED holder.

The diagrams were created using the Fritzing software.

We recommend checking that the circuit works at this point of construction. When you flick the switch one way, one of the LED's should be continuously lit. When you turn the switch the other way the other LED should strobe.

If the circuit does not work, please see Section 7: Trouble Shooting

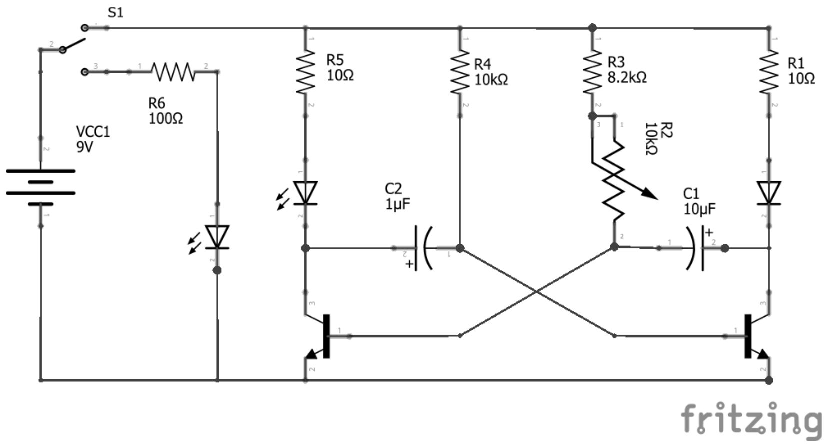


Figure 2 Circuit Diagram of Astable Multivibrator

This circuit diagram of the astable multivibrator shows the correct configuration of the components.

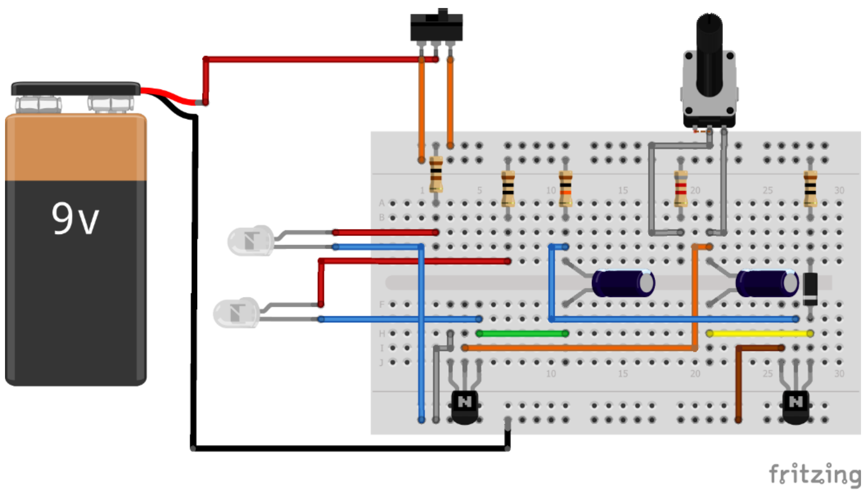


Figure 3 Breadboard Schematic of Astable Multivibrator

This is a breadboard schematic of the astable multivibrator circuit. Please note that the configuration of the components may differ for different transistors and this diagram may be inaccurate. For clarification please refer to **Figure 2 Circuit Diagram of Astable Multivibrator** and section **11 Appendix B – Transistor Data Sheet**

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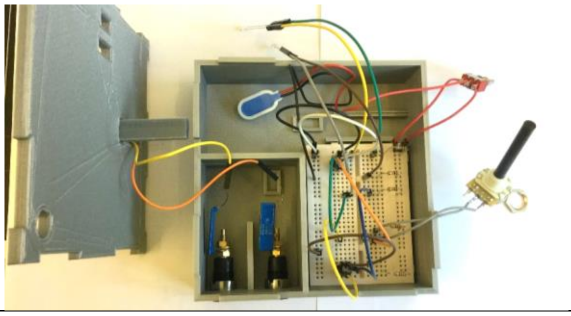
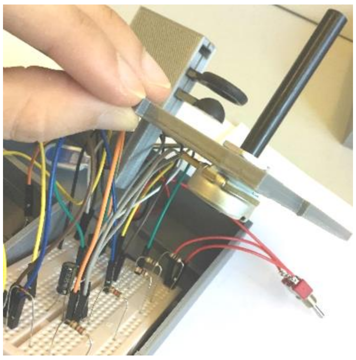
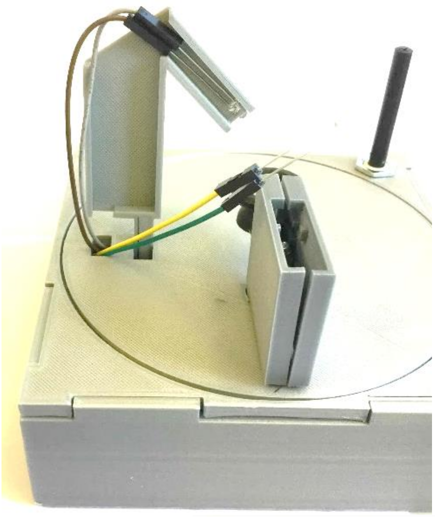
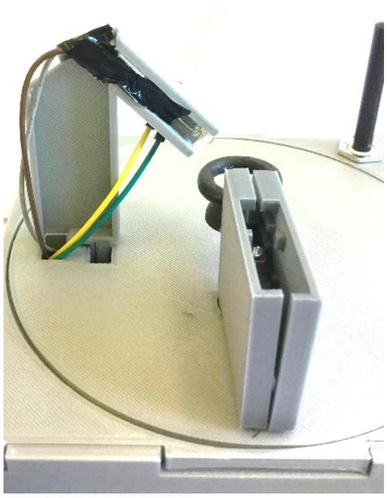
The capacitor on the left side of the diagram is 1 micro-farad and the capacitor on the right hand side of the diagram is the 10 micro-farad. Please note that it is possible to change the connection point of the positive leg of the capacitors such that the yellow and green leads are not required.

For help identifying resistors please see Section 10: Appendix A – Resistor Bands.

After constructing the circuit place it inside the base.	
Use the bolts to attach the switch and the potentiometer to the lid as shown in section 0 LED circuit. Note: you may not need all the provided bolts to attach the switch and potentiometer.	 
Thread the LED’s through the holes in the lid and insert the LED holder. We recommend using duct-tape to hold the LED’s in the correct position in the stand.	  

5. Operation Instructions

5.1. Safety Notes

This experiment involves using a high voltage power source (at least V_{rms}=2000 V). We recommend that students only perform this experiment under the supervision of a teacher. We also recommend that teachers check the student's circuit before they switch on their circuit.

Since a high voltage power source is being used, we recommend that students use touch-proof security cables. Students should never touch the electrodes. The 10 MΩ resistors should also be integrated into the electrode circuit to minimise the current (see section 4.1.2).

When turning on the power source set the voltage to 0V. After the students have turned on the power source safely, they can increase to voltage to V_{rms}=2000V. The trap should never be opened while it is connected to a high voltage source.

5.2. Trapping Spores

Once the quadrupole trap is complete it can be used to trap lycopodium powder. The first step is to set up the high voltage power source that will be connected to the electrodes. Please note that this must be an AC power source and be capable of reaching at least V_{rms}= 2000V AC. We do this by connecting a 20V AC power source to a transformer with voltage transformation ratio of 1:200. See image below:

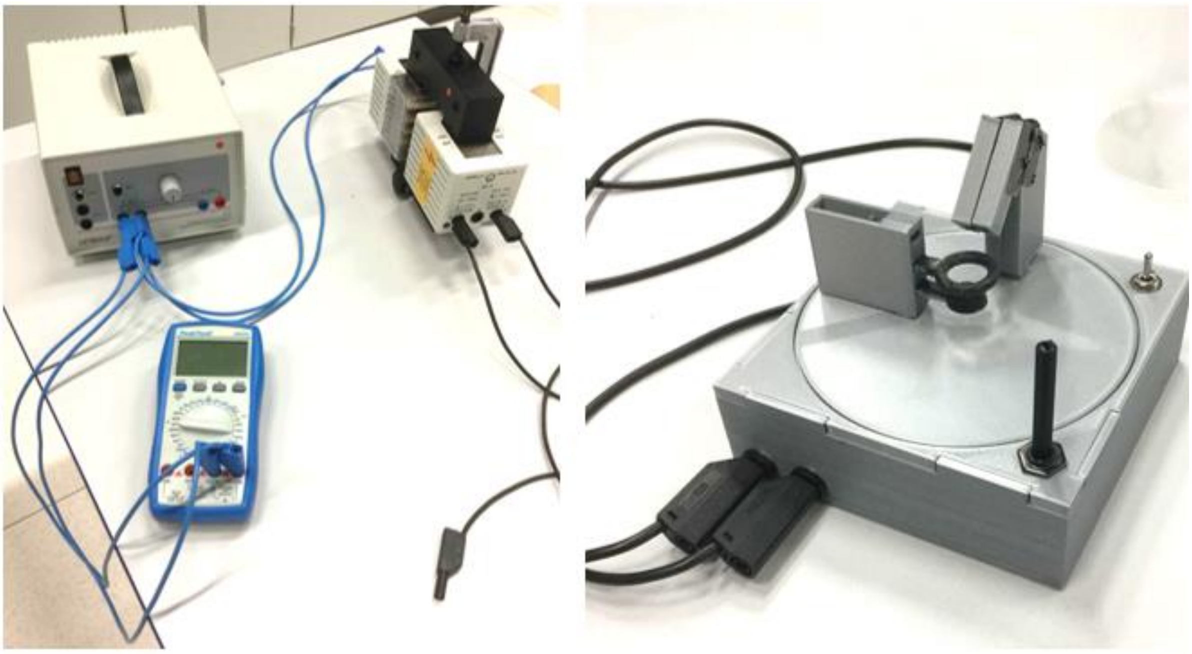


Figure 4: Image of power supply and transformer.

The 20V power supply is connected to a transformer with a transformation ratio of 1:200. Note: the multi-meter is connected in parallel to the transformer and is used to measure the input voltage into the transformer. The two black leads connect the transformer output to the quadrupole ion trap.

Place protective shielding around the trap to prevent air currents from removing the spores. If you use overhead slides this can be quite fiddly, so we recommend using sticky tape and or blue tack. See diagram below:

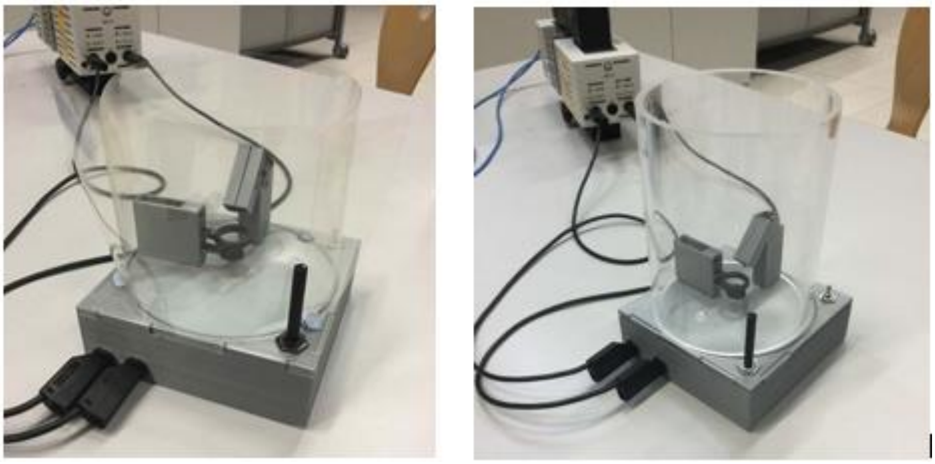


Figure 5: Protection of Spores against air-currents

On the left: overhead slides and blue-tack is used. On the right a Perspex tube is used.

Once the power source is connected, turn it on and set the voltage to 2000V. Use the switch to turn on the (non-strobing) LED light and darken the room (preferably turn all the lights off). Use a wooden skewer to place the lycopodium powder (spores) into the trap. If there are spores in the trap you should see faint green lines.

If spores do not remain in the trap, try increasing the voltage, for us it usually works best with the secondary voltage between V_{rms}=2400-2800 V. It is also possible that protection from air currents in the room is insufficient.

5.3. Using the strobe

It is also possible to view the spores using the strobing LED. Do this by flicking the switch to the strobing LED circuit. The LED should now be visibly flashing. The potentiometer can be turned to adjust the frequency of the flashing (it should range between 30Hz-70Hz). Note: it can be difficult for humans to distinguish the flashing of the LED from the continuous one once the frequency is greater than 40Hz.

The reason that the spores usually appear as lines is because they move back and forth 50 times a second. This movement is so fast that humans cannot see the spores moving and instead see blurry lines. When viewed under a strobe the spores should appear as points rather than lines. If the frequency of the light is exactly in tune with AC voltage of the electrodes then the spores should appear stationary because of the ‘stroboscopic effect’. If the frequency of the light is slightly off then the spores should appear to move slowly. By adjusting the frequency students can make the spores appear to move at different speeds.

6. Theory of the Quadrupole Ion Trap

A Paul trap is a type of quadrupole ion trap that uses oscillating electric fields to trap ions. The trap consists of two endcap electrodes and a ring electrode halfway between them. See diagram below:

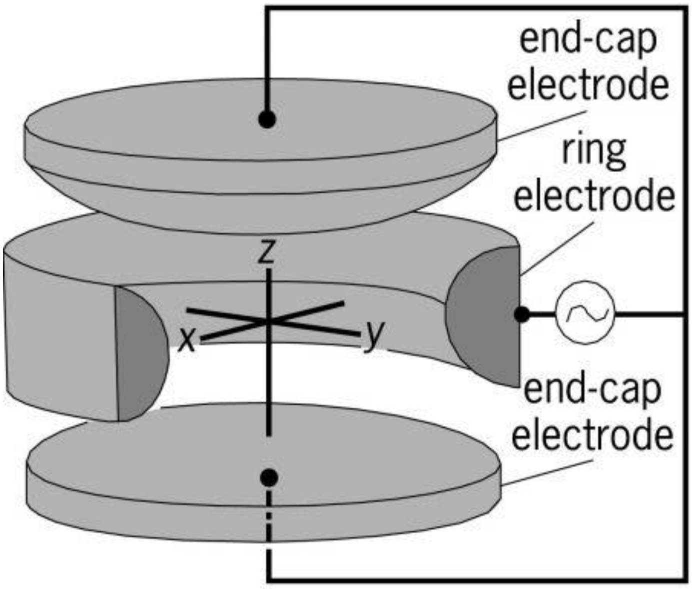


Figure 6: Diagram of Ring and Encap Electrodes

Image from https://encyclopedia2.thefreedictionary.com/particle+trap

Ions are trapped in the space between these three electrodes by the oscillating electric potential[1] (an AC driving Voltage). The AC voltage oscillates between the two hyperbolic metal end cap electrodes, as shown in the cross section below:

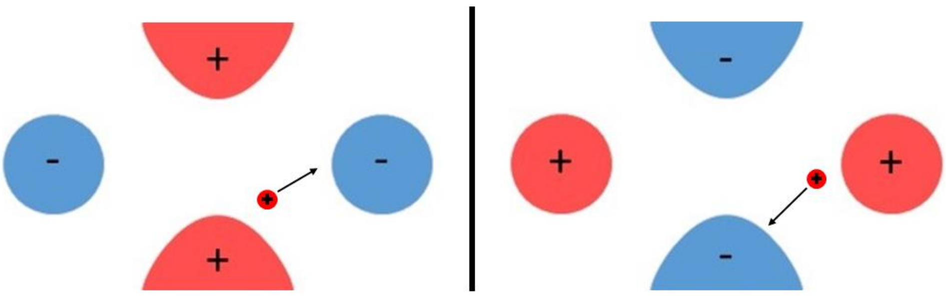


Figure 7: Quadrupole ion trap at two different moments.

Suppose there is a positively charged particle inside the trap, originally it is pulled towards the ring electrode, as shown on the left. Then the polarity of the electrodes would reverse and the particle is pulled to the end cap electrode, as shown on the right.

The trap pulls the ions back and forth very quickly. This movement is seen as small lines in the shape similar to the field lines. The frequency of the voltage must be faster than the time taken for the particle to touch the electrodes or escape the trap.

7. Trouble Shooting

It is possible to experience problems when building the quadruple ion trap. This section gives some guidelines that may help if the trap is not working.

a. Neither LED turns on

If neither LED turns on there are many things that could be wrong with the circuit. Carefully check that you have connected the circuit according to **Figure 2 Circuit Diagram of Astable Multivibrator**. It is possible that your breadboard will have a different arrangement of sockets to the schematic diagram, so please verify the connections are as shown in **Figure 2**.

If you are still struggling start with the simple LED circuit. There are only 4 components in series so there comparatively little that can go wrong. It is also possible that the following will be incorrect:

- **The LED may be the wrong way around** – The negative leg is the shorter leg. The casing of the LED will have a flat side with no rim on the negative leg side. Ensure that the negative leg is connected to the ground.
- **The LED may have burned out** – It is possible to destroy LEDs with a 9V battery. Try replacing the LED.
- **Battery** – Ensure the battery is securely connected to the switch and the ground. Test/replace the battery to ensure it is not flat.
- **Switch** – Try both on settings of the switch. Ensure that you have soldered the switch correctly as shown in the LED circuit section.

Once the continuous LED is working look at following sections.

b. Strobing LED does not turn on

There are various things to check:

- **Check all connections against circuit diagram** – One by one, ensure that the components are connected to the breadboard as shown in **Figure 2 Circuit Diagram of Astable Multivibrator**.
- **The LED may be the wrong way around** – The negative leg is the shorter leg. The casing of the LED will have a flat side with no rim on the negative leg side. Ensure that the negative leg is connected to the transistor.
- **The LED may have burned out** – It is possible to destroy these LEDs with a 9V battery. Try replacing the LED.
- **The transistors may not be plugged in properly** – Ensure that the transistors are plugged in all the way.

c. Strobing LED illuminates once and then fades

This problem occurs because one of the capacitors is not able to discharge. Perform the following checks:

- Ensure that the emitter legs of both transistors are connected to the ground.
- Ensure the negative ends of each capacitor are connected to the base leg of the corresponding transistors.
- Ensure both the diode and the LED are connected to the collector legs of the corresponding transistors.

d. Strobing LED shines continuously, or has a frequency that is erratic, too high or too low.

If available, use an oscilloscope to measure the frequency of the circuit. If the frequency range is between 20-200 Hertz refer to section1.f . Otherwise try the following:

- Try reversing the direction of the capacitors.
- Ensure that the diode is connected to the resistor and the collector leg of the transistor.
- Research the datasheet for your specific transistor online. See **section 11 Appendix B – Transistor Data Sheet**. Once you are sure which leg is which ensure that the circuit is connected correctly according to **Figure 2 Circuit Diagram of Astable Multivibrator** (note this may be different to **Figure 3 Breadboard Schematic of Astable Multivibrator**).
- Try reversing the direction of the capacitors.

e. Changing the Potentiometer does not change the strobing frequency

If the potentiometer does not affect the frequency of the LED this is an indication that it is not a part of the circuit.

- Check that the 8.2kΩ resistor is connected to the correct line of the switch.
- Check that the middle leg of the potentiometer is connected to the 8.2kΩ resistor and that the other side is connected to the negative leg of the 10µF capacitor.
- Ensure that no other resistor is connected to the negative leg of the 10 µF capacitor.
- Ensure the potentiometer is connected to the base leg of the corresponding transistor.

f. Strobing LED frequency is close to, but not quite on the 30-70Hz range

In cases where the LED is approximately the correct frequency but varies from the 30-70Hz range, it is possible that you have connected the circuit completely correctly. The internal resistance of some of the components varies between different brands and this will have an influence on the frequency.

If the frequency range includes 50-60Hz, there is no need to make any change as this will still allow students to use the stroboscopic effect to make the spores appear stationary.

If the frequency range does not contain these values or you would like to improve the frequency, range the best way to do so is to swap the 10Ω resistor connected to the diode, for a resistor of a slightly different value. Increasing this resistance decreases the frequency of the strobe.

For example, suppose a trap had a frequency Range of 45-90 Hz. Increasing the diode resistor to 15Ω would reduce the range to 30-70Hz.

8. Acknowledgements

The design for the S'Cool LAB quadrupole ion trap was based on the low cost particle traps presented by Schmitt, Coberger, and Wendt (2010). Ankatrin Kirchner worked together with Julia Woithe, Alexandra Jansky and Oliver Michael Keller in order to develop a 3D printable trap for her masters' thesis. This trap was tested with hundreds of students at CERN by S'Cool LAB tutors including Susanne Duhrkoop. Lachlan McGinness finalised the design in this manual.

9. References

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10. Appendix A – Resistor Bands

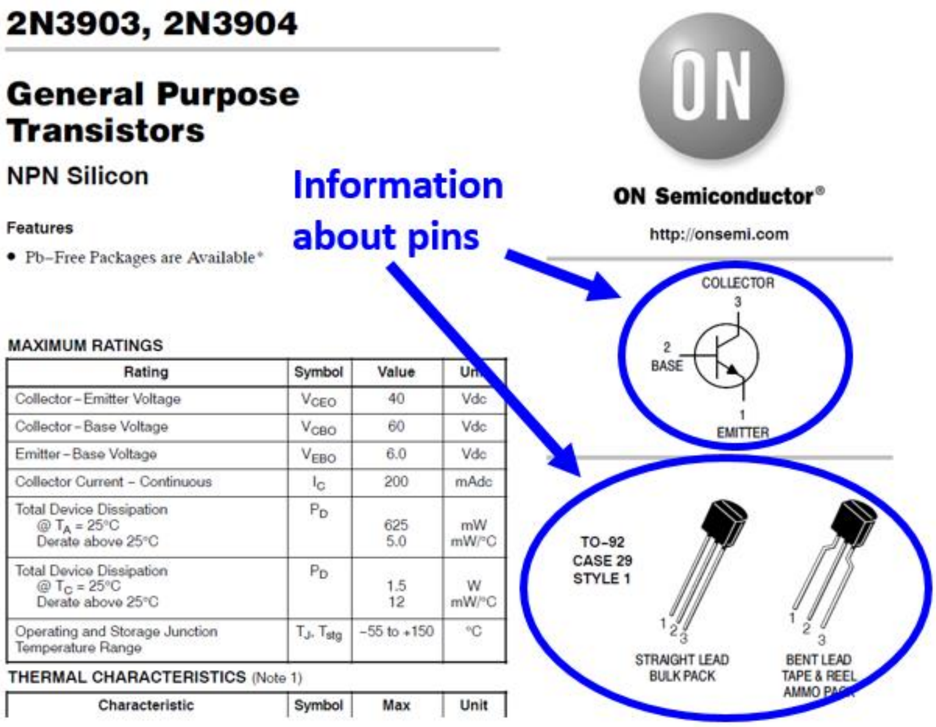
The chart below shows the colour bands for the resistors used in this ion trap:

Resistance	4 Band Code	5 Band Code
10Ω		
15Ω		
100Ω		
8.2KΩ		
10KΩ		

11. Appendix B – Transistor Data Sheet

Different brands of transistors have different arrangements of the pins.It may be necessary to research the datasheet of NPN transistor to ensure it is connected correctly. You can do this by googling the numbers that appear on the transitor and the word “Data Sheet“. For example google '2N3904 Data Sheet'.

The images below are examples of datasheets for transistors. The highlighted information is important for ensuring the transistors are the connect correctly. The LED/diode should be connected to the collector (c) leg of the transistor. The ground should be connected to the emmitter (e) leg of the transistor.



2N3903, 2N3904

General Purpose Transistors

NPN Silicon

Features

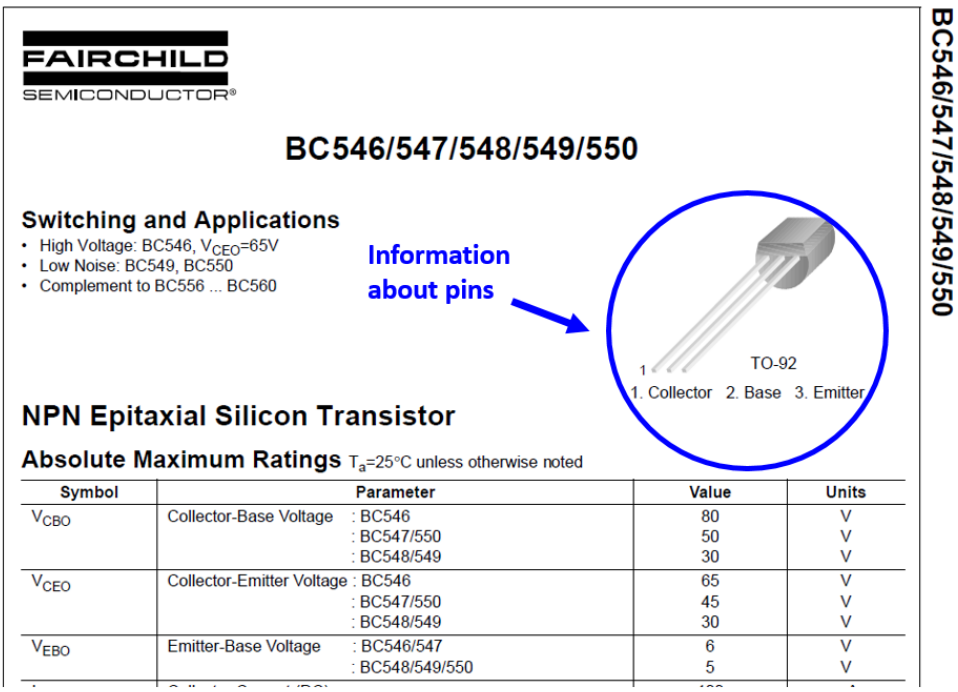
- Pb−Free Packages are Available*

MAXIMUM RATINGS

Rating	Symbol	Value	Un
Collector−Emitter Voltage	V_{CEO}	40	Vdc
Collector−Base Voltage	V_{CBO}	60	Vdc
Emitter−Base Voltage	V_{EBO}	6.0	Vdc
Collector Current − Continuous	I_C	200	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	625 5.0	mW mW/°C
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	1.5 12	W mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−55 to +150	°C

THERMAL CHARACTERISTICS (Note 1)

Characteristic	Symbol	Max	Unit



FAIRCHILD SEMICONDUCTOR®

BC546/547/548/549/550

Switching and Applications

- High Voltage: BC546, V_{CEO}=65V
- Low Noise: BC549, BC550
- Complement to BC556 ... BC560

NPN Epitaxial Silicon Transistor

Absolute Maximum Ratings T_a=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector-Base Voltage : BC546 : BC547/550 : BC548/549	80 50 30	V V V
V_{CEO}	Collector-Emitter Voltage : BC546 : BC547/550 : BC548/549	65 45 30	V V V
V_{EBO}	Emitter-Base Voltage : BC546/547 : BC548/549/550	6 5	V V