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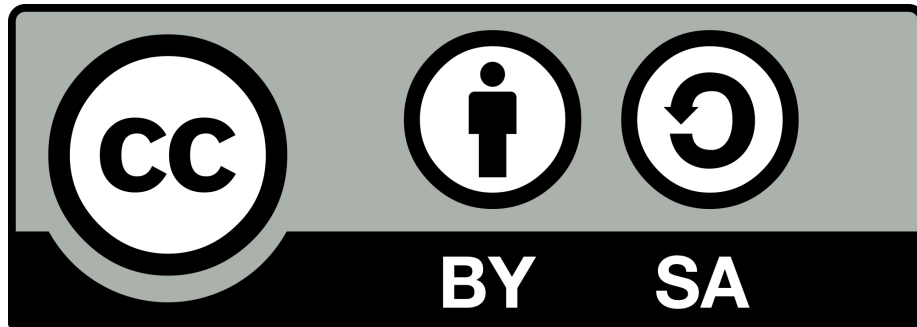


Figure 1: CC-BY-NC-SA 3.0

Tutorials from HackSpace magazine

Getting started with KiCad, schematics

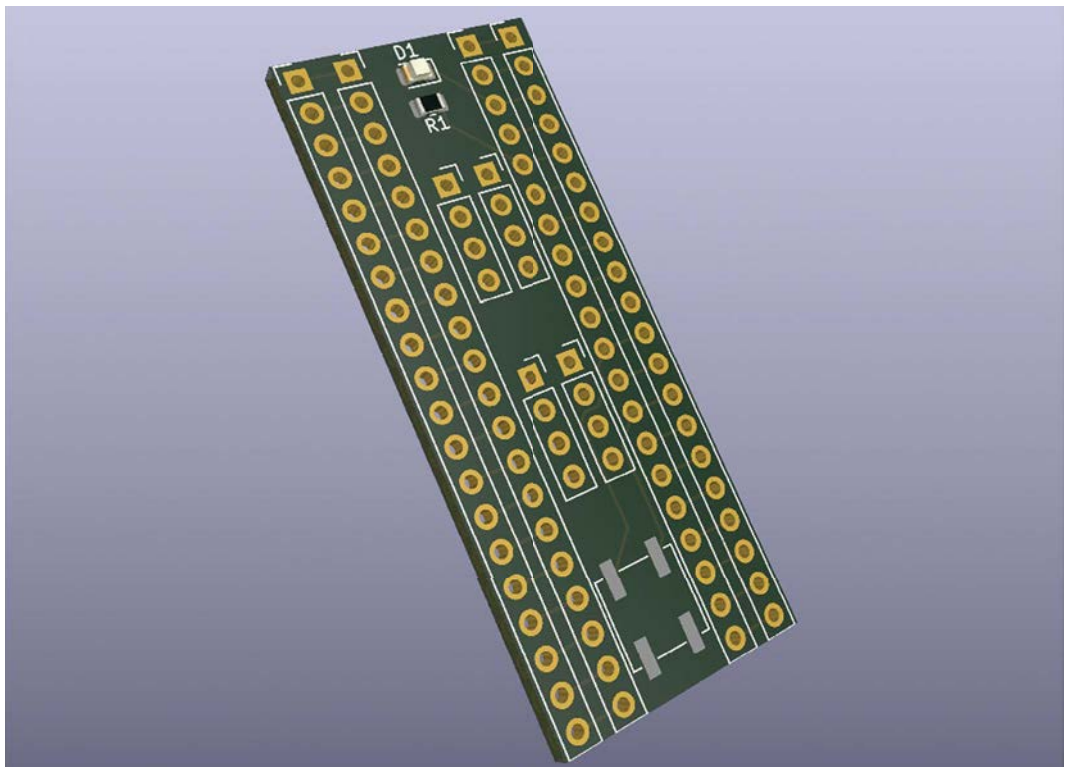
In this first of a series of articles around PCB creation with KiCad, let's dive into laying out a simple schematic



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Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!



KiCad is an amazing piece of free and open-source software that allows anyone, with some time and effort, to make high-quality PCB designs.

Couple this amazing software with numerous PCB fabrication companies and even PCBA services – companies that will make and assemble your PCB designs – and there's never been a better time to get into this aspect of making.

PCB design can be a steep learning curve. With that in mind, we wanted to start this series of tutorials with a hack – this is HackSpace magazine after all! In the first two parts, we are going to create

a PCB design to the point of getting it manufactured. However, to make this part accessible, we are going to cut some corners. Don't worry, we'll explain what the corner cuts are, and we'll do things more correctly in subsequent articles, once we have the basics down.

So, first thing, download and install KiCad – the current stable version is version 7, which was released in early February 2023. KiCad is available across a wide range of operating systems – Windows, macOS, and lots of Linux distributions. We're running it on Ubuntu, but it should be comparable across all the platforms.

Above 
The final simple add-on board for a Raspberry Pi Pico

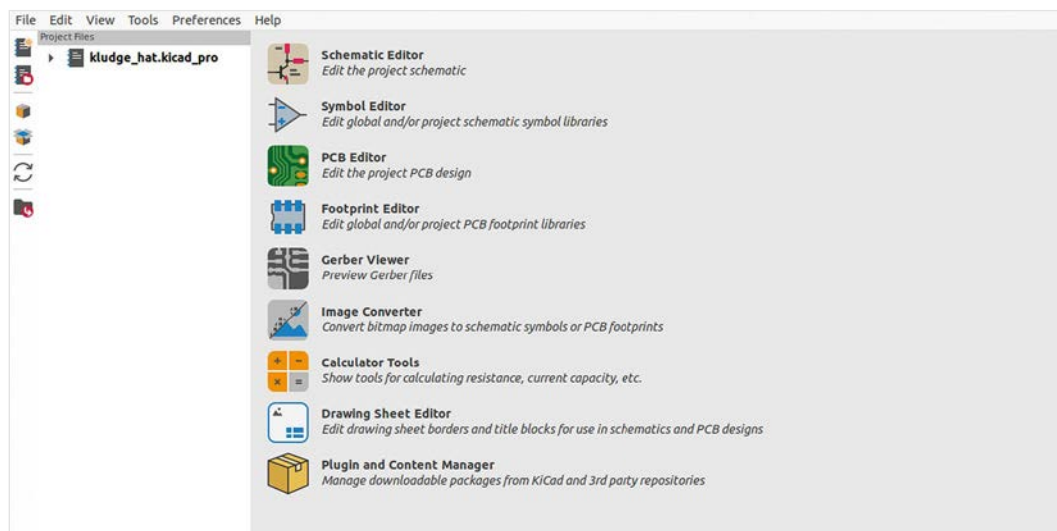


Figure 1 ♦
The opening page of KiCad with the different applications that make up the KiCad suite listed

With it installed, click on the main blue 'Ki' KiCad icon to open the main application. You should see a screen that looks like **Figure 1**. You'll see that, really, KiCad isn't just an application, it's more a suite of applications that work together. Whilst you can jump into any application from here, the most common workflow for KiCad is to first work in the Schematic Editor and then, after creating a schematic, move to the PCB Editor to lay out the PCB physically. Our first action should be to set up a new project. Click File > New to create a new project. It's worth putting projects into their own folder as each KiCad project generates around five project files and a folder in which it automatically generates some project backup files.

Once our new project is created, let's make a start. We're going to make an add-on board for the Raspberry Pi Pico. It's going to be a prototyping or 'kludge' board with not too many features on it for simplicity. It's going to have all the Pico pins broken out to through-hole pads, it will have a power-indicating LED, and it will have a reset button. After this, any spare area on the board will have simple through-hole pads on it to allow us to connect experiments to the board. As we said earlier, it's definitely hacked together, but will supply us with ample opportunity to learn some KiCad basics. To begin, open the Schematic Editor application by clicking the top icon.

You should now see a blank page ready for our schematic to be drawn (**Figure 2**). In the lower right-hand corner, you will see a small collection of text boxes which include various fields for the name of

the sheet, the revision number of the schematic, and more. If you left-click somewhere on this section and then press the **E** key, you should launch a window called 'Page Settings'. You can edit this to add any text details or comments you want to add to this section, but you can also change the page dimensions – it defaults to A4 – and the orientation and more. Experiment inserting text into the Page Settings window to see where the text appears on the schematic.

With your page set up, we can now begin to add schematic symbols to the schematic. The most correct way to make a Pico add-on board would be to place a Pico in the schematic and connect everything to it, but we are going to use a workaround to do this in a much simpler way. The

main idea of our target add-on board is for us to be able to solder in rows of header sockets so that we can connect it onto the pins of a Pico. In turn, we also still want to be able to solder to those pins, so we need each side row of

pins to be broken out to another collection of pads. To do this we'll add two 20-pin connectors, one on each side of our schematic. To add the first one, we are going to click the 'Add a Symbol' icon – the third icon down on the right-hand column. The first time you click this icon, it may take a few seconds for the libraries of schematic symbols to load. Once loaded, you should see a window called 'Choose Symbol'. On the left-hand side of this window, you should see a list of items, each of which is a library of a group of schematic symbols. These are grouped in related items; so, for example, you might find, →

It's definitely hacked together, but will supply us with ample opportunity to learn some KiCad basics

QUICK TIP

If you hover over any tool icon in KiCad, you get a description of the tool. We'll use these tooltips to describe tool icons throughout these articles.

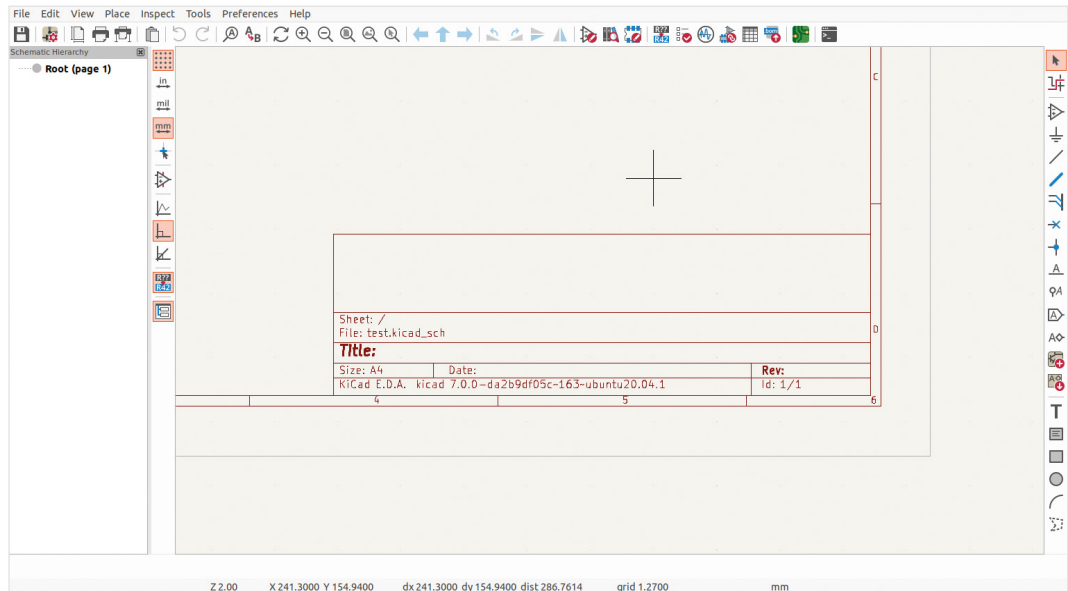



Figure 2  A blank Schematic sheet with text boxes for various schematic labelling and version numbering

KEYBOARD WARRIOR

Whilst you can do everything in KiCad with a mouse and pointer, it's really worth learning a few quick keyboard shortcuts that can help make life easier. Brilliantly, many keyboard keystrokes offer the same functions in both the Schematic Editor, which we are using in this tutorial, but also in the PCB Editor, where you will spend a lot of your time in the next part of the series. The first useful ones are the **F1** and **F2** keys for zooming. The **F1** key, when pressed, will zoom in, and **F2** will zoom out. Note that both of these zoom actions are centred around where your pointer is. With a little practice, it becomes second nature to move the pointer and zoom in and out to get the view you need. Next up are the **M** and **R** keys. If you select an object in the Schematic Editor or the PCB Editor, you can press **M** and then that object will move until you left-click to place the object again. Note that in the PCB Editor, you can select smaller parts than the complete footprint of a component. You can therefore select and move silkscreen labels and more. If you want to select the whole component, selecting a component pad will usually then select the entire footprint. With the **R** key, you can rotate a selected item in either the Schematic Editor or the PCB Editor, again single left-clicking to place the part when rotated correctly. Note that you can rotate the item repeatedly to get to the orientation you require. Finally, another useful shortcut is the **E** key. With an item selected, pressing the **E** key allows you to edit that item's properties. This can be any number of editable parameters, from labels to pad sizes to hole dimensions and more.

QUICK TIP

Whenever a tooltip has a letter in brackets, that letter is a hotkey to switch to that tool.

at the top of the list, '4xxx' which, if you click on the drop-down menu button next to the name will reveal a library full of the CMOS 4000 series of logic chips. You can of course manually scroll through the libraries and look through the items they contain, but you can also search the libraries to find what you need. We are going to add a connector symbol that represents the 20-pin header we eventually want to be able to fit. To do this, type 'conn' into the search bar and, as you type, you should notice the list items are now all the items that start 'conn'. Scroll down the list and select the item that reads 'Conn_01x20_Socket', and then click the OK button in the lower right-hand corner of the window (**Figure 3**). The Choose Symbol window will close and you will be back in the Schematic Editor, and you should have a symbol for our 20-pin socket attached to your pointer. Move the pointer to where you want to place the connector and left-click to place it.

A SACKLOAD OF SOCKETS

We are going to place three more of these into the schematic. We can again click the Add a Symbol tool icon but notice that, as the library list area populates, we now have a 'Recently Used' area at the top with our 20-pin connector listed underneath. Click this listing and then OK, and we can place the next connector in the schematic. Repeat this until you have four of the connectors placed. Next, use the **M** and **R** hotkeys to move and rotate the connectors so that we have two pairs of connectors in line with each other, with the small circle ends facing inwards

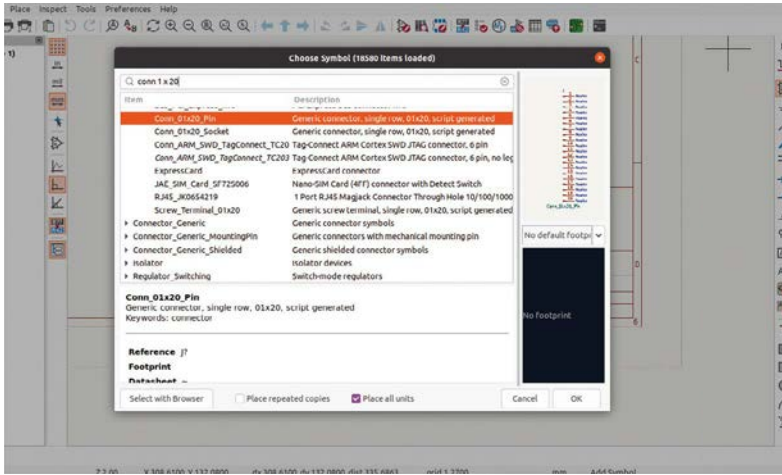


Figure 3 The Choose Symbol dialog that allows you to search for schematic symbols

towards each other. You can also right-click on a selected symbol and use the Mirror Horizontally tool. The small circles are the part of the symbol to which we will create connections.

Using the Add a Wire (W) tool, you can left-click on one of the connector pin circles and then draw a connector wire line across to the opposite connector pin (Figure 4). If you make a mistake, you can use **CTRL+Z** to undo the last action – or, to cancel the wire mid-draw, you can right-click and select Cancel from the drop-down menu.

Continue to wire between each of the opposite pins on each pair of our connectors until they are all connected together. Notice that each of the connector symbols have a couple of text references connected to them. It can be good practice to edit these so that they are useful and help you keep track of what things are. Select the whole of one of our connector symbols (use the selection tool to draw a box over the entire symbol) and then press **E**. You should now see a Symbol Properties dialog box (Figure 5). You can now edit the 'reference' (if required) and the 'value' text entries. We edited ours and gave each connector a descriptive 'value' such as 'Pico_Pins_1-20_Left' etc. This is useful when we lay out our PCB in the PCB Editor, as it ensures we can identify the multiple connectors correctly.

To finish our schematic, we are going to add more components and make more connections. To begin, let's add a resistor and an LED and connect them to pins 38 (GND) and 36 (3V3 (OUT)) on the Pico. These pins are the third pin and fifth pin down on our right-hand connector. Use the same techniques we used earlier to choose a symbol, searching 'R' for a resistor and 'LED' for an LED

// To finish our schematic, we are going to add more components and make more connections **//**

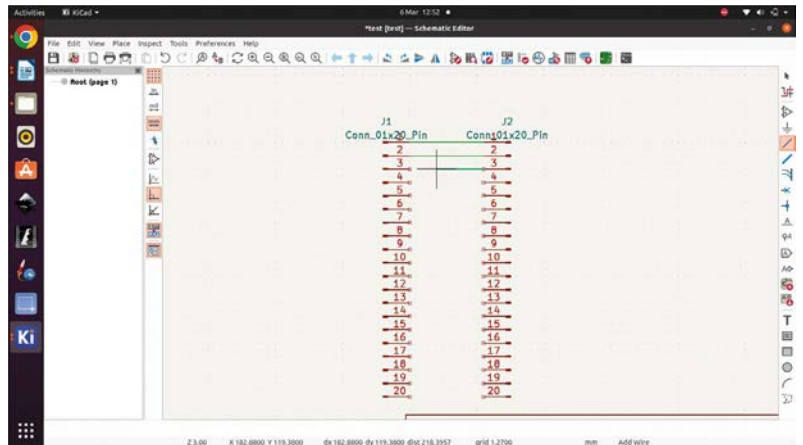


Figure 4 Adding our wire connections between the pins of the schematic symbols

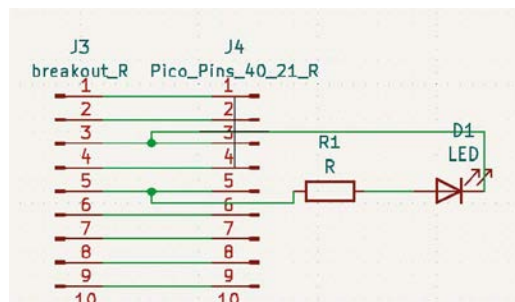
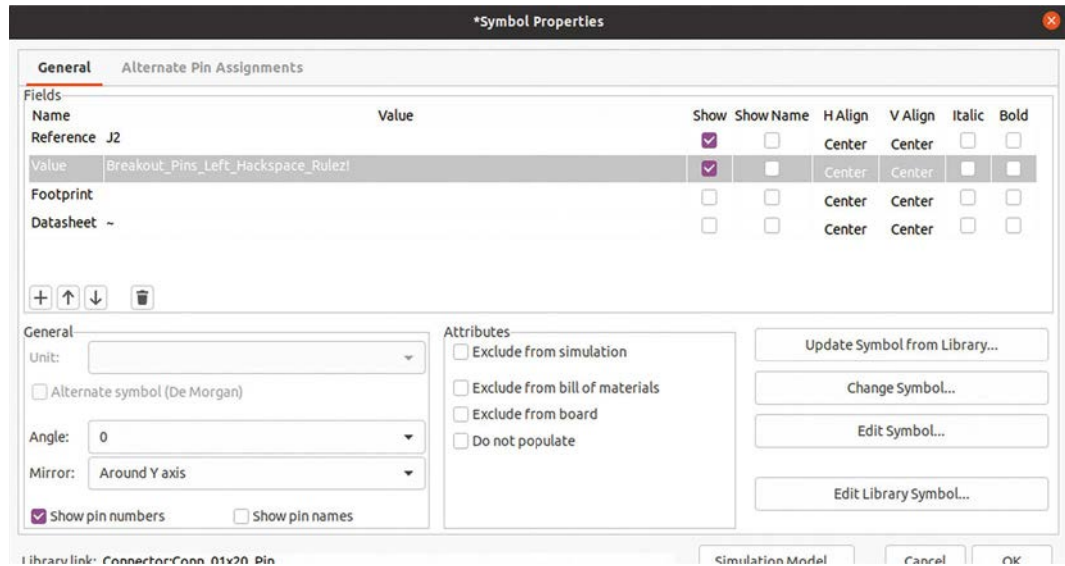
symbol. Add wires to connect the circuit together, as shown in Figure 6. Next, let's add a switch symbol which we will wire in as a reset button for the Pico.

Adding a reset button is a good example of a way that KiCad works that some other electronic design automations (EDA) don't. In some EDAs, the symbol you choose at the schematic level defines exactly the hardware package of the electronic component that will be on the PCB.

For example, in other packages you wouldn't place a generic resistor symbol, you would place a resistor symbol linked to a specific resistor, say a 6 mm long 1/4 watt carbon resistor placed horizontally. This would mean that, if we wanted to change the component on the PCB, we have to change the schematic. In KiCad, the schematic symbol has to be assigned a footprint – this is why we are going to place a symbol for a single-pole single-throw switch (SPST), but the actual component can be any SPST switch or any →

Figure 5 ♦
Editing a symbol's properties allows us to give symbols more meaningful names

Figure 6 ♦
Adding a resistor and LED to our schematic



button package. In our case, we'll choose some type of momentary push-button for the reset. This way of working means that if you find you need to replace a component with a different type (commonly as you can't find a component in stock), you simply change the footprint associated with the symbol and don't have to edit your correct schematic. It also makes the schematics concise and readable, which is important if you want to share your design.

SWITCHED ON

To add the switch, search the Choose a Symbol dialog with 'sw_spst' to take you directly to the single-pole single-throw switch and again connect wires, as shown in **Figure 7**. Finally, add four connectors to act as our prototyping areas on the board; search for 'conn_01x04' to take you directly to this symbol.

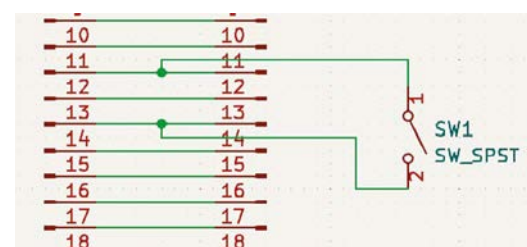
Let's now set up the associated footprints for each schematic symbol. Click the Run Footprint Assignment Tool icon. Similar to the Choose Symbol dialog, a window will appear with a list of footprint libraries down the left-hand side, a centre section with the schematic symbols of the project listed, and a right-hand column of filtered footprint results. You can see a collection of three icons at the top of

ADDING PARTS

As you can tell from this tutorial, KiCad uses Schematic Symbols and Component Footprints to create schematics and PCB designs. You should have a lot of standard libraries built in, and everything in this project is just using these libraries. Of course though, you can create your own schematic symbols, component footprints, and even 3D models of components and incorporate these into your own designs creating custom libraries. We'll cover this, and lots more in future sections.

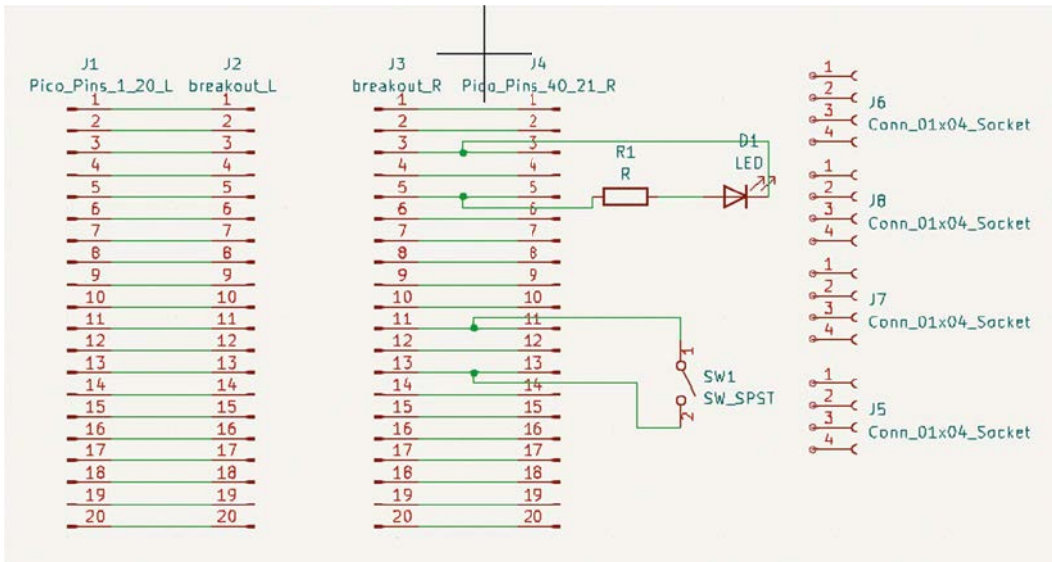
the window called 'Footprint Filters' and, in the first instance, make sure all these are selected. As you get used to component filtering, you might find you prefer to use different combinations of these filtering tools (**Figure 8**). Highlight in the centre section one of our 20-pin connector components. We need to find a footprint that has the same number of pins and has a footprint of a through-hole pad for each pin. As the Raspberry Pi Pico pins are spaced at the common 2.54 mm pitch between each pin, we also need to make sure our footprint is spaced similarly. You should

Figure 7 ♦
Adding a single-pole single-throw switch to the schematic to work as a reset button for the Pico



QUICK TIP

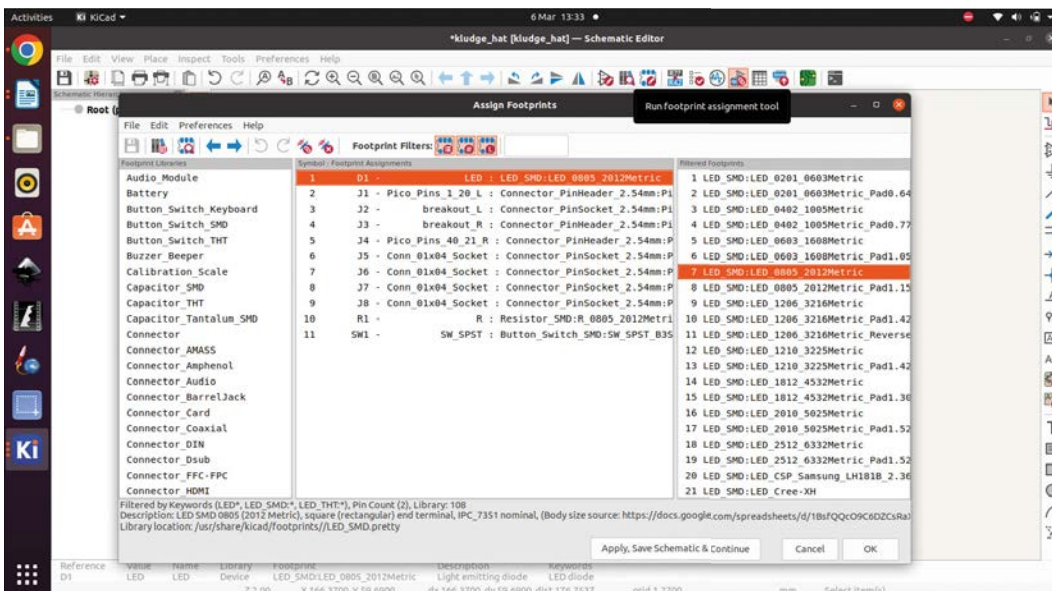
Obvious, but remember to press the Save button now and again to save your work!



have a filtered list on the right-hand side – it should be filtered to only contain items that would attach to the 20-pin connector symbol. We chose item number 33 from the connector footprint library, which reads ‘Connector_PinSocket_2.54mm:Pinsocket_1x20_P2.54mm_vertical’. A single left-click on the item highlights it in the list, and you can use the ‘View the selected footprint in the footprint viewer’ tool icon to open a window showing the PCB footprint layout design to check if it looks correct. Double-clicking the highlighted footprint should then add that footprint name opposite the schematic symbol in the central list. Continue and add the same footprint to all four connector symbol listings, although we’ll discuss later why that isn’t totally correct, and then click the ‘Apply, save schematic and continue’ button. We’ve decided

to add surface-mount components for the LED, resistor, and the button, although we have gone for SMD package sizes and footprints that would enable us to hand-solder these. For the LED, we chose the LED_SMD:LED_0805_2012Metric footprint; for the resistor, the ‘Resistor_SMD:R_0805_2012Metric’; and for the switch/button, a ‘Button_Switch_SMD:SW_SPST_B3SL-1002p’ component. For the detached 4-pin connectors, we simply selected ‘Connector_PinSocket_2.54mm:PinSocket_1x04_P2.54_Veritical’ for each connector. With all those footprints assigned, click ‘Apply, save schematic and continue’.

In the next instalment, we will import the list of component footprints into the PCB Editor and physically lay out our board design ready for fabrication! □



Above □ Our complete circuit schematic
Figure 8 □ The Assign Footprints dialog

Getting started with KiCad, PCB layout

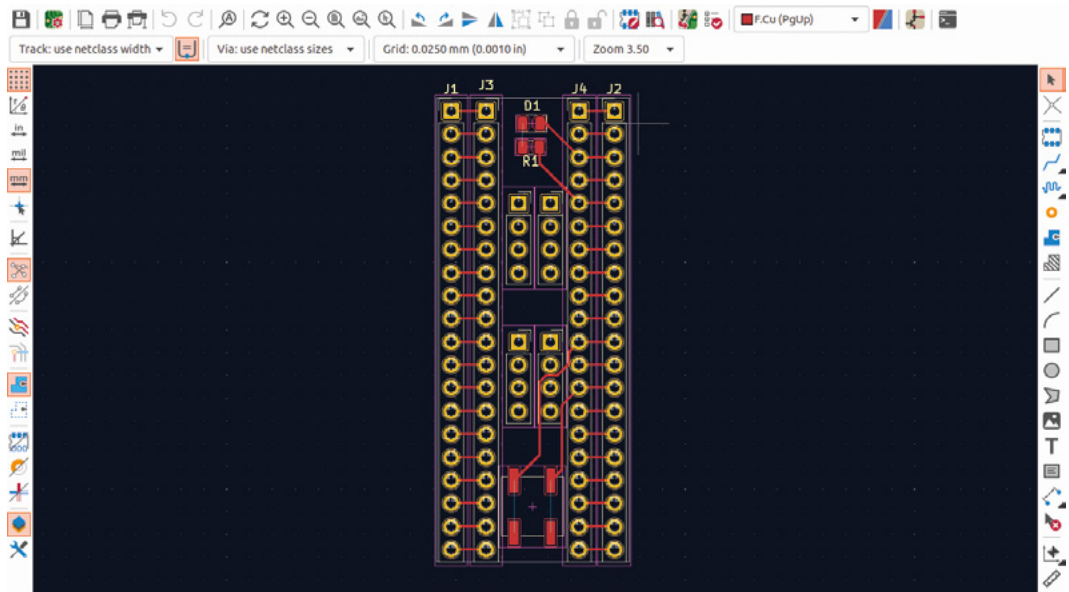
In this second part of the series looking at PCB creation with KiCad, we lay out our PCB ready for fabrication



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In the last issue, we got our schematic for our Pico add-on board created, and we assigned each schematic symbol a footprint which represents the individual component we are adding for each part of the design.

In this issue, we will finish this starter project by laying out the PCB design ready for manufacture. If you haven't opened KiCad, do so now. Open the previous project and select the PCB Editor icon from the available applications (Figure 1). If you have opened the project and the Schematic Editor, you can jump to the PCB Editor by clicking its icon in the Schematic Editor toolbar.

Having opened the PCB Editor, you should see a similar page to the Schematic Editor, but in black (Figure 2). You'll notice it is blank, so the first action is to pull in our footprints. To do this, we can click

the 'Update PCB from Schematic' icon. This opens a window, and we can simply click the Update PCB button and then click the Close button (Figure 3). Once back in the PCB Editor, we now should have our design as a collection of footprints attached to our pointer. Left-click to place the component bundle somewhere in the middle of the page (Figure 4).

The PCB editor has a grid feature which snaps footprints at useful points. In our current case, the pin socket footprints will snap with the centres of the pad holes on the grid. As the Pico conforms to 2.54 mm pin spacings, it's useful at this point to set the board editor grid to '2.54 mm (0.1000 in)'. You can select this from the centre drop-down menu on the upper toolbar. We can now align our two pairs of pin socket footprints so that they are in line with each other horizontally.

Figure 1 Our completed routed PCB design

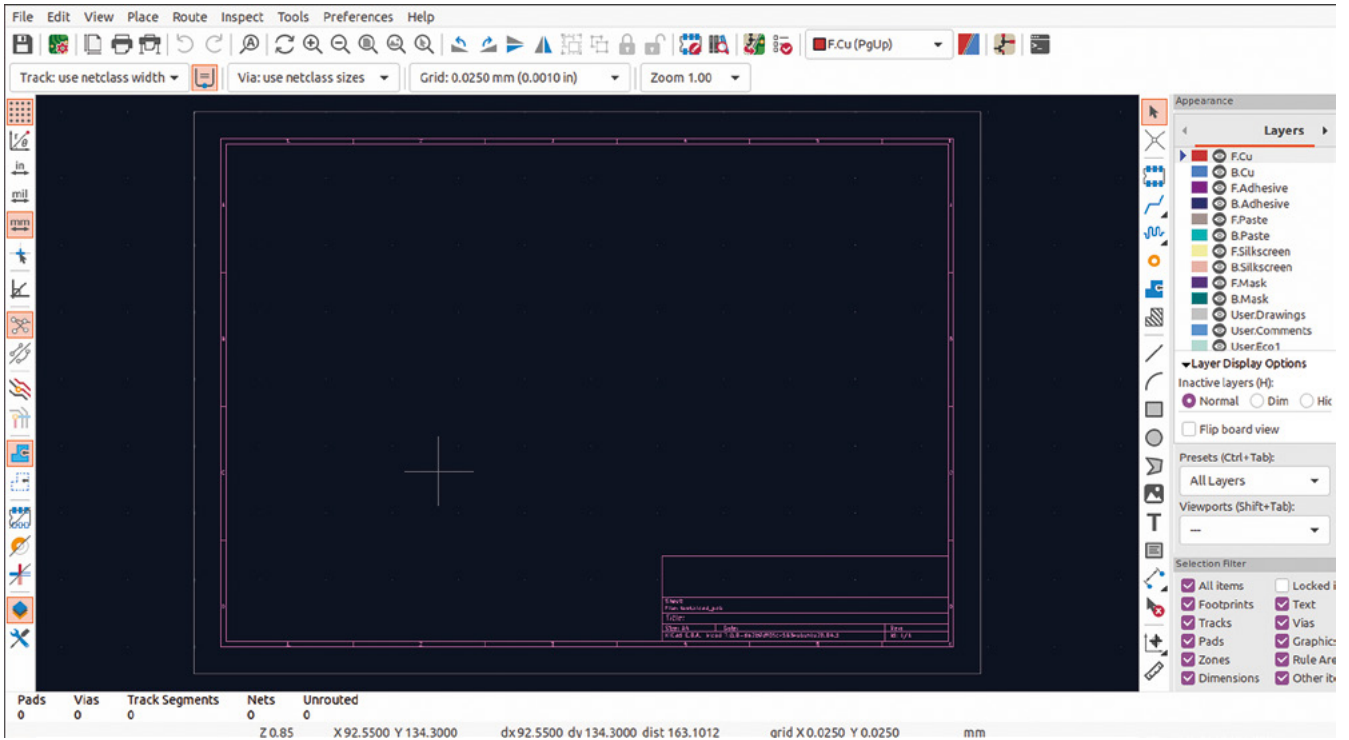


Figure 2 The blank PCB Editor ready to import our footprints

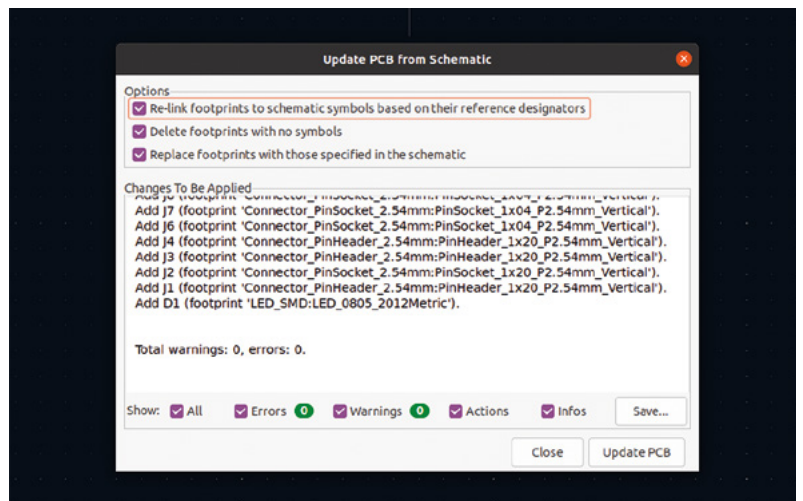
Next, move one element of one pair so that it lies two grid dots away from its connected pair. You do this by clicking on the centre of a pad on the footprint and then pressing **M**, similar to in the Schematic Editor. If you only move it across one grid dot, they will overlap. You should see a collection of small white lines connecting the pads between the two connected footprints – this is called the ‘rat’s nest’. We will remove these white lines when we lay the trace connections. It’s important that our board matches up to a Pico, so we used the dimensional diagram (**Figure 5**, overleaf) taken from the Pico data sheet documentation, available here: hsmag.cc/PicoDatasheet. You’ll notice that the distance between the vertical rows of pins is 17.78mm – this equates to 7×2.54 mm. This is why your Pico fits perfectly into a prototyping breadboard. Move the remaining outer pin socket footprints so that it is on top of one of the pairs you have placed correctly, and then move it seven grid spots to the right. You can now arrange the last footprint to be two grid spots inside. The outside pair of footprints should now match a Pico’s pin →



The PCB editor has a grid feature which snaps footprints at useful points



Figure 3 The Update PCB from Schematic window primarily brings in the component footprints and connectivity, or can be used to apply later changes to a schematic design



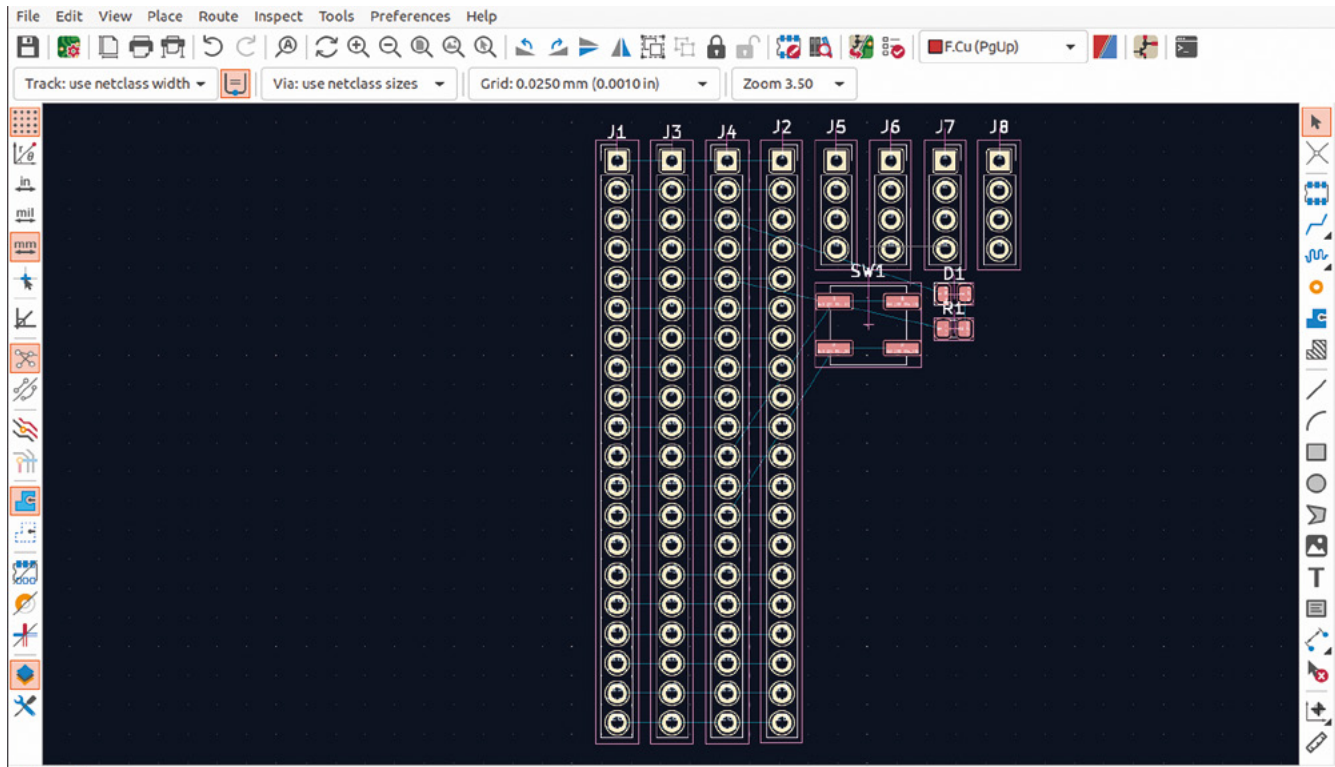
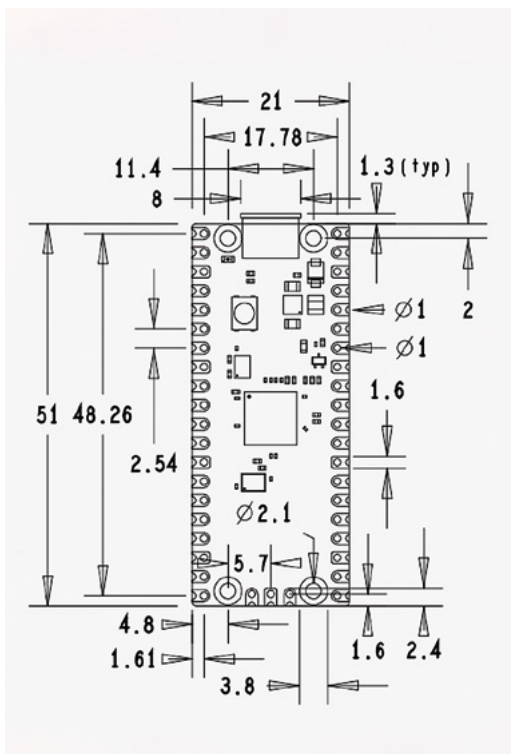


Figure 4

Our component footprints imported, with the rat's nest a representation of the connections between components and pads made of small lines

Figure 5

A technical drawing of the Pico taken from the data sheet gives us the dimensional information we need



positions, and the inner footprints should be close to them, and parallel. So far, we should have only been working on the F.Cu (PgUp) layer, which is the top copper layer on our PCB board. Before we route the tracks between our footprints, double-check that you are on this layer by checking the drop-down menu on the top toolbar.

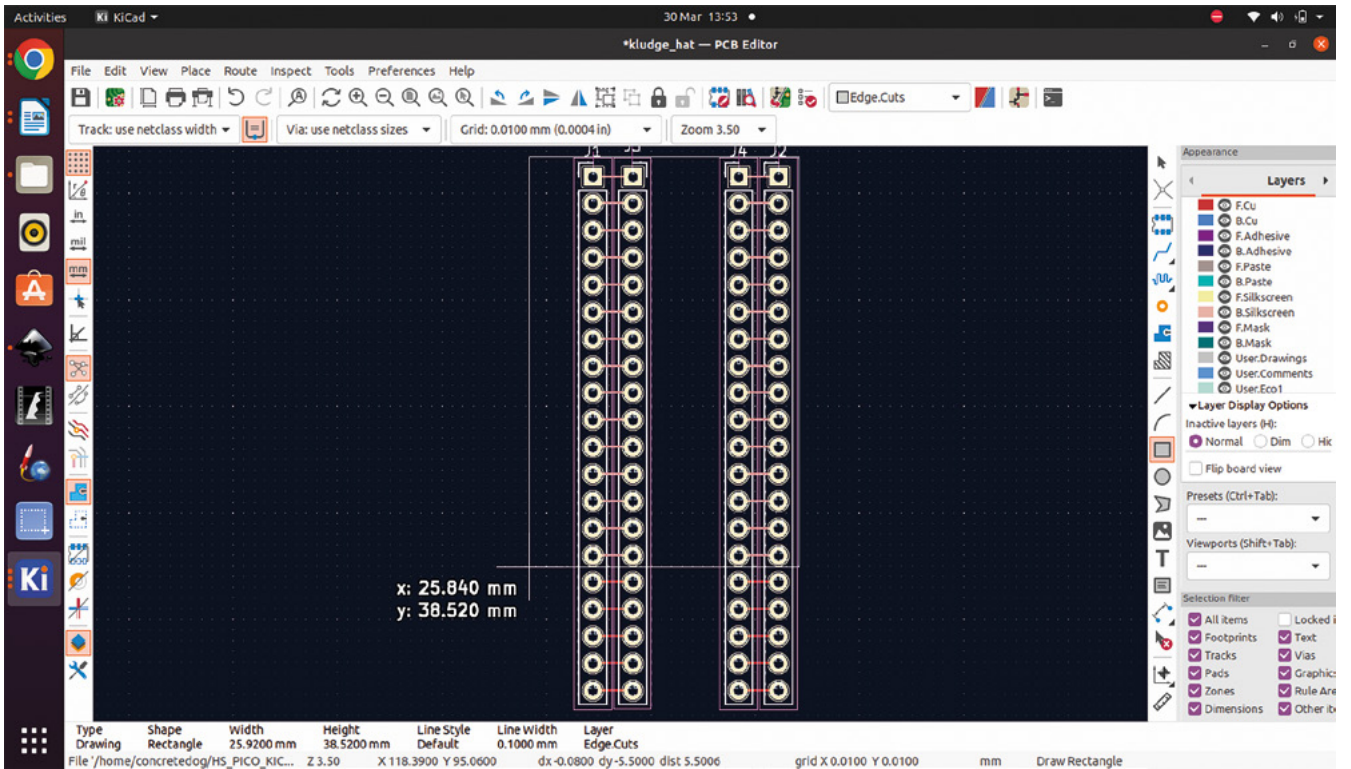
LEAVE ONLY FOOTPRINTS

Next, we can wire the pads on the opposite footprints together. To do this, select the Route Tracks (X) icon, then click the centre of a pad and drag the track over to the centre of the opposite pad. The track should be red, indicating that it's on the top copper layer. If we, for example, were to move to the B.Cu (PgDn) layer, the default colour for tracks on the lower copper layer is blue. Continue and connect all pads together, noticing that the rat's nest lines disappear as you do so.

Referring to our Pico technical drawing, it's a good time to define the shape and edges of the board. To do this, we can use the uppermost drop-down menu to move from the F.Cu (PgUp) layer to the Edge.Cuts layer. On this layer, we can use the Draw a Rectangle tool to create a cutout shape for our board. Before we select this tool, let's switch

QUICK TIP

Remember, a lot of your keyboard shortcuts are universal. For example, **F1** and **F2** zooming works in both the Schematic Editor and the PCB Editor.



the grid to a more useful spacing. Select the 1 mm grid spacing, then left-click the rectangle tool. Left-click anywhere in the PCB Editor page and drag a rectangle (Figure 6). The rectangle should be snapping to the grid – we can drag it out until the labels tell us we are drawing a 21 mm width by 51 mm height rectangle. Left-click one more time to create the rectangle. Moving back to the Select Items (S) tool, we can now select the rectangle and press the **M** key to move it into position. Notice

// Connect all pads together, noticing that the rat's nest lines disappear as you do so **//**

from the Pico technical drawing that the outside edge of the Pico sits 1.61 mm from the centre of the pin pad position. To position this accurately, we reduced the grid spacing to the smallest listed and used a technique to measure distances on the page. If you press the **SPACE** bar at any time when in the PCB Editor, you might notice that values labelled 'dx', 'dy', and 'dist' are set to zero. This is very useful as you can place your pointer at a point, say the centre of the top rightmost pad, press →

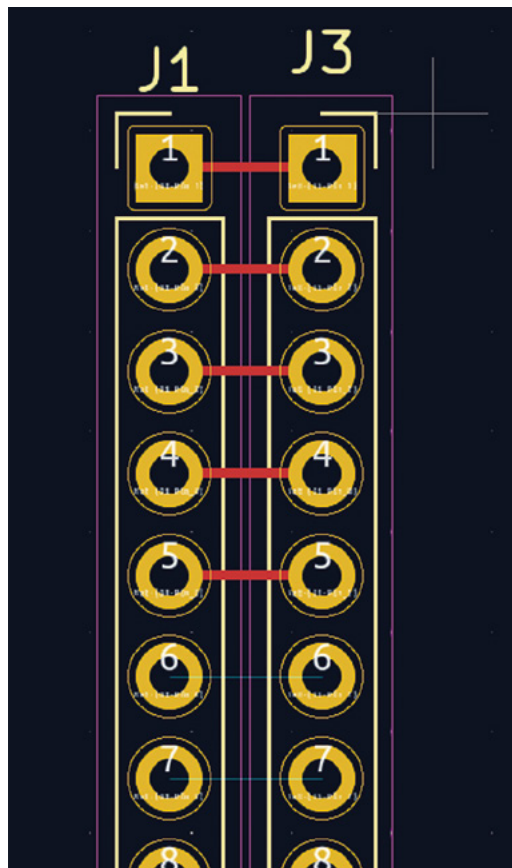


Figure 6 Drawing a rectangle that defines the cut edge of the PCB board

Left Routing tracks to connect the pads together

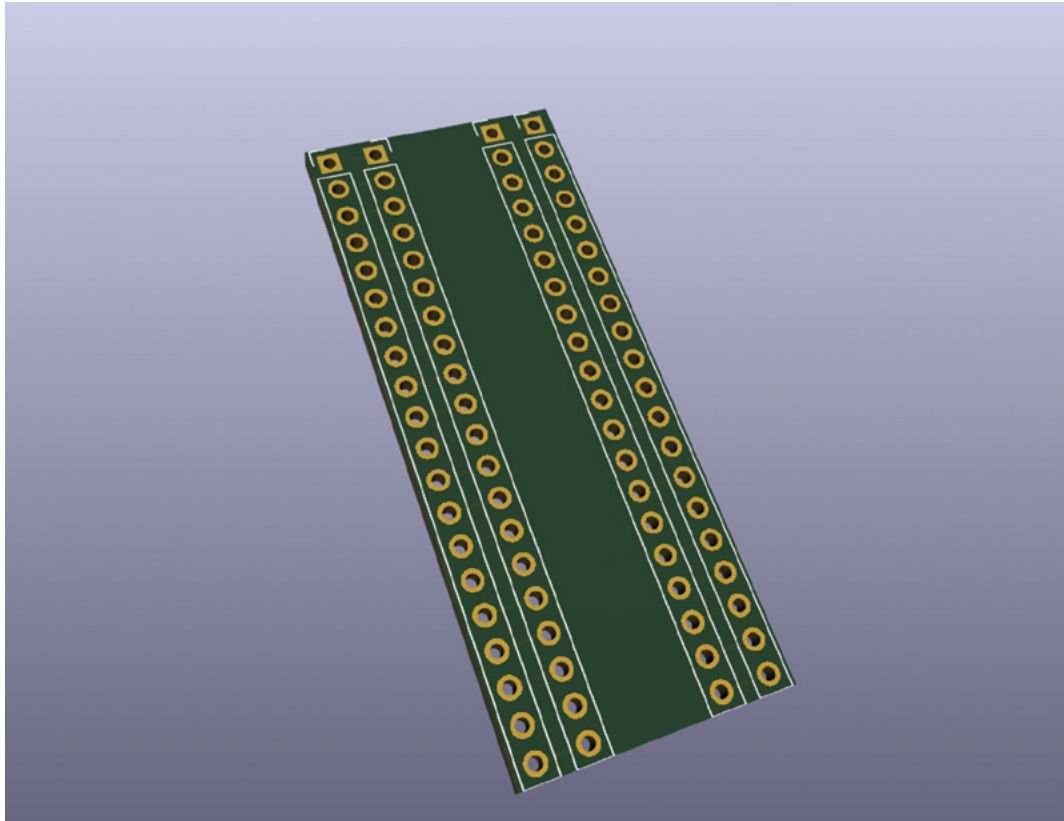


Figure 7  A first glimpse of our rendered PCB board

QUICK TIP

There are lots of drawing tools to create more complex edge cuts in KiCad. Also, in future articles, we'll look at importing graphical elements from other drawing software, such as Inkscape.

ASSIGNED AND SEALED

One point we mentioned earlier in this project is the idea that KiCad schematic symbols are generic – we assign the hardware footprint to them using the Assign Footprint tools. As an experiment, we could now show the advantage of this. Say we have our PCB layout completed and ready for manufacture, but after checking, we realise that our B3SL-1002P button package is not available or in stock anywhere. We can simply go back to the Schematic Editor and click the Assign Footprint tool icon. We can then edit the SW_SPST symbol to have a different, and hopefully, in stock, component. For example, we selected the B3SL-1022P footprint package, double-clicking it to ensure it is added to the centre console list. You can then click Apply > Save Schematic > Continue, and then click OK to close the dialog. Moving back to the PCB Editor, you can then once again click the Update PCB with changes made to the schematic (F8) icon, or press **F8** on the keyboard and the board will update with the replacement footprint added. If, as in this example, you replace the part with another part that is virtually the same footprint, you might not need to rewire the traces, but, of course, you should check and adjust connections and positioning as required.

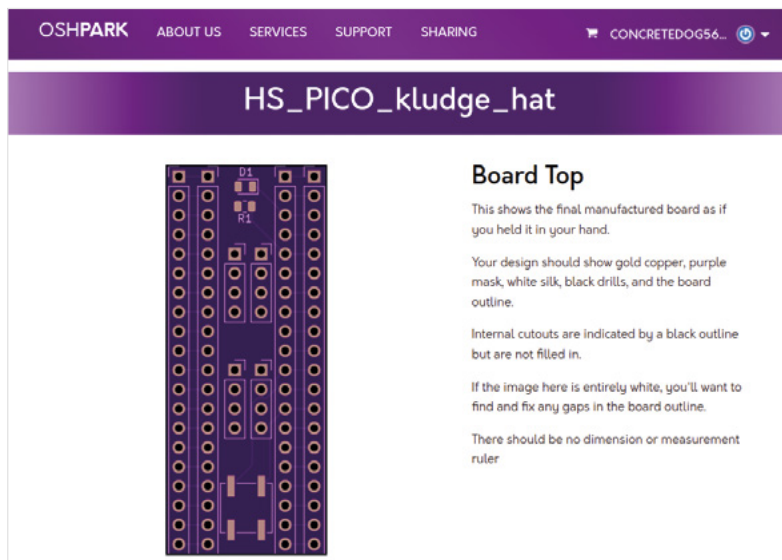
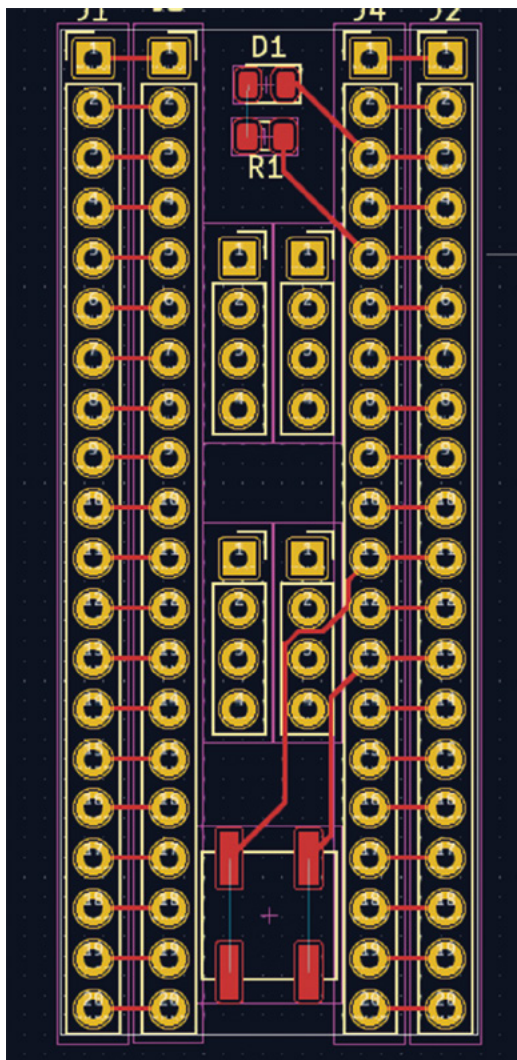
the **SPACE** bar to create a zero or datum point, and then move the pointer to, in this case, the edge cut rectangle. We can then use the dx and dy values to help us position this, or anything we need to, accurately.

Once we have positioned the board edge rectangle correctly, we can get a first glimpse of our board in the 3D Viewer. You can actually look at the board in the 3D Viewer before adding an edge cut, and it will render to a rectangle size that is the smallest that can accommodate all the footprints currently in the PCB. To view the PCB, click View > 3D Viewer. You'll see the board, but you'll notice that all the 3D models of the header sockets are all placed into the rows of holes. In reality, we would only want headers on the outer rows installed on the back of the board, with the inner rows left unpopulated, or possibly populated with header pins. We could edit the board and the component footprints to reflect this, but for this 'getting started' example, we can click the Toggle 3D Models for Through Hole type Components (T) icon to turn off the models (**Figure 7**). In future articles, we'll explore not only using correct 3D models but we'll

look at how we can add custom 3D models to our libraries.

FLOOD ZONE

We can now continue to arrange and wire our remaining components. For the LED and the switch/button, we are wiring traces directly to the pin connections to the Pico – this is perfectly OK, but in future parts of the series, we will look at using copper flood zones. A copper flood zone is where an area on a layer of a PCB is flooded with copper that is connected to a certain ‘net’, with the net value being chosen by the user. This means, for example, that we could make a PCB where everything on the back layer is a GND-connected copper flood, then any pads that connect to ground simply join the



flood with small traces. This can dramatically reduce the amount of traces in more complex designs, making them easier to route.

Finally, how do we get this board made? Well, there are lots of options – we will look at many of them throughout these articles. Globally, there are lots of services available from companies to manufacture and even assemble your boards. These services may need different approaches in terms of what information and files you need to upload to get the job done. Often we need to export Gerber files for each layer of the PCB, and also drill files which show the position and size

Above ♦ We'll use numerous PCB fabricators in this series, but a great place to start, where you can directly upload KiCad PCB files, is OSHPark

Below ☑ Our complete PCB with all components placed and routed

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In a few weeks – often less – you'll have 'Perfect Purple PCBs' through your door!

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of holes. Some companies might have limitations on what size holes they can produce and what tolerance they can produce the board too. We'll explore this in future articles, but the simplest way, if you wanted to get this board fabricated to an excellent standard, is you can upload the file that ends '.kicad_pcb' to the OSHPark website (oshpark.com). The website and service are brilliant. In-browser, it creates numerous renders of your board, which you can then inspect and check to see if they are correct before adding the PCB to your cart to be manufactured. In a few weeks – often less – you'll have 'Perfect Purple PCBs' through your door! ☑

KiCad libraries, symbols, and footprints

In this third part of a series of articles around PCB creation with KiCad, let's look at adding or importing custom libraries, schematic symbols, and component footprints



Jo Hinchliffe

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In the first two parts of this KiCad series, we've covered enough to make a basic PCB suitable for simple circuits, or maybe a breakout board.

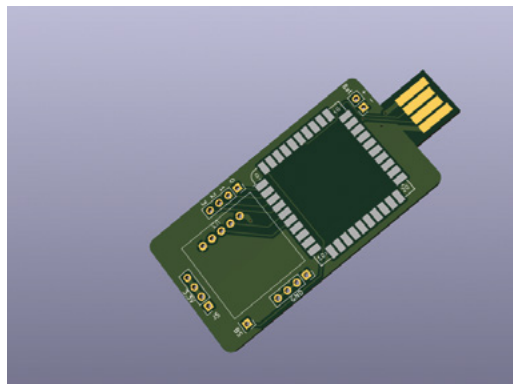
In this part, we are going to look at some next steps that open up the capabilities of what you can make in KiCad. We'll explore both creating libraries and contents from scratch, but also importing and using component footprints and schematic symbols from other sources. We'll also improve the quality of the boards by using flooded areas for common connections, such as all the circuit points that are connected to ground.

We've used a relatively simple design to show these techniques – making a PCB that essentially has two modules on board. Quite often, when making, we work with electronics modules on breadboards and a custom PCB can be the perfect way to take a breadboard project to a permanent home that's more rugged and usable. We aren't

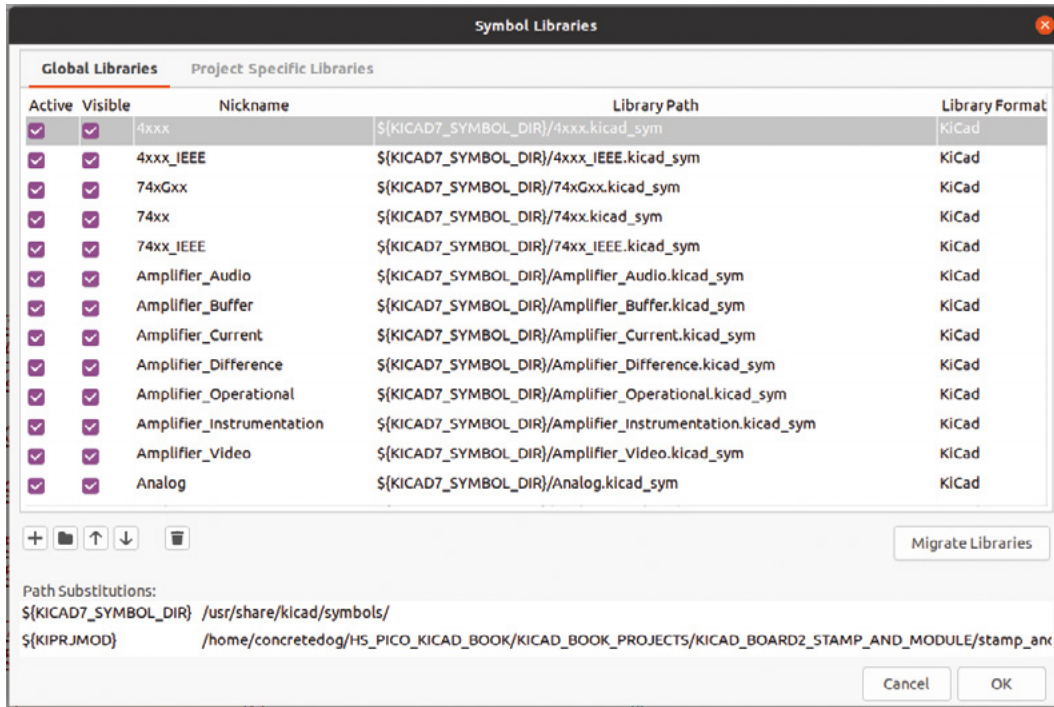
going to go step by step through the making of this board, but the project files are available at hsmag.cc/issue68, and the knowledge and techniques we used in the first two parts of this series, in combination with this section, should give you enough knowledge to recreate this project.

We've chosen to use a Solder Party Stamp and a Pimoroni BMP280 module connected together so that the resulting board can be used to measure and log temperature and barometric pressure. The Solder Party Stamp is an excellent board that has an RP2040 at its heart, and is operationally similar to a Raspberry Pi Pico. The RP2040 is fully broken out to header pins which are castellated, so you can also solder the Stamp onto a recipient PCB's pads without having to use header pins. The Stamp also has the USB connection broken out as well as on-board LiPo charging. This means if we add a USB connection, we can also add a LiPo cell and make the project stand-alone. The Solder Party Stamp is really well-documented and is open-source. Solder Party has also published KiCad schematic symbols and a PCB footprint for the Stamp, therefore we can use it to learn how to add libraries and import these useful items into KiCad.

To begin, go to the following link where you will find the Solder Party Stamp library components: hsmag.cc/StampFootprints. Click the drop-down menu on the green Code button and then select the Download ZIP option to download the libraries. Unzip the files somewhere on your machine. In the collection of folders you just unzipped, cut and paste the entire **KiCad** folder (N.B. not the **KiCad 5** folder) to wherever you want to store your additional



Right Our completed board, ready to receive a Solder Party Stamp and a Pimoroni BMP280 module



QUICK TIP

In the project schematic, we have sometimes used net labels to create connections between symbols rather than direct drawn wires. We'll cover this in some detail in an upcoming article.

Figure 1 The Symbol Libraries dialog where we can add or remove schematic symbol libraries

external KiCad libraries. We have a folder set up in our home directory for this.

Open KiCad 7 and, in the main page, click the Preferences drop-down menu and then select the Manage Symbol Libraries option. This should open a window with two tabs: the Global Libraries tab and the Project Specific tab, (Figure 1). Ensuring you are on the Global Libraries tab, find and click the small folder icon. Navigate to the folder we downloaded, extracted, and copy-pasted and open it to find a folder called **KiCad_stamp_lib**. Open this folder and select **RP2040_Stamp.kicad.sym** and then click Open. You should now see a new library listed at the bottom of the Global Libraries tab called RP2040_Stamp. If you create a new project and open the Schematic Editor, you can now use the 'Add a Symbol' tool to place a Solder Party Stamp symbol into the schematic. You can do this by searching for RP2040 and making sure you select the symbol from the RP2040_Stamp library (rather than the stock RP2040 symbol) or by scrolling down the list of libraries, selecting RP2040_Stamp, and then selecting the RP2040_Stamp symbol.

It's a similar experience to add a footprint library. Again in the KiCad landing page, click Preferences and then Manage Footprint Libraries. Again, on the Global Libraries tab, click the small

“ If we add a USB connection, we can also add a LiPo cell and make the project stand-alone **”**

folder icon (Figure 2). Navigate to the folder we downloaded and find **KiCad_stamp_lib** – open that folder once more but, this time, select the **RP2040_Stamp.pretty** folder and click Open. You should see three files inside, but you don't need to select any particular one – just click Open again. Now, back on the Global Libraries tab, you should be able to scroll down and see an RP2040_Stamp library entry. You can check that this has all worked by associating the correct stamp footprint to the RP2040_Stamp symbol we placed in the Schematic Editor, and then you can open up and import the part into the PCB Editor. If you need a reminder on how to do those tasks, check out the first and second part of this series in HackSpace #67 (hsmag.cc/issue67).

Using the BMP280 module gives us an opportunity to learn how to make both a custom schematic symbol and a custom footprint for the →

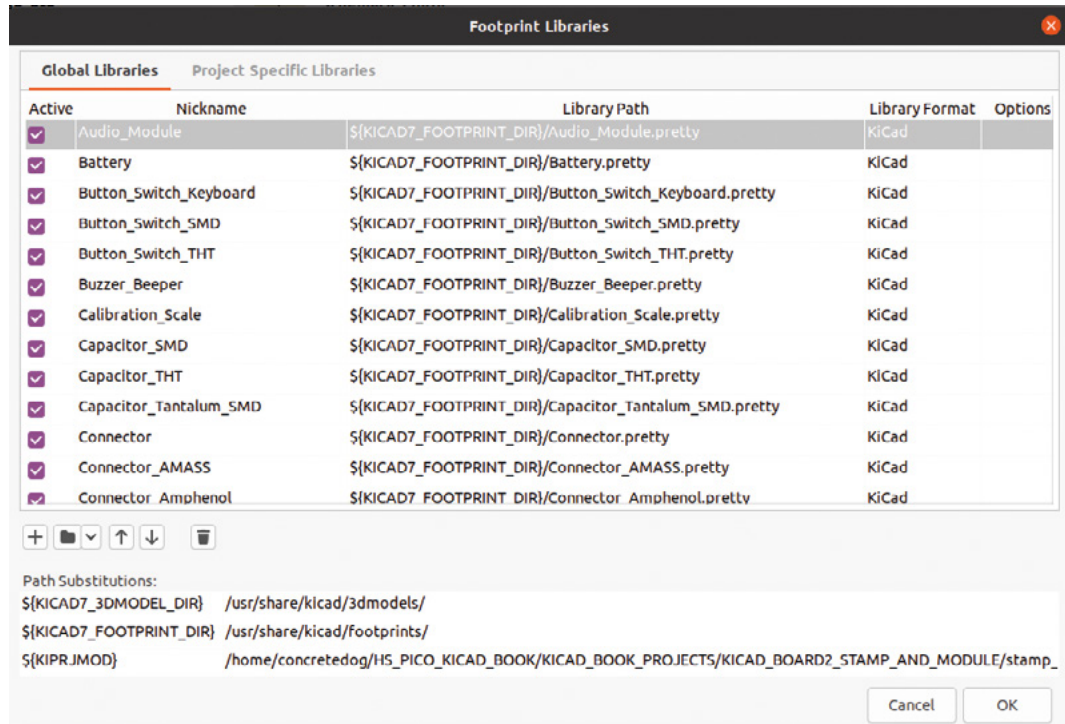


Figure 2 ♦ The Footprint Libraries dialog where we can add or remove PCB footprint module libraries

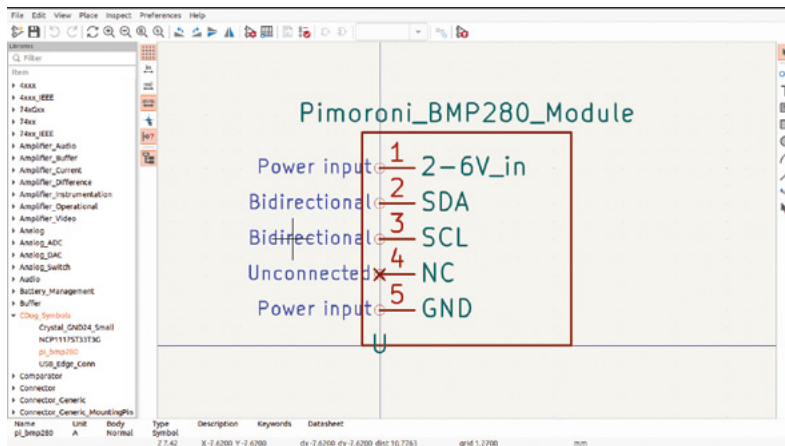
module to use in our board. To do this we will create our own custom libraries to contain these parts, and others in the future. Let's begin with a custom schematic symbol. In the Schematic Editor, click the 'Create, delete and edit symbols' tool button. This opens the schematic Symbol Editor.

In this new window, click File and then select New Library from the drop-down menu. You should now see a small dialog box called Add To Library Table. In this box, you can select to add your new library to the Global table. This means any project in KiCad can access this library; alternatively, selecting Project means only this KiCad project can access that library. As the BMP280 is something we might use in other projects, let's make sure 'Global' is highlighted and

then click OK. You'll now be asked to give your library a name – it can be anything you want, so name it, making sure to leave the '.kicad_sym' part of the file name intact, and click Save. You should now see your new symbol library name highlighted on the left-hand side of the Symbol Editor window. This means that this is the active library, so that when we select to create a new symbol, it will be stored in this library automatically. Click File and select New Symbol... from the drop-down menu. You should see a New Symbol dialog appear. Give your symbol a name that will be used in the library list – make it a useful name that reflects the part. We went for 'pi_bmp280'. Clicking OK, you should now see that a 'U' has appeared in the Symbol Editor window and that the name of the symbol now appears in the active library in the list on the left-hand side of the screen. The name will have a '*' next to it, indicating that the symbol has not been saved. In the Symbol Editor there are some familiar controls, such as the **F1/F2** to zoom in and out. Zoom out a little to give yourself some room and let's get started by adding some pins.

Click the 'Add a pin' tool icon. In the dialog, we can name the pin, give the pin a number, and set the 'Electrical type' and change other settings if needed. For our first pin, let's name it '2-6V_in', assign it pin number '1', and set the electrical type to 'Power input'. Continue to add pins 2, 3, 4, and 5, labelling them as you can see in **Figure 3**. As you place pins, notice that you can use the generic hot keys **M** for

Figure 3 ♦ The Symbol Editor window can be used to create or edit schematic symbols



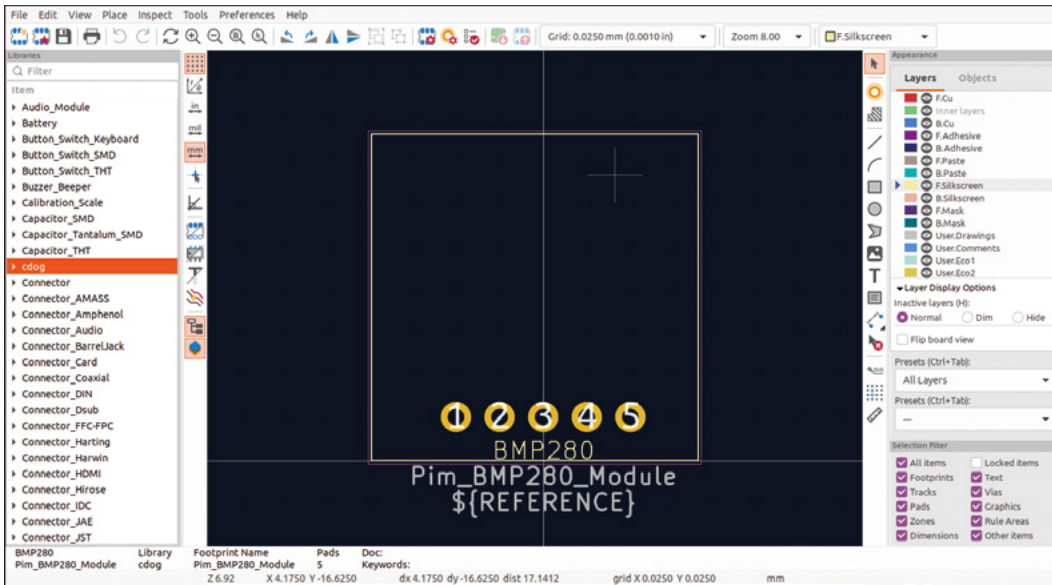


Figure 4 The Footprint Editor window can be used to create or edit component footprints

move and **R** for rotate, similar to the Schematic or PCB Editors. Once you have all your pins created, you can add a text label using the ‘Add a text item’ tool. This is useful so that you can identify the symbol quickly when looking at a schematic. Finally, let’s draw a bounding box around our schematic symbol so that everything is neatly grouped together. Click the ‘Add a rectangle’ tool, and draw a rectangle over your design. Click the Save icon

“ Give your symbol a name that will be used in the library list – make it a useful name that reflects the part **”**

in the top-left corner of the screen, and then close the Symbol Editor window. You can now go into the Schematic Editor and use the ‘Add a symbol’ tool to find and add your first custom symbol.

Next, we need to make a new footprint library and footprint for the Pimoroni BMP280 module. To begin, we first need to open the Footprint Editor (**Figure 4**). This is available either from the main KiCad project window, or indeed can be launched from the ‘Create, delete and edit footprints’ tool icon in the PCB Editor. Similar to the Symbol Editor, once you have the Footprint Editor open, the first thing to

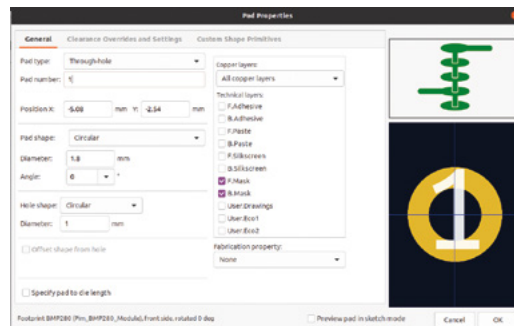


Figure 5 Editing the pad size and shape using the Pad Properties menu

do is to click File and then select New Library from the drop-down menu. Again, you can select to add a new library to the Global or Project table – select Global and name your library. Once the new library appears in the list, highlight it and then click File and select New Footprint. A dialog appears and we can name our new footprint. We called ours ‘Pim_BMP280_Module’.

We also need to select from the drop-down menu whether this is an ‘SMD’ or ‘Through Hole’ component. Selecting ‘Through Hole’, we are now ready to add the pads and other parts of our footprint. Similar to the PCB Editor, we can set the grid resolution and, as the pins on the BMP280 module are spaced at a standard 2.54 mm pitch, it is worth setting the grid to this initially to allow us to easily place the pins. Next, click the ‘Add a pad’ tool icon. We want to end up with five pads →

QUICK TIP
Note that if you use a schematic symbol or a footprint module from an external library, once it is saved in your KiCad project file, the symbol/ footprint is stored in that project. If you moved to another machine with KiCad that didn’t have the custom libraries added, you would be able to open the project as usual.

QUICK TIP

If you aren't in the Schematic Editor, you can open the Symbol Editor from the main KiCad project window.

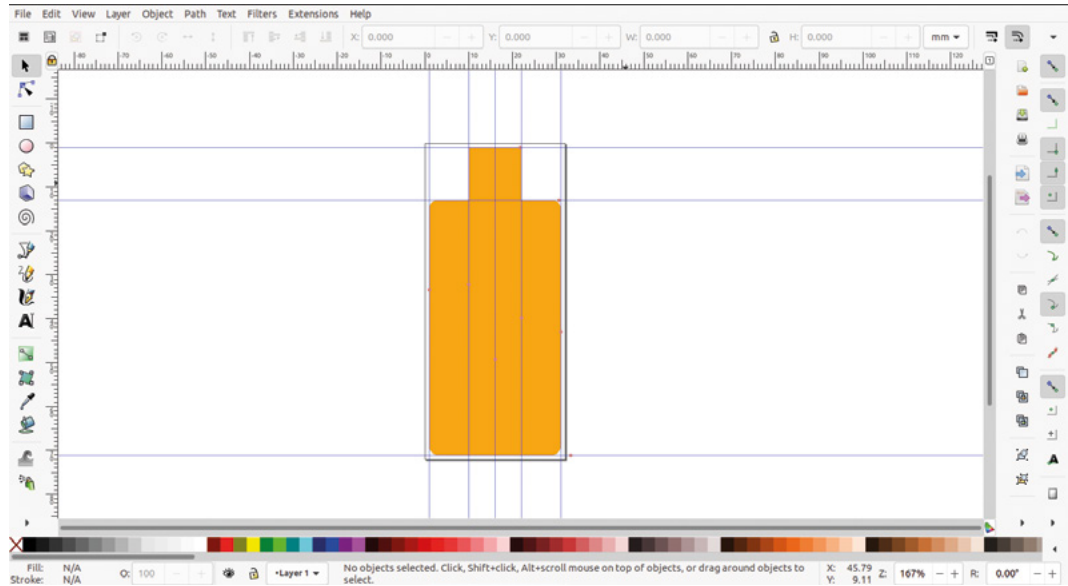


Figure 6 Using Inkscape to create an accurate graphic for the PCB edge-cut geometries



Many components will have physical package dimensions listed in their datasheet



labelled 1 to 5 moving from left to right. The easiest way to do this is to count two grid spacings out from the centre datum line and then click to place pad 1. Notice that the 'Add a pad' tool then increments the pad number so the next previewed pad is labelled '2'. Move one pad to the right of the pad you just made and click again. Continue to do this until you have a neat row of five pads.

Reverting to the general 'Select items' tool, hover over pad 1 and press the **E** key to open the 'Pad Properties' dialog (Figure 5). In this window you can change the geometry of the pad, the size of the hole, and many more options. We've found that increasing the pad size slightly from the default, and increasing the hole size, works well for soldering header pins between modules. You may have your own preferences, but we edited each pad to be a 1.8 mm circle with a 1 mm hole. With the pads created, we next need to add a silkscreen item that represents the physical area the module will occupy. Many components will have physical package dimensions listed in their datasheet, but that's not always the case with modules that are really designed for prototyping and breadboard use. In these cases, some investigation with a pair of callipers is a good approach to get some dimensions of the package. Measuring the Pimoroni BMP280, we realised a 19 mm square area with the pin pads 2.54 mm from the edge gave us a slightly oversized and therefore safe margin for the module. Select the 'F.Silkscreen' layer on the right-hand side of the screen and then use the 'Draw a rectangle' tool to draw this and position it correctly. Finally, let's add

USB ON BOARD

We've now nearly got everything we need to make the Stamp and BMP280 board! You might have noticed in the main image that we have added a USB edge connector directly onto the PCB. This is a cheap and cheerful approach to adding USB without adding any extra components, although we will need to add around 1 mm of material to the back of the 1.6 mm thick PCB in this area to actually make the USB connector fit. The reason we added this is to highlight another way of using libraries and components from other, suitably licensed, KiCad projects. In this example we found a project, the USB Armory, which, in an early Mk1 version, used the USB edge connector on PCB approach. The USB Armory is an open-source project and we can download the project repository here: hsmag.cc/USBArmory. Once downloaded, unzip the folder and use KiCad to navigate to the **hardware** folder, then **mark-one**, and then open the file **armory.kicad_pro**. Once open, move to the PCB Editor and select the USB edge connector footprint and press **E**. In the Footprint Properties window, click the Edit Footprint button. This should open the footprint in the Footprint Editor. You might get a warning that the footprint was made with an earlier version of KiCad, but saving the footprint in the editor should clear this warning. You should see that the footprint's pads and the silkscreen line (which doubles as a guide for the edge of the PCB board cut out) are now opened in the Footprint Editor. Across the top of the editor you should see a warning that you are currently only editing the footprint within the current project. You can use File then Save As to rename and save this footprint into your custom library that we created earlier. As that library is created on the Global table, this USB edge connector footprint is now available to use in any project. We edited our version a little, labelling the pads more clearly, and saved it to our library. Making a note of each pad's connectivity, we then repeated the earlier approach to create a custom symbol in our library to represent the USB connector in the schematic.

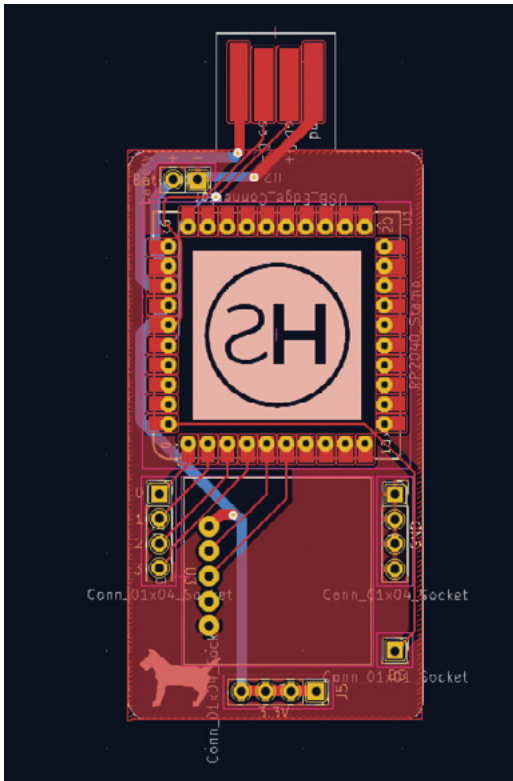


Figure 7 ♦ Flooding the board to connect all the GND connected pads

another square on the 'F.Courtyard' layer that sits just slightly outside the silkscreen layer square we just created. You can achieve this by setting the grid to a very small spacing value such as 0.01 mm and then drawing a rectangle away from the silkscreen rectangle to avoid it snapping. Make the new square 19.4 mm and then you can use the **M** key to move the square into position. This new square in the front courtyard layer provides a service called the 'DRC' or 'Design Rules Checker' with a boundary that shouldn't be overlapped. This means that later in the process, if a component is overlapping, this boundary on the PCB when we run the DRC will be highlighted as an issue. We'll look at using the DRC in the next part of this series.

To create the board outline, we decided to not use the graphical tools in the PCB Editor but, rather, we imported an outline we drew in the free and open-source Inkscape application (**Figure 6**). Whilst the included KiCad tools are excellent, Inkscape can offer some advantages when designing graphic components. We drew a simple outline object for the board in Inkscape, saved it as an SVG file, and then imported it into KiCad. To do this, click File and then select Import > Graphics... from the drop-down menus. In the Import Vector Graphics

File dialog, you can navigate to the file and select the working layer to import to. Setting the graphic layer as 'Edge.Cuts', notice that we can also set an Import Scale value. In this instance we designed the board outline to be the correct size in Inkscape, so we leave the import scale at 1.00 so that it imports at its original size. This function is useful. However, if we have an oversized graphic or logo to import to a silkscreen layer, like the HackSpace logo, we've reversed in Inkscape and then imported it onto the back silkscreen layer. We'll look at creating PCB artwork and components in Inkscape in more depth later in this series.

Finally, another technique that we've used on this board is to create flooded copper zones attached to a net label. This is an excellent way of automatically connecting groups of common connections (see **Figure 7**). You can create complex systems with lots of different flooded areas with differing connectivity, but in this project we have just used one flood on the front copper surface that connects all pads attached to ground. To do this, once the board is laid out, we used the 'Add a filled zone' tool. When you select this tool, you then left-click to start to draw a fill area over your board design, ensuring you are on the correct layer. A dialog appears and you can select the net connection from the list, so we selected 'GND' (**Figure 8**). Leaving all the other settings at the default values, we drew a rectangle over our board. Don't worry too much about accuracy as the flood will only appear inside the edge-cut geometry. Drawing three points of your rectangle you can then right-click and select 'Close outline' from the drop-down menu. The rectangle (or other shape you drew) should now flood, and you should see that all the previously disconnected GND pads are now connected together – neat! □

QUICK TIP

Note that the schematic pin numbers directly link to the assigned footprint pad numbers, so you must make custom symbols and footprints match.

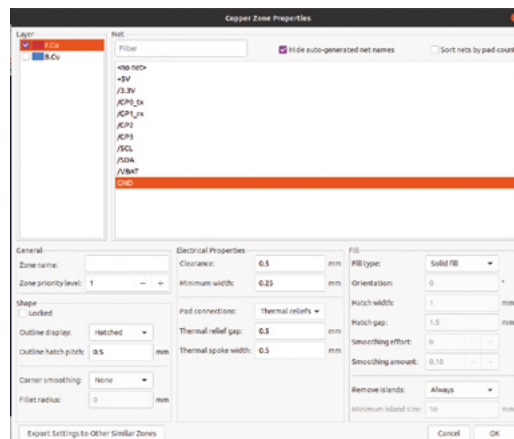
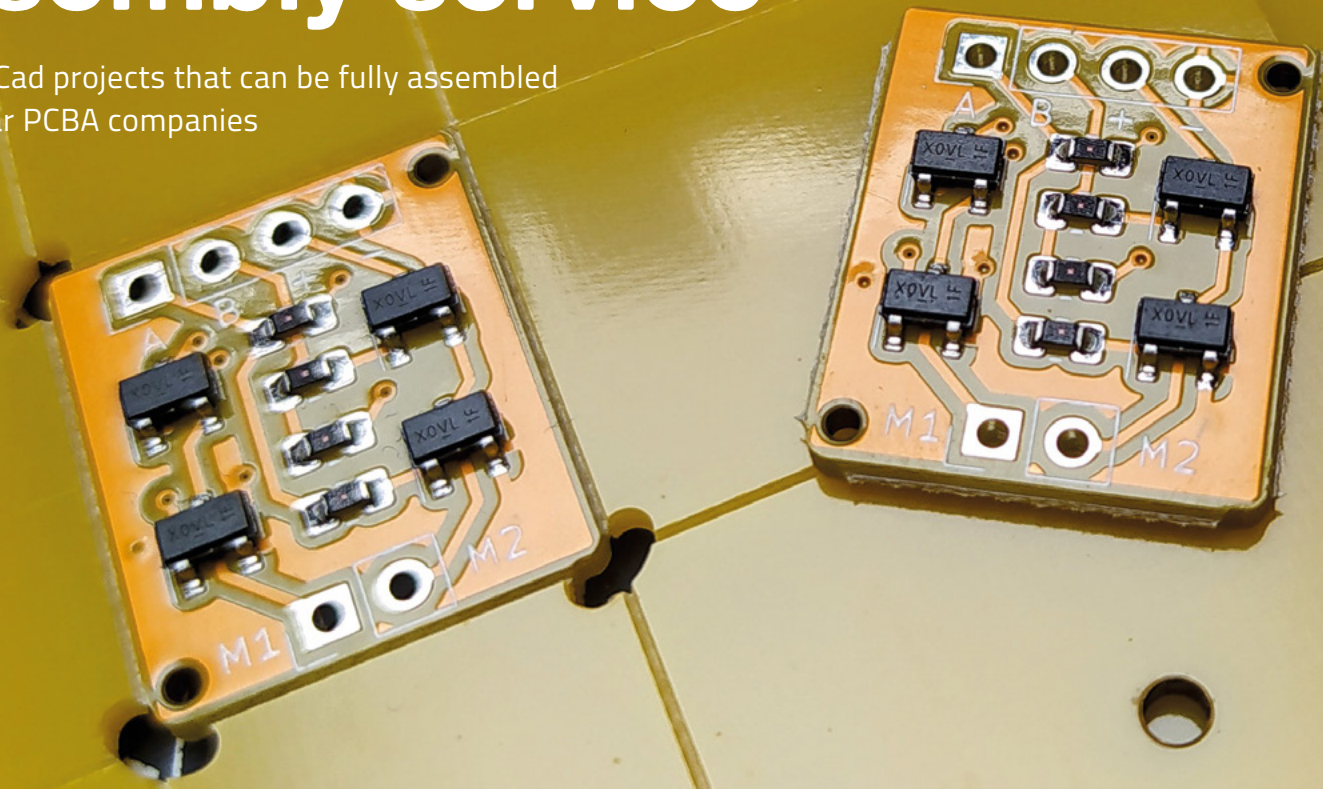


Figure 8 ♦ Selecting the net from a list to which the flooded copper zone will connect

KiCad: using a PCB assembly service

Create KiCad projects that can be fully assembled by popular PCBA companies



Jo Hinchliffe

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Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

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e've covered a lot in the previous three parts of this series. If you've worked through them all, you should be at a point where you can create simple board designs

pretty well. In the next part of this series, we are going to look at a more complex board, building a minimal RP2040 board example. The RP2040 chip itself comes in a QFN-56 package, and whilst that can be soldered at home using reflow or hotplate soldering techniques, for many, that will be a challenge too far. To avoid this, we are going to use a PCB assembly (PCBA) service.

There is a lot to look at in making an RP2040-based board, so in this article, we will prepare a simpler design for manufacture to help us learn the PCBA approach. Designing for PCBA adds complexity in that we have to create numerous files, not only defining

the PCB design, but also choosing and placing known components on the board. These components have to be available to the PCB assembly house, which again adds a little complexity. It's fair to say the first few times you do this process, it will seem like a lot of work compared to simply uploading your project file to OSH Park for it to create and send you a PCB!

So, for this exploration of PCBA services, we've laid out a small design in KiCad for a little H-bridge circuit prototype using four N-channel MOSFETs. We aren't going to step through the board design, particularly as we've covered the approach in earlier parts of the series. You can check out the project files here: hsmag.cc/issue69.

We're going to use the popular and reasonably affordable JLCPCB assembly service to manufacture and assemble our boards. This means that we need to consider what parts we are going to use on our board, as each part needs to be available in the JLCPCB

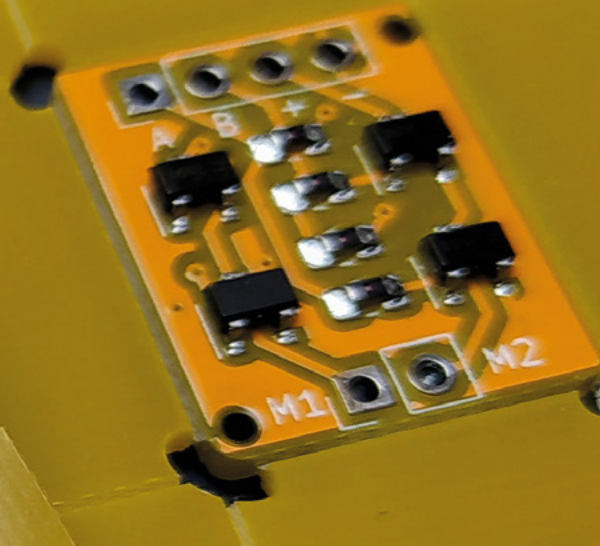


Figure 1 ♦
Our PCB design
successfully assembled
by the PCBA service

PCB ASSEMBLY

In earlier parts of this series, we used OSH Park to manufacture our PCBs – they make it super-easy by accepting KiCad PCB file upload directly. If you want to use other PCB fabrication services, or indeed as we are in this article, a PCBA service, it's much more likely you will need to plot Gerber files for your PCB and also files containing drilling information.

Gerber and drill files have some variables, and your fabrication service should give you some information regarding what they need in terms of Gerber files and drill files. For example, JLCPCB has a page (hsmag.cc/gerberdrillkicad) which outlines the settings required by the Gerber plotter in KiCad that their service needs. It's a little out of date in that the screenshots are from KiCad 5.19, but you can find all the same options on the KiCad 'Plot' dialog. To access the latter, you click File > Fabrication Outputs > Gerbers from the PCB Editor.

One thing of note is that plotting Gerbers creates a bunch of files for different layers of your PCB design, so make sure that at the top of the 'Plot' dialog, you create a folder for your Gerber files or else they all end up mixed into the main root folder of your project. You can also create the drill file from the 'Plot' dialog after you have plotted your Gerber files. Clicking the 'Generate drill files' button will launch a drill file dialog. For JLCPCB, place your drill file into the same folder as you did your Gerber files and, finally, compress this folder into a zip file for upload to JLCPCB.

Again, most PCB fabrication houses will have guidance on what format they require – JLCPCB list the settings needed on the link above. Don't worry too much if you upload something that doesn't work: it will show as an error and you can always ask the online chat service for help or guidance as to what settings to change.

parts library. The first thing to do is to head over to JLCPCB (jlcpcb.com) and register for an account. You can explore the JLCPCB parts library using the search function and filters – you will see parts' cost and availability. In fact, you can also advance purchase components so that they are held in your own virtual warehouse ready to be used on your board designs in the future. One thing of note is that available components fall into two distinct groupings: 'basic parts' and 'extended parts'. Basic parts will be added

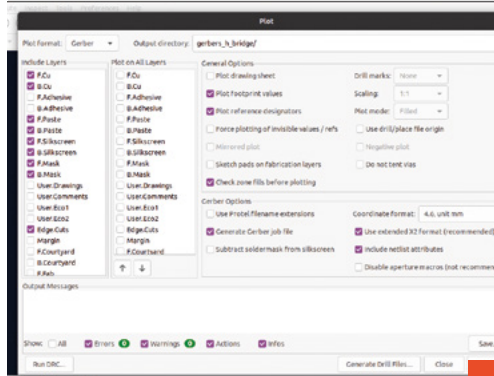
“

These components have to
be available to the
PCB assembly house, which
again adds a little complexity

”

to your board at the price listed. So, if you are adding five basic part resistors at 0.07 dollars each, then they will cost 0.35 per board. However, if that part was listed as an extended part, then that part will still cost the same unit price, but there will be a one-off \$3 setup cost of including that part in your project, as the part will have to be manually retrieved from storage and loaded into the pick-and-place machines.

As you peruse the JLCPCB parts library, make sure that if you spot a component that you are likely to use, you make a note of the part number – these usually start with the letter 'C' and are listed on the main component landing page. For our small H-bridge board example, we are only interested in having →



SCHOOL OF MAKING

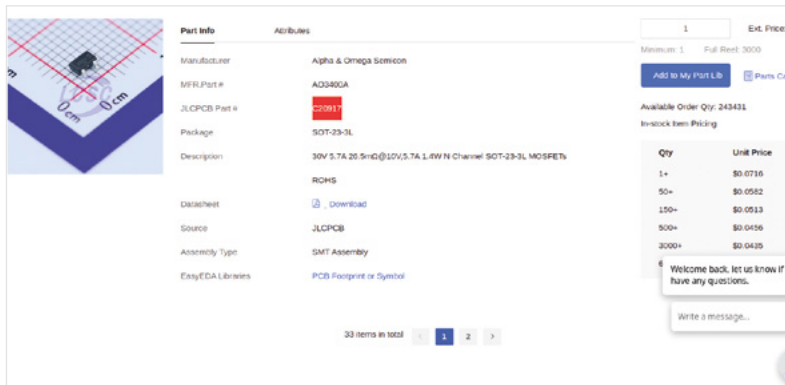


Figure 2 Searching for parts in the JLCPCB part library

Figure 3 Adding an extra LCSC field to Symbol Properties enables a correct BOM to be created

JLCPCB add the SMD components, so we chose some 10K resistors (part number C49122), and the four MOSFETs are going to be AO3400 chips (part number C20917) (Figure 2). We need to add these details to an extra field added to the Symbol Properties so that later, when we generate a bill of materials (BOM), these specific components will be identified. In order for JLCPCB to ignore the through-hole components in our design, we've simply not added this extra LCSC field to their schematic symbols, and therefore they won't be included in the assembly process later on.

To add these details, in the Schematic Editor, highlight a component and press the **E** key to open the Symbol Properties dialog. Click the + button, which is labelled 'Add field' when you hover over it (Figure 3). You should see a new field line appear. In the 'Name'

column, we need to label this field 'LCSC', and then in the 'Value' column, we need to add the CXXXXX number we researched for that component. For small projects, such as this example, you can do this manually for each schematic symbol. You need to do this for every component you expect JLCPCB to add to your board; you can't just add this field to one 10K resistor and expect it to work out to add the same part for the others. An alternate approach for larger projects is that you can edit the symbol at the library level, or copy the symbol to a custom library with the LCSC field and number populated at the symbol level. This means that whenever you place that custom symbol in the schematic, you have the correct LCSC part number ready for the BOM. Before creating the BOM, you still have to assign the footprints to the

symbols as you would for any PCB design.

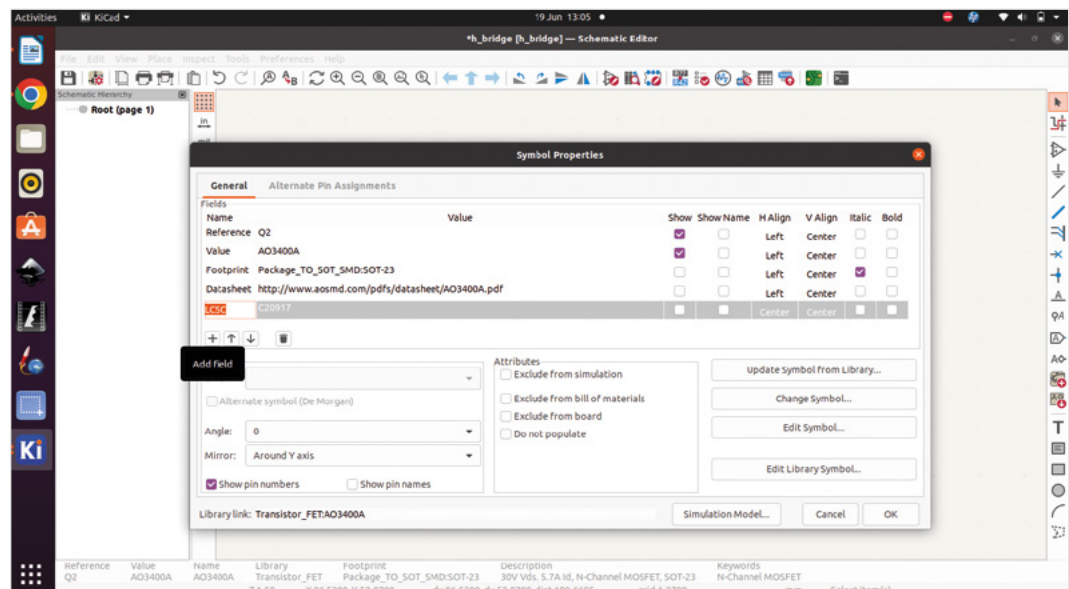
KiCad has a tool to generate a BOM – the tool icon is accessible from the Schematic Editor and shows 'Generate a bill of materials from the current schematic' when

you hover over it. If you click this tool, it will open the Bill of Materials dialog. On the left-hand side of the dialog, you'll see an area titled 'BOM generator scripts'. There are some scripts already installed, but there is an excellent script written by arturo182 which specifically creates a JLCPCB-formatted BOM. To use

You need to do this for every component you expect JLCPCB to add to your board

QUICK TIP

We covered creating and editing custom schematic symbols and libraries in the third part of this series.



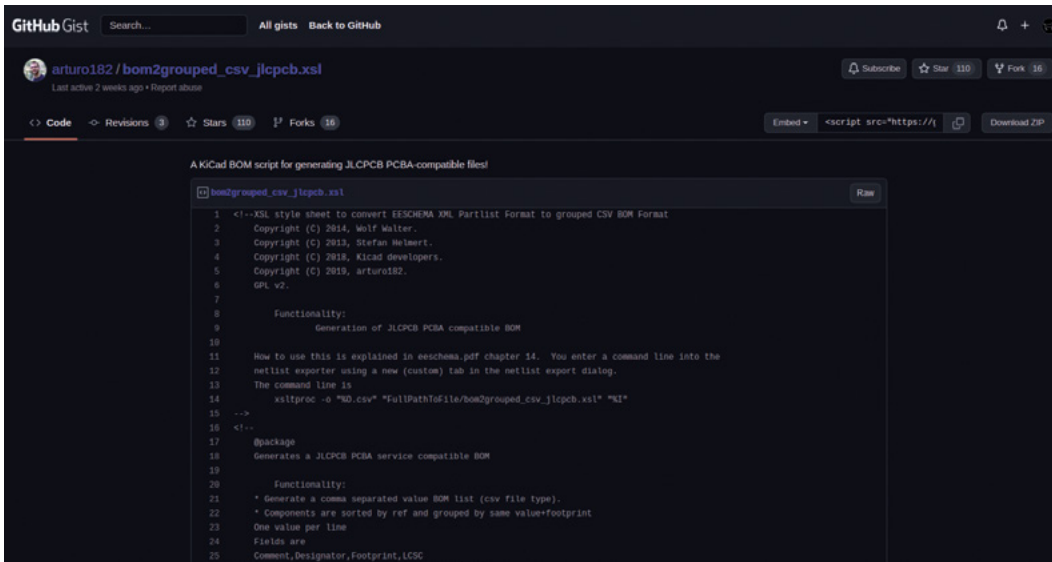


Figure 4 ♦ Downloading the custom JLCPCB BOM generator script

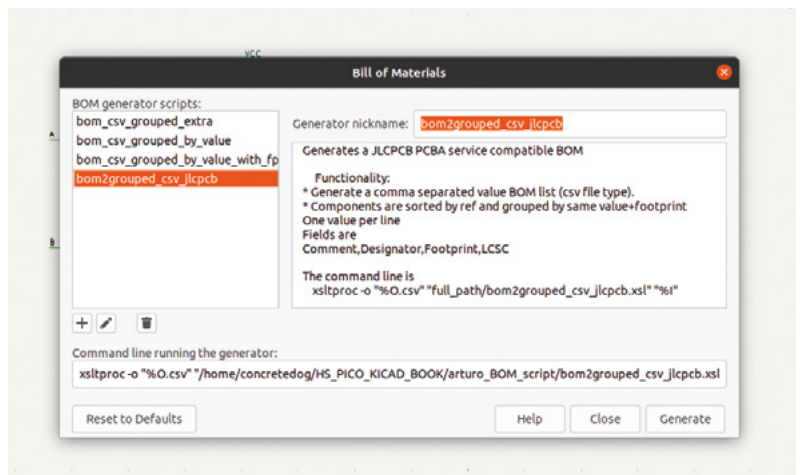
Figure 5 ♦ The BOM dialog with the custom JLCPCB generator script added and selected

this script, go to the GitHub repository, then in the upper right-hand corner, you will see a Download ZIP button. Click it to download, then extract the zip file (Figure 4). In the Bill of Materials dialog, click the + button and navigate into the folder you just unzipped and select the **bom2grouped_csv_jlcpcb.xml** file. Clicking the OK button will add this handy script to the list.

BOM SQUAD

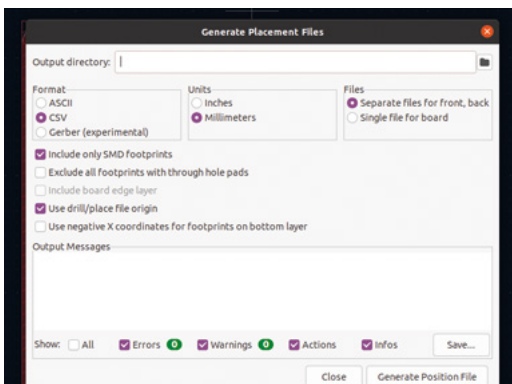
Once your board is complete and you have all the LCSC numbers attached to the schematic symbols, you can reopen the BOM dialog. Select the 'bom2grouped_csv_jlcpcb' script, then click Generate to create a BOM that the JLCPCB service will be able to use (Figure 5).

The final piece of the PCBA puzzle is to generate a footprint position file, also referred to as a centroid file. Similar to the BOM file, this is essentially a spreadsheet which contains details of each placed component, showing both coordinates and the rotational angle of the part. To generate this, in the PCB Editor, we need to select File > Fabrication



Outputs > Component Placement. Make sure that your settings match the dialog box shown in Figure 6. Note that if your project contains through-hole components that you want JLCPCB to include, you need to uncheck the 'Include only SMD footprints' option and include the LCSC numbers for those through-hole parts in the BOM. Note that for this component footprint POS file and the BOM file we generated earlier, we don't want those files inside the zip file of Gerbers, as they are uploaded separately. Once you are ready, click the Generate Position File button. Notice that this will generate two POS files: one for the upper layer and one for the lower layer. As our design is single-sided, we are only interested in – and later, need to upload – the upper layer file. With the upper layer POS file generated, we need to make a few alterations to the spreadsheet column header titles for it to work properly for JLCPCB. Open the file you have generated in your spreadsheet program. We use LibreOffice Calc, but MS Excel or Google Docs →

Figure 6 ♦ The Generate Placement Files dialog



SCHOOL OF MAKING

Figure 7 ♦ Using LibreCalc to edit the generated positional file column titles

	A	B	C	D	E	F	G	H
1	Designator	Val	Package	Mid X	Mid Y	Rotation	Layer	
2	Q1	AO3400A	SOT-23	96.078	-50.1165	90	top	
3	Q2	AO3400A	SOT-23	104.4	-50.3705	90	top	
4	Q3	AO3400A	SOT-23	96.078	-55.5475	90	top	
5	Q4	AO3400A	SOT-23	104.328	-55.5475	90	top	
6	R1	10k	R_0805_2012Metric	100.4335	-49.022	0	top	
7	R2	10k	R_0805_2012Metric	100.4335	-53.848	0	top	
8	R3	10k	R_0805_2012Metric	100.4335	-56.134	180	top	
9	R4	10k	R_0805_2012Metric	100.4335	-51.308	180	top	
10								
11								

should work. We need to make the following changes: the title of the first column, Ref, should be changed to Designator; PosX and PosY should be changed to Mid X and Mid Y; Rot should be changed to Rotation, and finally, Side should be changed to Layer (Figure 7). Save the POS file with these alterations – we now have everything we need to upload to the JLCPCB service.

With everything ready, we can now head to the JLCPCB website. Click on the Standard PCB/PCBA tab to upload our Gerber zip file. After a short upload, you should see a render of the upper and lower sides of your board in the preview window (Figure 8). You can make changes to the board type, material, thickness, and more on this initial page. However, apart from changing the colour of the board to yellow, we left everything at the default setting.

At the bottom of the page, you can click a button to add/expand the PCBA services. In Figure 9, you can see that we have opted to have the top side assembled only (as we only have components on this side). We've also ensured that the Edge Rails/Fiducials entry has the Added by JLCPCB option highlighted. This indicates that for our very small boards, JLCPCB

services will create any needed panel layouts. With all that selected, click Next.

You'll get another larger preview of the PCB layout generated from the Gerber uploads. Check it carefully and then click Next to move to the next

tab. This will look like Figure 10. It's reasonably self-explanatory. Click the Add BOM File button and upload the BOM file we created earlier, then click the Add CPL File button and upload the top layer CSV positional file we made and edited earlier. Clicking

// You should see a render of the upper and lower sides of your board in the preview window //

Figure 9 ■ The preliminary choices for the PCBA service

Figure 8 ♦ If the Gerber zip file uploads correctly, you'll be rewarded with the first of many preview images of your board

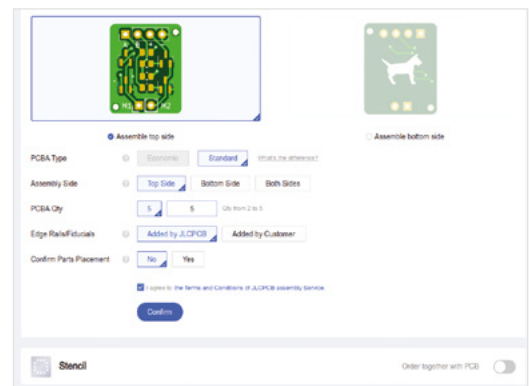
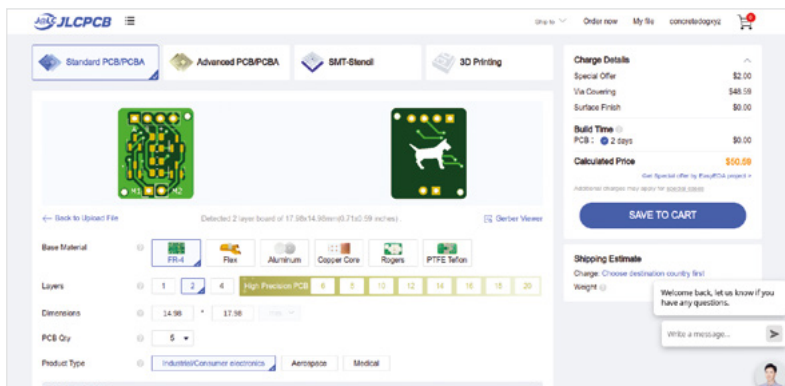



Figure 11  Correcting footprint rotational position can be done in-browser as part of the JLCPCB order process, or you can edit your positional file offline to create correct values

Next, these will be uploaded and processed, which may take a few minutes, and you should see a render with the board and the components placed.

SPIN ME ROUND

Often, at this point, you will find that components are not rotated correctly on the footprints. There are two ways to correct this, if your components are at standard angles, you can left-click to highlight a component in the render image and, when highlighted, use the rotation tools above the PCB render in the JLCPCB web page. You can continue to do this until your design looks correct. Clicking Next will save these orientations and take you to the Add to Basket ordering page. Whilst this is a fine approach, another approach is to open the positional file we created and uploaded offline and edit the rotational value of the components that have appeared incorrectly in the render. In our experience, either way is fine, and the JLCPCB engineers will question if a component isn't sitting on a footprint correctly.

All that's left to do is to add the order to your shopping basket and pay! Once the order is confirmed and paid, you get regular updates on the order listing and, if it's a complex design, it's worth checking back into your account four to six working hours after placing the order to check the DFM analysis regarding component placing in the order history details.


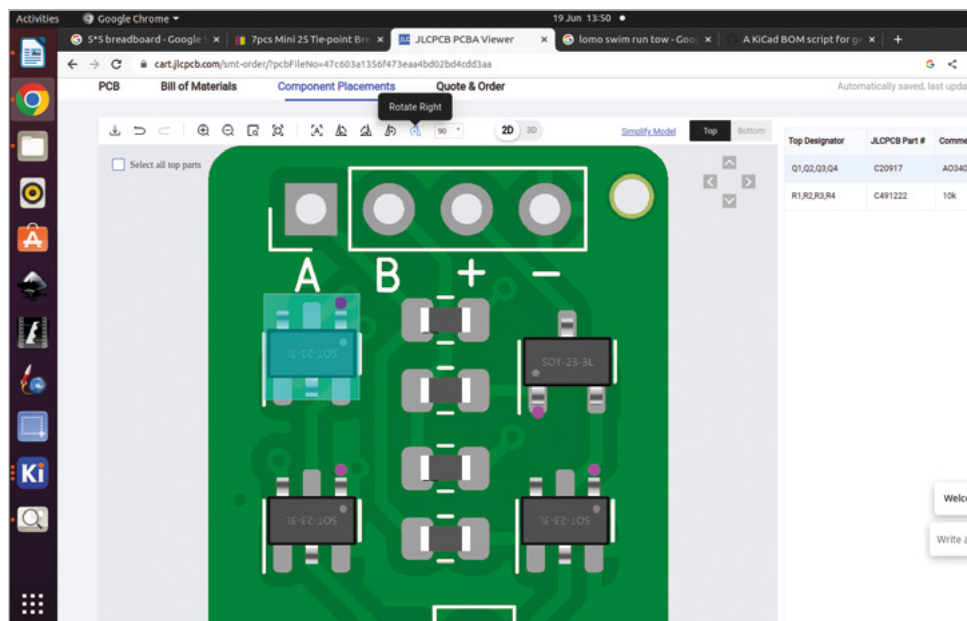
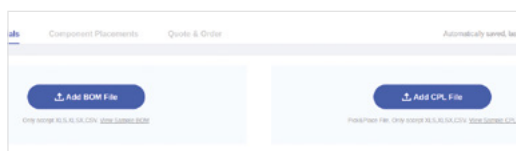
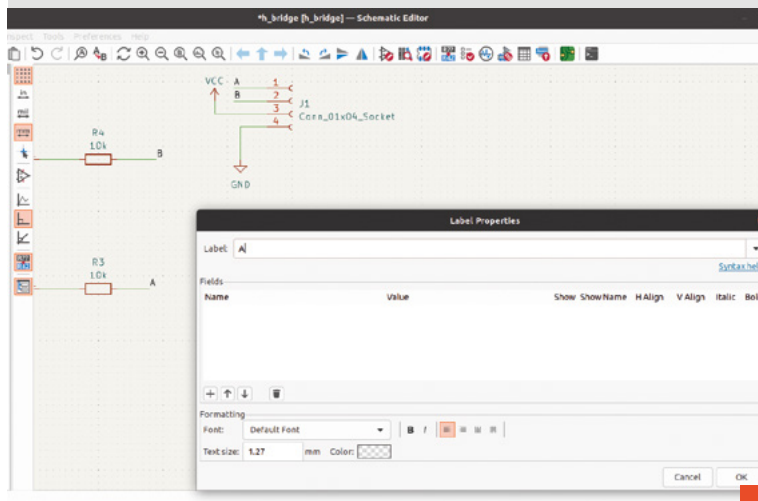
Once everything is ordered, all you have to do is wait! However, not for that long! We started this simple H-bridge motor driver design in KiCad and had the assembled PCBs (**Figure 1**) in our hand eight days later. 

Figure 10  Adding the BOM files and the positional file we made earlier



CASTING A NET

In the schematic for our H-bridge circuit, you'll notice that we haven't directly wired everything together and that the connections between the gate pins on each MOSFET are labelled 'A' or 'B'. In turn, there are also two pins on the connector marked 'J1' labelled 'A' and 'B'. These are 'net labels' and, to make one, you simply click the 'Add a net label (L)' tool icon. You then left-click in the schematic and the 'Label Properties' dialog will appear. Into this you simply type the name of your net label, so, for example, type the letter 'A'. You can change the font and size, but when you are happy, click the OK button and you can now place your 'A' label into the schematic. Notice that it has a small square connector. You can then connect a wire to the 'A' label as you would to any other component using the 'Add a wire' tool. You can recreate another 'A' label using the same method to attach to the other end of your wireless connection, or you can copy and paste the original net label. If you have more complex descriptive net label names, it can be a good idea to use copy and paste as if you create a net label with a spelling mistake, it will not connect and may take you a while to discover the error. In this simple H-bridge example, we didn't really need to use this technique but, in the next article with a more complex design, using net labels can really help to keep a schematic cleaner and more readable.



Designing an RP2040 board using KiCad

Build a custom microcontroller board and get it assembled



Jo Hinchliffe

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Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

In the previous parts of this series, we've worked through the basics of making PCB boards from schematic to board layout, and we've learned a variety of skills and approaches along the way. We built on this by exploring how to use KiCad and a PCB assembly (PCBA) service to not only have the PCB manufactured, but to also be populated with components and supplied to us fully assembled (Figure 1). If you've worked through the earlier parts, we now have enough skill and knowledge to tackle a more extensive project like creating an RP2040-based board.

RP2040 is a great target for PCB projects that will be assembled using industrial approaches. The bolder amongst us might successfully be able to solder up the QFN (Quad Flat No-leads) 56 package at home, but it's at the edge of where PCBA starts to make a lot of sense. Many commercially available boards that use the RP2040 are manufactured using PCBs with four or more layers. Of course, it's possible to do this in KiCad, but for many of us, four-layer boards can be difficult to debug or correct if something goes wrong.

Fortunately, for simpler boards, two layers is enough to get our microcontroller running and break out the features we need.

When the RP2040 was released, so too was a stack of excellent documentation, including the very readable 'Hardware design with RP2040' (Figure 2). The PDF is available to download from hsmag.cc/hardware_design_rp2040.

This document shows an example of a minimal RP2040-based board, a two-layer design, and then describes various aspects of the design and considerations. There is even a KiCad project file for the design. It's a great idea to download the project file and take a look around it (Figure 3). In this article, we are going to replicate this board design, but we will start from a blank project rather than use the one supplied.

Starting from scratch means that it's easier to adapt this project to your own needs. We'll also tweak the project because currently, JLCPCB doesn't supply some of the exact components used on the Raspberry Pi example. The Raspberry Pi example was built in a previous version of KiCad and uses in-house schematic symbols for the RP2040. Since then, the RP2040 has become a standard library component within KiCad, but some of the connections on the RP2040 schematic symbol are already made at a symbol level (like common power pin connections), so it makes sense to use the built-in KiCad symbols and footprints. With that all said, we aren't going to step through every stage of designing this board as we've learnt the approach in the previous parts of the series, so this article



Figure 2 ♦ The excellent Hardware design with RP2040 documentation from Raspberry Pi

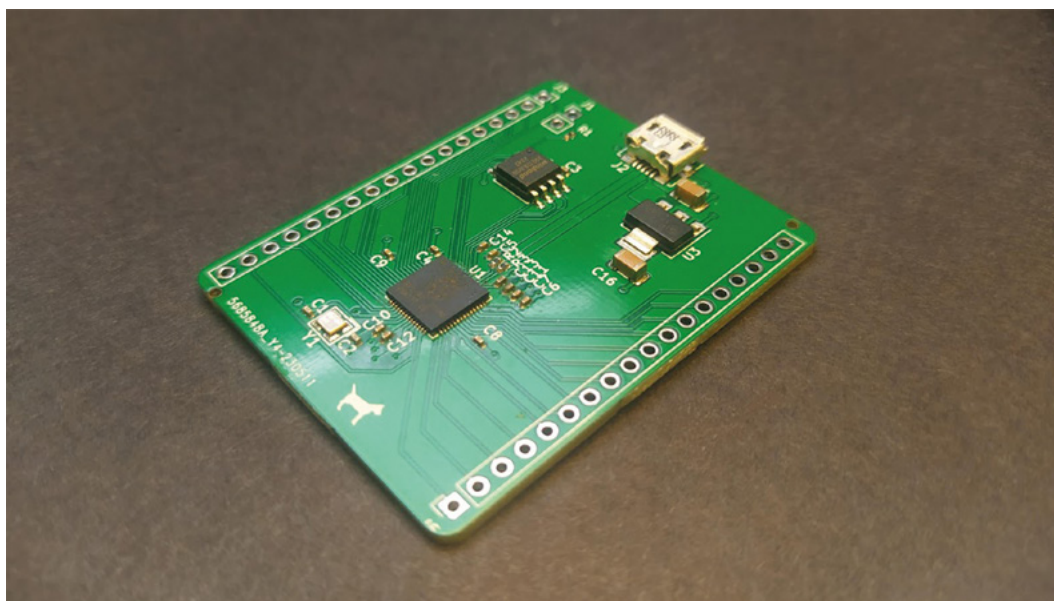


Figure 1 ♦
A fully assembled
and functional
RP2040-based board

looks at things we consider specific to creating an RP2040 board.

We've tended to emulate both the schematic layout and the PCB layout of the minimal design example and our project. Partly this is because the PCB layout has neatly solved a lot of the layout complexity, but also it allowed us to compare the project as we worked through building our own. With the USB symbol (and footprint) sourced, we added the RP2040 component from the KiCad

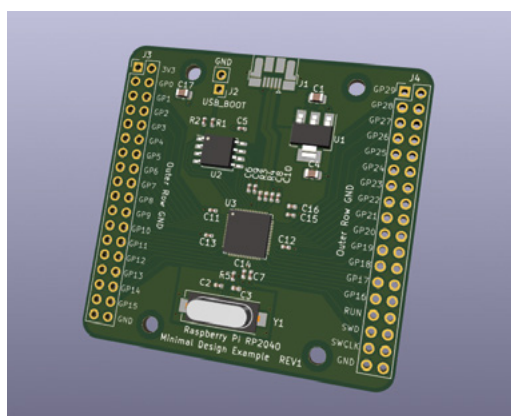


**Starting from scratch
means that it's easier
to adapt this project to your
own needs**



library. We added resistors and a pair of labels to connect the D+ and D- to the correct pins on the RP2040. The documentation states that we need to create the traces for these connections with accurate dimensions and clearances. We'll achieve this by assigning a custom net class to the connection, or 'net', so that when we draw these traces in the PCB Editor, they should be created correctly.

In the Schematic Setup dialog in the Schematic Editor, click the + button in the uppermost Net Classes window, add a new net class, and give it a name. Note that local net class names within a project should start with a '/' – we went with /USB_lines. Select a wire segment that connects the RP2040 D+ or D- pin out to the USB_D+ or USB_D- label that we added, and then right-click. Select Assign Netclass from the drop-down menu. In the Add Netclass Assignment dialog box, you should see the selected label USB_D+ and, to the right of it, a drop-down menu to select the net class – this is currently 'Default', but if you click down, you →



QUICK TIP

Reading through the Hardware design with RP2040 PDF a couple of times is beneficial to laying out an RP2040-based project!

Figure 3 ♦
The Hardware
design with RP2040
documentation also
includes a KiCad
example project

QUICK TIP

Do take care when creating custom footprints to ensure that the component pin number is compatible with your schematic symbol and vice versa.

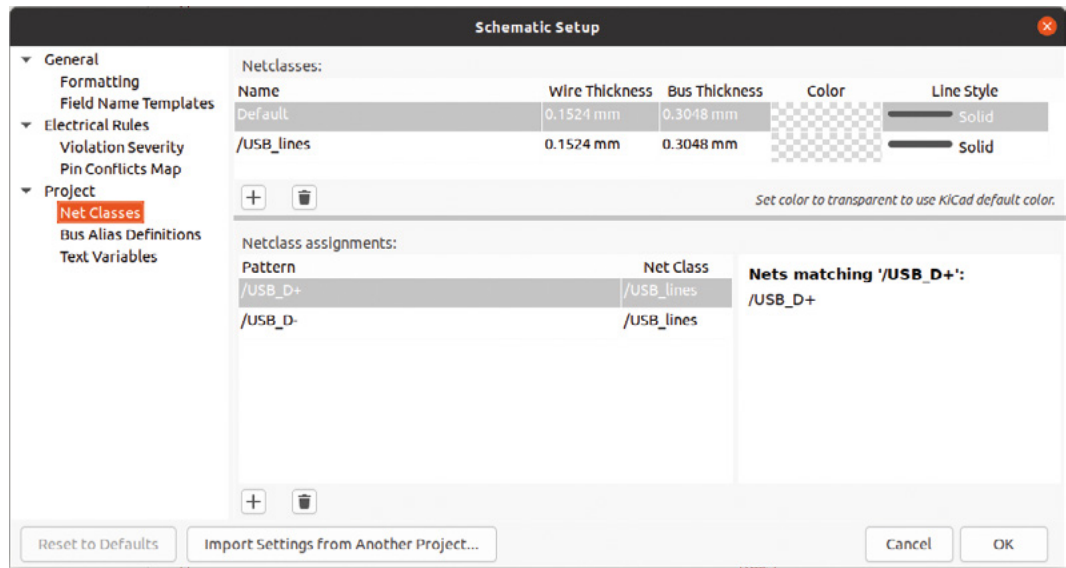
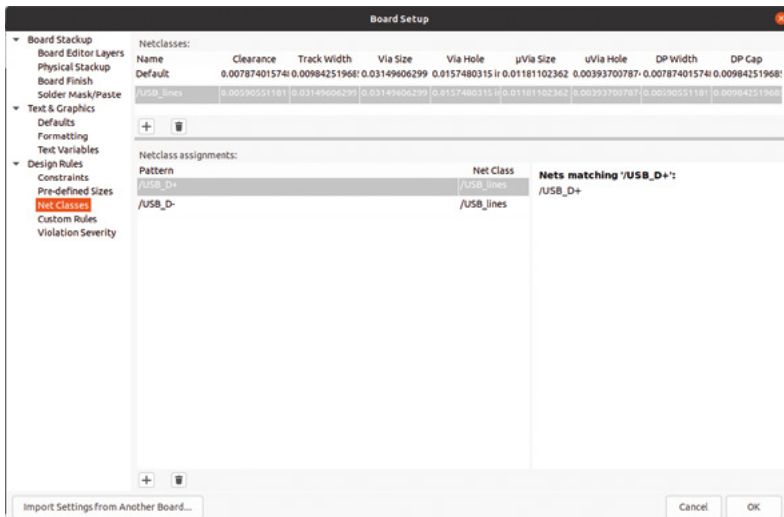


Figure 4 Setting up and assigning a net class

should be able to see the 'USB_lines' net class that we added earlier. Select this, then close the dialog box. Repeat this for the USB_D- label (**Figure 4**).

When you get to opening the PCB Editor, you can use the Board Setup tool (in the same position as the Schematic Setup tool) to adjust the net class variables. This includes the track width, track clearance, via size, and more (**Figure 5**). We are predominantly interested in the track width and the track clearance to create the track lines that we need for the USB lines – this information on track geometry was taken directly from the Hardware Design with RP2040 documentation (page 10).

Figure 5 Setting the net class variables for our USB lines in the Board Setup dialog in the PCB Editor



We laid out the power regulator and found a similar device to the minimal design example; however, the JLC component, C26537, had an extra pin and was in the SOT-223-3 package. We have a matching KiCad library footprint, but it was easier to just make a quick custom schematic symbol to ensure that the pin numbering was correct and matching (**Figure 6**).

One area that challenged us was, when looking up the components that the minimal design example project used for the crystal, we found no similar device available on the JLCPCB component library. Using a consummate hardware hacker's approach, we researched what other open-source RP2040-based designs used, making sure to limit the list to projects we knew worked well. Having used Solder Party's Stamp in an earlier part of this series, we checked out its design. It looked simple and straightforward with just two 12pF capacitors, and on checking JLCPCB, the crystal part was available as part number C521567. We again used the EasyEDA conversion website (see box, opposite) to create a custom footprint (**Figure 7**, overleaf).

Laying out the decoupling capacitors in the schematic is straightforward, but we've taken advantage of the KiCad text tool to add notes, occasionally acting as reminders for important information. In the Hardware design with RP2040 documentation, for example, it shows that the 1uF capacitors should be placed close to pins 44 and 45 on the RP2040, so it makes sense to add a schematic note as a reminder (**Figure 8**, overleaf).

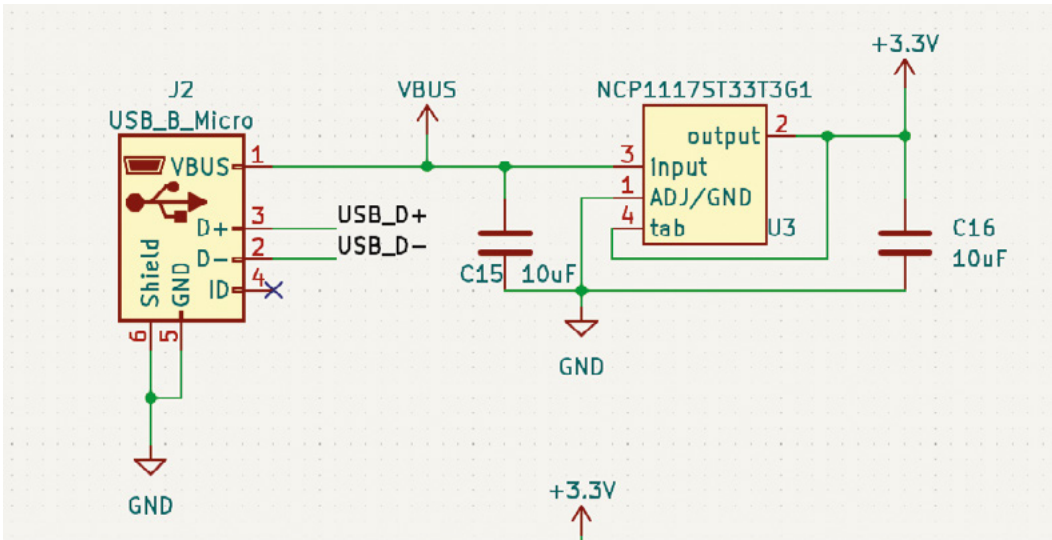


Figure 6 ◆
Setting up the power regulator is simple once the target JLCPCB components are identified

The flash memory chip used in the minimal design example is available at JLCPCB and, as such, we went with the same design. In the Hardware design with RP2040 documentation, they have added a footprint for an optional pull-up resistor but found, with this chip, that it wasn't needed, so we omitted that part of the design. The important thing about the flash chip and the associated traces on the PCB is that it all sits over a continuous ground plane. This adds some head-scratching with the lay up of a two-layer board, but again, use our project or the Raspberry Pi project as an example of the routing.

As we aren't aiming for any particular use case with this example, we simply broke out all the pins to a pair of headers that we will place on each side

// We simply broke out all the pins to a pair of headers that we will place on each side of the board //

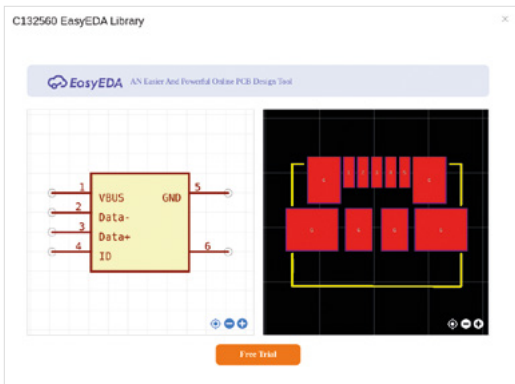
EASILY CONVERTED

When designing for JLCPCB, even at the schematic level, you need to be thinking about what component and footprint you will be using. For our RP2040 board, we wanted to use a surface-mount micro USB-B socket where all the USB chassis and ground points are on the upper layer – this means we could keep all the assembly as SMD components. As such, apart from the pin headers/sockets, the units would be fully assembled by JLCPCB.

Looking through the LCSC component library, we opted for the C132560 component. JLCPCB often supplies schematic and footprint symbols for EasyEDA, and, in the case of the component footprint, we can use a handy online tool to convert it into a KiCad component footprint and add it to our libraries (we covered working with custom libraries and components in the third part of this series – hsmag.cc/issue68).

To make use of this converter, you'll need to set up an EasyEDA account (easyeda.com). Click the link that says 'PCB Footprint or Symbol' on the component page on the JLCPCB library website, then click the Free Trial button underneath the pop-up window that shows the component symbol and footprint. After setting up a login, you should see a browser-based EasyEDA project with just the footprint of the component loaded. In the browser, go to File > Export, and then select EasyEDA ... from the list. This should then download a small JSON file. Navigate to hsmag.cc/EasyEDA2KiCad, click the Load EasyEDA File button, and then upload the JSON file. The website will automatically convert the EasyEDA project and will then download a KiCad footprint file to your Downloads folder. As a side note, we also used this approach for the crystal package we used on the board design.

Sadly there is no conversion available for the schematic symbols; however, with some careful checking of pin numbers to ensure compatibility, we found a built-in KiCad USB schematic symbol that worked well with the footprint. Again, though, if you've worked through all parts of this series, you should be happy to create your own custom symbol.



Above ◆
LCSC provide EasyEDA symbols for most of their components so you have to convert these before you can use them in KiCAD

TOOLING HOLES

When ordering assembled PCBs from JLCPCB services, you might need to consider tooling holes. These are small holes placed in your design layout that JLCPCB machines use to locate and hold the boards when they are being assembled. You can add these yourself, or you can omit them, knowing that JLCPCB will place them for you. It's fair to say that JLCPCB engineers will place the holes sensibly and won't plonk one through a trace or in the middle of a component footprint; however, you might want to manually add them into your design so that you decide where they are finally placed.

The rules are that a minimum of two, preferably three, holes should be placed in the PCB design, and they should be placed at opposite corners – as far apart as they can practically be. The holes should be 1.152 mm diameter circular non-plated holes with a 0.148 mm solder mask expansion. The simplest thing we found to do for projects where we want to add the tooling holes is to create a custom component in our KiCad libraries that we can drag into and place in our design.

To make a tooling hole component footprint in the Footprint Editor, you need to create a new footprint and then add a single pad. Selecting the pad, click the E key to edit and enter the Pad Properties dialog. On the first 'General' tab, set the pad as 'NPTH, Mechanical' in the pad type – NPTH stands for 'non-plated through-hole'. Staying on the General tab, make sure the pad shape is set to circular and the diameter is 1.152mm. Finally, click onto the second tab in the Pad Properties dialog called 'Clearance Overrides and Settings'. On this tab, set the solder mask expansion to 0.148mm. Save this as a footprint and you can place them when needed into JLCPCB-oriented designs.

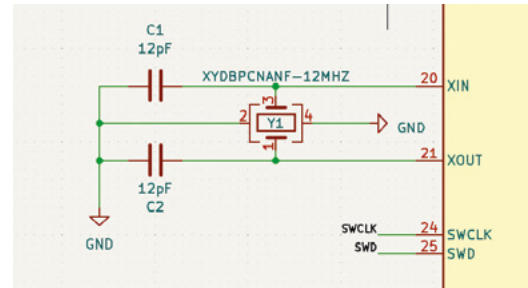
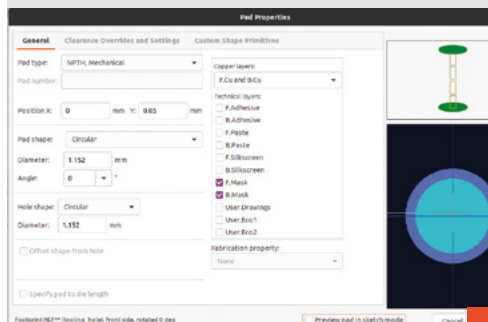


Figure 7 Due to JLCPCB not stocking the crystal that the RP2040 documentation recommends, we needed to rethink this part of the circuit

of the board. With the schematic largely complete, we moved over to the PCB Editor to begin the layout and routing.

One interesting aspect of the board design, that we haven't looked at yet, is that it has numerous different voltages which each have their own copper flood zones. Making these is similar to how you make any other copper flood, as we have done in previous boards, but you need to set a priority value so that the different floods know how to flood separately. So on the top layer of our board there is a general 3V3 flood, a flood connected to the VBUS, which is the 5V input from the USB to the voltage regulator, and there is a small 1V1 zone inside the footprint of the RP2040. Notice in **Figure 9** that we have assigned the 1V1 flooded area priority 2, the VBUS area priority 1, and the general 3V3 priority 0. This essentially shows that they are separate areas.

Components-wise, we decided that for the resistors and the majority of the decoupling capacitors, we would go for 0402 packages. Again, we wouldn't make this choice if we were planning to assemble this board by hand, but with the assembly engineers and robots doing this fine work, we might as well use the tiny packages. It's less common for

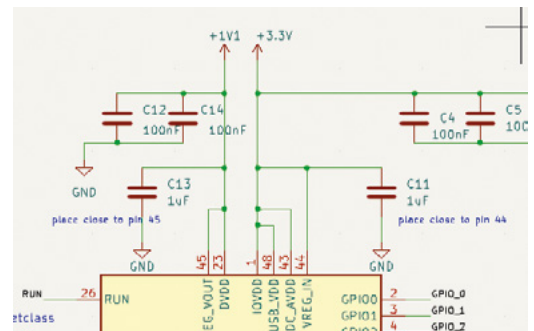


Figure 8 Laying out the decoupling capacitors in the Schematic Editor is largely straightforward

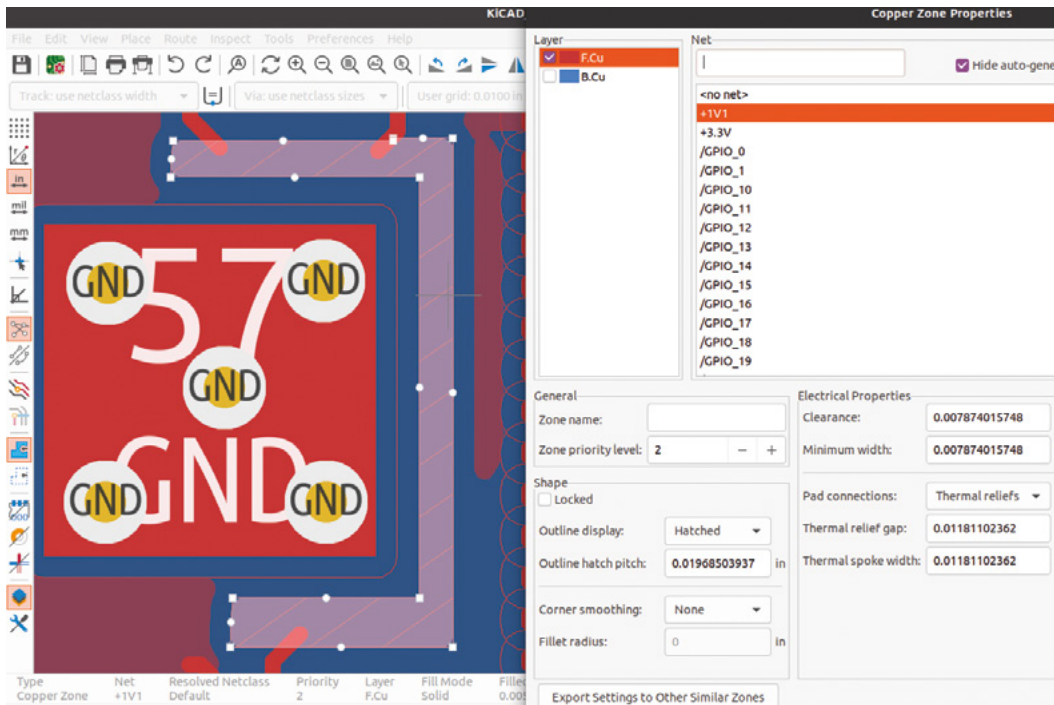
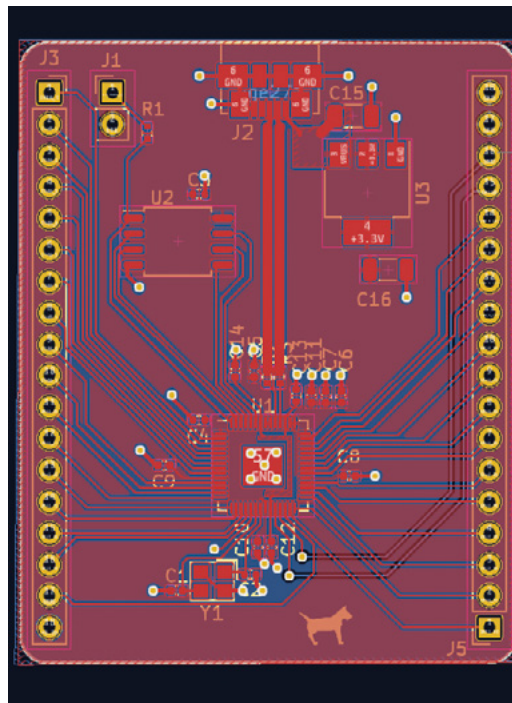


Figure 9 Setting up different priorities to allow different zones to coexist

With the assembly engineers and robots doing this fine work, we might as well use the tiny packages

the very tiny packages of capacitor to be of accurate value as they increase in capacitance. So, although JLCPCB does offer components that claim 10uF in 0402 packages, we went with a more common larger 1206 variant.

We've largely covered everything specific to this project in this article. If you've worked through the previous parts of this series, you'll be familiar with all the other aspects of the process. It's definitely worth working through some smaller projects (like the small H-Bridge design in the last part of the series – hsmag.cc/issue69) to get used to the JLCPCB-specific processes. We'd also reiterate that reading Hardware design with RP2040 a couple of times before tinkering with an RP2040 board is time well spent. Finally, be warned, having fully assembled and hopefully functional boards delivered to your door is highly addictive! The KiCad files for this project can be found at hsmag.cc/issue70.



Above Our completed layout in the PCB Editor

KiCad: schematic organisation and hierarchical sheets

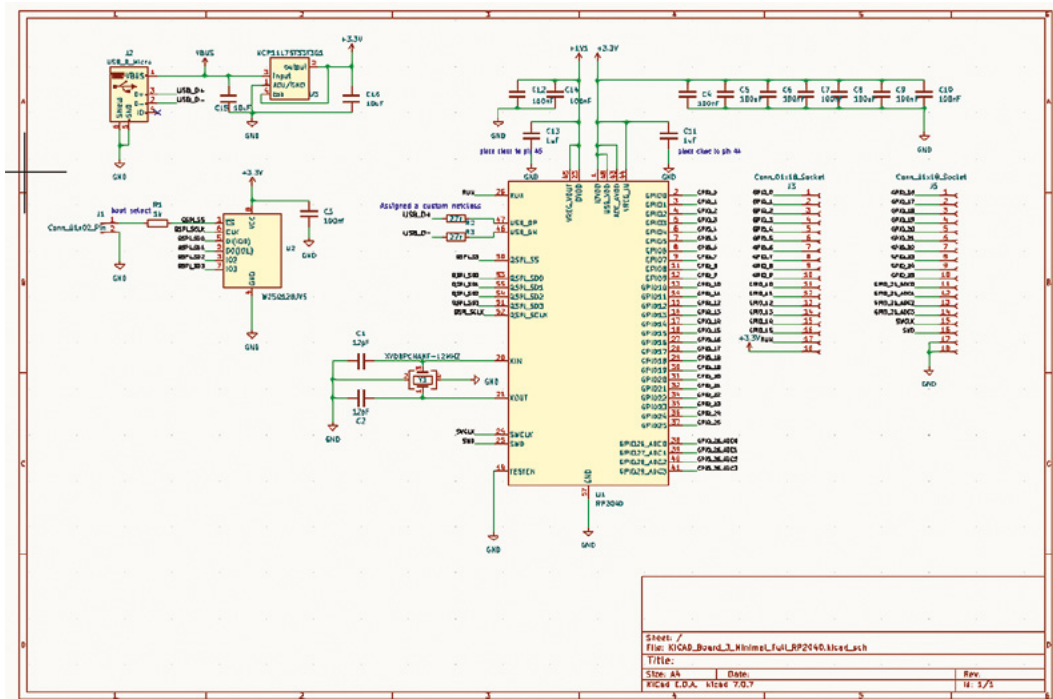
How to get your sheets in order before starting a larger project



Jo Hinchliffe

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Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!



In the last issue, we laid out our largest project so far – an RP2040 minimal layout example and, in the next issue, we want to add to this design. However, the schematic is already quite full and, if we're not careful, the whole thing could become unmanageable. Let's take a look at how we can keep things clean, tidy, and easy to work with.

If you view last issue's project (hsmag.cc/issue70), and jump into the Schematic Editor, it looks quite cramped (Figure 1). One of the first things we can do is to simply increase the schematic size. Navigate to File > Page Settings and, in that dialog, you can

swap the page size, currently at A4. Changing this to A3 will give us plenty more room. Whilst we are in this Page Settings dialog, we can add some detail to the Title Block fields. This is the lower right-hand corner collection of text boxes that list the title, revision issue date, and more. Whilst we don't always practise what we preach, clear titles and revision labels and dates are really useful if you plan to publish your project or use the schematic as part of documentation (Figure 2).

With our schematic size increased and neatly titled, we can look at other ways of organising our schematic content. One approach that we have seen,

Figure 1 Our schematic from the RP2040 minimal example project

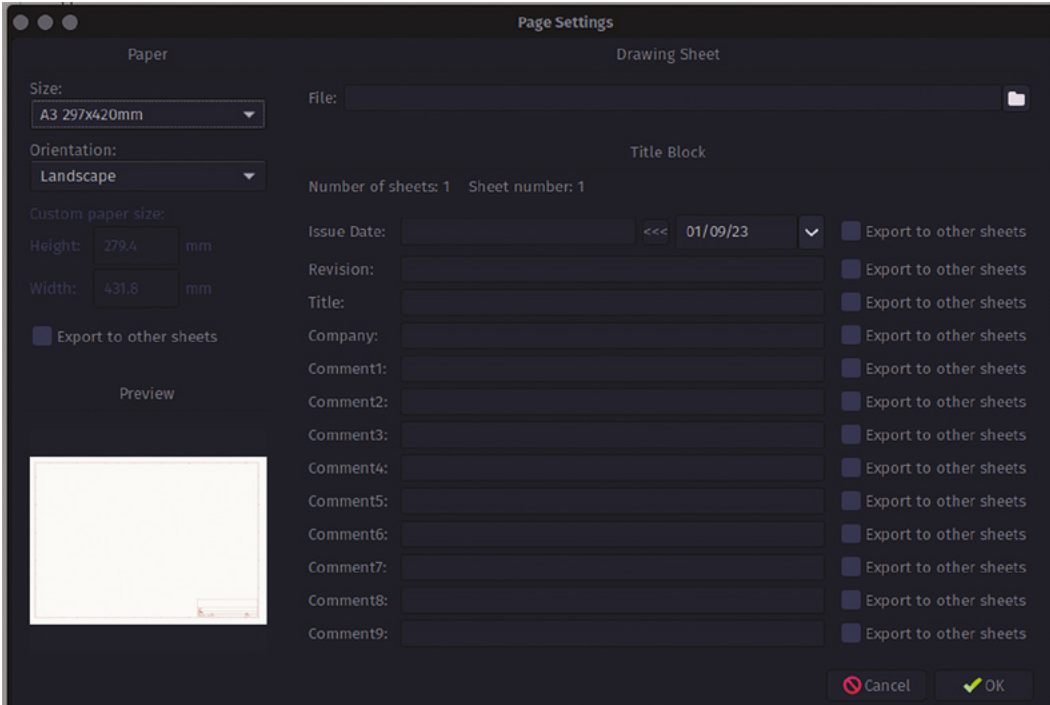


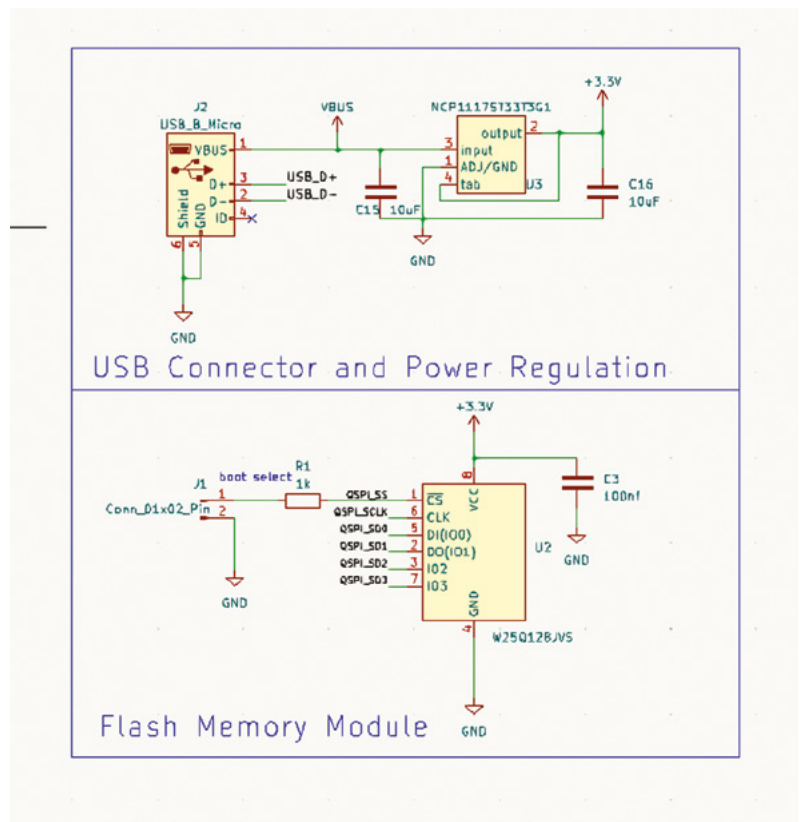
Figure 2 ♦ Increasing the schematic page size and adding clear labelling is a good start to keeping organised

Figure 3 ♦ Adding boxes and text labels can help organise sections of complex schematics

that some people like, is to create graphic boxes around different subsections of a project's circuits. For this we can use the 'Add a rectangle' tool, again in the lower right-hand side of the screen. You might need to use the selection tool to select and move parts of the schematic into a position where you can completely draw a rectangle around them.

Clear titles and revision labels and dates are really useful if you plan to publish your project

To draw a rectangle using the 'Add a rectangle' tool, you do a single left-click in the start position (a corner of your rectangle) and then move the pointer to the opposite corner position you require. Once the rectangle is drawn, clicking on it with the selection tool, you can either grab the anchor points to change its dimensions, or press **M** on the keyboard to move the rectangle as you would any other object in the Schematic Editor. With a section of your schematic now encapsulated in a rectangle, we can simply use the 'Add text' tool to create and then to place →



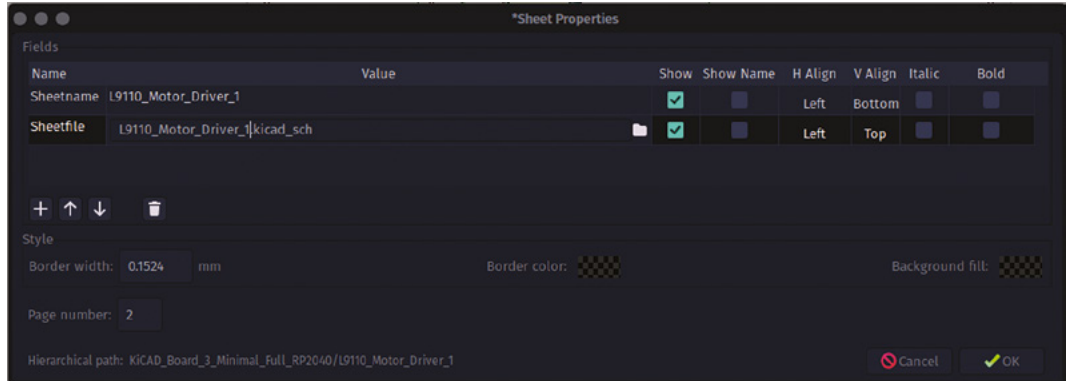


Figure 4 Adding a name for a new hierarchical sheet and a file name for the new hierarchical sheet schematic file

labels into our boxes (Figure 3). We did this in the original RP2040 minimal example project, in the last section of this series, when we added notes to place capacitors close to certain points etc. What we didn't make note of is that, new to KiCad 7, we can use any font for our text, allowing us to move away from the default KiCad fonts and bring a little of our own house style to our schematics.

ROVING ROBOT

We're planning to use last month's RP2040 example project as a base for a larger project. We're aiming to make a simple robot rover design with the main chassis of the robot being a PCB with all the essential components mounted on that single board. We want to keep our original RP2040 board project, so we

need to make a copy of our project to develop into our robot rover platform. This is one way we can almost use KiCad projects in a modular fashion.

To copy a project in the original project go to File > Save As, then select or create a new folder to save the project to. Insert a new name for the new project copy in the Name dialog box, then click Save. Although not completely necessary, it's not a bad idea to then open the new project folder in a file browser and delete any unneeded files for the new project. For example, if you have a Gerber file folder, these probably won't be relevant to the new project. Any backup files can also be removed as you would probably return to the original source project, if required, rather than use a backup from this new branched project.

The basic premise for our robot is that it is going to have four wheels, all of which are driven by N20-style motors. This gives us options down the line in that it can run with normal style wheels and tyres, but we are also interested in mecanum wheels, which need to be driven individually to create the interesting sideways and diagonal motions mecanum wheels are known for. This means that a primary part of the design is to add four motor driver circuits to our RP2040 board, one for each wheel. Again, considering

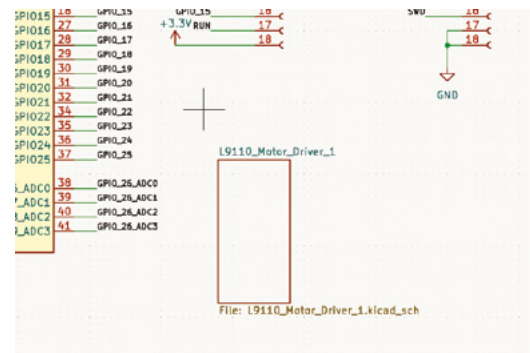
QUICK TIP

If you can't select a section of schematic completely using the selection box tool, select as much as you can, then press and hold the CTRL key whilst clicking any missed components or wires.

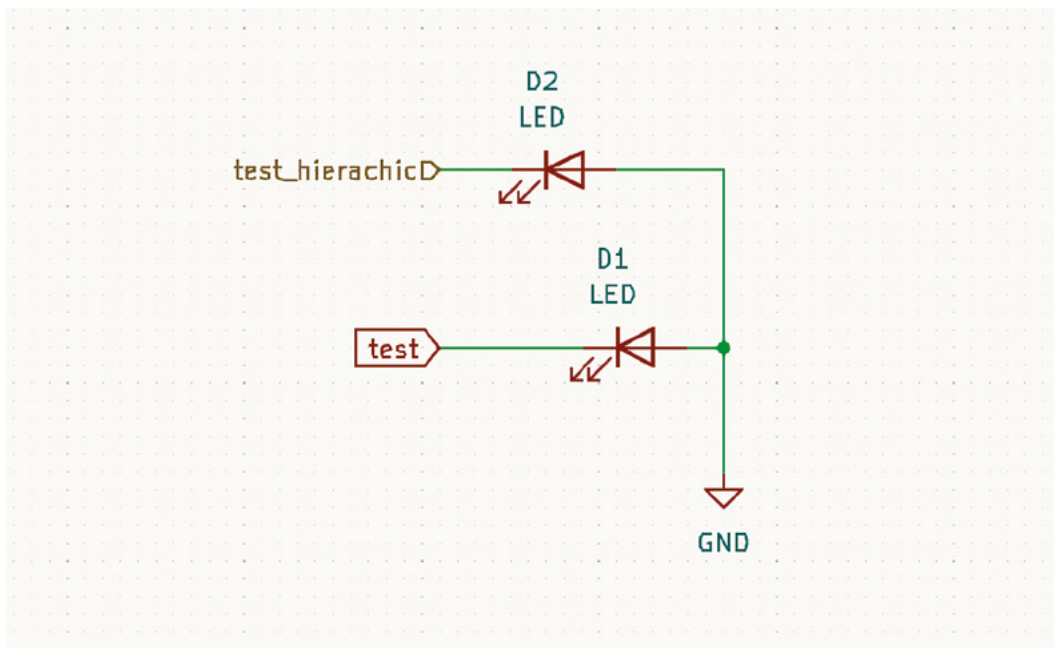
A SPLASH OF COLOUR

You can add images to schematics and, whilst you can place images anywhere on any page, a common use case for this is to add a company logo to the Title Block area. The Schematic Editor supports a wide range of image formats, including PNG, JPG, TIFF, BMP, and many more. Usefully, on import you can rescale the imported image. This is useful as you can import a larger, higher DPI image and then scale it down to fit the box. In the image, the dog logo has been created in Inkscape and exported as a PNG file with a transparent canvas. The image as exported is sized at around 700x500 pixels and has been exported at 300 dpi. This means that the image is good enough quality when scaled down to fit into the title block, but is still a comparably small file size at around 16kB.

To add your image to the schematic, simply click the 'Add a bitmap' tool icon on the lower right-hand side of the screen, and navigate to your chosen image file. Once the object is imported, you can move it and scale it whilst maintaining its aspect ratio by dragging the corners of the image bounding box.



Right Our empty hierarchical sheet placed in the original schematic



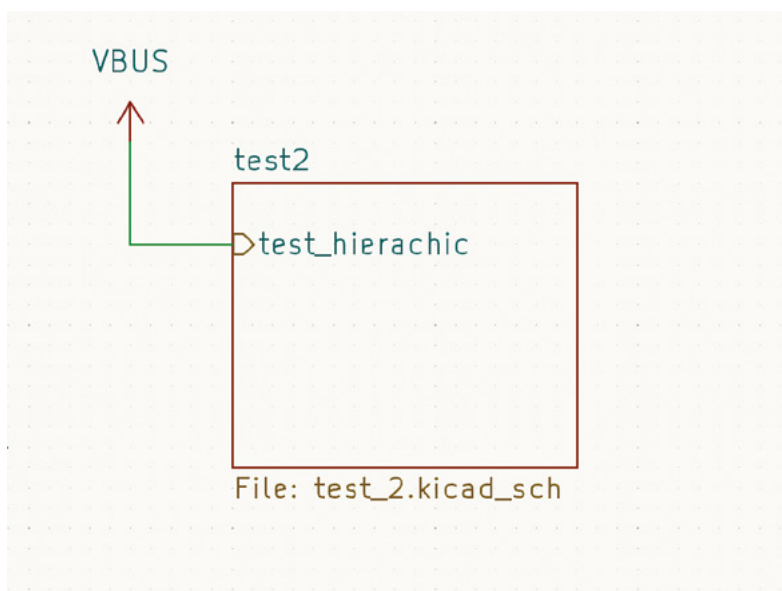
schematic clarity, we could just place the four motor driver circuits into our A3 schematic and wire them using either labels or direct wiring. However, another way we can add content to the schematic is by using hierarchical sheets. A hierarchical sheet can be thought of as a sub-sheet that exists in the schematic below the main page, into which we can insert designs which can be connected to the main top-layer schematic page.

To create a hierarchical sheet, you can use the 'Add a hierarchical sheet' tool icon found in the lower right-hand area of the Schematic Editor, or you can press the **S** key on your keyboard. Either way, you then click and drag to create a rectangle in the schematic. When you left-click to finish the rectangle, a dialog window will launch called 'Sheet properties'. Into this you can put a sheet name, which will be displayed in the rectangle on the main schematic page. We'll call our first sheet 'L9110_Motor_Driver_1'. Under this is an input box for a sheet file name. It will currently be populated with 'untitled.kicad_sch'. This is the name of a separate file that will be created for this hierarchical sheet. Again, we changed this to something appropriate, such as L9110_Motor_Driver_1.kicad_sch. Notice that there are checkboxes labelled 'show' and, by default, they will be ticked (**Figure 4**). This means that, in the main schematic sheet, our hierarchical sheet rectangle will appear with both of these pieces of information listed. It is advisable to show one, or →

// Another way we can add content to the schematic is by using hierarchical sheets **//**

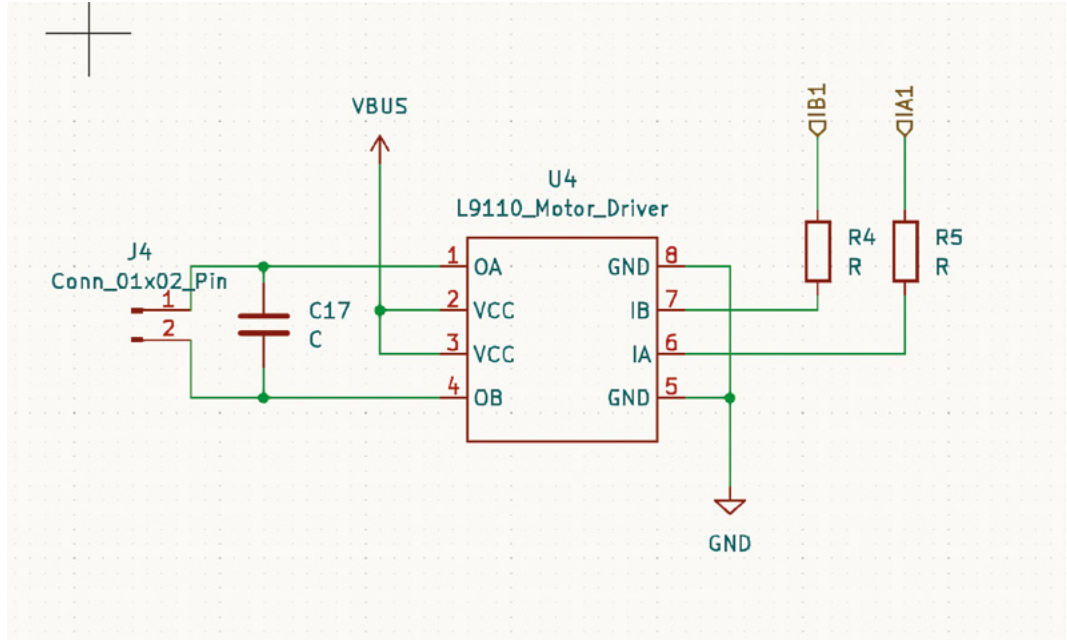
Figure 5 Inside a hierarchical sheet with a design using a hierarchical label and a global label

Figure 6 The test hierarchical sheet object viewed from the main schematic. The hierarchical pin has been connected to VBUS



QUICK TIP

As a hierarchical sheet is a separate schematic file, you can use 'File-page settings' to set the title, page size, and other details, as we did earlier.



both, of these pieces of information or else you have to navigate into the hierarchical sheet to see what it contains and it can be confusing if you have multiple hierarchical sheets. On a similar theme, notice that you can also play with the appearance of the hierarchical sheet rectangle, increasing or decreasing line width, background, and border colours. Whilst this might seem frivolous, if you end up working in a design with a lot of hierarchical sheets, being able to differentiate them by colour scheme can be an aid to productive working.

To enter your new hierarchical sheet from the main schematic page, you can either right-click on the rectangle and select 'Enter sheet', or you can double-

click on the hierarchical sheet rectangle. You should be met with a brand new empty schematic.

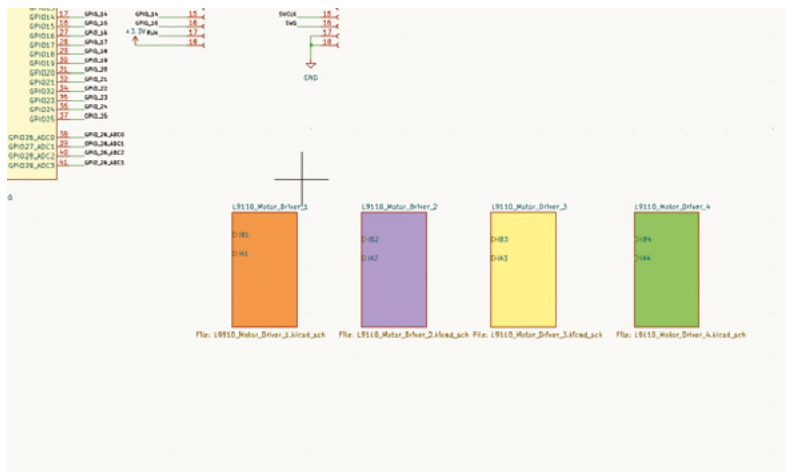
You can now begin to place components and create your circuit in the hierarchical sheet. The first thing to note is that anything connected to a global label or net will automatically be connected to those points globally. So if, for example, you add a component and connect it to a ground 'GND' symbol and to 'VCC', they will automatically be connected to those points in the top-layer schematic and will appear as GND and VCC connected when you import those components and connectivity to the PCB Editor. If you did place and connect such a component in a hierarchical sheet, when you return to the main sheet you won't see any connections coming out of the hierarchical sheet rectangle. For general ground and power connections this might be OK, but it may get confusing if you use this approach for all your connectivity. A common way of making connections into and out of hierarchical sheets is to use hierarchical labels.

Above

The L9110 circuit for each motor. Note the hierarchical labels used on the IB and IA pins

Below

Each of our L9110 driver circuits sits in its own hierarchical sheet, and the individual motor driver pins are broken out, ready to be wired into the RP2040



HIERARCHICAL LABELS

To place a hierarchical label, you can either click the 'Add a hierarchical label' tool icon or press **H** on your keyboard. A Hierarchical Label Properties dialog will appear. Insert a name into the Label field. You will now have a label you can place, move, and rotate and connect into your design. In **Figure 5**, we have made the hierarchical label 'test_hierarchic' and connected it to the cathode end of an LED component symbol. We've also placed a global label test to another

LED component. Moving out of the hierarchical sheet is simple: you can either right-click and select 'Leave sheet' or you can hold **ALT** and then tap the **BACKSPACE** key. Even after creating a hierarchical label inside a hierarchical sheet, you won't see that connection until you right-click over the hierarchical sheet rectangle and click 'Import Sheet Pin' from the drop-down menu. You should now see any hierarchical pins appear aligned with the edge of the rectangle. You can move these pins to any position around the rectangle, and you can connect and wire to these labels as you would any other symbol. In **Figure 6** you can see the 'test_hierarchic' label in the sheet rectangle, and we have wired it to VBUS. Note that you can't see the global label 'test', but that point inside the hierarchical sheet will be connected to any other connections with that global label anywhere in the project schematic. Note again that inside this hierarchical sheet, there is a connection to a GND symbol and, as such, that point is connected to the project's global GND label.

For our robot rover design, we are going to keep it simple and affordable and will use the L9110 motor driver IC as it's adequate for the N20 motors,



One of the great benefits of using hierarchical sheets is that we can copy them



affordable, and there is a large amount of stock available on JLCPCB. The circuit around the L9110 is pretty straightforward, with a couple of pull-up resistors and a decoupling capacitor across the motor outputs. Creating a hierarchical sheet for the motor driver circuit, we've used hierarchical labels to create the two signal inputs. We could have opted to have the motor outputs as hierarchical labels, but it was cleaner to add the motor output connector symbols inside the hierarchical sheet, avoiding more clutter on the main schematic.

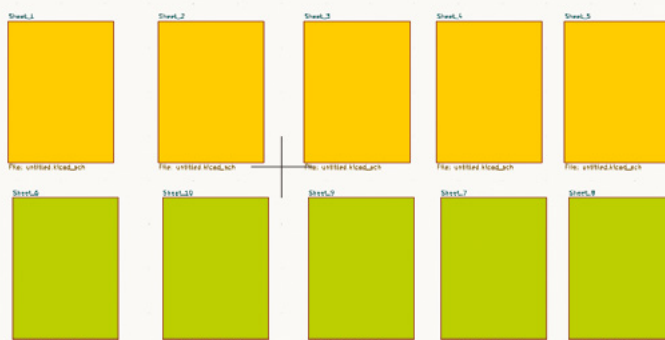
One of the great benefits of using hierarchical sheets is that we can copy them, or copy their contents, quickly to create multiples of similar modules, either within the same project or into other projects. In our robot rover project, we have simply added three more hierarchical sheets and named them sequentially as Motor_Channel_1, Motor_Channel_2, Motor_Channel_3, and Motor_Channel_4.

We then copied and pasted the contents of Motor_Channel_1 into each different hierarchical sheet. Whilst not wholly necessary, it seemed good practice to avoid confusion. So, each time we copied the L9110 circuit, we relabelled the hierarchical pins so that each motor channel was unique. We can then use the 'Import Sheet Pin' function that we used earlier on each of the motor channel hierarchical sheets, and we are ready to wire the pins to our chosen GPIO pins on the RP2040 – either directly or using labels to again keep the main schematic clean and tidy.

Hopefully you have found this guide useful. It's great to think about your practice with KiCad and how you can be organised in a way that suits you. A final good idea is to look through some open-source hardware projects that have used KiCad. You'll certainly find lots of different approaches to organisation and project management. □

LARGE PROJECTS

One thing about KiCad is that you can use many different approaches, depending on your needs or your particular way of thinking. One such approach we've seen out there in KiCad-land is to use a flat hierarchy for your schematic layout. This essentially turns the first schematic sheet into a kind of holding sheet where all the hierarchical sheets are held. You can then, in each sheet, use general and global labels so you don't need to draw any connectivity on the main topmost schematic. Although this might momentarily confuse anyone else opening your project, it's actually a brilliant way to organise a particularly large project into specific sections. Of course, as each hierarchical sheet is an individual schematic file, you can simply work on each file individually as needed in development. One tip that we noticed for this approach, or for working with multiple hierarchical sheets, is that if you copy and paste a hierarchical sheet rectangle in the main schematic, it will automatically add and increment a number to the name of the sheet. So 'sheet' would become 'sheet1', then 'sheet2'. We even noticed that if you created a first sheet called 'Something_1' and copied and pasted it, the clone would increment to 'Something_2'.



Sheet_7			
File: test_hierarchy_kicad_sch			
Title:			
Size: A4	Date:	Rev:	
KiCad EDA, sheet 7/10		id: 1/11	

KiCad, mechanical accuracy, and silkscreen features

In this part of the ongoing KiCad series, let's look at some techniques to increase accuracy when aiming to create a PCB to be used as a mechanical structure



Jo Hinchliffe

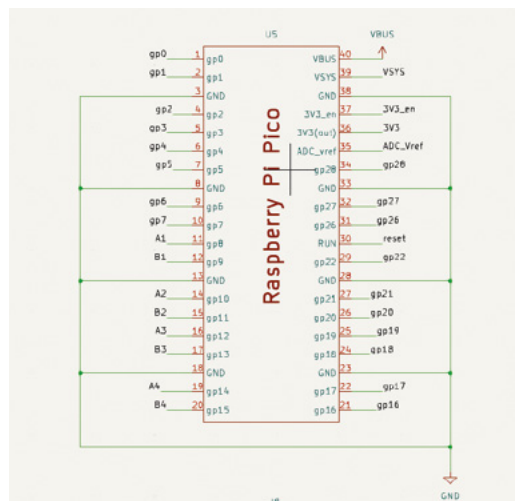
Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

It's increasingly common for projects to incorporate PCBs as a mechanical part of the mechanism. In our last section, we looked at hierarchical sheets and laid out a motor driving circuit that we could copy and paste to add motor drivers to a project. In this part, we are going to create a simple robot rover that we're calling 'stoRPer'. StoRPer is a tongue-in-cheek reference to a favourite childhood toy from the 1980s: the 'Stomper'. The Stomper, by toy company Schaper, was the first ever four-wheel drive electric toy car. Despite no form of remote control, they were great fun to try and build obstacle courses for, or to test on steep gradients. We wanted the reasonable torque and the four-wheel drive aspects

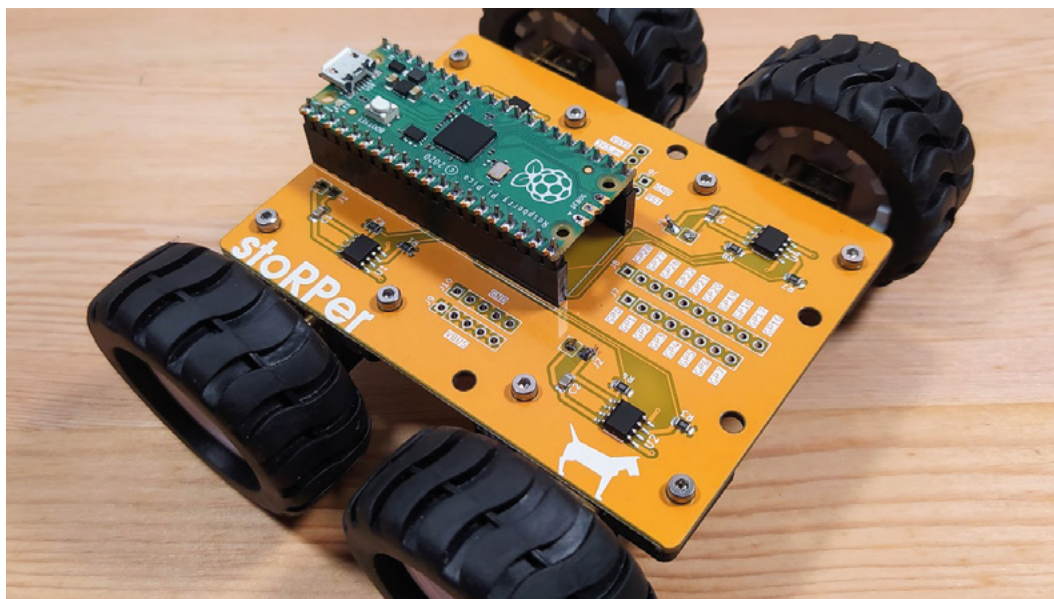
of the Stomper but with the addition of a Raspberry Pi Pico to make it a more interesting and controllable platform – so, 'stoRPer' it is. It's designed with all-wheel drive (AWD) so that Mecanum drive systems can be built and experimented with.

We are going to use Pico as a module on this build and focus on some aspects of particular importance when we are using a PCB as a mechanical part as well as for electronic purposes. The idea for the project is that the PCB will form the chassis of the stoRPer, with the motors being clamped to the PCB chassis using some 3D-printed parts. Therefore, we need to be capable of placing components and general PCB geometry accurately in order for everything to fit together. We'll also look at how we can check our PCB and 3D-printed models will fit together before we print or send the PCB for fabrication.

One of the first jobs is to create a Pico symbol component in the Symbol Editor. We covered creating symbols in the earlier sections of this series, so we won't recap that process too much. We decided not to include the Pico's three debug pins on either the schematic symbol or the PCB footprint. This was partly because, across the different Pico models, they are physically in different positions on the board and also, as we intend to have a Pico mounted onto this project, we can still interact/wire to the debug pins if needed. As such, we laid out a simple 40-pin component in the Symbol Editor and brought it into our Schematic Editor. After quickly connecting all the ground points, we set about connecting four hierarchical sheets, each with an L9110S motor driver



Right A custom Pico symbol has been created, with the majority of the pins broken out

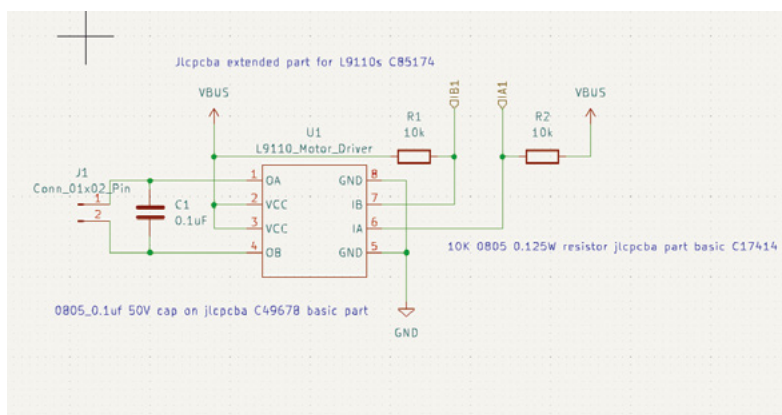


Left ♦ The stoRPer robot prototype using the PCB as its main chassis component

Figure 1 ♦ The layout of the L9110S motor driver circuit cloned into four hierarchical sheets

IC-based circuit inside. We covered working with hierarchical sheets in the last section of this series, but you can see the circuit layout in **Figure 1**. Each of the four motor drivers has its own sheet and has two pins broken out. We've connected these sets of pins to the Pico symbol using labels A1, B1, A2, B2, etc. The rest of the Pico's pins are broken out and connected to some multi-pin connectors, ready to be broken out on the PCB.

For the stoRPer project, we've decided to mount the Pico using the through-hole header pads on the Pico rather than the castellated edge connectors.



The rest of the Pico's pins are broken out and connected to some multi-pin connectors



This means that we won't be mounting the Pico flush to the project, but it does mean that the Pico footprint is thinner. We can also choose to use header sockets or not to allow the Pico to be permanently or temporarily mounted to the PCB.

The header pin pads on the Pico lie in a 2.54 mm pitch grid, with the 20 pins on either side being separated by 7*2.54 mm. This makes them easy to lay out – simply add pads on a 2.54 mm grid in the Footprint Editor (**Figure 2**). We also want to be able to place a rectangle on the silkscreen layer that accurately shows the position of the board.

Consulting the Pico documentation, we can find a technical drawing and see that the outer edge of the Pico is 51 mm x 21 mm. We also need to consider the position of this rectangle relative to the pads that we have just created. We can see in the technical drawing, for example, that relative to the centre of the upper left-hand pin (pin 1), the upper-left corner of the Pico is 1.37 mm higher in the Y axis and 1.61 mm over to the left in the X axis. To use this information, we can go back into the Footprint Editor and place our pointer on the grid point in the centre of the pad we placed for pin 1. If we then press the **SPACE** bar, we will set the local origin of the page to be 0,0 at this point. We can check this by looking at the bottom of the screen as we move our pointer, the distance should increase relative to this point. We can then set a user grid to 1 mm spacing and use this grid to draw our 51 mm x 21 mm rectangle. →

LOTS OF HOLES

When creating footprints with lots of through-hole pads, KiCad makes it pretty simple: you click to add a pad and then the tool indexes to the next numerical pad for you to place. If you've placed and positioned a lot of pads though, it can be annoying to realise that you need to change an aspect of the pad's properties for all of them. KiCad has you covered, though. As an example, when we made the footprint for a Raspberry Pi Pico and decided that after laying out 40 standard through-hole pads, we wanted to increase the internal hole diameter and the overall outer diameter to increase the size. The Footprint Editor conveniently recognises that this is a common situation and, as such, you can simply change one pad to your desired pad properties and then, with your adjusted single pad highlighted, you can right-click and select 'Push Pad Properties to Other Pads...' to make all compatible pads change to the new characteristics.

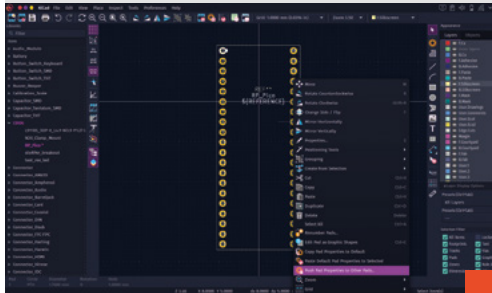
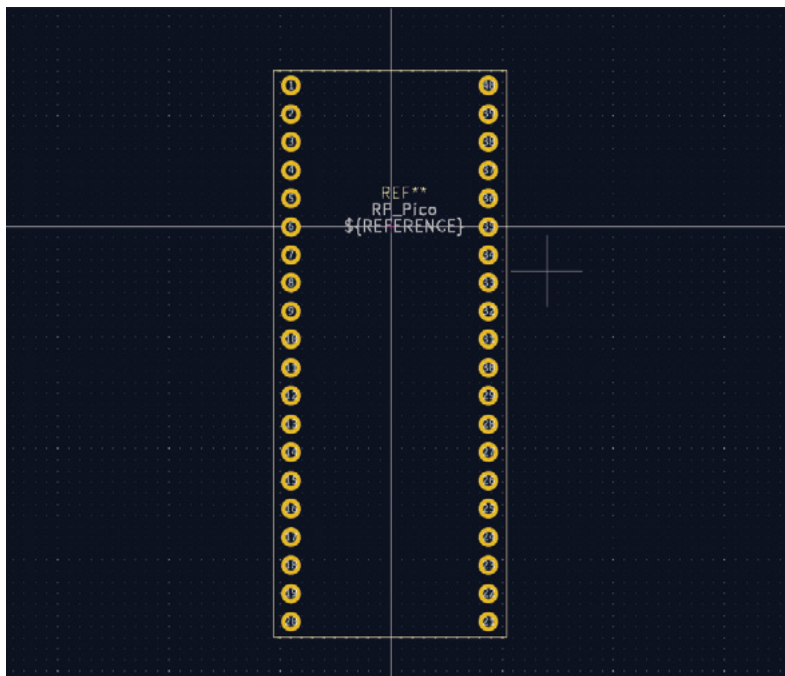


Figure 2 ♦ Creating the simple yet accurate Pico footprint



If we then select the rectangle, we can right-click and scroll in the drop-down menu to Positioning Tools > Position Relative To.... Selecting this, we will see a dialog box – in the dialog box, click to select 'Use Local Origin' and then adjust the 'Offset X' and 'Offset Y' by the amounts we derived from the technical drawing (Figure 3). Note that, by default, the origin corner of the rectangle is the top left-hand corner. Using this method, you should be able to place items with incredible accuracy.

One thing of note is that despite our stoRPer robot design being relatively simple mechanically – a rectangular PCB – we do want to be able to place footprints accurately within the edge cut area. When designing this and other footprints, it's worth considering where your origin point is in the Footprint Editor and placing the device in a



We want to 3D-print some brackets to clamp the motors into position



known position relating to it. We opted to place the Pico footprint so that the upper left-hand corner of the silkscreen box depicting the edge of the Pico was the origin point on a 1 mm grid spacing. This meant that later, when we placed a rectangle in the PCB Editor that represented the edge of the PCB, we could place it in a position such that the Pico is dead centre, with the larger box also placed on a 1 mm grid coordinate. After playing with a few test boxes in KiCad, we decided our rectangular chassis dimensions would be 64 mm × 86 mm. We used Inkscape to draw our rectangle as we could then easily add a 2 mm radius to each corner

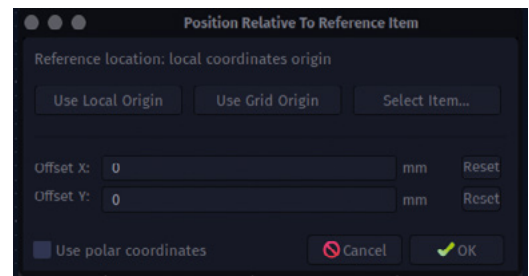
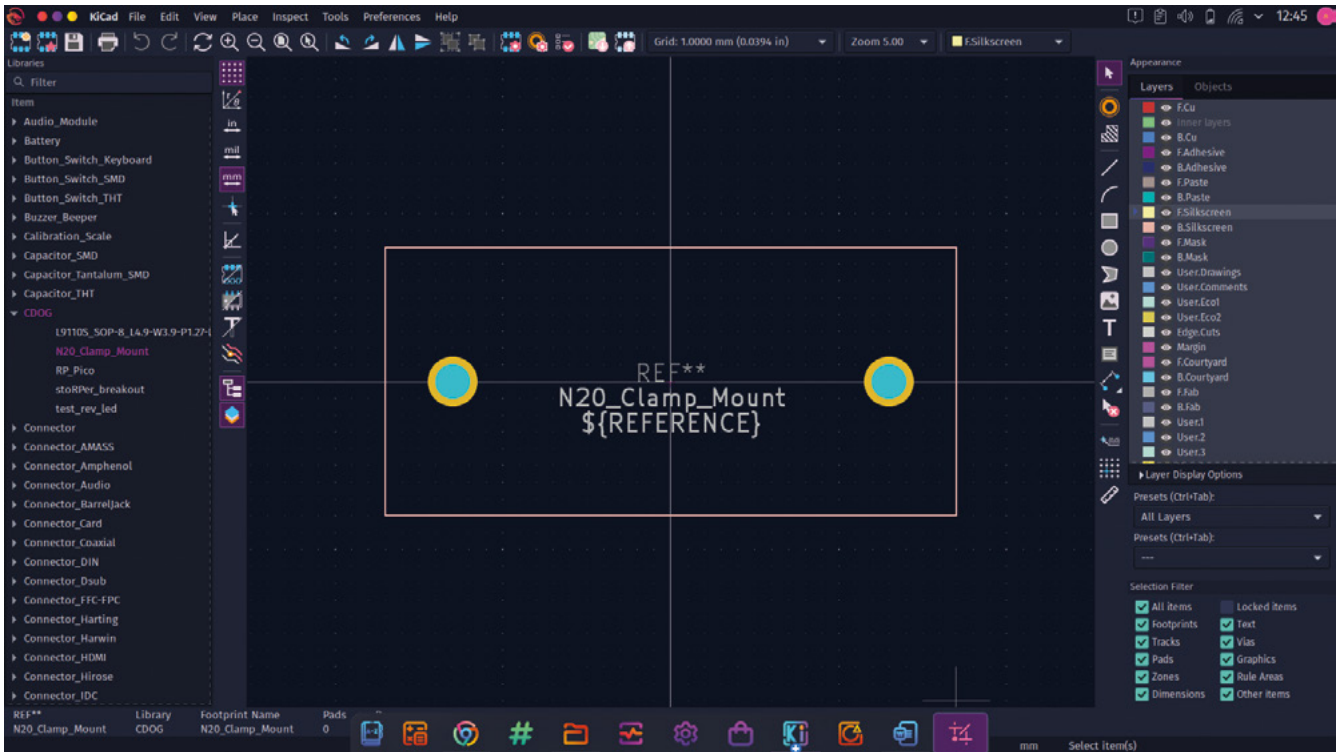


Figure 3 ♦ Using the 'Position Relative To...' positioning tool to accurately place objects in the Footprint Editor



of the rectangle. We've again covered importing graphics in an earlier section of this series, but we easily imported the rectangle we drew as an SVG in Inkscape into our edge cuts layer using the File > Import > Graphics function.

With the Pico placed and the PCB edge defined, we need to consider the physical mounts for the motors. We want to use the excellent and available N20-style geared motors, mounting one for each of the four motor driver circuits. We want to 3D-print some brackets to clamp the motors into position, so we need to leave some space for the 3D print material around the motor, and we need to take this into account when creating a footprint for the motor mount. After some consideration, we created a custom footprint which consisted of two non-plated through-hole (NPTH) mechanical pads placed in-line. These were placed at a distance between centres of 26mm, placed on a 1mm grid spacing. To place an NPTH mechanical hole, you place a regular pad and then press **E** to change the pad type in the Pad Properties dialog. We set each NPTH hole to 2.1mm internal diameter to create clearance for a small M2 bolt. To finish the footprint for the N20 motor mount clamps, we added a silkscreen rectangle set to the dimensions of the base of our 3D-printable mount design (**Figure 4**). Note that this is the first time in the series that we have placed extra components which aren't connected to anything or included in the schematic in the PCB Editor. To do this, we click

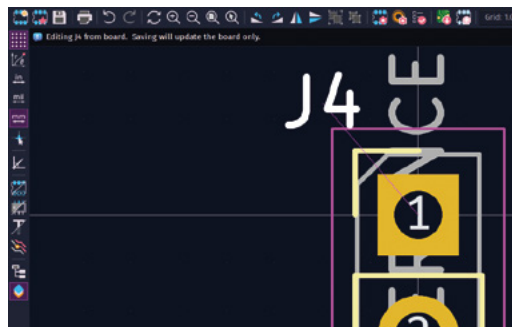


Figure 4 The mechanical footprint that will mount the N20 motor and clamp

Figure 5 Editing a footprint with the component selected and opened in the Footprint Editor from the PCB Editor gives the option of only editing that individual instance of the footprint

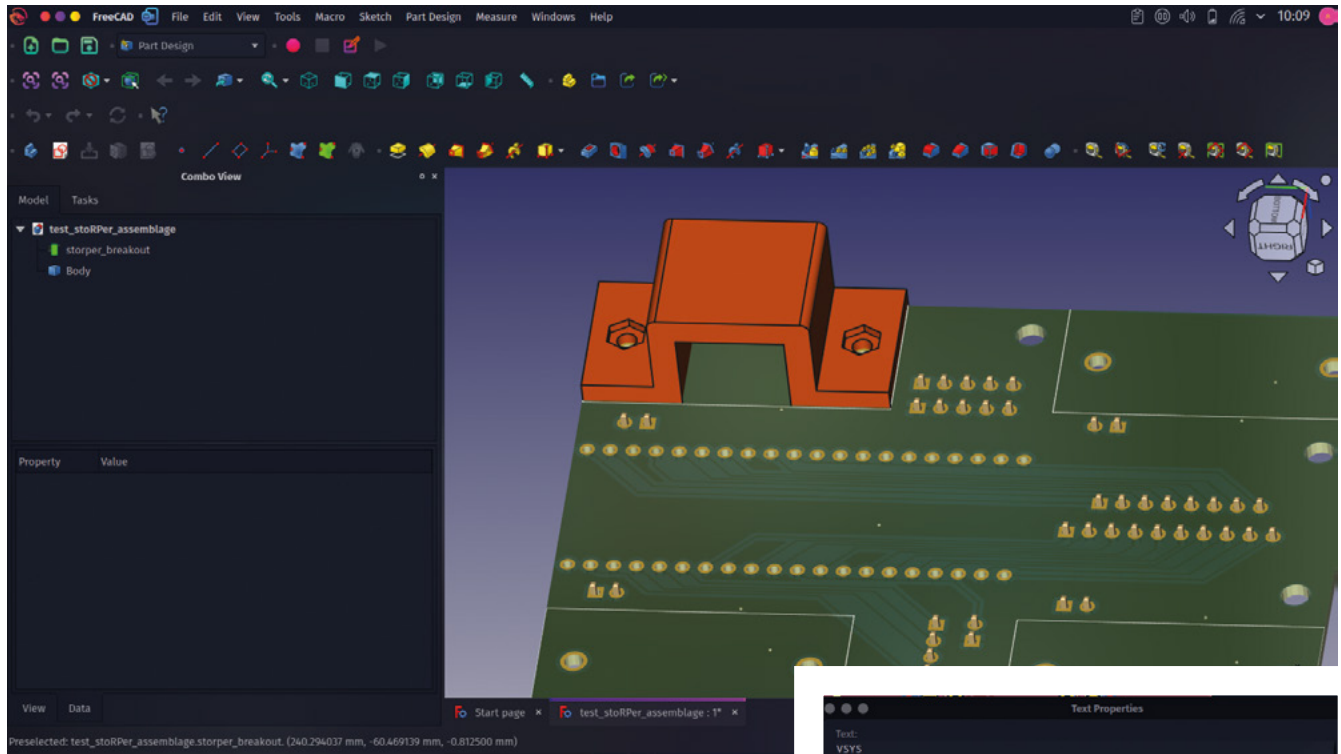
the 'Add a footprint' tool icon and select a footprint in a similar manner to how we would place a symbol in a schematic.

Adding and removing text-based elements to a silkscreen layer is reasonably straightforward in KiCad 7. On more technical PCBs, as opposed to artistic PCBs, we often lay out our PCB design with little regard for the silkscreen and then sort the silkscreen layer out later in the development. Often, one of the first tasks is to remove unwanted elements on the silkscreen that have been automatically placed by the use of default library footprints. We can select the correct silkscreen layer, often the front silkscreen 'F.Silkscreen', and for items such as footprint reference annotation, we can simply left-click to select them, then move them or press the **DELETE** key to remove the item. It's common for this reference to not be placed →

QUICK TIP

As the stoRPer design evolved, we used simple rectangular boxes drawn in KiCad on either the F.Silkscreen or the User.Comments layer as guides and visual aids.

TUTORIAL



Above The combination of KiCAD and FreeCAD make a great open source toolchain

FREE BOOK

In the free-to-download book *FreeCAD for Makers* from Raspberry Pi Press, we looked extensively at the use of the KiCad StepUp workbench which enables and simplifies importing KiCad projects as 3D objects into FreeCAD as well as the creation of 3D components for inclusion into KiCad's 3D PCB viewer. It's an incredibly powerful suite of tools and is definitely worth exploring. For this project, however, we just wanted to check if the motor clamp we had created in FreeCAD would fit our PCB chassis. You can use File > Export and select the 'STEP...' option to export a STEP file which can be imported into FreeCAD; however, this will lack the details of the copper layers and silkscreen which you might need to see to check if mechanical components cover aspects of your PCB design. One simple approach that solves this is to export a WRL file. WRL files are file types often used by assets destined for use in virtual reality, but they have the advantage in KiCad that a WRL export contains all the visual details of your PCB. We used File > Export > 'VRML...' to export a WRL file, and then we used File > Import in a new document in FreeCAD to import the file. We'd made a simple N20 clamp component which had 2 mm radius corners on two corners matching our PCB and N20 motor clamp footprint. While we could have used an Assembly workbench, such as A2plus in FreeCAD, to constrain the clamp in position, for a simple check, we can move the part into alignment to visually check how it looks.

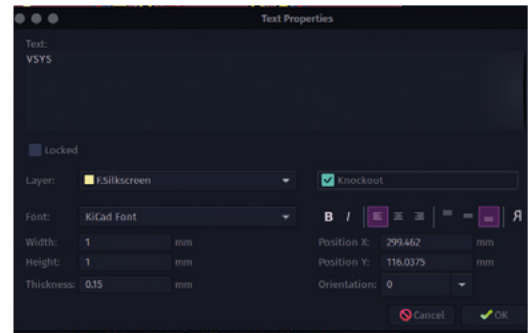


Figure 6 The Text Properties dialog where you can set text features, including the new 'Knockout' feature

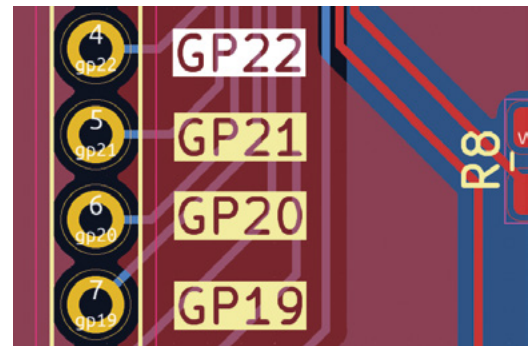


Figure 7 A new feature in KiCad 7 is the ability to add knockout text items, where the text is subtracted from a small block on the silkscreen layer

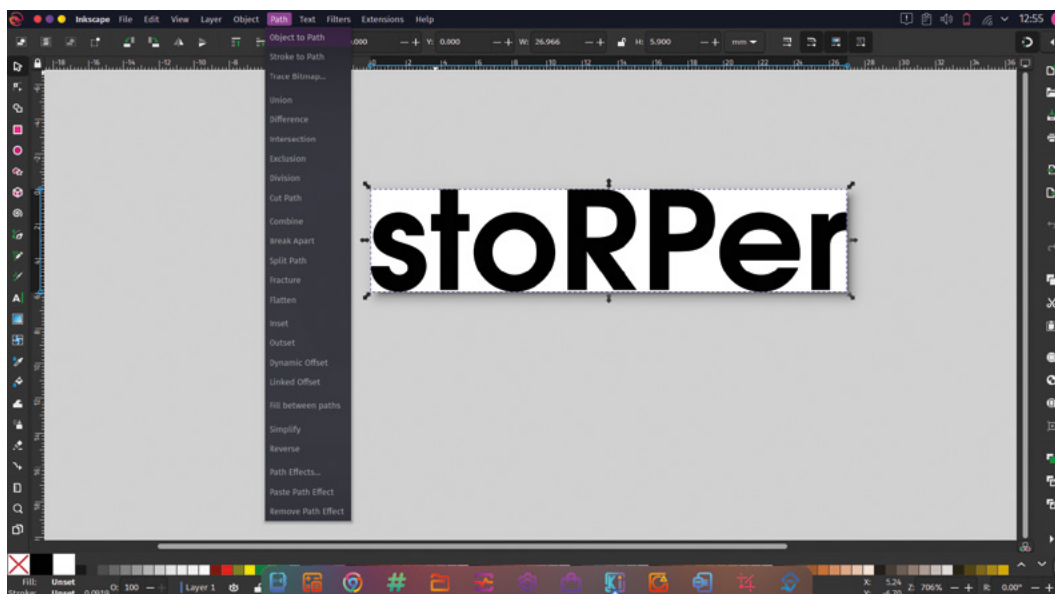



Figure 8  Converting a text object in Inkscape ready for import into KiCad

optimally and may sit under or across other parts and components. The annotated reference is formed from both the automatic annotation of the schematic during the footprint association process and the type of component it is, so R for resistor, C for capacitor, J for connector, U for IC, etc. As they replace the placeholder Ref* designator, they are independent of the main footprint design and, as such, can be removed with ease. If, when tidying the PCB design, you want to move a part of the silkscreen design of a footprint, you will need to edit that in the Footprint Editor. KiCad makes it easy to edit the footprint and apply the changes just to the individual footprint within this project rather than pushing the changes to the global footprint library. With a target footprint selected in your PCB, press **CONTROL** and **E** to open the footprint in the Footprint Editor. You should see the footprint in the editor with a message in the upper left-hand corner of the window that reads 'Editing J4 from board. Saving will update the board only', where 'J4' will be the reference of whatever footprint you have opened (**Figure 5**). You can now make any changes to the footprint that you require, including deletion or changes to the graphical silkscreen elements.

Of course, often we want to add text-based components to our board designs. Again, KiCad makes this pretty straightforward. We can simply click the 'Add a text item' tool icon and then left-click in the PCB design. The 'Text Properties' dialog

is pretty straightforward and we can insert text, make changes to the font and size as well as change the orientation of text. One interesting new addition to KiCad 7 is the 'Knockout' option (**Figure 6**). If you input some text into the Text Properties dialog and click the Knockout checkbox, then the text will be created as a solid silkscreen block with the text removed. It's a great effect, looks smart, and is very readable – a welcome new feature (**Figure 7**).

Finally on adding text, sometimes you might like to add text to the silkscreen layer as a graphic rather than directly as text. We've briefly looked at importing graphics before for either creating edge cuts geometry or for importing logo graphics from Inkscape. One notable point is that if you use the text creation tools in Inkscape and then directly try to load them as a graphic element, this will fail as KiCad SVG import doesn't recognise the text elements. This is pretty easy to rectify. As an example, we created our stoRPer text in Inkscape and then, with the text object selected, we click Path > Object to Path (**Figure 8**). As usual, we edit the document properties in Inkscape so that the document is the size of the text object – we then save the file as a standard SVG. In the PCB Editor, we then select File > Import > Graphics to import the file, ensuring to select the correct 'F.Silkscreen' as the graphic layer. The text graphic then imports correctly and can be placed in the design where required. 

KiCad, different PCB substrates

In this part of the ongoing KiCad series, let's look at some of the different materials PCBs can be fabricated from



Jo Hinchliffe

Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

So far in this KiCad series, we have designed our PCBs and had them manufactured using the common PCB material known as FR4. On FR4, our copper traces sit on top of fibreglass, and this is what most people think of when they hear the phrase 'PCB'. However, it's not the only option, and most of the PCB fabrication houses have a variety of different materials that they can make a PCB from. The circuit is typically still copper, but these traces sit on top of other materials. Let's take a look at the alternatives.

FR4 is a standard of material for the dielectric, the insulating non-conducting part of a PCB. FR4 is a type of composite fibreglass material, made up from fine glass reinforcing fibres and epoxy resin,

and is very non-conductive. The 'F' and 'R' are an abbreviation of 'fire-retardant', which is one of the many benefits and safety features of the material. Whilst fibreglass composite materials have inherent fire-resistant qualities, FR4 has bromine added which characteristically will reduce the spread of fire.

As well as being essentially fireproof, FR4 has a low thermal expansion coefficient – this means that it won't expand or contract very much in hot or cold environments. This is important because if a PCB expands or contracts a large amount, then it is likely that traces and components on the board will be damaged, crack, or disconnect. Fibreglass composites are strong and most PCB houses will offer a choice of thickness of FR4 boards, allowing you to choose a thickness and strength suitable for your application.



Right ♦ Some small polyamide flexible PCB antennas fabricated by OSH Park

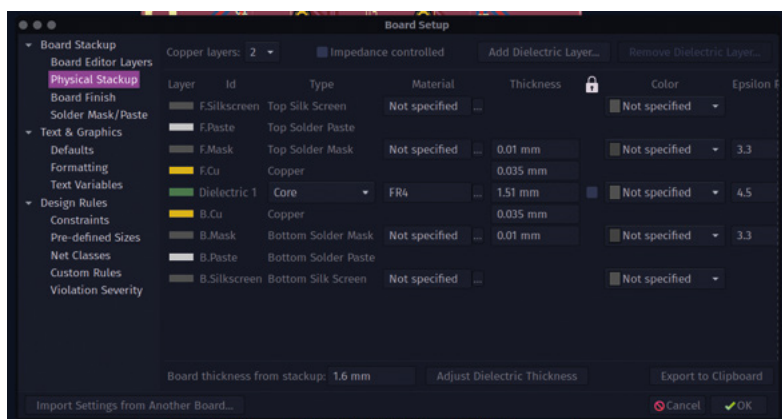
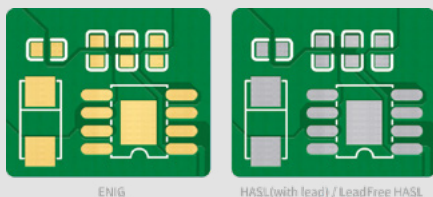
GOLD OR SILVER

There are lots of other choices that can be made when getting a PCB fabricated. One choice is the type of surface finish applied to any exposed copper pads. These take the form of differing types of covering or plating, which act to both allow the easy fitting of components, solder, or solder paste, whilst stopping bare copper pads from oxidising if left uncovered.

'Hot Air Solder Levelling' (HASL) is a common option where the board is dipped fully into molten solder, removed, and excess solder driven off. This results in all copper areas being covered in a flat, thin layer of solder. It's an older technology and has been used in PCB fabrication for multiple decades and, as such, it's usually an affordable option. It is easy to solder onto, offers good protection against oxidisation, and is stable and long-lasting. It has a long shelf life, so if you don't get around to populating your PCBs for a long time, they will still be in good condition. Finally, HASL is often offered with options that contain lead or options that are lead-free.

'Electroless Nickel Immersion Gold' (ENIG) is a newer technology that applies a two-layer coating to the exposed copper parts of a PCB. The layer directly on top of the copper is a thin layer of hard nickel which creates a barrier stopping the copper from oxidising. To stop the nickel plating from oxidising, a fine layer of gold is immersion-plated over the top. When components are soldered onto ENIG surfaces, they create a strong bond with the nickel layer, and therefore the copper underneath. ENIG is also suitable for covering larger planes on the PCB, so has become a popular choice.

There are other surface finishes, such as 'Immersion Tin', 'Organic Coating' (OSP), and 'Immersion Silver', but HASL and ENIG are most common. Most PCB manufacturers use either HASL, lead-free HASL, or ENIG, or some PCB manufacturers will offer them as choices. For example, JLCPCB has HASL selected as default, but you can switch to lead-free HASL or ENIG. OSH Park PCBs are all created with an ENIG surface finish. Over on PCBWay, you can select from a larger range that includes HASL, ENIG, OSP and more – you can even specify to have no coating whatsoever.



As FR4 is the most common PCB material, there aren't many special considerations or changes needed when designing a PCB for FR4. If you want to set up KiCad to display your target board thickness when using the 3D viewer, you can change this by adjusting the dielectric thickness value via the Board Setup. This dialog is found at File > Board Setup in the PCB Editor, then you need to select the 'Physical Stackup' option from the list, and then adjust the 'Dielectric 1' thickness variable (Figure 1).

Flexible PCB designs are commonplace in modern electronics, with many use cases. Probably the most

Figure 1 Changing the thickness of the 'Dielectric 1' layer to change the overall thickness of our PCB design

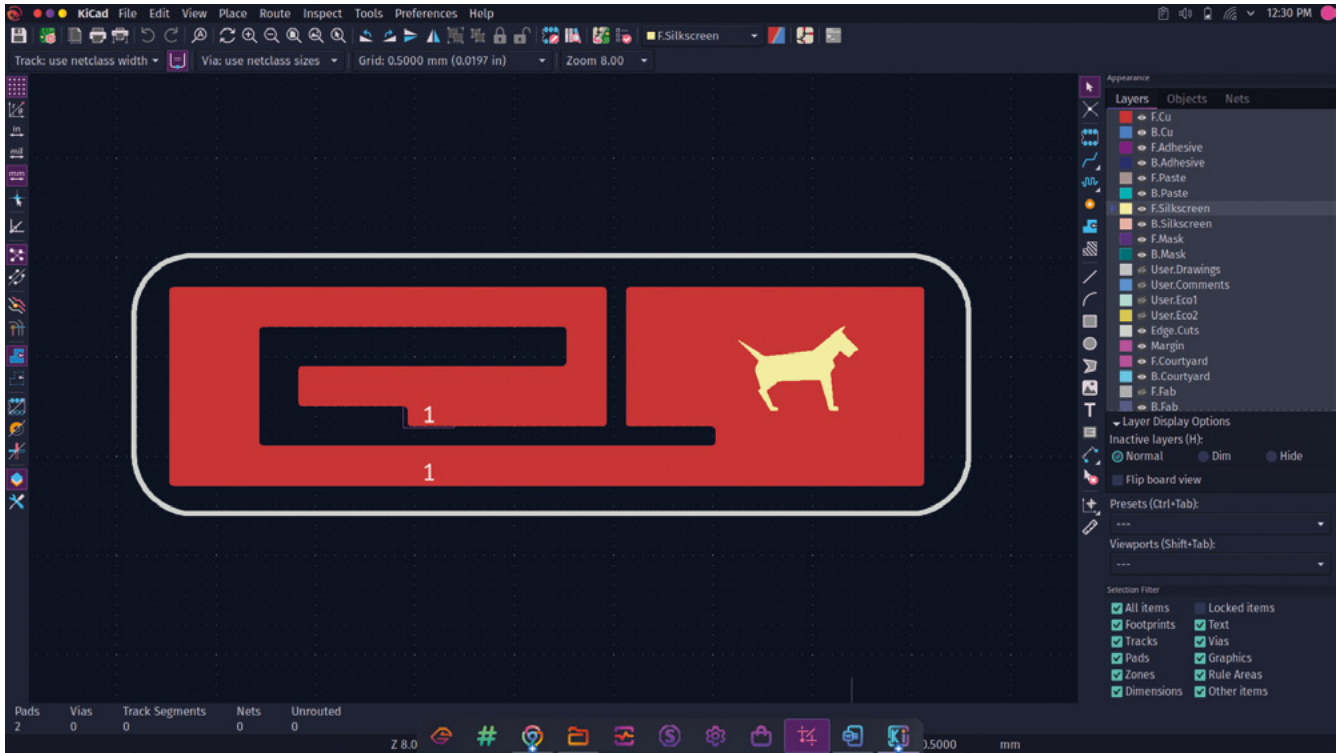
There are numerous types of flexible PCB substrate, with the most common being polyamide film

common to come across are simple flex connectors. These have obvious advantages, in that they can connect components or PCB modules in different locations in a system. Flex connectors can be inserted into specific clamping sockets or, indeed, can be designed to directly solder onto copper pads. They have the benefit of being able to fold and bend around, allowing complex layouts of PCBs which do not need larger header pins or sockets. There are numerous types of flexible PCB substrate, with the most common being polyamide film. Traces and pads work in a very similar manner to any PCB, →

QUICK TIP

Most PCB fabrication services have detailed information on the thickness of each layer of their PCBs. You can use this to emulate the PCB accurately in KiCad.

TUTORIAL

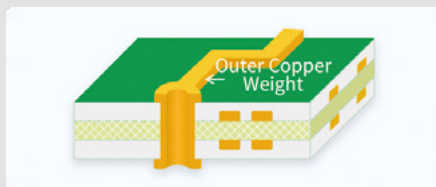


Above
Our flexible antenna design in KiCad

COPPER CONUNDRUM

Copper weight describes the thickness of copper at any given point on a PCB. It's often expressed as ounces per square foot, so a 1 oz/ft² copper weight will be thinner than 2 oz/ft². Copper weight can be important in terms of designing PCB traces, as the weight affects the depth of the trace. Different trace widths and weights may need to be used when considering the amount of current particular parts of a circuit may be passing. Similarly, track impedance and RF qualities of tracks may well come into play, as well as track sizes, when trying to match lengths of track in more complex PCB designs.

Most common copper weightings are 1 oz or 2 oz, and many PCB houses will offer these as a choice. If you require a precise copper weighting, it's possible, at a price, for some PCB fabricators to offer more bespoke weight of copper by plating or etching extra material to or from the board.



It's good advice to read any guidance your PCB fabrication house has to offer and to speak to them directly

in that they are a thin layer of copper. Flexible PCBs can become quite complex to design for, and many PCB fabrication houses will have options for custom layer materials in flex PCBs. These can also include rigid sections, which means you have to supply a design that can distinguish different substrates within it. If you plan to use this technology, it's good advice to read any guidance your PCB fabrication house has to offer and to speak to them directly to explain your concept. At the simpler end of flex PCBs, it can be as straightforward as laying out a regular PCB design, exporting some Gerbers, or sending a project file to your PCB fabricator.

A good use case for flex PCBs, and a good simple example, is a flexible antenna. We'd found a paper online with an image and dimensions for a dual-band 2.4GHz and 5GHz patch antenna, which piqued our curiosity, so we set about laying it out in KiCad. We actually began in Inkscape: the PDF source we

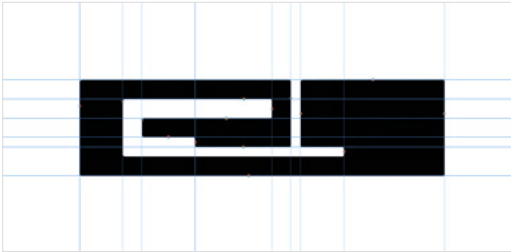
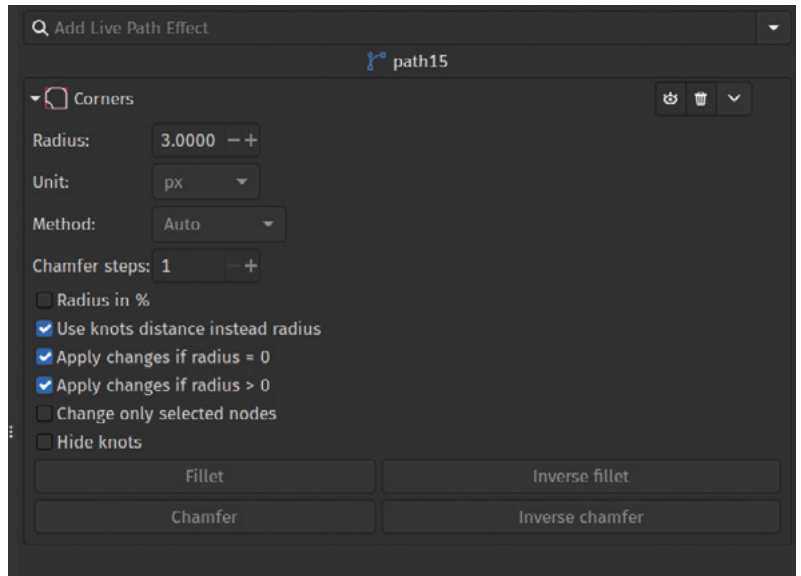


Figure 2 Using Guidelines in Inkscape to manually trace the antenna design image

had for the design was imported into Inkscape, but it had a gradient fill and therefore wouldn't export correctly as the whole object was full of nodes. If this was a bitmap image, it would have been a good candidate for Inkscape's 'Trace Bitmap' function, but as it was a vector file, this wouldn't work. However, as a vector image, it was straightforward to drag in vertical and horizontal guide lines and snap these to the edges of the PDF antenna drawing (Figure 2).

Once we had a guideline for every part of the antenna in place, it was a simple job to use the pen tool to draw a continuous line around the part, closing it to form a solid object. There is some discussion online around not using sharp 90-degree angles in traces when aiming for a flex PCB as, if the PCB is flexed, the sharp corners can be origin points for tears and failures. Whilst not a massive concern for this design, it was easy to add internal and external radial chamfers to the antenna object



by selecting the object, then using the 'Path effects' dialog to apply the 'Corners' path effect chamfer option (Figure 3). Finally, we deleted the original imported PDF, resized the document to fit our antenna design, and then saved it as an SVG.

In a new KiCad project, we actually ignored our usual workflow of creating a schematic and associating parts to schematic symbols and went straight to the PCB Editor. You can directly add components and create traces in the PCB Editor with no schematic in place. For a more complex project, we wouldn't recommend this approach, as you →

Figure 3 Using the 'Corners' path effect in Inkscape to add internal and external chamfers

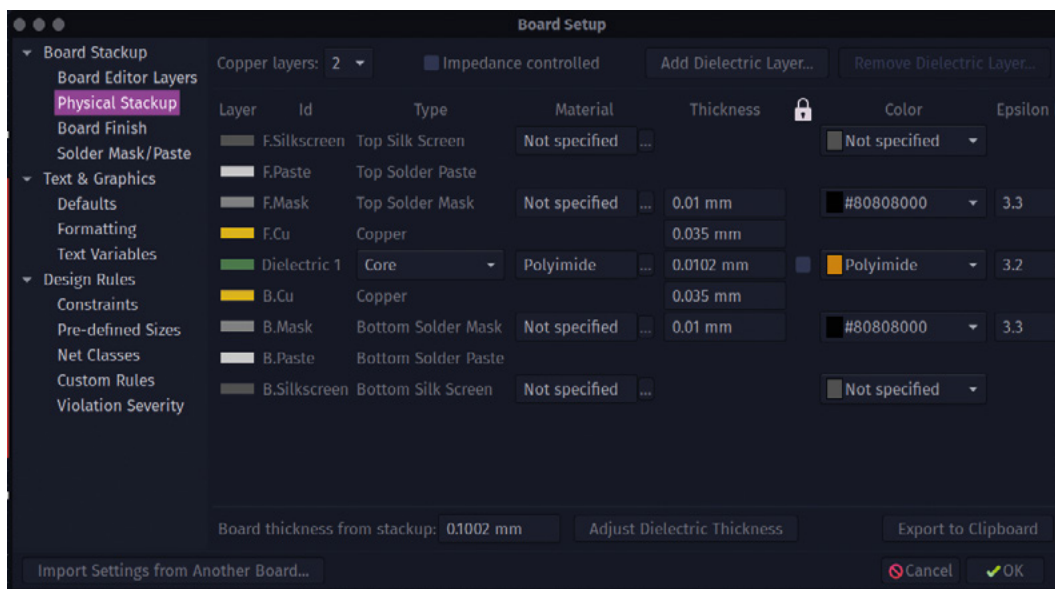


Figure 4 By setting the board material, dielectric thickness, and solder mask colours, we can emulate a flex PCB in the KiCad 3D viewer

TUTORIAL

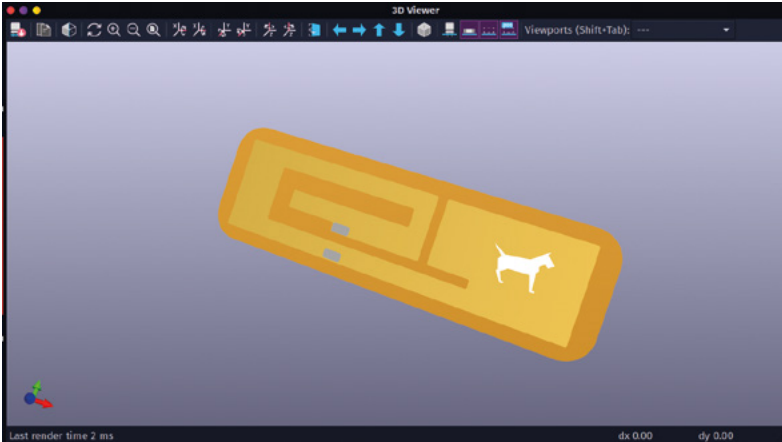


Figure 5 ♦
A 3D render of our flex circuit

have no means of checking connectivity or creating net connections, but for small simple projects like this, it's pretty easy.

We imported our antenna SVG, making sure to import it onto the Front Copper layer (F.Cu). We then used the 'Add a Footprint' tool to add two small SMD pads. We positioned these on the points in the antenna design that the original design had indicated. With no net connections due to no schematic, these pads will be directly connected to the large copper antenna design that we just placed, but of course, the pads will have no solder mask

|| All that remains is to then quickly draw another SVG for the outline of the antenna

over them, allowing us to solder on a connecting coaxial cable. All that remains is to then quickly draw another SVG for the outline of the antenna, which we did in Inkscape, but you could just draw in KiCad. With the outline imported to the edge cuts layer, we have a completed design. To get the design fabricated, we used OSH Park which has a flex PCB offering. One of the nice features of OSH Park is that you don't have to produce Gerber files to upload – you can upload your KiCad PCB file directly to the website for previewing and ordering. Conveniently, either project files or Gerber files don't particularly specify the board substrate or thickness, so we don't need to specify a thin flex board design in KiCad. However, we might want to model the board

FILLING HOLES

Vias, the small plated through-holes that connect different layers of the PCB, have different ways of being finished. For many projects, the PCB fabrication house default will be fine, but it's worth looking at the common options offered.

'Tented vias' are covered with the solder mask, so no solder would stick to them. The hole may or may not be filled, depending on the size of the via. Other benefits of tenting are that you reduce the risk of unintended shorts when boards are being assembled into products or being handled etc.

'Un-tented vias' have no covering, so are finished in the selected surface finish in the same way as exposed pads and other copper features. Whilst this may well be fine, there is a risk of accidentally soldering to vias or for short circuits.

'Plugged vias' are filled in a couple of different ways, or you may have a choice. One way is to fill the via with solder mask; another is to fill the via with epoxy resin. Some manufacturers may only be able to fill vias up to a certain diameter or, indeed, some PCB houses can offer custom approaches where you can ask for all vias of a certain diameter to be filled. The benefit of plugging vias is that the via can't accidentally become filled with solder or other conductive material.

'Conductive plugged vias' are not the most common choice, but some PCB houses can fill vias with conductive material. This can increase the amount of current the via is capable of passing. There are trade-offs in that the conductive filler may thermally expand at different rates than the other board materials, causing small flexes leading to potential failures. As an example, JLCPCB offers the option to fill vias with conductive copper-filled epoxy.

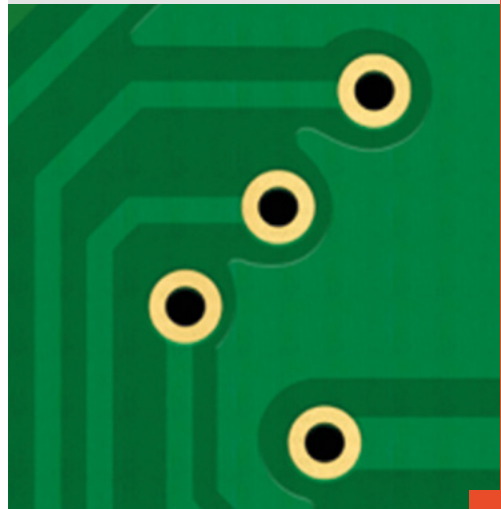




Figure 6 ♦
Our small aluminium
LED module

accurately in KiCad, especially if we are using either renders of the KiCad design in promotion or if we are exporting the board 3D model for use in other CAD programs.

Again, we can use the board setup dialog and the 'Physical Stackup' tab in the PCB Editor to emulate a flex circuit. Your PCB fabrication house will have data about all the thicknesses of each layer of their flexible PCB offerings and you can use this to set thicknesses in the board setup. If you just need a close enough PCB view that looks like your flex design, you can simply adapt the major thickness of the board by changing the material to 'Polyamide' and setting the thickness of that layer to 0.0102 mm (this is the OSH Park flex polyamide layer thickness), as in **Figure 4**. You can then set the colours of the top and bottom solder mask layers to transparent by reducing the opacity to zero using the 'Custom colour' option. This, in the 3D viewer, will then give you a reasonable approximation of a flex PCB (**Figure 5**). Often, PCB manufacturers offer metal substrates for PCBs, commonly copper or aluminium. These substrates can be useful when you need to dissipate heat quickly through a system. Often, aluminium substrates can make sense for

temperature sensor modules where you want the sensor to be accurate but the board not to soak up heat. Another application for metal substrate PCBs is where you want the PCB to act as a heatsink. For example, we had JLCPCB make and assemble some 1-watt LED modules (**Figure 6**). Running at 1 watt, these LEDs generate a reasonable amount of heat and, to promote their long life, it's useful to have some kind of heatsink attached. The reverse side of the LED has a large thermal pad which connects to the board, and the reverse of our aluminium board is bare metal. This acts as a heatsink for the LED module and the temperature is reduced. One thing of note is that aluminium and copper substrate PCBs can be bent if they are put under pressure or load. In fact, when your aluminium PCBs arrive in panels, it can be quite hard to remove them without bending the PCB!

FR4, flexible, and aluminium are not the only options often when we move to high-speed designs, designs running at microwave frequencies, or when we have very special applications like medical devices – there are other substrates available. Rogers, PTFE, Teflon, Copper Core – it's fun to read around some of these more esoteric materials. □

Exploring PCB services

In this part of the ongoing KiCad series, let's explore working with a range of PCB services



Jo Hinchliffe

Jo Hinchliffe is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

In the last part of this KiCad series, we looked at the different substrates and other hardware options that are available across a range of PCB fabricators and

PCBA services. In this section, we are going

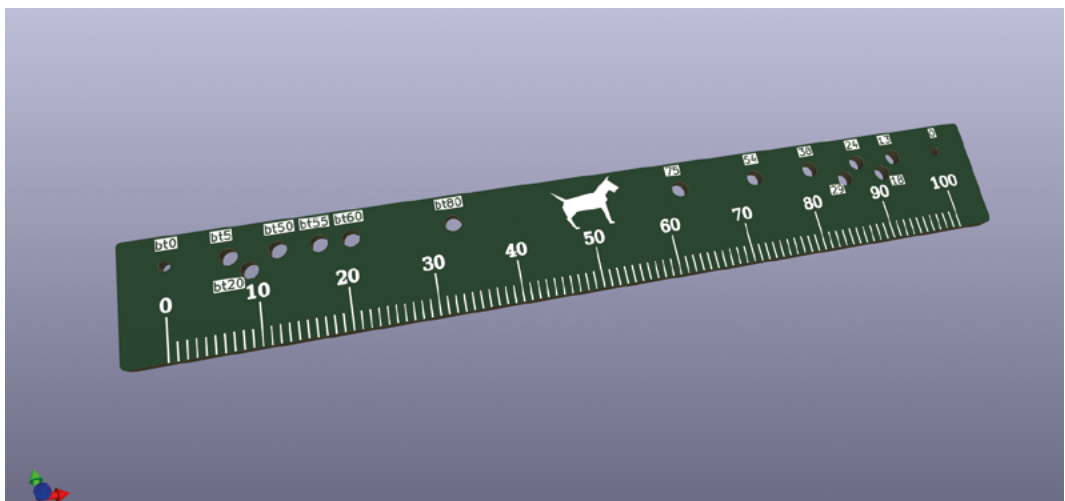
to generally look at the range of services that are available, and look at what some of the services and companies need from us to make our PCB projects. We'll also mention a few of the quirks we've found in some services that had us scratching our heads.

Each service is well-established and capable of creating quality PCBs and/or assembled PCBs. However, they each have different specifications and tolerances. In fact, that's often a good place to start when comparing or looking for a service to make

your project. Questions to ask yourself include: what minimum clearances and track widths do I need?

What is the smallest hole diameter? How accurate do I need things?

Over on OSH Park, they have a great collection of documents relating to the services they provide. The Drill Specs page details the minimum and maximum hole sizes, sizes for annular rings, and the via plating specification. Beware that all these specifications are different across OSH Park's various services, changing, for example, between the two-, four-, and six-layer options. The minimum track width specification on the OSH Park site is listed as 0.006", with 0.006" clearance on the standard two-layer boards, moving down to a very accurate 0.005" in the four-layer board offerings (it's common to



Right ♦
Our small PCB ruler project provided some interesting challenges to PCB services

OSHPARK SERVICES SUPPORT OSH PARK DOCS / DESIGN TOOL HELP / KICAD / DESIGN RULE SETUP

Design Rules > Constraints

These vary slightly based on production service.

Setting	2 Layer Services	4 Layer	6 Layer
Minimum Clearance	6mil (0.1524mm)	5mil (0.127mm)	5mil (0.127mm)
Minimum track Width	6mil (0.1524mm)	5mil (0.127mm)	5mil (0.127mm)
Minimum Connection Width	6mil (0.1524mm)	5mil (0.127mm)	5mil (0.127mm)
Minimum Annular Ring	5mil (0.127mm)	4mil (0.1016mm)	4mil (0.1016mm)
Minimum Via Diameter	20mil (0.508mm)	18mil (0.4572mm)	16mil (0.4064mm)
Copper to hole clearance	5mil (0.127mm)	5mil (0.127mm)	5mil (0.127mm)
Minimum Through Hole	10mil (0.254mm)	10mil (0.254mm)	8mil (0.2032mm)
Hole to hole clearance	5mil (0.127mm)	5mil (0.127mm)	5mil (0.127mm)
Minimum uVia diameter	20mil (0.508 mm)	18mil (0.4572 mm)	16mil (0.4064 mm)
minimum uVia Hole	10mil (0.254mm)	10mil (0.254mm)	8mil (0.2032mm)
Silkscreen Min Item Clearance	user preference		
Silkscreen Min Text Height	user preference		
Silkscreen Min Text Thickness	5 mil (0.127mm)	5 mil (0.127mm)	5 mil (0.127mm)

Left Technical details of the OSH Park PCB services

see limits given in thousandths of an inch because, apparently, you can have both metric and imperial at the same time if you try hard enough). You can find this and all the other details on the OSH Park KiCad Design Rules page at hsmag.cc/oshparkrules.

If you have questions about the OSH Park services, they have an excellent track record in communication. You can email the support email address and they will get back to you offering excellent advice. We have even had the OSH Park team open our KiCad project file and they have fixed problems and then taken the time to teach us solutions.

Different PCB manufacturers put the information in different places. Another PCB service, DirtyPCBs, bundle all their specifications and tolerances information on their About page. They similarly list a 0.006" minimum track width and clearance across both their two- and four-layer boards and cite their other specifications and tolerances. The DirtyPCBs service was designed as a minimal service with its emphasis on 'cheap', therefore, it has no chat service, and it's difficult to contact the company to ask questions. If you have challenges here, it can be a better option to use search engines and find forum conversations about the service to try and get the answers you need! ->

// You can email the support email address and they will get back to you offering excellent advice **//**

Left The DirtyPCBs PCB specification is in amongst a large About page

2/4 Layer Capabilities

ITEM	CAPABILITY
Material	FR-4 0.6mm-2.0mm 1oz copper ('standard' PCB material is 1.6mm thick, but we default to 1.2mm)
Layer number	4L
Maximum size	600*600mm (60*60cm)
Shape	Almost anything! We'll send it and see if they accept it
Min internal slot	32mil (0.8mm)
Min core thickness	4mil 0.09mm
Min prepreg thickness	16-96mil(inner) 16-118mil(out)
Min wfs	6/6mil(IL) (increased from 5/5 due to poor yield)
Min wfs	6/6mil(OL) (increased from 5/5 due to poor yield)
Min silkscreen line	0.15mm
Min BGA size	Oblong:10*13.5mil/circle:12mil
Min SMD width	8mil
Min solder dam	3mil(green)/3.5mil(black)
Min dielectric thickness	2.5mil
Min diameter of finished hole	12mil
Tolerance of drill position	+/- 2mil
Tolerance of finished hole sizePTH	+/- 3mil
Tolerance of finished hole sizeNPTH	+/- 2mil
PTH hole copper thickness	0.6-1.4mil
Max A.R of PTH	8:1
Surface copper thickness	1oz
Routing dimension tolerance	(Z0) impedance control 4mil
V-cut/V-groove	80mm (8cm) minimum, 380mm maximum. Optional, extra charge
(Z0) impedance control	+/- 15%
Ionic contamination	< 6.4ugNaCl/inch2
Surface treating	HASL (hot air surface leveling, not PB free unless special request)/Au/Sn/Ag/Cu/Electroplating/Ni/OSP*G.F
*OSP	Organic solder-ability Preservatives

For best results don't torture the board house! Be conservative. After all, these are crappy PCBs!

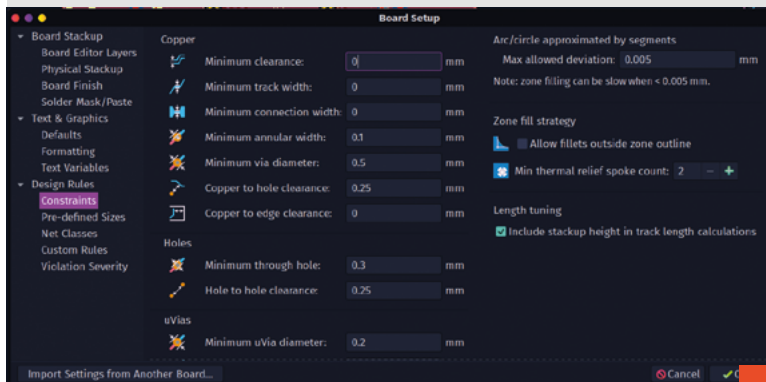
RULES RULE!

If, while developing a PCB project, you have a particular fabrication service in mind, you can ensure your board design's compatibility by setting up the Design Rules for your board to match the service. The Design Rules is nested under the Board Setup window we used in the previous section of this series to set up the different physical stackup characteristics for different substrates. In the PCB Editor, navigate to File > Board Setup and then open the drop-down menu labelled Design Rules. In the first section, Constraints, you can set up limits for the minimum clearances, minimum track widths, and other limits relating to the copper regions. You can also adjust the minimum via sizes, hole sizes, and clearances, and also the minimum dimensions for text objects on the silkscreen layer. The next item down in the Design Rules drop-down menu is the Pre-defined Sizes tab. We've used this earlier in the series to set track widths for projects. However, as a reminder, you could set this up at the beginning of a project whilst considering any limitations or constraints your target PCB service has. Also, notice that we can import the settings from a previous project – this is an excellent function if you set up a project for a particular PCB service specification.

Jumping to the bottom of the Design Rules drop-down menu, we can see the Violation Severity section. This section sets up how the Design Rule Checker (DRC) tool responds if any of the rules set for a project are broken. As a primary word of warning, think very carefully before setting any of these to 'ignore'. It may well be that for a current project you don't mind some of these issues, but it's possible under different circumstances or projects, an ignored error could be critical.

Back in the PCB Editor window, to run the DRC at any point in your project, you can either click the 'Show the design rules checker window' tool icon or you can select 'Design Rules Checker' from the Inspect drop-down menu. Once the window is open, you can then click the Run DRC button for the PCB to be checked against the defined design rules. Note that getting an error or a warning doesn't always mean that your PCB project isn't working, but they are simply indications that there is something that hasn't met the design rules.

Rules don't always have to be followed, but it's always good to check which rules are broken so you can be sure that any that are broken are broken intentionally. For example, on our ruler PCB design, we got numerous silkscreen errors as the ruler sat over the edge cut geometry, and we also got lots of courtyard errors where the courtyard areas of the mounting hole footprints we had used had overlapped. The actual distances between the mounting holes were all over the minimum clearance from each other, so neither of these sets of issues actually mattered – it's definitely worth checking though. The DRC, when run, will add small red arrows or markers on your PCB design, highlighting where the issues are located. If you close the DRC window, the markers still remain on your design. When selecting a marker when the DRC window is closed, the issue that the marker relates to will be shown in the lower toolbar on the PCB Editor. You can reopen the DRC window and delete single markers or all markers using the relative buttons. Obviously, if you don't make changes to the PCB design and run the DRC again, removed markers will be replaced.

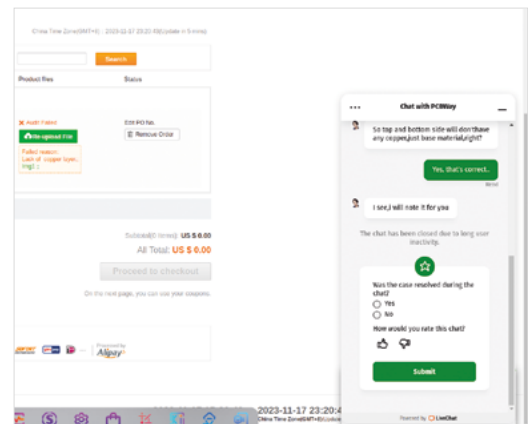


Features	Capability	Notes	Features
Layer count	1-20 Layers	The number of copper layers in the board.	
Controlled Impedance	48 types: 48-layer stack-up	Controlled Impedance PCB Layers (Micro) JLCPCB Impedance Calculator	
Material	FR-4 Aluminum Copper core Rogers PTFE (select)	FR-4: Tg 135 Tg240T Tg250 Tg270 Aluminum: Thermal conductivity: 205W/mK Copper core: Thermal conductivity: 385W/mK	Pre-preg Copper Copper
Delicate components	4.5-mil-thick PCB	1026 Plating A.4 3313 Plating A.2 2216 Plating A.3B	
Max. Dimension	400x400mm	The maximum dimension JLCPCB can accept.	
Dimension Tolerance	±0.1mm	±0.2mm (Prepreg) and ±0.2mm (Rogers) for CNC routing, and ±0.05mm for V-machining.	
Board Thickness	0.4 - 2.0 mm	Thickness for FR4 min: 0.40 (0.016), 0.5 (0.020) mm (2.0 mm only available with 12 layers or more.)	
Thickness Tolerance (Thickness > 0.8mm)	±0.2%	e.g. For the 1.6mm board thickness, the specified board thickness ranges from 1.48mm (7.01-0.016) to 1.72mm (7.12+0.016)	
Thickness Tolerance (Thickness < 0.8mm)	±0.3mm	e.g. For the 0.8mm board thickness, the specified board thickness ranges from 0.7mm (0.12) to 0.9mm (0.10)	

Above JLCPCB's specifications are found on their Capabilities page

We have, of course, used JLCPCB/A a fair amount in this series. JLCPCB have a pretty exhaustive list of their specifications over on their Capabilities page. They can offer up to a whopping 20 copper layers in their PCBs, with track widths and clearances a default minimum of 0.005" in the two-layer offering, moving to 0.0035" for four-layer options and more.

Similar specifications are available from PCBWay. An advantage of this service is the maximum dimensions of PCBs they can fabricate are 1100 x 500mm, whereas, for example, JLCPCB are 500 x 400mm. One thing of note about PCBWay is that you specify the board and the board dimensions and add it to your shopping cart prior to uploading Gerbers, which can seem slightly counter-intuitive compared to other services.



Above Many of the services offer online chat portals. These can be useful when trying to negotiate problems or challenges with a service

With all of these services, it's definitely worth contacting them using the chat function or emailing if you want to check specifications.

DIVING DEEPER

We have often featured OSH Park as a go-to company for PCB fabrication in HackSpace magazine. They have an excellent track record in supporting and promoting open-source projects, and they have that iconic purple solder mask finish which is very visible across lots of maker/hardware hacker projects. However, probably one of the main reasons that OSH Park have often featured as a service is that you can directly upload KiCad PCB files to their website – you don't have to go through the process of making compatible Gerber files. This makes the service really easy to use. If you are reading this after a new milestone version of KiCad has been released (for example, a future version 8), you might find that it takes a little while for the OSH Park website service to become compatible, but rest assured, you can also upload a zip file of Gerbers in the same way as other services in the interim. OSH Park's guidance on Gerber set up and requirements is available at hsmag.cc/Gen_Gerbers.

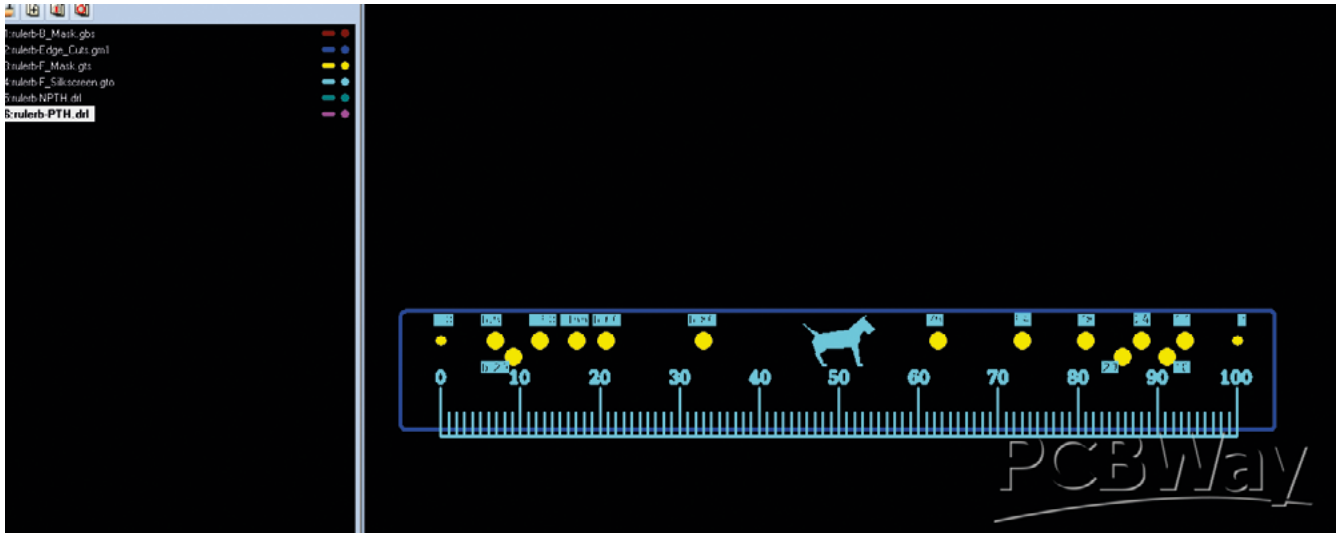
Beyond the standard OSH Park purple offering, there are options for the 'After Dark' finish (black

substrate and a clear solder mask), a lighter 0.8mm board with a heavier 2oz copper layer, and a flex option. Whilst they offer good quality, they are incredibly affordable when working with smaller PCB designs. Finally on OSH Park, they are excellent at communications. If you need to raise a ticket to ask a question, they go above and beyond many services.

Whilst they offer good quality, they are incredibly affordable when working with smaller PCB designs

Different fabrication houses have different needs around the files and file formats that you upload. One area we have noticed creating issues is the DRL or drill files. In KiCad, you can create either a pair of DRL files, one containing the non-plated through-holes and another containing the plated drill holes, or you can merge these two files into one. JLCPCB wants these files supplied as a pair, whereas if you upload Gerbers with two separate DRL files to →

Above An interesting issue occurred where JLCPCB didn't detect the edge cut geometry on the flex antenna design, which should have rounded corners



Above Whilst PCBWay rendered the ruler project correctly from Gerber files, it couldn't initially process an order due to an error being created as there was zero copper in the copper layers

OSH Park, you get an error message from OSH Park, but it conveniently will merge the two files online and also solve the issue for you. There can be other little glitches involving drill files.

Some fabrication houses want there to be drill files even if the PCB has no drill holes in the design, for example, in the design of a single-sided PCB. This caused an interesting issue when we designed the flex PCB antenna example in the last part of this series. We exported the design Gerbers and DRL

Some fabrication houses want there to be drill files even if the PCB has no drill holes in the design

files even though the design contained no drilled holes – this was just because we wanted to upload the Gerbers to a range of services to see how they rendered and get quotes.

With JLCPCB, when we uploaded the zipped Gerber file, the preview would ignore the edge cuts geometry, so the curved corners of the design would disappear and, incorrectly, the board would appear as having square edges. Chatting to the online chat

service, they confirmed that they could see the edge cuts layer and assured us that if we placed the order, the board would be cut correctly. We tried playing around with the Gerbers and we also posted the issue on the KiCad forum for discussion. It seemed that others generating their own Gerbers from our project would get a correct render on the JLCPCB site. The difference we spotted was that they weren't including any drill files. Re-uploading without drill files and the correct board outline and edge cut geometry rendered correctly. As part of this process, we discovered that OSH Park didn't have this issue and rendered the board correctly at upload. We placed the order with them.

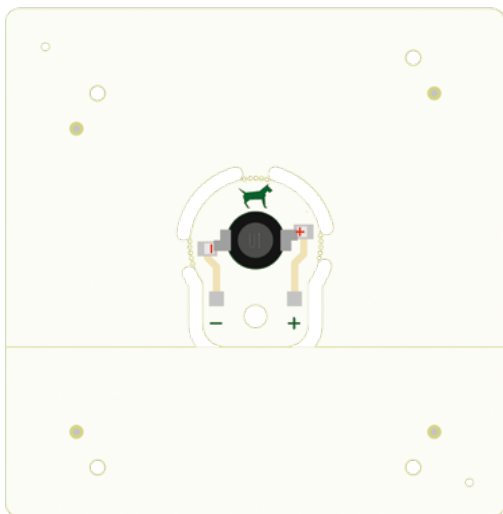
The moral of this particular story is that Gerbers aren't standard, so be sure to check what you need, and be prepared to talk to the PCB manufacturer if things don't look right.

We had another issue relating to empty layers when looking at different services to fabricate the ruler design. When uploading the design to PCBWay, it would throw an error with the upload as the Gerber file for the copper layers contained no copper. Obviously this is very unusual for a PCB as copper is usually the conductive layer connecting components and more. The ruler project shows that with a more artistic use of PCB fabrication, it's possible to cause headaches for fabrication houses.

We had a problem with one of our recent projects when submitting the aluminium substrate LED module project to JLCPCB services. The 1-watt COB LED we had identified in the JLCPCB parts library had a diagram on the datasheet of the LED which had polarity markings on the two semi-symmetrical flat SMD pin connectors. We'd actually seen these LEDs in real life – they have an etched - and + in these metal connectors.

When we uploaded to JLCPCB, the website rendered the PCB with the components placed and the JLCPCB 3D model of the LED had no polarity markings. We presumed it would be correct, and as only ordering a small number and the LED is a large part, it wouldn't be too onerous to swap them around if they arrived incorrectly. After ordering, the process was halted, and JLCPCB contacted us to discuss and check the polarity of the LED. We had to point out that it was an issue with their 3D model that meant it was impossible to tell if it was rotated correctly, and an engineer at their end would only be able to tell when they physically went and looked at the package. In the end, the aluminium LED PCBs were correctly manufactured.

Our main takeaway point for working with any PCB service is that most things are achievable with good communication, which increasingly becomes, in combination with the physical specifications we require, a valuable deciding factor in choosing which service to use. □



Above ♦

In the original render preview, the LED polarity couldn't be ascertained as JLCPCB had a problem with the 3D model. After an engineer inspected the part, the correct orientation was confirmed

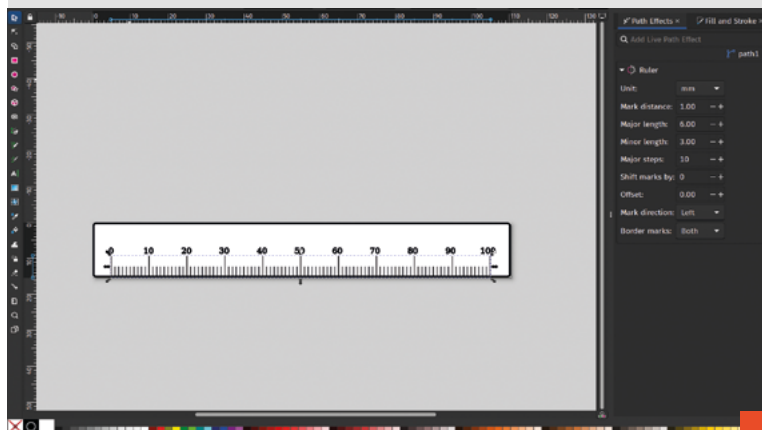
RULERS RULE!

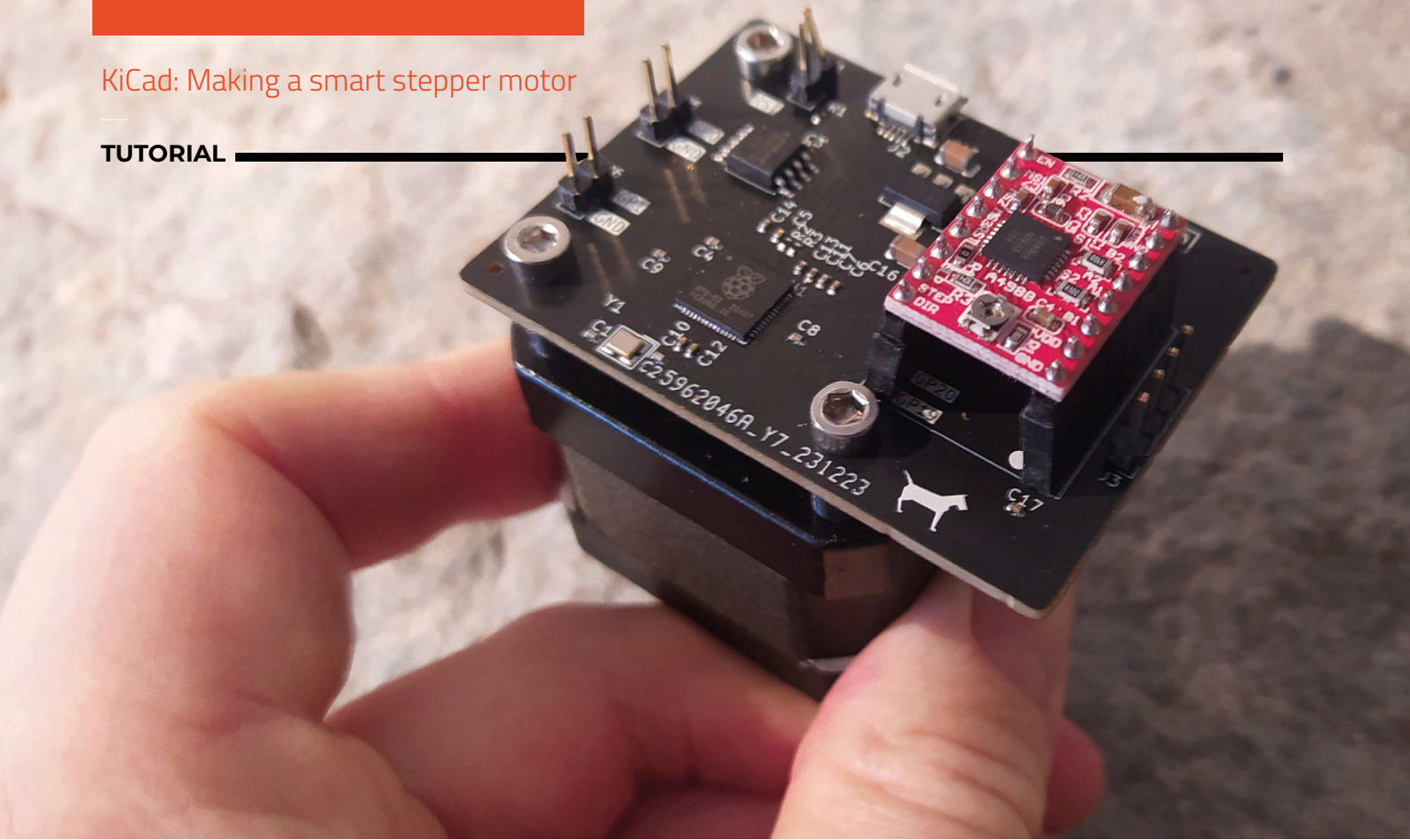
Making a PCB ruler is almost a right of passage in the PCB-making communities. They can be a simple, useful tool, a good business card, or perhaps even perform some extra function. Having an interest in model and high-power rocketry, we made a ruler which has some accurately placed holes in it, into which you can place a pen. You can then pin the hole at the 0 or 100mm marker and draw circles that match common rocket motor diameters or common Estes rocket body tube diameters. Handy for impromptu cardstock or balsa rocket component-making. It might seem strange to use a PCB manufacturer for this, but it's actually a very affordable way of getting very accurate 2D designs made.

One slightly tricky aspect of creating a PCB ruler in KiCad is how to actually draw a graduated line to give the ruler its measuring graphic element. Again, we've used the excellent open-source Inkscape to solve this in combination with KiCad 7's SVG import abilities.

In Inkscape, draw a straight line using the pen tool and use the height and width settings to set it to the length of the ruled section you require. We wanted a compact ruler PCB, so we went with a 100mm length. Next, select the line and then click Path > Path Effects. The Path Effects dialog box should open on the right-hand side of the screen – there should be a search bar at the top of this dialog. Type in 'ruler' and select the Ruler Path Effect that appears in the results. This, in turn, should launch the Ruler Path Effects dialog. Set the 'Units' to 'mm' and then set the 'Mark Distance' to '1'. This should then add a graduation line one millimetre apart along your line. Next, you can set the length of the major length for the longer graduation lines and the minor length for the shorter lines. Finally, set the 'Major Steps' to '10'. You should now have a ruler graphic with the commonly used idea of a longer marker every 10mm.

You could use KiCad to add the text to mark the numbers on your ruler graphic, but we went ahead and did this in Inkscape as it's pretty easy to use the align and distribute tools to bring a line of text labels into alignment with the ruler. We then resized the document using document properties to the size of the design and saved it as an SVG to be imported to the silkscreen layer in KiCad in the PCB Editor. We've covered this before in the series, but as a reminder, it's as simple as File > Import Graphics, and then, in the dialog, navigate to the SVG, set it to import to the correct layer (in this case, the front silkscreen), and make sure the scaling is set at '1'. It's worth setting the PCB Editor grid to '1mm' so that you can align other elements to the ruler design well. Finally, we were lazy and left the baseline in our ruler graphic and then used the edge cuts geometry to remove it – this ensures that the silkscreen ruler lines run right to the edge of the PCB. However, you can remove the original line back in Inkscape. When you have your path effect applied, you can select the entire ruler graphic and then use Path > Object to Path to convert the path effect into regular paths. Then, using the node selection tool, you can select the bottom line and delete it. A tip, as it's difficult to grab the nodes at the end of the baseline, is to zoom in and then bend the line away by dragging the baseline in between two of the graduation line nodes. Once the line is bent away from the graduations, you can click it and delete it.





KiCad: making a smart stepper motor

In this section of the KiCad series, we adapt our earlier minimal RP2040 design to create an 'Urumbu'-style stepper motor control board



Jo Hinchcliffe

Jo Hinchcliffe (AKA Concretedog) is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high-power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

Urumbu is a mechanical concept created by Neil Gershenfeld of MIT, which concerns creating multi-axis machines simply, sidestepping some common approaches, and leveraging the development of computers. The go-to standard for many machines for many years is to feed them G-code line by line, using some kind of G-code sending application to stream the lines into a controller. This, in turn, drives the individual stepper motors to move the relevant axis. It's a solid system, but it harks from an era where parallel processing capabilities were rare and incredibly expensive.

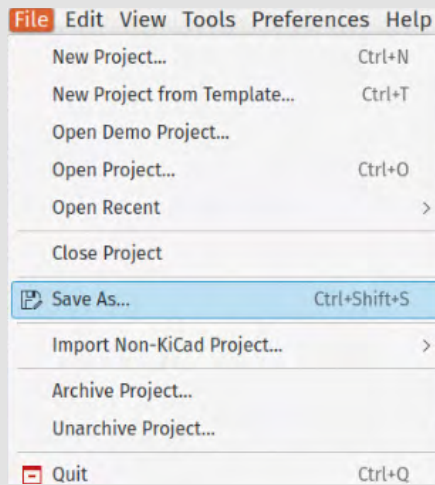
Urumbu is interested in streamlining the making of machines, reducing both the cost and the complexity. In simplified terms, it essentially uses stepper

motors (or theoretically other actuators) that have been adapted with an embedded microcontroller to run directly via USB connectivity. This means that, potentially, we can sidestep using G-code, and perhaps even avoid CAM altogether. Imagine building a machine where you perhaps parametrically define the output object and the script, or perhaps Python application, directly calculates the geometry of the form and directly controls the rapid prototyping machine connected to a convenient USB hub. This article won't cover all that, but it's well worth reading the article *Minimal Machine Building*, which you can download from hsmag.cc/urumbu.

You can also look around the Fab Lab depository, where you can find projects that have used the Urumbu approach, like this excellent pointing machine: hsmag.cc/point.

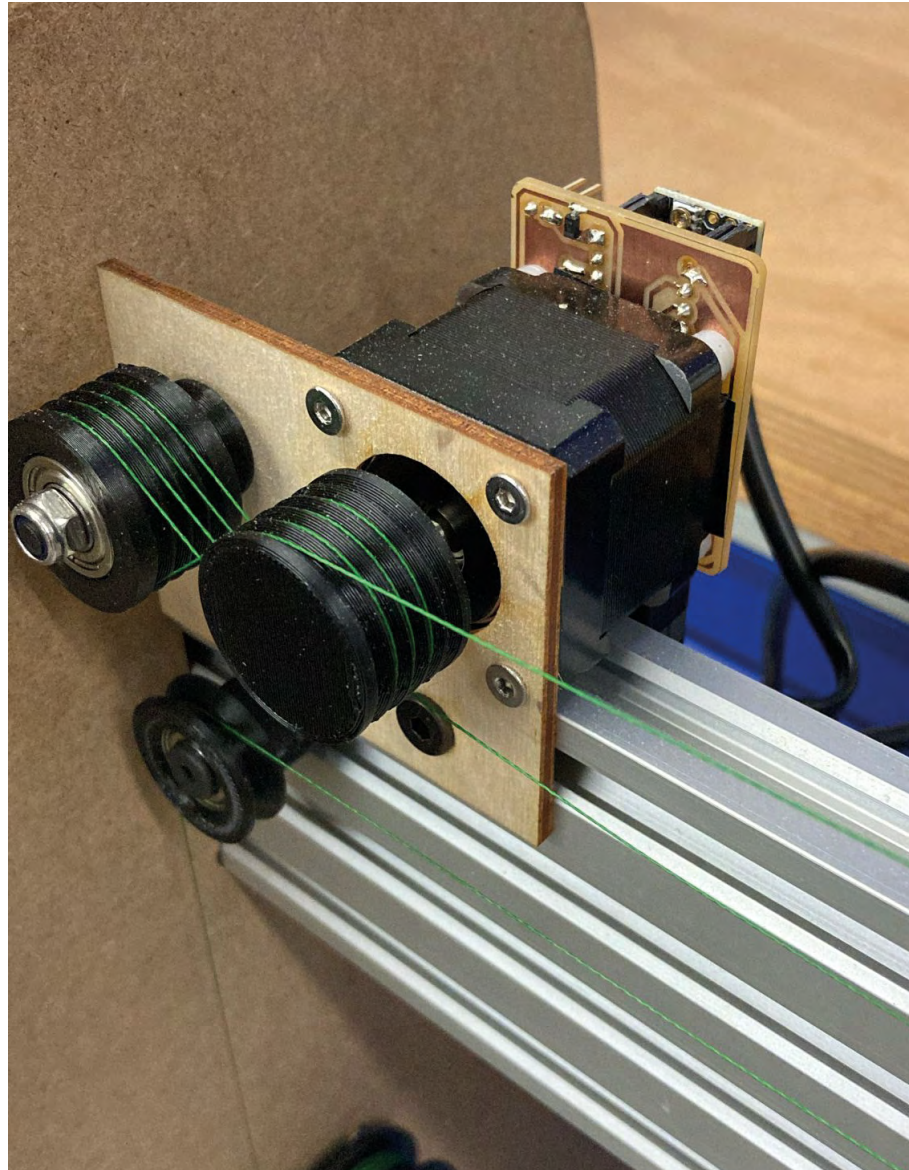
A NEW START

Let's create a separate copy of a KiCad project to work on. Open the Minimal RP2040 project we created, and then simply click File > Save As. We can then create another folder on our system and save the project into it with a new name. If you then open this folder in a file management application, you will see that all the KiCad-generated project files (the .sch and .pcb etc.) have been renamed to the new project name. We can also tidy and delete files which are specific to the old project and not relevant to the new project. For example, we won't be using the Gerbers, the CSV position and BOM files, as these will be different for the new project. Similarly, the edge-cut SVG that we created in Inkscape for the Minimal RP2040 project won't be used, so can be deleted. It's worth mentioning: make sure that you are in the right project folder before you start deleting files!



As the concept for Urumbu stepper motors is to use USB for control, the RP2040 IC is a great candidate for powering a driver board. There have been examples in the Urumbu community using NEMA 14 motors, which are convenient in the fact that they can often be controlled and powered by USB 2.0 and above. However, most small experimental rapid prototyping machines tend to use the larger NEMA 17 class of stepper motor. Check out any smaller home- or office-use 3D printer, smaller desktop CNC router, or hobby pen plotter and you'll find NEMA 17.

With NEMA 17 as our target, the first port of call is to find some mechanical dimensions and make some fundamental decisions. Looking at datasheets for NEMA 17, we find that the outer dimensions of the package are 42 by 42mm, and that they have a set →



Potentially, we can sidestep using G-code, and perhaps even avoid CAM altogether



Left (opposite page) ♦
The finished PCB attached to a NEMA 17 stepper motor

Above ♦
An Urumbu-style smaller NEMA 14 motor with a CNC-milled, SAMD11-based board attached

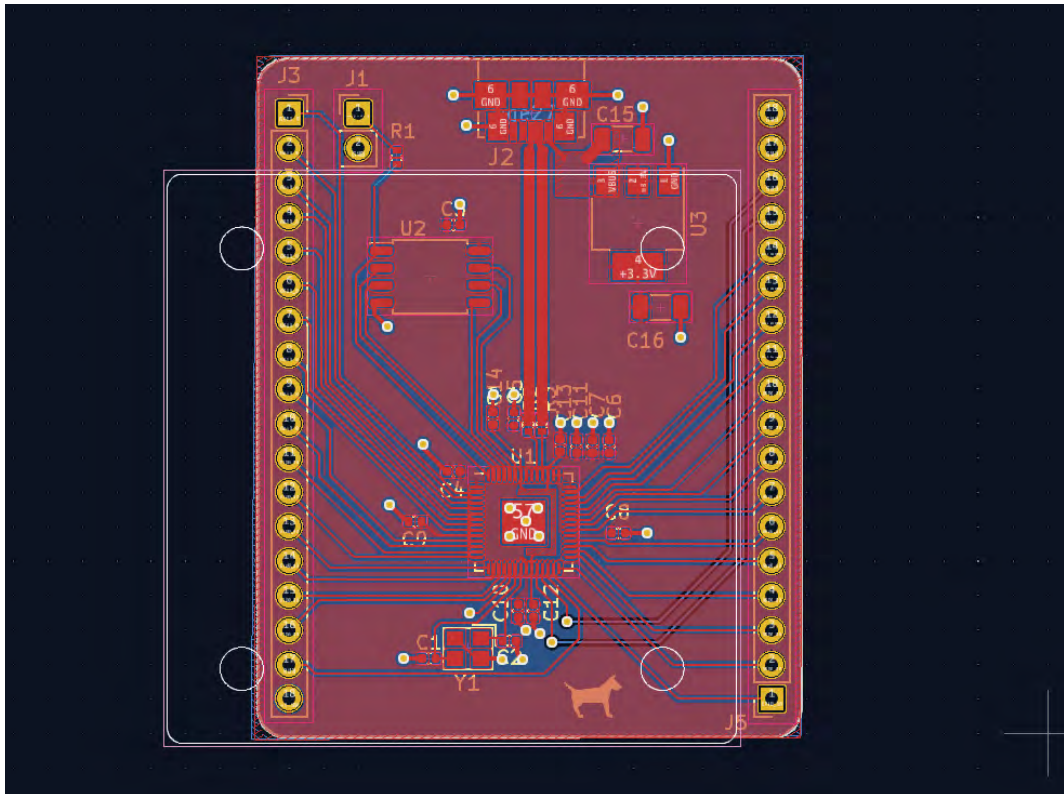


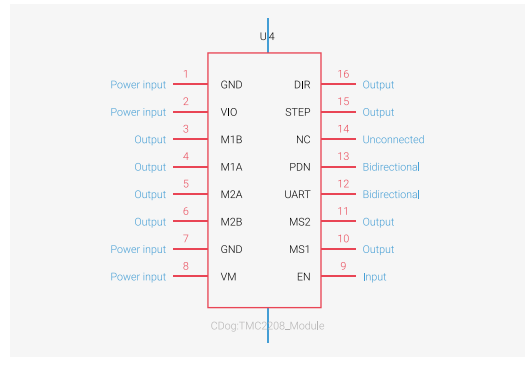
Figure 1 A NEMA 17 outline graphic laid out in Inkscape is imported as an SVG into the minimal RP2040 example to see what area we are playing with

Below Right Creating a custom symbol for any of the various similar form-factor stepper motor driver modules

of M3 bolts through the assembly in the corners of a 31 mm square. As we plan to use the minimal RP2040 circuit example as the basis of this project, it was a good starting point to draw up a NEMA 17 footprint and drop it into the minimal RP2040 design to see how things look (**Figure 1**).

We drew up a quick NEMA 17 footprint in Inkscape and imported it to the edge cuts layer in KiCad using File > Import > Graphics. It was obvious that we would have to reduce the size of some aspects of the minimal RP2040 layout, but not unreasonably. We wouldn't need all the GPIO pins broken out, so there were some easy space-savings to be had. There was probably just about enough room to also lay a motor driver IC and peripheral components on the board, but an early decision was made to actually use a module for the motor driver section as then the board would be compatible with a range of motor drivers. This meant it was necessary to expand the board dimensions in one axis. With this basic feasibility worked out, we set about editing the schematic to create our new project.

In the schematic editor, we first deleted all the GPIO breakout header sections as they weren't needed. We then used the symbol editor to create a custom symbol for our motor driver module (we covered creating symbols in the early parts of this KiCad series). With the symbol created, we then connected it to the RP2040 using labels to keep the general schematic sections easier to read.



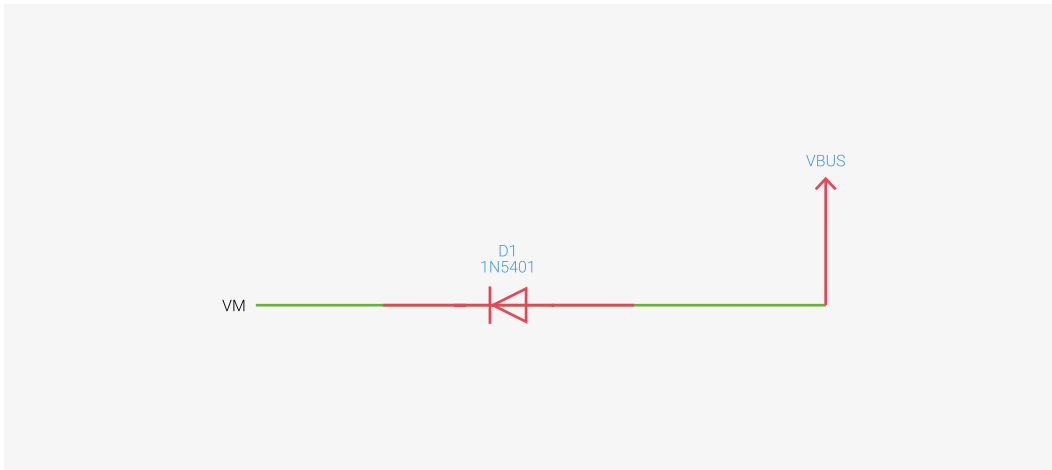


Figure 2 ♦
KiCad's workflow means that we can often simply add generic component symbols to a schematic and worry about which actual component each one will be later

One difference with running a NEMA 17 rather than a NEMA 14 is that although you could, in a slightly limited fashion, run the motor at 5V from a beefy USB supply, it's likely you might want to run it from a larger external voltage. Most of the common stepper driver modules have the ability to do this, and have a 'VM' pin into which you can connect an external supply. We wanted to retain the ability to use either USB or VM, so we needed to add a connector for an external supply and a diode to protect the USB side of the system when the external supply was used. One of the great things about KiCad, that we may have mentioned before, is that the workflow of separate schematic symbols to which you then assign a component footprint means that we don't have to work out exactly which diode we are going to use at this part of the process. We can simply place a diode symbol and wire it into the schematic and consider the package later (**Figure 2**).

In addition to our motor driver, we wanted to add two header sockets connected to GPIO and ground to which we could attach switches to act potentially as limit switches to provide feedback and control options for any machines that we might develop with these motors. Again, we simply added these to the schematic.

With our adapted schematic largely complete, we set about making decisions on component choices and we also began to check previously used components were available. This is where things can get very tricky and time-consuming when using PCBA services. We were glad to see ->

STARTING A WAREHOUSE

One way to avoid some of the component problems we have had in these projects is to pre-order components to be held ready for use in your project. This is sometimes referred to as a 'virtual warehouse', where you can buy an inventory of component stock and hold them until you are ready to place them onto a PCB assembly. This functionality is already built into your JLCPCB account and you can simply, once signed in to your account, move to the 'Parts Manager' page. On this page, you can use the 'My Parts Lib' to view and to add to your personal parts library. You can buy both Basic and Extended parts, and you can also pre-order out-of-stock extended parts for when they are hopefully restocked. For Basic parts from the JLCPCB parts warehouse, you have a minimum order requirement. However, basic parts are much less likely to go out of stock and, if they do, they are likely to have an alternate similar part available. One thing you need to know, though, is that these pre-purchased parts are only for use in assembly services – you can't suddenly have your library of parts mailed to you as a component order.

If you are creating a project and you think you are going to have a long development time where component stock might be an issue, this can be a great option for your peace of mind.

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What's the Global Sourcing Parts Service?

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Global Sourcing Parts Order Terms & Conditions

Notes on Global Sourcing Parts Orders

- Global sourcing parts orders cannot be canceled or returned once it's been paid.
- Global sourcing parts need to be reviewed. If the part doesn't support assembly, this part will be canceled and the refund will be issued within 1.7 days.

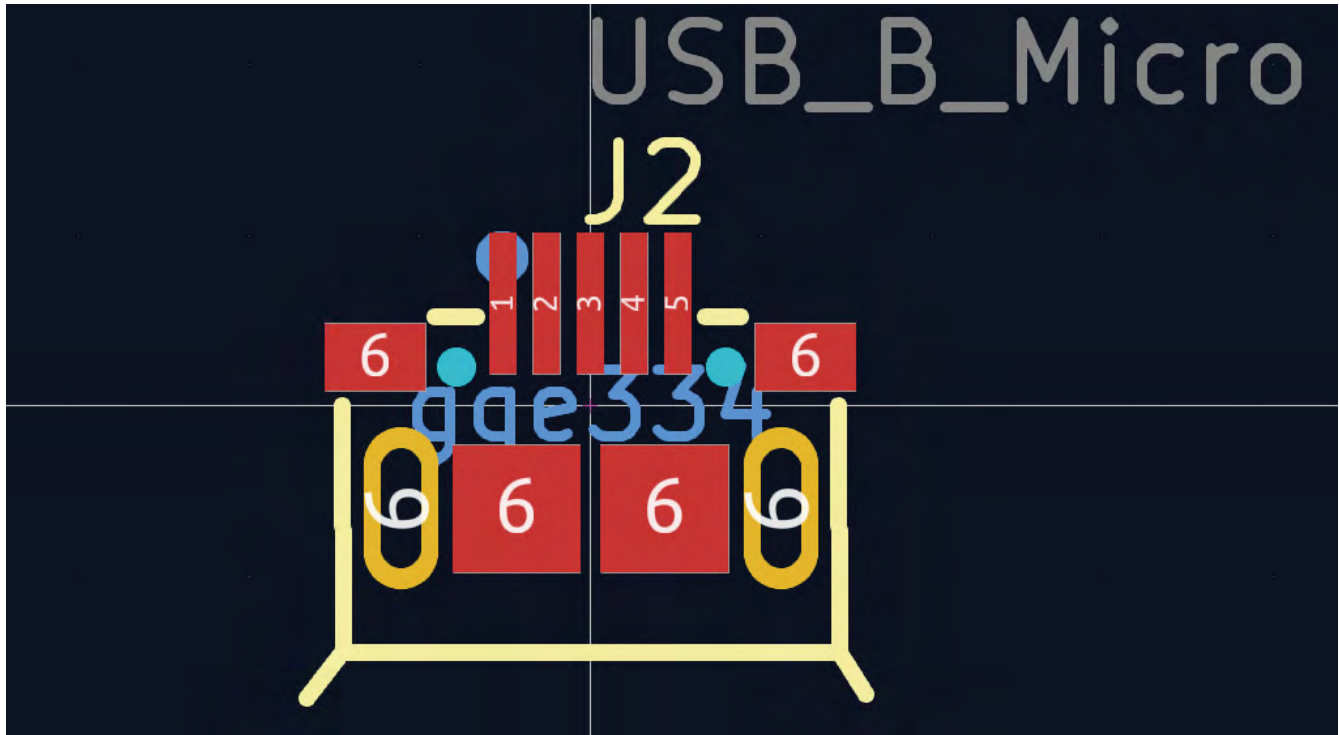


Figure 3 ♦ A new USB connector has been identified and the footprint created by converting the EasyEDA example on the product page

that the RP2040, the Winbond flash chip, and the 12MHz crystal were still in stock with JLCPCB. We also took the time to check that the smaller components, the capacitors and resistors, were all also in stock.

However, the USB socket and the 3V3 voltage regulator we had used previously were no longer in stock. Both of these are high turnover items and, at one point in this process, we couldn't identify any 3V3 voltage regulators in any package that were suitable for our project. We also found some challenges in that there would be a regulator listed, but not enough information available either in the listing or sometimes in the specific component's datasheet to actually make a decision on whether to include the part. With items like voltage regulators, it's fair to say that LCSC, the company that is the back end of the JLCPCB component warehouse, is continually changing and adding items and stock. What can appear a huge problem one day in your search results can suddenly have half a dozen more options in a couple of days' time.

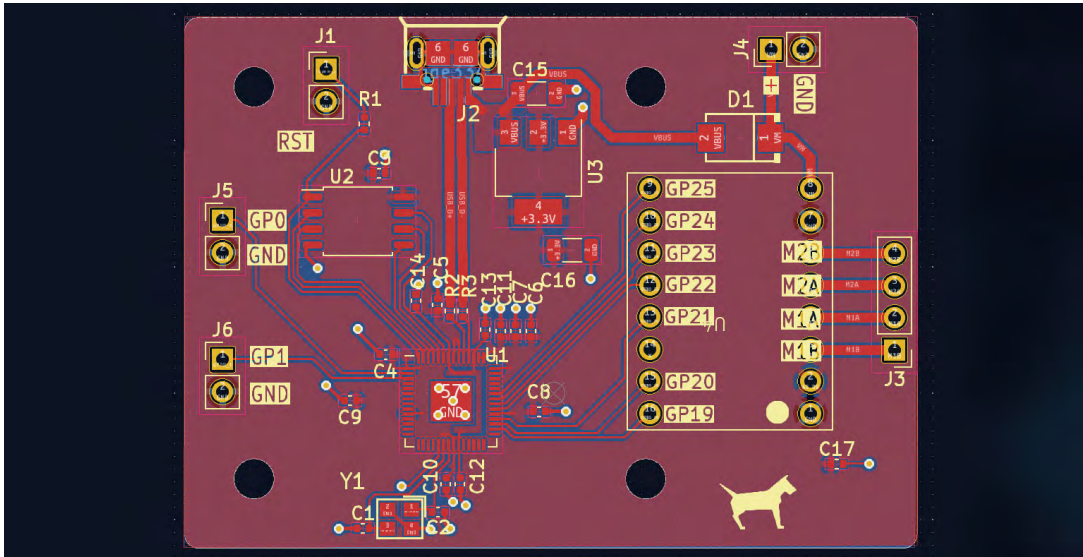
We eventually found replacements for all our non-stock components. The replacement USB


socket required a different footprint, and we used the approach of downloading the JLCPCB EasyEDA footprint and uploading it to the Wokwi EasyEDA to KiCad converter site, which again worked flawlessly (**Figure 3**). See earlier sections of this series for more examples of this in use.

The new USB connector had some through-hole chassis components, but was listed as an SMD. This concerned us, as the PCB assembly service charges quite a bit more for through-hole than surface-mount, but the part was attached via the single side surface-mount services without problems.

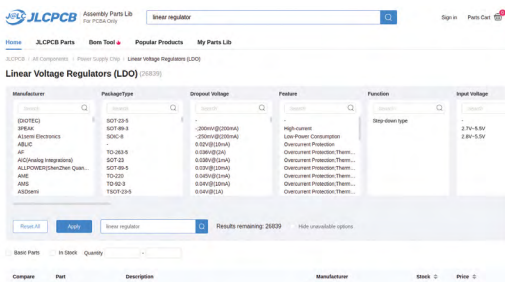
Having struggled to identify a suitable voltage regulator in any package at one point, having left the project for a couple of days we then found different stock available in the JLCPCB parts library and managed to find a drop-in replacement regulator which would sit on the same SOT23 footprint. It's definitely worth triple-checking the footprint and pinout of any swapped components to ensure that your wiring still works.

With most of the problems solved with regards to components, we set about editing the PCB layout. We needed to make the minimal RP2040




Left Below  When trying to minimise redesigns and faced with component changes, you'll spend a lot of time using the search options!

Left Above  The complete Urumbu RP2040 PCB layout



layout more compact to fit within the NEMA 17 footprint, and so we moved the actual RP2040 and crystal upwards, decreasing somewhat the distance between it and the USB socket. Sometimes, in reworking a PCB like this, the grab function is quite handy, where you can select a track, or a selection of tracks and components, and then use the 'G' hot key rather than 'M' and, instead of simply moving the objects, they are grabbed and the track connectivity remains which the tracks can move. This rarely results in a neat set of tracks in our experience, but it can be useful to create a quick new routing which you can then manually edit to neaten.

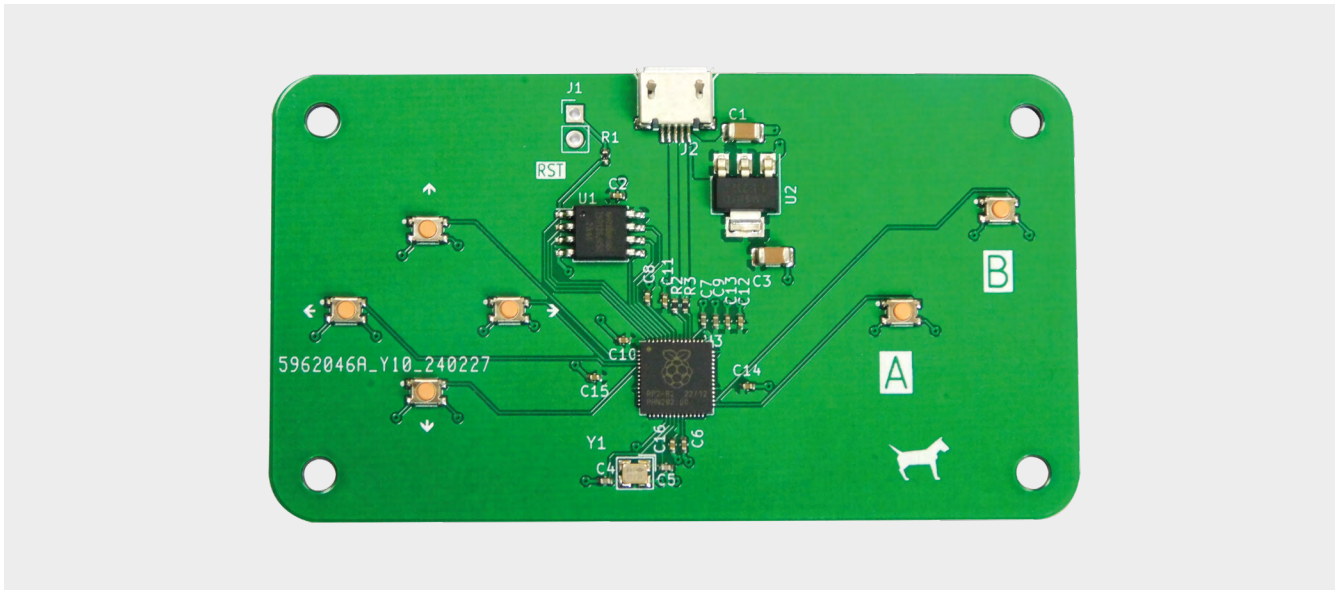
With the PCB design complete, it was the usual case of creating the Gerbers, BOM, and positional files for the project and uploading to JLCPCB. After a short production and delivery of the assembled PCBs, we created a standoff design for 3D printing using FreeCAD, and then the boards simply attach to a NEMA 17 using some longer M3 bolts. If you are interested in replicating these boards or playing with RP2040 Urumbu-style approaches, download this project from hsmag.cc/issue76. 

WHOOOPS-A-DAISY

In the spirit of failing out loud, we'd like to share a huge error we made in the production of this PCB. As you'll read in the main text, we decided to use motor driver modules rather than designing around a particular motor driver IC, as this meant we have lots of flexibility and redundancy with regard to motor drivers potentially going out of stock. The motor driver boards like the TMC2208 module, the DRV8833 module, and the A4988 module all share a common footprint with 16 pins, in two rows of eight pins in 2.54 mm spacing.

We didn't have the spacing between the rows, but a friend had a module on their desk and we messaged them for some dimensions. They sent me a collection of pictures with callipers held to the board, and also the module placed into a breadboard. We quickly counted across the breadboard to see how many columns wide the module was. It's six columns wide across the pin rows. When laying out the simple footprint for the module, we set the grid to 2.54 mm in the footprint editor and then drew one column of eight pins. We then counted across six rows and laid out the second column. Of course, that is an error: counting six rows across makes a module that would span seven columns of a breadboard, and is therefore 2.54 mm too wide. The simplest things are often the worst! The challenge with this sort of error is that they are not the kind of errors that can be detected by the DRC system, as connectivity to this simple footprint looks correct to the system. Only when the assembled PCBs arrived did we realise the error. Of course, this has been revised in the repository, so if you download this project, the footprint is correct. For the small number of boards we had manufactured, the horrid workaround is to slightly angle in the header sockets to bring them close to correct and then insert the module. Crude, but allows us to use the boards. We think it's fair to say that everyone will make mistakes; if and when it happens to you, try not to beat yourself up too much!





KiCad: making an RP2040 game controller

Let's explore adapting our RP2040 layout to make a USB game controller



Jo Hinchcliffe

Jo Hinchcliffe (AKA Concretedog) is a constant tinkerer and is passionate about all things DIY space. He loves designing and scratch-building both model and high power rockets, and releases the designs and components as open-source. He also has a shed full of lathes and milling machines and CNC kit!

In earlier articles in this series, we established that we have a reasonable working RP2040 layout, so now it's pretty trivial to create new RP2040 devices. In the last section we made an 'Urumbu'-style motor driver board, and in this section we are going to create a simple USB game controller (Figure 1).

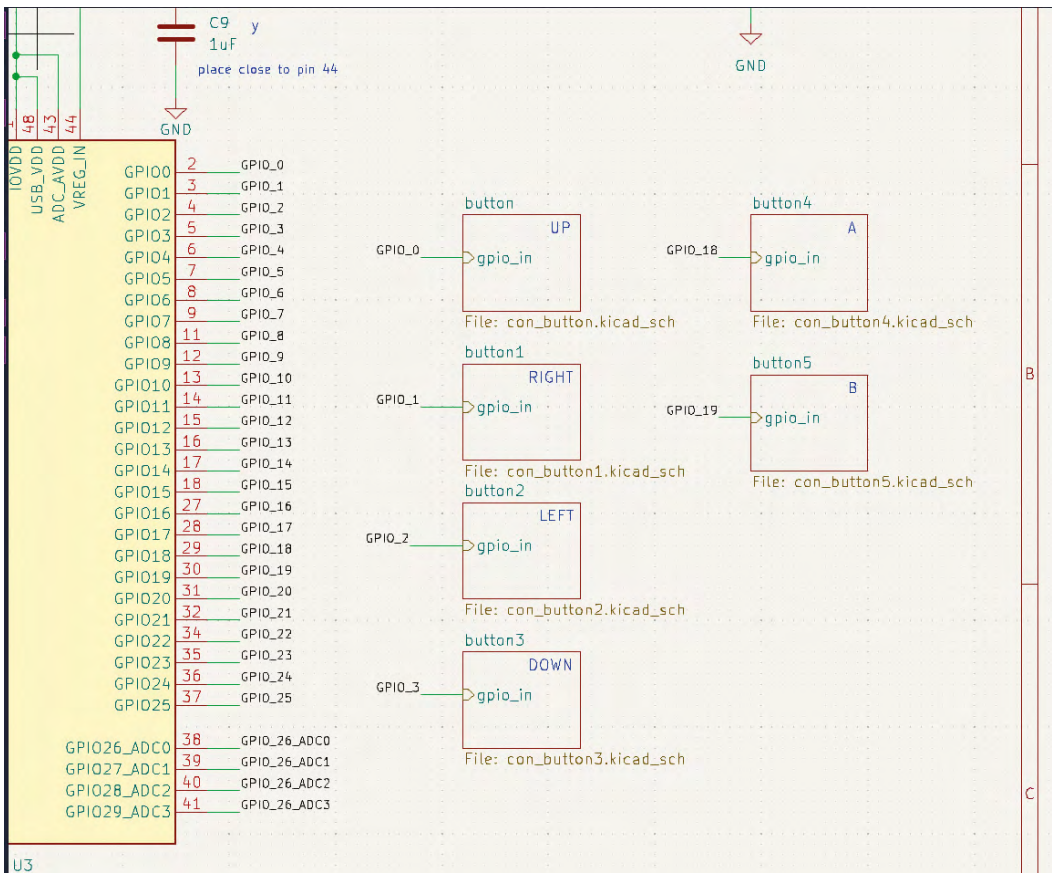
It's largely the same process we undertook for the Urumbu project, but simpler. We started by making a copy of our Urumbu project and cleaned out the files in the new project copy that we wouldn't need. So, any particular files like the board edge geometry, the Gerbers, and CSV files can be deleted as we will replace them with ones generated for the new project. We also quickly deleted all the Urumbu parts we didn't need from the schematic. Note that we don't really need to delete items in the PCB Editor, as when we eventually pull in the updated netlist and bill of materials, we can automatically delete unreferenced footprints, and the new footprints will be brought in.

We want to add six tactile buttons to our RP2040: four in a D-pad arrangement and two as A- and B-style buttons. We want these buttons to be momentary press buttons and 'push to make'. We then plan to use these buttons to connect one side to a GPIO and the other side of the button to ground.

Scouring the JLCPCB parts library, we came across the C221902 button. This part looked a nice size, so we took a look at the EasyEDA schematic and footprint. It has four pins and, reading the schematic, we could see that if we connected pin 2 to a GPIO and then connected all the other pins to ground, it would work as we wanted. Additionally, with the four SMD pads, it should mechanically be pretty strong.

With our choice made, we used the excellent Wokwi EasyEDA 2 KiCad website to convert the supplied footprint to a KiCad format: (hsmag.cc/easyEDA2KiCad). We then added it to our custom library. We covered this in earlier sections of this series, but it's pretty straightforward. You upload the EasyEDA JSON file, and it then downloads a KiCad PCB file with the footprint loaded into it.

Figure 1 ♦ The completed game controller PCB



To add the buttons to our schematic, we created a custom 4-pin schematic symbol and inserted it into a hierarchical sheet. We wired the GPIO pin and the other pins to ground and then brought out the GPIO hierarchical pin. We then copied the hierarchical sheet to create six versions, one for each button, adjusting the label and the sheet name as we added each (Figure 2). Again, we've covered this in earlier sections.

Next, we assigned the new footprints to the schematic symbols and began to edit the PCB layout. We created a new board edge geometry SVG in Inkscape with some mount holes before carrying out the usual exporting of Gerbers, BOM, and positional files for JLCPCB services (Figure 3).

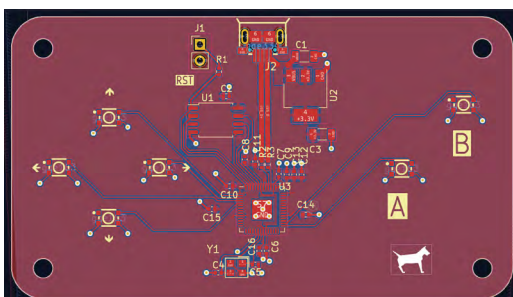


Figure 2 Using hierarchical sheets makes it easy to add multiple similar connected schematic blocks, such as the buttons

Figure 3 Our completed PCB layout

Additionally, with the four SMD pads, our PCB should mechanically be pretty strong

Having ordered the boards, one final fun activity on the hardware side of this build was to export a STEP file from KiCad to model around in FreeCAD. To export a basic STEP file from the KiCad PCB Editor, select File > Export and then choose STEP as the output format. Note that we haven't added custom 3D models for all of our custom components, so obviously the STEP file isn't completely correct, but it serves as a good enough guide to model around in FreeCAD. →

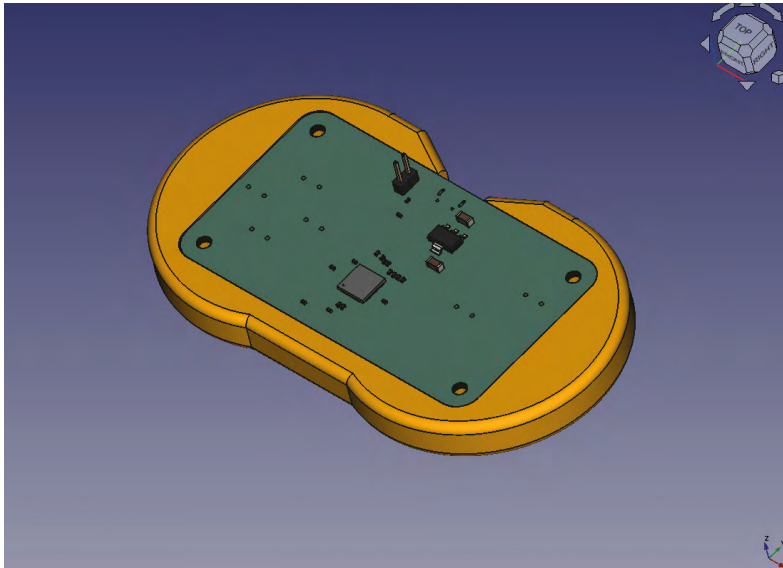


Figure 4 ♦
Modelling a simple enclosure in FreeCAD to make our controller a little more comfortable to hold

In the free-to-download book *FreeCAD For Makers*, we explored using FreeCAD and the KiCad StepUp workbench that allows you to create and position custom 3D component models for use in KiCad. We also explored all the skills needed to create all kinds of models. With the knowledge you gain from this book, you could certainly make a controller enclosure like the one we quickly modelled (**Figure 4**).

THE SOFTER SIDE

Now we have created our board, it's time to write some code for it. We could write our code in C using the Pico SDK. We could also use the Pico build of MicroPython or CircuitPython. However, since we've created a new board, let's create a firmware tailored specifically for it – we'll create a custom build of CircuitPython. This allows us to do a couple of things. Firstly, it lets us name the specific pins, so rather than using, say, GPIO0, we can use BTN_A. Secondly, it lets us select which modules we want to include. In our case, we'll add Adafruit HID, which enables us to use our game controller as an input device.

The general process for creating a build of CircuitPython is given in the documentation at hsmag.cc/BuildCP. We won't go through it in detail, so follow that guide to set up your environment.

Once you have everything set up, you need to create this board. In the directory `circuitpython/ports/raspberrypi/boards`, copy the Raspberry Pi Pico directory into a new one named appropriately

HIGH PERFORMANCE

In this tutorial, we've looked at creating a gamepad that's easy to understand and extend. However, if you're looking to build a high-performance gamepad, then there are lots of things that you need to take into account. Part placement is obviously a large part of it, as you need to be able to press buttons consistently and accurately.

However, another part is the software. Our CircuitPython code could be improved, but ultimately, if you're looking for high performance, CircuitPython isn't the right choice. Fortunately, there is another option.

GP2040-CE is a firmware for RP2040-based devices. You can configure it with details of what hardware is connected where. It understands more than just buttons, so you can add analogue inputs as well.

There's documentation on the project website: hsmag.cc/GP2040-CE.

for the gamepad. We've called ours **hackspace_gamepad**.

There are two files that we need to adjust to take into account our board. Firstly, there's `pins.c`, which should have the following:

```
#include "shared-bindings/board/__init__.h"

STATIC const mp_rom_map_elem_t board_module_globals_table[] = {
    CIRCUITPYTHON_BOARD_DICT_STANDARD_ITEMS

    { MP_ROM_QSTR(MP_QSTR_UP), MP_ROM_PTR(&pin_GPIO0) },
    { MP_ROM_QSTR(MP_QSTR_RIGHT), MP_ROM_PTR(&pin_GPIO1) },
    { MP_ROM_QSTR(MP_QSTR_LEFT), MP_ROM_PTR(&pin_GPIO2) },
    { MP_ROM_QSTR(MP_QSTR_DOWN), MP_ROM_PTR(&pin_GPIO3) },
    { MP_ROM_QSTR(MP_QSTR_BTN_A), MP_ROM_PTR(&pin_GPIO18) },
    { MP_ROM_QSTR(MP_QSTR_BTN_B), MP_ROM_PTR(&pin_GPIO19) },
};
MP_DEFINE_CONST_DICT(board_module_globals, board_module_globals_table);
```

In this, we're adding items to the board module. Specifically, one for each button.

```

ubuntu@lv-laptop:~/circuitpython/raspberrypi$
cd build-hackspace_gamepad/genhid/registration.h
D1H updated
cd build-hackspace_gamepad/genhid/strdefs_generated.h
Module registrations updated
cd build-hackspace_gamepad/genhid/moduledefs.h
root_pointer registrations updated
cd build-hackspace_gamepad/genhid/root_pointers.h
P1D1E ../frozen/Adafruit_CircuitPython_HID
PYTHONFEST ../frozen/Adafruit_CircuitPython_HID
pyy adafruit_hid/keyboard_layout_base.py
pyy adafruit_hid/consumer_control.py
pyy adafruit_hid/consumer_control_code.py
pyy adafruit_hid/mouse.py
pyy adafruit_hid/keyboard.py
pyy adafruit_hid/keyboard_layout_us.py
pyy adafruit_hid/keycode.py
cd build-hackspace_gamepad/frozen_content.c
tree: data: bin: doc: lib: libname
240 0 0 240 16 build-hackspace_gamepad/boot2.clf
/home/luke/arc-gpio/boot2/boot-112_mbl1300_6c_www-none-usb1/bin.c: /lib/gcc/arm-none-eabi/11.2.1/../../../../arm-none-
usb1/bin/ld: warning: build-hackspace_gamepad/firmware.clf has a LOOM segment with max permissions
Memory region Used Size Region Size Type Used
FLASH_ROMWARE: 84792B B 8000 KB 81.14%
RAM: 48608 B 256 KB 18.54%
SCRATCH: 0 KB 4 KB 0.00%
SCRATCH_X: 2 KB 4 KB 50.00%
COMPILING TO UF2: output: size: 1066256, start address: 0x10000000
Wrote 1066256 bytes to build-hackspace_gamepad/firmware.uf2
ubuntu@lv-laptop:~/circuitpython/raspberrypi$
  
```

Left We found it easiest to build CircuitPython using Windows Subsystem for Linux

“ We'll add Adafruit HID, which enables us to use our game controller as an input device **”**

OTHER GAMEPADS

This example should get you started in the world of game controllers, and there are loads that you can look at for inspiration:

- The Arduino Esplora is now retired, but was one of the first hackable game controllers on the market: hsmag.cc/ArduinoEsplora
- There's an online community at PCBWay's shared projects site that includes many game controllers, including: hsmag.cc/PicoGamepad
- Gamepads come in many shapes. They're usually designed around ergonomics, but you can get a little creative. For example, this maker has built a bat-shaped controller: hsmag.cc/BatController

Next, we need to edit **mpconfigboard.mk** to be the following:

```

USB_VID = 0x1209
USB_PID = 0xB182
USB_PRODUCT = "HackSpace gamepad"
USB_MANUFACTURER = "HackSpace magazine"

CHIP_VARIANT = RP2040
CHIP_FAMILY = rp2

EXTERNAL_FLASH_DEVICES = "W25Q128JVxQ"

CIRCUITPY__EVE = 1

FROZEN_MPY_DIRS += $(TOP)/frozen/Adafruit_CircuitPython_HID
  
```

make BOARD=hackspace_gamepad

In this file, we define the type of flash chip we have and also add any 'frozen' modules we want. Frozen modules can be anything that we want to be included on the build by default (other than the core modules that are automatically included). Frozen modules have to be in the **circuitpython/frozen** directory, but you should find that the Adafruit_CircuitPython_HID module is already there. You can now create your build by going to **circuitpython/ports/raspberrypi** and running:

```

This will compile your code, and you should end up with a build-hackspace_gamepad directory. In there, you'll find a firmware.uf2 file that you can load onto your gamepad just as you would any other UF2 file. Obviously this isn't complete firmware as it's only the programming language. We now need to write a program to get everything working. Fortunately, we have all the modules we need baked in, so there's no need for anything there. We've drawn inspiration from the CircuitPython example code here: →

import time
import board
import digitalio
import usb_hid
from adafruit_hid.keyboard import Keyboard
from adafruit_hid.keyboard_layout_us import KeyboardLayoutUS
from adafruit_hid.keycode import Keycode

# A simple neat keyboard demo in CircuitPython

# The pins we'll use, each will have an internal pullup
keypress_pins = [board.UP, board.DOWN, board.LEFT, board.RIGHT, board.BTN_A, board.BTN_B]
  
```

LEAD-FREE

It's often cheaper to get boards made using leaded solder. However, this might be a false economy. Leaded solder is harmful to both your health and the health of our planet. In the case of a games controller – something that you're going to hold in your hand time and again – it's more important than usual to opt for lead-free solder. Even if only a tiny amount gets on your hands each time you use it, that will still add up over the course of the controller's life, and could have negative effects on your health.

```
# Our array of key objects
key_pin_array = []
# The Keycode sent for each button, will be paired
with a control key
keys_pressed = [Keycode.UP_ARROW, Keycode.DOWN_
ARROW, Keycode.LEFT_ARROW, Keycode.RIGHT_ARROW,
Keycode.A, Keycode.B]

# The keyboard object!


time.sleep(1) # Sleep for a bit to avoid a race
condition on some systems

keyboard = Keyboard(usb_hid.devices)
keyboard_layout = KeyboardLayoutUS(keyboard)

# Make all pin objects inputs with pullups
for pin in keypress_pins:
    key_pin = digitalio.DigitalInOut(pin)
    key_pin.direction = digitalio.Direction.INPUT
    key_pin.pull = digitalio.Pull.UP
    key_pin_array.append(key_pin)

print("Waiting for key pin...")

while True:
    # Check each pin
    for key_pin in key_pin_array:
        i = key_pin_array.index(key_pin)
        key = keys_pressed[i]
        if not key_pin.value: # Is it grounded?
            print("Pin #%d is grounded." % i)
            # "Type" the Keycode or string
            keyboard.press(key) # "Press"...
        else:
```

Right  Our custom build of CircuitPython brings everything we need, including pin names and modules

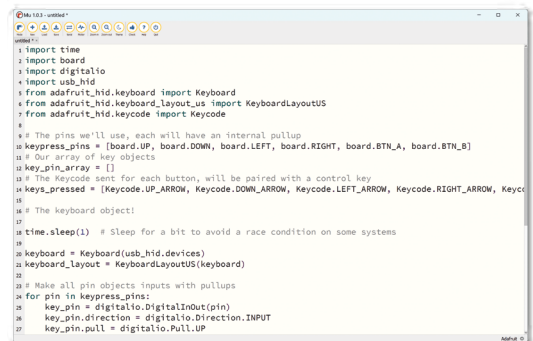
```
keyboard.release(key)
time.sleep(0.01)
```

As you can see, we can use `board.UP`, `board.DOWN`, `board.LEFT`, `board.RIGHT`, `board.BTN_A`, and `board.BTN_B` in our code. This has a couple of advantages. Firstly, it is more intuitive for programmers. Secondly, if we created another version of the board with the buttons on different pins, the same code could still run on both.

This code is a bit lazy. For example, there's no debouncing on the buttons. In practice, we've found that this doesn't cause many problems, especially with the `time.sleep(0.01)` in there. This means it's not the most responsive controller, so if you're playing games where hundredths of a second matter, you probably want to use something different, including tuned debouncing, written in C. However, this controller isn't suitable for that type of game anyway. This is also fairly cavalier with the number of reports it sends (a report being a status update sent from keyboard to computer). This will send six of them every loop, which means several hundred a second. Again, this isn't great for performance. However, it works reliably and is easy to understand.

With this code loaded, you should be able to plug the controller into any computer and it will recognise it as a USB keyboard. Press one of the buttons and the computer should recognise that button press just as it would from any keyboard. With this, you can control any game that takes input from a computer.

Creating a custom version of CircuitPython isn't essential when you build a new board; however, once you've been through the process once, it's easy, and makes life a little bit nicer, especially if you're distributing the board to other people. ▣



Tutorials from The MagPi Magazine

Design a circuit with KiCad



MAKER

Stewart Watkiss

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Design an electronic circuit for controlling high-power LED lights or model railway lighting

This tutorial will provide guidance on how to design your own circuit using KiCad. It will show how you can design a circuit that can be used with Raspberry Pi Pico. This will include choosing suitable components and designing a schematic diagram. This will then lead to creating your own custom printed circuit board (PCB) in the next tutorial.

This circuit is to control three sets of lights using buttons on the PCB or through a web interface. The design can be used for 5V or 12V lights, making it suitable for either home automation or model railway lighting.

01 Design idea

All projects start with an idea. When creating a breadboard circuit, you have an opportunity to experiment and change the design as required. Creating a custom PCB involves additional time and cost, so it is important to spend additional time in the design phase to get the circuit just how you want it.

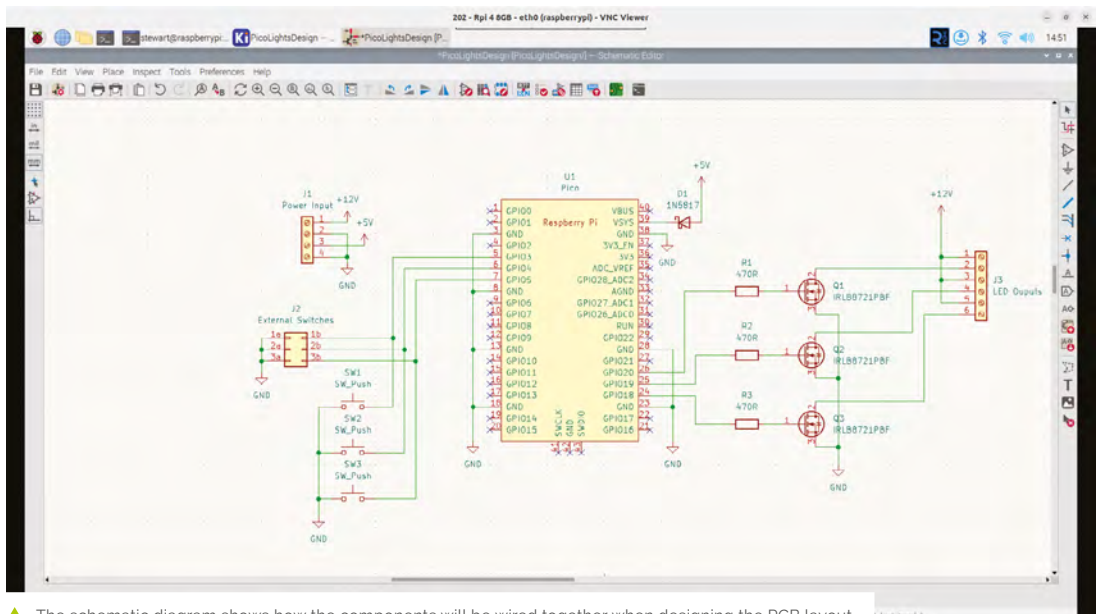
It is often useful to create a design specification that lists the features that you want, anything you want to avoid, and any restrictions it needs to be designed for. There may be restrictions on size, or you may want to provide additional flexibility to



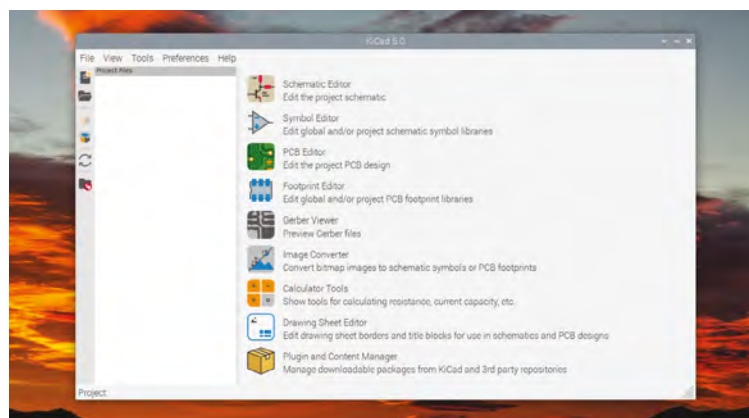
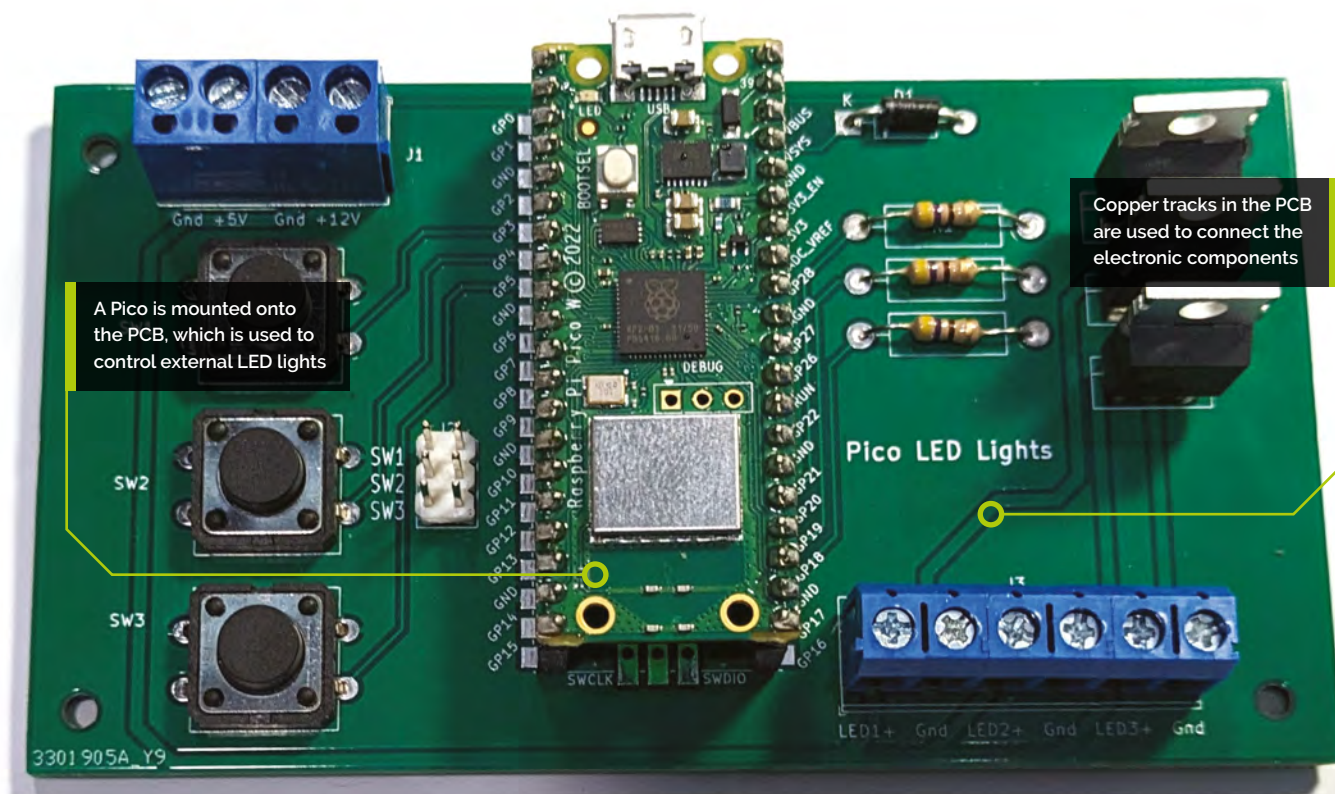
Warning!
Electrical Safety

Whilst 12V will not cause electrocution, it can cause a fire. Ensure power supplies have over-current protection and consider adding a fuse.

magpi.cc/electricalfires



▲ The schematic diagram shows how the components will be wired together when designing the PCB layout



add extra features. Sometimes these may conflict with each other, in which case you may need to make some compromises. Listing these up-front helps to keep your design on track.

02 Creating the initial design

With the idea and specification ready, you can start to make basic decisions about the circuit. Our first decision was to use a Raspberry Pi Pico. This project could be made using a Raspberry Pi computer, but it doesn't need

that amount of power for simple switching. Without the overhead of an operating system, Pico is more responsive, more reliable, and cheaper. A Pico W can be used to provide Wi-Fi access.

The plan is to switch high-power LEDs which are more than can be powered just using the GPIO pins on a Pico, so this is going to need MOSFET switch circuits.

It also needs to use switches for input, and these can be wired between GPIO pins and ground, using the internal pull-ups in Raspberry Pi Pico.

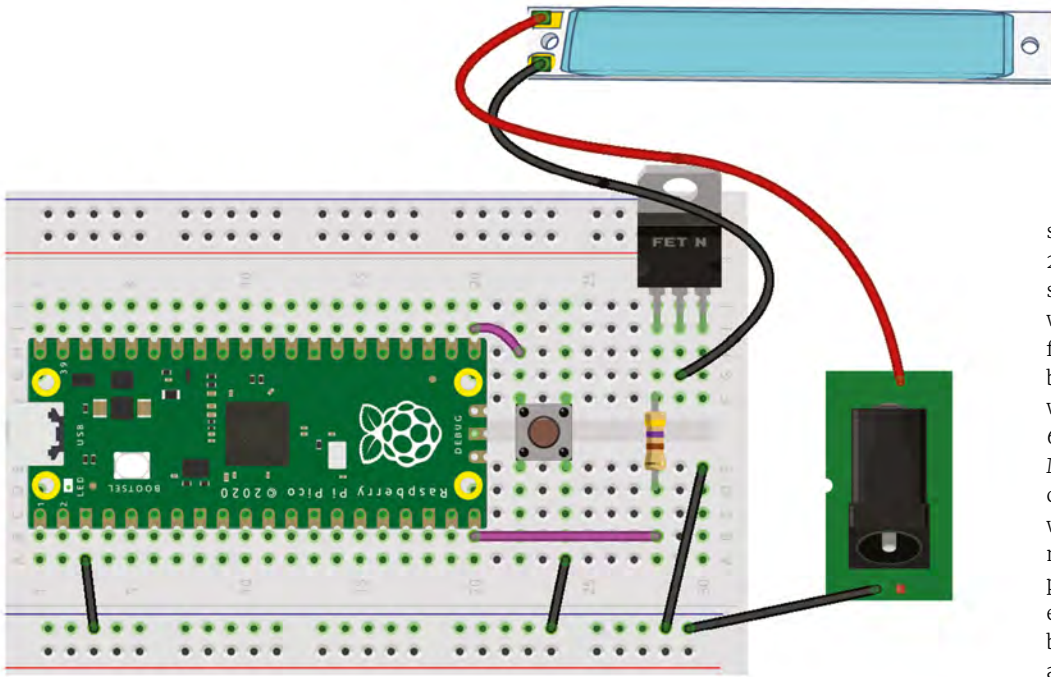
03 Flexible design

One thing to consider when designing a PCB is whether it will be used for a single circuit or whether it can be used for multiple purposes. It can be useful to include additional flexibility as that helps justify the cost of having a PCB made, but adding extra features will increase the size and cost of the PCB.

◀ **Figure 1:** KiCad includes different tools which can be used to help in designing printed circuit boards

You'll Need

- ▶ 470Ω resistors magpi.cc/470ohm
- ▶ 1N5817 diode magpi.cc/1n5817
- ▶ Switches magpi.cc/12x6switches
- ▶ PCB screw terminals magpi.cc/pcbterminal
- ▶ IRLB8721 MOSFET magpi.cc/mosfet
- ▶ 5V COB LED light magpi.cc/cobled
- ▶ Power adapter magpi.cc/jacktoscrew



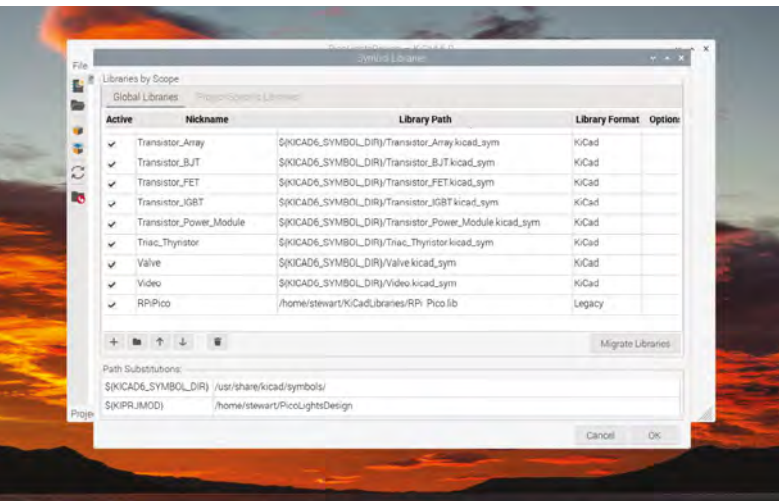
▲ **Figure 2:** A breadboard prototype with a COB LED light strip and a connector for a 5V power supply

The main thing here is what LED lights are to be controlled. In the specification for this build, it was decided that the board should be capable of controlling both 12V or 5V LED lights. The 12V lights would be useful for camping lights or model railways, and 5V would be useful for COB (chip-on-board) lighting strips. An appropriate voltage power supply is needed to match the LEDs used.

▼ **Figure 3:** To include a Pico in the design, add the RPi_Pico.lib library through the Manage Symbol Library menu option

04 Component selection

Having decided on the LEDs, you can now choose a MOSFET that is sufficient for controlling them.



A typical MOSFET for switching LEDs is the 2N7000. This MOSFET can switch up to 200mA, which will likely be sufficient for model railway lights, but not for the light strips which can draw up to 600mA. Looking at what MOSFETs are available, you can find the IRLB8721PBF which supports up to 62A, more than we need with plenty to spare. It is more expensive than the 2N7000, but the savings in having a single transistor type for different requirements

means that we can make savings by using a single PCB design for multiple projects.

05 Prototyping

The next stage is to test if your design will actually work. This is where the breadboard comes in useful because it allows you to try out

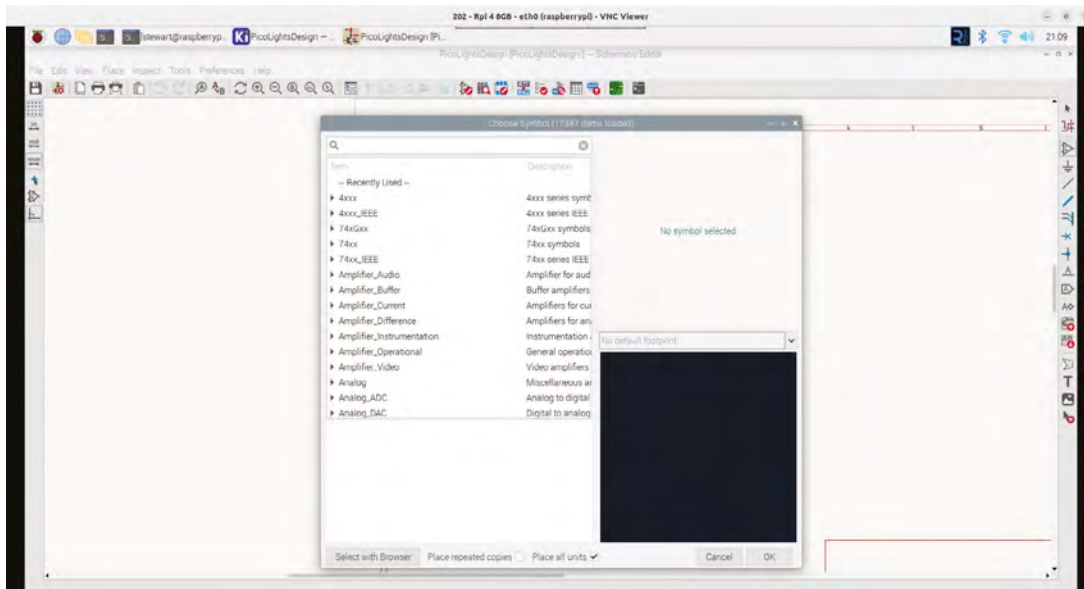
“ The next stage is to test if your design will actually work ”

different circuits and values. You may want to use a multimeter, or even an oscilloscope to check that the outputs are what you expect.

In this case, the electronics are made up of common circuit configurations, but as it's a different MOSFET than before, you may want to test it to see if it behaves in the way that you expect. The diagram in **Figure 2** shows an example using single switches and a single COB LED light strip to test the main components.

06 Moving to KiCad

In the design so far, you've hopefully been making notes about the decisions you've made. Now it's time to convert those to create a schematic diagram. The schematic diagram is



◀ **Figure 4:** There are over 15,000 different symbols available in the KiCad symbol library and many more are available to download from vendors

useful because it shows each of the components wired together without the difficulty of trying to follow individual wires.

The tool used here is KiCad, which is open-source software capable of creating professional circuits. You can run KiCad on most computers, including Raspberry Pi. To install on a Raspberry Pi, use the terminal command:

```
sudo apt install kicad kicad-packages3d
```

07 Creating the schematic diagram

After launching KiCad, you should see the project window. There should be no project selected and the right-hand side of the window shows the various tools which make up KiCad. This is shown in **Figure 1** (previous page). Create a new project by clicking on the new project icon and giving it a name, such as PicoLights. It will create a new directory and create a KiCad project file. You can then click on the Schematic Editor on the right to start a new schematic diagram.

You are presented with a blank drawing area. You can move around using a mouse with the right button pressed, and zoom using your mouse scroll wheel.

08 Adding a Pico footprint to KiCad

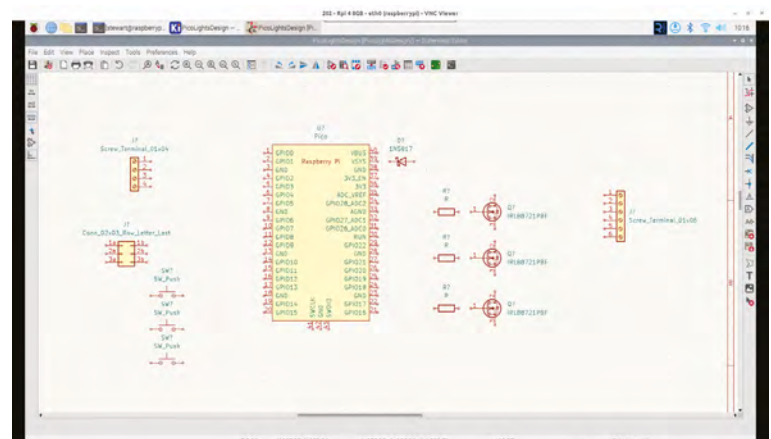
Whilst various models of Raspberry Pi are included in KiCad's component library, it does not currently include a Pico. To add a Pico symbol, first download the file from magpi.cc/kicadzip (note: direct download).

This file is a complete PCB design, but within the zip file are the files **RPI_Pico.lib** and **RPI_Pico_SMD_TH.kicad_mod**. Copy both files to a suitable directory (eg. KiCadLibraries) and choose Tools > Manage Symbol Libraries.

Click on the '+' icon to create a new library, name it 'RPIpico', then click on the folder icon in the Library Path column and select the lib file. It will add it as a Legacy library. This is shown in **Figure 3**. That .kicad_mod file will be used later when creating the PCB.

09 Adding components to the schematic

You can now add components by choosing Add Symbol from the Place menu, or by using the icon on the right-hand side of the schematic editor. Click the screen to bring up the symbol selector dialog, search for Pico, and select the one inside

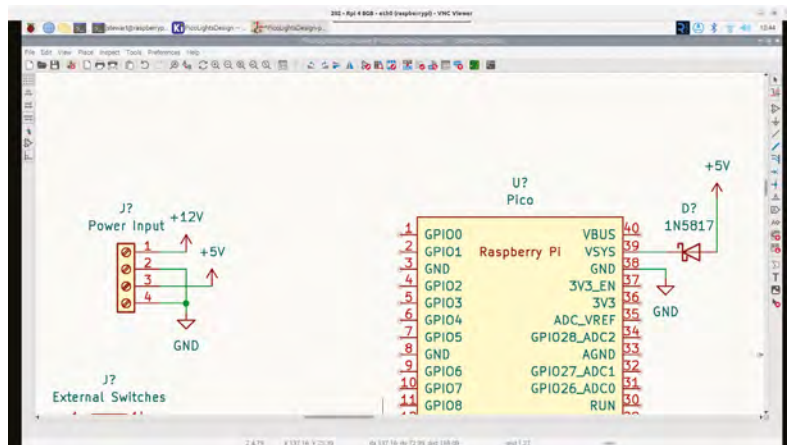


▼ **Figure 5:** All components are added and can be arranged by moving into position using the M key

Top Tip

Power options

Your Pico can be powered through a 5V connection to the screw terminal, or by using the USB port on your Pico



▲ **Figure 6:** Power label symbols are used to indicate the power supplies. Labels with the same name are treated as though they are connected

the RPiPico library, then click OK to add it to the schematic diagram. The symbol selector is shown in **Figure 4**.

For the button switches, use SW_Push. This will also provide headers which can be used to connect to an external switch that can be added as 'Conn_02x03_Odd_Even'.

The MOSFET is the IRLB8721PBF and add gate resistors (search for 'R' for the resistor symbol).

10 Powering the circuit

To provide power, a screw terminal is used. This needs two power supplies: one for your LEDs (12V or 5V depending upon LEDs) and one for the Pico (5V). These will be supplied using a 4-way terminal connector, Screw_Terminal_01x04. A 1N5187 diode is also needed to allow either the USB or screw terminal to be used.

The output will also be provided through screw terminals to connect to your choice of LED. Choose 'Screw_Terminal_01x06'.

The components can be moved into an appropriate position and rotated or mirrored using the right-click menu. Arrange the components so that they are similar to **Figure 5**.

11 Adding power connections

The value of the components can be changed using the 'Edit' value from the right-click menu. Change the resistors to 470R and rename the connectors to represent their purpose.

Rather than having to wire up all the different places where power is needed, power symbols can be used. Use +12V, +5V, and a common ground for both supplies' GND. If you place multiple power symbols with the same reference (you can use duplicate from the right-click menu) then they will all be connected together, reducing the number of wires needed. Connect the power symbols to the various components using 'Add wire' from the Place menu. The power connections for the input and Pico are shown in **Figure 6**.

12 Wiring

The rest of the components can be wired together to complete the circuit. When joining wires, there will be a circle over the connection to show that they are connected. If there is no circle, then crossing wires are not electrically connected.

You should also annotate the components by giving each a unique reference. You could do this manually using the properties of each component, changing 'J?' to 'J1' etc., or use 'Annotate Schematic' from the tools menu.

Code is provided (**simple-lights.py**) to allow you to test the prototype using the button LED. In the next tutorial, you will use the schematic to create a professional printed circuit board. [M](#)

simple-lights.py

► Language: **MicroPython**

DOWNLOAD THE FULL CODE:

magpi.cc/picolights

```
001. from machine import Pin
002. import utime
003.
004. sw1 = Pin(3, Pin.IN, Pin.PULL_UP)
005. sw2 = Pin(4, Pin.IN, Pin.PULL_UP)
006. sw3 = Pin(5, Pin.IN, Pin.PULL_UP)
007.
008. out1 = Pin(20, Pin.OUT)
009. out2 = Pin(19, Pin.OUT)
010. out3 = Pin(18, Pin.OUT)
011.
012. while(1):
013.     if (sw1.value() == 0):
014.         # Toggle out1
015.         out1.value(1-out1.value())
016.         utime.sleep (0.5)
017.     if (sw2.value() == 0):
018.         out2.value(1-out2.value())
019.         utime.sleep (0.5)
020.     if (sw3.value() == 0):
021.         # Toggle out3
022.         out3.value(1-out3.value())
023.         utime.sleep (0.5)
```

Create your own PCB



Warning!
Soldering

Soldering is relatively safe, but does use a very hot soldering iron. Take care to avoid getting burned.

magpi.cc/soldering

Make your own printed circuit board to make your circuits more professional. Use the finished PCB to control simple home automation



Stewart Watkiss

Also known as Penguin Tutor. A Maker and YouTuber who loves all things Raspberry Pi and Pico. Author of Learn Electronics with Raspberry Pi.

penguintutor.com

[@stewartwatkiss](https://twitter.com/stewartwatkiss)

You'll Need

- ▶ PCB
- ▶ Soldering iron and solder
- ▶ Bill of materials magpi.cc/picolightsbom

Previously, we looked at designing a printed circuit board (PCB) in KiCad. This time around, we will go from a schematic in KiCad to a printed circuit board design which can be sent off to manufacture. Add the components and solder it up to create a complete circuit. The design can be used for 12V lights, including bright light strips and model railway lighting, or the 5V COB lights used in the earlier tutorial.

Using Pico W allows wireless access, so you can control your lights using a smart phone or to integrate with home automation.

01 KiCad schematic

This is going to start with the schematic diagram from the previous tutorial. The diagram is shown in **Figure 1**. The circuit is designed and annotated but still needs some changes before turning it into a printed circuit board.

Our Raspberry Pi Pico documentation (magpi.cc/hwdesignrp2040) recommends connecting all the grounds on the Pico to ground. This should be set on pins 3, 8, 13, 18, 23, 28 and 38. All the rest of the pins should be set to unconnected, using the Add No Connect Flag from the Place menu.

02 Electrical rules checker

Next it is useful to run the electrical rules checker from the Inspect menu. This can be handy to identify pins that you've forgotten to connect, or are wired incorrectly.

Running this will bring up some errors and warnings. They will be listed in the Rules Checker

display as well as indicated by arrows on the schematic diagram.

The errors all relate to not driving power pins. This is because we are using the terminal connections to provide power and KiCad is not aware of that. To remove the three errors add a new power symbol, choosing PWR_FLAG. Add this to each of 12V, 5V and Gnd as shown in **Figure 3**.

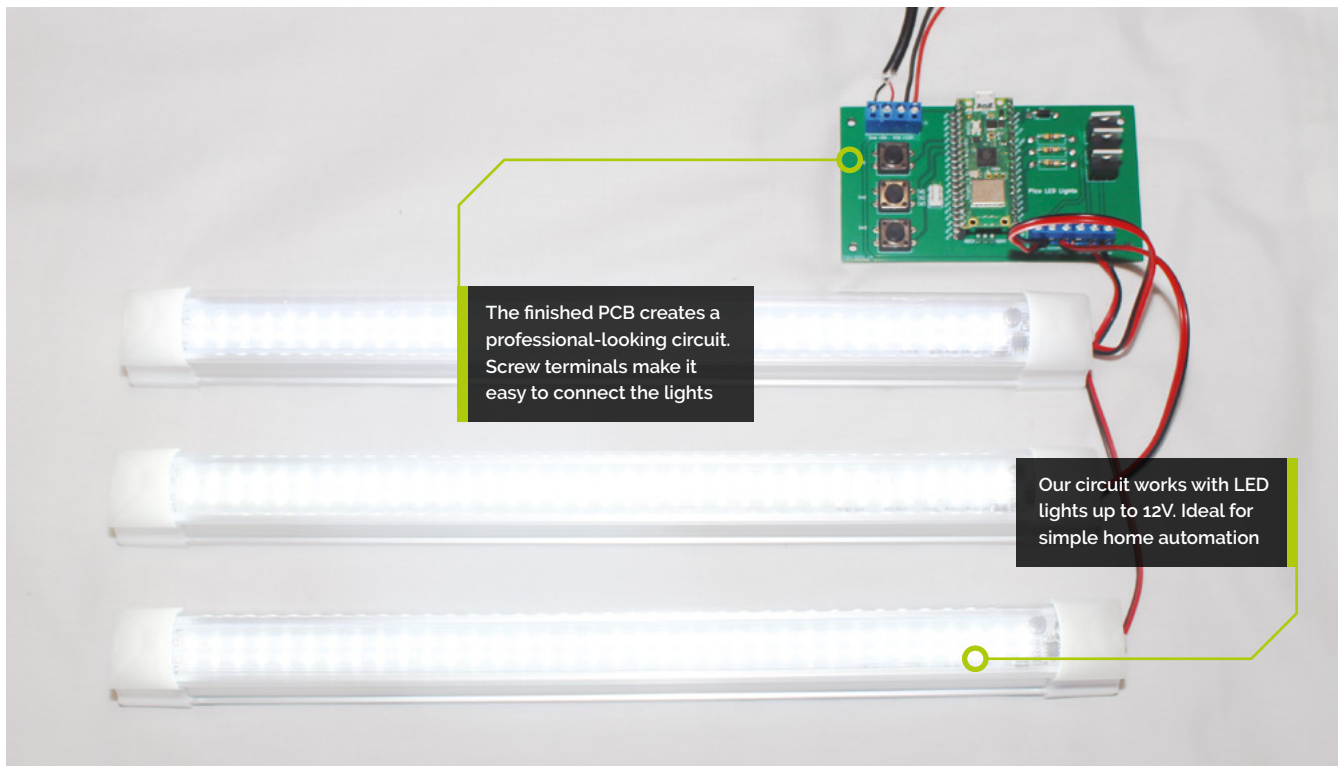
03 Update the Pico symbol

The rest of the violations are warnings which relate to some of the pins on the symbol of the Pico. For example, Pin 39 is listed as unspecified, but we are driving it as a power input. These could be safely ignored, but if you want to remove the messages edit the Pico symbol using the symbol editor.

Choose the pin table and change 38 to Power Input and 39 to Input. This is shown in **Figure 4**. Save the updated symbol and return to the schematic to run the electrical rules checker again. This will now just have the one warning saying that the symbol Pico has been modified. You can right click and exclude the violation.

04 Assigning footprints

Once the circuit passes the tests you can move on to assigning the circuit symbols to their physical symbols. This needs to be done because there are different components which need different pad positioning on the PCB. For example there are different resistor sizes and you need to tell KiCad which ones you intend to use.



Click on Assign Footprints from the Tools menu. You will see that some are already filled in based on their model number, including the MOSFETs and the diode.

For the rest, you will need to manually choose an appropriate symbol. There are three footprint filters across the top which can be useful, as well as clicking on the appropriate Footprint Libraries on the left side.

05 Choosing appropriate footprints

Then select the terminal screw connectors (labelled power input and LED outputs). Choose "TerminalBlock_Phoenix" and ensure the number of pins is selected in the footprint filters. Choose the appropriate terminal block based on the correct spacing, for example 5mm matches TerminalBlock_Phoenix_MKDS-1,5-4_1x04_P5.00mm_Horizontal. To ensure it looks correct, right click, and use View Selected Footprint. If you have installed the 3D package then you can also click on the 3D icon on the top of the view to see how it looks in 3D. See **Figure 5**. Double click on the footprint to associate it with the circuit symbol.

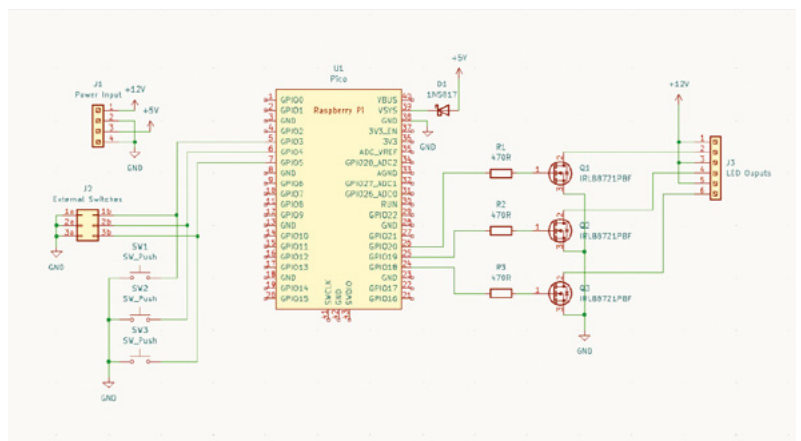
For the switch connection block use the library Connector_PinHeader_2.54mm (the same distance as the pins on a breadboard) and choose the one with 2x03 Vertical.

06 Different footprint options

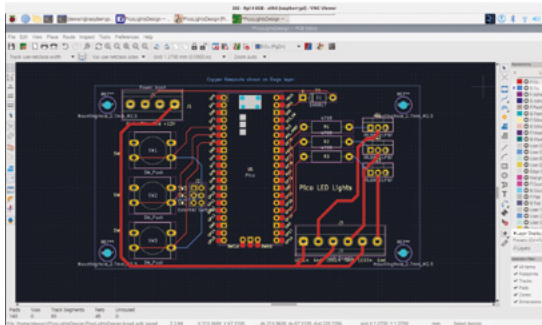
For the resistors then there are number of different resistor sizes under the Resistor_THT category (through-hole-technology). As well as representing different sized resistors they provide for different lengths of wires which can make it easier to solder. A typical 0.5W resistor has dimensions of approximately 9.9x3.6mm. Under Axial L9.9mm D3.6mm you can choose the one with P15.24mm which allows additional space for the resistor legs. Look at the 3D image to see how the resistor legs are bent a short distance from the resistor body.

The final components are the push buttons which you can use SW_PUSH-12mm.

▼ **Figure 1.** Here is our schematic diagram from the previous tutorial. The diagram shows the logical circuit design and how each of the components connect together



▶ **Figure 2.** The PCB design. The same components as the schematic diagram are instead positioned as they will on the final PCB



07 Adding the footprint library

The footprint for the RPi_Pico is listed but cannot be used yet as it has not yet been added to the footprint libraries. From the Preferences menu choose Manage Footprint Libraries and add the kicad mod file **RPi_Pico_SMD_TH.kicad_mod**, which was downloaded in the previous tutorial.

You can check that it is loaded using the footprint viewer. There is no 3D image for either the 12mm push buttons or the Pico footprint, so if you choose 3D viewer it will just show the position of the copper pads.

Top Tip

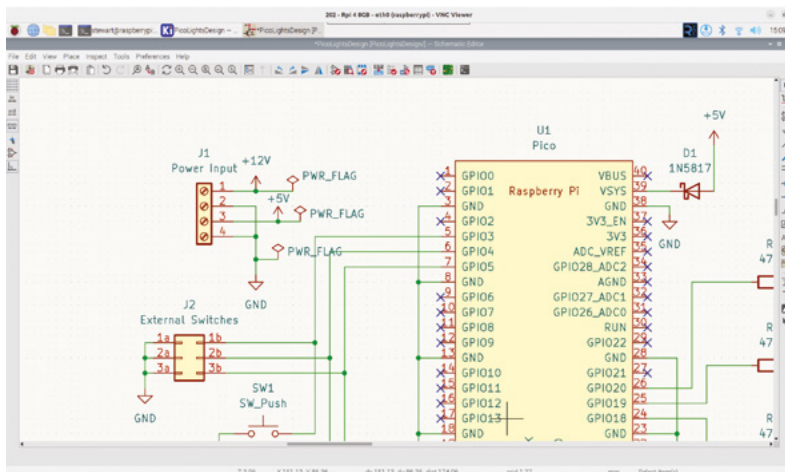
Different component packages

Electronic components are often available in different packages and sizes. Check that you use the KiCad footprint to match your components

▶ **Figure 3.** Adding PWR_FLAG symbols will fix the errors created from the electrical rules checker

08 PCB board editor

After choosing the footprints run the PCB editor, which can be launched from within the schematic designer or by going back to the project window. From the Tools menu click Update PCB from Schematic to import all the component footprints. The components will be imported, but all positioned close together. Choose each component individually and move them around to the positions you'd like them to be on the PCB. The switches should be on the left and the MOSFETs with their resistors on the right near to the GPIO pins assigned. Usually, you will want to put the components close together to reduce the size of



the PCB, but not too close that it makes routing wires more difficult. A suggested layout is shown in **Figure 6**.

09 Adding mounting holes

Before starting routing it is useful to ensure that all features are included in the layout. The one thing that is useful for many PCBs is to add mounting holes to make it easier to mount in an enclosure. This could have been done in the schematic but it's not relevant there, so it can be added just to the PCB.

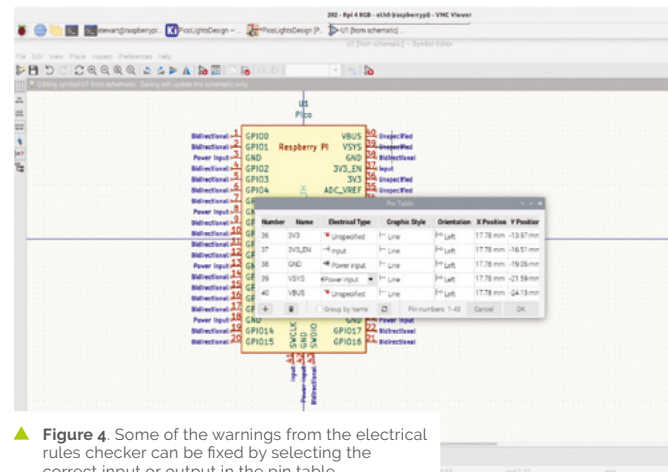
Choose Add footprint from the Place menu and search for 'mounting hole'. You can choose any appropriate size. M2.5 is a common size for PCB mounts, so you could use MountingHole_2.7mm_M2.5.

Once you have placed all the components you can draw a rectangle to show where the edge of the board will be. Choose the Edge.Cuts"layer before drawing the rectangle. This is shown in **Figure 7** (see the blue arrow indicating the Edge.Cuts layer is selected).

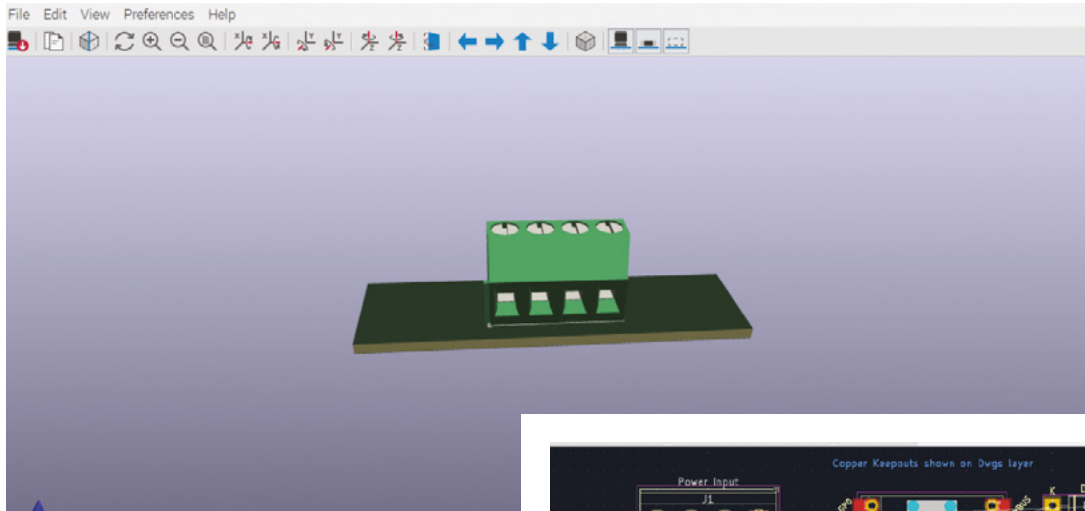
10 Laying the 12V tracks

When designing PCBs you can normally use the default track width. For this project the current from the power input could be as high as 1.8A so will need wider tracks for those. Click on the Track pull-down menu in the top left and choose Edit pre-defined sizes.

Add a track width of 0.25mm (standard size for KiCad and useful for most purposes) and one for



▶ **Figure 4.** Some of the warnings from the electrical rules checker can be fixed by selecting the correct input or output in the pin table



▲ **Figure 5** The 3D viewer can be useful to check that you have selected the correct component

1mm (for high current connections). Use the pull-down menu to switch between those as required.

You can now start by routing the connections around the board. First select the top copper layer (F.Cu) and start drawing the wide tracks for the 12V power connections and connections to the MOSFET drain. Ignore Gnd as that will be done last.

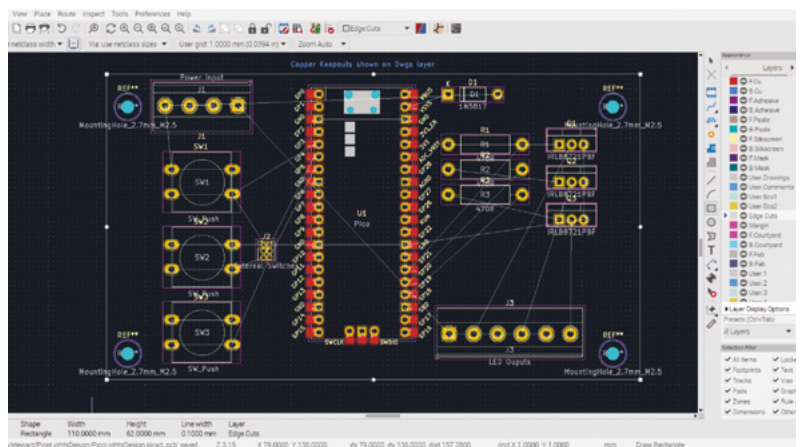
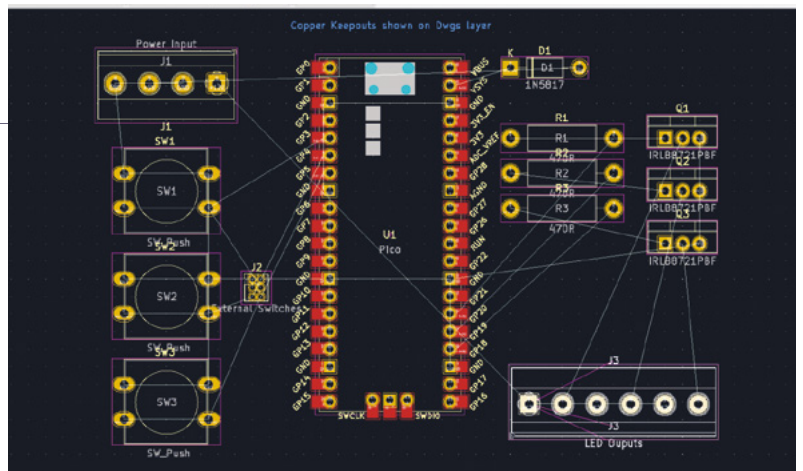
11 Completing the tracks

Switch to the 0.25mm track size and continue laying out the rest of the tracks. KiCad shows the require connections (called nets) using thin lines. You may find it useful to rotate some of the components if that will make routing easier. If it is not possible to run a connection without crossing another track then you can switch to the back copper layer B.Cu. The front layers are coloured red and the back layers are blue to make them easier to identify.

The ground connections can be handled using a ground fill which can be placed on the front and back layers. This will fill all the unused space on the board with copper and connect it to ground, which can help reduce electrical noise. Use Add Filled Zone and draw a rectangle along the entire PCB enabling both layers and GND. There will be small lines around the PCB to indicate there is a copper fill.

12 Inspect the PCB

Choose Fill all zones from the Edit menu to connect the ground connections to the ground plane. You can turn the display of the fill on and



▲ **Figure 7** The Edge Cut layer is used to mark where the edge of the PCB will be cut

off using the 'show filled zone' and 'show zone' boundaries icons on the left. The status bar on the bottom should now show 'unrouted' as 0 to indicate that all the appropriate pins are connected. If not, then add any missing connections and re-run Fill all zones to update.

You can then run the Design Rules Checker to test the PCB for potential errors. There will be warnings about drilled holes being co-located (which relates

Top Tip

Check the PCB

It is worth taking time to check all the routing and component positioning on the PCB. This can help reduce delays and the cost later

to the mounting holes) and silkscreen being clipped by solder mask. These messages can be ignored. Any warnings about silkscreen overlap can be fixed by re-arranging the labels from the components.

13 Labels and final checks

The final part of the board design is to add any additional text or labels which should normally be on the F.Silkscreen layer. Only the text shown on that layer (yellow) will be printed on the PCB.

As a final test you should also print a paper copy of the PCB to check that the components fit correctly. At a minimum, print the front Silkscreen layer and compare it with the size of your components.

14 Export for manufacturer

The final stage in KiCAD is to export the PCB and send it to a manufacturer. The exact process depends upon your PCB manufacturer, the example used here is for JLCPCB and the process is explained here: magpi.cc/jlpcbprocess.

Choose Fabrication Outputs and Gerber. Set Output directory to `picolights-gerbers`. Select Protel filename extensions and Subtract soldermask from silkscreen (this will fix some of the warnings in the design rules checker). Then click plot. See **Figure 8**.

In the same dialog box, click Generate Drill Files. Choose Alternate drill mode for Oval Holes. Use mm

for drill units. Then Generate Drill File and then Generate Map File.

You can then use the Gerber Viewer to check the files. Look to ensure that all the layers line up correctly and that the outline is shown without any breaks.

Finally you can zip the file, submit it to your chosen manufacturer, and wait for the results.

15 The PCB arrives

Depending upon your the manufacturer and shipping times it may take a week or two before you get the PCB back. This should provide time to buy any parts you need ready to solder it together when it arrives. A link to the bill of materials (BOM) is included, which lists all the components. You will also need a soldering iron and some solder. The list is based on 12V light strips, but you could also use the 5V COB LED strips and appropriate power supply which were used in the previous tutorial.

16 Soldering

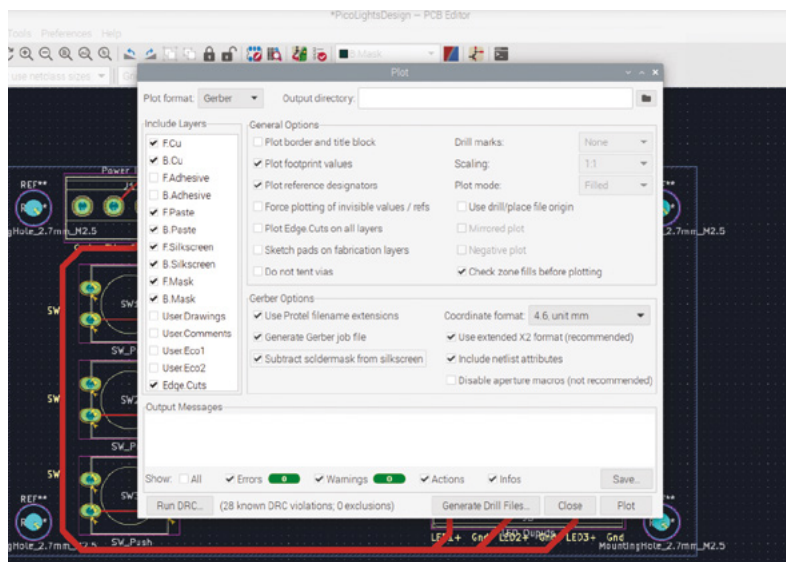
The components listed are all through hole components which should make soldering fairly easy. For best results, hold the soldering iron so that it is in contact with both the pad on the PCB and the lead of the component (see **Figure 9**). Then, feed the solder in: it will melt and make a metal joint between the component and the PCB. After removing the soldering iron it should cool down quickly to form a permanent electrical connection. It's usually easier to start with the smaller components, such as resistors, as they fit flush to the PCB. If a component won't stay still then you can use Blu Tack (sticky putty) or something similar to hold the component in place whilst it is soldered.

17 Connecting to the lights

Once soldered, mount Pico into the headers with the USB connector towards the top of the board. Then connect suitable power supplies to the terminals at the top. The 12V connection may be a different voltage if using LED lights designed for other voltages. The 5V supply is used for powering Pico.

Connect an LED light to each of the three outputs at the bottom of the PCB and it just needs the code to be uploaded to your Pico.

Figure 8. Use the plot option to export ready for manufacture. You may need to adjust settings for different manufacturers

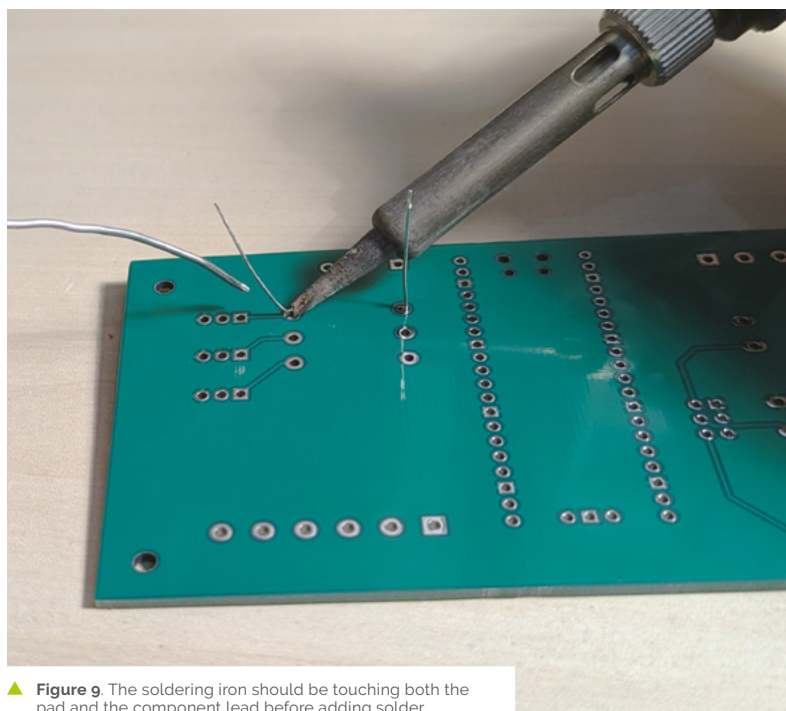


18 Upload the code

The code is provided for a basic web server which needs to be installed on a Pico W. You will need to use the network-enabled version of the UF2 file, which can be installed using the installer within the Thonny editor. The code file is named **web-lights.py**, which can be saved on your Pico as **main.py** to run automatically. A file called **secrets.py** also needs to be saved onto your Pico with entries for the SSID and PASSWORD for your local Wi-Fi network.

When the code is running, you can connect to the web server using a web browser. You will need the IP address of the Pico which you can see through the Thonny console or by looking at the address allocation on your Wi-Fi router.

As well as using the web interface you can also turn the lights on and off using the three button switches. 



▲ **Figure 9.** The soldering iron should be touching both the pad and the component lead before adding solder

web-lights.py

> Language: **MicroPython**

**DOWNLOAD
THE FULL CODE:**



magpi.cc/picolights

```

001. from machine import Pin
002. from utime import sleep
003. import network
004. import socket
005. import uasyncio as asyncio
006. import secrets
007. import re
008.
009. # Indexed at 0 (board labelling is 1)
010. # These must be the same length (ie 3)
011. outputs = (20, 19, 18)
012. switches = (3, 4, 5)
013.
014. # shortened version for the pin objects
015. out = []
016. sw = []
017.
018. html = """<!DOCTYPE html>
019. <html>
020. <head> <title>Pico Lights Plus</title> </head>
021. <body> <h1>Pico Lights Plus</h1>
022. <ul>
023. <li><a href="/lights?light=1&action=toggle">LED
024. 1</a></li>
025. <li><a href="/lights?light=2&action=toggle">LED
026. 2</a></li>
027. <li><a href="/lights?light=3&action=toggle">LED
028. 3</a></li>
029. </ul>
030. </body>
031. </html>
032. """
033. # Uses out to toggle - sets led to same
034. def toggle_out (pin):
035.     new_state = 1 - out[pin].value()
036.     print ("Setting out {} to {}".format(pin,
037. new_state))
038.     out[pin].value(new_state)
039.
040. def connect():
041.     #Connect to WLAN
042.     wlan = network.WLAN(network.STA_IF)
043.     wlan.active(True)
044.     wlan.config(pm = 0xa11140) # Disable power
saving mode
045.     wlan.connect(secrets.SSID, secrets.PASSWORD)
046.     while wlan.isconnected() == False:
047.         print('Waiting for connection...')
048.         sleep(1)
049.     ip = wlan.ifconfig()[0]
050.     print(f'Connected on {ip}')
051.     return ip

```


web-lights.py cont...

> Language: **MicroPython**

```

052.
053. def setup_pins ():
054.     # uses length of outputs
055.     for i in range (0, len(outputs)):
056.         out.append(Pin(outputs[i], Pin.OUT))
057.         sw.append(Pin(switches[i], Pin.IN,
Pin.PULL_UP))
058.
059. async def serve_client(reader, writer):
060.     print("Client connected")
061.     request_line = await reader.readline()
062.     print("Request:", request_line)
063.     # We are not interested in HTTP request
headers, skip them
064.     while await reader.readline() != b"\r\n":
065.         pass
066.
067.     # Regular expressing Looking for toggle
request
068.     m = re.search ('light=(\d)&action=toggle',
request_line)
069.     if m != None:
070.         led_selected = int(m.group(1))-1
071.         # check valid number
072.         if (led_selected >=0 and led_selected <=
2) :
073.             print ("LED selected "+str(
led_selected))
074.             toggle_out (led_selected)
075.
076.         writer.write('HTTP/1.0 200 OK\r\nContent-
type: text/html\r\n\r\n')
077.         writer.write(html)
078.
079.         await writer.drain()
080.         await writer.wait_closed()
081.         print("Client disconnected")
082.
083. # Initialise Wif
084. async def main ():
085.     setup_pins ()
086.     print ("Connecting to network")
087.     try:
088.         ip = connect()
089.     except KeyboardInterrupt:
090.         machine.reset
091.         print ("IP address", ip)
092.         asyncio.create_task(asyncio.start_server(
serve_client, "0.0.0.0", 80))
093.         print ("Web server listening on", ip)
094.         while True:
095.             #onboard.on()
096.             # Enable following line for heartbeat
debug messages
097.             #print ("heartbeat")
098.             await asyncio.sleep(0.25)
099.             # Check gpio pins 10 times between
checks for webpage (5 secs)
100.             for i in range (0, 5):
101.                 check_gpio_buttons()
102.
103. # Main loop
104. def check_gpio_buttons ():
105.     for i in range (0, len(sw)):
106.         if sw[i].value() == 0:
107.             toggle_out(i)
108.             sleep (0.5)
109.
110. if __name__ == '__main__':
111.     try:
112.         asyncio.run(main())
113.     finally:
114.         asyncio.new_event_loop()
115.     except KeyboardInterrupt:
116.         machine.reset
117.         print ("IP address", ip)
118.         asyncio.create_task(asyncio.start_server(
serve_client, "0.0.0.0", 80))
119.         print ("Web server listening on", ip)
120.         while True:
121.             #onboard.on()
122.             # Enable following line for heartbeat
debug messages
123.             #print ("heartbeat")
124.             await asyncio.sleep(0.25)
125.             # Check gpio pins 10 times between
checks for webpage (5 secs)
126.             for i in range (0, 5):
127.                 check_gpio_buttons()
128.
129. # Main loop
130. def check_gpio_buttons ():
131.     for i in range (0, len(sw)):
132.         if sw[i].value() == 0:
133.             toggle_out(i)
134.             sleep (0.5)
135.
136.
137. if __name__ == '__main__':
138.     try:
139.         asyncio.run(main())
140.     finally:
141.         asyncio.new_event_loop()

```