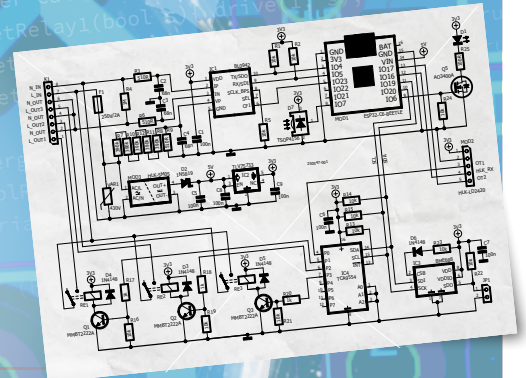
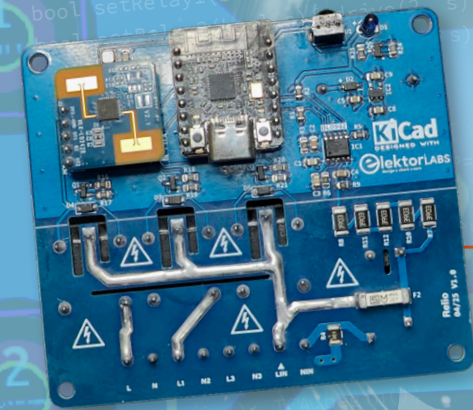


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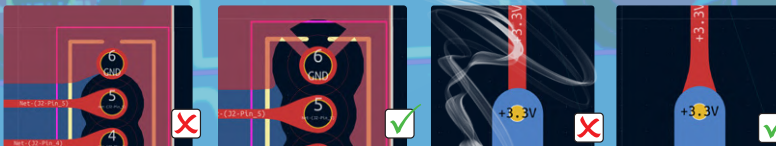
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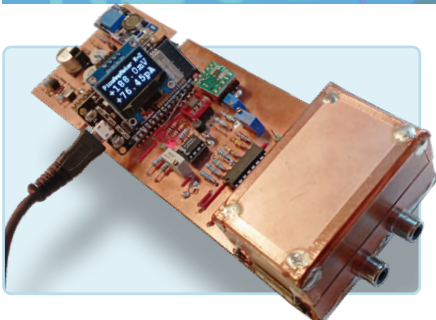
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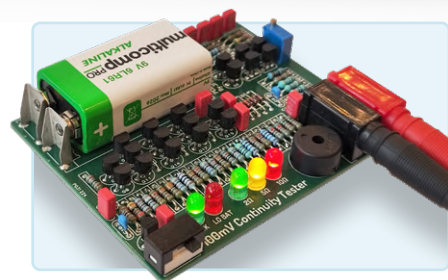
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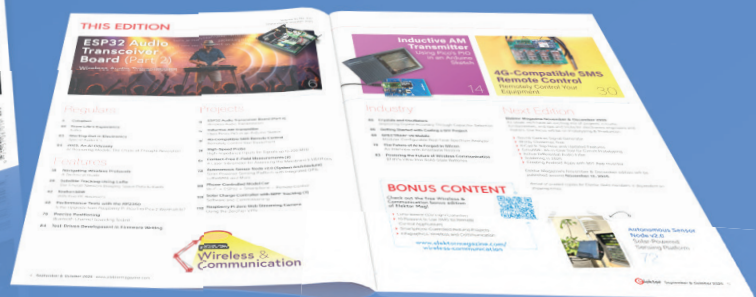
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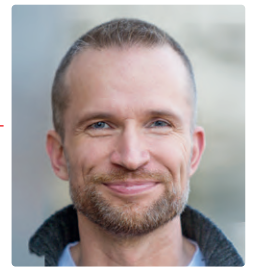
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Jens Nickel

International Editor-in-Chief, Elektor Magazine



Every Hour Is Worthwhile

At the end of the year, we traditionally focus on prototyping and production. This is a very broad field, ranging from brainstorming about an idea to assembling and testing a circuit board. These topics also have a personal connection for me: Never before have I spent so much of my free time on development, circuit board design, soldering, and testing various prototypes as I have this year. But you'll agree with me: When you use your device for the first time, it's a really great feeling, and you've also learned a lot and gained a lot of experience — every hour is worth it.

In an issue like this, an article with tips and tricks for circuit board design is a must. The one in this edition was written by my colleague Saad Imtiaz, whose expertise has always been the final authority for my boards (page 14). Saad's favorite ECAD program has become KiCad, and he now shares this preference with most of our readers. We therefore asked our long-time book author Peter Dalmaris to write an article on the latest features of this open-source software package (page 22).

For those thinking in terms of larger quantities, a trip to Munich may also be worthwhile. At productronica, which opens its doors from November 18 to 21, circuit board manufacturers and suppliers of soldering and assembly equipment will be presenting their latest products, services, and trends (page 56).

As always, this issue also features interesting projects from colleagues and external authors. To highlight just one project: Johannes Sturz has developed not only a clever analog front end for his precision picoammeter, but also a great software interface that can be used to record and display characteristic curves (page 33).

Did I say "at the end of the year" at the beginning? We're not quite at the end of 2025 yet, because there's another issue coming in December that you won't want to miss — hopefully you're already a member of our Elektor community and receive all the issues. With Edge Impulse, we have gained one of the most interesting players in AI as an editorial partner. I can promise you that the magazine will be filled with amazing projects. In addition, there will be tutorials that make AI that works directly on microcontrollers understandable and reproducible, even for beginners.



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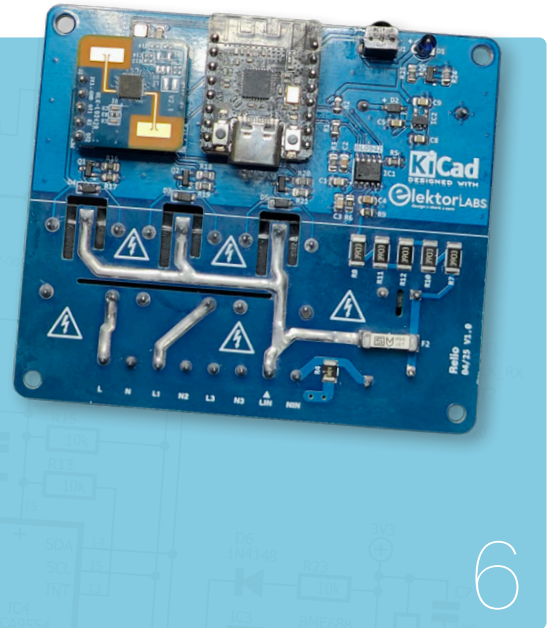
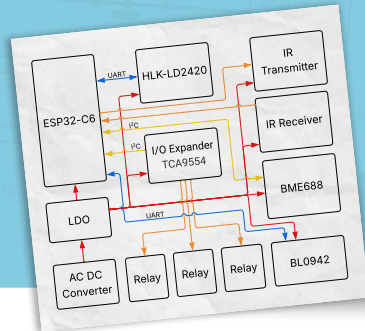
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Relio v1.0 — Presence Detection and Remote Control

A Matter-Enabled
Smart Controller for
AC Appliances



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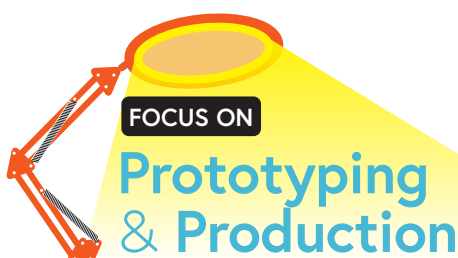
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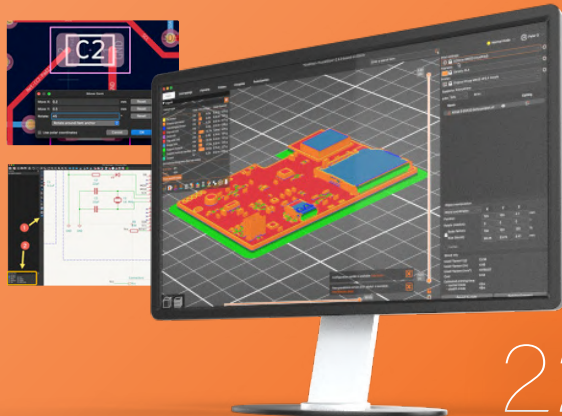


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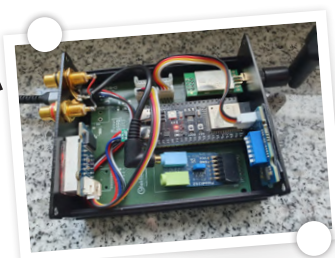
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For the next edition, Elektor editors are teaming up with experts from Edge Impulse to bring you a special Guest-Edited Edition. As you would expect from Elektor, DIY projects are the heart of this edition, but you'll also find in-depth tech tutorials, exclusive interviews, and much more.

- PCB Defect Detection: Computer Vision with Raspberry Pi
- Tutorial: Keyword Spotting
- ESP32 Energy Meter: Using AI to Recognize Household Loads
- AI Toaster: When Edge AI Meets Breakfast
- Edge Impulse on the Arduino Nano 33 BLE Sense
- Analog Gauge Reader

Elektor Guest-Edited Edition 2025 will be published around **December 10, 2025**.

Elektor Magazine January & February 2026

As usual, we'll have an exciting mix of projects, circuits, fundamentals, and tips and tricks for electronics engineers and makers. Our focus will be on Power & Energy.

- Low Noise PSU
- Adjustable USB-C-Power Supply
- Dynamic DC-Load
- Mains Frequency Meter
- Lithium Battery Practice

Elektor Magazine's January & February 2026 edition will be published around **January 14, 2026**.

Arrival of printed copies for Elektor Gold members is subject to transport.

Relio v1.0

Presence Detection and Remote Control

A Matter-Enabled Smart Controller for AC Appliances

By Saad Imtiaz (Elektor)

Relio is a compact, Matter-enabled smart device that integrates presence detection, environmental sensing, IR control, energy monitoring, and relay switching. Built around the Beetle ESP32-C6 controller module, it provides a universal way to bring intelligence to existing room appliances.

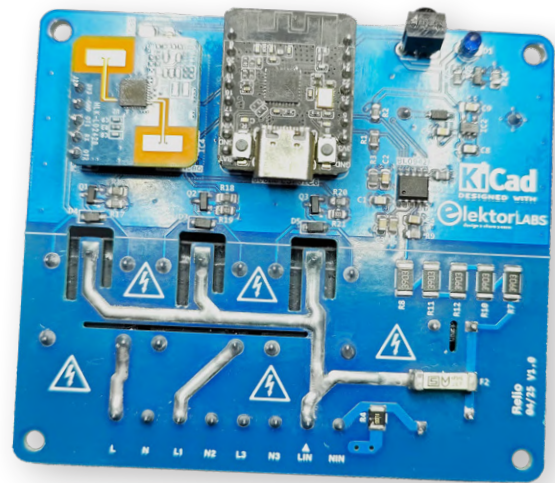


Figure 1: Relio, a Matter-based Smart Controller.

The idea for this project came from a very practical need. I wanted to automate my lab in a way that felt seamless and didn't require rewiring or installing multiple separate devices. On most days, I'm switching between workbenches, equipment, and coding, and often leave the lab in a bit of a rush. I needed something that could automatically switch off the lights or AC when I step out, but also keep them running while I'm at the desk working. The goal was to avoid leaving anything running unnecessarily, without having to constantly reach for switches or remotes. I also wanted the same compact device to control the lab lights, AC, or heater — depending on the season — with real power monitoring built-in. This led to the design of *Relio* (Figure 1), short for Relay + I/O, a small module that combines multiple switching and sensing functions into a single, Matter-enabled device.

Most smart home products can only handle a single appliance type or rely on cloud ecosystems that don't work well offline. I wanted a local-first solution, preferably Matter-compatible, that could fit into a wall box or surface-mount panel and support IR-controlled devices as well. This led to designing a single compact module that combines presence sensing, IR control, power monitoring, and high-voltage relay switching — all managed through a Beetle ESP32-C6 controller module

which is based on the popular ESP32-C6 by Espressif. The device now forms the foundation of a smarter lab environment that adapts to occupancy, controls appliances intelligently, and logs power usage, all without depending on external servers.

What Is Matter?

Matter is a connectivity standard created by the Connectivity Standards Alliance (CSA) [1], with support from Apple, Google, Amazon, and others. Its goal is to solve the fragmentation in smart homes by allowing devices from different brands to work together. Instead of relying on proprietary cloud services or hubs, Matter devices communicate locally using IP-based networks such as Wi-Fi, Ethernet, or Thread.

For makers, the big advantage is that Espressif now provides native Matter support in the ESP32 family, including the ESP32-C6 used in this project. This makes it possible to build custom devices that appear in commercial apps like Apple Home or Google Home with only minimal firmware changes. A more detailed look at Matter's protocol can be found in another Elektor article [2].

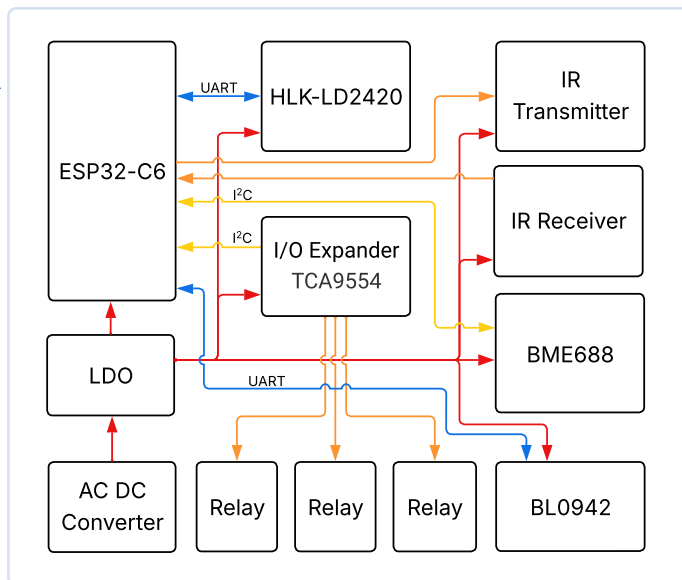


Figure 2: The block diagram.

At a minimum, it is important to understand that Matter devices require a controller — typically a smartphone running a smart home app such as Apple Home or Google Home. In this project, Relio acts as the Matter device, while the phone and app serve as the controller that pairs with it, manages communication, and provides the user interface.

Although the standard is still evolving and not all device categories are covered yet, Matter is quickly becoming the preferred foundation for building local-first, secure, and interoperable IoT devices.

Block Diagram

Relio brings together several functional blocks into a compact unit that can be fitted into a wall box or surface-mounted enclosure. At its core is the Beetle ESP32-C6 [3], chosen for its native Matter support, Wi-Fi 6 and Thread capability, and small footprint (see the block diagram in **Figure 2**). For sensing human presence, the design uses the HLK-LD2420 by Hi-Link [4], a 24 GHz radar module that offers more reliable occupancy detection compared to traditional PIR sensors. Environmental data such as temperature, humidity, pressure, and air quality are monitored using the Bosch BME688 sensor [5].

To control appliances directly, Relio integrates three relays capable of switching more than 5 A at AC mains, making them suitable for lights, heaters, and small air conditioners. Power consumption of the connected loads is measured using the BL0940 energy metering IC by Belling [6], allowing users to track voltage, current, and real-time power usage. For devices that rely on infrared control, such as TVs or split-type AC units, an IR transmitter and receiver provide compatibility. Finally, a TCA9554 I²C expander is included to manage the relay outputs without consuming excessive GPIO pins on the ESP32-C6.

The Schematic

The schematic (**Figure 3**) is organized into several functional blocks that work together under the control of the Beetle ESP32-C6 module.

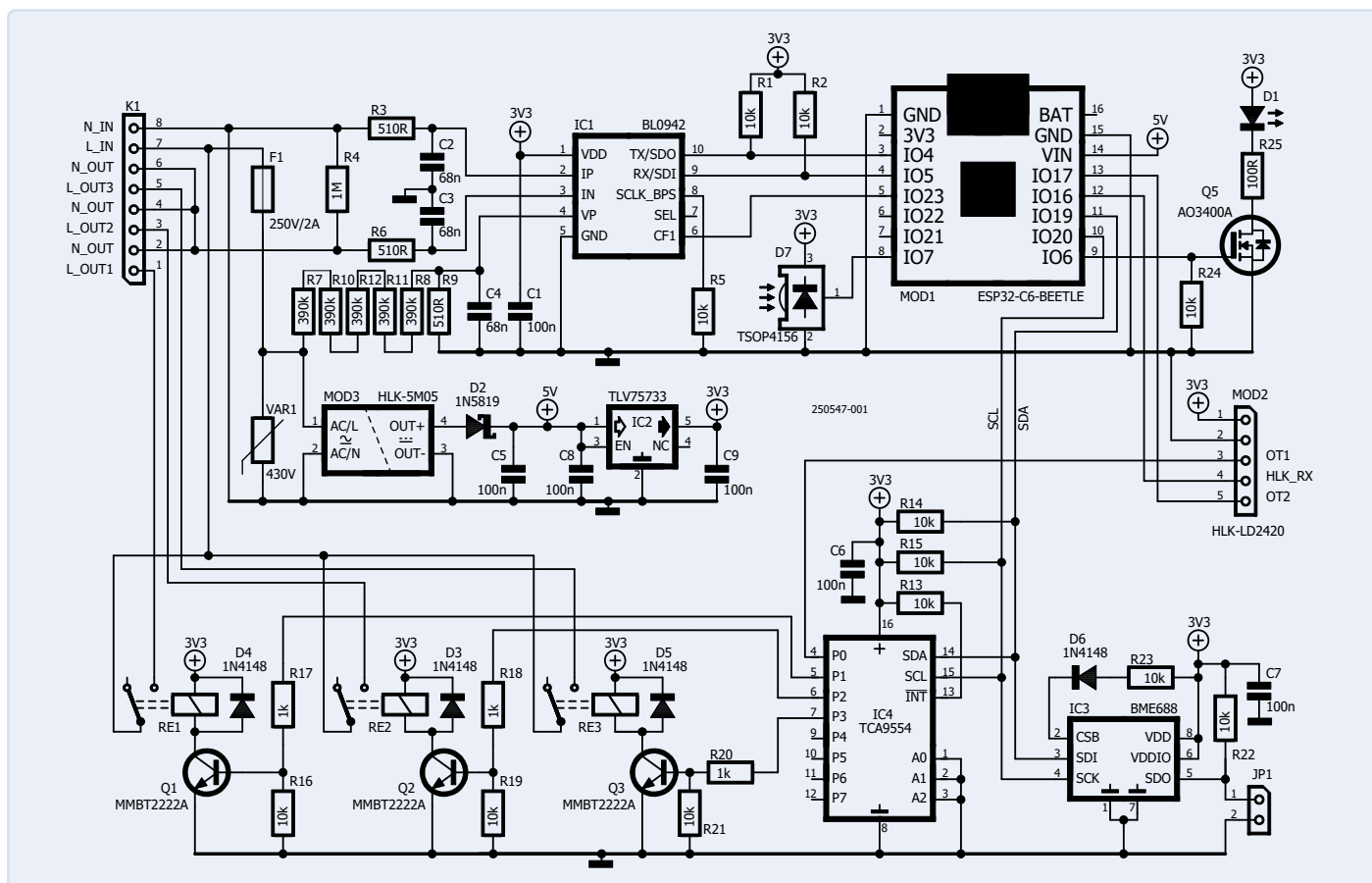


Figure 3: Schematic diagram.

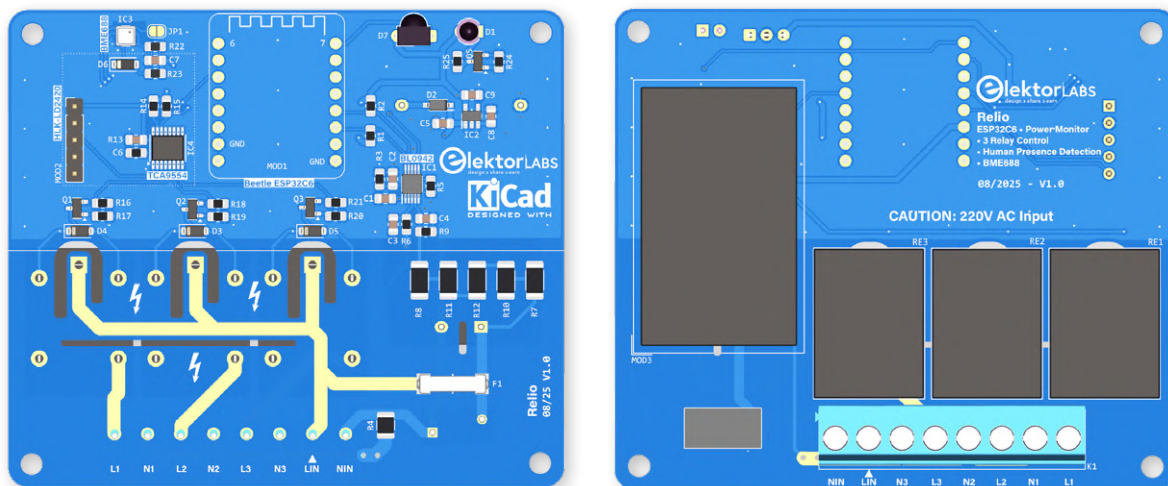


Figure 4: PCB rendering of the project, front and back.

Starting from the power input: The AC mains are routed through a fuse and MOV (Metal Oxide Varistor, which protects the circuit from voltage spikes by acting as a surge protector), before entering a compact AC-DC converter module HLK-5M05 by Hi-Link [7], which provides a stable 5 V output. This supply is then regulated down to 3.3 V through an LDO, powering the ESP32-C6, sensors, and digital circuitry. The use of fuse and surge protection components ensures that the low-voltage electronics remain protected from mains disturbances.

For load control, three independent relay circuits are provided, each driven by a transistor stage (Q1–Q3 in the schematic). These relays can switch AC loads and each is equipped with a flyback diode to handle inductive transients. To save I/O pins on the ESP32-C6, relay control is handled via an I²C I/O expander TCA9554 by Texas Instruments [8], which provides additional GPIO lines dedicated to the relay drivers.

Sensing functions are distributed across several modules. The BME688 environmental sensor is connected via I²C, allowing Relio to measure temperature, humidity, barometric pressure, and air quality (JP1 can be used to change the I²C address). Occupancy detection is provided by the HLK-LD2420 radar module, which communicates through a UART interface (RX and OT2 as TX) with the ESP32-C6. HLK-LD2420 also has an IO (OT1) for reporting detection status, high for occupied and low for unoccupied, which makes integration simple.

Q5 (a transistor) and D1 (the IR LED) form the IR transmitter. The ESP32-C6 drives Q5, which switches current through the IR LED (D1) to emit the modulated infrared light used for controlling appliances. The TSOP module nearby is the IR receiver, which demodulates incoming IR signals from a remote control and passes them back to the ESP32-C6 for decoding.

Energy monitoring in Relio is handled by the BL0942 (IC1), designed for single-phase applications such as smart sockets and appliances. The IC integrates two high-precision sigma-delta ADCs to simultaneously measure current and voltage, and it computes RMS voltage, RMS current, active power, active energy, and frequency internally with a built-in DSP. Voltage input at VP is limited to about ± 100 mV differential and the current input to ± 50 mV differential, which is why external resistor networks and shunts are required for scaling. The current channel connects across a low-value shunt resistor (R4) via the IP/IN pins, while the VP input measures mains voltage through a high-value resistor divider (R7 to R12). According to the datasheet, the

device supports current measurement from 10 mA up to 35 A (with a 1 m Ω shunt) and active power measurement from 1 W to 7700 W at mains voltage. The BL0940 outputs pre-calculated data over UART (4800 bit/s, 8N1, half-duplex) or SPI, greatly reducing the processing load on the ESP32-C6. Additional features include zero-cross detection, over-current monitoring, and built-in temperature sensing. In Relio, this IC provides real-time power and energy data, complementing the relay control and presence/environment sensors to make the device a complete smart energy-aware controller.

The PCB

The printed circuit board for Relio measures 84.3 mm $\times$ 72.3 mm, making it compact enough to fit inside a wall box or surface-mount panel. The layout is carefully divided into two regions: the high-voltage AC section at the bottom and the low-voltage control and logic section at the top (Figure 4). This clear separation ensures both safety and signal integrity, while also making routing of the power and logic traces straightforward.

In the lower half of the PCB, the high-voltage section carries the mains input, relay outputs, and the BL0942 metering circuitry. The relays are placed along the bottom edge, connected to thick copper traces designed to handle switching of AC loads. To further increase the load capacity, the solder mask has been removed from these traces so that extra solder can be added along the current paths, effectively reinforcing the copper and reducing resistive heating. Adequate creepage and clearance distances are maintained between high- and low-voltage areas to ensure safety.

The upper half of the PCB hosts the low-voltage section. At the center, the Beetle ESP32-C6 module, with the BME688 environmental sensor, IR transmitter/receiver, and the HLK-LD2420 radar sensor positioned next to the ESP32-C6. Grouping the logic components in this region minimizes interference from the power stage. The AC-DC converter and LDO regulator are also located here, providing stable 5 V and 3.3 V rails for the control electronics. Signal lines such as I²C and UART are routed in short, direct paths to ensure reliability. Ground planes are carefully separated between digital, analog, and power sections to reduce noise coupling.

This project was sponsored by NextPCB [9], who handled the entire manufacturing process. Their service extended beyond fabrication: they sourced all the components, managed assembly of the parts, and

carried out production with excellent attention to detail. The engineering team at NextPCB was proactive, asking questions during the review stage to clarify design details and avoid potential issues before production. Their estimated lead time was accurate, and the final boards arrived exactly as expected, with both the PCB quality and assembly workmanship at a professional standard.

Firmware

To keep the article readable, the firmware can be represented in a condensed version that highlights the most important structures without showing every detail. The full project code, with preferences, commissioning helpers, and IR functions, is available in the GitHub repository along with the PCB files [10].

The sketch begins by including the required libraries for Matter, the TCA9554 I²C expander, the BME688 environmental sensor, and the

BL0942 energy metering IC. These provide all the building blocks to connect Relio's hardware with its Matter endpoints.

Three `MatterOnOffLight` objects represent the relays (`L1`, `L2`, and `L3`). Additional endpoints are defined for temperature, humidity, and occupancy, ensuring that Relio exposes its full functionality to any Matter-compatible controller.

Relay control is abstracted through a helper function `drive()`, which writes a High or Low signal to the TCA9554 expander depending on the relay state. Each relay has a callback (`setRelay1`, `setRelay2`, `setRelay3`) that is triggered when the corresponding Matter endpoint changes. This direct mapping means that when the user toggles a switch in the Apple Home app (or any other Matter-compatible controller app on a smartphone), the software endpoint is updated and the physical relay state changes instantly on the hardware.



Firmware (Condensed Version)

```
#include <Matter.h> // By Espressif
#include <Wire.h>
#include <TCA9554.h> // By Rob Tillaart
#include <BME688.h> // By Saurav Sajeed
#include <BL0942.h> // By Santeri Lindfors

// ---- Matter Endpoints (3x relays + sensors) ----
MatterOnOffLight L1, L2, L3;
MatterTemperatureSensor Temp;
MatterHumiditySensor Hum;
MatterOccupancySensor Occ;

// ---- Hardware Interfaces ----
TCA9554 TCA(0x20); // I2C expander for relays
BME688 bme; // Temp/Humidity sensor
bl0942::BL0942 bl(Serial1); // BL0942 energy meter (UART)

// Relay control helper
void drive(uint8_t pin, bool state){ TCA.write1(pin, state ? HIGH : LOW); }

// Matter callbacks map endpoints to hardware
bool setRelay1(bool s){ drive(1, s); return true; }
bool setRelay2(bool s){ drive(2, s); return true; }
bool setRelay3(bool s){ drive(3, s); return true; }

// Energy meter callback
void blRx(bl0942::SensorData &d){
    Serial.printf("V=%.1f I=%.3f P=%.1f\n", d.voltage, d.current, d.watt);

    // (Full version also logs energy, frequency, and could publish to Matter)
}
```



```

void setup() {
  Serial.begin(115200);
  Wire.begin(); TCA.begin();

  // Initialize relays OFF
  for(int i=0;i<3;i++) TCA.pinMode(i, OUTPUT), drive(i,false);

  // Init sensors (BME688, BL0942)
  bme.begin(0x76);
  Serial1.begin(4800, SERIAL_8N1, 4, 5);
  bl.setup(); bl.onDataReceived(blRx);

  // Matter endpoints
  L1.begin(false); L2.begin(false); L3.begin(false);
  L1.onChange(setRelay1); L2.onChange(setRelay2); L3.onChange(setRelay3);
  Temp.begin(0.0f); Hum.begin(0.0f); Occ.begin();
  Matter.begin();

  // (Skipped: commissioning helper, QR pairing, button handling)
}

void loop() {

  // Periodically read sensors
  static uint32_t t=0;
  if(millis()-t > 5000){
    t = millis();
    Temp.setTemperature(bme.readTemperature());
    Hum.setHumidity(bme.readHumidity());

    // (Skipped: extra BME688 data like pressure, gas)
  }
  bl.update(); bl.loop(); // Poll BL0942

  // (Skipped: occupancy logic, IR transmitter/receiver, state persistence)
}

```

The BL0942 energy meter is initialized on a UART port and uses a callback (`blRx`) to handle new measurements. In the condensed code, these are simply printed to the serial console as voltage, current, and power. In the full version, additional parameters such as energy consumption and line frequency are also recorded, with the possibility of publishing them to Matter once standard endpoints are available.

Inside `setup()`, the code initializes I²C, configures the relays to start in an Off state, and begins communication with the sensors. The Matter endpoints are then registered and linked to their callbacks. Finally, the device enters commissioning mode, which is the process of pairing a Matter accessory with a controller. As said, in this project the controller is a smartphone running a Matter-compatible app, such as Apple Home on iOS or Google Home on Android. The controller manages secure onboarding, provides the user interface, and allows the relays and sensors in Relio to appear as standard smart home devices.

The `loop()` routine handles runtime tasks. Every five seconds, the BME688 sensor is read, and updated values are pushed to the Matter temperature and humidity endpoints. Meanwhile, the BL0942 is continuously polled via `bl.update()` and `bl.loop()`. In the condensed listing, occupancy detection, button handling, and IR functionality

are omitted, but in the full code they provide additional interaction and control paths.

Current State

At this stage of development, the firmware already allows full control of the three relays, monitoring of the occupancy sensor, and live readings of the temperature and humidity in the room. These features integrate smoothly into Matter and can be accessed directly from a standard smart home app.

I also experimented with exposing the BL0942 power consumption data to Matter, but the endpoint support is not yet working as expected. This part requires further development and is actively being worked on. A future firmware update will make real-time voltage, current, and power data available through Matter once a proper endpoint is finalized.

In addition, the IR functionality is currently stubbed and will be added in a future version. The plan is to implement IR learning and replay, allowing Relio to act as a bridge for older appliances that still rely on infrared remotes. The new firmware revisions, once tested, will be uploaded to the project's GitHub repository, along with the PCB design files.

This way, anyone following the project can keep up with improvements and experiment with their customizations.

Pairing

Once the firmware is uploaded and Relio powers up, it automatically enters Matter commissioning mode. The serial monitor shows a pairing code along with a link that can be opened in any browser (**Figure 5**). By pasting this link, a QR code is generated, which can then be scanned directly from the iPhone. The process is straightforward: open the Home app, tap **Add Accessory**, and point the iPhone camera at the QR code. After a short setup phase, Relio is added to the app and shows up as a controllable accessory with its relays and sensors. You can also follow the step-by-step flow in **Figure 6**.



Warning & Disclaimer

Relio operates with mains AC voltage, which is hazardous and can cause serious injury or death if mishandled. Only qualified individuals should attempt wiring or testing. Always disconnect power before working on the device. The author and publisher accept no liability for any damage, injury, or misuse of this project.

Matter Node is not commissioned yet.
 Open your Matter controller to add this device.
 Manual pairing code: 34970112332
 QR code URL: <https://project-chip.github.io/connectedhomeip/qrcode.html?data=MT:Y.K9042C00KA0>
 Waiting for commissioning...
 ESP-ROM: esp32c6-20220919

Figure 5: Pairing QR code link, shown in the Serial Monitor after flashing the firmware.

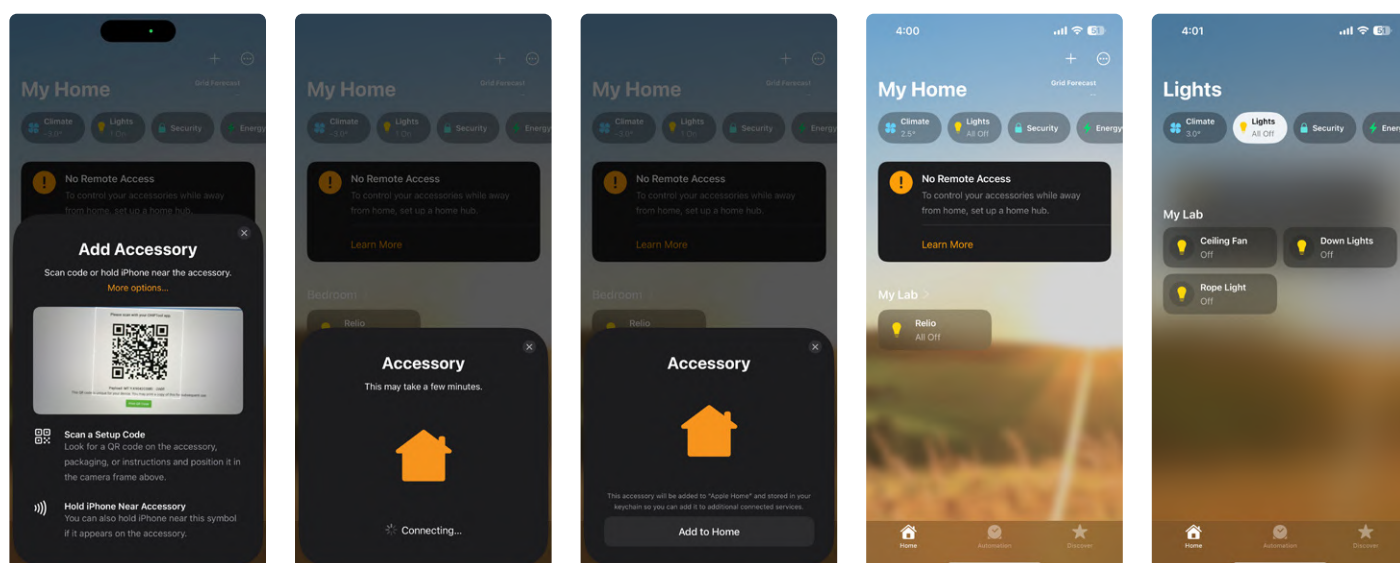


Figure 6: Pairing steps on the iPhone's Home app.

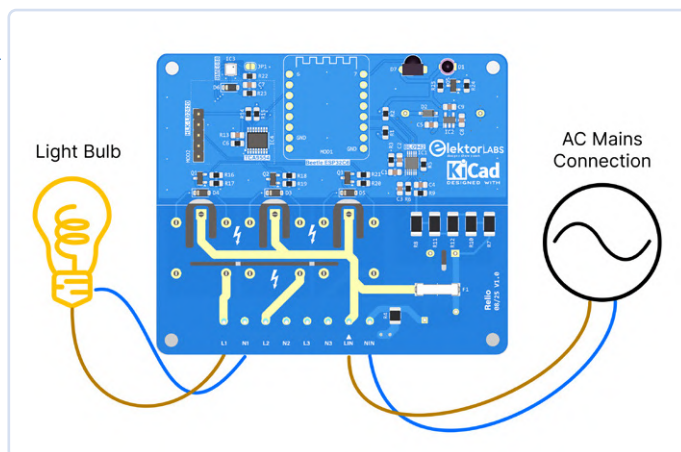


Figure 7: Wiring diagram: how to connect Relio with mains and load.

Relio in Action

After commissioning, the board can be disconnected from the computer and wired into the loads. The connector K1 provides two terminals for each relay output, as well as the L_IN and N_IN inputs. The live mains wire is connected to L_IN, while the neutral is connected to N_IN. Each load is then connected to its respective relay channel—for example, to control a lamp, the lamp's live wire goes to L1, and its neutral wire goes to N1, as illustrated in **Figure 7**. This makes it simple to route multiple appliances through the relays without needing extra wiring complexity.



Component List

Resistors

R1, R2, R5, R13...R16, R19, R21...R24 = 10 k Ω
R3, R6, R9 = 510 Ω
R4 = 1 M Ω
R7, R8, R10...R12 = 390 k Ω
R17, R18, R20 = 1 k Ω
R25 = 100 Ω

Capacitors

C1, C5 = 100 nF
C2, C3, C4 = 68 nF
C6, C7, C8, C9 = 0.1 μ F

Semiconductors

D1 = TSAL4400
D2 = 1N5819HW-7-F
D3, D4, D5, D6 = 1N4148W
D7 = TSOP41xx
Q1, Q2, Q3 = MMBT2222A
Q5 = AO3400A
IC1 = BL0942
IC2 = TLV75733PDBVR
IC3 = BME688
IC4 = TCA9554DBQ

Modules and Connectors

K1 = TB001-500-08BE
MOD1 = Beetle ESP32-C6
MOD2 = HLK-LD2420
MOD3 = HLK-5M05

Relays

RE1, RE2, RE3 = G5LE-14 DC3

Other Components

F1 = 3403.0169.24
RV1 = TND10V-431KB00AAA0

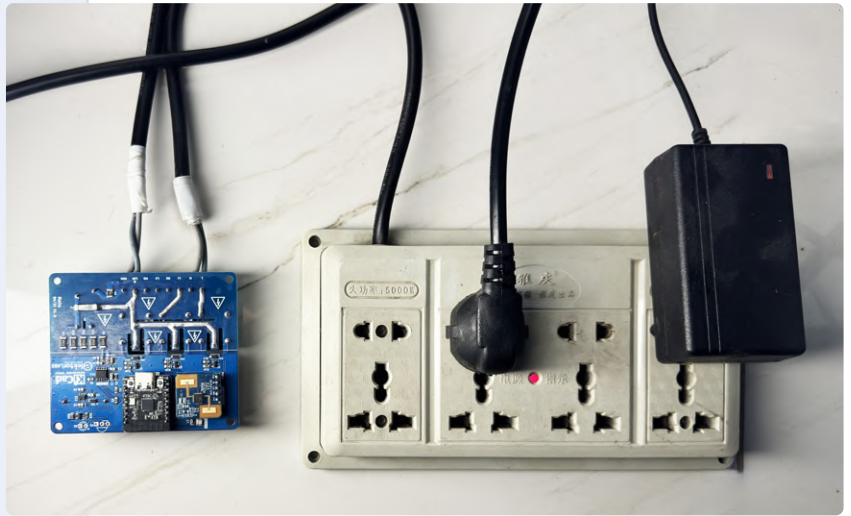


Figure 8: Relio in action, the test setup.

still required for remote access when outside the local Wi-Fi. Despite these conditions, Relio's local performance was solid, responsive, and stable throughout all tests.

Future Improvements

Although Relio is already functional in its first version, several improvements are planned for both firmware and hardware. On the software side, the main goal is to properly expose the BL0942 energy data through Matter so that real-time power consumption can be viewed directly in smart home apps. The IR section will also be extended with learning and replay capability instead of relying on hardcoded commands, making it more flexible for different devices. Presence detection may also be improved by combining radar and environmental data for more context-aware control, and over-the-air updates are planned to simplify future feature rollouts.

On the hardware side, an improved PCB layout is also being worked on—because, let's be honest, no project is ever completely finished. This revision will include status LEDs for each relay, connection status, and occupancy indication to provide quick visual feedback. The relay drivers will be switched to the IRLML6344TRPBF MOSFETs, which offer a compact and efficient solution. At the same time, the I/O expander will be migrated from the current TCA9554 to the TCA9537DGSR, which should lower the overall BOM cost and simplify the design. More over, I am also working on designing the enclosure, which can be mounted on the wall. These incremental but useful updates will make the hardware more user-friendly and refined.

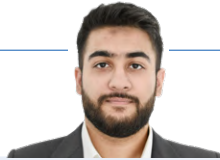
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For testing, I built a small setup (**Figure 8**) using a power strip connected to Relio, with multiple loads attached to check switching performance. The device performed reliably and without issues. In one test, a 7-A load was run continuously for 10 minutes, and no overheating was observed on the relays or PCB traces. The reinforced copper with solder coating on the high-current paths proved effective in carrying the load safely.

During connection testing, Relio worked seamlessly with iOS. The three relays appeared as individual switches, while occupancy and environmental data updated instantly in the Home app. On Android, however, the system required a Google Hub in order to complete pairing, which is a current limitation of Matter on that platform. Even on iOS, while everything worked perfectly on the same network, a hub is

Questions or Comments?

If you have questions about this article, feel free to email the author at saad.imtiaz@elektor.com or the Elektor editorial team at editor@elektor.com.



About the Author

Saad Imtiaz, Senior Engineer at Elektor, is a mechatronics engineer who has extensive experience in embedded systems and product development. His journey has seen him collaborate with a diverse array of companies, from innovative startups to established global enterprises, driving forward-thinking prototyping and development projects. With a rich background that includes a stint in the aviation industry and leadership of a technology startup, Saad brings a unique blend of technical expertise and entrepreneurial spirit to his role at Elektor. Here, he contributes to project development in both software and hardware.

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- [2] Kedar Sovani, "The Smart Home Leaps Forward with Matter," Elektor Guest Edited Edition 2023: <https://www.elektormagazine.com/230617-01>
- [3] 24G Ultra Low-power Radar Sensing Module LD2420 | Hi-Link: <https://hlktech.net/index.php?id=1176>
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- [5] Gas Sensor BME688 | Bosch: <https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors/bme688/>
- [6] BL0940 | Belling: https://www.belling.com.cn/media/file_object/bel_product/BL0940/datasheet/BL0940_V1.1_en.pdf
- [7] HLK-5M05 AC to DC 5V 5W PSM | Hi-Link: <https://hlktech.net/index.php?id=1284>
- [8] TCA9554 8-bit I2C/SMBus I/O expander | Texas Instruments: <https://www.ti.com/product/TCA9554>
- [9] NextPCB: <https://www.nextpcb.com/>
- [10] Relio Project Files | GitHub: <https://github.com/ElektorLabs/Relio>

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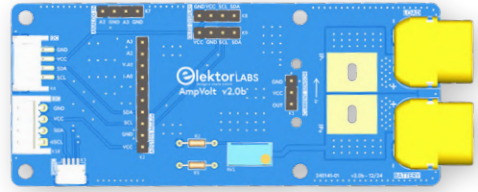
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Designing Better PCBs



A Practical Guide for Professionals and Makers

By Saad Imtiaz (Elektor)

PCB design is not just about getting the circuit to work. A professional design balances electrical performance, manufacturability, EMI compliance, modularity, and even aesthetics. This article takes you through the design journey step by step, highlighting common pitfalls, pre-production checks, and techniques that improve both function and presentation.

The printed circuit board is more than just a carrier for components: it is the backbone of every electronic product. For beginners, the first goal is functionality, but as designs mature, other factors emerge: signal integrity, EMI compliance, cost efficiency, manufactureability, and aesthetics. A clean, disciplined layout is easier to debug, inspires confidence, and often performs better electrically.

This article draws on some guidelines, common best practices, and insights. We will move through the full process, starting at the schematic, progressing through layout and routing, addressing impedance

and grounding, checking EMI considerations, and finishing with aesthetics, modularity, manufacturing awareness and more.

Reviewing the Schematic

The schematic is where most critical errors are born. Before moving to layout, every power rail should be validated against regulator capability. For example, a 5-V regulator feeding a high-current motor driver might look fine on paper, but if its maximum output current is lower than the motor startup surge, the design will fail as soon as the load is applied. Bulk capacitors should always be present to buffer these surges, while each IC must have a local 0.1- μ F ceramic capacitor tied directly to its supply pins.

Proper grounding is crucial for maintaining signal integrity and minimizing electromagnetic interference. Analog, digital, and high-power grounds should only be separated if there is a sensitive circuit. Each ground should be confined to its domain and then connected at a single, well-controlled tie point. This practice helps to prevent noise coupling between different functional sections of the circuit. For most designs, it is best to not split the grounds.

Protection features — like ESD diodes, polarity diodes, fuses, and transient suppressors — should be added at every external interface. Unused inputs should not be left floating; tie them to ground or set a known state. Check the component

datasheet, as some inputs may be safe to leave floating. Status LEDs for power and system heartbeat are inexpensive but invaluable, while reset buttons, boot-mode jumpers, and programming connectors make the board far easier to debug.

Schematic readability also matters: all nets should be named, pin 1 orientations marked, and reference designators included. Operating procedures such as “JP1 closed for battery mode” can be noted directly. A schematic that anticipates both assembly and service will save hours during bring-up.

Main points: Verify supply and decoupling. Add protection. Provide status LEDs and debug points. Separate grounds. Label polarity and orientation.

Transitioning to PCB Layout

PCB layout begins with proper component placement. Clustering regulators, decoupling capacitors, and the devices they supply keep loops short and noise low. Spreading them across the board makes routing messy and increases EMI. Connectors should always be near the board edge and aligned logically — scattering USB, UART, and power connectors across all four sides of the board leads to tangled cabling and poor usability. Large or heavy components such as transformers or electrolytic capacitors should be positioned near mounting holes so mechanical stress doesn’t crack solder joints.

Working within manufacturing constraints is equally important. Suppose your PCB manufacturer supports 4/4 mil trace/space, but you design everything at the absolute minimum. The result might work — but yield will drop, boards may fail at inspection, and costs can increase. Instead, give yourself margin: use 6/6 mil wherever possible, choose via drills with 0.3 mm minimum, and keep mask slivers wide enough for reliable processing.

Another common mistake is ignoring clearance for pick-and-place machines. If connectors or electrolytic capacitors are packed too close to small passives, the placement head may collide with them during assembly. Leaving 0.5 to 1.0 mm around larger parts makes both assembly and later rework easier.

Main points: Zone by function. Stay above fab minimums. Size traces per signal type. Place connectors logically. Anchor heavy parts.

Routing, Widths, and Impedance

Routing is not only about connecting pads; it defines performance. A common begin-

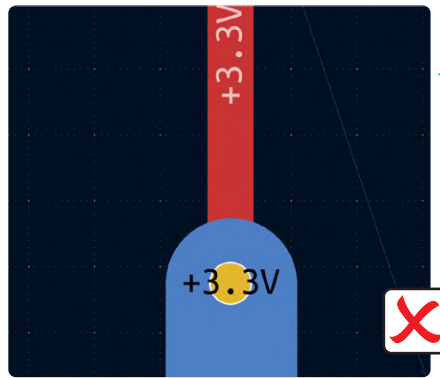


Figure 1: Abrupt trace width change. Sudden transitions cause impedance discontinuities and hotspots.

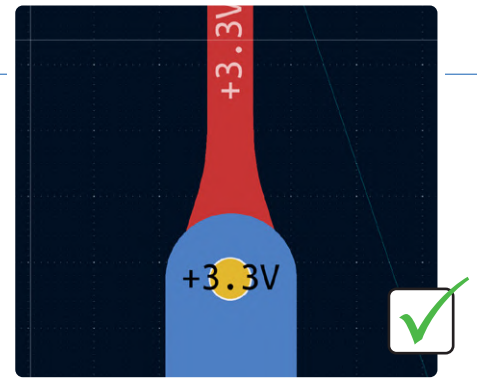


Figure 2: Proper tapered transition. A smooth width change maintains impedance and current flow.

ner error is using the same trace width everywhere. A 0.15 mm (6 mil) trace may handle a digital signal perfectly but will overheat if used for a 2 A motor current. According to IPC-2221 [1], with 1 oz copper, about 10 mil of width is required per amp for a 10 °C rise. If ignored, traces will discolor, lift, or even burn. For higher currents, always size traces properly using calculators or IPC-2152 guidance [2], and use planes for power distribution. For convenience, tools like the Saturn PCB Design Toolkit [3] can quickly provide width estimates and much more without having to manually search through lengthy standards documents.

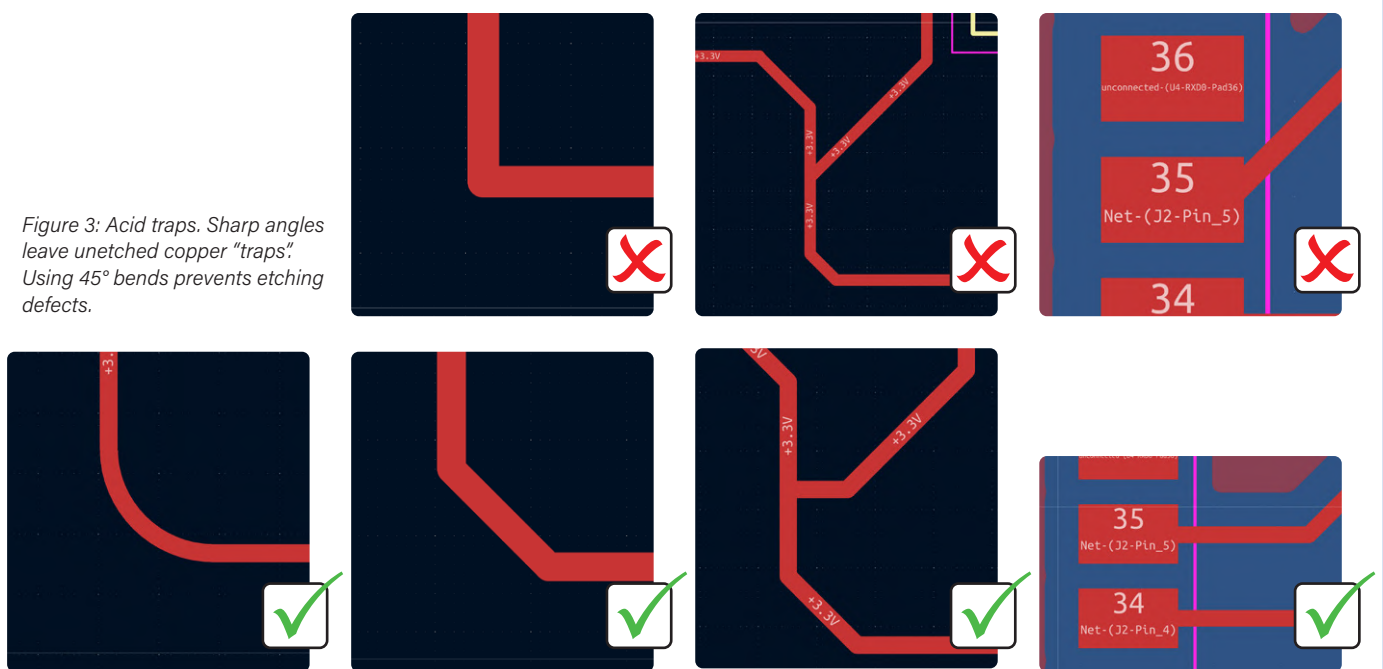
Impedance-controlled routing is essential for high-speed designs. USB 2.0 differential pairs, for example, must be $90\ \Omega \pm 10\%$. If the trace widths or spacing are chosen arbitrarily, the link may enumerate but fail

during data transfers. Built-in CAD impedance calculators let you size traces and gaps using the actual stackup parameters from your fabricator. Most manufacturers also have their own impedance calculators, which compute track width values and recommended stack-ups from user parameters for the particular trace.

Avoid abrupt trace width changes (Figure 1). A sudden jump from a 6 mil line to a 30 mil pour creates an impedance step that reflects signals. IPC guidelines recommend tapering transitions with a 3:1 ratio of length to width for smooth current flow (Figure 2).

Signals should enter pads through the center, avoiding “acid traps” that cause weak etching and poor aesthetics (Figure 3). Teardrops can be added where thin traces

Figure 3: Acid traps. Sharp angles leave unetched copper “traps”. Using 45° bends prevents etching defects.



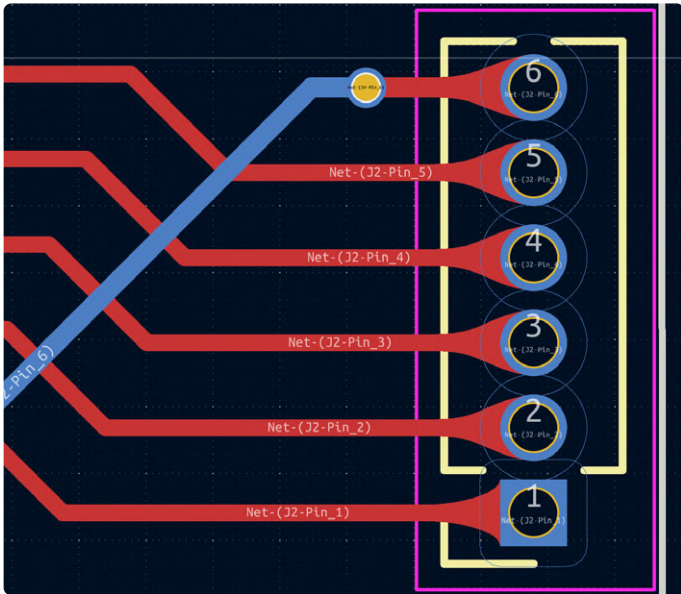


Figure 4: Teardrops at pad-to-trace junctions strengthen mechanical reliability and smooth current transitions.

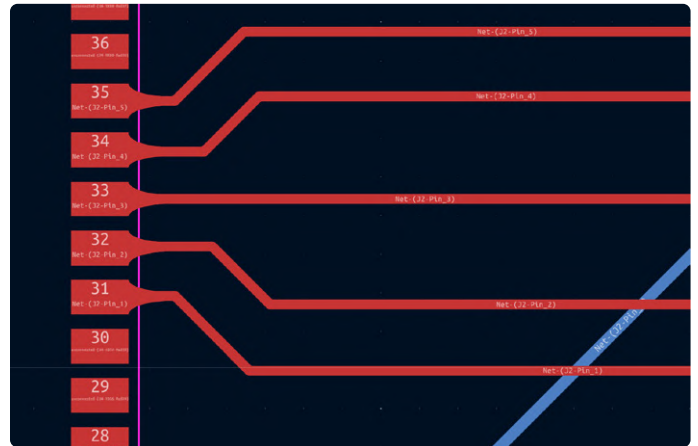


Figure 5: The 3W Rule. Maintaining at least three times the trace width as spacing reduces crosstalk.

meet wide pads to smooth the transition and reduce mechanical stress (**Figure 4**). Vias should be minimized in critical paths, and when signals change layers, nearby ground vias should be added to provide a return path continuity.

Main points: Keep loops small. Match trace lengths. Route into pad centers. Add teardrops. Provide ground vias.

Differential Pairs and Signal Integrity

Differential routing keeps signals immune to noise, but only if done correctly. A poorly matched USB pair, with one line routed 3 mm longer than the other, can cause eye diagram collapse and failed certification. Always keep pairs side by side with constant spacing, and match lengths within the tolerance for the protocol (USB HS within

10–50 mil, DDR memory often tighter).

While routing differential pairs, it's important to maintain constant spacing and avoid stubs or asymmetric vias. For single-ended signal lines such as I²C, SPI, and UART, trace width matters as well: making these traces too thick can increase parasitic capacitance, which may slow signal edges and degrade communication integrity.

If a 6 mil trace is routed only 6 mil away from its neighbor for a long distance, capacitive coupling will cause crosstalk. Using the 3W rule (18 mil clearance for 6 mil traces) drastically reduces this risk (**Figure 5**). For critical clocks, 5W spacing is even better.

To avoid excessive capacitance and maintain signal fidelity, it's generally recommended to keep these signals within a track width of 0.15 to 0.20 mm (about 6 to 8 mils).

This strikes a balance — wide enough to ensure reliable fabrication and manageable resistance, yet narrow enough to limit capacitive loading and crosstalk.

Improvements can include keeping such traces as short as possible, minimizing their proximity to noisy or high-speed signals, and routing them over continuous ground planes to further reduce noise pickup and maintain consistent impedance. Where signal integrity is especially critical, consider using ground guard traces or increasing spacing from interfering lines. Guard traces are thin grounded traces routed alongside sensitive nets such as clocks or analog inputs. These guard traces act as shields, intercepting noise and providing a defined return path, which reduces crosstalk from neighboring signals (**Figure 6**). Another simple way to improve isolation is by increasing

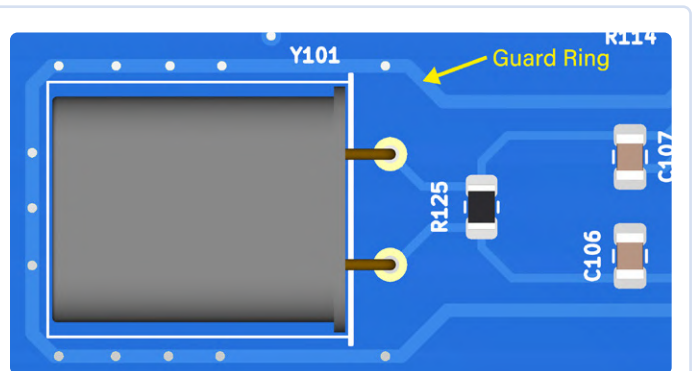
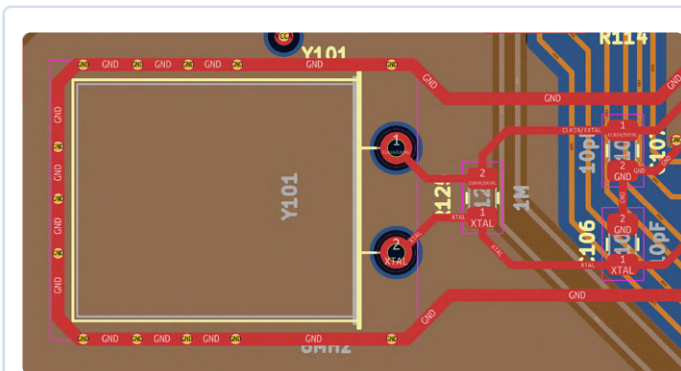


Figure 6: Example of a guard ring.

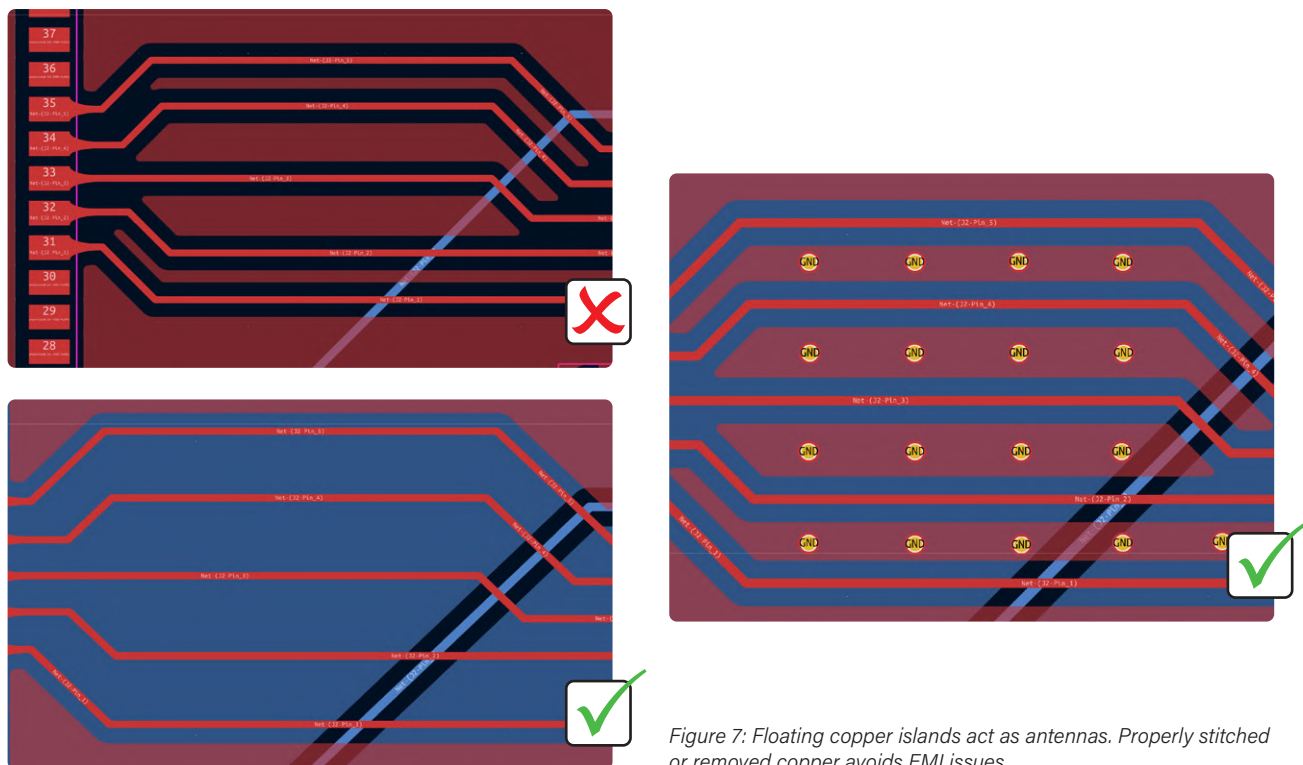


Figure 7: Floating copper islands act as antennas. Properly stitched or removed copper avoids EMI issues.

the spacing between critical nets and other traces. Additionally, rather than routing across split ground plains, give priority to signal tracks over solid ground planes underneath.

Main points: Follow fab stack-up. Keep spacing constant. Match lengths. Avoid stubs and skew.

QFN pads to save space, only to discover solder wicking into the holes during reflow, leaving open joints. If via-in-pad is unavoidable, it must be filled and capped by the manufacturer — which adds cost but ensures solderability.

Ground stitching vias are your ally, not your enemy. Without them, a ground pour becomes a “floating copper island” that

radiates like an antenna (**Figure 7** and **Figure 8**). Stitching every 1–2 cm (or 50 to 100 mil for RF sections) ties planes together and provides low-inductance return paths.

Main points: Minimize vias on fast nets. Use parallel vias for power. Never leave via-in-pad unfilled. Stitch ground pours frequently.

Vias and Layer Transitions

Every via adds resistance and inductance. A clock trace that passes through four vias may still work, but its edges will degrade, and EMI emissions can rise. As a rule, avoid routing critical signals through more than two vias.

For power distribution, vias can actually be beneficial. A single small via has limited current-carrying capability, so instead of relying on one, place multiple vias in parallel between layers. For example, if a regulator output connects to a ground or power plane, using an array of vias lowers overall resistance and inductance, ensuring stable power delivery. Standard practice is to use via drills of at least 0.3 mm for these current-carrying paths.

Unfilled via-in-pad is another common pitfall. Beginners may place vias inside

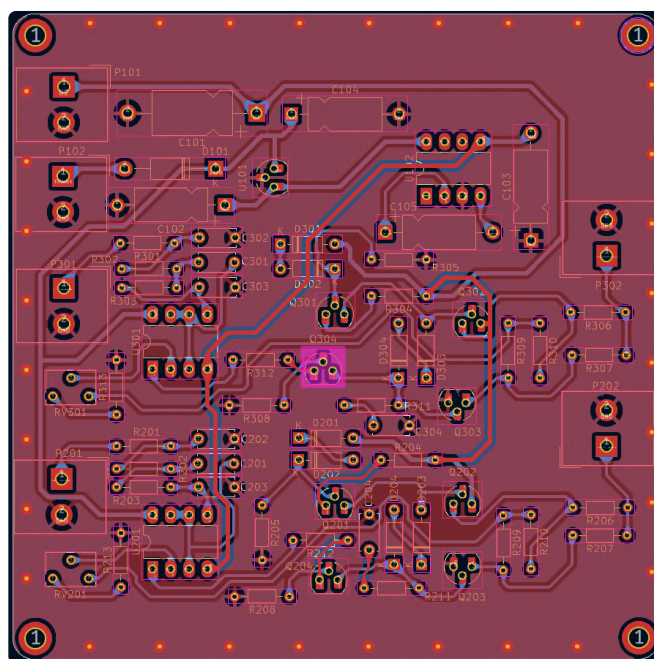


Figure 8: Ground stitching around the edges of the PCB.

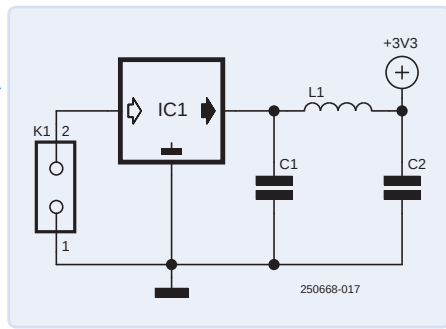


Figure 9: Low-pass PI filter. Example of ferrite bead and capacitors suppressing switching noise on supply rails.

Power Distribution and Grounding

Power delivery is both a necessity and a source of noise. High-frequency current should be supplied by decoupling capacitors placed directly at IC pins, with the shortest possible connection into the ground plane. Ferrite beads and PI filters can isolate noisy switching regulators from sensitive analog rails (**Figure 9**). When using PI filters, always design them according to your application requirements; for example, component values that work well for an MCU may be ineffective for a high-speed RF front end. Selecting the right bead impedance, capacitor type, and layout is just as important as including the filter itself.

Grounding is the foundation of noise control. Use continuous planes where possible, and stitch them together frequently. For mixed-signal systems, separate analog and digital grounds but connect them at one low-impedance point, usually near the ADC. For RF circuits, ground via fences should be placed along transmission lines and under shielding cans.

Antenna placement is a special case: antennas should be at board edges with a clear copper-free keep-out area as specified in the datasheet. Feedlines should be short, matched to 50 Ω , and include a matching network placed as close as possible to the antenna pad.

Main points: Place decoupling close. Isolate noisy domains. Use solid planes. Stitch grounds. Respect antenna keep-outs.

Copper Pours and Thermal Management

Poor thermal design is another common issue: connecting a regulator tab directly

to a massive copper plane without thermal reliefs can cause cold solder joints during reflow (**Figure 10**). Configuring pours for thermal relief around pads prevents this.

Copper density balance also matters. If one side of the board is 80% copper and the other is sparse, the PCB can warp in the oven. Working with your fabricator to balance pours across layers prevents bowing and assembly defects.

Main points: Use thermal reliefs. Balance copper density.

Stack-Up and Layer Strategy

Choosing the wrong stack-up can doom a design before routing begins. A two-layer board with USB 3.0 routed across a split plane will radiate heavily and fail compliance. Instead, work with your fabricator early to define layer count, copper weights, and dielectric thicknesses. Controlled impedance stack-ups are mandatory for high-speed protocols like DDR, USB, and HDMI.

For signal integrity, ground-signal-ground sandwiches provide ideal stripline routing. For power integrity, thicker inner copper (2 oz) improves current handling and thermal spreading. If stack-up isn't validated early, last-minute changes become expensive and time-consuming.

Main points: Define stack-up with fab early. Use ground-signal-ground sandwiches. Select thicker copper for high current. Validate impedance stackups.

Footprints and Assembly Concerns

Incorrect footprints are a silent killer of projects. A connector footprint with misaligned pin spacing will make the entire board unusable. CAD tools like Altium offer footprint wizards that generate IPC-compliant pads automatically but always cross-check dimensions against the datasheet.

3D step models are invaluable. For instance, a tall capacitor placed too close to a USB connector may not be obvious in 2D but will immediately show clearance issues in 3D. Always import vendor models and run mechanical clearance checks. For this, you can import parts via Library Loader [4] and select parts from Mouser or Component Search Engine [5], which already has a 3D model and footprint of the part you are using.

Main points: Use IPC footprint standards. Size component pads correctly. Verify against datasheets. Import 3D models.

Design Rule Checks and Autorouting

While autorouters can help, they are not a substitute for judgment. If left unconstrained, they produce zigzag traces, long loops, and excessive vias. A USB HS signal routed this way may technically connect but fail EMI tests. Always set constraints first: widths, clearances, via costs, and layer priorities. Route critical nets manually — clocks, differential pairs, and memory buses — and reserve autorouting for less critical nets.

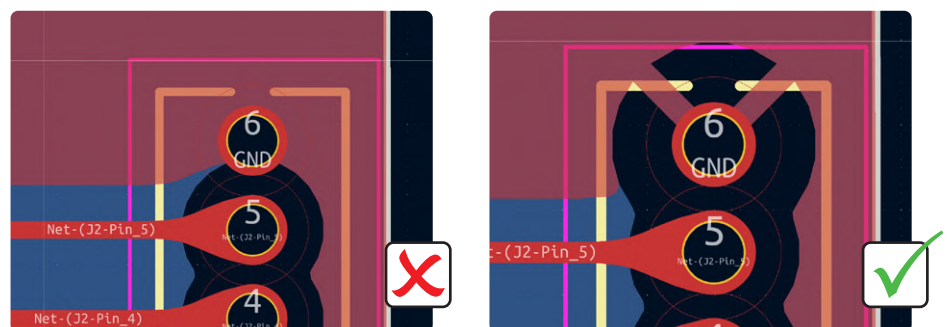
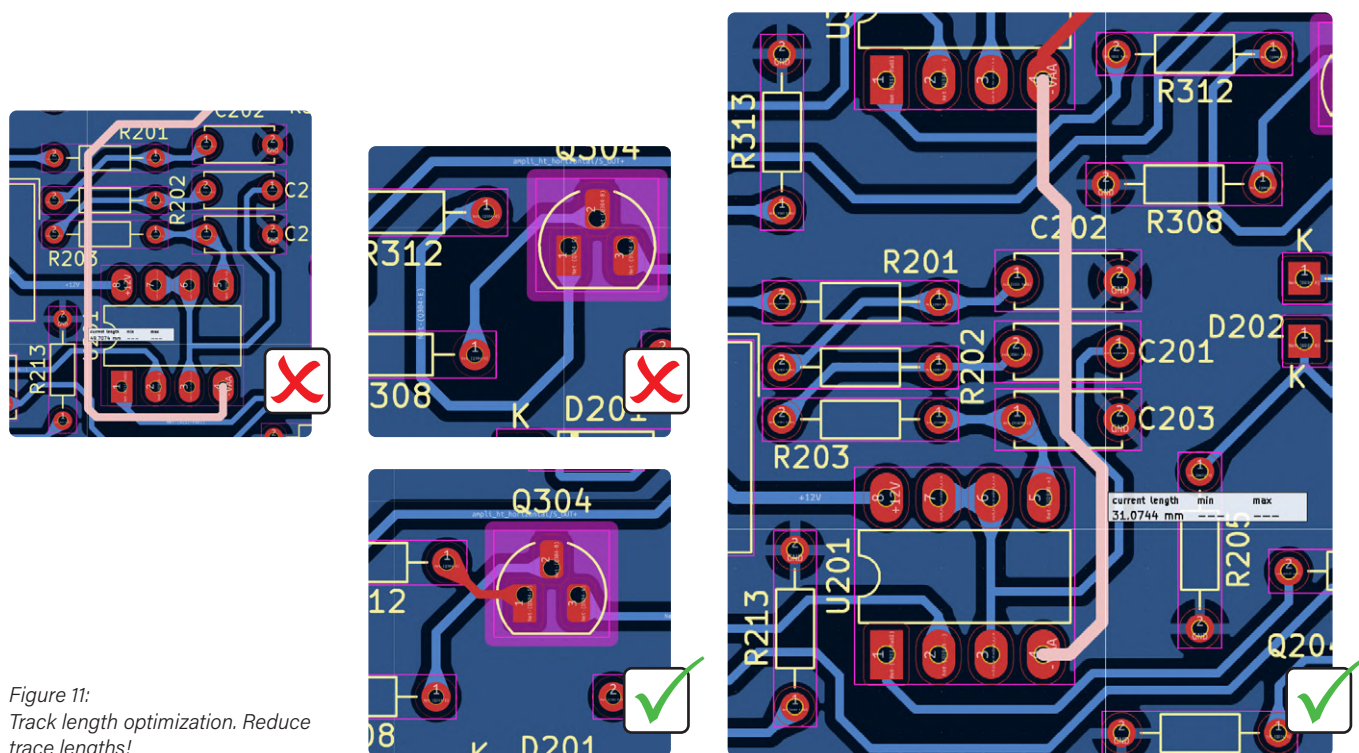


Figure 10: Thermal reliefs. Direct copper connections can cause cold solder joints. Thermal spoke pads ensure solderability.



After autorouting, cleanup is mandatory. Remove long detours, redundant vias, and awkward angles (**Figure 11**). A disciplined post-process ensures the layout looks professional and performs reliably.

Pilot Runs and Validation

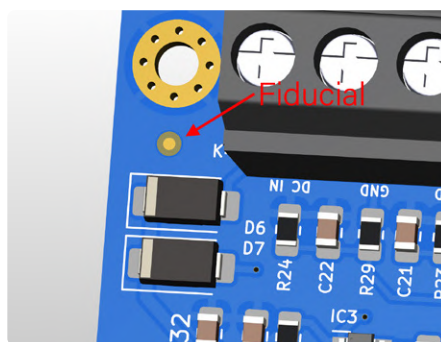
Electrical validation is equally important. Power sequencing should be checked with scopes; shorts and opens verified with probing. Using structured checklists ensures nothing is missed. Once validated, volume production can proceed with confidence.

Final Checks Before Fabrication

Solder mask and paste layers must follow manufacturer constraints. Bridges between fine-pitch pads must not fall below minimum width (typically 100 to 125 μm). Gerber previews should be inspected externally to catch errors not visible in the CAD tool. Fiducials — at least three global, plus local near BGAs — are necessary for pick-and-place alignment (**Figure 12**).

Modularity and Variants

Just as important as designing for variants is keeping track of versions. Every PCB will go through revisions as features are added, footprints adjusted, or mistakes corrected. To avoid confusion during testing or production, always mark the version number directly on the PCB silkscreen, along with the date of the finalized design (for example, “V1.0 Rev B – 05/25”).



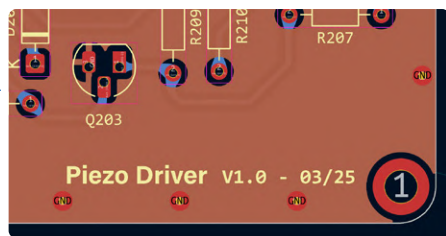


Figure 13: Versioning and batch code on silkscreen identifies board revision and production date directly on the PCB.

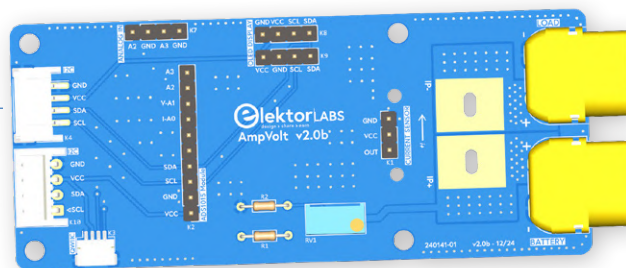


Figure 14: Finalized PCB. Clear silkscreen labeling, version marking, and test-point identifiers make the board production-ready.

Including a batch code or production date makes it simple to differentiate boards without having to compare them side by side. This small practice saves countless hours when troubleshooting or validating units from different builds (**Figure 13**).

Main points: Plan for variants. Use modules where practical. Mark version, date, and batch code on every PCB.

Aesthetics and Presentation

Though functionality comes first, aesthetics strongly influence manufacturability and usability. Components should be placed on consistent grids, with clear alignment and symmetry. Connectors grouped by function make the board intuitive, and evenly spaced traces improve both crosstalk performance and visual appeal.

Rounded corners look professional and align with milling processes. Edge plating or stitched copper around the perimeter can reduce EMI while giving a premium look. Silkscreen, if well executed, makes assembly and debugging far easier: label LEDs, connectors, and switches clearly, include revision markers, and add a company logo (**Figure 14**).

Surface finishes and solder mask colors also contribute. ENIG (immersion gold) improves solderability and pad planarity while giving a polished appearance. Matte black or blue solder masks, though pricier, may be justified for high-end products or visible PCBs.

Main points: Align on grids. Use symmetry. Round corners. Label clearly. Choose finishes wisely.

Cost and Manufacturing Awareness

At every step, cost must be considered. Extra layers, blind vias, and exotic mask colors add price. Standardizing board thickness

(1.6 mm), drill sizes, and copper weights helps keep boards affordable. For small designs, panelization reduces assembly cost.

Above all, avoid designing to the manufacturer's minimums unless absolutely necessary. Leaving margin in trace widths, spacing, and via sizes increases yield and reliability.

Main points: Stick to standards. Panelize small boards. Stay above minimums.

The Perfect PCB

PCB design is equal parts engineering and craft. A schematic verified with discipline prevents hidden mistakes. Careful placement, routing, and impedance planning ensure signal and power integrity. Thoughtful grounding, antenna placement, and EMI practices create robust designs. Aesthetics and labeling improve usability and confidence. And by respecting manufacturer constraints and cost factors, designs move smoothly to production.

Yet even when you follow every standard, rule, and best practice, no PCB is truly "finished." There will always be revisions — a trace adjustment, a new connector, or a component swapped to suit availability. These changes are not failures but part of the learning process. Each board version is an opportunity to refine, test, and improve.

In that sense, the idea of a "Perfect PCB" is less about achieving a flawless first try and more about building a process of continuous improvement. Every iteration makes

you a sharper designer, every respin adds practical experience, and every lesson learned makes the next board closer to perfect. And truthfully, no one is ever a complete PCB expert — each project teaches something new. If you have tips or practices I've missed, I'd love to hear them, because PCB design is as much an art as it is engineering, and I continue to learn with every board I make. ◀

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Questions and Comments?

If you have questions about this article, feel free to email the author at saad.imtiaz@elektor.com or the Elektor editorial team at editor@elektor.com.



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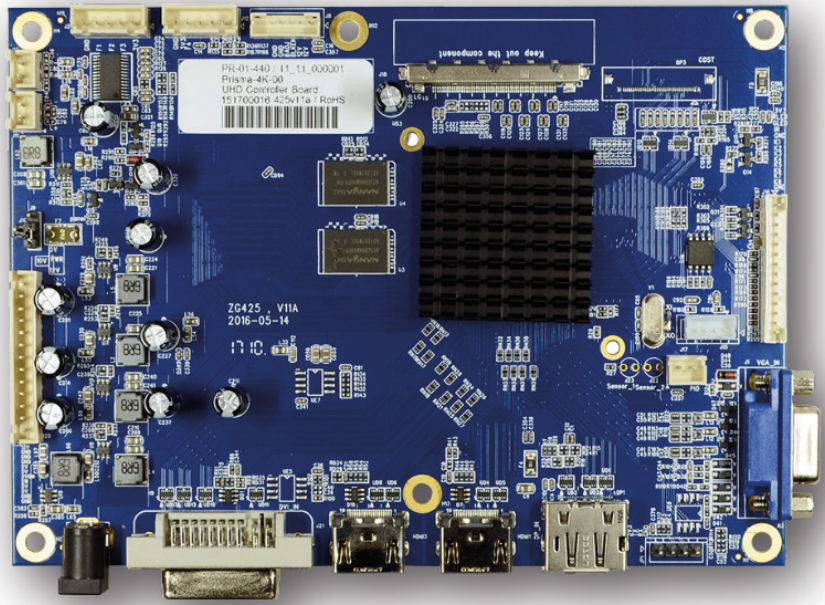


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- [3] Saturn PCB Design Toolkit: <https://saturnpcb.com/saturn-pcb-toolkit/>
- [4] Library Loader, SamacSys: <https://www.samacsys.com/library-loader/>
- [5] Electronic Component Search Engine: <https://componentsearchengine.com/>

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KiCad 9

Top New and Updated Features

By Peter Dalmaris (Australia)

A new version of KiCad, the open-source electronics CAD software, is available. KiCad 9 is a major update that brings dozens of improvements across the entire design workflow. In this article, I'll focus on a few features that I think make a real difference in day-to-day use.

I'll go into detail on four of my favourite new additions: *Jobsets*, which simplify output generation; the new *Zone Manager*, which centralizes control over copper zones; *Design blocks*, aimed at enhancing schematic reusability and efficiency; and the improved 3D model export system, which makes it easier to generate accurate and useful mechanical representations of your boards.

After that, I'll highlight three other features that, while smaller in scope, offer clear productivity gains: the *Precision Positioning Tool*, the schematic editor's new *Selection*

Filter, and the introduction of *Component Classes*. Together, these features represent just a sample of what's new in KiCad 9, but they give a good sense of the direction this release is taking.

For a comprehensive overview of KiCad 9, I recommend reading the official announcement blog post available at [1]. Let's look at my top three new features in detail.

Jobsets

The new *Jobsets* feature is designed to streamline the export process in electronic design projects. A Jobset is a bundle of multiple export tasks, all packaged into a single executable action. This simplifies operations like generating schematic PDFs, Gerber files, 3D models, and more. Automation significantly reduces the manual effort traditionally associated with generating outputs, ensuring consistency and minimising human error across various projects (**Figure 1**).

Before KiCad 9, exporting outputs was a labor-intensive and repetitive task. Designers had to manually initiate each export individually, whether it involved generating schematic PDFs, BOM files, drill files, Gerber data, or 3D model files. This process was not only tedious but also prone to incon-

sistencies and errors, particularly in larger projects involving multiple revisions and frequent updates.

With Jobsets, you can configure your desired outputs once and execute that configuration repeatedly. This ensures that every set of project outputs is consistent and error-free. This is particularly beneficial for professionals who frequently publish their designs online, collaborate with external stakeholders, or manage complex workflows involving multiple types of exports.

How to Create a Jobset

The process of creating and configuring Jobsets commences from KiCad's primary interface. Begin by selecting the option to create a new Jobset file. This file is integrated with the project, facilitating easy maintenance and management throughout its lifecycle. In **Figure 2**, I've highlighted the *New Jobset File* option located under the *File* menu.

A window will pop up, requesting a file name. Enter a reasonable name. For instance, I entered "Blog.jobset" because I intend to use the outputs of this Jobset for a blog article. After creating the Jobset file, it will be opened in a new tab within the main KiCad window (see **Figure 3**).

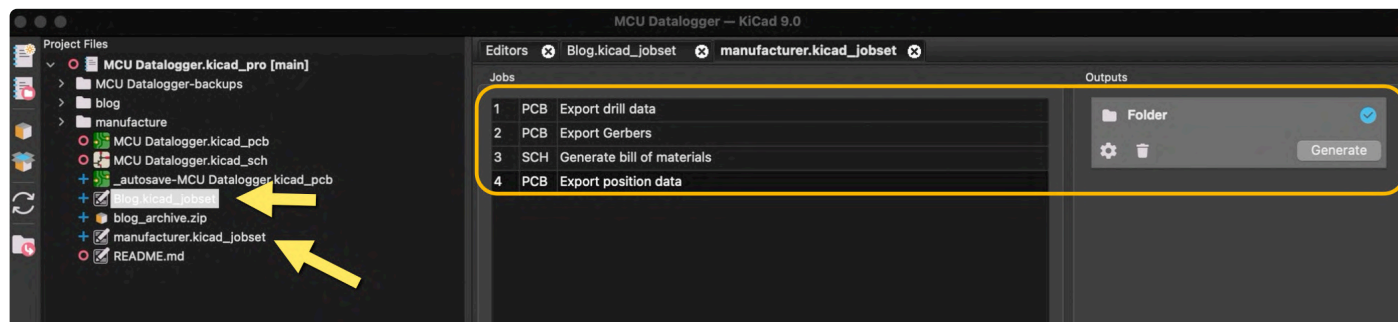


Figure 1: An example of a Jobset file that contains four jobs. Notice I have created two Jobsets in this project, each under a tab.

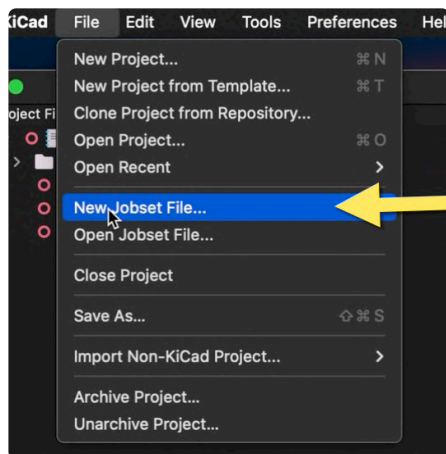


Figure 2: Create a new Jobset file.

In the newly introduced *Jobset* tab, you can create an unlimited number of individual jobs. To do this, simply click on the + button to open the *Add New Job* dialogue box. Now, select a new job type from the available options. For instance, let's choose the *PCB: Export 3D Model* job. Once you've selected the job, click OK to launch the PCB exporter window. This window provides an opportunity to configure the specific export settings for this particular job.

For this example, I've chosen the STL 3D file format, which is compatible with my desktop 3D printer (**Figure 4**). In the *File* field, I've created a variable-based filename using the `${PROJECTNAME}` and `${CURRENT_DATE}` variables. This way, I can export files with unique names without the hassle of manually entering new ones. KiCad 9 offers detailed customization of file names for exported outputs using dynamic text variables. Users can include variables like the project name, revision number, date, and time directly in the file naming configuration. These variables ensure that exported files have clear, informative, and organised naming conventions, making file management and retrieval easier. For more information about text variables, refer to [2] (KiCad documentation).

Click OK to close the 3D export file configuration window. You'll notice that the new job item is now listed in the *Jobset* tab (see **Figure 5**). I'll add a few more jobs before exporting all the files. In **Figure 6**, you can see three jobs in the set: a 3D model, two PDFs, and the Bill of Materials, labeled as "1." Click on *Save Jobset* (labeled as "2") to create a new *.kicad_jobset* file in the project directory (labeled as "3"). Now, let's proceed with running this jobset.

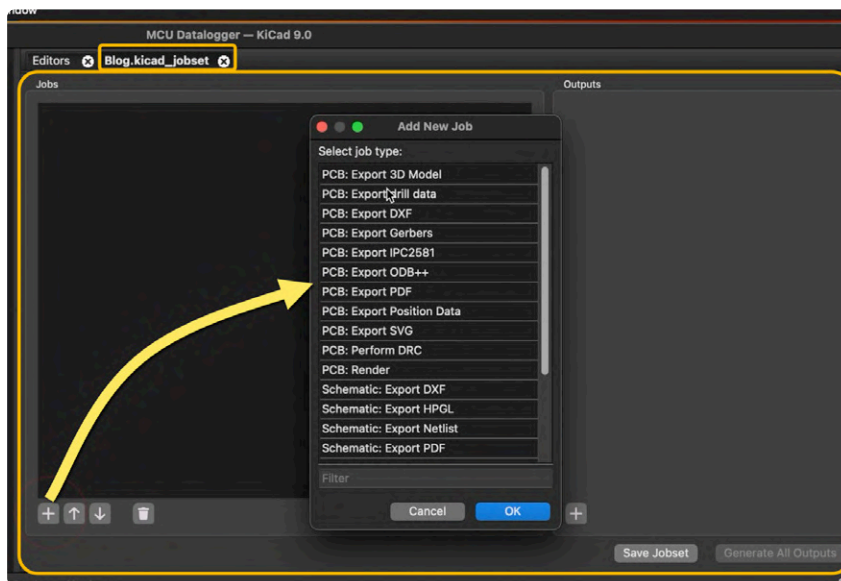


Figure 3: A new tab for the Jobset appears in the main KiCad window. Click the + button to create a job.

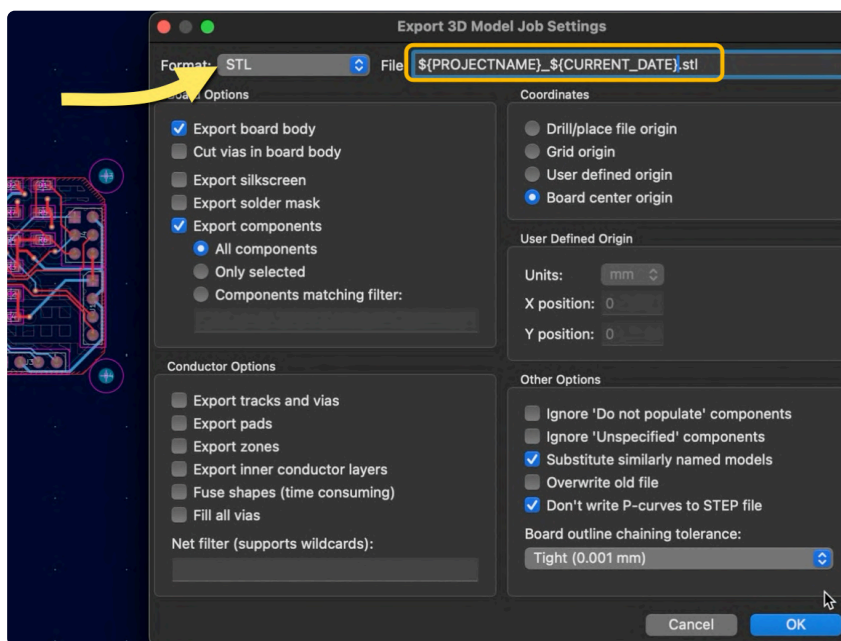


Figure 4: KiCad will automatically show the appropriate dialog box to configure the selected job type. In this case, it's the 3D model exporter.

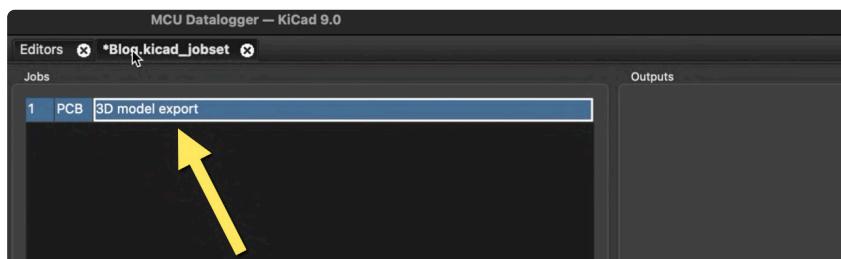


Figure 5: This Jobset contains one job.

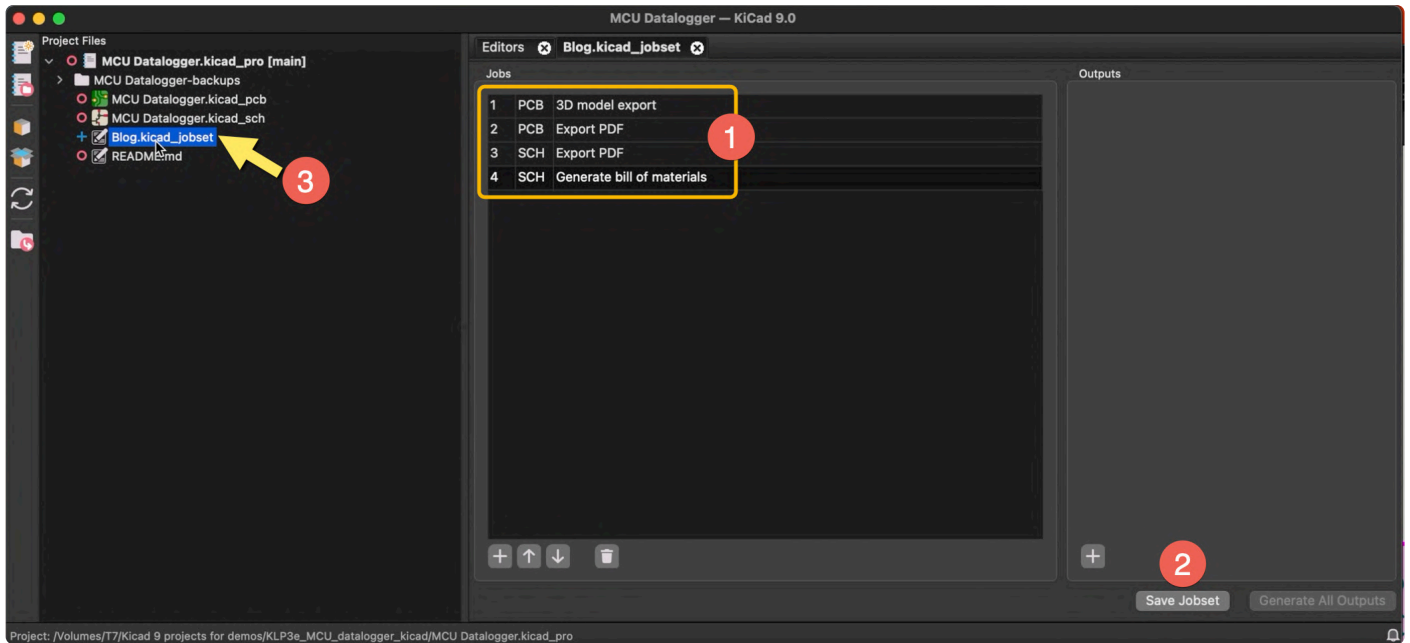


Figure 6: This Jobset contains four jobs.

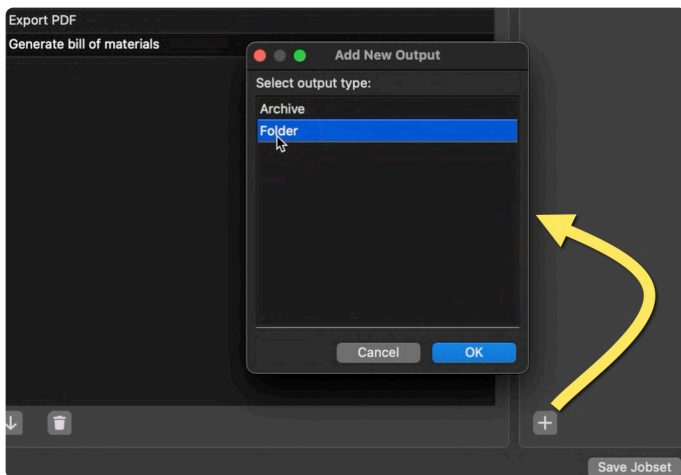


Figure 7: Create a new output.

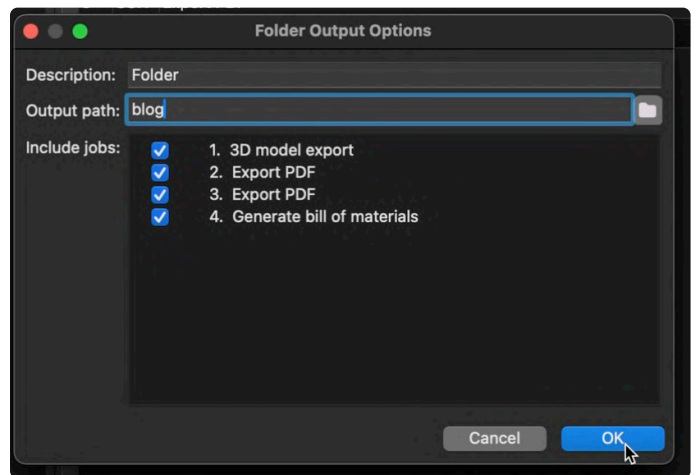


Figure 8: Setting Output Options.

To execute the jobset, you need to create an **Output**. You can have multiple outputs, each with its own configuration, which enhances the flexibility of your workflow. To create an **Output**, click on the + button located in the right pane of the **Jobsets** tab (as shown in **Figure 7**).

Folder Output generates files directly into a designated project directory, providing quick access and immediate use. On the other hand, **Archive Output** automatically compresses all output files into a ZIP archive, making it suitable for distribution, storage, or submission to manufacturers. This flexibility enables you to tailor your outputs to different use cases, such as internal documentation, online publication, or external collaboration. Since I prioritise

immediate access to my exported files, I've chosen the **Folder** output type. Click **OK** to proceed with the **Output Options** window.

In the **Output Options** window, specify the location where the export files will be stored. Then, select the individual jobs you

want to include in this output (**Figure 8**). I've set the path to the *blog* subdirectory within my project directory (a relative path), but you can also use an absolute path anywhere in your file system. I've included all jobs in this output. In **Figure 9**, I've created two outputs for the Jobset.

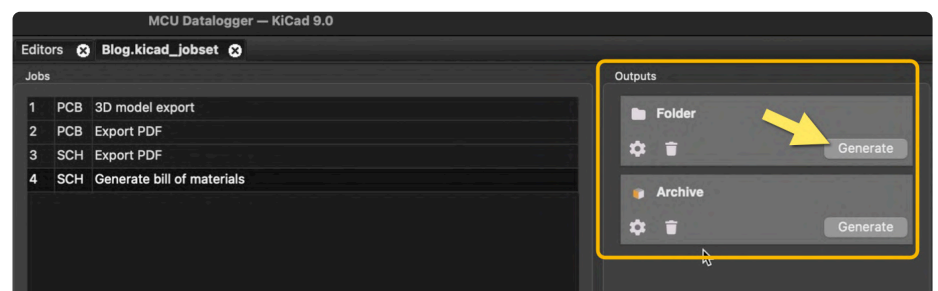


Figure 9: This Jobset contains two outputs.

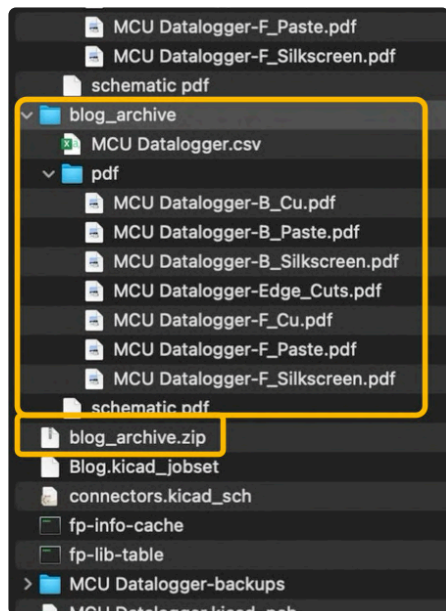


Figure 10: The export files.

To generate the output, click on the *Generate* button for each output. I did this for both the *Folder* and *Archive* outputs. Within a few seconds, the exported files were available in the project directory (see **Figure 10**).

Practical Use Cases

Many projects necessitate detailed documentation for internal reference or external publication. Jobsets, a configuration tailored for documentation, can include:

- PDFs of schematics
- PNG or SVG images of the PCB layout
- STEP files for interactive 3D visualisation

Another use case is in manufacturing. Manufacturing PCB designs requires precise and error-free data generation. Jobsets specifically designed for production typically include:

- Gerber files for PCB fabrication
- Excellon drill files for accurate hole positioning
- IPC-D-356 netlist files for electrical testing
- Component placement files for pick-and-place machines

For more information about Jobsets, I recommend visiting the documentation on the KiCad website [3].

Zone Manager

KiCad 9 introduces the *Zone Manager*, an advanced feature specifically designed

to simplify the management of copper zones in complex PCB layouts. Copper zones, crucial for grounding, power distribution, thermal management, and shielding, can become intricate and challenging to manage when dealing with intricate, multi-layered designs. The Zone Manager centralises control, significantly enhancing efficiency, accuracy, and ease of adjustment. In **Figure 11**, you can see the Zone Manager displaying the list of zones on an ESP32 sensor board I designed recently.

Prior to the implementation of the Zone Manager, working with multiple copper zones was tedious, especially in dense layouts with overlapping zones. The new Zone Manager improves the ergonomics considerably by consolidating zone-related management and configuration tasks into a unified, easy-to-use interface.

The Zone Manager Interface

The Zone Manager presents a user-friendly and organised interface that allows users to easily access and manage all copper zones within their design from a single location. Each copper zone is presented with crucial details, such as layer assignments, clearances, fill patterns, and priority status. To access the Zone Manager, simply open the layout editor and click on *Tools* → *Zone Manager* (see **Figure 12**).

With reference to Figure 11, you'll find the list of zones in the top-left pane labeled "1." The order of the zones is crucial. The tool provides explicit control over zone hierarchy

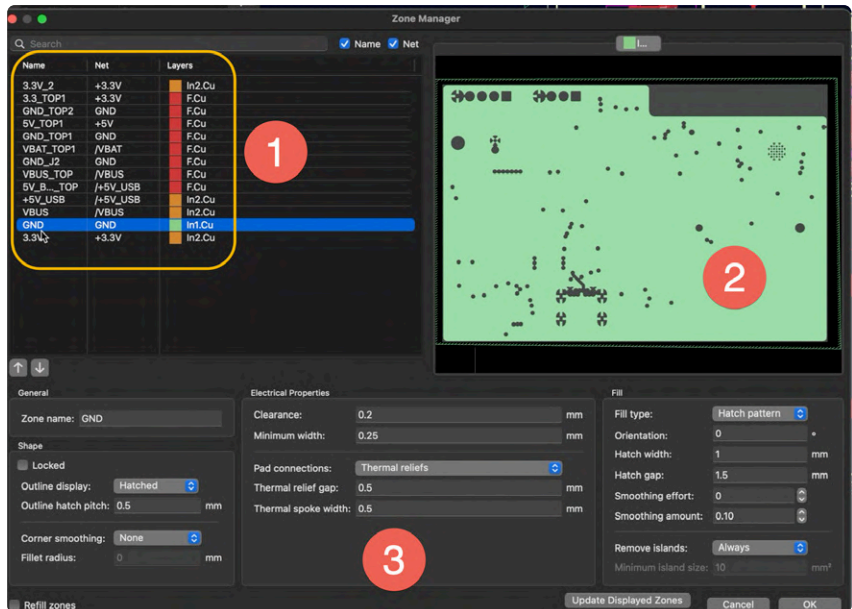


Figure 11: The Zone Manager is showing a list of several zones in this 4-layer PCB.

and priority — essential features for managing overlapping copper zones. Zones listed higher in the manager take precedence over lower-ranked zones, automatically resolving conflicts. You can quickly rearrange zones by using the up and down buttons below the list. Notably, the list displays the zone's name, connected net, and used layer.

On the top right pane, you'll find the graphical view of the selected zone labeled "2." You can zoom in and out and pan the view.

In the bottom half of the *Zone Manager* window, you'll find the properties pane for the selected zone. This pane displays all the available properties for the zone, as well as those that you can edit by directly selecting the Zone's properties window.

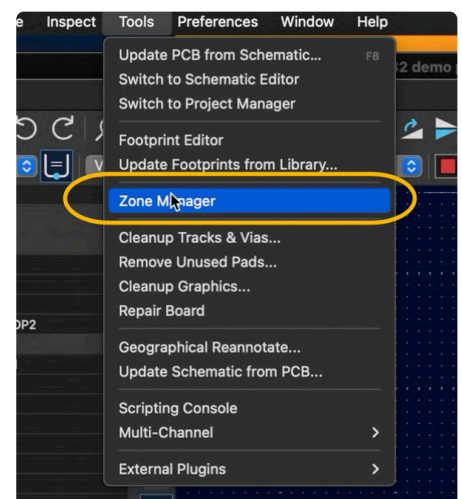


Figure 12: Open the Zone Manager.

Best Practices and Troubleshooting

As your PCBs become more complicated, you will find that they will contain more copper zones. Keep these best practices in mind to help you design better boards with fewer defects:

- **Consistent Naming Conventions:** Clearly label zones according to their functional role to facilitate quick identification and adjustment during iterative design processes.
- **Prioritize Zones Strategically:** Prioritize critical power and ground planes at higher levels within the Zone Manager, ensuring their dominance and proper electrical functionality. This is important, especially when zones overlap.
- **Regular Validation and Adjustment:** Periodically review and adjust zone clearances and thermal settings, especially after significant design changes or component repositioning.

Inevitably, there will be bugs. In one of my recent 4-layer designs, much of my debugging time was spent fixing issues that were caused by overlapping zones with incorrect priorities. Other issues can be caused by incomplete zone fills, for example, GND pads not connected to a GND ground zone because that zone was not filled.

The new Zone Manager will help you with all that.

Design Blocks

Design Blocks is a tool that aims to enhance schematic reusability and efficiency. By allowing users to save commonly used sub-circuits in a centralised, globally accessible library, design blocks significantly accelerate schematic creation across multiple projects. This capability enables efficient maintenance of consistency, reduces duplication efforts, and substantially streamlines the overall workflow.

Reusable schematic blocks offer several key advantages in PCB design. Regularly used circuits, such as power supply modules, filtering networks, voltage regulators, sensor interfaces, or standard connectors, can consume considerable time when repeatedly recreated from scratch. With

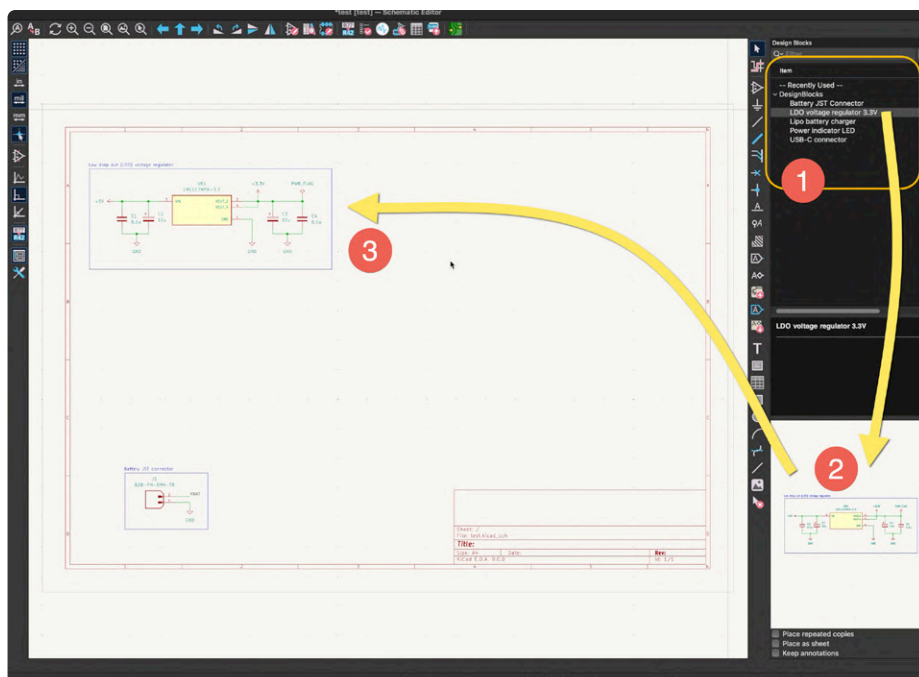


Figure 13: Design Blocks in action. In this example, drop a circuit from the Blocks list to the schematic sheet.

KiCad's design blocks, designers store these circuits in a reusable format, dramatically shortening project timelines and ensuring uniformity across various schematics. This reuse also significantly reduces the potential for errors introduced during repetitive manual entry, thereby enhancing overall design reliability.

In **Figure 13**, you can see the *Design Blocks* list labeled as “1” in the schematic editor. I’ve selected one of the blocks from the list, and its thumbnail appears below the list, labeled as “2”. To use the block, simply drag and drop it anywhere on the schematic

sheet, as indicated by “3”. The blocks in the *Design Blocks* list in Figure 14 are original designs from my various projects. Before the introduction of design blocks, you would have had to recreate these commonly used circuits every time they were required in a new PCB.

Setting up and Using Design Blocks

I'll demonstrate how to create a design block using an example. Take a look at the schematic from **Figure 14**. I intend to convert some of the sub-circuits into design blocks so that I can reuse them in other PCB projects.

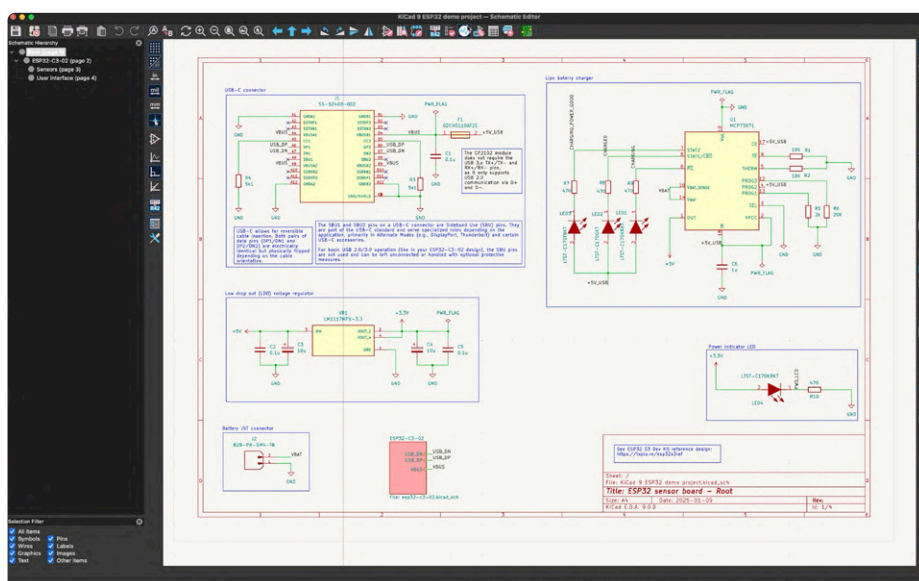


Figure 14: I will convert this sub circuit to a design block.

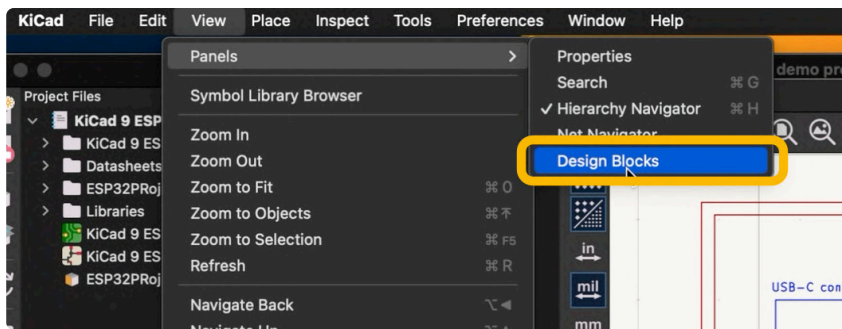


Figure 15: Open the Design Blocks panel.

To begin using design blocks, first open the *Design Blocks* panel by selecting it from the *View* menu in KiCad's schematic editor (**Figure 15**).

This dedicated panel serves as the central hub for managing and accessing your stored schematic blocks.

To create a new global library, follow these steps (**Figure 16**):

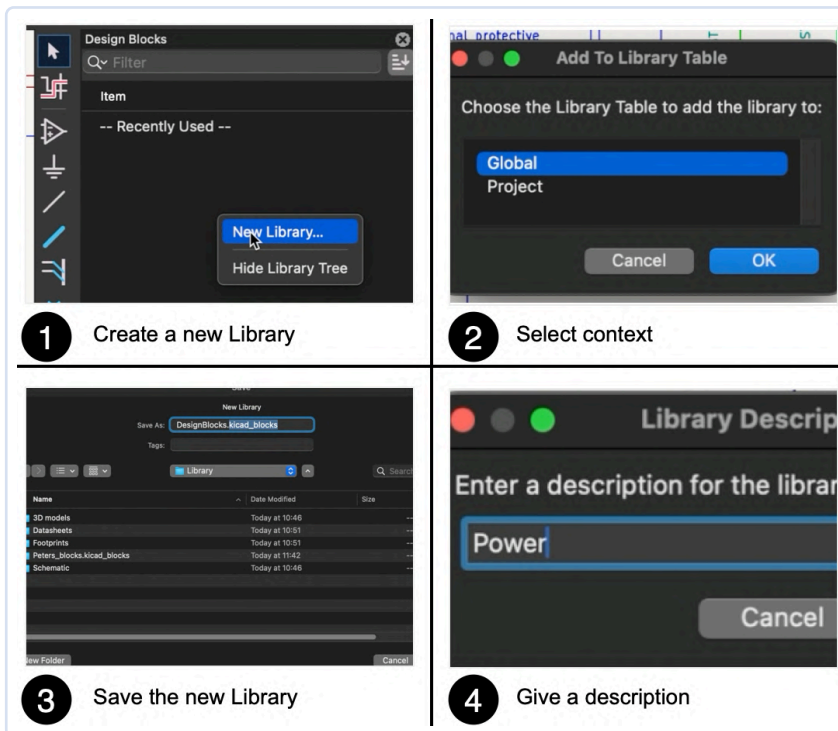


Figure 16: Create a new Design Blocks Library.

1. In the empty list pane of the *Design Blocks*, right-click and select *New Library*.
2. Choose the context for the new library, such as *Global* or *Project*. I've opted for *Global* to enable the use of blocks in this library across all my projects.
3. Select a location and file name for the new library. Since it's a global library, I'm placing it in my *Global Library* folder.
4. Assign a descriptive name to the library that reflects its category or function, for example, "Power Modules," "Audio Circuits," or "Sensor Interfaces."

The library is now ready to receive a design block. You can convert an entire schematic sheet to a design block, but it's more practical to be selective. Let's create the first design block from the power indicator LED subcircuit from Figure 15. Use your mouse to select the subcircuit ("1" in **Figure 17**), then right-click in the *Design Blocks* panel and select *Save Selection as Design Block...* ("2").

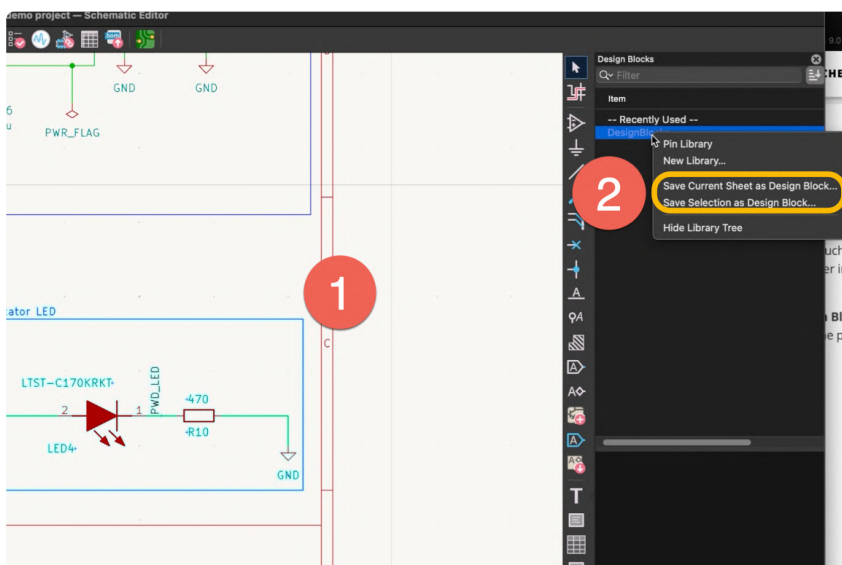


Figure 17: Convert the power indicator LED circuit into a design block.

Give the block a name in the window that pops up. I named mine "Power indicator LED". The new block now appears in the *Design Blocks* list (see **Figure 18**).

I've added several more design blocks to my global library. Now, let's put them to use. In new projects, open the *Design Blocks* panel to see a list of available blocks. To import one, right-click on the block, select *Place Design Block* (the option labeled "1" in **Figure 19**), and position the block where you want it on the schematic sheet ("2").

Design Blocks Library Management

As with symbol, footprint, and 3D model libraries, you can have multiple design block libraries. KiCad provides a panel

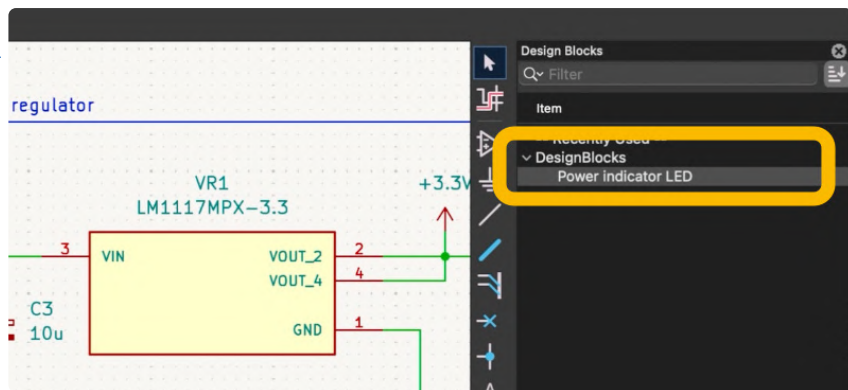


Figure 18: The new design block.

the location of these libraries (highlighted this with yellow).

You can modify the storage location of your libraries by using this Manager window.

Using Design Blocks

The integration of *Design Blocks* into your schematic workflow offers practical benefits in various scenarios.

- **Consistency Across Projects:** Reusable schematic blocks ensure uniformity in circuit implementation, reducing variability and enhancing overall reliability.
- **Rapid Development and Prototyping:** Quick access to pre-validated, reusable blocks accelerates prototyping phases, allowing designers to focus on project-specific innovations rather than repetitive component selection and layout tasks.
- **Error Reduction:** Consistent reuse significantly reduces the risk of manual entry errors, improving the overall quality and reliability of designs.

3D Model Export Improvements

KiCad 9 introduces a new export capability that significantly enhances its 3D model export capabilities. This latest update broadens your options for creating and exporting detailed, accurate, and versatile PCB model files. KiCad now supports multiple formats, including STL, boundary representation (BREP), and polygon file formats. This expansion accommodates diverse

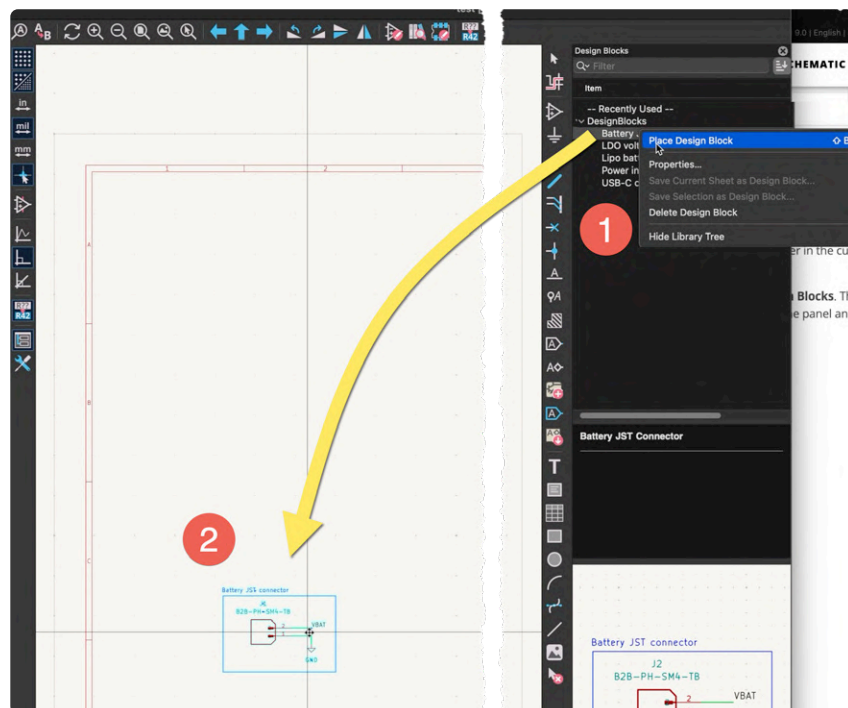


Figure 19: Using a design block in a new schematic.

that lists all registered design block libraries, including project and global libraries. You can find it in the *Preferences* menu (see **Figure 20**).

In **Figure 21**, you'll find the *Design Block Libraries Manager* window. It displays the global and project-specific libraries, along with the path variable indicating

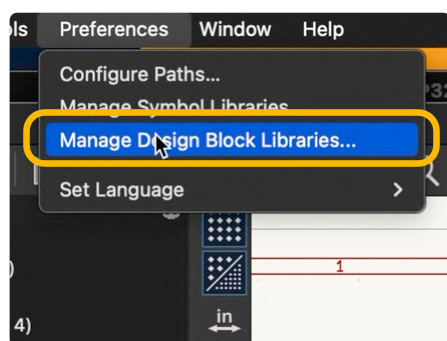


Figure 20: Access the Design Block Libraries Manager.

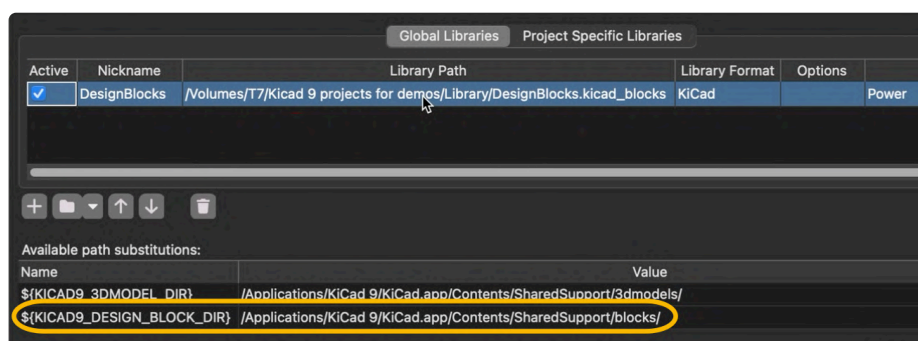


Figure 21: The Design Block Libraries Manager.

applications, ranging from desktop 3D printing to advanced engineering simulations and detailed CAD integrations.

Here's a list summarising these export formats:

- > **STEP (Standard for the Exchange of Product Data):** STEP files provide accurate, detailed geometric data widely used in professional mechanical CAD systems for precise mechanical integration, assembly simulations, and detailed mechanical validations. Learn more about STEP [4].
- > **STL (Stereolithography):** Designed for rapid prototyping and desktop 3D printing, STL represents 3D models as triangular meshes, facilitating quick physical validation and mechanical checks. Learn more about STL [5].
- > **BREP (Boundary Representation):** This format precisely defines geometry and topology, making it ideal for detailed mechanical engineering applications and compatibility with high-end CAD software. Learn more about BREP [6].
- > **GLB (glTF Binary):** A compact binary format designed for efficient transmission and loading of detailed 3D models, ideal for online viewing, augmented reality (AR), and virtual reality (VR) applications. Learn more about GLB [7].
- > **X3D (Extensible 3D Graphics):** Primarily used for real-time 3D web visualisations, interactive simulations, and multimedia-rich documentation. Learn more about X3D [8].
- > **PLY (Polygon File Format):** This format includes additional attributes like colours, textures, and transparency, which are useful for high-quality renderings, visualisations, and presentations. For more information, visit [9].

In **Figure 22**, you can see the result of printing an STL file of one of my PCB designs on my desktop 3D printer. Although I haven't cleaned up the filament threads, the print-out is remarkably accurate in terms of the board's shape and size, as well as the components on it.

The ability to export precise 3D models of PCB designs facilitates seamless integration with mechanical CAD software. This integration enables accurate enclosure design, fit checks, and assembly validation before physical prototyping. By doing so, it significantly reduces the risk of costly manufacturing errors, ensuring that mechanical constraints and clearances are adequately addressed during the early design stages.

For instance, I can utilise the print depicted in **Figure 23** to design an appropriate enclosure in, for example, FreeCAD. Subsequently, I can print that enclosure and conduct tests to verify if the PCB model fits within it. This process allows me to work on the actual PCB manufacturing and assembly while saving considerable time.

Exporting 3D models also finds applications in various other fields, such as thermal analysis. By accurately simulating heat dissipation and identifying poten-

tial thermal issues, engineers can optimise cooling solutions and enhance product reliability and performance. Visualising the PCB layout within realistic mechanical environments provides valuable insights into how to effectively cool the PCB and ensure its optimal functioning.

Exporting 3D PCB Models

To explore a 3D model in one of the available formats, start by checking the 3D viewer. The exported 3D model will closely resemble what you see in the 3D viewer. Once you're ready to export, open the *Layout Editor* and click *File* → *Export STEP/GLB...* to bring up the export window (see **Figure 23**).

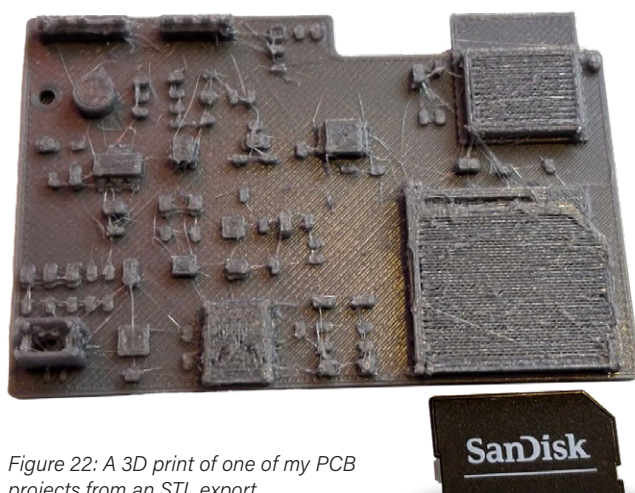


Figure 22: A 3D print of one of my PCB projects from an STL export.

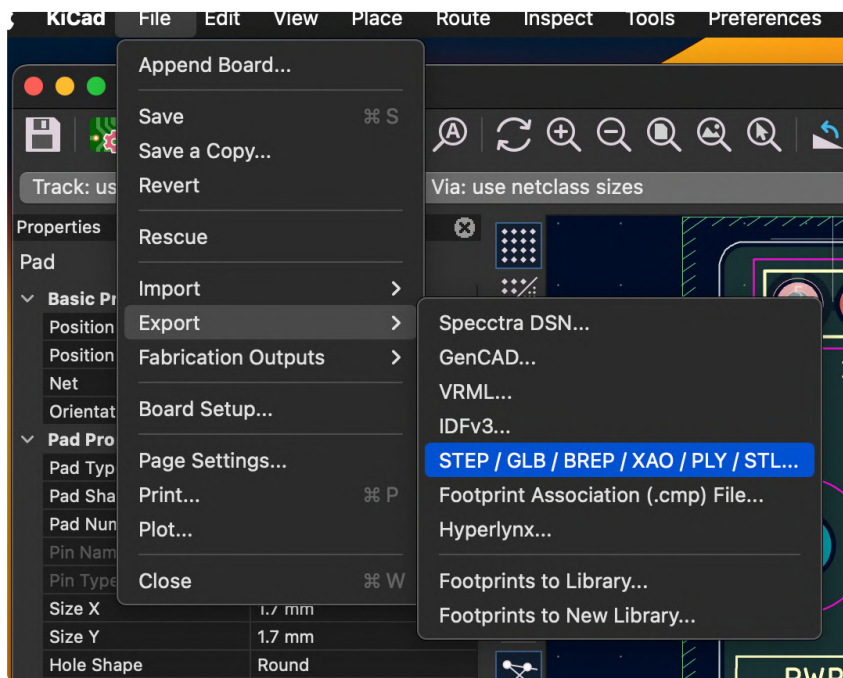


Figure 23: Bring up the 3D export window.

In the 3D model exporter window, select your preferred format and the export file location (see **Figure 24**).

Select the various board options and other settings, and then click *Export* to create the file. When deciding which options to enable or disable, consider your objectives and the capabilities of the software or hardware that will read the exported file. For instance, in my experiment, my goal was to print the model on my desktop 3D printer. Therefore, I disabled the silkscreen and solder mask export options because they are not compatible with my 3D printer. I enabled all the components on the board because they can be printed, and I wanted to ensure that their positioning is correct, especially in relation to the enclosure I plan to design.

Once I had the STL file, I opened it in my 3D printer's slicer software to prepare for printing. In **Figure 25**, you can see the model ready for printing.

About an hour later, I had the printed model you can see in Figure 23.

Integrating with FreeCAD

Exporting 3D models from KiCad into CAD software like FreeCAD can significantly enhance your PCB workflow by bridging the gap between electronic and mechanical design processes. By creating accurate 3D models, mechanical engineers and PCB designers can collaborate effectively, ensuring that components and connectors precisely align with enclosures and other mechanical parts. This collaborative approach reduces prototyping iterations and minimises the likelihood of manufacturing issues.

FreeCAD is particularly compatible with STEP and BREP file formats, both of which maintain high geometric precision. STEP files are widely preferred for FreeCAD due to their reliable preservation of exact geometric dimensions. They are ideal for precise mechanical assemblies, complex enclosure integrations, and detailed clearance checks. BREP files can also be effectively utilised in FreeCAD, especially for advanced mechanical analyses. They provide support for

defining complex geometries and ensuring accuracy during simulations and mechanical validations.

Other Notable New Features

In addition to the headline improvements like Jobsets, Design Blocks, and the Zone Manager, KiCad 9 includes several smaller but highly useful enhancements that contribute to a more efficient and precise design workflow. Next, I'll introduce three

of these features: the *Precision Positioning Tool*, the *Selection Filter* in the schematic editor, and *Component Classes*. I won't go into detailed usage instructions here, but I'll explain what these tools are and how they can improve your design experience.

The new **Precision Positioning Tool** in KiCad 9 is designed to provide precise and adaptable control over the placement of components and items.

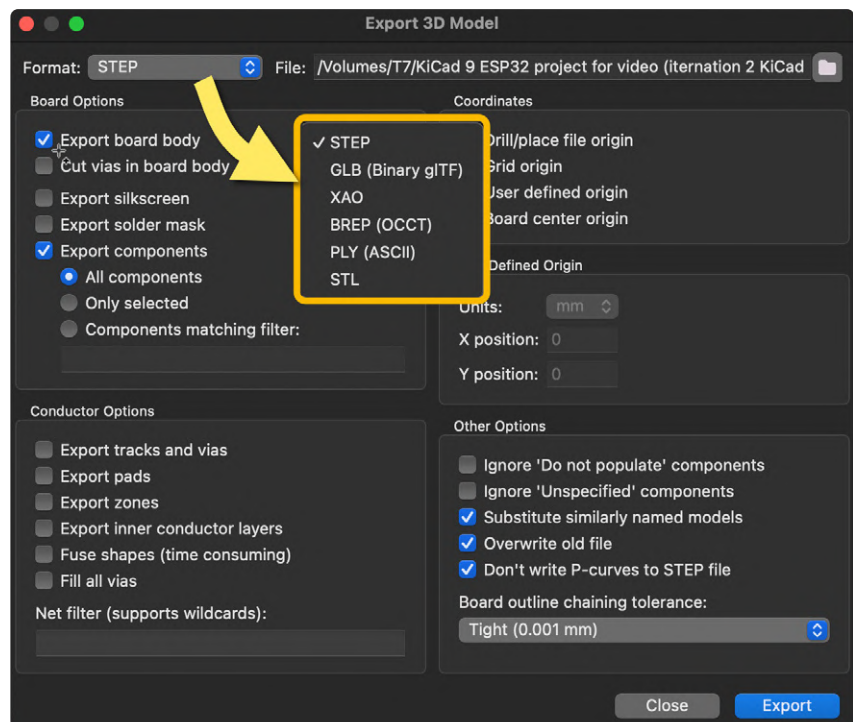


Figure 24: The 3D exporter window.

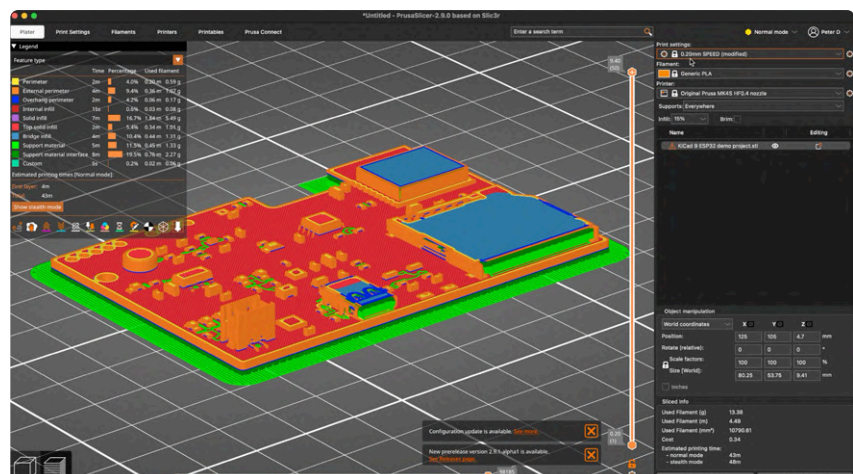


Figure 25: The 3D model in the slicer, ready for printing.

Accurate positioning is paramount in contemporary PCB designs, as even minor misalignments can jeopardise mechanical compatibility, electrical performance, and manufacturability. In high-frequency circuits, even slight positional errors can adversely impact impedance matching and signal integrity. Mechanical applications necessitate precise placements to ensure components fit flawlessly within enclosures or align precisely within stringent mechanical constraints. KiCad's latest *Precision Positioning Tool* effectively addresses these challenges, enabling super-precise control over component positioning and alignment (**Figure 26**).

The **Selection Filter**, a productivity feature previously exclusive to the PCB editor, allows users to define precisely which types of schematic objects are selectable. This feature enhances editing efficiency, especially in complex or densely populated schematic designs.

While schematic editors generally appear less cluttered than PCB layouts, complex schematics often involve overlapping elements such as symbols, wires, labels, and graphical annotations. Selecting a specific object within these overlapping elements can be challenging and prone to errors, potentially disrupting workflow and causing unintended edits. KiCad's schematic Selection Filter addresses these challenges by ensuring precise object selection and streamlining the editing process.

In **Figure 27**, you can see the Selection Filter in the bottom left panel of the left panel ("2"). If the left panel is closed, you can open it by clicking on the *Properties* button of the left toolbar ("1").

Component Classes enhances organisation and enforces targeted design rules by grouping schematic symbols and their corresponding footprints. This feature builds upon the existing net classes, which have been around for many KiCad versions and define electrical constraints for signal routing. The new Component Classes provide a structured approach to managing component-specific layout requirements,

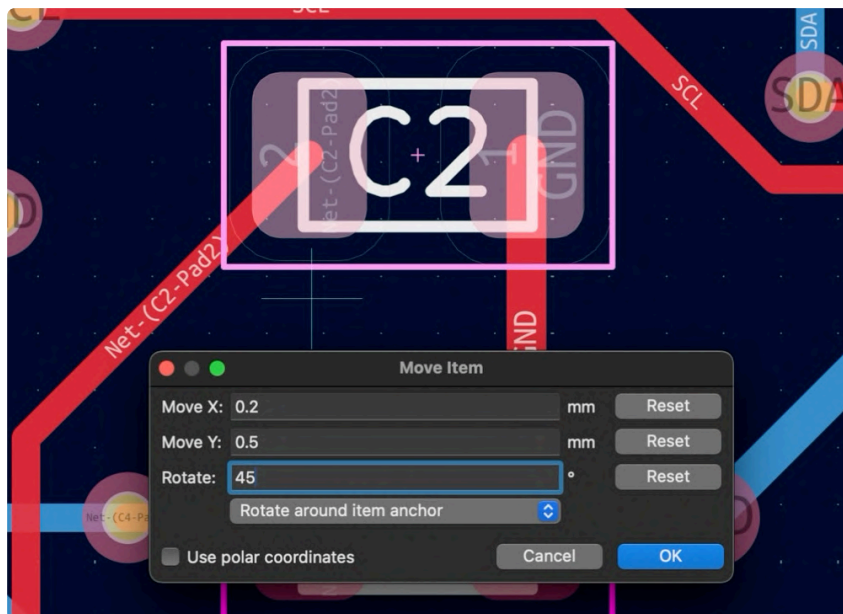


Figure 26: An example precision move operation.

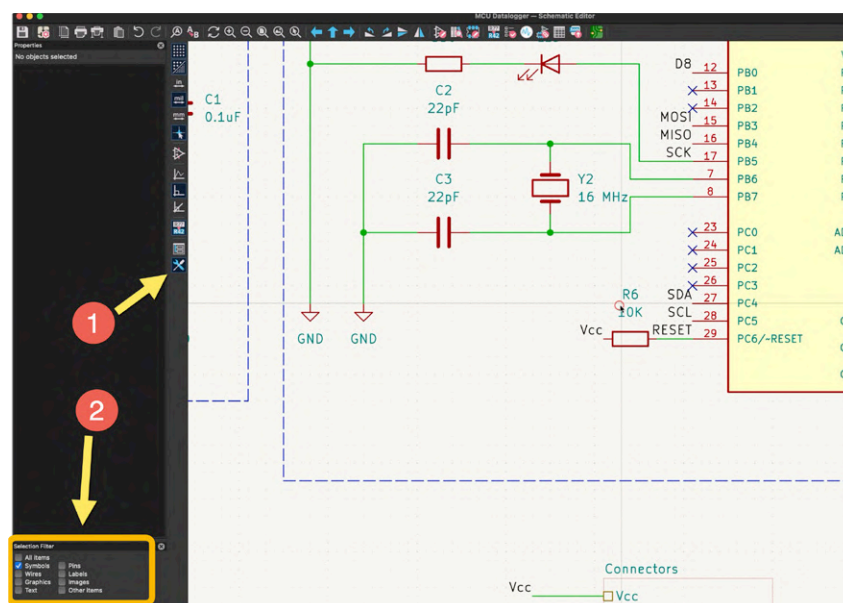


Figure 27: The selection filter.

improving workflow efficiency by allowing designers to apply consistent rules to functionally related components, reducing errors, and ensuring adherence to design constraints.

Component Classes simplify design rule enforcement and visual organisation in both the schematic and PCB layouts. By categorising components into logical groups, designers can ensure uniform

design constraints, such as clearance, courtyard space, pad-to-pad distances, and silkscreen overlap restrictions. This approach is particularly useful in mixed-signal designs, high-density layouts, and regulatory compliance enforcement, where different component groups require specific handling. In **Figure 28**, I demonstrate the graphical method of defining a component class using zones and labels to contain two enclosed components.

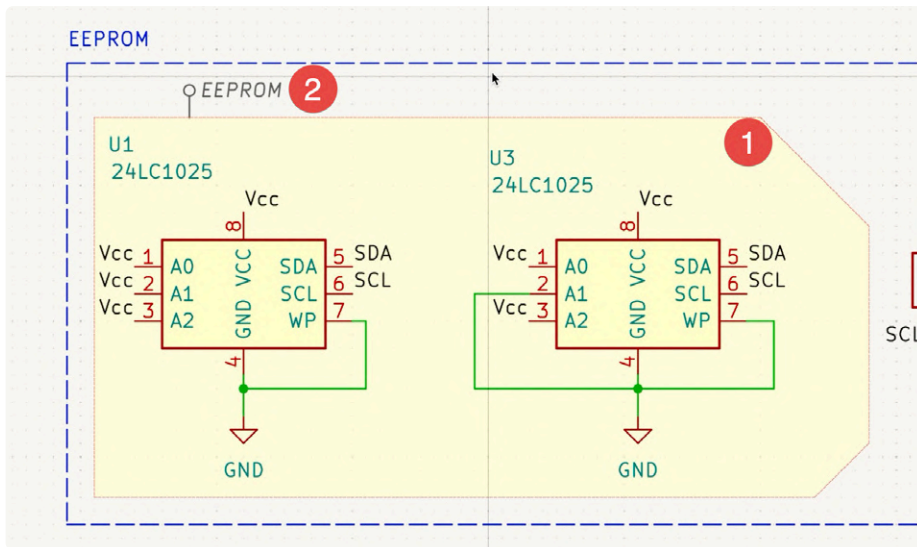


Figure 28: I have defined a Component Class using a zone and a label.



About the Author

Dr. Peter Dalmaris is an educator, electrical engineer, electronics hobbyist, and Maker. Creator of online video courses on DIY electronics and author of several technical books including the series *KiCad Like a Pro*, *KiCad 6 Fundamentals and Projects* and their updated versions. His company, Tech Explorations, offers a variety of educational courses and bootcamps for electronics hobbyists, STEM students, and STEM teachers.

These are just some of the highlights. KiCad 9 also introduces other enhancements like the *Multiple Track Drag* for smoother layout edits, support for pad stacks with different copper shapes, *Tables* for improved documentation, and more.

If you haven't tried KiCad 9 yet, I encourage you to explore it. Whether you're working on a simple board or a complex multi-layer design, the new features are designed to help you work faster, more precisely, and with greater confidence. ◀

250252-01

Questions or Comments?

Do you have technical questions or comments about this article? If so, please contact the Elektor editorial staff at editor@elektor.com.



Related Products

▶ Peter Dalmaris, *KiCad Like A Pro - 4th edition - Volume 1* (Elektor, 2024)
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▶ Peter Dalmaris, *KiCad Like A Pro - 4th edition - Volume 2* (Elektor, 2024)
www.elektor.com/20930



WEB LINKS

- [1] KiCad Version 9 Released: <https://www.kicad.org/blog/2025/02/Version-9.0.0-Released/>
- [2] KiCad documentation: Text variables: <https://txplo.re/6ac92>
- [3] KiCad documentation: Jobsets: https://txplo.re/kicad_jobsets
- [4] ISO 10303-21, Wikipedia: https://en.wikipedia.org/wiki/ISO_10303-21
- [5] STL (file format), Wikipedia: <https://txplo.re/stl>
- [6] Boundary representation, Wikipedia: <https://txplo.re/brep>
- [7] glTF, Khronos Group: <https://txplo.re/glb>
- [8] "What is X3D?", web3D Consortium: <https://txplo.re/x3d>
- [9] PLY (file format), Wikipedia: <https://txplo.re/ply>

Precision Picoammeter (1)

With Curve Tracer Functionality Down to the pA range!

By Johannes Sturz (Germany)

The measurement of infinitesimal currents is critical, mainly due to the need for very low-noise and high-sensitivity signal amplifiers and a robust input stage that is insensitive to EMI. This picoammeter, with auto-ranging capability and a rather advanced HTML GUI, overcomes these drawbacks, allowing for the creation of a reliable, low-cost instrument capable of measuring currents down to the pA range!

Among the plethora of mid-range or low-mid-range measuring instruments, only a few offer current ranges below 1 mA at full scale.

The ammeter described in this first installment of the article covers a measurement range of 10 decades (pA...mA). This is achieved using 9 ranges. An additional programmable voltage source enables this device to generate and display I-V curves. This curve tracer functionality can perform high-resolution spot and sweep measurements, with the ability to display them as graphs. Comparable devices cost several thousand euros.

Why Is It Useful?

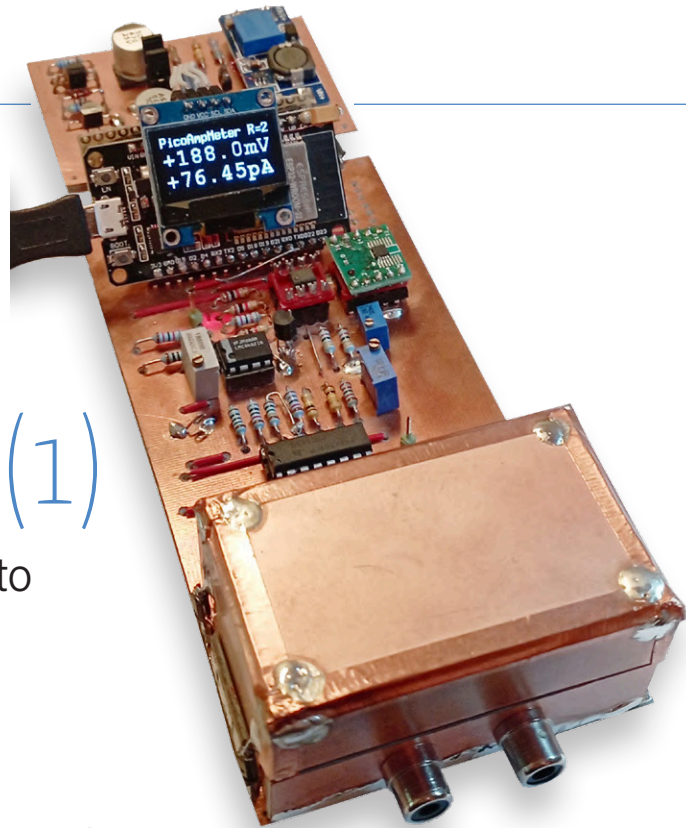
- Checking of components after potential damage due to ESD or overloading.
- Testing of photodetectors and sensors, science experiments.
- Capacitor leakage measurement.
- Leakage current testing in insulators, switches, relays, and other components.

- Checking of ESD protection materials (conductivity), with an external high-voltage source of around 250 V DC.

Key Parameters

The main features of this design can be summarized as follows:

- Resolution: 100 fA
- 50 pA...5 mA in nine ranges
- Up to 32 readings/second
- Bluetooth/Serial interface
- Accurate Programmable Voltage Source: ± 5 V, Accuracy = 1 mV, Resolution = 153 μ V
- Low voltage burden: less than 1 mV
- Automated voltage sweep for I-V characterization



- Taking a look "inside" a device, i.e. to investigate the leakage current of bipolar or MOS transistors or the sub-threshold current of MOS transistors.

Circuit Diagram

The main diagram of the Picoammeter is shown in **Figure 1**. It's quite a straightforward design. The essential circuit blocks are:

- Transimpedance amplifier (TIA)
- Programmable gain amplifier (PGA)
- Voltage level shifting and scaling
- 16-bit ADC
- Voltage reference
- Programmable voltage source
- Power supply

Furthermore, an ESP32-WROOM, an OLED display, and two relays are required.

Transimpedance Amplifier (TIA)

In contrast to the voltage drop method on a shunt resistor, the usage of a TIA as an input stage has several advantages. A transimpedance amplifier acts as a current-to-voltage converter and — by leveraging the very high input impedance of the IC — features nearly no voltage drop (<1 mV), with a much lower noise at low currents. Thus, it makes it possible to measure currents in the pA range and below.

The output voltage (V_{out}) of transimpedance input stage IC1A can be calculated using the formula

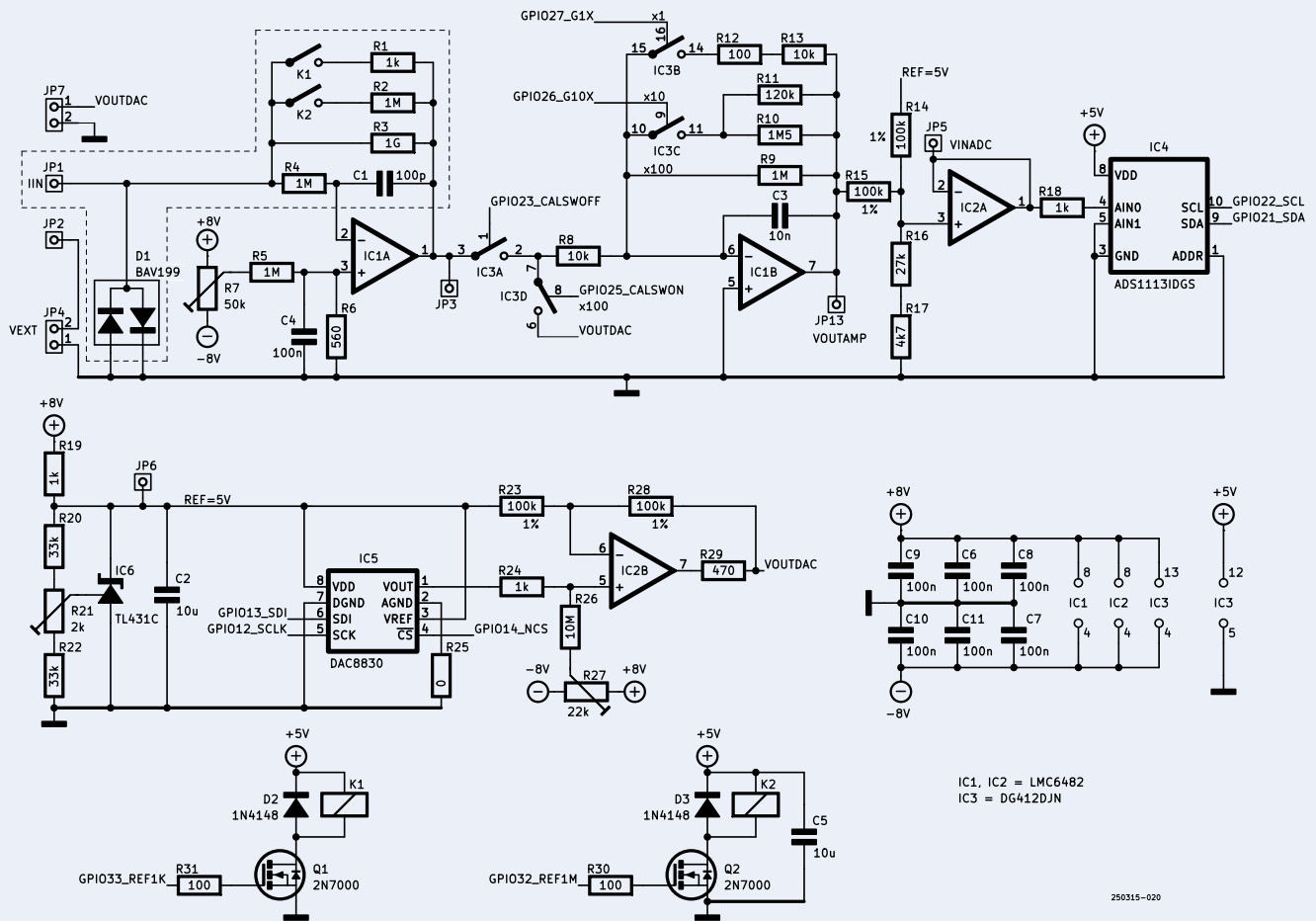


Figure 1: Schematic diagram of the main section of the Picoammeter.

$$V_{out} = -I_s \times R_f$$

where R_f = feedback resistor, and I_s = input current. More information can be found at [1] and [2].

The LMC6482 op-amp by Texas Instruments (IC1A) is quite cheap; it's an improved version of TI's TLC272/TLC277 with rail-to-rail input/output stage and ultra-low input current (20 fA). The TLC272 has an input current of about 60 pA. What is the difference? Both are CMOS op-amps. The higher current is caused by the input protection circuit. This can be prevented using various tricks. Either with a guard driver (Figure 2, left) that supplies the protection diodes or with matched low-current input protection diodes (Figure 2, right), which are used by LMC6482.

Core range settings are performed with two low-leakage current relays, K1 and K2. If both switches are off, then only R3 (1 GΩ) is left in the feedback path.

Input transient protection is provided by resistor R4 (1 MΩ) in series with the input. With R7, the output of IC1A can be trimmed to zero. The input protection double-diode (BAV199) is only necessary with an external voltage source. C1 increases stability. The dashed line in the circuit diagram indicates which signals

must be surrounded by ground (shielded) to minimize leakage currents.

A guard driver is usually used, but in this application, where the input is regulated by the TIA at 0 V, it can be omitted. In picoammeters, tiny leakage currents through insulation or

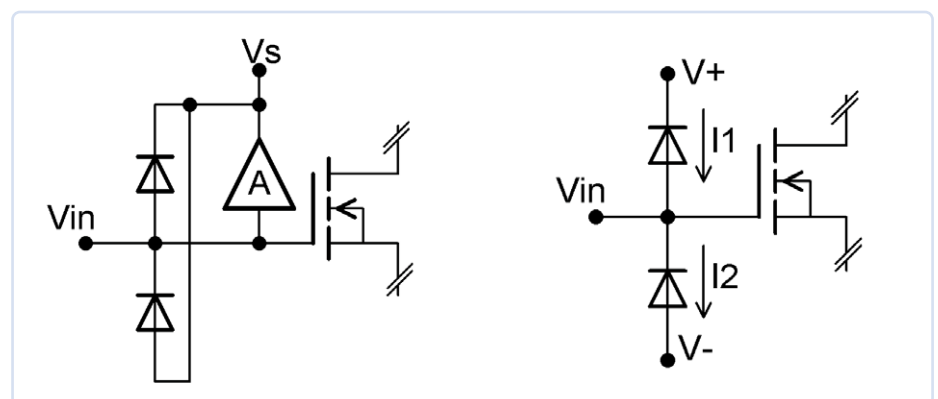


Figure 2: In the example on the left, guard driver A ensures that V_s is nearly equal to V_{in} . Thus, almost no current flows through the diodes. In the circuit on the right, due to the diodes' special circuit design, I_1 and I_2 are almost equal. This means that the input current is almost zero.

PCB surfaces can introduce significant errors. A guard driver holds the surrounding guard conductor at the same potential as the sensitive wire or component, creating a zero-voltage drop across the leakage path and thus preventing current from flowing through it.

Programmable Gain Amplifier (PGA)

The PGA stage uses the second opamp of IC1. The gain of the inverting op-amp is set by using analog switches IC3B and IC3C. The highest gain is selected when both switches are open.

The resistance values and the offset of the op-amp are not critical because an automatic calibration is performed. Switches IC3A and IC3D are used for this purpose. IC3D connects a DAC output to the amplifier's input. In this case, IC3A disconnects the output of the TIA section. Offset and amplification are calculated for all gain ranges and stored in the "EEPROM" area of the controller.

Voltage Level Shifting and Scaling

The output of op-amp IC1B spans -5 V to +5 V, but the ADC input is scaled in a 0 V...2 V range. The resistor network made by R14, R15, R16, and R17 does the job. Op-amp IC2A acts as an impedance converter (buffer). Resistors R14 and R15 should match well, because the positive and negative ranges are no longer symmetrical.

The output of IC2A is fed to IC4, the ADS1113IGDS — a 16-bit, 860 sample/s delta-sigma A/D converter by Texas Instruments. It sends the sampled values via its I²C interface to the NodeMCU-ESP32 board.

Programmable Voltage Source and Voltage Reference

DAC8830, a 16-bit DAC by Texas Instruments, is used for the programmable voltage source. The DAC's VREF input is supplied with 5 V (REF), which guarantees that the DAC output voltage can be as high as Vref is. The load of Vref, due to the DAC's power consumption, is quite low — just a few μ A. With R27, the DAC's output voltage can be adjusted exactly to 0 V, with IC2B used as a non-inverting buffer.

To generate Vref, an inexpensive, readily available voltage reference was chosen (IC6). The output voltage can be adjusted using R21 and measured at JP6. Resistors R20 and R22 narrow the adjustment range, thus facilitating an accurate adjustment.

Power Supply

The whole power supply circuit, shown in **Figure 3**, is supplied through the USB port via the ESP32. ESP32 power out is VIN+ 5 V. But this labeling is actually not correct, since the measured voltage at VIN+ 5 V is, in the best case, around 4.7 V, or even less, because of a Schottky diode connected in series.

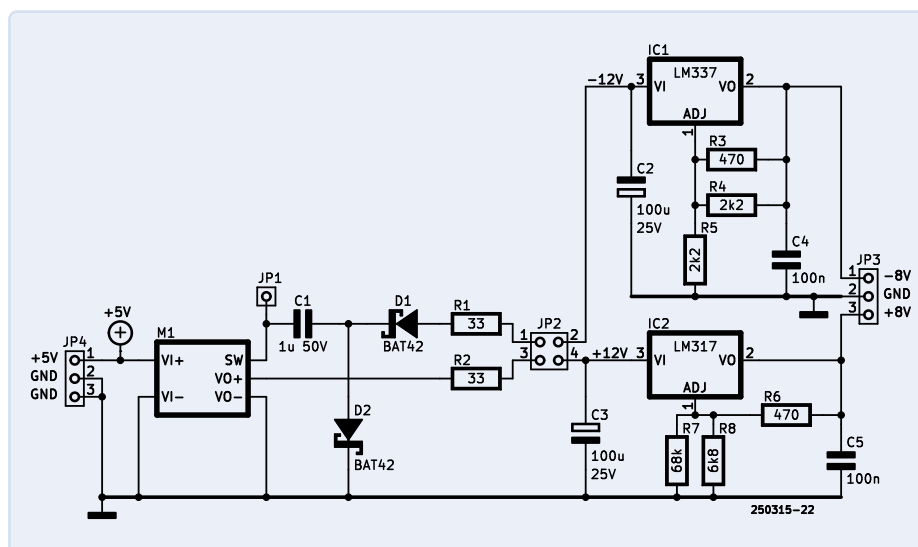


Figure 3: The power supply section, which includes a step-up converter and a ± 8 V voltage regulator.

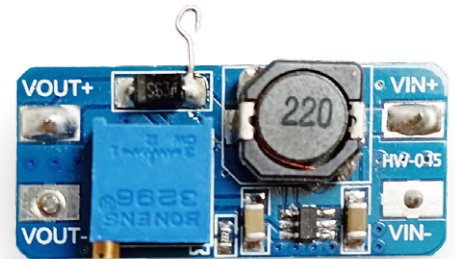


Figure 4: The step-up converter module that supplies the ± 8 V regulators. The soldered link for the SW signal is visible on the top.

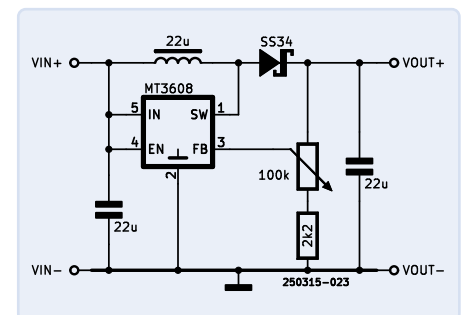


Figure 5: Schematic diagram of the step-up converter.

A simple step-up converter (**Figure 4**) has been used to regulate the ± 8 V we need; in Figure 3, this module is symbolized as M1. Using a trick, it is possible to create a negative voltage with the following components: C1, D1, and D2. C1 is connected here to pin 1 of the switching regulator IC (see **Figure 5** or the top of the board on Figure 4). Resistors R1 and R2 reduce the inrush current of the step-up converter, because C2 and C3 are not yet charged. An output voltage of 12 V is set with the multi-turn potentiometer on the step-up converter module. Be sure to insert jumper J2 of Figure 3 (1-2 and 3-4) only when the output voltage is correct.

Low-Leakage Relay

The relay used for K1 and K2, a COTO 9011-05-11 by COTO Technologies (**Figure 6**), is characterized by the outstanding insulation resistance of 1 T Ω . If you decide to realize this design, do not replace this component with others, unless they provide equivalent specs.

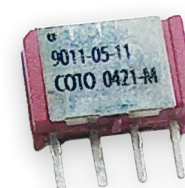


Figure 6: The 1 T Ω -isolated relay by COTO Technologies, dismantled from an early version of the prototype.

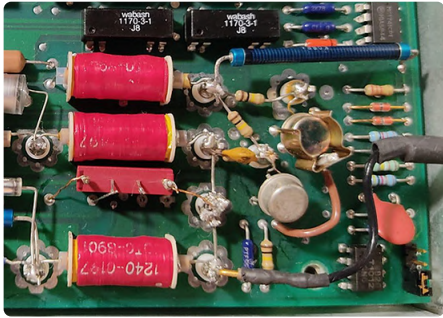


Figure 7: Detail of the circuit board of a professional electrometer — owned by the author — showing (left) three high-isolation reed relays.

Many relays achieve an isolation resistance of about 1 GΩ *only*. The problem here is the molding compound.

This can also be solved by instead using reed relays, which feature a completely insulated coil, as shown in the detail in **Figure 7**. The reed contacts can be mounted on the circuit board

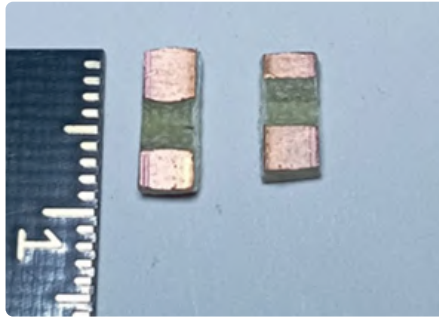


Figure 8: FR4 support strips, made by the author.

using stand-offs, best made of Teflon. I have achieved excellent results using FR4 strips cut from scrap PCBs, as shown in **Figure 8**.

ESP32 Board and OLED Display

Please note that various versions of ESP32 are available, with different pinouts and memory sizes. If you want to use a module other than

the one described, pay attention to the pin assignment, see **Figure 9**. If necessary, edit the Arduino software accordingly. The flash size should be 4 MB. The OLED display is not strictly necessary, but it also makes the setup phase easier. I got it from the supplier specified in the **Component List** box. All the versions with an SSD1306 controller, I²C, and 128 × 64 pixels should be compatible.

Ranges

As anticipated, the Picoammeter works in 9 ranges. **Figure 10** shows the starting and ending values for each. The table in the bottom-right corner shows the relationship between feedback resistor value, gain, and range.

Figure 9: The digital heart of the Picoammeter. Make sure to adopt pin-compatible versions of the ESP32 for this project. The OLED display is not mandatory, but helpful in the setup phase.

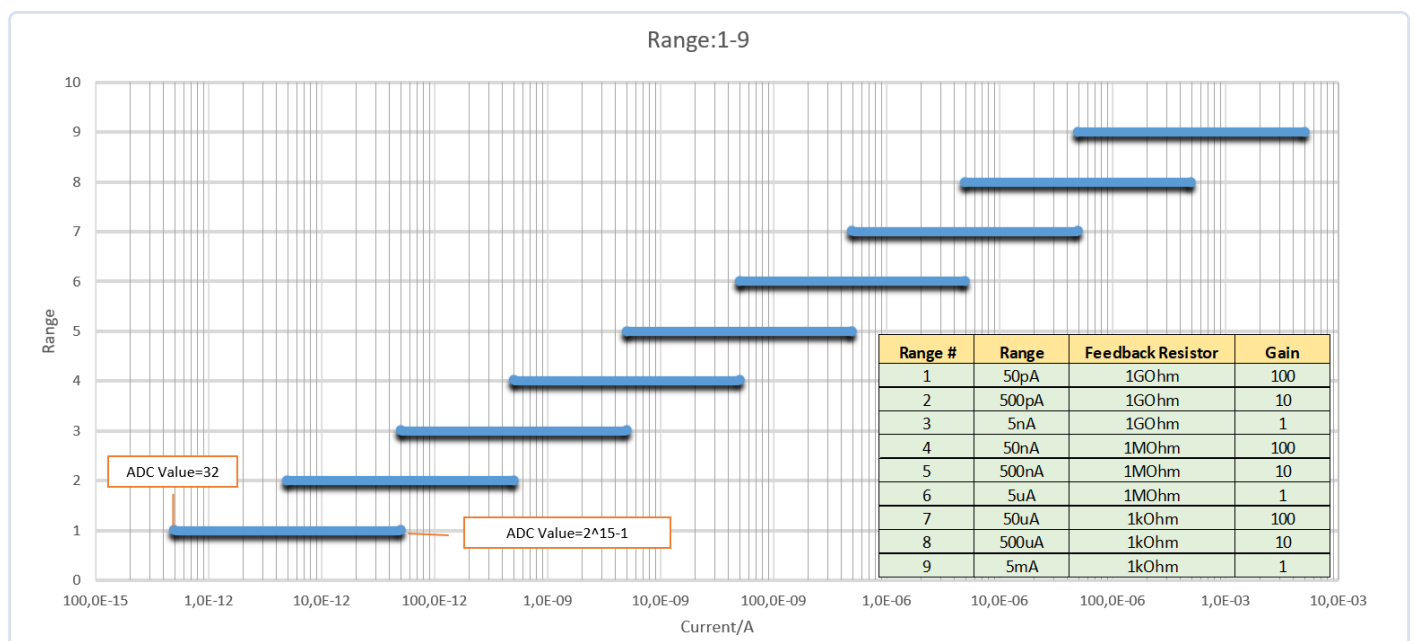
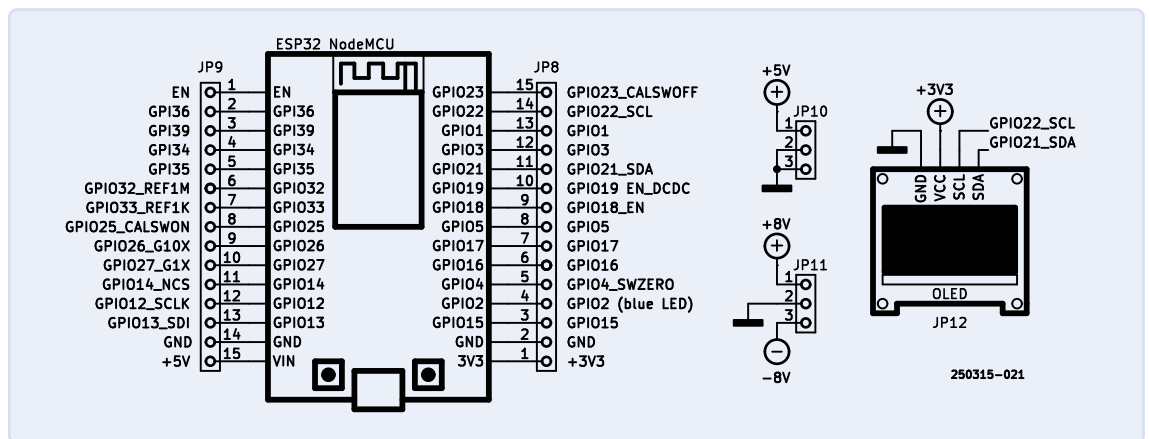


Figure 10: The Picoammeter's nine measurement ranges.

Graphical User Interface

Measurement GUI

The GUI is implemented as a web application, served by the ESP32, running in a browser (Download at [3]). It has four components

- > *index.html*
- > *meter.js*
- > *serial.js*
- > *style.js*

The basic serial communication functions are located in *serial.js*, and the functions that communicate with the ESP32 controller firmware are in *meter.js*. To start the GUI, all you need to do is double-click on the *index.html* file. Next, the correct port must be selected. Then all controls are visible, as shown in the screenshot of **Figure 11**.

It is important that all files are in the same folder, and the referenced browser must be Microsoft Edge, Google Chrome, or Opera.

There are *zoom* and *pan* functionalities included. When the mouse pointer is over a measuring point, the corresponding value is displayed. With the *callback* functionality, it is possible to label the Y-axis meaningfully. The measured current/resistor value will be updated every second in the upper-left field.

Menu

The menu (see the detail in **Figure 12**) is divided into the following fields:

- > **Measured Current/Resistor:** The measured current or resistance is continuously displayed, depending on what was selected in the *Display Mode* field.
- > **Set Output Voltage:** The desired output voltage can be entered here or the slider can be used.
- > **Display Mode:** Here you can choose between current and resistance measurement. The resistance measurement is more accurate the higher the set voltage.
- > **Sweep Output Voltage:** The sweep range is ± 5 V and the minimum step size is 1 mV. The recorded data can also be saved in .csv format.
- > **Average, Zero Input and Calibration:** Noise can be reduced at currents below 1 nA using averaging. Zero eliminates input offset current, and Calibration compensates for amplifier errors.
- > **Chart, Y-Axes:** Here, the scaling can be switched between linear and logarithmic at any time — even during a sweep.
- > **Console:** All serial data will be printed here.

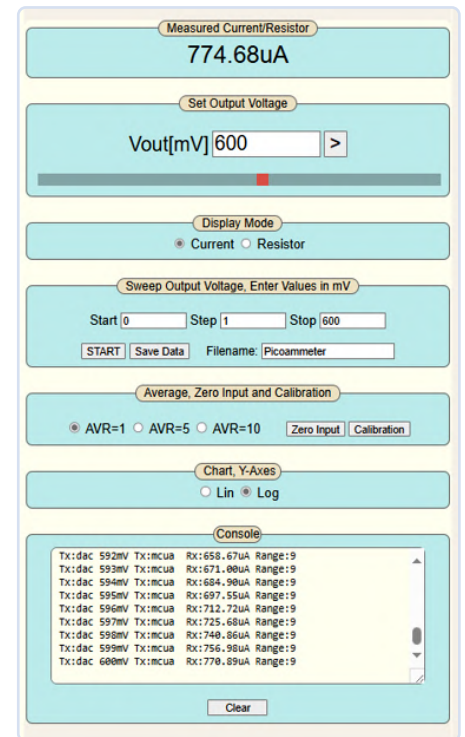


Figure 12: Detailed view of the menu section.

Let's See Some Graphs!

Although assembly, testing, and the Arduino sketch for the picoammeter will be described in the second installment of this article, it is still interesting to illustrate the behavior of this device as a curve tracer, with some practical examples.

Range Alignment Check with a Bipolar Transistor

To verify the functionality of the self-calibration process, a preliminary test with a bipolar transistor (BJT) was performed. The relationship between base-emitter voltage (V_{be}) and collector current can be described with the following exponential function:

$$I_c = I_s * e^{\frac{V_{be}}{V_t}}$$

I_c = collector current

I_s = reverse saturation current (constant: 1 fA...1 pA)

V_t = thermal voltage (≈ 26 mV at room temperature)

When the current (I_{cb}) is plotted onto a logarithmic scale, it is shown as a straight line because the logarithmic function is the inverse of the exponential function.

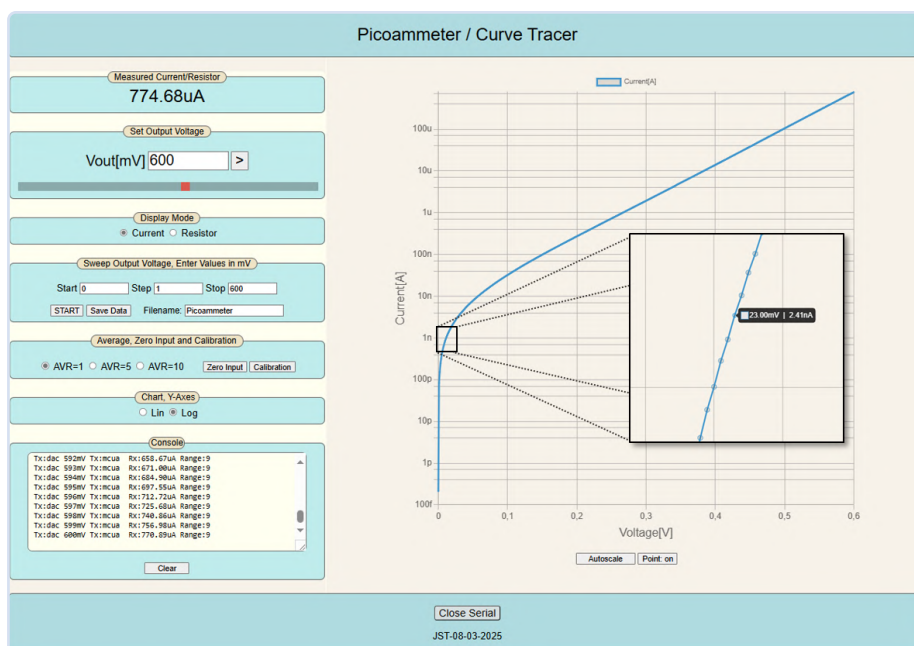


Figure 11: Screenshot of the Picoammeter/ Curve Tracer's measurement GUI.

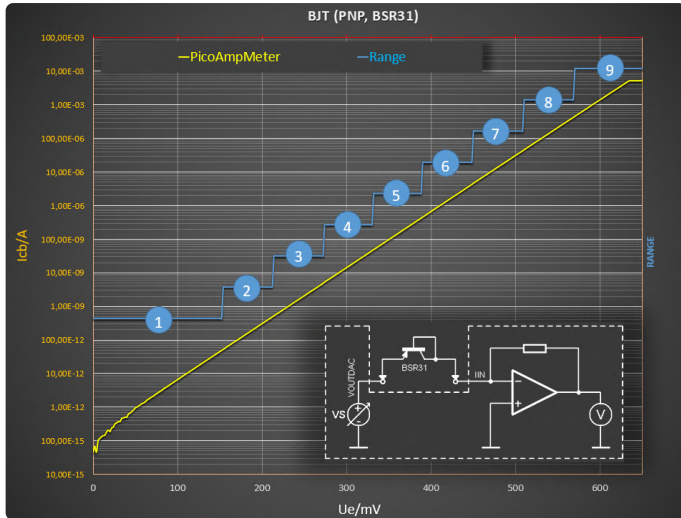


Figure 13: The auto-calibration process works! This graph shows how smooth the transition is among the nine available ranges. No steps on the trace — they all match correctly!

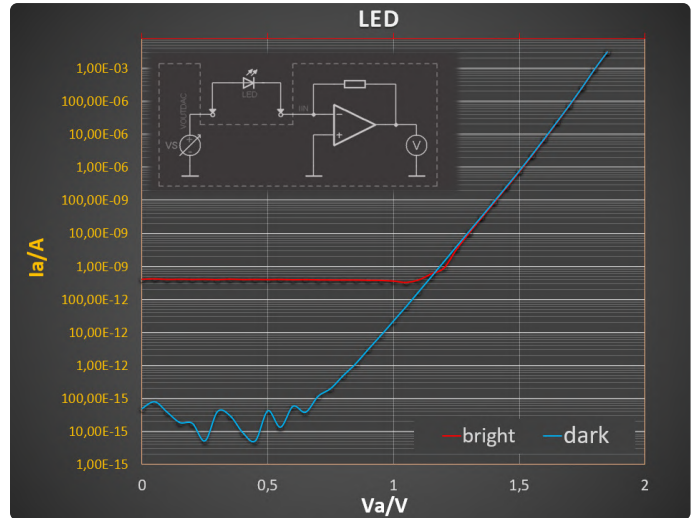


Figure 15: Characteristic curve of an LED with FW polarization. Note the coarse difference between the red trace (measurement taken with ambient light) and the blue one (in the dark).

As you can see in the graph shown in **Figure 13**, there is no misalignment of the ranges visible due to auto-calibration. At currents below 1 pA, noise is visible, but the trend is still recognizable.

With the current limited at 5 mA, transistor BSR31 shows excellent logarithmic behavior, down to the pA range. Noise can be reduced by averaging over a larger number of samples.

Measurement Examples

Diodes

Three diode characteristics are shown in a conventional way — on a linear scale (**Figure 14**, left). Here you cannot see how high the currents are below the threshold voltage, but you can see them on Figure 14, on the right. Interestingly, the JFET connected as a diode (yellow curves on both graphs) shows the lowest leakage current. This makes it a

suitable replacement for an input protection diode, such as a BAV199.

The yellow curve does not look as smooth as the others, since a larger step size was set here (20 mV instead of 2 mV).

LED

The graph illustrated in **Figure 15** shows the characteristic curve of a forward-supplied LED.

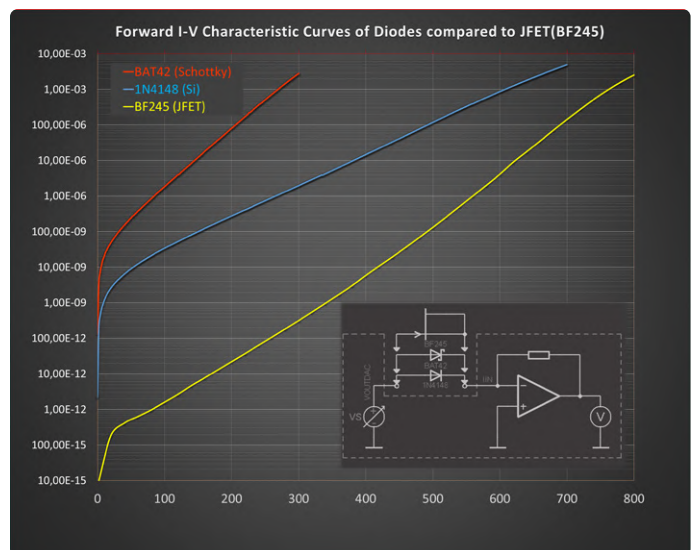
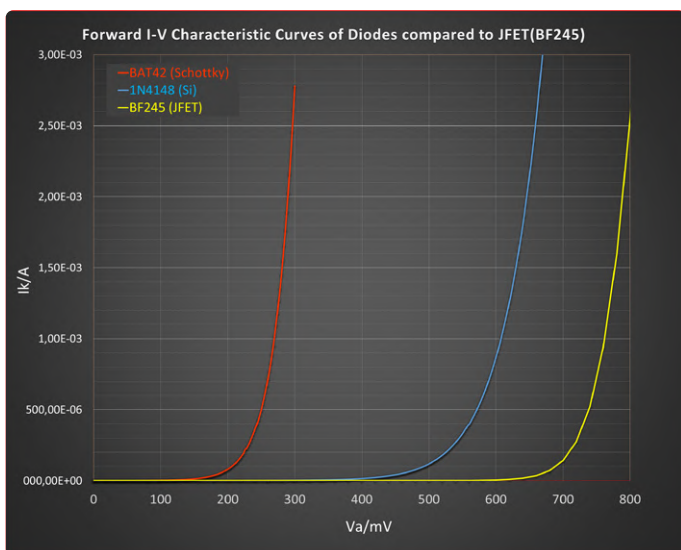


Figure 14: Comparison between a linear representation of two diode curves (red and blue, left) and the same measurement done onto a logarithmic scale (right), which you can't get from a standard curve tracer. Interestingly, a JFET connected as a diode (yellow curves) showed a quite lower leakage current in both charts.

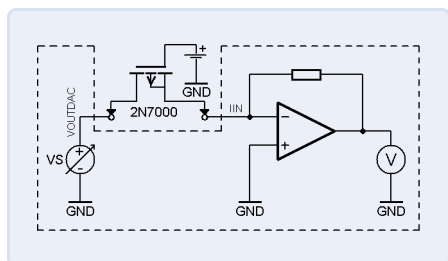


Figure 16: Simplified diagram of the test circuit; an external power supply is required to control the gate. The DUT and external power supply appear outside the dashed line.

The blue curve refers to a test carried out in darkness, and the red one in ambient light. It is easy to see that the leakage current is significantly higher when light is present. With a suitable driving circuit, an LED can also be used as a light sensor.

N-Channel MOSFET Subthreshold Current

The simplified diagram in **Figure 16** shows the test circuit. The gate voltage is controlled by an external, adjustable power supply. The subthreshold current in a MOS transistor refers its gate voltage, which is lower than the threshold voltage, and yet a small current flows through it. The gate threshold voltage for the transistor used is a minimum of 1 V.

The red curve of **Figure 17** shows the drain current at a gate voltage of +0.5 V (approx.

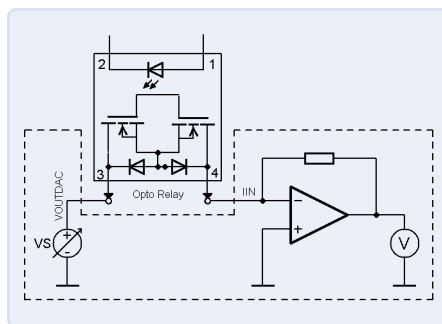


Figure 18: A simplified diagram of the setup needed for testing a photorelay.

$I_d = 20 \text{ pA}$), which is significantly different from 2 pA at $V_{GS} = 0 \text{ V}$. In the blue curve, a negative voltage was applied to the gate. It is interesting to note that this allows the drain current to be further reduced.

Transistors are usually not operated in this range because there are large process variations and temperature dependencies. However, there are companies that develop ICs that operate in this range and consume extremely low power, for example Nanopower and Ambiq.

Toshiba Photorelay

The simplified circuit in **Figure 18** shows the necessary connection. In **Figure 19**, it is clearly visible that a higher on-state current type of photorelay also results in a higher leakage

current (off-state current). The reason lies in the larger transistor area. The TLP3555 with the highest current rating shows a lower output impedance ($\Delta V_d / \Delta I_d$, where $V_d > 250 \text{ mV}$). This is likely a different IC design or process.

Measurement Comparison with a DC Analyzer (HP4155B)

The DC analyzer (HP4155B) illustrated in **Figure 20** can measure currents down to femtoamperes. This device is over 25 years old and is still in industrial use. It features, among other things, four source measure units (SMUs). The SMU is an electronic instrument capable of both sourcing and measuring at the same time. It can precisely force voltage or current and simultaneously measure precise voltage and/or current.

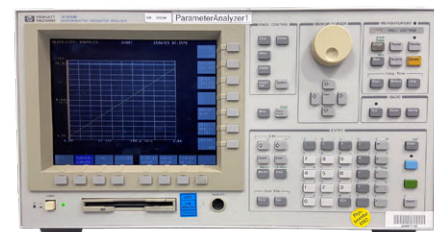


Figure 20: The HP4155B DC Analyzer used by the author to compare the measurements done with his Picoammeter.

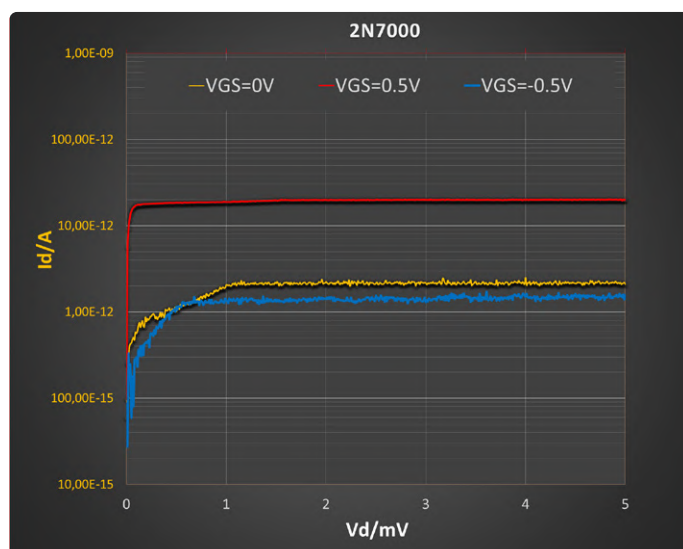


Figure 17: Curves related to the MOS transistor driven at $V_{gs} = 0.5 \text{ V}$, 20 pA (red), $V_{gs} = 0 \text{ V}$, 2 pA (yellow) and $V_{gs} = -0.5 \text{ V}$, 1.5 pA (blue).

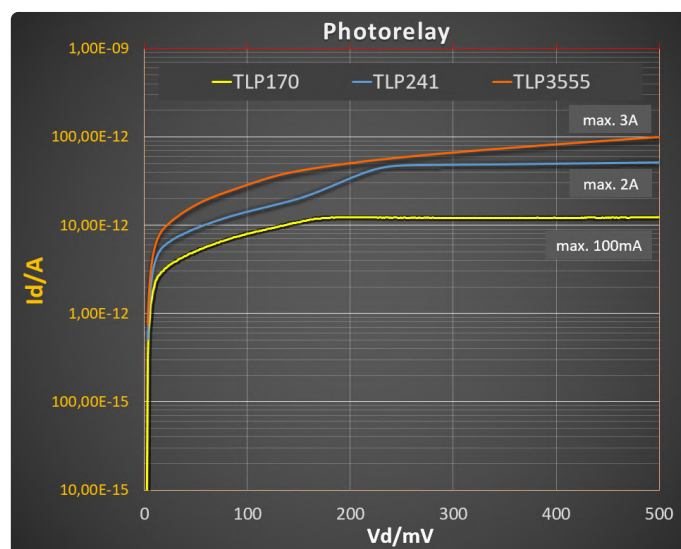


Figure 19: The curves show a correlation between a photorelay's on-state current capability and its typical leakage current in the off-state.

I used this equipment for a comparison measurement. **Figure 21** shows the results. Deviations in the lower current range can be caused by a sweep that is too fast. Unfortunately, I no longer have access to this testing instrument. It should be noted that slight temperature changes cause the curve to shift vertically.

More to Follow — Stay Tuned!

As mentioned, in the next installment of this article, we will deal with the assembly, calibration, and testing of the prototype of the Picoammeter. We will also go into detail about the Arduino sketch, which is managing the HTML interface for this project. ◀

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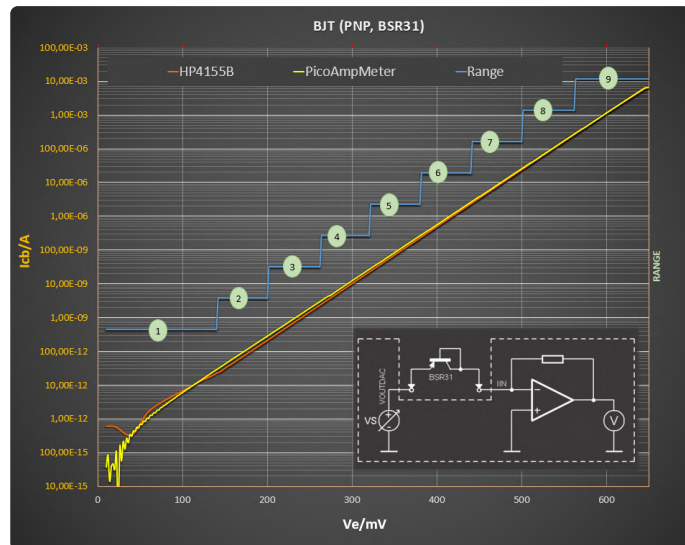


Figure 21: What a rewarding match! The readouts of the Picoammeter (yellow), compared with the ones from the professional HP4155B test equipment.



Component List Picoammeter

Resistors

(All TH, 5%, 0.25 W, unless diff. noted)

- R1, R18, R19, R24 = 1 kΩ
- R2, R9 = 1 MΩ, 1%
- R3 = 1 GΩ, 1%
- R4, R5 = 1 MΩ
- R6 = 560 Ω
- R7 = 50 kΩ, trimmer (*)
- R8 = 10 kΩ
- R10 = 1.5 MΩ, 1%
- R11 = 120 kΩ, 1%
- R12 = 100 Ω, 1%
- R13 = 10 kΩ, 1%
- R14, R15, R23, R28 = 100 kΩ, 1%
- R16 = 27 kΩ
- R17 = 4.7 kΩ
- R20, R22 = 33 kΩ
- R21 = 2k Ω, trimmer (*)
- R24 = 1 kΩ
- R25 = 0 Ω
- R26 = 10 MΩ
- R27 = 22 kΩ, trimmer (*)
- R29 = 470 Ω
- R30, R31 = 100 Ω
- (*) Vishay T93XA series, multi-turn cermet

Capacitors

- C1 = 100 pF, SMD 1206, film or NP0
- C2 = 10 μF, SMD 1206, X7R
- C4, C6...C11 = 100 nF, SMD 1206, X7R
- C2 = 10 μF, SMD 1206, X7R

Semiconductors

- D1 = BAV199, SMD (optional)
- D2, D3 = 1N4148, TH type
- IC1, IC2 = LMC6482, DIL
- IC3 = DG412DJN, DIL
- IC4 = ADS1113, adapter PCB SMD to DIL
- IC5 = DAC8830, adapter PCB SMD to DIL
- IC6 = TL431C, TO92
- Q1, Q2 = 2N7000, N-ch. MOSFET

Modules

- ESP32 = NodeMCU ESP32 WiFi and Bluetooth
(i.e., Reichelt, order no. DEBO JT ESP32)
- OLED = 0.96" OLED SSD1306 Display I2C
128 × 64
(i.e., AZ-Delivery)

Miscellaneous

- JP1...JP6, JP13 = header 1× 1 pin, female, 90°
- JP12 = header 1× 4 pin, female, 90°
- JP7 = header 1× 2 pin, female, 90°
- JP8, JP9 = header 1× 15 pin, female, 90°
- JP10, JP11 = header 1× 3 pin, female, 90°
- K1, K2 = COTO_9011-05-11, relay



Component List Power Supply

Resistors

- (All TH, 1%, 0.25 W, unless diff. noted)
- R1, R2 = 33 Ω, 5%
- R3 = 470 Ω
- R4, R5 = 2.2 kΩ
- R6 = 1.2 kΩ
- R7 = 68 kΩ
- R8 = 6.8 kΩ

Capacitors

- C1 = 1μF, 50V, X7R
- C2, C3 = 100 μF, 25V, d = 10 mm
- C4, C5 = 100 n, SMD 1206

Semiconductors

- D1, D2 = BAT42, TH type
- IC1 = LM337, TO92
- IC2 = LM317, TO92

Miscellaneous

- M1 = MT3608, DC/DC step-up converter
- JP1 = header 1× 1 pin, male, 90°
- JP2 = header 2× 2 pin, male, 90°
- JP3, JP4 = header 1× 3 pin, male, 90°

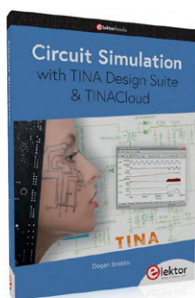


Questions or Comments?

Do you have technical questions or comments about this article? You may contact the author at johannes.sturz@web.de or the editorial team of Elektor at editor@elektor.com.

About the Author

Johannes Sturz has been passionate about electronics since he was 12 years old. His interest was aroused by electronic construction kits. He worked for a semiconductor manufacturer as a validation/characterization engineer for several decades. One part of the job was debugging of decapped ICs of mixed-signal devices with a probe station, mainly RFID devices and microcontrollers. He retired at the beginning of 2024. This means he has now more time for his own projects and other activities he loves, like hiking and cycling.



Related Product

> Dogan Ibrahim, *Circuit Simulation with TINA Design Suite & TINACloud* (Elektor 2022, incl. One-year License of TINACloud Basic Edition)
www.elektor.com/19977

WEB LINKS

- [1] Design femtoampere circuits with low leakage, EDN: <https://tinyurl.com/mw9jx68v>
- [2] What's All This Rail-to-Rail Amplifier Stuff, Anyway?, ElectronicDesign: <https://tinyurl.com/p2epnp2s>
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Christmas Star 2025

A Star Is Soldered



By Ton Giesberts (The Netherlands)

Christmas is coming soon, right? In any case, it's time to start looking for Christmas decorations. How about this blinking poinsettia? In keeping with the times, it is based on a tiny microcontroller that controls colored LEDs.



Figure 1: The front side of the finished Christmas Star 2025 is as white as possible.

What is this project about? A classic five-pointed, star-shaped PCB with 20 digital RGB LEDs controlled by a in the truest sense of the word tiny microcontroller — an ATtiny48A from Microchip. It is all powered with 5 V, which allows to revitalize one of the many simple smartphone chargers laying around.

This project is primarily focused on the PCB design, a perfect five-pointed star. The schematic is not a case of applied rocket science: A microcontroller sends data to a chain of 20 serially connected and digital controlled RGB LEDs. Three little push buttons allow the pattern of the LEDs to be set. To avoid solder pads of through hole components ruining the clear appearance of the front of the star, all components, except the LEDs, are SMDs and mounted on the bottom side.

The Circuit

As **Figure 1** proves the minimum number of LEDs needed to position them in a clear starlike shape is 20. IC1 in **Figure 2** is a microcontroller from the ATtiny series of Microchip: an ATtiny84A in a 14-pin SOIC package. Its internal 8-MHz RC-oscillator is used as system clock. One of the features of this microcontroller is in-system programming (ISP). For that purpose a 6-pin SMD header with a 1/20" spacing (K1) is placed next to the IC and connected to its SPI port. The Pins from K1 provide MISO, MOSI, SCK, Reset, +5 V, and ground. The 8 KB of flash memory of this microcontroller is sufficient to store a large variety of lighting patterns for the LEDs. I/O Pin PA5 (which also functions as MISO) is set as output and connected to the LED1. Three very small buttons are available to set the lighting patterns of the LEDs and their properties.

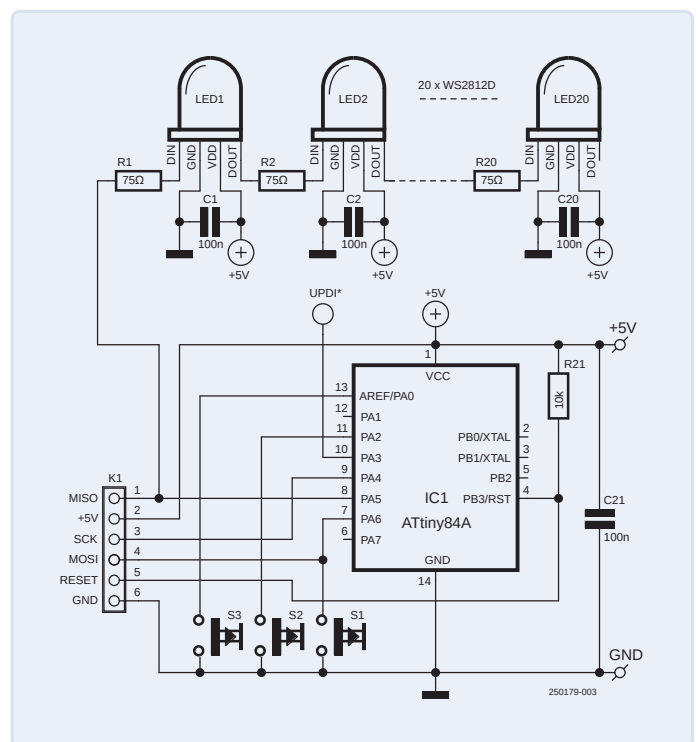


Figure 2: Schematic of the Christmas Star 2025.

The data inputs of the LEDs are connected through 75-Ω resistors, as recommended in the datasheet. Since the LEDs and especially their input and output solder pads are very close to each other, these resistors are not absolutely necessary and can be replaced by a solder bridge.

The power supply of each LED is decoupled with a 100 nF capacitor. Resistors and capacitors are relatively small 0603 SMDs but still solderable by hand with a fine tipped soldering iron.

There exist two versions of WS2812D-F5 LEDs. The first is shaped like other standard 5-mm LEDs and is therefore almost 9-mm high. The other version is called “straw hat” and is about 5-mm high. When testing the software in combination with the latter form, the mixture of colors of the LEDs was not really good, because their housing is too clear. Even from a distance, the three individual LEDs inside the housing were clearly visible. In addition, the three LED chips are located in the same half of the housing. The standard shape was therefore used in the prototype, as its housing is more diffuse. Consider this aspect before ordering the LEDs.

ATtiny Variants

If the 8-KB flash memory is not sufficient for your experiments or samples, a newer ATtiny series with more flash memory is also available in the same 14-pin SOIC housing. The ATtiny1604-SSN, for example, has 16 KB and the ATtiny3224-SSU with 32 KB even more. Both are also in-system programmable, but in different ways: By using a single-pin UPDI (Unified Program and Debug Interface) only three connections to an external programmer need to be established. This means: K1 is not needed if one of more modern types is used. To use UPDI, three wires can be connected to solder pads next to IC1: UPDI, GND and +5V. On the Internet (and in Elektor [1]), you can find information on how to use USB/serial converter chips such as an FT232 or CH340 as a programmer by connecting Tx and Rx via a resistor or diode. On these two microcontrollers, UPDI is connected to pin 10 (only on the 14-pin SOIC housing).

Be careful with static charges when soldering a wire to the UPDI pad as it is directly connected to IC1. If a soldering station is not earthed, the internal mains filter can result in half of the mains voltage being applied to the tip of the soldering iron — not directly, but capaci-

tively coupled and therefore low-resistance and destructive, enough for CMOS chips. Therefore, check the earthing of the soldering iron and earth it if necessary. This applies in particular if the circuit is still connected to the programmer and/or the power supply.

Internally, there is a pull-up resistor on the reset pin of the ATtiny84A. The data sheet states: *“The pull-up resistor on the $\overline{DW}/(RESET)$ line must be in the range of 10 k Ω to 20 k Ω . However, the pull-up resistor is optional.”* When programming an early board with an AVRISP MkII, strange errors sometimes occurred. After connecting a pull-up resistor of 10 k Ω (R21 on PCB v1.1) to the reset pin, the problems disappeared. The ATtiny3224 datasheet states: *“AVR devices have an internal pull-up resistor on the RESET pin and an external pull-up resistor is usually not required.”* Besides that this is not mentioned in the ATtiny1604 datasheet, on the PCB v1.1 there is no need to populate this external pull-up resistor for these two microcontrollers.

PCB

The 20 RGB LEDs are arranged in the shape of a five-pointed star and that determines the outline of the PCB. The size of the PCB according to the design is horizontally 69.30 mm and vertically 65.91 mm both from tip to tip. Due to milling precision, the size of the manufactured PCB can be a little smaller. My prototype is about 65.8 × 62.6 mm, for example.

The diameter of the flange of the round LEDs is 5.8 mm. A small flat piece marks pin 1, the data output of the digital LED. In order to make the front of the star’s PCB as uniformly white as possible, there is no information text next to the LEDs and the shape of the footprints are not visible. (See the left side of **Figure 3**.)

To indicate pin 1 of the LEDs, the solder pad for this pin is rectangular, this is where the flat side of the flange must be located. The other three pads are rounded. The number of the LEDs is the same as the number of the decoupling capacitor next to it (see right side of Figure 3).

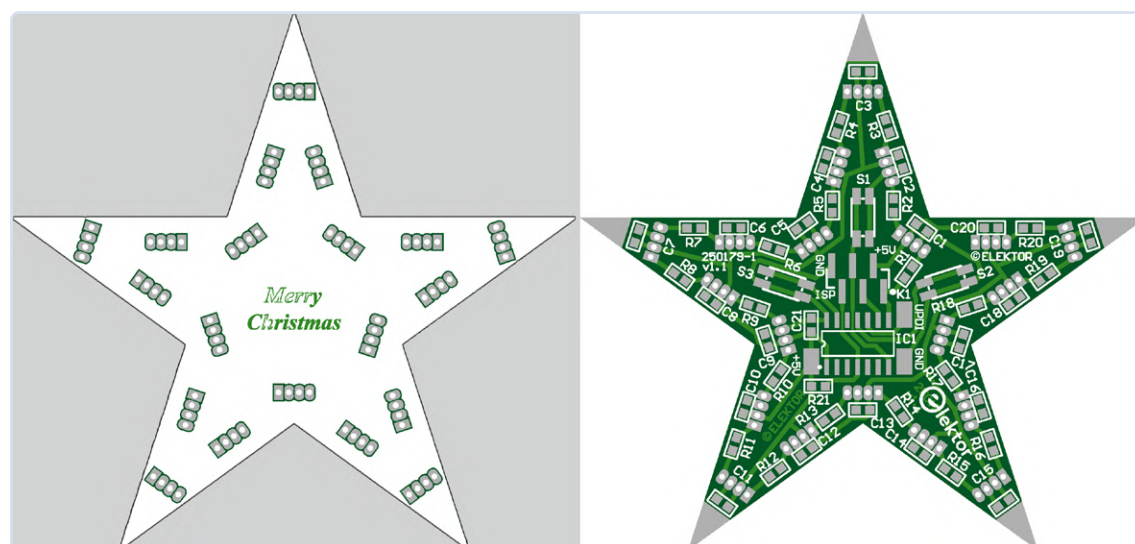


Figure 3: The top side (left) and the bottom side (right) of the PCB layout.

On the bottom side all five tips have small area on which a piece of wire can be soldered. This way a small hook can be added to fasten the star to or in a Christmas tree. Alternatively, more sturdy wires can be used as a stand to place the star on a flat surface.

Construction

All parts can be soldered by hand using a soldering iron with a fine tip and 0.35-mm solder (or thinner). Start with the smallest 0603 resistors and capacitors. Put a little solder on one pad of each resistor and capacitor. Place each component with tweezers on the PCB and solder the component side where the soldered pad is. Then solder the other side and solder the first side now properly. Be careful not to use too much solder. Next, do the same with the three switches, IC1 and the 6 pin header. To solder the IC, first apply solder to a pad, place the IC and solder this pin to the board while pressing the IC onto the board without moving it. Make sure that it is placed symmetrically on the footprint. Then solder the opposite pin on the other side (i.e., first pin 1 and then pin 8, or first pin 7 and then 14). All pads of the SMD components are slightly extended to make soldering by hand easier and to distribute the solder better on the pads so that not too much is used. Finally, the LEDs can be soldered. By gently wriggling the pins, they will fit through the holes in the pads, but better is to cut them just above the small widening. **Figure 4** shows how to do that.

The remaining length of the wires is still more than enough to protrude on the bottom side and be soldered. When placing the LEDs check



Figure 4: Cut wires. The top wire in the photo is pin 1. The flange is partially missing here.

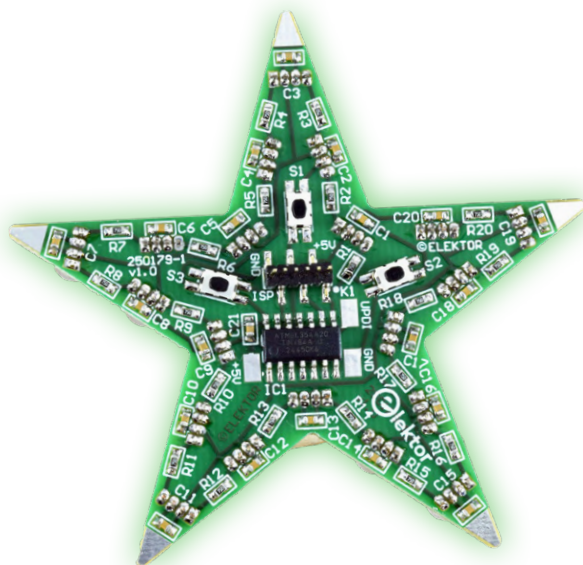


Figure 5: Bottom side of the populated PCB of the Christmas Star 2025.



Component List

Resistors

R1...R20 = 75 Ω , SMD 0603 *

R21 = 10 k Ω , SMD 0603 *

Capacitors

C1...C21 = 100 nF, 50 V, X7R, SMD 0603

Semiconductors

LED1...LED20 = WS2812D-F5 Worldsemi, through hole, 5 mm *

ATtiny84A, SMD SOIC-14 *

Others

K1 = 6-pole pin header, SIL, pitch 1.27 mm (1/20"), M50-3630642

Harwin or DS1031-03-1*6P8BS311-3A Connfly

6-pole socket, SIL, pitch 1.27 mm (1/20"), M50-3030642 Harwin or

DS1065-01-1*6S8BV Connfly or DS1065-07-1*6S8BV Connfly

S1...S3 = Tactile switch, SPST-NO, SMD, KMR221G LFS C&K

Components

2x3-pole header, pitch 2.54 mm (1/10"), for ISP adapter (Figure 6)

PCB 250179-1 v1.1

* see text

each LED if the orientation is correct and double check after placing them all. Then solder only pin 1 of each LED. When placing, check each LED if it sits flat on the PCB surface and check this again after you have placed all of them. Correct the ones that are not sitting flat enough. Then solder the other leads.

A 5-V power supply could be connected to a SIL socket to power the Christmas Star through the ISP connector K1. The +5V and ground pin of K1 are labeled. A more stable connection is to solder two wires to the pads next to IC1 (see the solder side of the PCB in **Figure 5**).

Software and Programming

The software was developed for the ATtiny84A using BASCOM-AVR 2.0.8.6. An additional license is required to develop software for the newer ATtiny microcontrollers (such as 1604 and 3224). The ATtiny84A can be programmed via ISP. As said, for this purpose, a 6-pole pin header with 1.27 mm (1/20") spacing must be soldered onto the PCB. An adapter can be made to connect a AVRISP MkII or a similar in-circuit programmer to this small pin header. **Figure 6** shows how a 1x6 pin socket with 1.27 mm spacing can be soldered directly to a 2x3 pin header with 2.54 mm (1/10") spacing without the need of having to use additional wiring.

Be careful! The pins of the small SIL header are fragile and break easily, I broke two of them while developing the software. Maybe glue struts between the two headers so they can't move and thus relieve any strain on the solder joints and pins. Perhaps the type DS1065-07-1*6S8BV from Connfly is more solid. The type M50-3030642 from Harwin also looks less fragile.

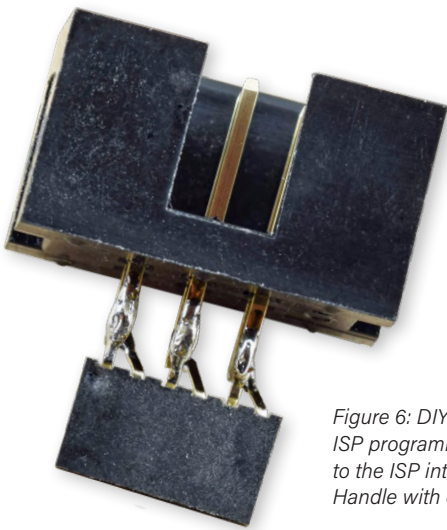


Figure 6: DIY adapter to connect an ISP programmer like AVRISP MkII to the ISP interface of a ATtiny48A. Handle with care!

The screen dump in **Figure 7** shows the correct fuse settings for the ATtiny84A. For the Rainbow commands to function correctly the clock rate of the microcontroller must be 8 MHz. So the fuse CKDIV8 (Divide Clock by 8) must be turned off. Something else: When connecting the PCB to different power supplies, the LEDs sometimes stayed off. Pushing buttons until some LEDs froze and then switching the power

off and on again seemed to solve the problem. This happened without brown-out detection. Obviously the EEPROM data in which the values for the patterns are stored was not read correctly at power-up. I then set the fuse for the Brown-out detection to 4.3 V. This seems to have solved the problem.

Now to the example software in Bascom AVR. The switches S1, S2 and S3 control the pattern of the LEDs, the delay of changes in the pattern and the maximum brightness. Several patterns are possible:

- 0: The color of all LEDs changes randomly.
- 1: All LEDs are white, but their brightness changes randomly.
- 2: All LEDs are red.
- 3: All LEDs are green.
- 4: All LEDs are blue.
- 5: All LEDs are white.
- 6: The colors red, green, blue, yellow, magenta and cyan shift outwards, from the five inner LEDs to the ten middle LEDs to five LEDs in the tips.
- 7: Four LEDs in each tip have the same color and the 5th tip has a different color. Five colors (red, green, cyan, yellow and magenta) rotating clockwise.

AVRISP mkII (000200019906) - Device Programming

Tool: AVRISP mkII | Device: ATtiny84A | Interface: ISP | Device signature: 0x1E930C | Target Voltage: 5.1 V

Interface settings: Tool information, Device information, Oscillator calibration, Memories, **Fuses**, Lock bits, Production file

Fuse Name	Value
EXTENDED.SELFPRGEN	☐
HIGH.RSTDISBL	☐
HIGH.DWEN	☐
HIGH.SPIEN	☒
HIGH.WDTON	☐
HIGH.EESAVE	☐
HIGH.BODLEVEL	Brown-out detection at VCC=4.3 V
LOW.CKDIV8	☐
LOW.CKOUT	☐
LOW.SUT_CKSEL	Int. RC Osc. 8 MHz; Start-up time PWRDWN/RESET: 6 CK/14 CK + 64 ms; default value

Fuse Register	Value
EXTENDED	0xFF
HIGH	0xDC
LOW	0xE2

☒ Auto read
☒ Verify after programming

Copy to clipboard | Program | Verify | Read

Starting operation read registers
 Reading register EXTENDED...OK
 Reading register HIGH...OK
 Reading register LOW...OK
 Read registers...OK

Read registers...OK

Close

Figure 7: Settings for the ATtiny84A.



Figure 8: Photos of different patterns to give a first impression. In reality the LEDs appear much more brilliant. Upper row from left to right: All LEDs are red, green or blue. Lower row from left to right: Random changing colors, seven colors shift outwards and colors rotate clockwise.

Pattern 1 is an attempt to mimic a twinkling star. The Patterns 2, 3 and 4 were primarily intended as a test to see if all LEDs work properly and the internal red, green and blue LEDs have the same brightness.

Figure 8 shows a selection of different patterns. The photos cannot reproduce the brilliance of the LEDs correctly. The current of the LEDs was set very low to avoid overexposure of the camera. Otherwise, all the LEDs would have simply appeared white.

After pushing one of the switches, the ten LEDs in the middle of the five tips are used to indicate the new setting. Color white symbolizes the S1 (pattern), color yellow the S2 (delay) and color magenta the S3 (brightness). The number of LEDs that blink twice show the value of that setting. For the pattern, one white blinking LED means pattern number 0.

Last not least: The portpins used for the LEDs depend on the microcontroller variant used (**Table 1**). This means that the software must be adapted/changed when using one of the newer ATtiny's. Feel free to develop other patterns and software and share it on Elektor Labs [2], where you can download the PCB layout as PDF files and the example software for ATtiny48A.

Table 1: Used pins for different ATtiny controller types.

	84A	1604/3224
LED1	PA5	PB1
S1	PA6	PB2
S2	PA2	PA1
S3	PA0	PA3

Power Supply

Power supply voltage is 5 V. Absolute maximum is 5.3 V, defined by the LEDs. At the current maximum brightness setting (110 for each color; the maximum for the WS2812D-F5 is 255 per color) the supply current reaches about 300 mA. However, to keep tracks on the PCB as short as possible, pin 5 of port A was used to control the LEDs, which is also used for MISO of the programming interface. So when programming the microcontroller, the LEDs will receive random data and the current can be much higher, at almost 700 mA. After programming, disconnect the programmer and switch the power off and on again. The circuit will now behaves normally. ◀

250179-01

Questions or Comments?

If you have questions about this article, feel free to email the Elektor editorial team at editor@elektor.com.



About the Author

Ton Giesberts started working at Elektuur (now Elektor) after his studies, when we were looking for someone with an affinity for audio. Over the years, he has worked mainly on audio projects. Analog design has always been his preference. Of course, projects in other fields of electronics are also part of the job. One of Ton's mottos is: "If you want to have it done better, do it yourself." For example, for a PCB design for an audio project with distortion figures on the order of 0.001%, a good layout is crucial!



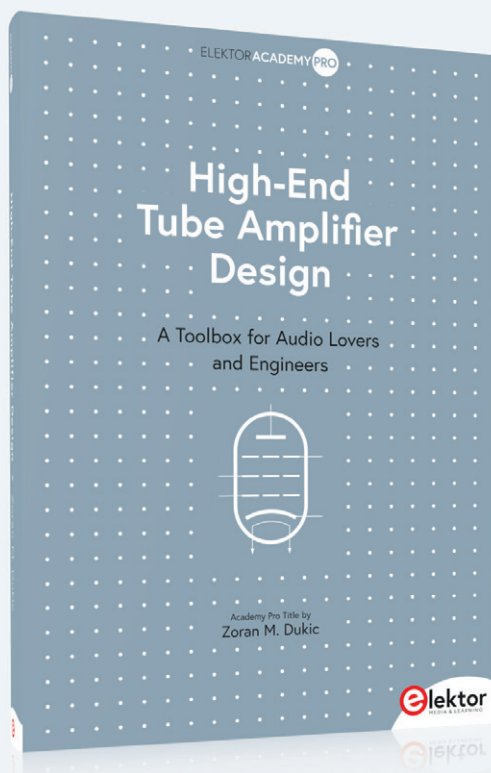
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- [1] Burkhard Kainka, "DDS Generator with ATtiny," Elektor Circuit Special 2025: <https://www.elektormagazine.com/250211-01>
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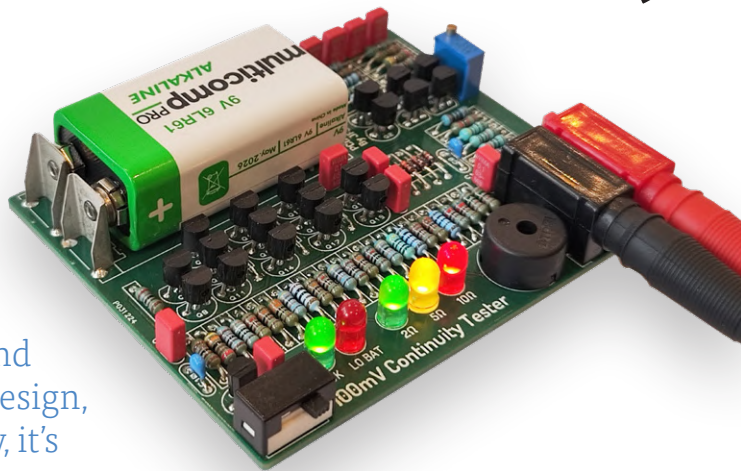


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100 mV Continuity Tester



By Jez Siddons (United Kingdom)

Most continuity testers are very simple and therefore have simple capabilities. This design, however, is unique in several ways. Firstly, it's based (almost) entirely on discrete components, implementing several opamp type circuits with just transistors. Secondly, this design has some very useful features, such as multiple thresholds, different audible tones and also an open circuit probe voltage of just 100 mV. This makes it particularly useful when testing for shorts in-circuit, whilst ignoring semiconductor junctions and high value capacitances. All built on a single self-contained board assembly complete with battery, switch, probe sockets, LEDs and the sounder.

This design started as a "self challenge." I wanted to design a good quality continuity tester that would not be fooled by semiconductors and large capacitances. I also wanted to make it with no ICs. Crazy? Yes, of course. The design would be much simpler with a couple of cheap quad opamps, or even a little micro, but where's the fun in that?

Apart from the voltage regulator (which is a low dropout 5-V regulator in a TO92 package), there are no ICs at all in this design. The design is based around Long Tailed Pairs (LTPs). LTPs are most frequently seen at the core of opamps. One LTP is used as a linear amplifier, to amplify the small voltage across the test probes. Further LTPs are used as comparators to detect the various thresholds associated with 2 Ω , 5 Ω and 10 Ω being

across the test probes. A final Long Tailed Pair is used for low battery monitoring.

Design Overview

The design comprises of the following stages:

Input Front End

The test probes could potentially be connected to any component, even in-circuit. Many semiconductors (ICs, transistors, diodes etc) don't start conducting until the voltage across them reaches about 0.6 V in a forward direction. Schottky diodes, germanium diodes and germanium transistors can start conducting at voltages as low as 0.2 V or even slightly less. To ensure that this tester is not influenced by any of these components, the maximum test voltage generated by the tester is limited to 0.1 V (100 mV). This greatly

Salient Features

- › Test continuity in or out of circuit instantly.
- › Only 100 mV test voltage across an open circuit.
- › 3 low resistance thresholds: 2 Ω , 5 Ω and 10 Ω .
- › 3 tones of audible alert.
- › Low battery warning.
- › Not affected by semiconductor junctions.
- › Highly immune to even very large capacitances.
- › Fast response (faster than many multimeters).
- › Nearly all transistor based (except the regulator).
- › Standard 4-mm sockets.

enhances the ability to use this tester "in-circuit" without risk of false readings that could otherwise be caused by conducting semiconductor junctions.

Linear Amplifier

Testing low resistances with a modest test current, and with a maximum voltage span of 100 mV means that the signals we are

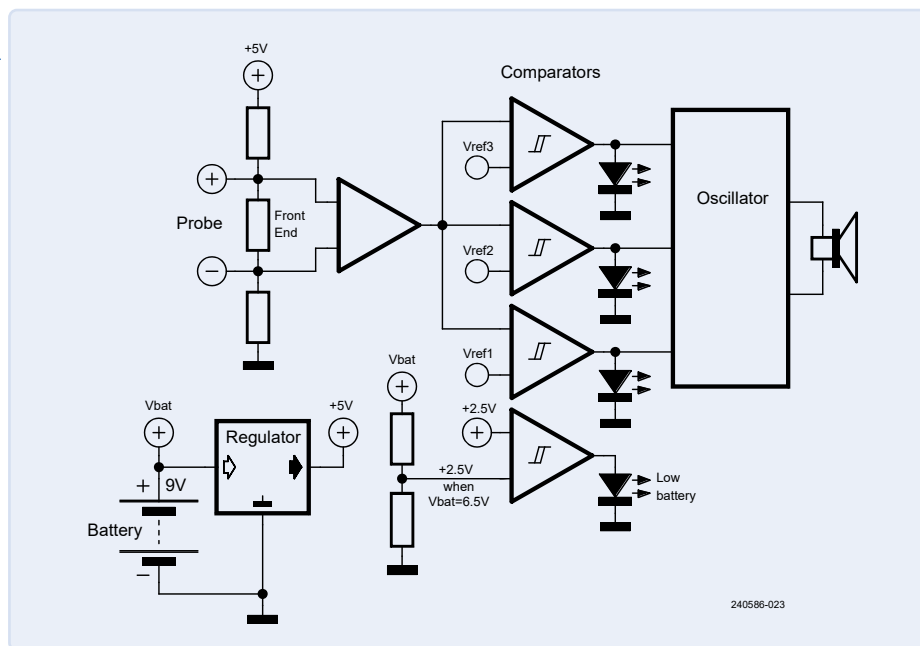


Figure 1:
Overall Scheme.

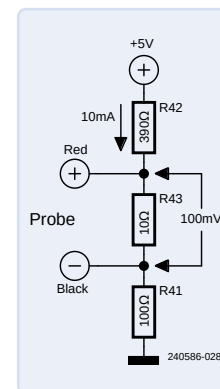


Figure 2:
Input Front End.

measuring are quite small. We could feed that small voltage directly into comparators, but the accuracy of the thresholds would be poor due to any small drifts or offset changes caused by temperature changes or component tolerances. Amplifying the front-end signal, even by a modest number, greatly improves the precision and stability of the comparators that follow. Clearly, we need to amplify the signal by a predictable and consistent factor, so an amplifier with DC negative feedback is required.

Comparators

The design of this tester provides a simple indication on three LEDs of the various test thresholds for resistance on the probes. By implementing simple comparators, each with fixed voltage thresholds, allows us to determine the resistance on the probes that would cause each LED to light.

Typical Specifications

Parameter	Value	Unit
Open circuit test voltage	100 $\pm$ 6.0	mV
Threshold 1 resistance	10.0 $\pm$ 2.0	Ω
Threshold 2 resistance	5.0 $\pm$ 1.0	Ω
Threshold 3 resistance	2.0 $\pm$ 0.5	Ω
Threshold 1 beep frequency	320 $\pm$ 100	Hz
Threshold 2 beep frequency	750 $\pm$ 200	Hz
Threshold 3 beep frequency	1900 $\pm$ 400	Hz
Low battery threshold	6.5 $\pm$ 0.5	V
Current consumption (open probes)	29.2 $\pm$ 5.0	mA
Current consumption (shorted probes)	51.6 $\pm$ 5.0	mA

Audible Oscillator

It's not always possible to be looking at the LEDs when using the tester. The audible oscillator is included to produce discrete different tones for each of the three chosen thresholds. With a little use, the operator will quickly become accustomed to the tones associated with each resistance threshold. This is great for rapidly testing many connections in sequence without taking your eyes off the probes.

Low battery detection

The battery voltage is regulated down to 5 V for operating the tester. This means that all the thresholds, LED currents and oscillator tones remain consistent over the life of the battery. It's important for the user to know if the battery voltage is dropping too low for the regulator to maintain the 5 V rail. If the 5 V rail started to drop, then the performance of the tester would start to be affected. A simple compara-

tor is included for monitoring the battery level and a pair of LEDs shows if the battery level is sufficient or too low.

These stages are outlined in **Figure 1** and detailed in the following sections.

Input Front End

The input stage is a simple resistor chain comprising of R42, R43 and R41 (shown in detail in **Figure 2**) and is connected between the supply rails. The current flowing through the whole resistor chain is 10 mA. The voltage across the middle resistor (R43) is therefore 100 mV. Both ends of R43 are brought out to test probes. So that means that the voltage across the test probes when nothing is attached to the probes would be 100 mV, much lower than you would see in conventional testers such as your multimeter on continuity or resistance settings. If there was a short circuit across the probes, then the voltage would be 0 mV of course.

For other test resistances, the voltage across the probes would be as shown in **Table 1**.

Test resistance (Ω)	Voltage across probes (mV)
0	0.0
2	16.9
5	33.8
10	50.5
Open Circuit	100.0

Table 1: Resistance vs probe voltage.

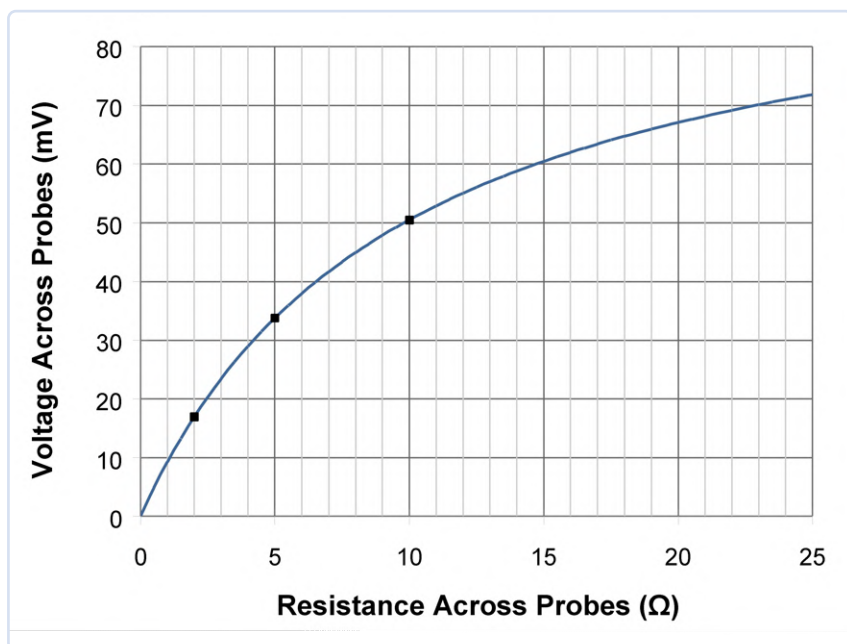


Figure 3: Voltage vs Resistance across the probes.

The same information is plotted in the graph shown in **Figure 3**.

Linear Amplifier

The first active stage of this design is a linear amplifier which is based on a Long Tailed Pair with some simple enhancements. Creating

a simple linear amplifier with transistors is a little more complex than using an opamp IC. However, in this design, we are confident of the full range of input and output characteristics that we need to accommodate, and this allows us to implement transistors with relative ease. Additionally, using transistors for

the linear amplifier provides a useful insight into a fundamental part of real opamp design, something that is often hidden from us when we use opamp ICs. In this design, we can inspect the actual voltages and behavior of the amplifier design that would be inaccessible with a chip. A simple long-tailed pair is shown in **Figure 4a**.

Such a simple long-tailed pair is "in balance" if both bases of the two transistors are at the same voltage. All things being equal (in theory), both transistors would have the same current flowing through their collectors and emitters. The sum of the pair of emitter currents goes through the tail resistor (hence the name). If one base becomes slightly higher than the other, then that transistor will turn on more and dominate the current that flows through the emitter resistor. In that situation, the current through the other transistor drops. The effect is quite "sharp", meaning that the current through the transistors swings fairly quickly from one transistor to the other when one of the bases is at a slightly higher voltage than the other. For small voltage changes on the bases, the emitter current stays fairly constant, it's behaving like a pair of emitter followers feeding current into one resistor.

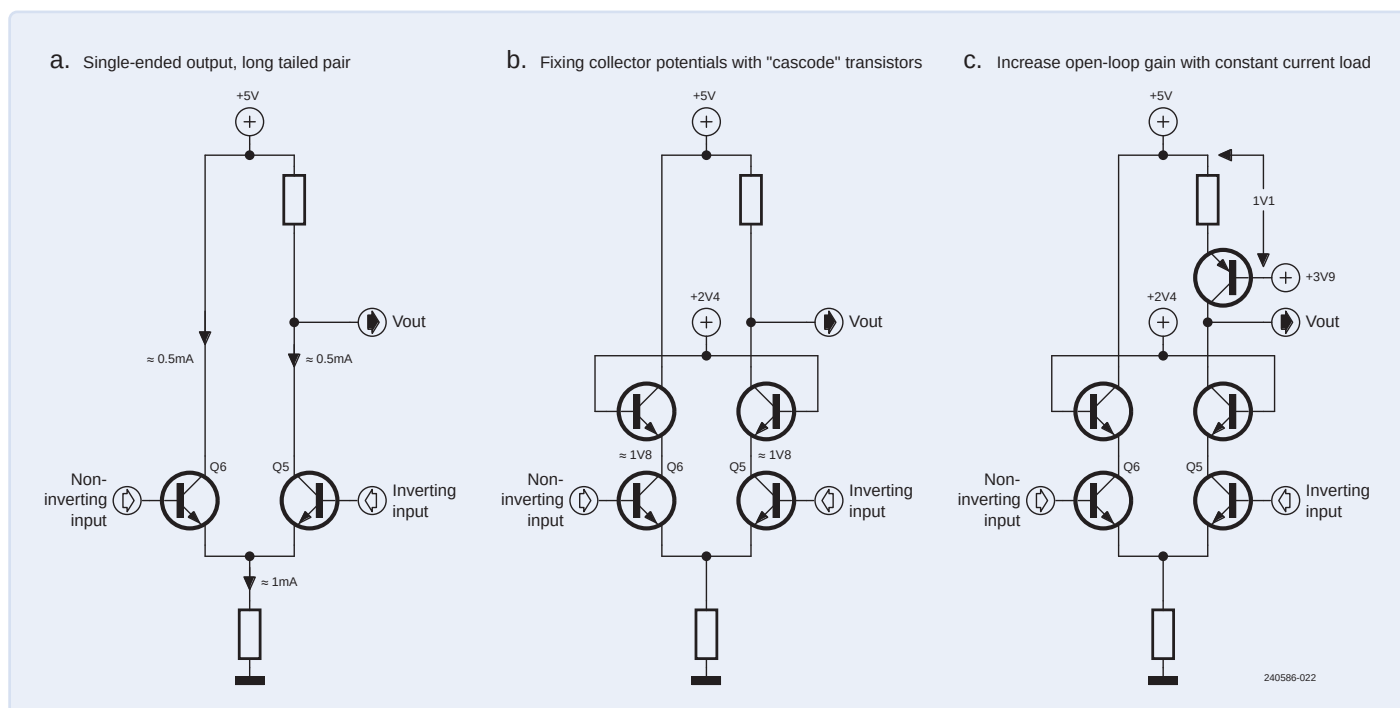


Figure 4: Simple Long Tailed Pair with some enhancements.

In real life, the two transistors may not be very well balanced even if the base potentials (voltages) are at the same voltage, especially if the collectors of the two transistors are at different potentials. That's because the real transistor collector-emitter current can vary slightly with changes in collector potential (ideally the current is unaffected by collector potential). That's where the first enhancement comes in.

The performance of the amplifier is enhanced here in two ways. Firstly, **Figure 4b** shows the collectors of the two main Long Tailed Pair transistors, Q5 and Q6, are "fixed" in potential by means of two extra transistors. This is called a *Cascode* arrangement and reduces the voltage changes that occur across the Long Tailed Pair transistors, which in turn reduces the voltage difference between the two bases, thus reducing offset voltages when the long-tailed-pair transistors are in balance. The addition of cascode transistors has very little influence on the collector currents of Q5 and Q6.

The amplifier is further enhanced in **Figure 4c** by introducing a constant current source as the main load. The constant current source effectively behaves like a very high impedance load and therefore exhibits a large voltage swing with just tiny changes in current through it, which increases the gain of the amplifier hugely.

It is common to implement a constant current sink in the "tail" of the amplifier, in place of the resistor, although that generally only improves the capability to use the inputs over a wider common mode voltage range. As we are operating the inputs over a small, closely defined voltage range, then adding a constant current sink in the "tail" provides little benefit.

As the constant current load of the amplifier is a very high impedance, the output is buffered by a simple emitter follower, Q2,

which is shown in the full schematic, **Figure 5** (see next page).

To yield a fixed, definable gain, resistors (R39 and R40 in the Figure 5) configure the amplifier as a non-inverting amplifier with a gain of around 46.5. For a simple amplifier like this, the open loop gain is not as big as a standard opamp. The resulting gain of the amplifier here is slightly lower than the calculated value of 46.5, measurements on the prototype suggest the gain is about 44.1. The resistors R39 and R40 however do help to ensure that the gain does remain very stable even if the individual transistor gain (h_{FE}) varies quite a bit.

The resulting non-inverting amplifier is effectively sitting on a virtual earth voltage of about 1.0 V (the negative test probe potential), so any amplified voltage is added to that 1.0 V. In addition to that 1.0 V offset, we can impose our own small deliberate offset by means of a trimmer potentiometer. That allows us to achieve voltages that are very convenient for checking against some simple references from a fixed potential divider chain. The output from the amplifier for the various test resistances would be as shown in **Table 2**.

Comparators

As can be seen in Figure 1, there are three measurement comparators, one for each resistance threshold of 2 Ω , 5 Ω and 10 Ω . Each comparator is a very simple Long Tailed Pair, fed with the output from the linear amplifier (Vamp) into one of the bases and a reference voltage from a fixed resistor chain fed into the other base. The output of each comparator is further squared up with an extra transistor.

To obtain useful thresholds for the comparators, a simple potential divider resistor chain shown in **Figure 6** comprises of R3, R1, R2 and R4. The resistors have been chosen to give suitable steps in voltages that match the desired threshold intervals and also sit well within the linear amplifier's output swing.

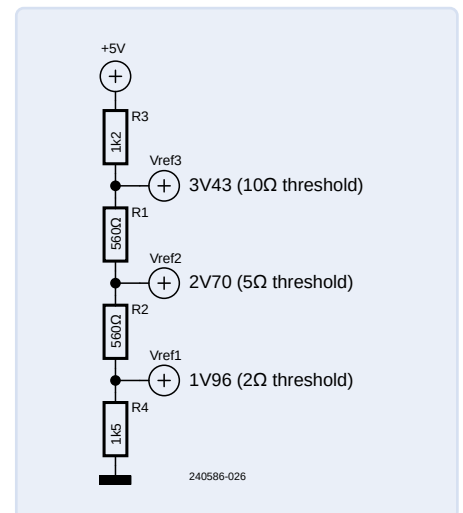


Figure 6: Threshold voltage reference resistor chain.

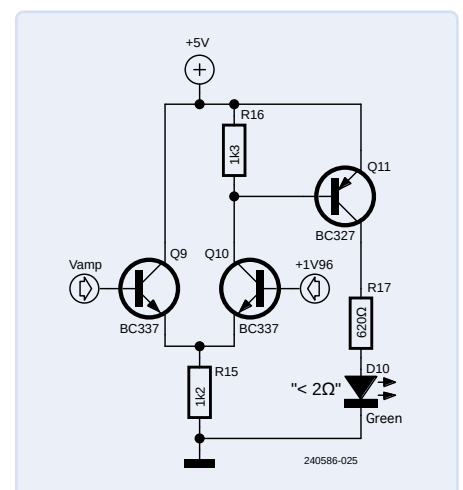


Figure 7: Comparator for the 2 Ω threshold stage.

For example, the 2 Ω threshold comparator, shown in **Figure 7**, consists of Q9, Q10 and Q11. The Long Tailed Pair is formed by Q9 and Q10 with a current in the tail of about 1 mA (when we're close to the 2 Ω threshold). When the Long Tailed Pair is in balance there is about 0.5 mA going through both the transistors. That means that the voltage across R16 is starting to reach enough voltage for Q11 to start switching on.

If Vamp falls below 1.96 V, the current balance quickly swings over from Q9 to Q10 and the voltage across R16 allows Q11 to switch on hard. If Vamp rises above 1.96 V, the current balance quickly swings over from Q10 to Q9 and the voltage across R16 rapidly falls and

Test resistance (Ω)	V_R (mV)	Gain	Vamp (inc 1V)	Vamp + offset adj.
2	16.9	44.1	1.75	1.96
5	33.8	44.1	2.49	2.70
10	50.5	44.1	3.23	3.43

Table 2: Amplifier output voltage vs Resistance on Probes.

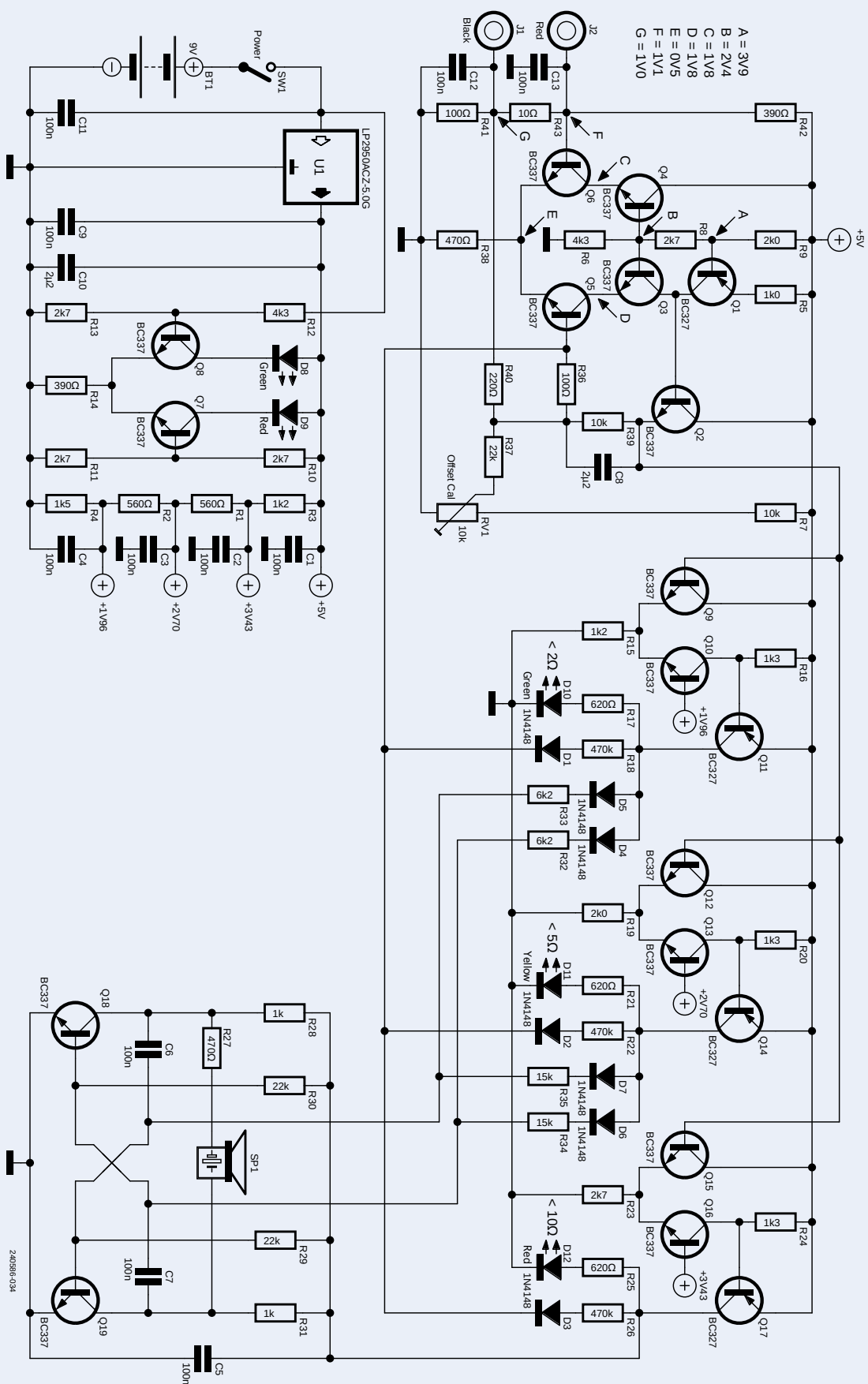


Figure 5: Complete schematic of the project.

Q11 is switched completely off. This gives quite a good sharp on/off response for relatively small changes in V_{amp} .

It can be seen in the full schematic that the other measurement comparators are almost identical. Consider the comparator formed by Q15 and Q16. When the voltage from the linear amplifier is less than the reference voltage of 3.43 V, the currents in the pair of transistors become imbalanced and Q17 turns on. The 10 Ω LED switches on along with the audio frequency oscillator (more on that below), so you hear a beeping sound.

If the voltage from the amplifier falls below 2.70 V (due to a resistance on the probes falling below 5 Ω), then the 5 Ω LED is lit and the frequency of the audio oscillator is increased by means of D6, D7, R34 and R35.

If the voltage from the amplifier falls below 1.96 V (due to a resistance on the probes falling below 2 Ω), then the 2 Ω LED is lit and the frequency of the audio oscillator is increased further by means of D4, D5, R32 and R33.

Although the comparators have quite a sharp on/off transition, it's still possible for them to be in their linear region if the voltages at each base are very close to each other. To ensure a sharp on/off transition of the comparators, a small amount of positive feedback is employed by means of D1, D2 and D3. The positive feedback, determined by the resistor values of R18, R22 and R26, introduces a small amount of current back into one of the inputs of the linear amplifier resulting in a few mV of hysteresis.

Audio Oscillator

The oscillator shown in **Figure 8** is required to generate audio tones. The oscillator is switched on when the resistance on the probes is less than 10 Ω .

This oscillator is a simple two-transistor multivibrator formed by Q18 and Q19. The frequency is determined by resistors R29, R30 and capacitors C6, C7.

The frequency of this type of oscillator is not precise, but for a "beep" sound then the exact frequency is not important. Approximately, the frequency can be calculated with the

following formula (determined by experiment):

$$F \approx 0.7 / R \times C$$

Where R is R29 and R30 (equal values), and C is C6 and C7 (equal values).

The standard (bottom) frequency for the 10 Ω threshold is around 320 Hz (determined by the 22 k Ω resistors and the 100 nF capacitors).

In this design, the timing resistors are "shunted" by extra resistors when we want the frequency to be increased for the 5 Ω and 2 Ω thresholds. This is achieved by means of diodes D6, D7 with resistors R34, R35 and also diodes D4, D5 with resistors R32, R33.

Construction

Assembly is straightforward. Fit the 7x 1N4148 diodes first. Take care with the diode orientations, they are not all pointing in the same direction. Then move on to the 43 resistors. There are many different values, so be careful to select the correct ones.

Matched Pair

Before fitting the transistors, it's worth selecting 2 out of the 15 NPN transistors that have

good characteristics matching for use in positions Q5 and Q6. It's not essential, but having a pair of matched transistors reduces the influence of temperature changes on the thresholds.

Transistor current gain (h_{FE}) and transistor base-emitter voltage (V_{BE}) characteristics can vary considerably from part to part and also with temperature changes. It's good practice to design circuits that are not greatly affected by changes in transistor characteristics. Transistor current gain (h_{FE}) for example can vary by a huge amount between parts, even for identical part numbers. Gains from 100 to 500 are not unusual. Similarly, base-emitter voltage characteristics for transistors can vary from one part to another, although not by such large factors as h_{FE} . Typically, base-emitter junctions will start to conduct current when the forward voltage approaches 0.6 V, sometimes up to around 0.7 V. As temperature rises, the base-emitter voltage (for a particular base current) will gradually fall (negative temperature coefficient). Although we are used to resistors having tight tolerances (accuracies) of $\pm 1\%$, we can see that transistors exhibit vastly bigger variations.

In this project, the current gains (h_{FE}) and base-emitter voltages (V_{BE}) are largely unimportant. As a rule of thumb, the h_{FE} figures need to be at least 10x the overall amount of gain that we want when negative feedback is implemented. That means that the negative feedback ratio dominates the overall gain rather than the h_{FE} . Similarly, when we're using the transistors in their saturated condition when driving the LEDs for example, we aim for an h_{FE} that is at least 10x the amount required to ensure the desired LED current is achieved at a particular transistor base current.

This project does involve the amplification of quite low voltages, and so there is some benefit in making sure the transistors we use for the front-end amplifier stage are fairly well-matched. That helps to reduce the influence of temperature on any offset voltages. Generally speaking, if a pair of identically numbered transistors have similar h_{FE} and V_{BE} at a certain test condition, then they will stay fairly well-matched over wider test conditions and over temperature too.

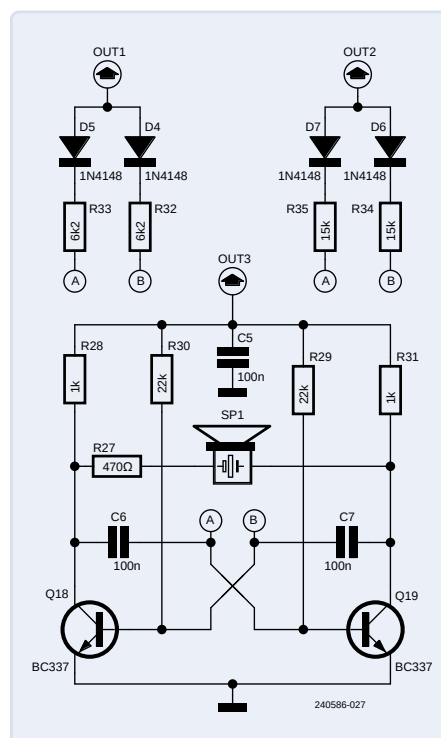


Figure 8: Audio Oscillator.



Component List

Resistors

all 1%, 0.25 W
 R1, R2 = 560 Ω
 R3, R15 = 1k2
 R4 = 1k5
 R5, R28, R31 = 1k0
 R6, R12 = 4k3
 R7, R39 = 10 k
 R8, R10, R11, R13, R23 = 2k7
 R9, R19 = 2k0
 R14, R42 = 390 Ω
 R16, R20, R24 = 1k3
 R17, R21, R25 = 620 Ω
 R18, R22, R26 = 470 k
 R27, R38 = 470 Ω
 R29, R30, R37 = 22 k
 R32, R33 = 6k2
 R34, R35 = 15k
 R36, R41 = 100 Ω
 R40 = 220 Ω
 R43 = 10 Ω
 RV1 = 10 k multitrn trimmer pot, vertical, in-line pins

Capacitors

C1...C7, C9, C11...C13 = 100 nF, 50 V X7R ceramic, 2.54 mm pitch.
 C8, C10 = 2.2 μ F, 16 V X7R ceramic, 5.08 mm pitch.

Semiconductors

D1...D7 = 1N4148
 D8, D10 = green LED, 5 mm
 D9, D12 = red LED, 5 mm
 D11 = yellow LED, 5 mm
 Q1, Q11, Q14, Q17 = BC327 PNP transistor
 Q2...10, Q12, Q13, Q15, Q16, Q18, Q19 = BC337 NPN transistor
 U1 = LP2950ACZ-5.0G, 5 V low dropout regulator (not 78L05)

Miscellaneous

SP1 = Piezo sounder, TDK PS1440P02BT (eg. Farnell 3212600)
 B1a = Negative battery terminal, Keystone 593 (eg. Farnell 1702642)
 B1b = Positive battery terminal, Keystone 594 (eg. Farnell 1650706)
 B1 = Alkaline 9V battery (PP3 style).
 J1 = Black 4 mm socket, Multicomp 24.243.2 (eg. Farnell 1698983)
 J2 = Red 4 mm socket, Multicomp 24.243.1 (eg. Farnell 1698982)
 SW1 = Slide switch, 90°, Multicomp 6MS1S3M1RE (eg. Farnell 1550250)

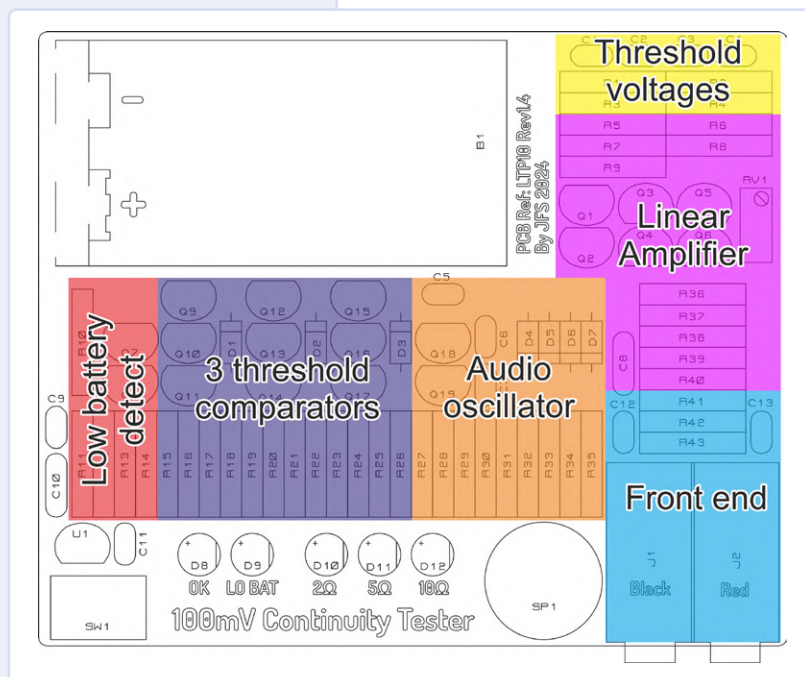


Figure 9: Highlighted sections of the PCB layout.

other pins with plenty of solder. The pins of the battery connectors need plenty of solder to fill the plated-through-holes of the PCB, that way the connectors will be rock solid and easily withstand the forces of battery installation and removal. The PCB and project files are available on the Elektor Labs platform [1].

Setting Up and Testing

Make sure the probes are open circuit. Don't fit the battery yet. If you have a variable bench PSU with a current limit, set it to 9 V with a 60 mA current limit. Apply power to the battery connectors, taking care of polarity. Make sure the switch SW1 is in the *On* position (slider rightmost). All the threshold LEDs should be extinguished and the sounder should be silent. The *OK* LED should illuminate and the current consumption should be 25 to 35 mA. If the current is outside that range, then switch off and check all joints and components.

If you don't have a PSU with a variable current limit, then use a 9 V battery and consider using a multimeter on the current setting, in series with the battery, to check the current consumption before fully fitting the battery to the PCB battery connectors (see **Figure 9**).

Now connect a 10 Ω resistor across the test terminals. Adjust RV1 until the 10 Ω LED is on the cusp of lighting. Illumination of the 10 Ω

If possible, use a transistor analyzer or suitable multimeter to select 2 transistors that have matching V_{BE} (within ± 5 mV) and matching h_{FE} (within $\pm 5\%$). From my batch of 15 BC337 devices for this project, it was easy to find several pairs with good matching. Don't worry too much about the matching though, adjustment of RV1 allows for sufficient calibration later on.

There's no benefit in trying to obtain matched pairs for the comparator sections, any small

offsets will be insignificant compared to the thresholds being monitored. Take care with picking up the NPN (BC337) transistors, PNP (BC327) transistors and the regulator, they're all in TO92 packages.

Fit the LEDs, the switch SW1, the trimmer potentiometer RV1, the test sockets and the battery connectors. For the battery connectors, it's best to do one at a time. Solder just one pin to start with, check alignment, adjust if necessary and then secure by soldering the

LED should coincide with a beep from the sounder. If the adjustment range of RV1 is not sufficient to achieve this then it's worth checking various voltages on the board while the board is powered up and the probes open circuit. Typical voltages are shown on the circuit diagram, most of which are relative to the 0 V rail (battery negative). Note that the negative test terminal is *not* the 0 V rail. Checking the various voltages will help to identify where any problem is located, or thereabouts.

Assuming that you've been able to adjust RV1 to achieve the 10 Ω LED to be on the cusp of lighting when a 10 Ω resistor is connected to the test terminals then you can proceed to check the other thresholds with a selection of resistors that sit nicely between the three resistance thresholds.

If your board is being powered from a variable power supply, reduce the voltage slowly and verify that the *Low Battery* LED begins to illuminate when the PSU voltage is around 6.5 V $\pm$ 0.5 V.

Finally, you can fit a 9 V battery to the battery connectors, shown in **Figure 10**. Most types are suitable for this application (except for Zinc-Carbon or Zinc-Chloride batteries as they have poor current delivering capability and low capacity). ◀

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Questions or Comments?

Do you have technical questions or comments to submit about this article? Feel free to write to the author at jez240586@highpeak100.co.uk or to the Elektor editorial team at editor@elektor.com.



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About the Author

Jez Siddons is based in the Peak District National Park, UK. With a passion for designing test equipment for both his hobby and his professional work, Jez likes to explore fundamental principles (like in this project) as well as more advanced micro-controlled designs and complex number based network analysis. One of Jez's early designs for an automatic transistor analyser in 1987 was a prize winner in the "Young Engineer for Great Britain" competition. That prize-winning design became the basis for Jez's first products when he founded Peak Electronic Design Limited in 1995.

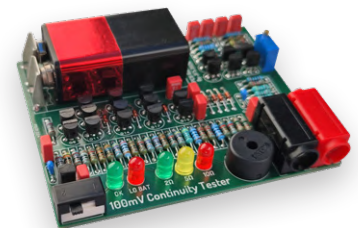
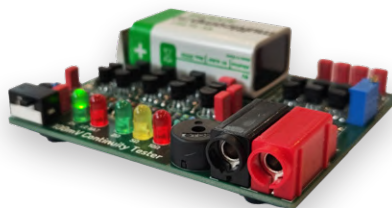


Figure 10: The assembled PCB.

WEB LINK

Project on Elektor Labs: <https://www.elektormagazine.com/labs/100mv-continuity-tester>

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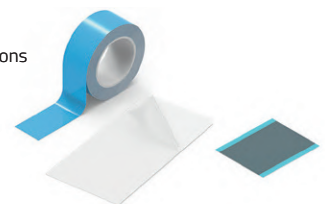
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#THERMAL



Who's Pushing the Boundaries of European Electronics? Companies to Watch

Compiled by the eeNews Europe Team

From dissolvable circuit boards to electric aircraft, Europe's innovators are redefining how electronics are designed and built. Discover some of the groundbreaking technologies that are shaping the future of energy, mobility, and manufacturing.

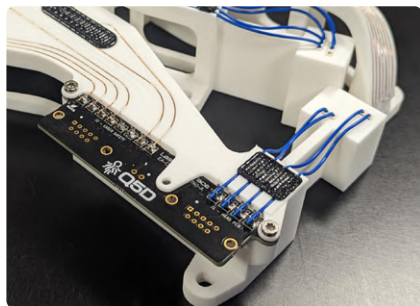
Europe hosts a wide range of companies that are not only innovating in product technology but also the production processes. From roll-to-roll manufacturing for organic photovoltaic cells for equipment in the IoT to the latest robotic systems inspired by biology to new technologies for electric vehicles, several companies will have innovative technologies on display at productronica 2025 (www.productronica.com) in Germany.

Sealing Battery Systems

Battery sensors play a crucial role in controlling and managing the performance and safety of electric vehicle batteries. They monitor parameters such as temperature, voltage, and current, and report this information to the battery management system (BMS), which controls and monitors the battery's charging and discharging processes. Highly viscous liquid sealants are used to protect these sensitive electronic components from external influences such as dust, road salt, and moisture, as well as temperature-related stress and physical shock, and vibrations. These liquid sealants are typically identified as Cured-In-Place-Gaskets (CIPG), and bdtronic in Germany is a global supplier of automated dispensing systems for CIPG applications in the growing EV market. These systems can also incorporate modules for plasma pretreatment/surface treatment, UV curing, and camera inspection. www.bdtronic.com

Wiring Harness Automation

Q5D in the UK has developed a robot that can automate the assembly of a wiring harness for vehicles or large equipment. A wiring harness is assembled by hand and often shipped to several different locations before integration into the end system. The Q5D robot cell can be co-located with the assembly line to cut down the cost and complexity of



Q5D wiring harness
demo product
(Source: Q5D)

the process and can build to order to avoid the need to build up and store inventory for the future. Process technology is a key element in innovation, and Europe has a strong base in this area. Developing a new process allows companies to produce ground-breaking equipment, pushing the boundaries of sustainability and performance. www.q5d.com

Inkjet Printed Photovoltaic Cells and Batteries

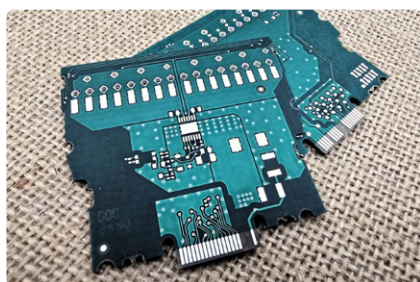
Dracula Technologies in France is using inkjet printing techniques to produce organic photovoltaic solar cells and batteries to store the resulting energy. This reduces the reliance on glass or silicon-based cells from China and gives designers more flexibility in the design of equipment used across the Internet of Things. www.dracula-technologies.com

Electric Aircraft

Elektra Solar is known for its electric-powered Elektra Trainer and Elektra VTOL, as well as its Elektra One and Elektra Two solar aircraft. As the first and only electrically powered aircraft certified in the German ultralight (UL) class, the Elektra Trainer supports sustainable aviation. Recently, the company unveiled a groundbreaking two-seater version of its Elektra Trainer aircraft. The fixed-gear (FG) version, specifically designed for flight schools, is of particular interest due to its outstanding flight performance and advanced safety features. To provide maximum safety, the aircraft is equipped with a fully integrated electronic cockpit, cloud connectivity, an automatic system monitoring tool, and a dual-redundant propulsion system. The aircraft has a cruising speed of 120 km/h, a range of up to 300 km, and a best glide ratio of 25, as well as a very low noise level of less than 50 dB and efficient energy consumption. www.elektra-solar.com

Dissolvable Circuit Boards

Jiva Materials in the UK has developed a material that enables printed circuit boards that dissolve in hot water at 90°C while still delivering the structural requirements and reliability needed for equipment designs.



Dissolvable circuit
boards (Source: Jiva)

The flax-based Soluboard provides a much easier way to recover components and to recycle electronic equipment without dangerous chemicals. www.jivamaterials.com

Roll-to-Roll Photovoltaic Cells

Epishine in Sweden has developed flexible organic photovoltaic cells that can be produced cost-effectively on a high-speed roll-to-roll production system. The cells are sensitive enough to generate energy from indoor lighting, and the production technique, adapted from a newsprint process, enables costs suitable for the consumer market. www.epishine.com

Bionic Learning

Festo in Switzerland is famous for its autonomous robot birds, bees, and butterflies, but the underlying bionic learning technology is also applied to the controlled pneumatics and ultra-lightweight robotic systems in industrial, food, and logistics. The company celebrates its 100th anniversary this year with equipment to automate the assembly of smart-phones, printed circuit boards, and battery systems. www.festo.com



eMotionButterflies
(Source: Festo)

System-in-Board Packaging

RAM Innovations in the UK is embedding power devices into modules and printed circuit boards to boost the thermal management in higher power system designs, reduce the size and improve the reliability. The embedded die packaging (EDP) process allows passives and heat sinks to be incorporated very close to the primary device. The shielding effect of the metal layers within the board can also offer a design advantage along with shorter track lengths, resulting in improved package efficiencies and reduced parasitics. www.ram-innovations.com

Digital Twin Robotics

Sunrise Robotics in Slovenia recently emerged from stealth mode with a combination of digital twin and AI that enables robotic cells to be deployed and operational in a matter of weeks rather than months. By using digital twins and AI-powered simulation, robots can be trained in a virtual environment, significantly reducing the time and resources needed for on-site programming and training. The robotic cells are designed with mostly off-the-shelf components, making them more cost-effective and easier to scale as production needs change. www.sunriserobotics.co 

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productronica 2025: What's New in Electronics Development and Production



Questions by the Elektor Team

Celebrating its 50th anniversary, productronica 2025 will showcase the latest in advanced packaging, power electronics, and secure microelectronics, alongside live demonstrations and experience zones. Barbara Müller, Exhibition Director at Messe München, explains what attendees can expect, the state of global electronics manufacturing, and which emerging technologies are set to disrupt the industry.



What to Expect at productronica 2025

Elektor: What can attendees expect to see that's new or expanded at productronica 2025 compared to the previous edition in 2023?

Barbara Müller: First of all, we are celebrating an anniversary this year! productronica is turning 50. Half a century as the world's leading trade fair for electronics development and production. Accordingly, there will be a special area looking back on the past five decades. Apart from that, however, our focus is on the present and the future. That is why three key topics will shape this year's event: Advanced Packaging, Power Electronics, and Secure Microelectronics. Advanced Packaging enables completely new combinations of technological components and manufacturing processes, which can then be used in automation technology or automotive industry, for example. Innovative power electronics is considered the key to decarbonizing and digitizing society. Secure microelectronics contributes to the reliable functionality of supply chains, right through to cybersecurity.

Elektor: How has international exhibitor participation evolved for this year's show? Are there any new countries, types of exhibitors, or major brands debuting at productronica 2025?

Müller: Basically, we are very pleased that all the key players from the electronics manufacturing industry are on board again this year and will be showcasing their innovations. The current level of international exhibitor

participation is on the same level as in 2023. Leading the way are exhibitors from Italy, the USA, Great Britain, France, Switzerland, and China.

Elektor: What are your expectations regarding visitor turnout in 2025, especially given the evolving global business climate and trade show attendance trends?

Müller: At the last event in November 2023, we welcomed 42,000 visitors to productronica and SEMICON Europa. We would like to achieve this same number again this year. Looking at the visitor numbers for the trade shows that have already taken place in Munich this year, we are optimistic that we will achieve this goal. Trade shows remain an important platform for knowledge exchange and networking. However, we are aware that we are also dependent on the global economic and political situation. Unfortunately, we have no influence on these external factors. That is why we are focusing on our work and organizing a first-class event and program for our exhibitors and visitors.

Elektor: Are any new features, live demonstrations, or experience zones being introduced in 2025?

Müller: As mentioned at the beginning, we will be celebrating the 50th anniversary of productronica with a special exhibition area. Visitors can also look forward to the usual wide-ranging supporting program with various forums. The special shows are also an important part of the event. Among other things, together with our conceptual and technical sponsor VDMA Productronic we will be presenting practical examples related to this year's key topics. I can already reveal that the special exhibit will even feature a small aircraft on the topic of power electronics. Our partners from the Fraunhofer Institute for Reliability and Microintegration IZM showcase a "Future Packaging" line that will comprehensively highlight aspects of the value chain of packaging processes and technologies. The Global Electronics Association Hand Soldering Competition, where the best soldering champions compete for the world title, has also become something of a tradition.

The State of the Electronics Manufacturing Industry

Elektor: How would you describe the current health of the global electronics manufacturing industry, particularly in terms of supply chains and automation adoption?

Müller: The global electronics manufacturing industry is showing signs of stabilization after several turbulent years. Supply chains, while more resilient than during the



European manufacturers are focusing on high-value innovation, quality engineering, and sustainability to remain competitive.

peak of the pandemic, remain vulnerable to geopolitical tensions and raw material constraints. On the upside, we're witnessing a robust uptick in automation adoption. Companies are investing in smart factories, AI-driven processes, and robotics—not only to increase efficiency, but also to counteract skilled labor shortages. The overall sentiment is cautiously optimistic, with innovation and digital transformation acting as key growth drivers.

Elektor: What are the major challenges your exhibitors and partners in the electronics production value chain are facing in 2025 — labor shortages, material costs, tariffs, or something else?

Müller: In 2025, the most pressing challenges are labor shortages and raw material volatility. Many companies are struggling to find skilled technicians and engineers, which slows down innovation cycles and production capacity. At the same time, high material costs — especially for rare earth elements and semiconductors — continue to squeeze margins. Regulatory complexity and new



Governments and industry players are pushing for regional diversification to reduce dependency on single-source geographies.

trade policies, particularly between major economic blocs, also add uncertainty. Our exhibitors are actively seeking solutions through automation, nearshoring, and smarter supply chain planning.

Elektor: How are European manufacturers positioned today in terms of competitiveness, innovation, and resilience against larger global players in Asia and North America?

Müller: European manufacturers are focusing on high-value innovation, quality engineering, and sustainability to remain competitive. While they may not match Asia's scale or North America's capital intensity, Europe excels in specialized applications, precision

manufacturing, and integration of green technologies. Strong R&D networks, public-private partnerships, and strategic investment in digital and energy-efficient production help maintain resilience. However, the pace of scaling up remains a challenge, especially in semiconductors and battery technologies.

Elektor: We've seen increasing convergence between electronics manufacturing and AI, robotics, and sustainability. How are these forces shaping production priorities today?

Müller: This convergence is fundamentally reshaping how manufacturers prioritize investments. AI is being integrated into quality control and predictive maintenance, robotics into flexible and modular production lines, and sustainability into material selection and energy usage. Many exhibitors at our fair are showcasing solutions that combine these dimensions. For example, zero-defect manufacturing powered by AI and energy monitoring systems built into factory infrastructure. Environmental impact, once a compliance issue, is now a driver of competitive differentiation.

Emerging and Disruptive Technologies

Elektor: Which technologies or processes do you believe will be most disruptive to electronics manufacturing over the next few years?

Müller: Several technologies stand out. Advanced packaging, chiplet integration, and heterogeneous integration are redefining how electronic components are designed and assembled. Additive manufacturing is starting to make inroads in prototyping and low-volume production. AI-driven automation, digital twins, and machine vision are enabling smarter, more adaptive factories. Additionally, sustainable manufacturing processes — like solvent-free PCB production or closed-loop recycling systems — are poised to transform the ecological footprint of electronics manufacturing.

Elektor: Are you seeing concrete adoption of AI-driven process optimization, predictive maintenance, or generative design in factory settings yet, or are these still mostly aspirational?

Müller: These technologies are moving from pilot projects to production environments, particularly in larger, innovation-driven companies. Predictive maintenance, powered



by real-time sensor data, is already delivering measurable ROI in many factory settings. AI-driven process optimization is being used for yield improvement and quality control. Generative design is still more common in R&D phases, but adoption is growing as software becomes more accessible. While not yet widespread across all tiers, the direction is clear: data-driven, AI-enabled manufacturing is becoming the new standard.

Elektor: With global emphasis on securing semiconductor supply chains, do you think we'll see a fundamental shift in where and how electronics are developed and manufactured by 2028?

Müller: Yes, we anticipate a significant shift. Governments and industry players are pushing for regional diversification to reduce dependency on single-source geographies. This includes building new fabs in Europe and North America and reinforcing existing ecosystems. By 2028, we expect to see more vertically integrated production closer to end-markets, supported by digital supply chain tools and cross-border innovation hubs. However, global interdependence won't disappear — what we'll see is a more balanced, risk-aware manufacturing landscape. 

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About Barbara Müller

Barbara Müller joined Messe München over 15 years ago. She has gained experience in both B2C and B2B trade fair business. Since 2017, she has been working in the New Technologies division for electronics trade fairs in Munich and abroad. Since 2021, she has been responsible as project manager and global industry lead for productronica, the world's leading trade fair for the development and manufacture of electronics, in Munich, China, and India, as well as for cooperation with SEMICON Europa.

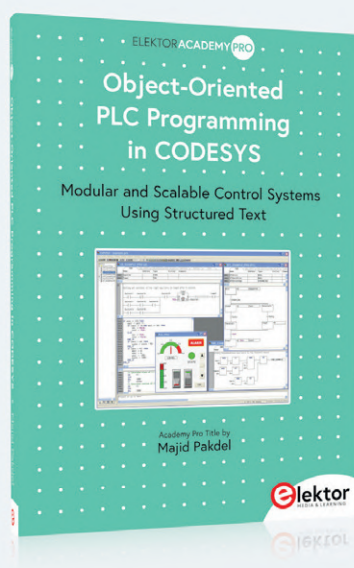


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Automation to Tackle Reshoring Manufacturing, Tariffs and Labour Shortages

By Jean-Pierre Joosting (eeNews Europe)

Supply chains are typically complex logistics systems that rely on entire ecosystems of suppliers, resources, skilled labour, and manufacturing capabilities. China excels in this area, particularly evident in 5G communications and electric vehicles. Furthermore, Chinese companies produce the majority of the world's electric vehicle batteries and its factories are implementing state-of-the-art automation technologies. This competitive landscape is being perceived as a threat other country's markets. The resulting trade tensions are driving a push of reshoring manufacturing and supply chains.

Initially, most countries began to seriously consider reshoring manufacturing and the role of automation during the COVID-19 pandemic, which severely disrupted international supply lines between countries. However, due to COVID-19, many companies managed to implement resilience through multiple manufacturing points and shorter supply lines rather than reshoring to high-wage countries. Today, the situation is far more serious, as reshoring is once again at the forefront due to protectionism in the form of tariffs and geopolitics forcing organisations to consider manufacturing in expensive countries, many of which have meagre manufacturing resources that have been hollowed out over decades.

The uncertainty caused by sudden tariffs has led to a reevaluation of where to prioritise reshoring manufacturing and whether this is even possible. For many industries, it will simply be too expensive unless prices rise significantly, which, unfortunately, will drive inflation once again or slow down the economy. The initial reason for offshore production was to leverage cheap labour and regulation-light manufacturing, such as in China, India, Mexico, and Eastern Europe. Since then, whole ecosystems have developed in such countries and cannot be reversed quickly without economic dislocation.

Several factors determine whether production can be reshored. The cost of automation is paramount in deciding whether high-wage countries can bring production back and mitigate labour costs. The availability of sufficient resources and skills is also key. Other important aspects include the cost of input materials for local manufacturing, the regulatory environment and the availability of parts and technology needed to produce products cost-effectively. In the United States, tariffs will ironically increase the cost of many input materials for local manufacturing.

The idea of a factory employing thousands of workers to produce goods is a remnant of a bygone era. Today, standards are being created for the factories of the future, often referred to as Factory 4.0, to ensure modern, fully automated, interactive, and flexible production lines.

Challenges of Automation

Most factories have some form of automation, especially in the automotive industry. Pick-and-place machines for electronics assembly and welding robots in the automotive industry are two notable examples of success. However, one key challenge in electronics manufacturing is assembling non-standard or irregular components, which is where manual labour often comes in. These components make their handling and precise placement challenging for insertion machines, especially as electronic designs become more intricate and the diversity of irregular components increases. In other industries, manual labour is still required for many assembly tasks, which cannot be addressed by current automation technology. Humanoid robots could play a key role here in future factories. Some other key challenges include various disruptions, such as labour shortages, limitations of current technologies, and costly downtime on production lines.

Advancing Automation Technology

To increase the efficiency of an assembly line with automated processes and provide the ability to reconfigure production lines quickly, Factory 4.0 digitises manufacturing and industrial processes, creating a manufacturing environment where systems can exchange information, trigger actions, and control each other autonomously. In such smart factories, machines, devices, and systems are interconnected, enabling the collection of real-time data, advanced analytics, predictive maintenance, digital twins, and autonomous decision-making.

Tackling labour shortages or enabling reshoring in high-labour-cost economies is a key driver of investment in automation. Training and upskilling programmes also need to be considered, not only to supply skilled labour for the required roles but also to ensure workers possess the necessary expertise. Here, the use of Generative AI

is viewed as a potential facilitator that not only reduces costs but also prevents accidents and damage to machinery.

To illustrate this, researchers from the University of Georgia developed a new virtual reality (VR) space named VR Co-Lab to help humans working with robots train more efficiently and effectively. Detailed in a recent study, VR Co-Lab trains employees digitally to practice disassembling recyclables without damaging materials and to learn how to avoid injuries and collisions with robots [1].

To assist companies in reducing the initial costs of automation, Robotics as a Service (RaaS) is a business model similar to Software-as-a-Service (SaaS). RaaS enables organisations to access robotic technologies via a subscription or leasing plan, allowing them to deploy, manage, and expand their robotic operations more flexibly and cost-effectively. RaaS is used to automate repetitive tasks, including warehouse management, customer service, and complex surgeries, among others.

Manufacturing Operations Management (MOM) and the Industrial Internet of Things (IIoT) are transforming manufacturing, with the IIoT enabling real-time data collection and analysis to optimise MOM processes. MOM encompasses a wide range of activities, including planning, scheduling, and quality management. At the same time, the IIoT focuses on connecting devices and systems to gather and act on real-time data from the shop floor. The integration of IIoT with MOM systems delivers enhanced efficiency, predictive maintenance, improved quality control, and more effective supply chain management.

AI and machine learning can identify subtle anomalies that might lead to a breakdown, enabling manufacturers to carry out repairs before a breakdown causes costly downtime or damage. Known as predictive maintenance, this operating process requires a continuous stream of operational data from sensors installed on the machine, as well as data persistence and other sources of information, such as maintenance records, failure events, inspection records, and engineering diagrams, to enable holistic monitoring. AI in predictive maintenance can identify patterns and anomalies that traditional data analysis and condition monitoring cannot easily detect. Furthermore, it can employ a feedback loop to improve over time.

For example, Senseye Predictive Maintenance is a cloud-based software platform that combines AI with human insights to automatically generate machine behaviour models that analyse machine data and predict potential failures. It is machine-agnostic and integrates with



*The idea of a factory
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any asset, system, or data source, using either existing data or newly installed sensors. Senseye is used across various industries, including pulp and paper, metals and mining, and manufacturing, to provide proactive maintenance, minimising unplanned downtime and its associated costs. Siemens also offers generative AI functionality to make predictive maintenance more conversational and intuitive [2].

IIoT and 5G Tie It All Together

Automation in factories requires communication between machines, sensors, and computing platforms, often referred to as IIoT. Traditionally, communication is facilitated by Ethernet-based protocols such as PROFINET, POWERLINK, EtherCAT, EtherNet/IP, SERCOS III, CC-Link IE, and Modbus TCP. However, wireless protocols such as Wi-Fi, Bluetooth, Zigbee, WirelessHART, and LoRaWAN are increasingly being implemented in modern factories to reduce installation and maintenance costs, enable the quick movement of equipment on the factory floor, and facilitate remote access and control of machinery and processes. This results in improved asset management and is key to enabling predictive maintenance. Furthermore, wireless technology is also well-suited for real-time data collection and control. However, in wireless systems, security and interference are key concerns, but they can be addressed with careful planning.

To further advance factory automation, 5G is being increasingly considered due to the benefits it brings to robotics and automation, including real-time communication and enhanced operational efficiency. Features such as high bandwidth, low latency, and reliability make it ideal for demanding industrial applications. With the use of AI and machine learning, the IIoT uses vast amounts of data, making the speed and capacity of 5G key requirements.

The high bandwidth and low latency of 5G networks enable more advanced and accurate automation tasks, including the use of robots and drones, as well as remote control of machines, processes, and automated systems. Remote operation also reduces the need for human workers in hazardous environments. 5G also supports rapid inter-machine communication, increasing efficiency and allowing quick responses to changing production

demands by enabling switching between product batches or types with minimal delay. 5G can also cover extensive areas with ease and link smart factories with their supply chains and logistics.

Since Private 5G offers greater reliability, control, and security, it is being increasingly deployed in factories and plants. 5G can also easily cover large areas and connect smart factories with their supply chains and logistics. Private 5G networks offer dedicated connectivity, ensuring high performance and dependability while giving manufacturers more control over network parameters to optimise performance. However, the key feature driving Private 5G for many organisations is that these networks are isolated from public networks, enhancing security and minimising the risk of cyberattacks, an increasingly important consideration as threat levels continue to rise and state-sponsored cyberattacks become the norm.

Additive Manufacturing

Additive manufacturing is also emerging as a useful technology in manufacturing. It excels at prototyping and making obsolete parts, but it is also entering more mainstream processes in industrial applications as the technology matures. In electronics, it can create 3D parts, such as antennas, that would not be possible using traditional methods.

To illustrate this, the Italian automation company Comau is collaborating with several international companies involved in digital additive manufacturing to bring its technology to new market segments that require affordable and easy-to-use advanced automation. For example, CEAD leverages Comau robotic arm technology, integrated into its Flexbot system, to help companies worldwide revolutionise their manufacturing processes by delivering large-format thermoplastic composite 3D printing. Comau is also collaborating with Titomic, a world leader in cold spray technology, enabling large-scale additive manufacturing, coatings, and repairs utilising novel and high-performance materials [3]. In another example, Comau and Prima Additive have joined forces to deliver dual-layer laser cladding innovation, having developed a high-speed, fully automated brake disc coating system [4]. Comau customers will be able to print parts on demand with consistent, repeatable results, allowing them to optimise material usage, reduce waste, and improve overall production efficiency.

Additive manufacturing extends far beyond electronics manufacturing, covering almost every industry and is a field undergoing rapid development as materials and processes improve. The technology can print tiny parts as well as large formats, such as boat hulls, car parts, or surface coatings.

Fitting Into an Integrated Supply Chain

An integrated supply chain encompasses not only factories but also inventory management and warehousing for raw materials and goods, as well as the dispatching of finished products. Automated warehousing is essential for overseeing inventory movement to and from smart factories. These warehouses rely heavily on robotics, particularly Autonomous Mobile Robots (AMRs), which transport parts and goods throughout the facility. AMRs can also interface with automated systems to select necessary parts with minimal or no human input. Wireless communications such as 5G, Wi-Fi 6E, Bluetooth, and LoRaWAN are vital for enabling AMRs. These robots require low latency, accurate positioning, obstacle detection, collision avoidance, and rapid rerouting. Small, modular factories and regional warehouses could offer solutions to challenges posed by tariff trends, geopolitical upheavals, pandemics, or natural disasters.

Looking to the near Future

Smart factories are poised to leverage robotics and automation software and systems to deliver reconfigurable, fully automated factories and supply chains with minimal labour requirements. Although automation addresses current labour shortages in manufacturing and logistics, it will likely result in virtually no growth in jobs.

Reshoring driven by tariffs and sovereign concerns requires the cost of automation and robotics to decrease to a level that makes economic sense. The International Federation of Robotics (IFR) predicts that the use of physical, analytical, and generative AI will expand, enabling robots to perform a wide range of tasks more efficiently. Analytical AI, for example, allows robots to process and analyse considerable amounts of sensor data for managing variability and unpredictability in high-mix and low-volume production, as well as in public settings. Physical AI enables robots to train themselves in virtual environments and operate based on experience rather

than programming. Generative AI will permit robots to integrate seamlessly into human environments and query information for maintenance, servicing, and operational procedures. Although the IFR finds that humanoid robots are currently limited to performing single-purpose tasks in industrial manufacturing, they see potential for humanoid robots in logistics and warehousing, especially if issues related to cost and complexity can be resolved [5]. Other reports predict that humanoid robots will number in the hundreds of millions within a decade or two.

Automation Is the Way Forward

Tariffs and digital sovereignty are driving the need for automation and robotics in manufacturing and supply chain logistics, which in turn is prompting countries to push for reshoring. However, due to the high costs of materials and manufacturing in advanced economies, this is generally not feasible without significantly higher prices. Automation and robotics in smart reconfigurable factories are seen as a key enabler to drive reshoring, address sovereign and tariff issues, as well as remove labour costs and shortages.

To illustrate the potential disruption that automation technology can cause, Space Forge has just confirmed the successful launch of its first in-space manufacturing satellite, developed entirely in Wales. This first-of-its-kind in-orbit manufacturing demonstration is designed to prove the viability of producing advanced materials in the unique environment of space [6]. 

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Editor's Note

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Beyond Future Proof

Circularity in Electronics

By Nick Flaherty (eeNews Europe)

Circularity and design-for-reuse have been niche concepts in electronics for many years. However, there is an increasing focus on the approach for electronics, with several groups promoting the philosophy to boost sustainability across the industry.



Source: eeNews Europe

Fairphone in the Netherlands [1] has been at the forefront of reusable, repairable electronics. Since the launch of its first modular, repairable phone back in 2013, the cycle of new designs has increased, with the Fairphone Generation 6. More recently, Framework in the US has developed laptops [2] and even a desktop AI PC [3] with reusable parts.

The move to design for reuse is also being driven by regulations. The Ecodesign Act and Right to Repair Act in the European Union are mandating more commitment to sustainable production and longer lifetime for devices. This is even reaching the AI datacentre. Trooper AI is "upcycling" second-hand gaming cards from Nvidia to provide low-cost GPU access in datacentres in Germany, France, and the Netherlands.

Despite growing investment in sustainability, the world is moving backwards on circularity: the share of recyclable materials in the global economy has dropped from 9% to 6.9% in recent years [4]. Approximately 62 million tons of electronic waste is generated globally, with this figure estimated to rise to 82 million tons in 2030.

John Mitchell, GEA



Circularity Hub

"As we talk with industry, too many people are asking 'how do I do this?'" says John Mitchell, CEO of the Global Electronics Association, formerly the IPC. The GEA has just launched a circularity hub [5] with hints and tips to guide designers in the ways of reuse.

Similarly, contract manufacturing giant Jabil has been part of the increasing drive to circularity.

"It's important to us to contribute to the industry as that's where we can share the lessons we learned," said Cassie Gruber, director of sustainability business solutions at Jabil, which acts as a contract manufacturer but also makes its own equipment through a network of acquisitions.

"There are six pathways that all need to be addressed to create a true circular economy," she said. "It is simple to create a circular business model, but the challenging piece is the circular supply chain."

"We need to change habits, so it's about change management," she said. But it is also about standards for design and for data. "A big gap is that suppliers across the globe do not encompass sustainability metrics, so we are going through this chaos of transformation."

Jabil is also working with GEA on developing standards for circularity.

"A lot has to do with reclaiming materials, end of use vs end of life, collaborating with the recycling industry. The electronics industry is set up to build things, not reuse or recycle things. Electronics drives 20% of world trade today, and with that, there is already concern about the cost and landfill of e-waste," says Mitchell.

"A lot of the manufacturers I encounter don't even realise circularity is even possible, let alone the cost savings, so we are raising the awareness and highlighting the cost savings. It is a change of mindset and I'm seeing that changing. Even five years ago, it was regionally different. Just a couple of years ago, that changed," he said.

Reclaiming Chips

Gruber points to the acquisition of Retronix [6] for thermal reclamation of embedded chips on PCBA to recycle devices at Jabil.

"We do manual and laser re-balling of BGA packaged chips, and we offer them with three times life," she said. Jabil also recycles datacentre equipment for Tier Ones, such as cables and components and will reuse racks rather than ship a rack for recycling.

"There's a lot of options," she tells *eeNews Europe*. "At times, customers want the chip to be redeployed within their supply chain. In most cases, we are reballing the chip, testing it, even for manufacturing lines outside of Jabil. In other cases, there can be assessments of components, we reclaim two to four chips that have value on the secondary markets, and we work with tier 2 or 3 manufacturers, even brokerage companies, but you have to be careful."

Jabil is part of the Circular Electronics Partnership and one of the pathways for Design for Circularity. It is also working with 3PL logistics in certain countries that are challenging with logistics for take-back programmes to recycle equipment.

"We are looking to build some standards around the circular economy with benchmarking and baselining, as well as life cycle assessment (LCA).

Circular Electronics Partnership

Even the US is catching up, with the Circular Electronics Design Guide [7] published by the partnership. This includes contributions from more than 60 experts and 25 organizations, many in Europe, on strategies for repair, refurbishment, and recycling. This includes contributions from Accenture, Bang & Olufsen, Danfoss, Ellen MacArthur Foundation, ERI, Fairphone, Fraunhofer IZM, Global Electronics Council, Globant, HMD, HP, iFixit, Logitech, Microsoft, Partners For Innovation, Pezy, Philips, the Royal College of Art, Schneider Electric, Signify, Studio Elk, Synapse, TU Delft, and Versuni.

The design guide includes:

- A blueprint for building a circular innovation process
- Tools to scale circular initiatives in repair, refurbishment, and recycling
- Insights into creating the enabling conditions for successful circular initiatives
- Case studies showcasing how industry leaders navigate the challenges.

"This guide is one of the most comprehensive resources on circular design developed by practitioners for practitioners," said John Shegerian, Chairman and CEO of ERI, the largest fully integrated IT and electronics asset disposition (ITAD) provider and hardware destruction company in the US.

"It is the result of an extensive cross-company effort, and we are proud to have been asked to play a role."

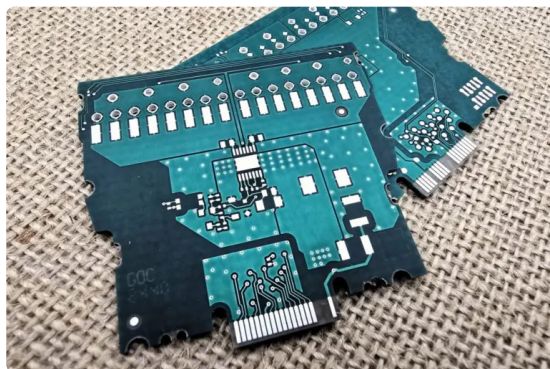


▲
Cassie Gruber, Jabil



Barriers to implementing circular economy practices go beyond the lack of properly equipped recycling facilities.

►
The Jiva Soluboard [11]



There are technology solutions for circularity as well as business models. One that comes up regularly is Jiva Materials in the UK, which has developed a printed circuit board that dissolves in water. This dramatically simplifies the dismantling of the boards and the easy recovery of the components. It has worked with Infineon Technologies and PCB maker ICAPE and is raising £2.8 million in a seed round, including a crowd-funding element.

Dissolvable Boards

The patent-protected Soluboard is an alternative rigid PCB laminate with improved environmental credentials that is compatible with two-layer through-hole designs. It is manufactured by impregnating natural fibres with a water-soluble polymer and a halogen-free flame retardant. The composite material is then supplied to PCB fabricators as panels of copper clad laminate (CCL), available in a range of sizes, and can be taken from bare laminate through to an assembled PCB using equipment available to a standard PCB fabricator. It is fully compatible with processes including water-based etching, electroplating, drilling, routing, and curing.

Another UK company, In2tec, has patented a suite of materials, manufacturing processes, and proprietary design techniques that enable printed circuit board assemblies (PCBAs) to be fully disassembled at end-of-life or for repair. Alongside this ReUSE process, the ReCYCLE process allows these PCBAs to be returned to their original components without damage, allowing the reuse in new products or resale in the second-life market. The technology has been nominated for the EarthShot awards later in 2025.

Meanwhile, data collected by European industrial automation giant ABB over the last four years by ABB Energy Industries Service and its recycling partners shows the amount of electronic waste returned by customers and then sent to landfill reduced by 93 percent since the launch of a Parts Circularity Program. Of 32,000 faulty items processed across the four years, 214.5 kg went to landfill in 2020, but by the end of 2023, this had fallen to 14.2 kg, supporting ABB's global efforts to enable a more sustainable future.

The initiative focuses on the repair, reuse, and recycling of faulty parts to extend their life and help reduce waste

and conserve resources that would otherwise be used to manufacture new parts. "The success of this program has already been proven at industrial plants around the world where our customers have service agreements that enable them to play an active role in striving for a circular economy," said Paul Sundt, Service Segment Manager at ABB Energy Industries.

Automotive Electronics

The three-year Transition of the European Automotive Supply Chain Towards a Circular Future (TREASURE [8]) project finished last year, developing an online platform as well as multiple reconfigured recycling units to help recover the critical metals used in modern car electronics.

Barriers to implementing circular economy practices go beyond the lack of properly equipped recycling facilities. TREASURE developed a framework to connect disassembly, recycling, and design actors, and the project created a policy guideline to provide industry players and politicians with needed information.

TREASURE also created the first in-depth assessment of the car electronics lifecycle and circularity [9]. A digital platform composed of a four-module toolbox that uses an AI-based scenario assessment tool to compare different perspectives on disassembly processes, recyclability, and circularity performance is a major achievement. The automotive industry has responded well to the resources provided by TREASURE, and the platform is seen as the first step in enabling secure information exchange in recycling.

Digital tools are critical to improving automotive electronics, but the recovery of critical materials requires new recycling operations as well. TREASURE built on earlier EU-funded projects to reconfigure a hydrometallurgical processing plant for the recovery of precious, critical, and base metals. "The modular hydrometallurgical plant developed in TREASURE is a process fully dedicated to the recovery of precious metals from both obsolete car electronics, LCD displays and IME (in-mould electronics) parts. Specifically, the recovered silver has been reused to produce new IME parts," said coordinator Paolo Rosa at Milan University.

Another reconfigured process developed by TREASURE involves the deconstruction of PCBs with robotics.

"AI and robotics have been adopted to develop a semi-automated PCB disassembly process dedicated to the recognition of electronic components present on obsolete PCBs and their subsequent desoldering. This improves the recovery rate of materials for the subsequent hydrometallurgical process," said Rosa.

The project had 15 partners across seven EU countries and produced digital resources to support communication and recovery of critical materials along the automotive industry value chain. It also built on technological solutions to improve recycling so that the materials can be reused in manufacturing electronic car parts, avoiding downcycling of degraded materials.

Digital Tools

In the UK, the Digital Innovation and Circular Economy Network Plus (DICE Network+) [10] started in January 2025 to explore how digital technologies, including artificial intelligence (AI), can accelerate the shift to a circular economy.

This is led by the University of Exeter in collaboration with eight UK universities and industry partners, including the Ellen MacArthur Foundation, Arup, and SAP. The network aims to address two key challenge areas of embedding circular design principles.

"We know most companies are now invested in both digital transformation and circular economy goals, with half of organisations implementing AI in their infrastructure and 55% of large businesses committed to circularity," said Professor Fiona Charnley, DICE Network+ Lead and Co-Director of the Exeter Centre for Circular Economy.

"For the UK to meet its ambitions in AI and clean energy, we must embed circular economy principles at the design stage. By connecting partners across sectors, DICE Network+ will help build this capacity across the UK and beyond — creating digital innovations that are sustainable and using those innovations to supercharge the adoption of circular models."

"We need circularity now because we're hitting planetary boundaries," said Darren West, Global Head of Circular Economy Solutions at SAP, during his keynote on agentic AI. "The good news is that circularity drives both sustainability and profit. We're already seeing how AI can save hours on ESG reporting, or how digital product passports can help track and recover high-value materials. With new regulations like ESPR on the horizon, manufacturers must start designing modular, repairable, and traceable products. That's where this network can help."

The three-year project starts with a call for demonstrators scheduled for early 2026 and highlights the need for data standards throughout the supply chain for circularity.

"The biggest problem, not just for Jabil, is the synchrony with the supply chain and the availability of data sources," says Gruber at Jabil. "From material declarations to country of origin we have a plethora of data but we didn't know to put the data in a certain format in one place. We can tackle circular business models all day long but all of that is patching a hole, we need the circular markets and supply chain to connect and the biggest gap is the supply chain alignment," she says. 

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Passive Components

Low-Loss Inductors Enabling High-Efficiency DC/DC Converters

By Annika Frankemölle
(Würth Elektronik eiSos)

SiC and GaN power transistors with a wide band gap have made power supplies more compact and more powerful. To further increase their efficiency, particularly low-loss power inductors are required.

Due to the ongoing miniaturization of end devices, rising power densities, and increasing regulatory demands on modern electronic systems, low-loss energy conversion has become a central focus of current research and development. The continuously rising requirements have made efficiency not just an optimization parameter, but a primary design objective in electronic system development. The basis for energy-efficient devices is essentially influenced by the power supply unit. While linear regulators were widely used in the past, today switch-mode power supplies are found in modern power electronics. This transition is driven not only by the steadily

decreasing voltages of digital circuits but also by advancements in semiconductor technologies. Modern switching regulators based on Gallium Nitride (GaN) and Silicon Carbide (SiC) transistors allow operation at significantly higher switching frequencies in the megahertz range. Higher switching frequencies enable the use of smaller passive components, such as inductors and capacitors, resulting in more compact and lighter power supplies. Additionally, GaN and SiC devices show lower switching losses and improved thermal performance, increasing the overall efficiency. The higher switching speed also enhances transient response and stability of the power supply, meeting the demanding performance and size requirements of modern electronic systems.

Key Requirement: Energy Efficiency

The efficiency η of a power converter is defined as the ratio of output power P_{out} to input power P_{in} :

$$\eta = P_{out}/P_{in}$$

This ratio represents a key parameter for evaluating the performance and cost-eff-

fectiveness of electronic systems. The power that is not transferred from the input to the output is defined as power loss. Increased power losses — caused by non-ideal switching elements, magnetic components, and parasitic effects — are dissipated as heat into the environment. These losses can limit the maximum power density of a system, require additional cooling, and affect the lifetime and reliability of electronic components significantly. Therefore, energy-efficient power converters are essential for conserving resources and reducing environmental impact. The more efficient the electronics, the longer the battery life for mobile devices, and in large-scale industrial and server installations with thousands of loads, the energy requirement is markedly reduced.

Types of Loss in Power Inductors

The efficient operation of modern power converters requires an optimized interaction of all components. Besides semiconductor switching losses, inductor losses play a significant role in determining the overall system efficiency. The losses of a power inductor arise from core material losses and winding losses [1]:

- Core losses are caused by magnetic hysteresis and eddy currents within the core material. These losses depend on the material properties like electrical resistivity and magnetic flux density, as well as the operating conditions like ambient temperature, output current, and switching frequency of the converter.
- Winding losses include:
 - DC losses, which are determined by the resistance of the copper windings.
 - AC losses, which arise from skin and proximity effects.

In modern converters operating at high switching frequencies, the AC losses of an inductor become increasingly dominant. Minimizing these losses requires a careful selection of inductor geometries and core materials. Therefore, accurate determination of the losses is a critical step in selecting the appropriate component. To predict temperature rise, AC losses must first be quantified with precision. Würth Elektronik has developed a state-of-the-art loss model capable of reliably calculating the total losses in inductors. This model is based on empirical data obtained with a real-time application set-up. Here, the total losses of the inductor are divided into AC and DC losses. The empirical data comes from measurements with a DC/DC converter. A pulsed voltage is applied to the inductor, whereby the input power P_{in} and the output power P_{out} are measured.

Figure 1 shows the schematic set-up of the DC/DC converter used for measuring the losses of the tested inductor.

Based on these measurements, the total power loss is calculated as $P_{loss} = P_{in} - P_{out}$ and

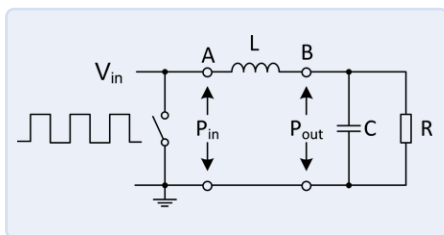


Figure 1: Set-up of the DC/DC converter for determining losses.

the AC losses of the coil P_{AC} are separated. Using this empirical data, a model is created for the calculation of the AC losses as a function of the test conditions:

$$P_{AC} = f(\Delta I, freq, DC, k1, k2)$$

The online tool REDEXPERT [2] developed by Würth Elektronik, assists engineers in selecting a suitable inductor for the respective application, enabling components to be compared and selected within the shortest time. **Figure 2** shows an example of the REDEXPERT interface for a buck converter. Specific application parameters — such as input and output voltage, switching frequency, duty cycle, and output current — are entered, while the corresponding inductor losses and temperature rise are calculated and displayed. The two lower graphs illustrate how power loss varies with input voltage and switching frequency, enabling engineers to evaluate the efficiency of a chosen inductor under varying conditions [3].

Advances in Low-Loss Inductors

In recent years, molded power inductors based on fine metal powder with a distributed air gap have gained popularity. The material used for the powder consists of pure iron or an iron alloy coated with a thin insulating material. The powder is pressed around the enameled copper winding under high pressure with insulating synthetic resin as a binder agent. The powder particles typically have a crystalline structure in which the iron or other metal ions are arranged in a specific lattice form. The distributed air gap ensures a uniform magnetic flux distribution, enabling high saturation currents and reduced core losses. **Figure 3** shows a microscopic view of the powder structure of a molded inductor [4].

While crystalline powders provide reliable performance, their magnetic properties can be further enhanced. Recently, amorphous and nanocrystalline materials have gained attention for their ability to enable high-efficiency designs. Amorphous metals exhibit a completely disordered atomic structure, whereas nanocrystalline materials consist

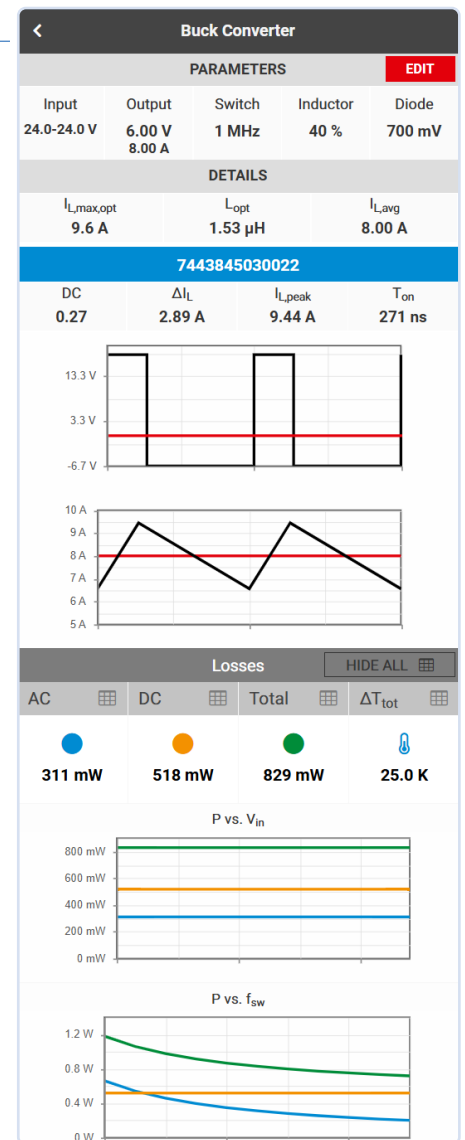


Figure 2: AC and DC losses of a 2.2-µH inductor (WE-MXGI) in a buck converter with 24-V input voltage, 6-V output voltage, 8-A output current, and 1-MHz switching frequency.

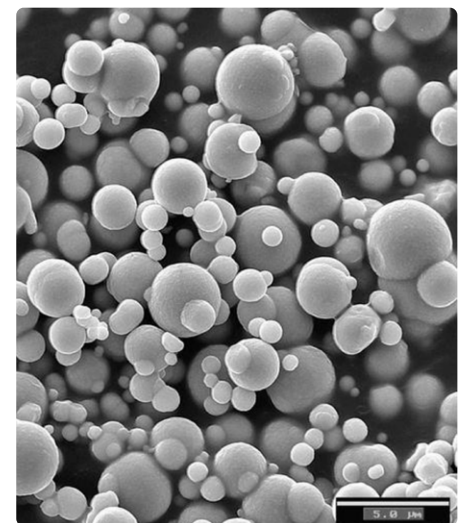


Figure 3: Microscopic analyze of a powder structure of a molded inductor (zoom: 5 µm).

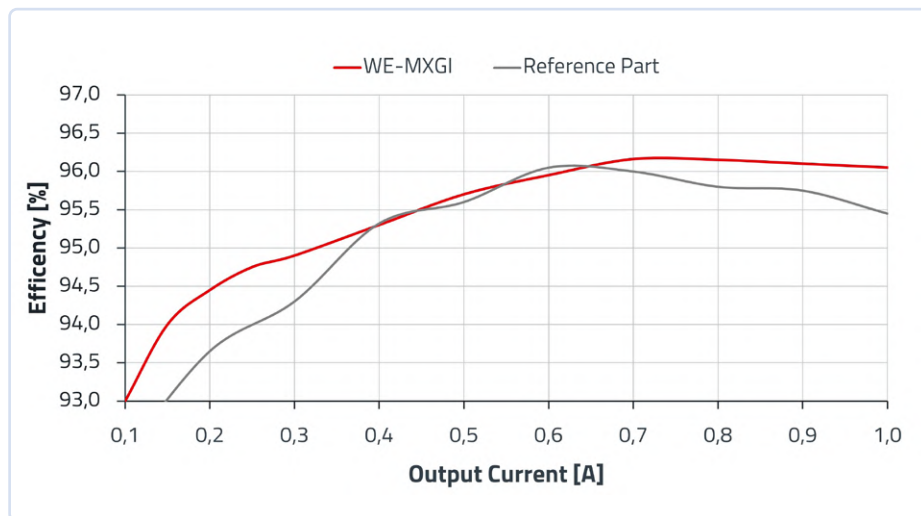


Figure 4: Efficiency across the output current measurement on an evaluation board of WE-MXGI in comparison to a comparable reference part.

of crystalline grains measuring 10-100 nm embedded within an amorphous matrix. This microstructure provides the core with high magnetic permeability, very low coercivity, and minimal magnetic losses in comparison to conventional crystalline magnetic alloys. Because of their excellent soft magnetic properties, nanocrystalline alloys have become a popular magnetic material for a new generation of power molding inductors used in high-frequency electronic applications [5].

Based on this knowledge, Würth Elektronik offers the newest molded power inductor WE-MXGI [6]. It includes an innovative metal alloy core material that enables maximum power density and excellent current handling capability with minimal losses. **Figure 4** shows a comparative efficiency measurement on an evaluation board. Note that the WE-MXGI has top-notch efficiency across the output current compared to similar parts on the market.

Beyond the choice of the core material, the winding design also plays an important role in the total losses of an inductor. In high-frequency applications, flat wire windings are increasingly used. The large conductor cross-section reduces current crowding and distributes the electric field uniformly, which minimizes the parasitic

capacitance and reduces the EMI effects (**Figure 5**). By using flat wire, low R_{DC} values can be achieved, resulting in reduced DC losses and consequently enhancing converter efficiency.

With the WE-PMFI [7] and WE-XHMI [8] performance series, Würth Elektronik has recently introduced inductors that combine an optimized core material

mixture with flat wire technology. They are specially designed for low losses to enhance efficiency and minimize self-heating. While the WE-PMFI series focuses on ultra-compact designs, making it ideal for space-constrained electronic devices, the WE-XHMI performance series covers large footprints to meet the demands of high-current applications.

Further Development in Various Directions

Würth Elektronik is actively investing in ongoing research and prototyping, exploring innovative magnetic materials and advanced manufacturing technologies. Development is a continuous process, driven by the rapidly changing demands of dynamic markets. As switching frequencies rise and power densities increase, magnetic components must deliver higher efficiency and better thermal performance in a smaller packaging size.

One technology shaping power inductors is based on the principle of combining magnetic powder with a binder system made of polymers. This advanced process enables the production of mechanically robust and reliable power inductors,

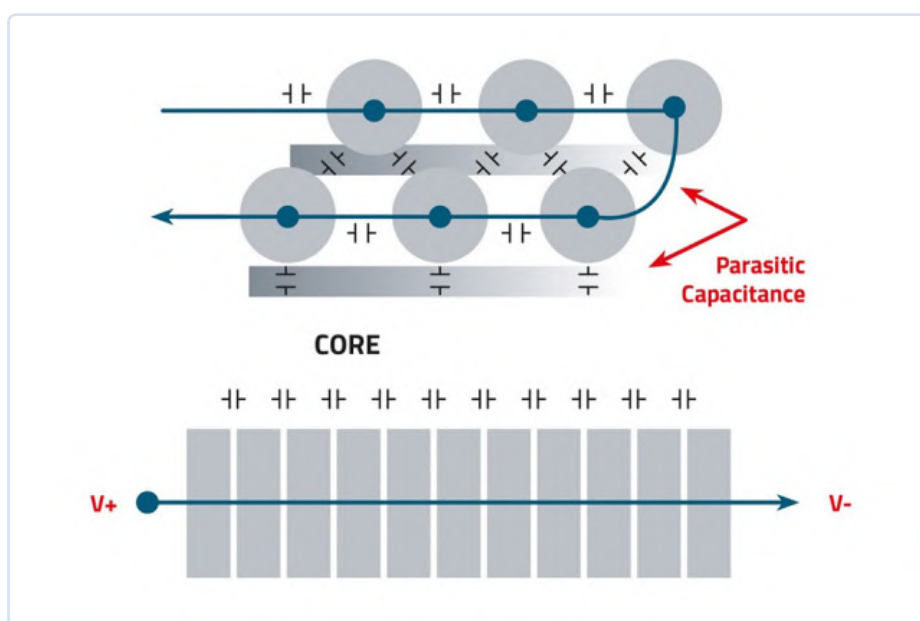


Figure 5: Flat wire enables uniform distribution of the electrical field, minimizing parasitic capacitance and optimizing EMC effect at the source.

featuring a high degree of miniaturization and functional integration. Due to its high level of design flexibility, this approach is well-suited for applications with strict size and weight constraints, such as compact DC/DC converter designs, where high electrical performance and efficient thermal management are required.

Another approach involves an advanced manufacturing process to produce thermally stable, low-profile inductors. This enables components to be specifically designed for complex multiphase power supply applications, such as high-performance computing platforms, low-profile electronic devices, and power modules in data centers and automotive systems. They are engineered to deliver low inductance values for fast transient response, while supporting high saturation currents and

minimal DC resistance. This performance is achieved by integrating the magnetic core and conductor into a compact, monolithic structure. The resulting design ensures excellent current handling capability, low electromagnetic interference (EMI), and stable performance across a wide operating temperature range.

Together, these advanced manufacturing techniques represent powerful technologies for the next generation of magnetic

components. They offer a broad platform for continued innovation and development, paving the way for magnetic solutions that meet the growing demand for compact, thermally efficient, and high-performance power conversion systems. 

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About the Author

Annika Frankemölle studied industrial engineering, innovation, and product management at the DHBW (Mosbach), where she graduated with a Bachelor of Engineering degree. Since 2022, she has served as Junior Product Manager at Würth Elektronik eiSos and has been enrolled in the part-time Master's program for an M.Eng. in Integrated Engineering at DHBW CAS (Heilbronn) since the end of 2023.



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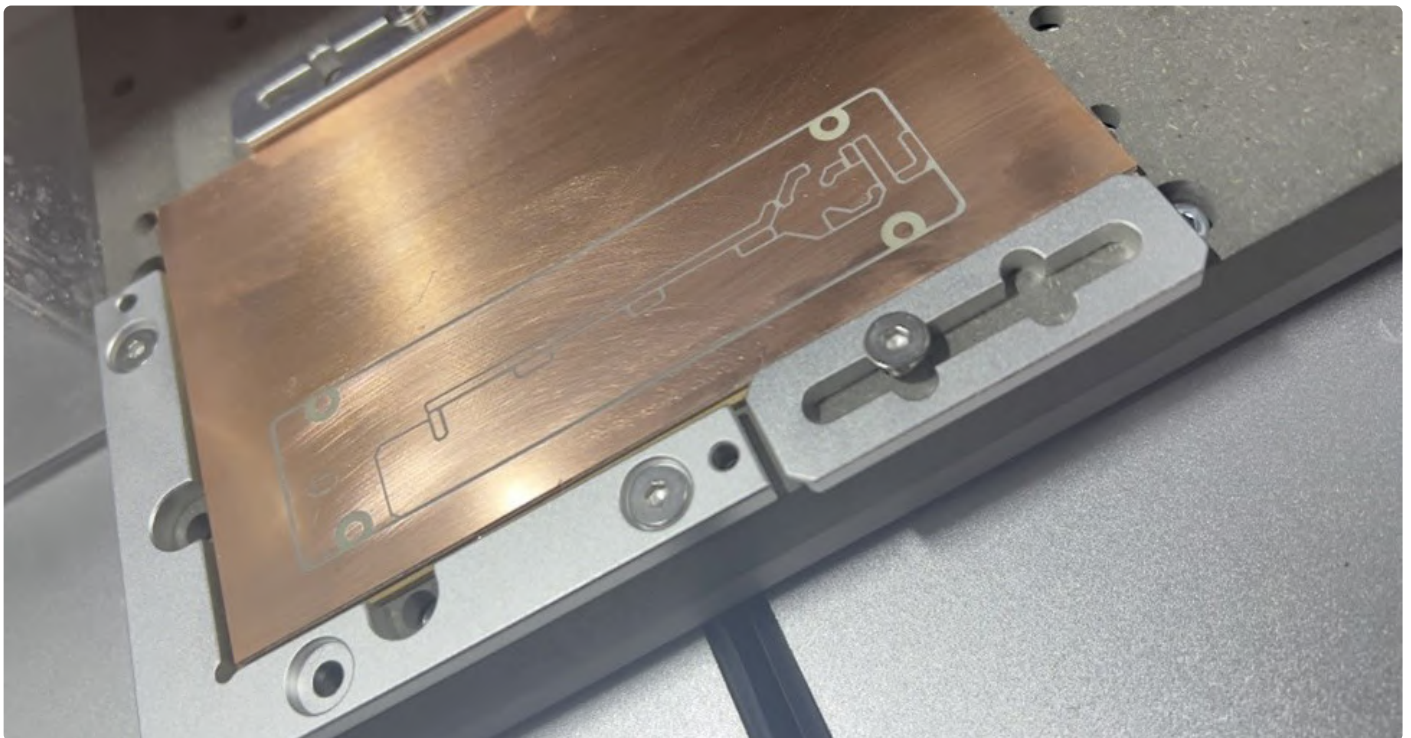
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How Desktop Manufacturing Machines Are Democratizing PCB Production

By Michael Parks (Mouser Electronics)

In recent years, the demand for digital engineering, rapid prototyping, short-run production, and the DIY electronics movement has driven significant innovations in desktop circuit board manufacturing machines. These machines enable hobbyists, researchers, and small-scale producers to design, iterate, and fabricate circuit boards in-house, drastically reducing the time from concept to working prototype.

While the speed of board turnaround is the chief advantage of desktop manufacturing machines, there are many other considerations when choosing such a machine. Cost is a significant driver in that choice, and the machines available for desktop circuit board manufacturing can run from the low thousands to tens of thousands of dollars. Obviously, the cost variances are driven by available features and the underlying technologies of the different classes of machines. In this article, we highlight some of the differences between desktop board manufacturing and traditional manufacturing techniques. We will also explore the different machine categories and digital tools available on the market for desktop circuit board manufacturing.



A circuit board created by a desktop milling machine. (Source: Green Shoe Garage)

Desktop Manufacturing Versus Factory-Based Manufacturing

There are numerous advantages to locally manufacturing circuit boards using desktop machines. There are also drawbacks, of course. Your board layouts will likely need significant changes if they were initially created for traditional circuit board manufacturing infrastructure. Let's begin by looking at some of the benefits of using desktop machines for circuit board manufacturing.

- **Cost-Effective for Prototyping:** Instead of outsourcing to large-scale manufacturers, companies and individuals can produce small batches of PCBs at a fraction of the cost.
- **Rapid Prototyping:** Iteration cycles become much quicker. Designs can be tested and modified in-house without waiting for external manufacturers. With reduced lead time, there's no need to wait for shipping or deal with potential delays from an external manufacturer.
- **Convenience:** An on-site machine allows immediate adjustments and reduces the logistical challenges of communicating with third-party manufacturers.
- **Learning Opportunity:** For educational institutions and hobbyists, these machines provide hands-on experience with PCB manufacturing, fostering a deeper understanding of the process.
- **Control Over Intellectual Property:** Keeping the prototyping process in-house can protect intellectual property and sensitive designs from potential leaks.
- **Customization:** Small-scale production allows for greater customization without the constraints often imposed by larger manufacturers.

Of course, every engineering decision comes with both positive and negative consequences. One should be aware of numerous differences and potential negatives when deciding to leverage desktop circuit board manufacturing machines. These include:

- **Limited Scalability:** Desktop machines are not designed for large-scale production. For bulk manufacturing, larger industrial machines or outsourcing are still necessary.
- **Quality Variance:** The quality of PCBs produced on desktop machines might not always match those produced by specialized, industrial-grade equipment.
- **Material Constraints:** Desktop machines might have limitations on the type of materials they can work with or may not be optimized for all types of PCB materials. Single- and double-sided copper-clad boards FR-1 and FR-4 are the most common for entry-level machines.
- **Maintenance:** Like all machinery, desktop PCB machines require regular maintenance, which can be time-consuming and require specialized knowledge.
- **Space Requirements:** Although designed for desktop use, these machines still occupy space and might require specific environmental conditions to operate optimally.
- **Initial Investment:** Despite being cost-effective in the long run, purchasing the machine has a considerable upfront cost.

- **Skill Requirement:** The machine's proper operation, maintenance, and troubleshooting require training and experience.
- **Limited Features:** Depending on the model, some desktop machines might not support advanced features like multi-layer PCB production, fine-pitch components, or advanced surface finishes.

Digital Engineering Tools Available for Desktop Circuit Board Manufacturing

Several types of engineering tools are suitable for desktop circuit board manufacturing. Understanding their nuances is necessary to pick a machine that meets your needs and financial capability. Let's take a look at some of the most common digital engineering tools used for desktop circuit board manufacturing.

Milling Machines

Milling machines use rotary cutting bits to remove material from a PCB blank to produce circuit tracks. Some of the most popular PCB milling machines for desktop use include the Bantam Tools (formerly OtherMill) desktop CNC milling machine and the Makera Carvera. These are fast and reliable machines ideal for producing circuit boards, and these two particular manufacturers make user-friendly machines that can mill PCBs down to very fine traces, making them suitable for SMD components. Typically, copper-clad FR-1 and FR-4 boards are used for milling operations. Negatively, milling consumes more material due to the subtractive nature of the process. Milling can also be noisy and produce debris.

PCB Printers

In contrast to the subtractive nature of milling machines, circuit board printers adopt an additive approach, depositing conductive ink onto a substrate to create circuit patterns. Popular machines on the market include the Voltera V-One, which not only prints PCBs but can also dispense solder paste and reflow components, making it a comprehensive desktop PCB production solution. The BotFactory Squink is another innovative PCB printer that, in addition to printing circuits, can also place components and cure the ink, enabling complete board production on the desktop. The main benefit of PCB printers is that they are fairly clean, with very little debris created during production. The particular machines mentioned here offer additional features to make them nearly one-stop shops for low-volume PCB manufacturing. One of the shortcomings of PCB printers is the fact that the conductive inks might not be as robust as traditional, etched copper. Also, traces and pads might be limited to larger sizes due to the resolution of the print head, which can make printers ill-suited for very fine pitch components.

Laser Etchers and Cutters

Another class of CNC machines includes laser etchers and cutters. While laser cutters may not be purpose-built for PCB manufacturing, they can be used to either etch away unwanted copper from a PCB or cut the PCB material itself. Recent advancements in laser technologies are pushing down costs, and combined with

their highly detailed precision, lasers are gaining popularity for PCB production. Laser cutters are increasingly finding their way onto workshop benches and can create very fine details that are perfect for making circuit boards. Companies such as LPKF Laser & Electronics and Glowforge offer a range of laser-based PCB prototyping machines suitable for various applications, from simple PCBs to RF circuits. The chief advantage of laser technology is the high precision with clean edges. This is fantastic for very fine-pitched components and traces. Additionally, lasers are suitable for both etching and cutting tasks. Countering the positive aspects of laser cutters are the obvious safety concerns that arise when using a laser. It requires HEPA-grade filters to quickly and safely extract fumes from the cutting volume. Laser cutters are susceptible to the smoke generated by the etching process and can have a negative impact on quality. Lastly, laser cutters, especially high-wattage cutters, can be more expensive compared to other methods.

Complete Desktop PCB Production Systems

Making PCBs is just one part of the battle. Electronic components must be attached to the circuit board to realize a working system, resulting in an assembled printed circuit board (PCBA). In addition to the PCB manufacturing hardware, reflow ovens and pick-and-place machines are additional equipment required to go from PCB to PCBA. Some companies, such as Neoden, offer machines with a comprehensive PCBA solution that integrates multiple stages of the circuit board production process. Neoden offers a family of desktop products for low-volume yet professional PCBA manufacturing. The Neoden FP2636 stencil printers provide a reliable and repeatable mechanism to apply solder to

PCBs. The Neoden YY1 is a desktop pick-and-place for moving components from reels to the PCB. Lastly, the Neoden IN6 offers reflow soldering. Combined, these machines are ideal for those who want to go beyond just producing PCBs and move into complete board assembly. While these machines are one-stop solutions that streamline the manufacturing process, they are not entirely out of the realm of professional and serious makers, as they cost only a few thousand dollars. However, they do stretch the definition of desktop manufacturing since they tend to require a larger footprint both physically and electrically.

Conclusion

The rise in desktop circuit board manufacturing machines has democratized access to PCB prototyping and production. Depending on the specific requirements—be it precision, speed, versatility, or the nature of production (subtractive vs. additive)—there's likely a machine tailored to those needs. As technology advances, we can anticipate further improvements in speed, affordability, and capabilities, ensuring that in-house PCB production remains accessible to all. ◀

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About the Author

Michael Parks, P.E., is the owner of Green Shoe Garage, a custom electronics design studio and technology consultancy located in Southern Maryland. He produces the S.T.E.A.M. Power podcast to help raise public awareness of technical and scientific matters. Michael is also a licensed Professional Engineer in the state of Maryland and holds a Master's degree in systems engineering from Johns Hopkins University.



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Starting Out in Electronics...

...Needs Power

By Eric Bogers (Elektor)

In this and the next installment, we talk about good power sources — essential for reliable electronic circuits.

Without power, even the best-designed electronic circuit is useless, and that's why "power supply" or voltage regulation is a central theme in electronics. In previous episodes of this series, some important aspects of this topic have already been discussed — rectifiers and filter capacitors, Zener diodes, and stabilization.

In practice, hardly anyone still bothers to build a stabilization circuit "discretely" — after all, there are plenty of ready-made ICs for this purpose.

The Fixed Voltage Regulators 78xx and 79xx

The most well-known family of fixed voltage regulators is undoubtedly the 78xx series, where "xx" is a two-digit number indicating the output voltage. So, a 7805 has an output voltage of 5 V and a 7812 has an output voltage of 12 V. The members of the 79xx family are fixed voltage regulators for negative output voltages.

The 78xx includes internal overload protection: if the IC becomes too hot, the current is limited. In the standard series, the maximum output current is 1 A — but this current can only be drawn if the chip temperature due to internal dissipation does not exceed the shutdown temperature. In the event of a short-circuited output, the current is limited to a value below 1 A to keep dissipation within more or less safe limits and to protect the connected circuit from damage.

With fixed voltage regulators, countless practical problems can be solved easily and cheaply. They are especially easy to use: connect the input voltage and ground, and the stabilized output voltage is available.

To avoid oversimplification, we have also indicated the correct wiring method in **Figure 1**. On the left, we see the bridge rectifier (represented by a simplified circuit symbol). The plus and minus of the rectifier go to the corresponding terminals of the buffer capacitor, to which the voltage regulator is also connected. By wiring the circuit this way, it prevents hum voltage caused by the voltage drop over the connecting wires from being superimposed on the buffered output voltage.

The fixed voltage regulator — as we already noted — has three terminals: input, ground, and output. When the circuit is required to perform at a high level, a low-inductance ceramic capacitor of 100 pF to 100 nF should be placed between output and ground; in addition, a modest electrolytic capacitor (around 10 μ F) should be placed at the output between plus and ground.

These capacitors are often omitted (or at least one of them); the circuit will still work, but it will not achieve the interference resistance that would be possible with an "ideal" configuration.

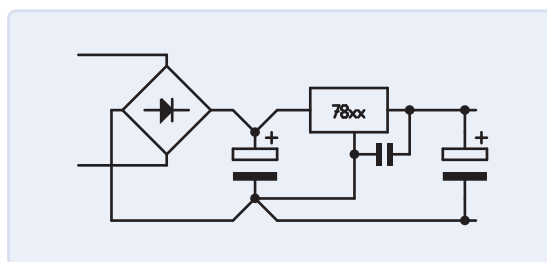
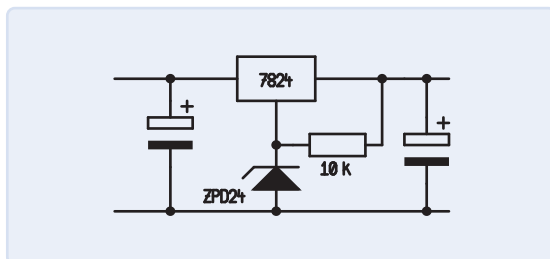


Figure 1: Use of a fixed voltage regulator.

Figure 2: Increasing the output voltage.



The input voltage must be at least 2 V above the desired output voltage — so a 7812 must be supplied with at least 14 V. The maximum input voltage (for a 7812) is 35 V. (Always check this against the datasheet!) If the input voltage actually reaches this maximum value and the output current is 1 A, then 23 W of power is dissipated in the IC (that is, converted into heat) — and the regulator must be cooled accordingly.

The 78xx series comes in TO220 packages. There is also the 78Lxx series in TO92 packages; these regulators have a maximum output current of 100 mA.

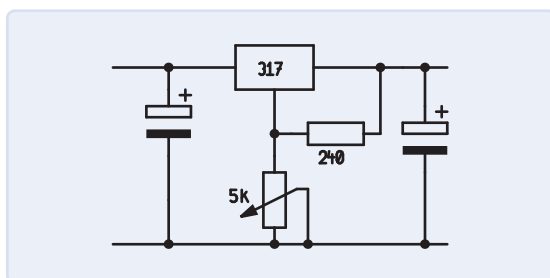
Higher Output Voltages

Fixed voltage regulators from the 78xx family are available for output voltages up to 24 V, which is sufficient for most applications — but not for phantom powering microphones, for which (officially) we need 48 V. (Many manufacturers reduce this voltage to 24 V, which usually does not cause problems.)

Figure 2 shows the *quick-and-dirty* way to coax a higher output voltage from a 78xx regulator: simply place a Zener diode in the regulator's ground connection. (Note: in Figure 2, we have not drawn the bridge rectifier.) However, this solution has an important drawback: in the event of a short circuit, the output voltage drops below ground potential, for which the component is not designed.

But, since phantom power always uses 6.8-kΩ resistors in series with the microphone, this (just in this case!) will not be a problem. In other applications, it is wise to use a different regulator (or a different circuit).

Figure 3: Adjustable voltage regulator.



Low-Drop Voltage Regulators

Standard voltage regulators need a minimum voltage difference of 2 to 3 V between input and output. To reduce dissipation, or to get the highest possible output voltage from a given transformer voltage, we can use so-called low-drop voltage regulators. These only require a difference of 0.5 to 1 V between input and output voltage.

The Adjustable Voltage Regulator 317

The 317 series includes voltage regulators whose output voltage can be set by the user. **Figure 3** shows the standard circuit with this IC.

With the 317, there is a voltage difference of 1.2 V between the output and the reference terminal. By means of voltage dividers, the output voltage can be set between 1.2 V and 37 V. If the output voltage must be adjustable down to 0 V (as with lab power supplies), you need to provide a suitable negative voltage at the reference terminal.

The LM317T comes in a TO220 package and the LM317K in a TO3 package; both can provide a maximum output current of 1.5 A. The TL317P comes in a TO92 package and can provide up to 100 mA.

The otherwise identical LM350T (TO220) and LM350K (TO3) allow a maximum output current of 3 A, while the LT1038CK can even provide 10 A. The LM337SP is a negative adjustable voltage regulator in a TO220 package with a maximum output current of 1.5 A. Adjustable voltage regulators are also available in low-drop versions.

Dissipation

The greater the voltage difference between the input and output of a voltage regulator, the greater the dissipation (the power loss) in the regulator. Suppose we have a power supply for a mixing console that must provide 18 V at a (relatively modest) current of 3 A. Suppose further that it uses a standard voltage regulator with a voltage drop of 2 V — in this case, the input voltage of the regulator must be at least 20 V.

Finally, let's assume that the power supply is equipped with substantial buffer capacitors of 10,000 μF. With full-wave rectification, we must allow for a voltage drop of 3 V during half a cycle of the mains voltage:

$$\Delta U = \frac{1}{2 \cdot f \cdot C} = \frac{3 \text{ A}}{2 \cdot 50 \text{ Hz} \cdot 10000 \text{ } \mu\text{F}} = 3 \text{ V}$$

If we also account for 1.4-V voltage drop across the rectifier, the transformer must supply a peak voltage

of 24.4 V — and the effective value of the transformer voltage is then 17.3 V. This is the voltage that the transformer must supply at a minimum for a stable output voltage and to prevent the mixing console from producing hum.

In practice, *front-of-house* mixing consoles are often powered via heavy-duty cable reels — and in PA technology, transmission losses can easily add up to astonishing heights, so it's not unreasonable to demand that the power supply works reliably even at a mains voltage of 180 V.

If the transformer must still provide 17.3 V at a mains voltage of 180 V, then at the nominal mains voltage of 230 V it produces as much as 22.1 V, and at 250 V (if the generator is not otherwise loaded) 24 V. However, this means that the buffer capacitor is charged to 32.5 V under these conditions. (Note: in practice, always calculate with the worst-case scenario!)

During each half-cycle of the mains voltage, there is still that voltage drop of 3 V — on average, that's 1.5 V. The average input voltage of the regulator is thus 31 V and the average voltage drop across the regulator is 13 V. Multiplying that by an output current of 3 A, we get a power loss of 39 W, which is about twice as much heat as a small electronics soldering iron produces.

The cooling of the power supply must be rated for this power loss, or rather, the cooling of *this* voltage regulator. If a power supply provides multiple voltages, the above naturally also applies to the other voltages and regulators; the various power losses must be added together, and the total loss must be dissipated from the device by cooling.

Dissipating heat can lead to problems: with passive cooling, a correspondingly large heat-radiating surface (heatsink) is needed, possibly in combination with ventilation slots; this affects the size of the device. Moreover, ventilation openings make the device vulnerable to dust and moisture. Active cooling (with a fan) requires extra energy and is not silent.

Limiting Power Loss

There are solutions to limit power loss. **Figure 4** shows such a circuit (greatly simplified).

Between the rectifier and the buffer capacitor, there is a transistor that can interrupt the charging process of the buffer capacitor. The Zener diode is dimensioned so that charging is interrupted when the voltage reaches a certain level. Because transistor T1 is used as an on/off switch, it does not dissipate any signifi-

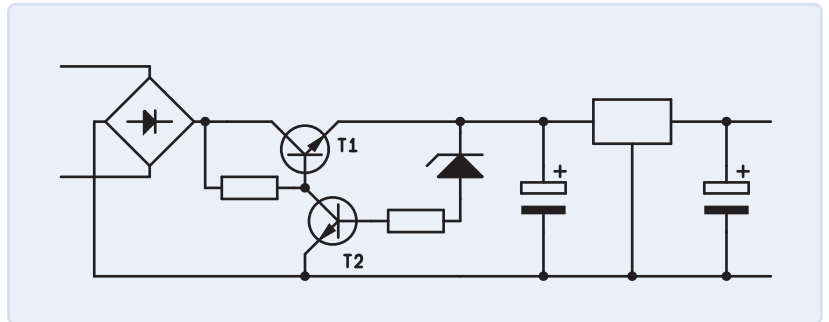


Figure 4:
Limiting power loss.

cant power. In this way, the power loss in the voltage regulator is effectively limited by reducing the input voltage.

Of course, a circuit like the one sketched in Figure 4 would actually be built with a power MOSFET and a control circuit with some hysteresis — but here, we just want to demonstrate the *principle* of this circuit. ◀

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Editor's note: This series of articles, "Starting Out in Electronics," is based on the book, Basiskurs Elektronik, by Michael Ebner, which was published in German and Dutch by Elektor.

Questions or Comments?

Do you have technical questions or comments about his article? Send an email to Elektor at editor@elektor.com.



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UHD Displays

Driven with Ease

Your Guide to Easily Put Various TFT-LCDs Into Operation Quickly

By Matthias Keller (FORTEC Integrated GmbH)

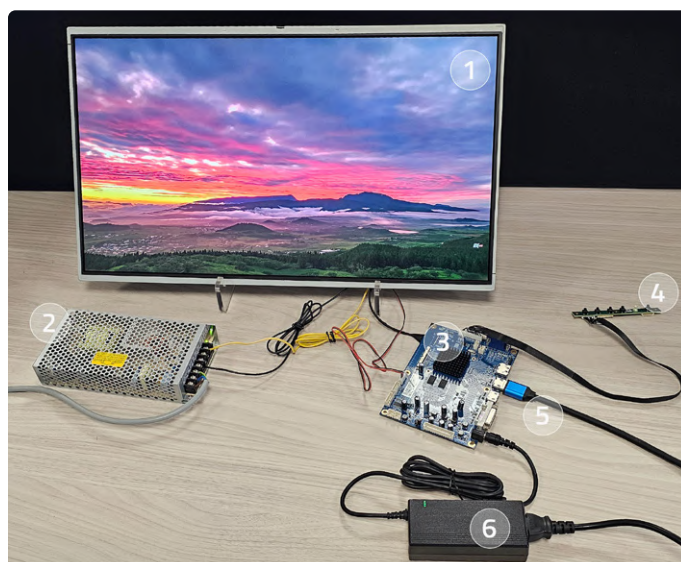
High-resolution displays are everywhere now. Phones sharper than microscopes, televisions that seem to outshine daylight. Yet in the world of engineering, resolution alone isn't the goal. What matters is control: the quiet, precise kind that turns a panel into an instrument. Whether it's guiding a surgeon's hand, keeping an air-traffic map alive, or monitoring a production line, those pixels need discipline.

That's where FORTEC Integrated's Prisma-4K [1] steps in — a controller built not to dazzle, but to deliver. It treats video like mission data: clean, synchronized, and steady. It speaks HDMI, DisplayPort, DVI, and even VGA, then drives modern panels in flawless 4K through modern interfaces such as V-by-One or eDP. No fireworks, no firmware tantrums; just unshakable performance.

Inside the Prisma-4K

At first glance, it looks modest: a clean, tightly laid-out board with no unnecessary clutter, just the right balance of connectors and copper. But inside, the design reads like a checklist written by someone who's spent years elbow-deep in control cabinets. Dual 4K at 60 Hz. HDMI 2.0, DisplayPort, DVI, and even good old VGA. Two panel interfaces, V-by-One HS and eDP, to cover everything from a 10.1-inch medical display to a 98-inch industrial monitor. It doesn't try to predict what panel you'll use; it simply accepts that engineers need options.

The board is equally versatile on the input side and accepts multiple video sources. Each input is backed by its own receiver circuitry to preserve signal integrity.



Example Setup, Front: (1) Display, (2) Power Supply, (3) Prisma 4K TFT Controller, (4) OSD Board, (5) HDMI Cable, (6) 12 V Power Supply.

In mixed environments, this flexibility saves hours of adaptation work. And engineers who have spent hours wrestling with mismatched standards will appreciate this kind of attention to real-world detail.

The outputs are equally versatile. With both V-by-One HS (eight-lane, 10-bit) and eDP (four-lane) interfaces, the board can drive a wall-sized display or a compact medical screen without complaint. Switching panels doesn't mean redesigning the whole system, a practical detail that quietly saves time, budget, and nerves.

The Prisma-4K keeps the essentials: clean input detection, stable firmware, and hardware built to last.

Quick Installation Example

Getting the Prisma-4K board up and running with a UHD TFT LCD panel is easier than wrestling with outdated drivers. In the following



Example Setup, Back: (1) Backlight Cable, (2) LED Backlight Driving Board, (3) Schuko Power Cord, (4)(5) Power Supply for Backlight Driver, (6) Backlight Control Cable, (7) Signal Cable.

section, we'll guide you step by step to ensure a smooth, trouble-free installation, whether your input comes from a laptop, an industrial PC, or any other external device.

Step 1: Prepare the Power Supply

- The Prisma-4K board requires only a single 12 V DC power source.
- Verify that jumper J9-2 (panel power select) is set to the appropriate panel voltage specified in the display datasheet before powering on.
- Correct jumper setting ensures safe and reliable operation for both the board and the panel.

Step 2: Connect the Input Source

- Choose your input device (e.g., laptop, media player, or PC).
- Select the appropriate input interface on the Prisma-4K board: HDMI (recommended for modern laptops and PCs); Display-Port (DP1.2); VGA (legacy input support).
- Use a compatible cable to connect the device's output to the corresponding Prisma-4K input port.

Step 3: Connect the TFT-LCD Panel

- Locate the backlight connector on your LCD panel and connect the backlight cable.
- Locate the panel backlight connector on the Prisma-4K board and connect the other side of the backlight cable
- Connect the main panel interface: eDP (Embedded Display-Port); V-by-One (VBO, 10-bit, 8-lane).
- Secure cables firmly to avoid intermittent connections during testing.

Step 4: Install Correct Firmware

FORTEC can provide software and hardware for customers to flash the firmware (also in-system programming is possible).

Flashing is carried out via the HDMI 2.0 interface using a USBISP board:

- Start Flash Tool.
- Open the Firmware Folder and navigate to the directory containing the firmware to be flashed.
- Switch on the power supply.
- Press the *Start* button to begin flashing.
- The flashing process runs automatically and takes approximately 2 minutes.

Step 5: Done

- Prisma-4K will automatically detect the input source.
- The panel should display in 4K @ 60 Hz, delivering sharp, vibrant images.

On-Screen Menu and Operation

The Prisma-4K fully supports an On-Screen Menu (OSD) to control all functions of the board. The OSD can be operated either via a Keypad or IR Remote. This small but versatile accessory lets engineers navigate menus and adjust display settings easily in a way everyone knows from TV sets or monitors at home.

For those who'd rather build than browse, FORTEC's pre-built kits make getting started refreshingly straightforward. It combines the Prisma-4K controller with many UHD panels available from stock and includes every essential: cables, keypad, LED driver, and pre-flashed firmware in one tidy package. Connect it, power up, and you're good to go.

There's quiet satisfaction when hardware simply performs — no flicker, no heat tantrums, no mysterious resets. Prisma-4K belongs to that rare breed of boards that stay calm under pressure and invisible in success. You wire it up once, and it keeps showing up, year after year, shift after shift. In a field where reliability is key. 

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About the Author

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WEB LINK

- [1] Prisma-4K, FORTEC Integrated:
<https://www.fortec-integrated.de/en/products/tft-components/tft-controller/detail/fortec-integrated/prisma-4k-01/>

Soldering in 2025

Practical Soldering Tips Straight from the Workbench



Figure 1: Traditional iron with separate heating element and soldering tip.

By Jean-François Simon (Elektor)

At Elektor, soldering has always held a special place, with well over a dozen major articles on the topic over the past 20 years, not to mention the countless bits of soldering advice given by authors in their project write-ups. So, why yet another piece? Because tools and techniques evolve, and we love to share updated practical advice!

Over the years, among the most discussed subjects has been the impact of the RoHS directive, which came into effect in 2006 and banned the use of traditional lead-based solder across the EU. Nearly two decades later, most have adapted... or stocked up generously on lead solder while they still could! We've also explored several soldering station projects using Weller RT cartridges. These included a version based on the Elektor Platino board in 2015 [1], a follow-up using a Microchip ATmega32 in 2019 [2], and most recently, a 2021 redesign [3] featuring the ATmega4809 and a 3D-printed enclosure. In "Soldering – So What?" [4], author Peter Beil shared practical insights into making the most of lead-free solder. And just last year, in "Tin Soldering Techniques" [5], Davide Scullino devoted a full eight pages to an impressively thorough overview of gear tailored to beginners.

Nevertheless, soldering remains one of the cornerstones of electronics, and the tools keep evolving. We've put together a fresh

round of buying tips to help you choose the right gear, along with practical techniques and recommendations to sharpen your skills. Of course, nothing beats hands-on experience. So, once you've read this article, fire up your iron and start practicing! And if we've missed your favorite tip or time-honed technique, don't hesitate to share it with us by email so we can include it in our next "Corrections, Updates, and Readers' Letters" section.

Among the most important tools, the soldering iron (or soldering station) still holds the top spot, so let's have a look at them first. Several technologies coexist today, typically falling into three main categories: traditional irons, cartridge-type irons, and magnetoelectric irons. The former are the most basic and consist of a heating element made from a resistive wire coil embedded in a ceramic core (**Figure 1**). In temperature-controlled versions, a temperature sensor such as a thermistor or thermocouple is integrated into the heating element. The soldering tip fits around this

heating element, and is typically made of copper and coated with multiple layers of iron, nickel, and tin to enhance durability and “wetting” of solder on the tip.

Active Tips

Cartridge systems, sometimes called *active tips*, represent a more advanced approach. In these, the heating element, sensor, and soldering tip are combined into a single, compact unit called a cartridge (**Figure 2**). This design allows for highly efficient heat transfer and superior temperature accuracy, since the sensor is located right near the working tip, without any air gap in the assembly. Once reserved for high-end professional tools from manufacturers like Weller (RT series), Hakko (T12 cartridges), and JBC (C210, C245, and others), cartridge technology has now become more accessible. Thanks to affordable Chinese clones of Hakko’s and JBC’s cartridges, the benefits of this system are now within reach of a broader audience. While the clones may not match the performance of the originals, they’ve played a major role in popularizing the technology.

RF Secret Sauce

The third, and perhaps most fascinating category includes magneto-electric soldering irons. These don’t rely on traditional resistive heating. Instead, the tip is made of a ferromagnetic material, usually hollow, which is heated by an alternating magnetic field generated by a miniature coil located within the central bore. The coil is driven at a high frequency, often around 13 MHz, or sometimes 450 kHz for entry-level models. When exposed to this field, the ferromagnetic material heats up until it reaches its Curie point [6], at which it loses its magnetic properties and stops heating. This elegant self-regulating mechanism doesn’t rely on a temperature sensor, or any electronic temperature feedback loop to maintain a fixed tip temperature. Indeed, the RF power supply is appropriately sized and the heating element draws exactly the amount of power it needs to remain at its Curie temperature.

Of course, this means that the tip temperature is determined by its metallurgic composition. These come in different variants, and swapping them is the only

way to adjust temperature. In practice, the thermal responsiveness of these irons is outstanding. They deliver heat almost instantaneously, making them ideal for working on multilayer PCBs with large ground planes. These irons are primarily manufactured by Metcal (such as the entry-level PS-900 shown in **Figure 3**) and Thermaltronics, although Hakko rather quietly released its FX-100 model a few years ago. All of these are costly, but second-hand units occasionally appear at somewhat reasonable prices in the classifieds. If you come across one, it’s well worth adding to your bench.

More Exotic Irons?

In “Tin Soldering Techniques” [5], the author recommended a “20–70 W stylus soldering iron, preferably electric.” That’s great, but what would be the other options? Two of them are shown in **Figure 4**. Portable gas-powered irons, like those from Portasol, are best suited for quick repairs in the field where no electrical outlet is available. While convenient for on-the-go fixes, their butane consumption and limited control over heating power make them poorly suited for regular use in an electronics workshop. Still, when equipped with a tubular hot-air-style tip, they can come in handy for shrinking heat-shrink tubing.

Soldering guns fall into a similar category. In my view, they’re generally too bulky and heavy for fine electronics work. That said, some users have mastered them and even turned them into a personal trademark, most notably Danyk on his DiodeGoneWild YouTube channel [7]. For the purposes of

this article, however, I’ll be focusing exclusively on usual soldering irons and stations, electrically powered and with the hand tool designed to be held like a pen, which generally gives better precision and control.

A Few Solid Options

The ideal soldering iron depends largely on the user’s priorities. Some value affordability or ease of use; others may focus on durability, the availability of spare parts (replacement tips and heating elements), whether it uses a cartridge system, brand



Figure 2: A selection of cartridge systems: Hakko T12, Elektor/Atetool AE970D, JBC C245.



Figure 3: Just an on/off switch and nothing else on this Metcal PS-900: not adjustable, but tons of heating power.



Figure 4: Those are for very special use cases and not ideal for daily work.



Figure 5: The AE970D, a simple cartridge-based soldering station with an easy to use interface.

reputation, etc. For those looking for a reliable, brand-name station that's robust and a pleasure to use, the Hakko FX-888DX, typically priced around €150, is a good option. It uses T18 tips, which are long-lasting and easy to find. The station's interface is very simple, relying on a single rotary control, much like its predecessor, the FX-888, which I personally started with. This is a welcome improvement over the FX-888D, whose button-based interface was less intuitive. The Atten AT-969 is a worthy alternative too. It's quite similar to the Hakko model in design and performance, though it uses T900M tips and costs about a third of the price. Both of these stations follow the traditional design, meaning they do not use cartridge-type tips.

Looking into cartridge systems, the AE970D station, of which you can read my detailed review at [8] and shown in **Figure 5**, is convincing. This station was designed by Atetool (an Atten subsidiary) and has been sold under the Elektor brand name, and is now available from Eleshop. It's simple, not too expensive (around €100), and comfortable to use. At the time of writing, a variety of compatible tips (T80 type) are available in the Elektor store or at Eleshop. However, this family of cartridges is less common than the more widely available T12, C245, or C210 cartridges. Speaking of those, a vast array of Chinese brands offer T12-, C245-, and C210-compatible stations with varying levels of quality, power, and user interface sophistication. Listing them all in this article would be impractical, but for detailed reviews, Steve Gardner's YouTube channel [9] is a great resource.

For those who prefer to support Western manufacturers, the most affordable official C245-based station from JBC is the BT-2BQA (cartridge not included), or -2BWA (one cartridge supplied). However, this model will set you back around €300. Another professional-grade option using cartridges is the PACE ADS200. And for traditional systems with separate heater and tip, it's worth looking into entry-level models from Ersa and Weller as well.

Personally, I recommend owning not just one, but two soldering irons. This can be a huge advantage when desoldering 2-terminal SMD components, as it allows you to heat both sides simultaneously. This technique also works for small ICs with a bit of finesse. For a secondary iron, consider a portable model (**Figure 6**), which can work from almost any USB-C laptop charger or

battery, especially if you ever need to solder outside your workshop during holidays, visits to friends, or even outdoors when paired with a power bank. In this category, I recommend the Fnirsi HS-02A that you can find in various places including the Elektor Store. Like many modern USB-C powered irons, it's compact and versatile. But unlike most, it supports C245 cartridges (official or otherwise), giving you far greater flexibility in choosing tip shapes for a variety of tasks.

For quickly desoldering 2-terminal components when troubleshooting PCB, there's also the matter of heated tweezers. Until recently, they were prohibitively expensive, reserved for industrial users. But they're getting more popular, with models like the Sequire HT140 now available at more accessible prices.

Practicing

There's no substitute for hands-on experience. A classic way for beginners to get started is to train with soldering kits. While older generations remember the classic Velleman kits (which still exist!), today the options have expanded greatly, especially on platforms like AliExpress. All these inexpensive kits are both fun and educational: you get to practice your soldering skills while puzzling out how the circuit actually works. For surface-mount components, specific training kits are also available. Although these aren't always very useful once assembled, they



Figure 6: Two portable soldering irons, ideal as secondary irons. Check particular models as cartridges are not always interchangeable.

Extra Tips & Tricks

- › **Keep your work from slipping:** Use a PCB holder to elevate your work from the bench, improving vision and reducing neck strain. For holding wires and connector pins together before soldering, the Omnifixo tool is excellent. To keep PCBs flat on the bench for hot-air rework, try a Stickwise with Teflon jaw option.
- › **Hold through-hole components steady:** Use Blu-Tack or painter's tape to keep parts in place while soldering. For batch soldering, sandwich components under a soft foam block held in place with a custom-cut MDF board and small clamps.
- › **Temperature doubts?** If your soldering iron feels too hot or too cold despite its display, get an FG-100 tip thermometer, available for around €20 online.
- › **Clean oxidized parts gently:** For pads or leads that don't solder well due to age, try an eraser, possibly for ink (Faber Castell refs. 7057 or 187040 give you flexibility). This works well and is less abrasive than a fiberglass pen, which should be reserved for serious corrosion or solder mask removal.
- › **Desoldering:** Desoldering stations like the ZD-915 or ZD-985 (or variants) are very useful, though prone to clogging. Avoid the ZD-8915, which clogs even more due to a narrower barrel. After each desoldering, hold the trigger for 1s more to fully clear the nozzle. If you need some desoldering braid, I recommend the pre-tinned variant for best results. For removing ICs without hot air, try the SMD1NL low-temperature alloy from Chip Quik, to help lift entire chips with a single soldering iron.
- › **Automated Soldering:** Don't overlook PCB assembly services (PCBA). It might save you a great deal of time if you have multiple boards to assemble. In one of his recent YouTube videos [12], Mike Harrison walks through the process of ordering assembled PCBs from JLCPCB, offering helpful guidance along the way.

do offer a progressive challenge by including resistors and capacitors in decreasing sizes (0805, 0603, 0402, etc.), letting you test your dexterity and limits.

Magnification

With SMD work, or enough time spent soldering through-hole components, your eyes will eventually meet their limits, regardless of age. Magnification is essential, a selection of tools I use is shown in **Figure 7**. However, don't expect miracles from the many electronic microscopes on the market with LCD screens, USB or HDMI outputs. These lack stereoscopic vision, making it difficult to gauge tip height above the PCB, and are best suited for post-soldering inspection. If you plan to solder under magnification on a regular basis, the best is to invest in a proper optical stereo microscope. The ideal magnification varies by user, but you'll find solid recommendations on YouTube channels by popular laptop repair experts like Louis Rossmann and NorthridgeFix. The brand Amscope is generally well regarded.

I haven't yet invested in a stereo microscope myself. Instead, I use a lightweight plastic



Figure 7: Even without a proper optical stereo microscope, these affordable tools are very helpful.

headband magnifier from Edsyn, which I found very convenient, but a bit on the expensive side. I use mostly the 2.5× and 4× lenses. I later discovered an identical model available from RS Components [10]

for under €20, including four lenses with up to 3.5× magnification. Edsyn also offers separate 4×, 5×, and 7× lenses, which are likely compatible with the RS headband if you need higher magnification.

Solder Wire

A good approach is to keep two sizes on hand, one for fine SMD work and the other for regular work with THT components. Personally, I use diameters of 0.46 mm and 0.7 mm, respectively, for those, but you may experiment yourself. In any case, do yourself a favor and don't buy solder from AliExpress. Apart from the shameless scams (like selling "50 g" of solder, with a spool weighing 35 g when empty and fitted with 15 g of solder), you'll never know what you actually get in terms of alloy, flux, etc. — it's a recipe for disappointment. Stick to name brands, such as Loctite, Kester, Stannol, MBO, Cynel, Felder, etc. as shown in **Figure 8**. I recommend solder embedding either "No Clean" or "RMA" flux. "Water Soluble" flux can be tempting, but I found the smell to be much more annoying than the others, and its flux residue must always be removed (with a water-based solution, then); otherwise, it may become conductive or corrosive. On the other hand, if you're not too worried about aesthetics, No Clean and RMA flux residues can be left as-is on the board.

Unplug First!

Never solder on a powered device. This isn't just a safety precaution for yourself, it's also a good way to avoid accidentally damaging the circuit. A soldering tip that bridges multiple pins could short a sensitive node to a power rail or ground, with very unfortunate consequences. Also, ensure your soldering iron tip is connected to earth ground. That way, if you do forget to unplug a device and accidentally touch a live circuit with your iron, the leakage current through the grounded tip will instantly trip your RCD breaker to remind you of this oversight. If the tip is floating (i.e., isolated), you may not notice the first contact with mains thanks to your iron's insulating handle and could receive a dangerous shock when bringing in the solder wire with your other hand.

Cleaning Off Flux Residue

Flux residues are inevitable. If they're black and burnt, your iron is probably too hot. To clean these residues, a few options are shown in **Figure 9**. Isopropyl alcohol is safe



Figure 8: A selection of solder wires and flux.



Figure 9: After flux comes flux removal, which can be harder than anticipated.



Figure 10: The ubiquitous "858D" is great to get started with very little money.

and inexpensive, but not very effective. A 50/50 mix of isopropyl alcohol and acetone improves cleaning power. If you can afford it, a proper flux remover such as Fluxclene is very effective, although it can get costly over time. For stubborn rosin-based residues that have hardened, nitrocellulose-based paint thinner can help. Brake cleaner spray is another option, as its strong jet can dislodge residues stuck under components. Use these last two options with care and precision though, as they can damage plastics (connectors, relays, etc.) or erase markings from components.

Hot-Air Soldering

Hot-air soldering can seem intimidating at first, but it's a powerful technique that opens up possibilities not achievable with a standard iron. Even the most basic hot-air station can perform invaluable tasks, like desoldering and replacing large ICs for repair work. For beginners, the widely available "858D" hot-air station is considered the entry point (**Figure 10**). It comes under countless brands and colors on platforms like AliExpress, Banggood, and eBay, but are virtually identical inside. Choose whichever branding or style you like; they typically cost under €40 including shipping. Then, grab a few discarded PCBs from the trash and start practicing your desoldering and resoldering skills! Apply flux to the chip leads before heating to make the process easier. A good quality gel flux in syringe format, such as the V3 TF from Stirri (Amtech's new name for distribution in Europe) or SMD291 from Chip Quik will make both desoldering and resoldering smoother. As with solder wire, for best results and most importantly, repeatable results, avoid generic or unknown-brand fluxes from AliExpress.

After some practice, you may begin to feel the 858D's limitations. Its airflow is relatively weak, which forces users to crank up the temperature, often burning flux and stressing components. If you find yourself having these problems, you might consider upgrading to a more capable model like the Atten ST-862D or the Quick 861DW, which are similar. The latter is very well known and slightly more polished inside but comes at a higher price. As a side note, whichever



Figure 11: Solder paste and tools to work with hot air.

model you choose, you can also use it to neatly shrink heat-shrink tubing without the risk of burning it.

Hot-air stations are also very useful when assembling new boards from scratch. With a freshly manufactured PCB, a matching stencil (don't forget to include it in your order!) and some solder paste (**Figure 11**), you can place your components manually and reflow them quickly with hot air this way. This saves the hassle of dealing with a reflow oven, which is more expensive and comes with its own set of complexities. For solder paste, I recommend Chip Quik's TS391AX (lead) or TS391SNL (lead-free) which give consistent results and don't require to be stored in the fridge. If you need larger quantities, "M10 183°C" paste from Amaoe (China) [11] is much less expensive and works as well. In any case, make sure to keep them sealed airtight to increase their shelf life. It's best to start by soldering the

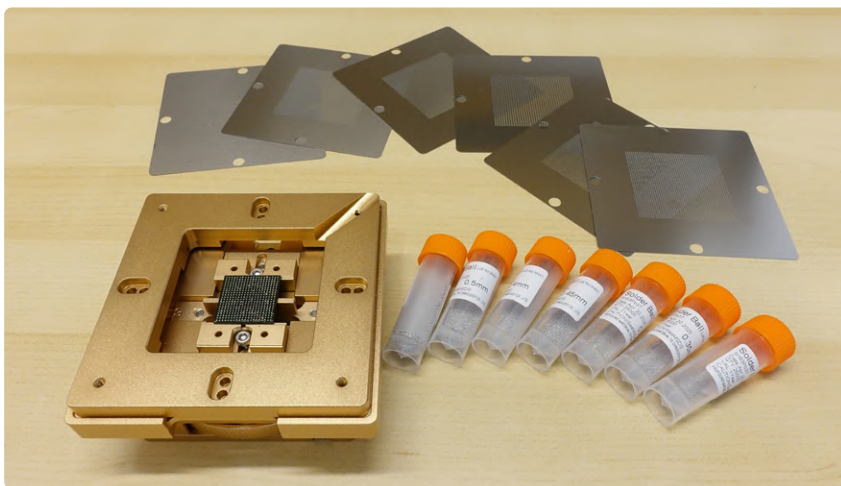


Figure 12: A few tools from AliExpress to practice BGA reballing.

small heat-resistant components with hot air, and solder larger, temperature-sensitive parts (such as connectors) later using an iron. However, whether you're soldering or desoldering, if you need to work on a densely populated area, you can control your working zone using aluminum tape (in some cases, Kapton tape works too) to protect nearby components.

Keep Experimenting!

I hope this article has sparked your curiosity and inspired you to try out new tools or techniques. There's so much to explore in the world of soldering. Personally, I've promised myself to finally experiment with BGA reballing, and I gathered the essential tools: stencil holder, stencils, and an assortment of solder balls (**Figure 12**), but haven't yet carved out the time for proper practice.

Happy soldering! ◀

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Questions or Comments?

Do you have questions or comments about this article? Please contact Elektor at editor@elektor.com.



About the Author

Jean-Francois Simon has a longstanding passion for electronics and enjoys topics as varied as circuit design, test and measurement, prototyping, playing with SDRs, and more. He likes to create, modify and improve his tools and other systems. He has an engineering background and also enjoys mechanics, machining, and all things technical.

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- [12] Mike Harrison, "USBCing all the things," YouTube: <https://www.youtube.com/watch?v=BEIU9LPbaA8>

SimulIDE

An All-in-One Tool for Circuit Prototyping

By Dr. Gamal Labib (Egypt)

SimulIDE is an open-source circuit simulator. It simplifies prototyping circuits of different complexities, ranging from combinational logic to MCU-based. The simulator relieves designers from tracing cluttered breadboard wiring and investing in expensive debugging tools.

SimulIDE is an open-source circuit simulator providing groups of analog and digital components and a set of microcontrollers to build your circuit, a code editor, a debugger, subcircuits, DIP/Logic symbols, circuit

animation, basic shapes, an oscilloscope, a logic analyzer, a serial port connection, and a serial monitor. [1,2] The main structure of the simulator window (see **Figure 1**) is composed of five main areas: the compo-

nent palette (A), the toolbar (B), the circuit canvas (C), the simulator metrics (D), and the message area (E).

Building a circuit prototype is a straightforward task. It starts with a click on the New circuit icon in the toolbar to create an empty canvas and then drag the required components from the component palette into it, using the mouse (see **Figure 2**). Wiring the components comes next with left-clicking the mouse on the source components' pins and dragging the cursor to the destination pins to stretch a wire, and then releasing and clicking the mouse again to finish the wire drawing.

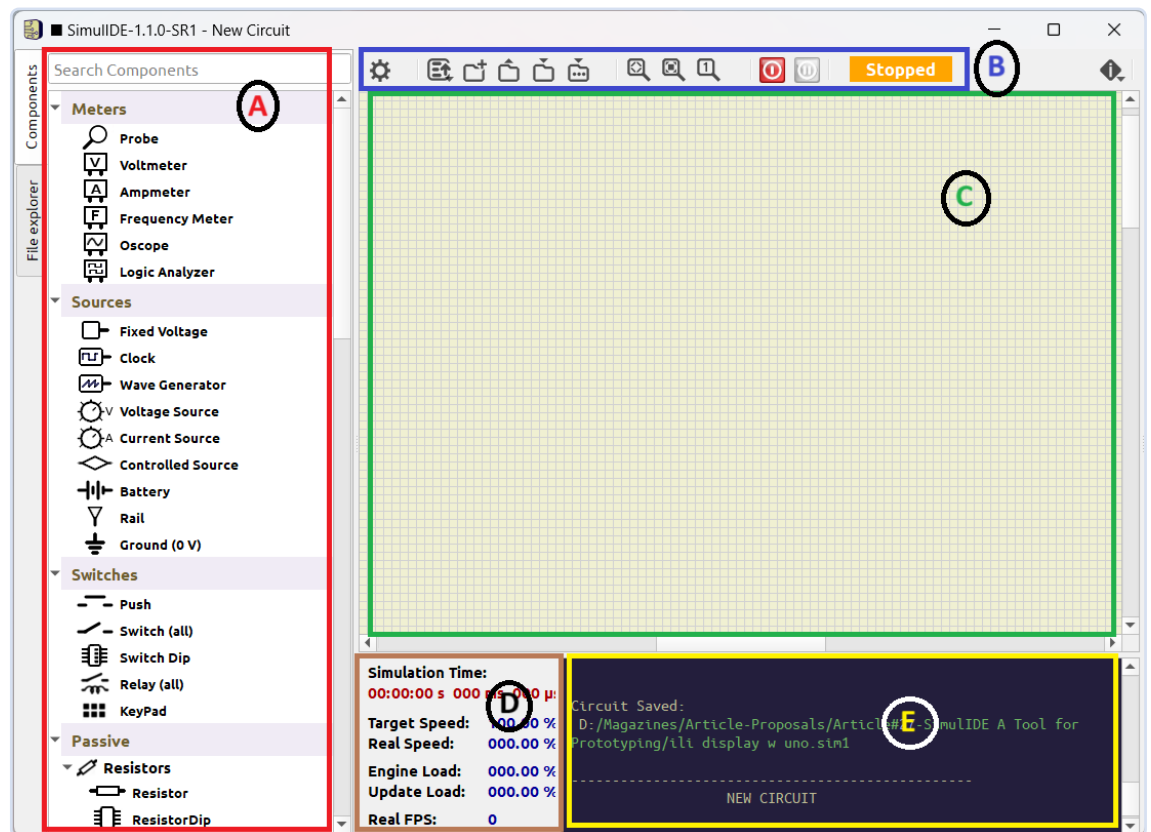


Figure 1:
The SimulIDE GUI is divided into five main areas: A: the component palette, B: tool bar, C: circuit canvas, D: simulator metrics, E: diagnostics messages.

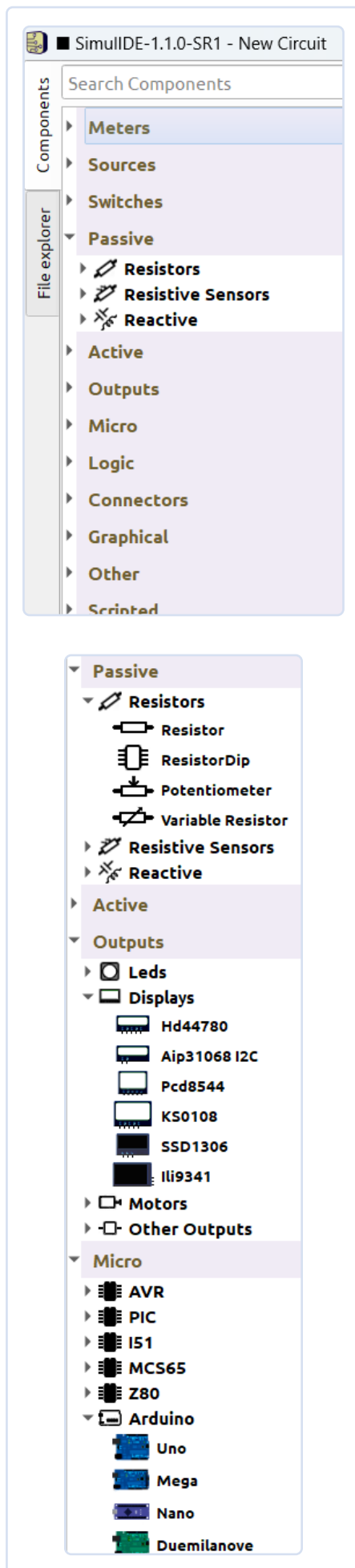


Figure 2: The component palette categories (top), and the expansion of three categories referenced in this article (bottom).

The simulator provides a bunch of debugging versatile tools: a voltage probe, an oscilloscope, a logic analyzer, a set of meters, and a couple of signal generators. It is worth noting that some ICs, which in real life have input pins that can be either left floating or grounded to select an option, are not fully modeled that way in SimulIDE. These pins cannot be left unconnected and thus require fixed voltage feeds instead. SimulIDE simplifies circuit prototyping by adjusting the properties of the components being used. For example, an LED can be set

to *Grounded* instead of wiring them to the *Ground* component. Wiring similar components to buses is simplified, for example for LED bar and resistor DIP components.

SimulIDE supports some Arduino MCU modules into which you can load realistic sketches from Arduino IDE and even launch a serial monitor during simulation run. **Figure 3** illustrates the steps to follow in order to prepare the executable binary and load it into the simulated MCU. In Arduino IDE, the user prepares the

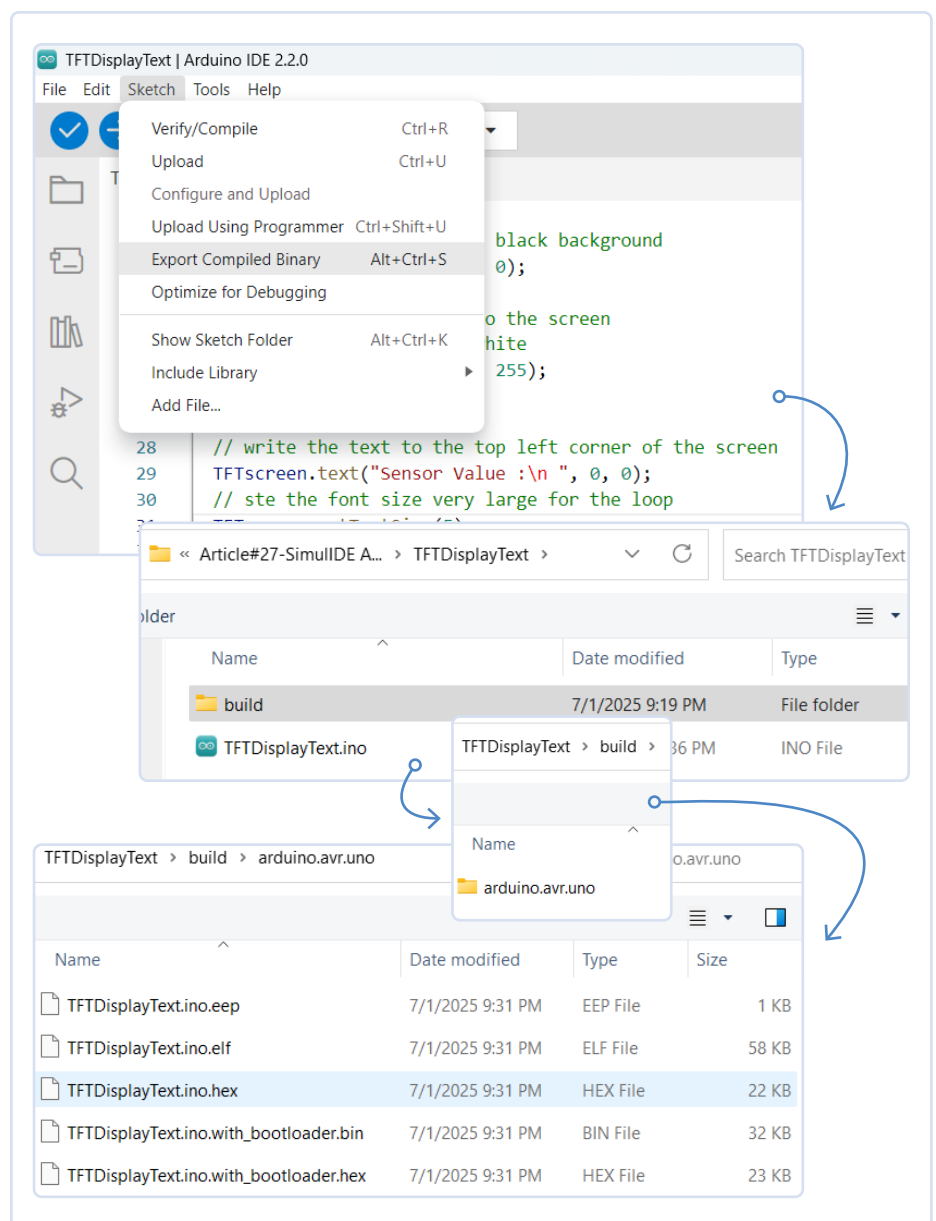


Figure 3: Preparing loadable code of the simulated MCU, in Arduino IDE: exporting compiled binary generates a build folder containing a HEX file to be loaded into SimulIDE.

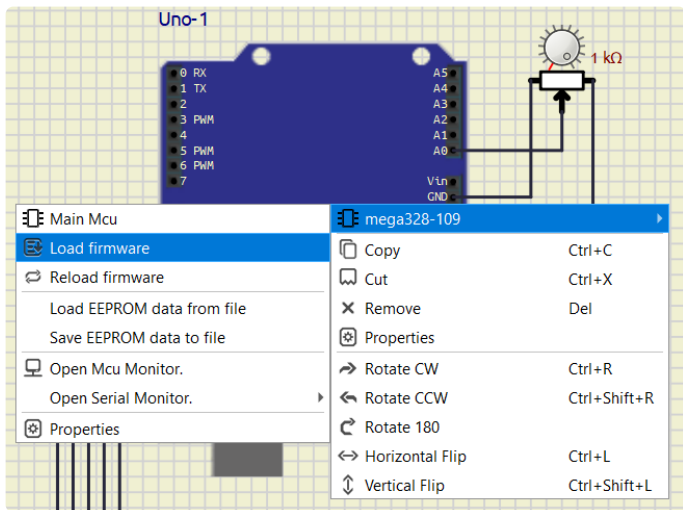


Figure 4: Loading HEX code of the compiled sketch into the simulated MCU by right-clicking on the UNO, selecting mega328-109, and clicking on Load firmware. A file selection pop-up window appears to locate and to choose the HEX file generated by the Arduino IDE.

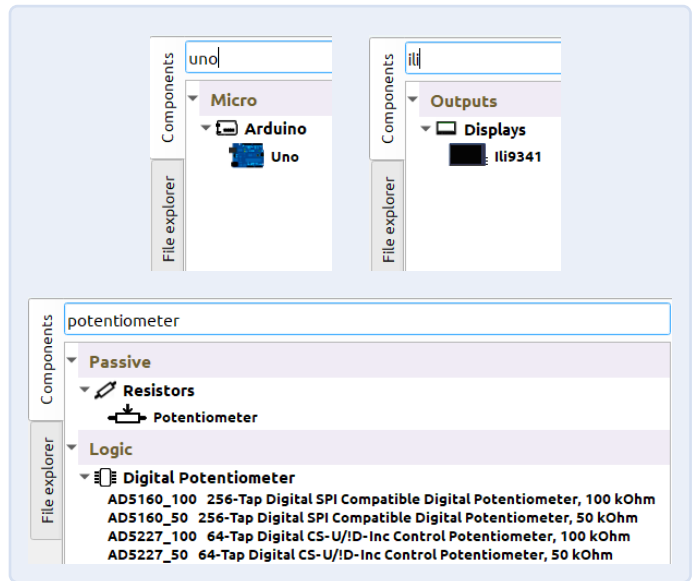


Figure 5: Selecting project components from the palette: the UNO, the ILI9341, and the analog potentiometer.

sketch as usual but rather than compiling and uploading it to the MCU, he/she should choose *Export Compiled Binary* that generates a *build* folder containing the loadable binary and a corresponding HEX file. The Arduino IDE role ends here, and the user moves to the steps of uploading the HEX file into the simulated MCU (see **Figure 4**). Those steps are done within the simulator by right-clicking on the MCU component and choosing *Load Firmware* from the pop-up window. There you will find also the option of starting the *Serial Monitor*.

Clicking on the red button at the top toolbar starts and stops the simulator. During a simulation run, you can start and stop controlled components such as switches, power supplies, and signal generators. By doing this, you can master the operation of your circuit and check it thoroughly.

Examples

SimulIDE provides a wealth of examples demonstrating its capabilities and features. Nevertheless, users accustomed to other integrated development environments such as Arduino IDE might need to see how SimulIDE complements their available tools in prototyping their designs. For that purpose, I chose a couple of projects from Arduino IDE's library examples to implement using SimulIDE and demonstrate the prototype building and the simula-

tion process. The first is *TFTDisplayText* [3] (see **Listing 1**), which reads the analog value generated by a 1-kΩ potentiometer, in the range 0 to 1000, and displays it on an SPI TFT display. The second example, *graphicstest*, is a more complex graphics sketch written for the ILI9488 touch display shield from Adafruit [4] (see **Listing 2**), which demonstrates the graphics and textual capabilities of the display module.

In setting up the simulation circuit, I picked up the UNO MCU board, the analog potentiometer, and I used the only SPI display module available in the component palette, which was the Adafruit ILI9341 [5] (see **Figure 5**). I did the wiring of those components as depicted in **Figure 6** taking into consideration the SPI pins of the UNO and their match in the ILI9341. Clicking on the potentiometer dial and moving the cursor

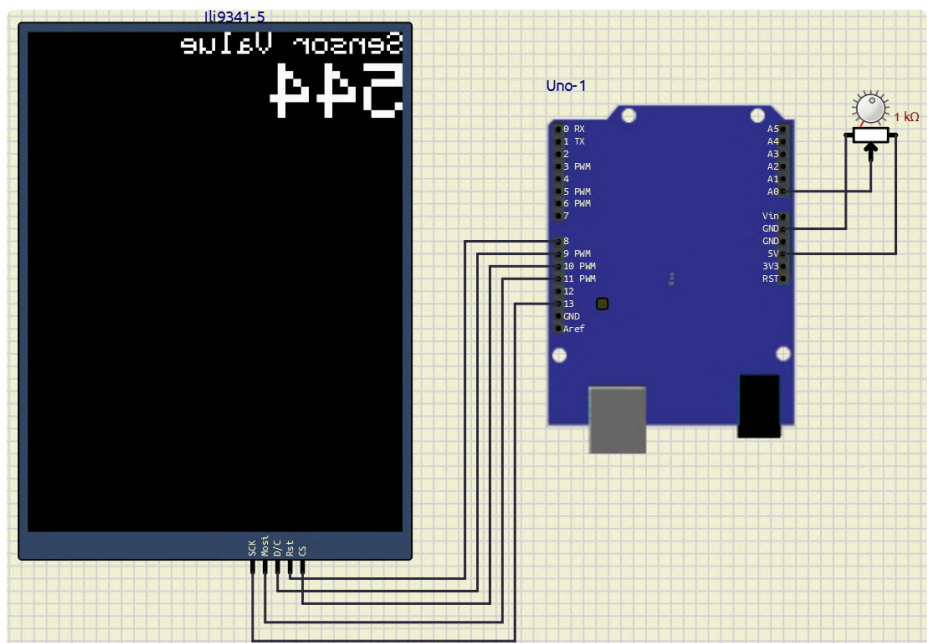


Figure 6: A simple circuit for both TFT projects consisting of an UNO development board, an ILI9341 SPI display, and an analog potentiometer.



Listing 1: The TFTDisplayText project code from Arduino IDE examples.

```
#include <TFT.h> // Arduino LCD library
#include <SPI.h>

// pin definition for the Uno
#define cs 10
#define dc 9
#define rst 8

// create an instance of the library
TFT TFTscreen = TFT(cs, dc, rst);

// char array to print to the screen
char sensorPrintout[4];

void setup() {
  // Put this line at the beginning of every sketch that uses the GLCD:
  TFTscreen.begin();

  // clear the screen with a black background
  TFTscreen.background(0, 0, 0);

  // write the static text to the screen
  // set the font color to white
  TFTscreen.stroke(255, 255, 255);
  // set the font size
  TFTscreen.setTextSize(2);
  // write the text to the top left corner of the screen
  TFTscreen.text("Sensor Value :\n ", 0, 0);
  // set the font size very large for the loop
  TFTscreen.setTextSize(5);
}

void loop() {
  // Read the value of the sensor on A0
  String sensorVal = String(analogRead(A0));

  // convert the reading to a char array
  sensorVal.toCharArray(sensorPrintout, 4);

  // set the font color
  TFTscreen.stroke(255, 255, 255);
  // print the sensor value
  TFTscreen.text(sensorPrintout, 0, 20);
  // wait for a moment
  delay(250);
  // erase the text you just wrote
  TFTscreen.stroke(0, 0, 0);
  TFTscreen.text(sensorPrintout, 0, 20);
}
```

around the potentiometer dial changes the measured resistance and its value instantly shows on the display. Amazingly, the display module worked fine with both examples despite the use of different TFT display libraries: the `<TFT.h>` in the text example, and the `<Adafruit_GFX.h>` with `<ILI9341.h>` in the graphics example. At first, the display appeared flipped and mirrored. I reached out for the pop-up configuration window of the ILI9341 and chose *Horizontal flip* to correct the display orientation (see **Figure 7**).

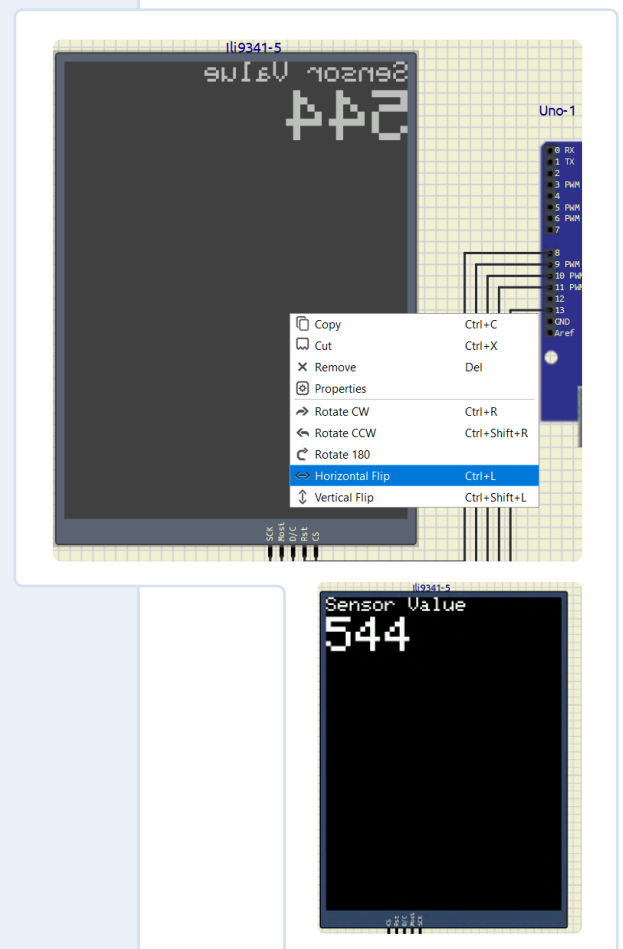


Figure 7: Running the TFTDisplayText code; as result you get a flipped display (top). The ILI9341 configuration pop-up menu provides controls for the direction of display (instead of using TFT control commands). I used Horizontal flip to correct the display orientation (bottom).



Listing 2: The graphicstest project code from Arduino IDE examples.

```
#include "SPI.h"
#include <Adafruit_GFX.h>
#include <ILI9488.h>

#define TFT_CS      10
#define TFT_DC      9
#define TFT_RST     8

// Use hardware SPI (on Uno, #13, #12, #11) and the above for CS/DC
ILI9488 tft = ILI9488(TFT_CS, TFT_DC, TFT_RST);

void setup() {
  Serial.begin(9600);
  Serial.println("ILI9488 Test!");

  tft.begin();

  // read diagnostics (optional but can help debug problems)
  uint8_t x = tft.readcommand8(ILI9488_RDMODE);
  Serial.print("Display Power Mode: 0x"); Serial.println(x, HEX);
  x = tft.readcommand8(ILI9488_RDMADCTL);
  Serial.print("MADCTL Mode: 0x"); Serial.println(x, HEX);
  x = tft.readcommand8(ILI9488_RDPIXFmt);
  Serial.print("Pixel Format: 0x"); Serial.println(x, HEX);
  x = tft.readcommand8(ILI9488_RDIMGFMT);
  Serial.print("Image Format: 0x"); Serial.println(x, HEX);
  x = tft.readcommand8(ILI9488_RDSELDIAG);
  Serial.print("Self Diagnostic: 0x"); Serial.println(x, HEX);

  Serial.println(F("Benchmark                Time (microseconds)"));

  Serial.print(F("Screen fill                "));
  Serial.println(testFillScreen());
  delay(500);

  Serial.print(F("Text                      "));
  Serial.println(testText());
  delay(3000);

  Serial.print(F("Lines                     "));
  Serial.println(testLines(ILI9488_CYAN));
  delay(500);

  ...

  Serial.println(F("Done!"));
}

void loop(void) {
  for(uint8_t rotation=0; rotation<4; rotation++) {
    tft.setRotation(rotation);
    testText();
    delay(1000);
  }
}
```

The *graphicstest* executable code was loaded into the simulated UNO following similar steps of the first example. Its code runs autonomously without user intervention; the program displays preset text of different sizes and colors and shows dynamic graphics patterns of different shapes and colors (see **Figure 8**).

Simulation Is Fun!

SimulIDE offers a dynamic and accessible platform for learning and experimenting with electronics. Its intuitive interface and seamless integration with Arduino IDE make it an excellent choice for electronics enthusiasts of all levels. By simulating circuits in a virtual environment, users can explore and understand components without needing physical hardware. This is not only practical but also an enjoyable way to learn. The interactive nature of SimulIDE fosters deeper understanding and sparks creativity. I hope this brief introduction encourages you to explore simulation for your next projects! Of course, there are other good simulators available. Notable options include Wokwi, a browser-based simulator for Arduino and ESP32 projects, and Tinkercad. I recommend you try all of them and decide for yourself which one works best for you. ◀

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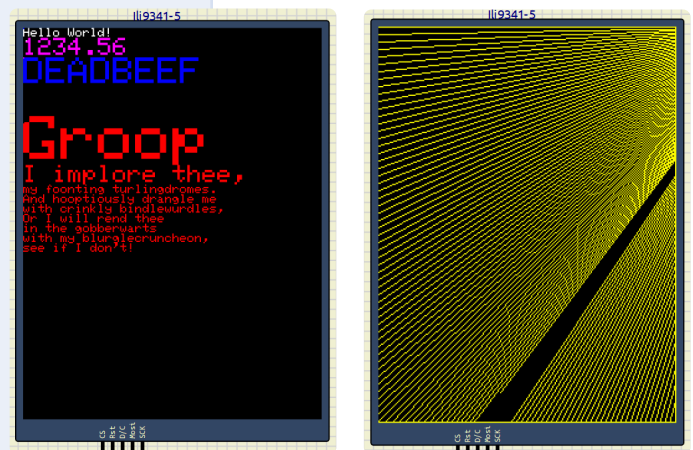


Figure 8: Snapshots from the simulation run of the project *graphicstest* with corrected screen orientation.



About the Author

Gamal Labib has been an enthusiast of embedded systems for two decades and is currently a mentor (at codementor.io). He holds an MEng and a PhD in IT. Besides writing for technical magazines, he is a visiting associate professor at Egyptian universities and a certified IT consultant.

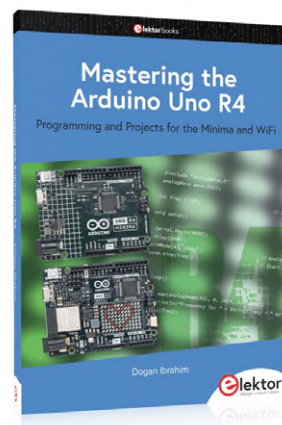
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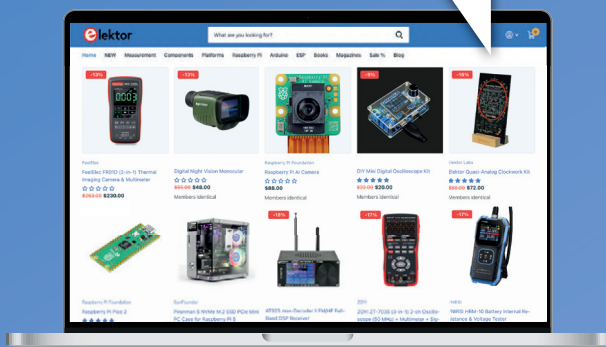
➤ Dogan Ibrahim, *Mastering the Arduino Uno R4* (Elektor, 2023)
www.elektor.com/20619



WEB LINKS

- [1] SimulIDE: <https://simulide.com/p/>
- [2] SimulIDE, Launchpad: <https://launchpad.net/simulide>
- [3] TFTDisplayText example sketch, Arduino: <https://docs.arduino.cc/retired/library-examples/tft-library/TFTDisplayText/>
- [4] Adafruit 2.8" TFT Touch Shield for Arduino: <https://www.adafruit.com/product/1651>
- [5] Ilitek ILI9341, Adafruit: <https://cdn-shop.adafruit.com/datasheets/ILI9341.pdf>

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2025: An AI Odyssey

From Autocomplete to Colleague

By Brian Tristam Williams (Elektor)

Generative AI started out like an autocomplete on steroids. Now, with reasoning models such as OpenAI's o3, machines work step by step, much like engineers do. This installment looks at how that shift changes debugging, design, and everyday problem-solving.

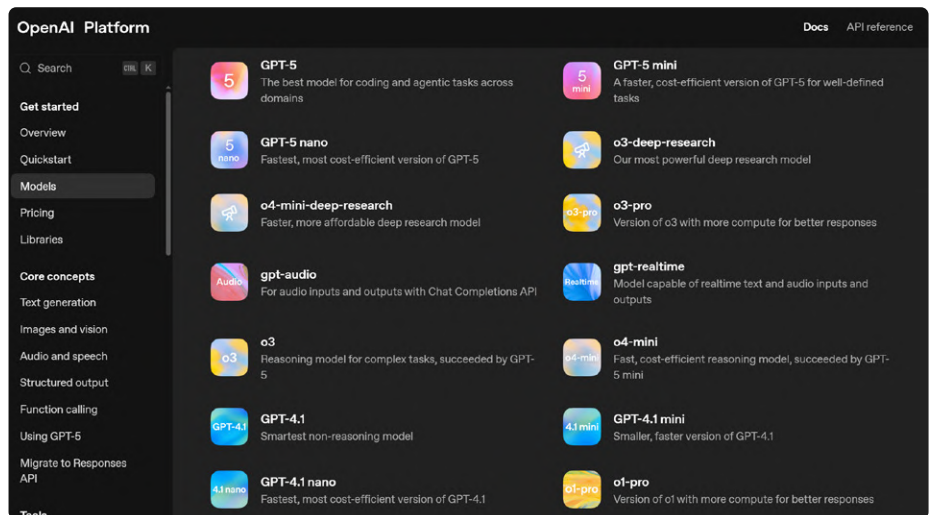


Figure 1: OpenAI's o3 model sits snugly within the almost 60 other models on offer. Source: [2].

For a while now, generative AI has felt like a very clever — but very impatient — colleague. You ask a question, and it spits out the most statistically likely answer, often a list of shotgun-style guesses. It's impressive, sure, but it's a parlor trick, not genuine thought. The real story of late is not just about more data or layers. Rather, the market is working very hard on *reasoning*.

In the previous installment of this column, I made some basic reasoning comparisons between different models. The one I'm testing, OpenAI's o3, works differently. It doesn't just blurt out an answer, but rather takes its time, reasoning step-by-step, much like an engineer at a bench methodically checking voltages and probing a circuit.

For those of us who spend our days solving real-world technical problems, that difference is tangible.

I was testing for some time, when OpenAI quietly revoked access to o3 on their Plus subscription, taking the cost of access from \$20 a month to their \$200 a month Pro plan.

Googling proved it wasn't my imagination [1]. I wanted to swim a bit deeper with the "smartest reasoning model for complex tasks," but without breaking the bank.

\$200 per month is a pretty penny above the \$20 Plus plan that I'm on. Fortunately, there's a workaround — the OpenAI Platform's API, which I have been trying out. There is a cost to using the API, but it's on a pay-as-you-go model that turns out much cheaper for early testing.

Aside from o3, the "models" page [2] lists some 55 other models — everything from GPT-5 to text-to-speech, speech-to-text, image generation, deep research, etc (**Figure 1**). It is a veritable rabbit hole that could keep you busy for at least a weekend.



Source : Adobe Stock

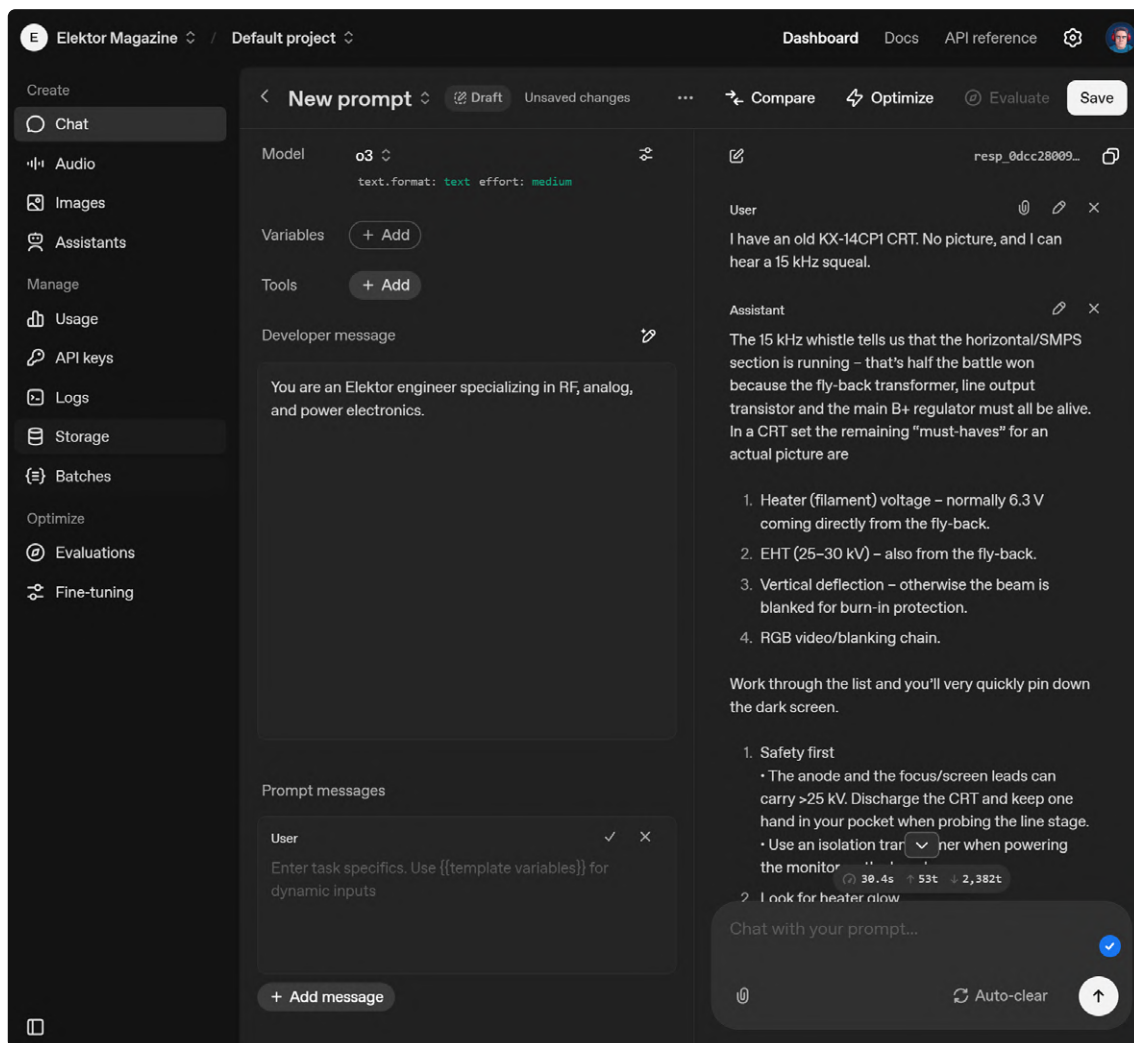


Figure 2: I posed o3 a question about a broken CRT monitor and got a very thorough response.

The Autocomplete Era

Think back just a couple of years. When you asked an older model why a microcontroller wasn't responding, you got a list of perfectly sensible but unordered guesses:

- > "Check the power rail."
- > "Replace the crystal."
- > "Look for shorts."

These responses often felt like the brainstorming of a distracted colleague: a pile of possibilities with little sense of order. You were still left to apply your own systematic thinking to figure out which guess mattered.

Reasoning

Now, contrast that with a reasoning model such as o3. Instead of guesswork, you get a process:

- > "First, confirm that your 3.3 V rail is stable under load."
- > "Next, verify that the clock source is within tolerance by checking the oscillator spec."
- > "If both are sound, measure reset line behavior during power-up to rule out brownout resets."
- > "Only after those checks should we move on to firmware or timing-level analysis."

Instead of autocomplete, we now have a process. It mirrors exactly how experienced engineers work: Break the problem into parts, verify the basics, then dig deeper. See an example problem I posed in **Figure 2**.

This isn't confined to simple electronics problems. Benchmarks tell the same story. On research-level mathematics problems, where earlier models managed 2% success

at best, o3 reached over 25% [3]. That's still far from human expert level, but it shows we've moved beyond sophisticated memorization into something resembling methodical reasoning.

It should be noted that this benchmark improvement, while impressive, came with some caveats that weren't initially disclosed. The *FrontierMath* benchmark consists of problems across three difficulty tiers, from olympiad-level to problems that would challenge expert mathematicians for weeks. The 25% headline figure didn't specify which tiers o3 solved, and OpenAI had exclusive early access to the problem set during development. Still, the fundamental shift toward systematic reasoning remains clear, even if the headline numbers require more skeptical and careful interpretation.



Figure 3: "Come with me if you want to solve that phantom ground loop." Source: Urbanscape/Adobe Stock.

A Junior Engineer Who Never Tires

An analogy I enjoy is to think of o3 as the keenest junior engineer you've ever worked with. They explain every step. And, like the Terminator (**Figure 3**), they don't get bored. They don't lose track. They may not always be correct — you still need to validate on the scope or in SPICE — but they prevent you from chasing shadows.

Always showing their working is a very valuable trait. That transparency transforms AI from a black-box answer machine into something more like a teaching partner. You don't just get the "what," you see the "why."

Practical Payoffs

For electronics engineers, this new class of AI opens especially useful doors. It moves beyond simple information retrieval and into active, co-creative problem-solving.

> Circuit analysis partnership:

Instead of just spitting out a schematic, reasoning models engage in a dialogue. For example, describe a power-supply target — say, a 5 V, 2 A buck converter for a portable device — and the model can walk you through the design process. It can explain why a specific topology fits your requirements,

calculate thermal constraints, and analyze efficiency trade-offs with rationale at every step. It's a true co-design session that can help you understand the "why" behind component choices and topology decisions.

- > **Debugging assistant:** This is where the systematic reasoning truly shines. Instead of a generic "check your wiring," it builds a full diagnostic tree. For a non-responsive device, it might start by saying, "Since the device powers on but doesn't respond, we can eliminate a dead short or a supply fault. Next, let's examine the communication protocol layer..." It behaves like an engineer who asks the right questions to systematically narrow down a fault, preventing you from wasting time.
- > **Component selection:** Reasoning models don't just pull part numbers from a spec sheet. They can weigh a multitude of real-world engineering constraints simultaneously — environment, cost, and supply chain availability. Ask about op-amps for a precision measurement circuit, and you'll get not just part numbers but explanations of why offset voltage matters more than bandwidth for your specific application, guiding you to a more informed decision.

- > **Firmware development:** Programming assistance shifts from mere auto-completion to genuine collaboration. When you describe an algorithm, the model explains the trade-offs in its design and architectural choices. It's the difference between getting a working function and understanding why a particular approach, such as using a state machine for a complex protocol, works best for your specific timing and memory constraints.

Not Instant, But Thorough

There is a catch: speed. While the old models gave you answers relatively quickly, o3 sometimes spends 30 seconds or more thinking through a problem like a chess opponent without a timer. For rapid-fire questions about pin assignments or quick sanity checks, this feels sluggish. But that's often exactly what you want for the hard problems. When debugging a twitchy PCB or deciding on a regulator topology, thorough beats instant every time.

Because I'm testing the API in bare-bones JavaScript that spits out ugly plaintext, my project doesn't currently have any way of seeing any progress while o3 thinks. The request is submitted to the API via https, and then I just have to wait, not knowing if something has crashed or if we're on the right path, watching the *Network* tab in Google Chrome's Developer Tools to see that "pending" request turn into a "200 OK" status code.

That trade-off — time for depth — may frustrate those accustomed to rapid-fire AI responses, but it is precisely why reasoning models feel useful in engineering. Designing a power stage or analyzing an intermittent failure is less about instant gratification and more about methodical elimination of errors.

Fortunately, no one has to use my project's ugly JavaScript/HTML interface. There is the *Playground* [4]. You will still have to pay to play, though.

From Answers to Education

Perhaps the most exciting part is how transparent the reasoning is. Instead of presenting



About the Author

Brian Tristam Williams has been fascinated with computers and electronics since he got his first “microcomputer” at age 10. His journey with Elektor Magazine began when he bought his first issue at 16, and since then, he’s been following the world of electronics and computers, constantly exploring and learning. He started working at Elektor in 2010, and nowadays, he’s keen on keeping up with the newest trends in tech, particularly focusing on AI and single-board computers such as Raspberry Pi.

a polished answer, the AI shows intermediate steps. That transforms it into a teaching tool: You don’t just get the “what,” you see the “how.”

Imagine learning RF design. A traditional AI might present formulas and final values. A reasoning model will walk you through the derivation, explain why certain approximations matter, and adapt its explanation to your level of background knowledge. It is like having a tutor who spots gaps in your understanding and adjusts in real time.

For hobbyists and students, this lowers barriers dramatically. The “Illustrated Primer” analogy I drew from Neal Stephenson’s *Diamond Age* over a year ago [5] feels more real than ever. Except now, the book doesn’t just tell stories — it reasons with you.

Where This Leaves Us

Last year, I was tinkering with TensorFlow Lite on a Raspberry Pi, struggling to get object detection to behave reliably [6]. By the end of the year, I was reflecting on how AI had crept into PCB design, firmware automation, and chip layout [7]. Earlier this year, I wrote about “vibe coding” and how AI was starting to generate whole applications from natural language prompts [8].

Now, we’re standing at another threshold: models that don’t just predict but actually reason. That shift — from autocomplete to colleague — may turn out to be the most transformative leap yet.

It doesn’t mean we can pack away our multimeters and soldering irons. But it does mean we have, for the first time, AI tools that think the way we do. That’s a game-changer worth paying attention to.

Overall, we’re not just getting better answers anymore, but better thinking. For engineers who live in a world of systematic problem-solving, that’s the difference between a tool and a partner. And, by the time you read this, things will have moved on again — this business is a moving target. Place your bets! ◀

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Questions or Comments?

Have you tried reasoning models in your own electronics work? Did they save you from a dead end or send you down one? I’d love to hear your experiences. Write to me at brian.williams@elektor.com or find me on X @briantw.



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WEB LINKS

- [1] X user @Sveta0971 annoyed at OpenAI’s fiddling with the subscription models: <https://x.com/Sveta0971/status/1961525873452204444>
- [2] OpenAI Developer Platform: <https://platform.openai.com/docs/models>
- [3] Some lessons from the OpenAI-FrontierMath debacle, LessWrong.com: <https://tinyurl.com/lesswrongfm>
- [4] API Playground — o3, OpenAI: <https://platform.openai.com/chat/edit?models=o3>
- [5] B.T. Williams, “2024: An AI Odyssey — It’s Not Letting Up,” Elektor Magazine 01-02/2024: <https://elektormagazine.com/magazine/elektor-324/62632>
- [6] B.T. Williams, “2024: An AI Odyssey — Getting Object Detection Up and Running,” Elektor 05-06/2024: <https://elektormagazine.com/magazine/elektor-341/62897>
- [7] B.T. Williams, “2024: An AI Odyssey — A Look Back at the Future,” Elektor 11-12/2024: <https://elektormagazine.com/magazine/elektor-358/63346>
- [8] B.T. Williams, “2025: An AI Odyssey — The Transformative Impact on Software Development,” Elektor 05-06/2025: <https://elektormagazine.com/magazine/elektor-425/63839>

Wordy Christmas Tree

A Festive Electronics Project with a Linguistic Twist



By Clemens Valens (Elektor)

This year's Elektor Christmas gadget brings together blinking lights, multilingual cheer, and a healthy dose of PCB ingenuity. Say hello to the Wordy Christmas Tree — a charming, LED-lit creation that speaks seven languages (silently, mind you) and just might become the most eloquent decoration on your workbench.

Each year, as Christmas approaches, the good people at Elektor set about the cheerful but increasingly tricky business of creating a new festive project. It's no small challenge, mind you. Nearly every Christmas-themed gadget one might imagine seems to have been done already: trees, baubles, snowmen, snowy cottages, Santas, elves, reindeer, angels,

stars... the lot. Some flash merrily with colourful LEDs, others chime away with carols, and quite a few do both at once. All of which makes coming up with something truly original rather a tall order.

So, it may not come as a great surprise that this year's Elektor Christmas gadget isn't revolutionary. That said, it does introduce a fresh little twist, and it comes as a well-designed kit — just the thing for an electronics enthusiast or a keen maker looking for a festive project to tinker with over the holidays.

It's... a Tree!

But enough of the preamble, time to lift the veil on this year's festive creation: a Christmas tree adorned with a respectable array of colourful LEDs. Now, before you roll your eyes and mutter something about déjà vu, do give us a moment as we believe we've managed to sneak in a novel twist.

You see, this particular tree doesn't merely flash its lights about randomly, as is so often the case. Instead, it puts its LEDs to more refined use, subtly illuminating Christmas greetings in no fewer than seven languages, each one neatly milled into the tree itself. And, perhaps most welcome of all, it does so in dignified silence. Not a jingle, not a chirp.

We've taken to calling it the Wordy Christmas Tree, and while the name may raise an eyebrow, the heart of the contraption is reassuringly solid: a Raspberry Pi Pico module that orchestrates the whole affair, commanding 27 addressable RGB LEDs with quiet precision.

A Fully Three-Dimensional Undertaking

The Wordy Christmas Tree is no mere flat PCB with a splash of green soldermask and a few twinkly bits hastily soldered on. Oh no! It's a fully three-dimensional undertaking, built with the sort of structural ambition that would make an architect pause thoughtfully and nod.

Rather than relying on a single circuit board, this festive contraption is assembled from no fewer than eleven PCBs. The base board, home to the Raspberry Pi Pico and the gateway for power, forms the foundation (**Figure 1**). From there, things get positively architectural: a rear panel in the shape of a



Figure 1: The addressable RGB LEDs of the Wordy Christmas Tree are controlled by a Raspberry Pi Pico board.



Christmas tree, a matching front panel, and a clever framework of small interconnecting boards between them. These side pieces serve as both the physical frame and the mounting spots for the addressable RGB LEDs.

Seven Languages

It's the front panel, though, where things get particularly festive. Milled into its surface are Christmas greetings in seven languages: Danish, Dutch, English, French, German, Italian, and Spanish (in alphabetical order) (**Figure 2**). The original plan included Arabic and Chinese as well, but, alas, those scripts proved rather too intricate for the available milling technique.

Inside, a set of eight "bone" boards forms the internal skeleton. These act as partitions, separating each word of each greeting into its own private compartment (**Figure 3**). Once the front panel is in place, it functions as a tidy cover, and the result is a tree in which each word is illuminated independently thanks to its own dedicated LEDs (long words have three, shorter words get by with one). It's a neat bit of engineering, and, if we may say so, rather a handsome display.

Now, one might be forgiven for assuming that building a Christmas tree of this sort would be a quick jaunt. A few LEDs here, a Raspberry Pi Pico there, job done. But alas, reality proved to be rather more fiddly than that.

Extreme PCB Milling

One of the first hurdles to present itself was the matter of engraving the multilingual greet-

ings into the front panel. Selecting the phrases was the easy part; the real challenge was getting them properly into the outline milling layer of the PCB. We employed KiCad for the design, a splendid tool for placing footprints, routing tracks, and suchlike, though admittedly not blessed with the flair of an artistic sketchpad. And since KiCad doesn't come with a font fit for milling, we found ourselves drawing each letter by hand, using arcs and straight segments, all while adhering to the milling specifications of our PCB manufacturer. Letters with enclosed areas (your 'a's, 'b's, and 'o's) needed especially delicate handling, lest their middles drop out and make a mockery of our message.

The Prototype

In its first incarnation, the Wordy Christmas Tree had its LEDs mounted on the rear panel, each one shining bravely behind a word. The skeletal frame inside the tree merely provided structural support, with no electronic duties to speak of. While technically functional, the result was rather harsh on the eyes: LEDs glaring out like searchlights whenever one dared to admire the thing up close. What's more, longer words (such as "Weihnachten" and "Kerstfeest") looked a bit underlit with just one LED apiece.

Thus followed Version Two: this time, the LEDs were affixed to the skeleton frame itself, providing a more flattering top-down illumination. A marked improvement, both in appearance and temperament.

Structural Improvements

We might have stopped there, but the mechanical design still left something to be desired. The original frame relied on soldering the skeletal boards directly to the rear panel and to each other. This was simple in theory, but rather fiddly in the heat of assembly. And so, further refinements were made. Mounting tabs were added to the skeleton boards, and the rear panel received matching slots. This small change had a rather large impact, making the whole structure easier to align and assemble.

As a final flourish, we decided to move the bulk of the circuitry onto the skeleton itself, and we added more LEDs. Only the ground plane now remains on the rear panel. The result is a rather elegant self-contained LED frame, which, should the mood take you, can be detached and paired with custom-designed front and rear panels of your own choosing (and material).

The schematic of the Wordy Christmas Tree is shown in **Figure 4** (see next page). It shows how a string of addressable RGB LEDs (spread out over multiple PCBs) is driven from a Raspberry Pi Pico board, placed on the base board.

And Then There Was Software

Having gone over the nuts, bolts, and milled panels of the Wordy Christmas Tree in some detail, we now shift our gaze to the inner workings, the software, without which the whole thing would amount to little more than a static festive sculpture.

At the heart of the operation lies a Raspberry Pi Pico, selected not only for its agreeable price tag and tidy proportions, but also for its compatibility with the well-loved Arduino development environment. Much credit here goes to Earle Philhower's excellent board support package, which makes getting started with the Pico a positively civilised experience.

As for the LEDs, due to the unpredictable winds of component sourcing, we've steered away from the familiar WS2812 (a.k.a. NeoPixel) variety and instead employed RGB devices from Dialight. Happily, these are fully compliant with the WS2812 data protocol,



Figure 2: Seasonal greetings in seven languages are milled in the front panel.



Figure 3: Each word has its own compartment lit by its own LED(s).

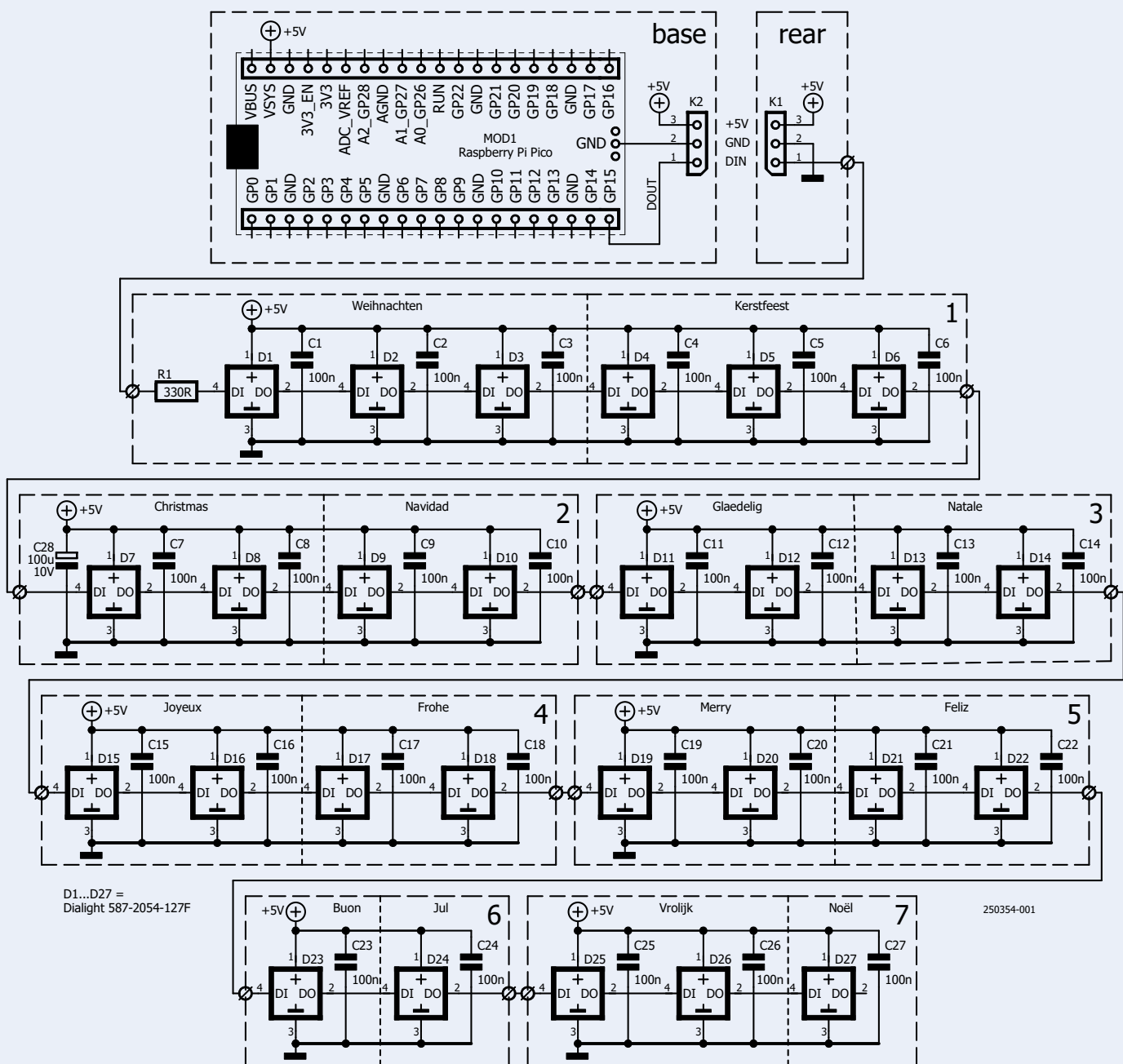


Figure 4: The circuit of the Wordy Christmas Tree is spread out over 10 of the 11 PCBs that make up the tree. If you count well, you'll see only nine here. That's because the front panel (PCB 11) has no components or wiring and therefore is not part of the schematic. The connections drawn here between the boards run over the spine board, PCB 10.

so our tree gets along splendidly with the standard *Adafruit_NeoPixel* library. Once installed in the Arduino IDE, LED control becomes an absolute breeze.

Display Handling

Of course, creating attractive glow effects for our multilingual greetings does require a modicum of programming effort. Our

approach treats the LEDs much like a miniature graphical display: instead of writing directly to each LED, we work with a display buffer in memory. This buffer is periodically copied to the LEDs, decoupling the drawing process from the updating process, a neat and tidy solution. Modifying the buffer lets us conjure up all manner of delightful lighting effects with ease.

While each LED can be addressed individually, allowing for quite intricate effects particularly for longer words that have multiple LEDs, we've opted for simplicity and grouped the LEDs per word. All greetings on the tree consist of two words, so we've given the animation a natural flow: first the initial word fades in, followed by the second. After a brief pause, the first word gently fades away,

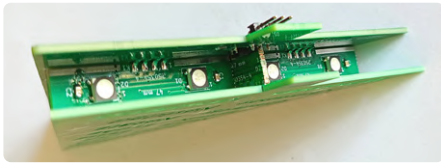


Figure 5: Light is allowed to flow out of the sides of the tree (real trees don't, but this tree has sides).

and the second follows soon after. Colours are selected at random for each word, and fade and hold times are entirely customisable, should one feel inclined to tinker. The greetings are shown in a fixed order, but this too is entirely under your control, if desired.

It's also worth noting that the tree is open on the sides (Figure 5), providing scope for more dramatic running or fading effects around the contours. A nice touch, if we may say so.

A brief word on colour theory and practicalities: since the tree is constructed from green PCBs, it follows that green light is the most efficiently reflected. Furthermore, the human eye is most sensitive to yellow-green light (around 555 nm), meaning that to achieve a balanced brightness, red and blue LEDs must be driven at higher levels than green. A small technical footnote, but one with real visual impact (Figure 6).

Finally, a word of warning: illuminating all 27 LEDs at full white intensity is not only a fast track to temporary snow blindness but also results in significant current draw. Each LED channel draws up to about 15 mA, which quickly adds up. A 5-V power supply capable of delivering at least 1.5 A is therefore strongly recommended to keep the whole affair running smoothly and without incident.

Merry Christmas!

And there you have it — the Wordy Christmas Tree, a festive fusion of multilingual goodwill, tasteful illumination, and thoughtful engineering. It may not sing, dance, or dispense sherry (yet), but it does what a good Christmas



Component List

Resistors

R1 = 330 Ω (0805)

Capacitors

C1...C27 = 100 nF (0805)

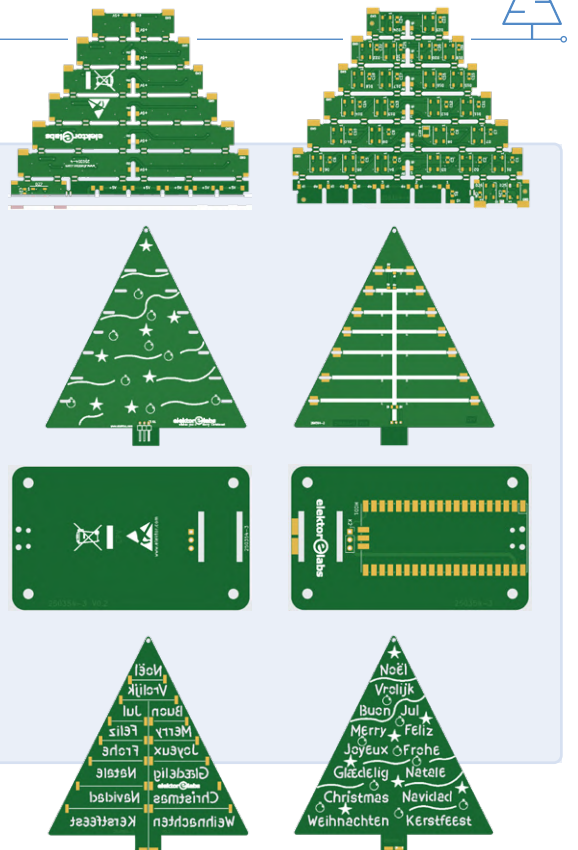
C28 = 100 μ F, 10 V (Kemet B)

Semiconductors

D1...D27 = Dialight 587-2054-127F (5050 PLCC-4)

Miscellaneous

K1 = 3-way pin header,
2.54 mm pitch, horizontal
K2 = 3-way pin socket,
2.54 mm pitch, vertical
MOD1 = Raspberry Pi Pico



gadget ought to: it brings a smile, invites a bit of tinkering, and glows merrily without making a fuss. Whether you're a seasoned electronics enthusiast or simply someone who appreciates a project with a bit of heart and sparkle, we daresay this tree has something to offer. At the very least, it will look rather splendid on your workbench — and isn't that what Christmas is all about?

Of course, the source code and other support files for this project can be downloaded from [1].

250354-01



Figure 6: Green light clearly is most efficient.

Questions or Comments?

Do you have technical questions or comments about his article? Email the author at clemens.valens@elektor.com or contact Elektor at editor@elektor.com.

About the Author

After a career in marine and industrial electronics, Clemens Valens started working for Elektor in 2008 as editor-in-chief of Elektor France. He has held different positions since and currently is a member of the product development department. His main interests include signal processing and sound generation.



Related Product

> Clemens Valens, *From Rubbing Amber to Swiping Glass* (Elektor, 2025)
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WEB LINK

[1] Project's page on Elektor Labs: <https://www.elektormagazine.com/labs/wordy-christmas-tree>

Err-electronics

Corrections, Updates, and Readers' Letters

Compiled by Jean-François Simon and Roberto Armani (Elektor)

High-Speed Probe

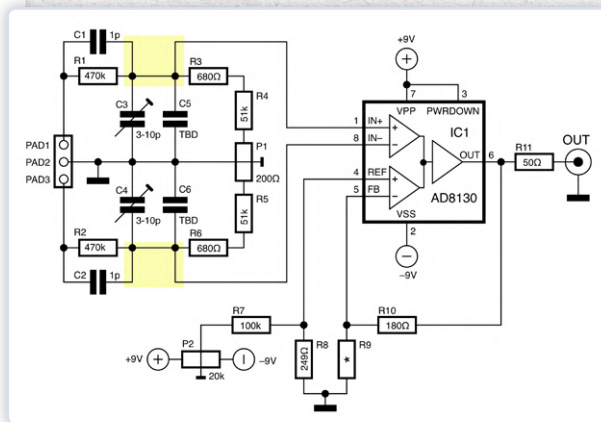
Elektor 9-10/2025, p. 36 (250270)

In the September/October 2025 issue, there is an error in the circuit diagram of the High-Speed Probe on page 36 (Figure 1). The inputs Pad1 and Pad3 are not connected to the inputs of the AD8130. As shown, Pad1 and Pad3 are only connected to Pad2 via a capacitive series connection.

Volker Schulze (Germany)

Thank you for your email. As you correctly reported, the schematic published on that printed page was not in its final version, and the connections were missing (see yellow highlighted in the corrected part of the schematic). We've changed this for the online downloadable versions of the magazine and apologize to our readers for the inconvenience.

Roberto Armani (Elektor)



Meshtastic: A Demo Project

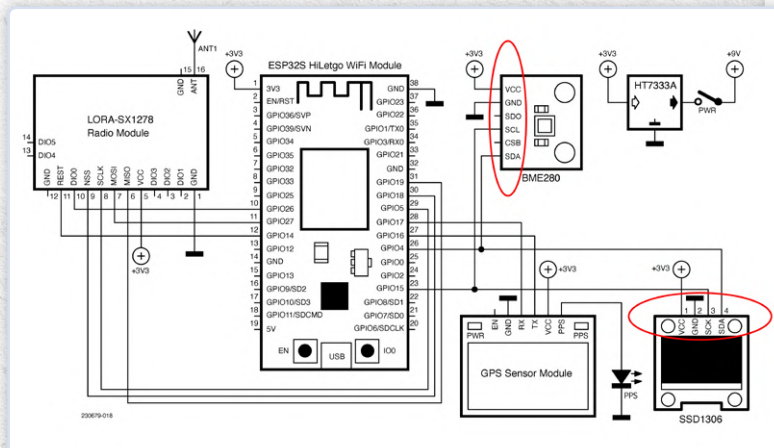
Elektor 7-8/2025, p. 102 (230679)

I am interested in building the Meshtastic Demo Project. However, when I look at the wiring shown for the BME280 in the schematic on page 103, Figure 4, it seems this is not correct. I think the correct connections should be BME280 SCL to GPIO 15 (same as SSD1306 display SCL) & BME280 SDA to GPIO 4 (same as SSD1306 display SDA).

David Williams (Australia)

Thank you for bringing this issue to our attention. The published diagram does indeed contain an error in the pinout of the BME280. In the attached image, the areas highlighted by the ellipses show the correct definitions and links to be made for the circuit to function properly.

Roberto Armani (Elektor)

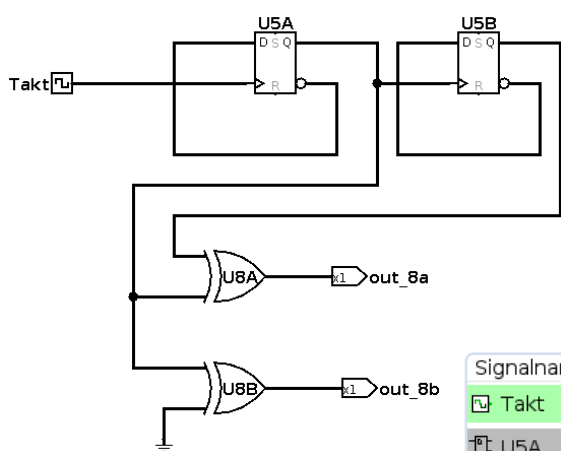




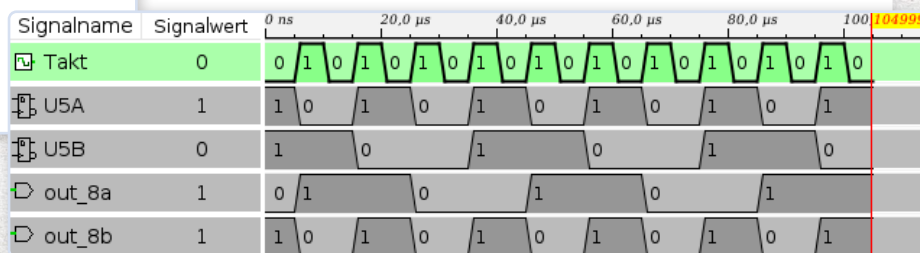
Contact-Free E-Field Measurements (1)

Elektor 7-8/2025, p. 28 (240279)

I cannot quite grasp the generation of the reference signals shifted by 90°. The circuit and the corresponding timing diagram are shown in my drawings, considering ideal components and assuming that in the original circuit /R and /S are positive. Here you can see that the outputs of U5B and XOR gate U8A are shifted by 90°, but the outputs of the two XOR gates are not. If one feeds the output signal instead of the input signal of U5B into XOR U8B, then one apparently has two signals shifted by 90°. The problem, however, arises at the output signal of XOR U8A, namely at the positive edge of the output U5A, which is the clock for U5B. Considering propagation delays, the output of U5B only changes after T_{pd} , which results in a negative or positive "spike" of length T_{pd} in the output signal of XOR U8A.



Source: Jack Aarts



That is, at 90° of the signal a negative dip occurs, and at 270° a positive bump. Is my view correct, or am I overlooking something?

Jack Aarts (Germany)

Thank you very much for your interest! When designing this circuit portion, I did not pay further attention to the fast range (a few tens of nanoseconds) and instead implemented the simplest (idealized) solution using available components. This is justified here, since the resulting signals are subsequently processed only in analog, integrating circuit components. As the typical times of the integrated signals lie in the millisecond range (1e-3 s) and any possible "glitches" caused by digital delays are below 100 ns (1e-7 s), the maximum possible error is on the order of 1:10000, which is clearly below the generally expected or targeted accuracy of the entire setup. Practical measurements with my quick-and-dirty solution show no impairments. I hope this clarifies the reasons for the simple circuit design! You are of course right that for other applications, a more precise consideration/correction of the gate delays would be necessary.

Michael Monkenbusch (author of the article)



Stand-Alone Crystal Tester

Elektor 5-6/2025, p. 72 (240048)

In case someone needs a 3D-printed enclosure (including the lid on top), instead of buying the Hammond (or other bigger) case, I recently designed a perfect fitting box for the PCB, with the holes for the standoffs. It is even lower than the other enclosures, and printed in about 3.5 hours on my old but trusty Ender 5 Pro printer (with firmware upgraded to Marlin). You can find the corresponding RAR file on a comment with my nickname "Alectronic" on the project's page at Elektor Labs: www.elektormagazine.com/labs/stand-alone-crystal-tester.

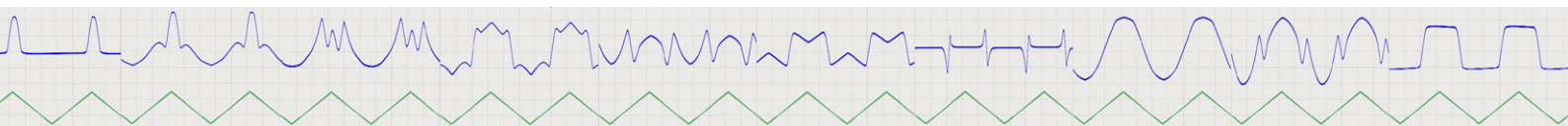
Albert van Bemmelen (The Netherlands)

Ideas or Feedback?
Got a bright idea or valuable feedback for Elektor? Reach out to us at editor@elektor.com. We're eager to hear from you!

250650-01

Analog Pipeline Distortion

A Cool Audio Effect For Guitars and Other Instruments



By Raymond Schouten (The Netherlands)

This versatile project provides flexible and dynamic signal distortion as a sound effect for synthesizers and guitars. A chain of saturating amplifiers with switchable summation allows for many kinds of overdrive curves. A low-frequency modulator creates dynamically changing distortion. With a fully optimized design, the PCB works as an operative panel with knobs and switches, having other components at the back.

The concept behind this project is to connect several identical amplifier stages in cascade. An increasing input signal will first saturate the last amp, then the amp before that, and so on. Now, if you take the output of each amplifier and send this to an adjustable output summing circuit, you can create all kinds of overload behavior. You can see/hear this in YouTube demo movies at [1] and [2].

Concept Implementation

To prevent getting a too complex user interface, I simplified things a bit, as visible in the first version of the panel layout shown in **Figure 1**. Four amplifiers are used, and each one of them has a 3-position switch that allows the user to add-ignore-subtract the signal from it. In this design, whose fully implemented (final) version is shown in **Figure 2**, you could also use 100 kΩ potentiometers instead of these switches if you want more adjustment possibilities.

Circuit Diagram

To keep things simple and the project affordable, for the main part of this circuit I used a single chip (less than €1) that hosts six ampli-

fiers: the hex CMOS inverter CD4049UB by Texas Instruments [3], where *UB* stands for *unbuffered version*.

These six unbuffered logic gates are actually high-gain inverting amplifiers that can very well be used for analog purposes. This chip is widely available and active in production, even

in DIL-package. Adding negative feedback using resistors sets the gain of each amplifier. Cascading then four of these stages gives a circuit (the pipeline) where an increasing input level sequentially saturates: Amp 4 (U1D), then Amp 4 and Amp 3 (U1C), Amp 4, Amp 3 and Amp 2 (U1B), and finally all the four stages, Amp 4 to Amp 1 (U1A).

The gain of Amp 1 — being the input gain — is made variable with P1, whilst the gain of Amps 2,3,4 was chosen to be fixed (3.3 V/V, 10 dB). To allow both addition and subtraction of these four amp signals, each amp stage can be routed via a summing analog inverter (U1E) or can be directly sent to the overall summing amp, the output variable-gain stage (U1F).

The whole circuit runs best on a supply voltage of 4 V...5 V and draws only a few milliamps, so it is feasible to use a battery supply.

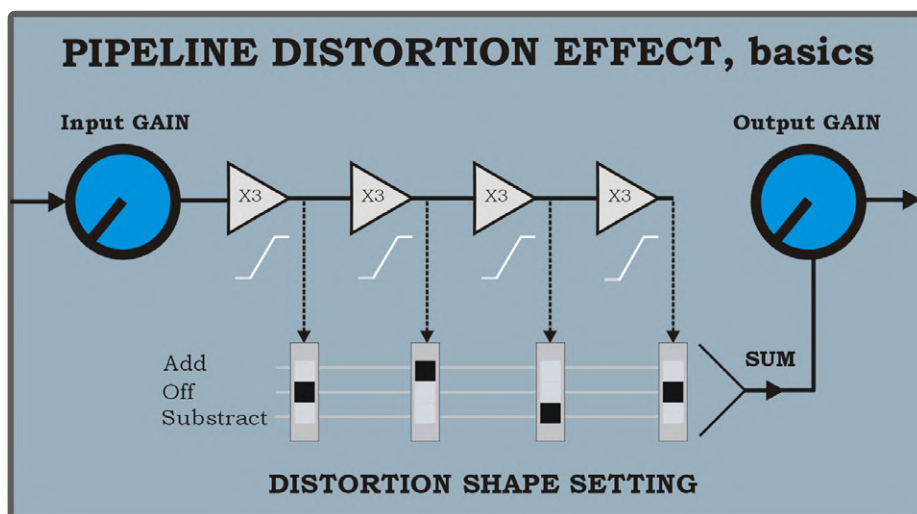


Figure 1: The first, simplified version of the panel for the Analog Pipeline Distortion.

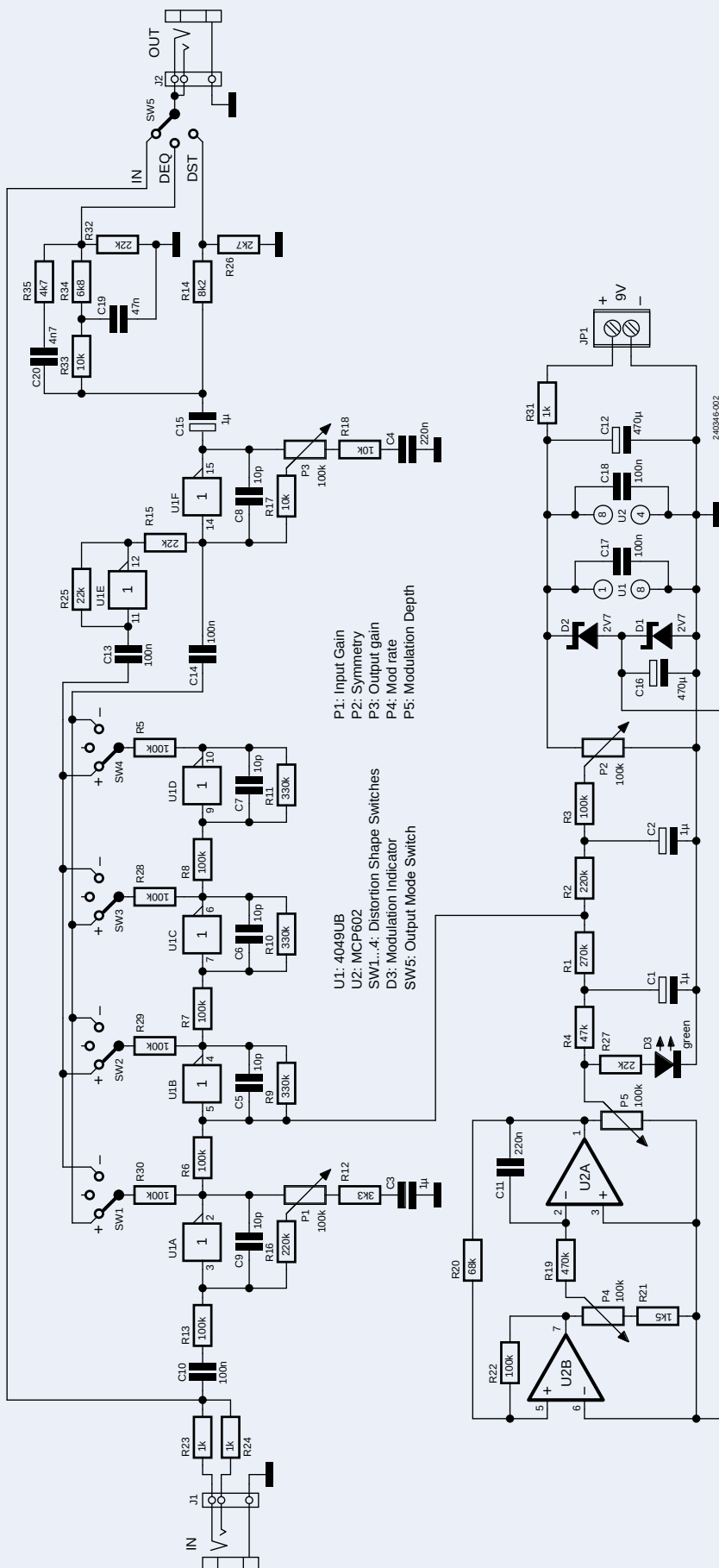


Figure 2: Schematic diagram of the fully implemented version of this design.

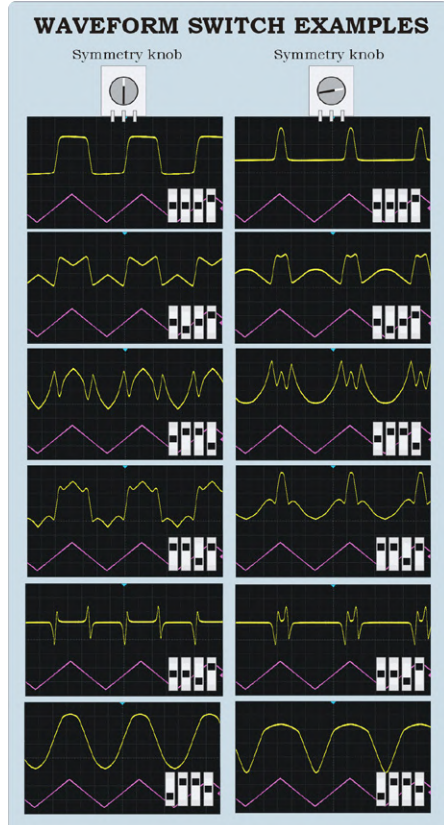


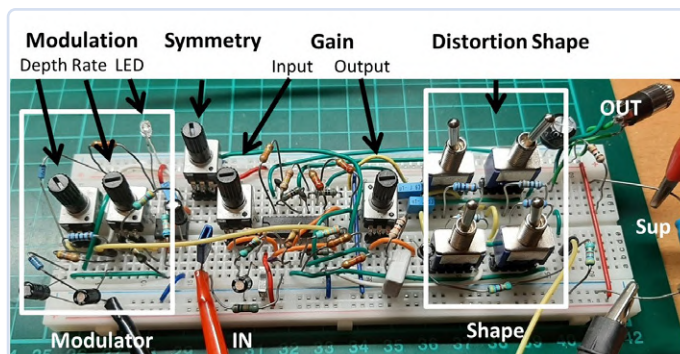
Figure 3: Effect on waveforms of the various setup of SW1...SW4 control switches.

Circuit Add-Ons

If saturation occurs symmetrically, you create odd harmonics, so a potentiometer labelled *Symmetry* has been added that allows the user to also tune in asymmetrically, thereby having more even harmonics. The potentiometer P2 signal is smoothed by the RC filter R3-C2. The effects of that manual setting, for the various setup of SW1...SW4 switches, is shown in **Figure 3**.

To make the effect more lively, a low-frequency oscillator (LFO) is added that can slowly sweep the symmetry setting. The LFO has a *Modulation Depth* and a *Mod Rate* potentiometer, the resulting modulation signal is made visible with a LED. This LFO add-on to the main circuit has been realized through U2, a MCP602 dual CMOS opamp by Microchip (see the bottom-left part of the circuit diagram of Figure 2). In this section, U2A is a classic integrating stage, while U2B acts as a non-inverting comparator. The combination of the two outputs a triangle wave at pin 1 of U2A, which is smoothed by the RC filter made by R4-C1. The triangle wave signal and the manual setting via P2 are summed up via resistors R1-R2.

Figure 4: The first version of the prototype, wired on a breadboard.



Using a 3-position switch for *In/Bypass* or *Distortion* selection, I decided to make the 3rd position *Distortion and Equaliser* (DEQ), adding a simple fixed bass and treble boost filter, through the RC network made by C19, C20 and R32...R35 on the top-right of the circuit diagram.

PCB

The first version of the prototype was built on a breadboard, as shown in **Figure 4**. Afterward, I decided to implement the whole project in a compact and less noise-sensitive layout, designing a compact PCB, shown in **Figure 5**, and housing it in a metallic box (**Figure 6**).

For the PCB version, I connected two 2.7-V Zener diodes D1 and D2 in series via a 1-k Ω resistor to a 9 V DC input source. Doing so, I've created both 5-V supply and 2.5-V mid-rail reference voltage. The total circuit has been built as a small (10 $\times$ 5 cm) stand-

alone effects unit for connecting to my (also home-built) synthesizers.

All the downloadable materials (in a quite comprehensive set) for this project are available at the respective Elektor Labs webpages of the author at [4] and [5]. [◀](#)

240346-01

Questions or Comments?

Do you have technical questions or comments about this article? You may contact the editorial team of Elektor at editor@elektor.com.

About the Author

Aside from his daytime job developing low-noise instrumentation electronics, Raymond Schouten runs hobby projects designing tiny music synthesizers and other compact circuits. Most of his designs aim to achieve maximum results with the simplest hardware. He is also frequent in posting projects on Elektor Labs, YouTube, and on his personal website at rs-etc.nl.



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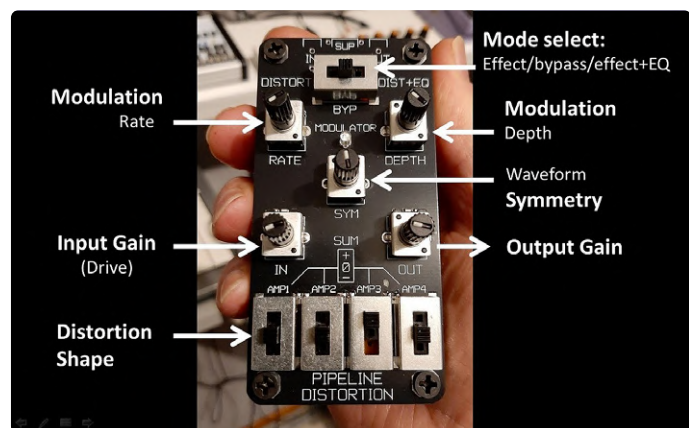


Figure 5: The compact, handy PCB of the final version of this design.

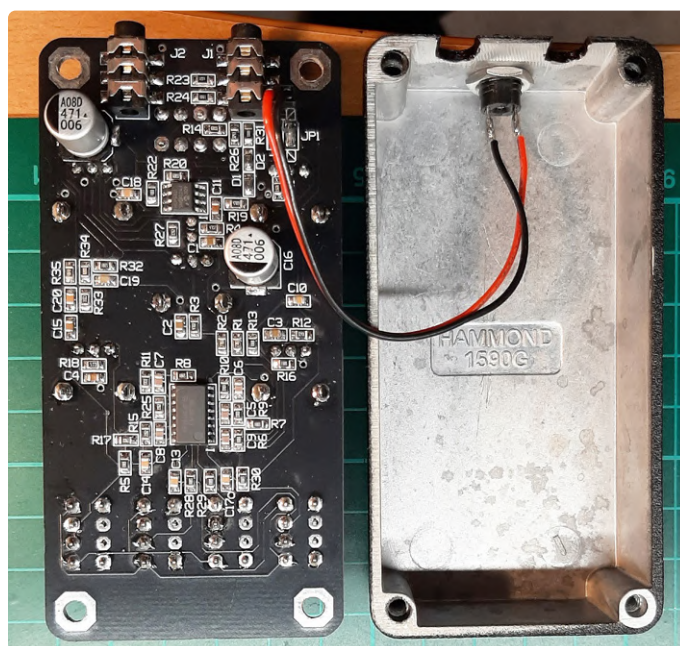


Figure 6: Back view of the PCB, with all the components fitted. Its shape fits perfectly the Hammond 1590 G aluminum housing, that has shielding capabilities, too.

WEB LINKS

- [1] YouTube demo video for this project: Basics: <https://youtu.be/f3LLInagCY>
- [2] YouTube demo video for this project: Build: <https://youtu.be/wRkLFAZR-kE>
- [3] CD4049UB datasheet, Texas Instruments: <https://www.ti.com/lit/ds/symlink/cd4049ub.pdf>
- [4] Analog audio FX: Pipeline Distortion (basics) on Elektor Labs: <https://tinyurl.com/47k45vur>
- [5] Analog audio FX: Pipeline Distortion (build) on Elektor Labs: <https://tinyurl.com/25au8kxw>

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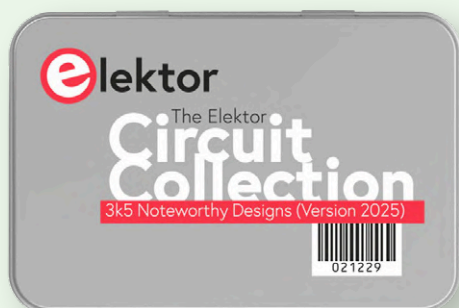


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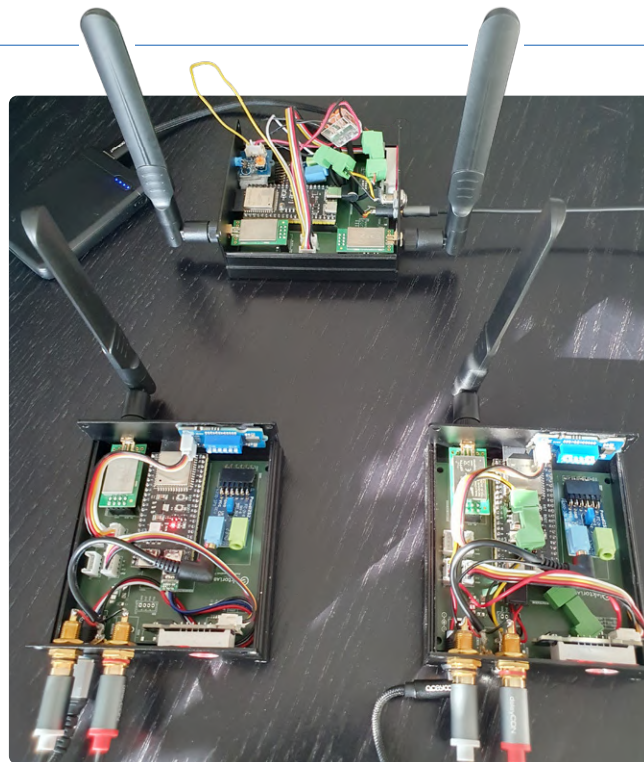
Stereo Transmission and Dual Radio

By Jens Nickel (Elektor)

In the second part of this series, we realized the digital wireless transmission of audio, but the data rate of the prototype was only usable for a mono signal. In this article, a higher data rate allows stereo transmission. Additionally, we present a working solution to enhance the robustness against interferences — two radio modules connected to the same microcontroller and clever software on the receiver side.

In the previous part of this series [1], I reported extensively on the background, the development, and the software of a digital wireless audio transmission line. As for hardware, I was using two audio transceiver boards, equipped with an ESP32, an nRF24 radio module, and an I2S-DAC/ADC module (see part 1 [2]). A large share of the article was filled with issues, which everyone developing such a transmission line will face. That goes from latency summing up over the different stages, limitations of data rates, issues with timing leading to crackling or ringing sounds, to interferences by other radio sources and even people moving around. Finally, if you use two independent receivers to play the left and right audio channels, even a slight timing mismatch between them can distort the stereo image.

In this article, I present an implementation that helps to solve most of the problems. Instead of a transmission line for 32 kSamples/s with 16 bit and mono, we will have one with 32 kSamples/s, 16 bit and stereo (with only one transmitter and receiver). Additionally, bringing in a second transmitter and a second radio module at the receiver side, we will have a much better reliability and immunity against other



radio sources. All this is possible with stable timing and the ultra low latency of around 5 ms, as we have already seen in the second part of this series. Everyone building two transmitters and one “dual radio” receiver can now have a good and reliable consumer-grade stereo transmission line in order to transmit audio in the studio, in a flat, or even in a whole house to some stereo speaker system (**Figure 1**). So, for most of your applications, the presented hard- and software in this article should be good to go.

Wanted: The Perfect Sync

Ironically, the application that let me stumble into this project is still not yet perfectly covered. Also, with a stereo transmission, if you want to equip a left and a right speaker with an independent receiver each, you will have timing differences, which are most likely due to slight differences in the crystal clock frequency of the ESP32 controllers on both sides. This leads to a drift in timing, which is — interestingly — not audible. But every other minute, there could be a jump of around 100 μ s, and these jumps occur, of course, differently at your “left” and “right” receiver, which can be perceived as a stereo panorama shift.

I am currently investigating this and also possible solutions, but I am not sure if I will be able to solve it perfectly at the end. At least, I was able to transmit 48 kSamples/s (better than CD quality) in mono, and I had 8 bytes left to transmit a timestamp from the transmitter, so I could detect the drifts and sudden jumps.

With the latest version of the Espressif I2S driver, available in the Arduino IDE with the latest board package, there comes a `i2s_channel_tune_rate()` function to tune the I2S clock. This could be quite helpful, but first, I would have to port the software to this latest driver. All in all, I will have enough material for another article in one of the next issues!

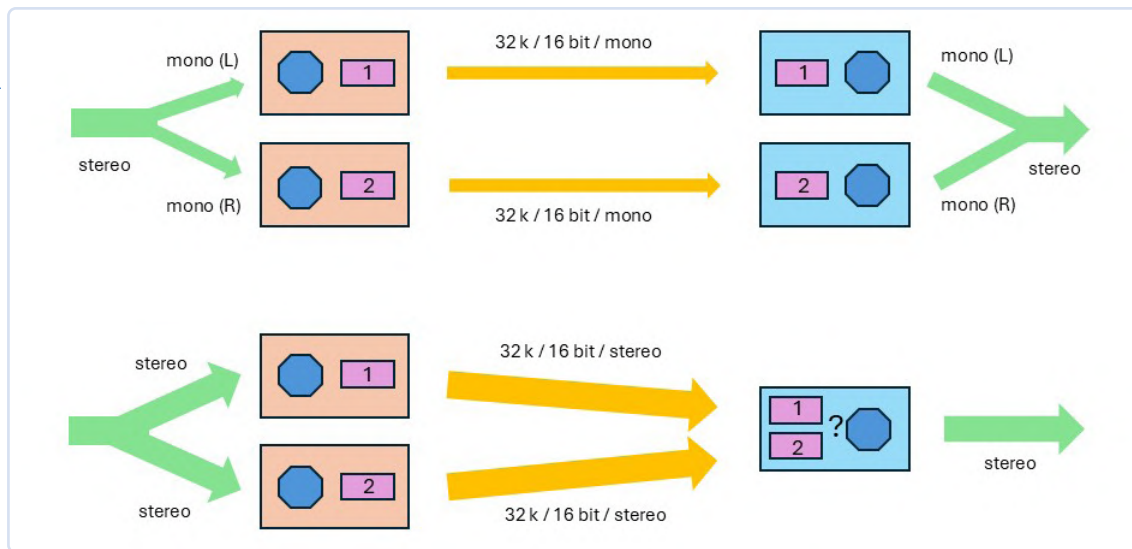


Figure 1: Comparison of the transmission lines for part 2 (top) and this part of the series (bottom). As you can see, we have still two pairs of radio modules (pink) communicating in one direction, and the pairs must be separated by two different radio channels. However, as we are now transmitting stereo signals, we just have to build one receiver for stereo output, and furthermore, the connection is much more reliable because of the redundancy of the data. On the other hand, you can clearly see that the receiving microcontroller (blue octagon) faces now four times more packets arriving than before.

Higher Data Rate

I already mentioned it in the last article: Instead of around 500 kbit/s as for the tested mono transmission line, with the help of the good *RF24* library [3], I could also achieve 1 Mbit/s, which is then half of the maximum nominal data rate of the nRF24. TMRh20, the creator of the *RF24* library, had implemented a special `writeFast()` function for streaming applications. This offers the option to transmit 32 kSamples/s, with 16 bit, in stereo. However, as the maximum packet size for the proprietary Nordic radio protocol [4] remains the same (32 bytes), you can still transport only 16 samples (i.e., 8 stereo frames) in one packet. That means we have a new packet frequency of now 4000 packets instead of 2000 packets per second, and a packet period of about 250 μ s, which leads to new challenges. To get it stable, without a singing sound occurring after a certain time period, I had to enhance the number of buffers on the receiver side from 2 to 4; but on the other hand, I was able to reduce the length of the buffers from 32 to 16. So, at the end, I could “save” the ultra low latency of around 5 ms.

Even Higher Data Rates?

It goes without saying that I also tried to transmit 44.1 kHz and even 48 kHz in 16-bit stereo but I failed to get it stable, even after enlarging the SPI frequency for communication between the ESP32 and the nRF24 module. In my eyes there is a certain practical limit of about 50% of the highest nominal data rate (which means about 1 Mbit/s practically).

When doing some research with my colleague Saad Imtiaz for 5 GHz (instead of 2.4 GHz) radio modules, the specs often offered double nominal data rates (4 Mbit instead of 2 Mbit/s). And interestingly, I discovered indeed some wireless transmission audio equipment with 5 GHz radio transmission, offering up to 64 kSamples/s and 16 bit in stereo. That would be again a practical data rate which is half of the nominal data rate. Unfortunately, 5 GHz radio chips and modules which can be purchased in small quantities are very rare and exotic up to now — and I am not even speaking about solder- and maker-friendly ones.

Dual Radio

The reliability of the transmission line which I reported on in the last article is usable; but especially moving human bodies directly in front of the receiving antenna can lead to lost packets, which is clearly audible. I already thought on mounting my transmitters and receivers to the ceiling, or on stands in the field and such things. However, one guy of the (obviously not so big) community of audio transmission tinkerers had mentioned in some forum that he was able to attach two nRF24 modules at his microcontroller, listening on two different radio channels; and let the receiver software decide which packet came through. That raised my interest, and one evening, I set myself the goal to come at least to the point that I could control two of the radio modules with one and the same ESP32-S3. The S3 has more than one SPI interface, but connecting two nRF24 at two different SPI interfaces was not successful. So I turned to the way my colleague Saad had already used on the Audio Transceiver PCB, in that case for the nRF24 and the SD card socket. Both share the same MISO, MOSI and SCK lines, but with two different CS lines the ESP32 can decide which device it wants to talk too. I extended this with two different CE lines, which the nRF24 modules additionally need for proper communication, too. It worked, but I needed some hours, after which I could properly activate both nRF24 modules right after another.

Now, I could indeed receive packets from two different transmitters on two different radio channels, with one and the same receiver. At a data rate of 500 kbit (32 kSamples/s, 16 bit, mono) I was able to query all the samples of all the data packets from both radio modules right after another. When you have access to the music samples coming from two transmitters, you are able to detect if both are working, and even if a cinch cable is disconnected, or the like. However, at a data rate of 1 Mbit (32 kSamples/s, 16 bit, stereo), “looking” into all the 8000 data packets per second arriving from two different transmitters was not possible anymore. If I did, the music sounded distorted. After some experiments, I could retrieve at least three-quarters of all the 256 kBytes/s coming in, but that brings not much for now (and there may be even issues when you cannot read out all the bytes of one packet).

Seamless Switching

However, to establish a reliable dual radio connection, getting access to all the samples is not needed. At the beginning of my loop, I just query if both radio modules got a packet. If the first radio module gets one in time, the ESP32 just opens this packet and puts it via I2S to the DAC.

First, I thought to have a main radio module and a backup radio module which comes into play in case of failure of the main one. However, it turned out to be better to have a full symmetrical approach. One of the radio modules (starting with number 1) is the active one. The “naive timing” turned out to be most successful: Whenever the ESP32 receives a packet from radio number 1, this packet is given to the `I2S_WriteSamplesFromBuffer()` function (which then blocks until a I2S DMA buffer is free and the data is written to it). When receiving a packet with radio module 1, the software also stores the time in microseconds, and if - until the next packet arrives — a certain timeout is exceeded. This simply lets radio number 2 be the active one from now on, taking over the timing.

The results were really astonishing: switching between the radio modules works seamlessly, and the dual radio approach catches by far the most of the glitches caused by interferences. You can also switch off the active transmitter completely without hearing anything weird on the receiver side. It all worked out so well that up to now it was no more needed to switch from busy radio channels to other ones — with two radio channels 90 and 125 I could cover all the range experiments I did, including sending packets from floor 4 to floor 1 in the house where I live. It goes without saying that there is still a range limitation. At a certain distance between the transmitters and the receivers, the packets on both radio channels get lost. And here, the software gets a bit tricky.

Some Limitations

The inactive radio module will still report that a packet was received, even when no new packets have arrived, because it retains the last unread packet in its buffer. With that said, it was — unfortunately — not possible for me to detect in software if both radio modules get or don't get packets regularly. Pity, so an LED which flags if both transmission lines are (still) well working is out of reach. However, the following solution is possible: If the active module times out, the system switches to the other module. The ESP32 then checks whether this second module receives a packet within the expected time window. If not, the I2S interface is reset. This prevents weird sounds coming out of the loudspeaker when both radio modules did not get any music data.

Because not all packets coming in from both of the transmitters can be properly investigated, I had to leave the semi-automatic switching of channels (as you may remember from the previous part, the transmitter could send a command, instead of music, to “its” receivers, that the radio channel should be changed). As said, up to now, I never had the case that I had to switch to another channel, but of course there is a chance that you or me once will come to a place where this must be done. So I opted for a manual switching of channels on all the devices, with a push button and a seven segment display, showing the radio channel. As for the project of the second part, the software offers a

pre-selection of five radio channels for one of the transmitters and five different radio channels for the other one, in order to not interfere. Assigning one of the transmitters to audio channel 1 and the other one to audio channel 2 is obsolete, so I called the instances of the transmitters `RadioChannelDefaultType 1` and `RadioChannelDefaultType 2`. Instead of hardcoding the type of the transmitter in software like last time, I am using a DIP switch. From now on, it is possible to change the type of the transmitter without uploading new software.



Dual Radio Transmitter and RS485

The well-working “dual radio approach” will double the amount of transmitter devices needed. Unfortunately, also with some heavy tinkering I could not get two nRF24 radio modules working at one ESP32 on the transmitter side, there was always heavily distorted sound.

Working with two full equipped transmitter boards (same as in part 2), also side by side and with opened metal housings, was rather successful, though. So it may be possible to have two transmitter boards (with two different ESP32s) in a common housing. But there is another and better solution, too. I was able to transmit stereo audio from one ESP32 to another one via UART (2 Mbit/s); and with some cheap UART/RS485 converters, you can send the same signal also to more than one ESP32 controller via wires. So I could use one ESP32 to sample the music, pushing the bytes via RS485 then to two other ESP32s transmitting it, with one nRF24 connected to each of them. This ensemble (see photo) can compete in terms of range and latency with the two fully equipped transmitters. We need one microcontroller more but can save one of the expensive sample modules. This approach should be also scalable to four transmitters at the RS485 bus; and furthermore, as only one microcontroller takes music over sampling, we may have some benefit for synchronization too. More about that in the next article.

Hardware

To build a stereo transmission line with the dual radio approach, I took the same transmitter hardware as was built for the last article, but two pieces, and I drilled an additional hole in the housings,

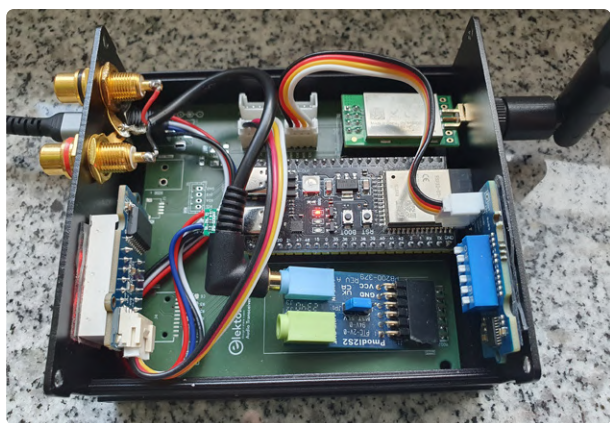
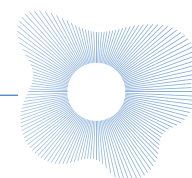


Figure 2: Prototype of the transmitter, with the new DIP switch module at the right side.

for the second cinch connector (**Figure 2**). On both transmitters, a Grove 4-digit 7-segment display [5] is connected to the Grove connector J7 (GPIO18/GPIO17) on the Audio Transceiver Board. Between GPIO5 at Grove connector J9 and GND, a simple push button is connected. Additionally, a Grove DIP switch [6] is wired to the Grove connector J10 (GPIO15/GPIO16, SCL/SDA). Via I²C, the position of up to six switches can be queried. We use only the first one (see below), others are reserved for future use.

For the receivers, my colleague Saad Imtiaz and I made a new PCB [7], where two nRF24L01 modules from Ebyte [8] can be plugged on (circuit diagram in **Figure 3**, see next page). The position of the first one remains the same, with the antenna looking through the front of the metal housing [9]. The other radio module is located at the backside of the board (**Figure 4**). You can see at the circuit diagram and the PCB that we sacrificed two Grove connectors J7 and J9. But that will be most likely improved again in a upcoming revision.

Between GPIO16 and GND of J10 a push button is connected, where you can switch the radio channel locally. GPIO15, VCC and GND of J10 goes to a Grove LED [10] (visualizing the radio module which is currently active). But you can, of course, also attach an LED (with resistor) of your choice. The LED should be active high in this case. At the remaining connector J8 with GPIO7/GPIO6 a Grove 4-digit display is attached, which can visualize the selected radio channels.

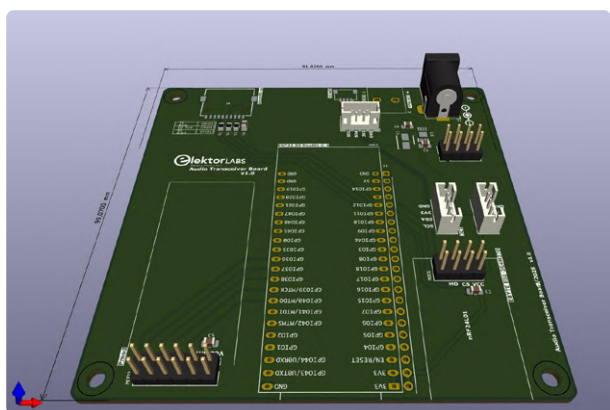


Figure 4: 3D rendering of the new dual radio PCB. As you can see, the power jack connector would collide with the second radio module at the backside of the board, so do not populate it! By the way, the three pin headers depicted here should be all pin sockets (female).

Figure 5 shows a prototype, where you can clearly see the two Ebyte radio modules.

Transmitter Software and Libraries

The software [7] on the transmitter side remains basically the same as the software for the last project. Of course, this time `audiochannelcount` is set to 2, and the option to send a command message to change the radio channel (instead of a packet with music samples) is wiped out. The `Output.h` file abstracts the visualization of values (like the `RadioChannelIndex`); the `Input.h` file handles the inputs (in that case, pressing the push button). New is the `Config.h` module, which abstracts retrieving configuration values at the start of the software. In that case, this module is querying the first DIP switch and puts the value in `Config_Value[CCHAN_RADIOCHANNEL_DEFAULT_TYPE]`, which can then be requested by the main program. These modules aren't libraries in the usual sense, they belong to the application itself, as well as the `BoardPin.h` definitions.

Transmitter and receiver software are using the same `I2S_Stream` and `Radio_nRF24` libraries. The first one was more or less not changed since this series was started. The latter one is still based on the external `RF24` library by GitHub user TMRh20 [3]. However, I took a look in the source code; the creator and his collaborators obviously have spent a lot of time to make the library fitting to all kinds of hardware platforms, including Linux boards like the Raspberry Pi and different microcontrollers. To have a deeper inside what is playing, in my own `Radio_nRF24` lib, I started to replace the calls of the external library functions by the corresponding basic SPI transactions, filling and reading out registers of the nRF24 chip. For the second radio module, I implemented extra functions in my library. (Yes, I know, this could be done in the future a bit cleverer with a class library.) Furthermore, the `Radio_Init()` function has now the parameter `_RadioChannelDefaultType`, in order to preselect the right five radio channels for the transmitter, which can be switched with the push button. The new `Radio_Init_Dual()` function fills all 10 radio channels which can be selected into an array to be available for the receiver.

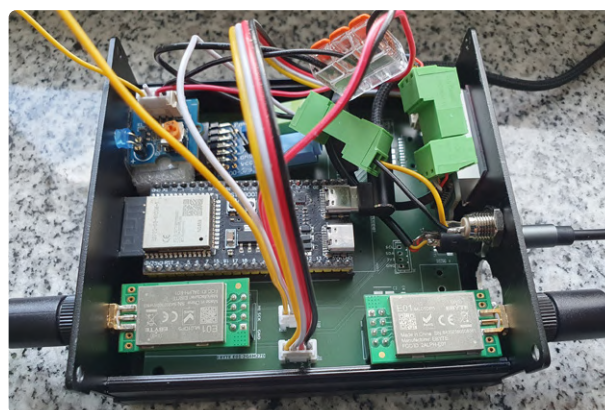


Figure 5: Prototype of the receiver, with the two Ebyte modules at the front and the backside. The Wago clamp was needed because I only had one Grove connector left for the LED and the pushbutton.

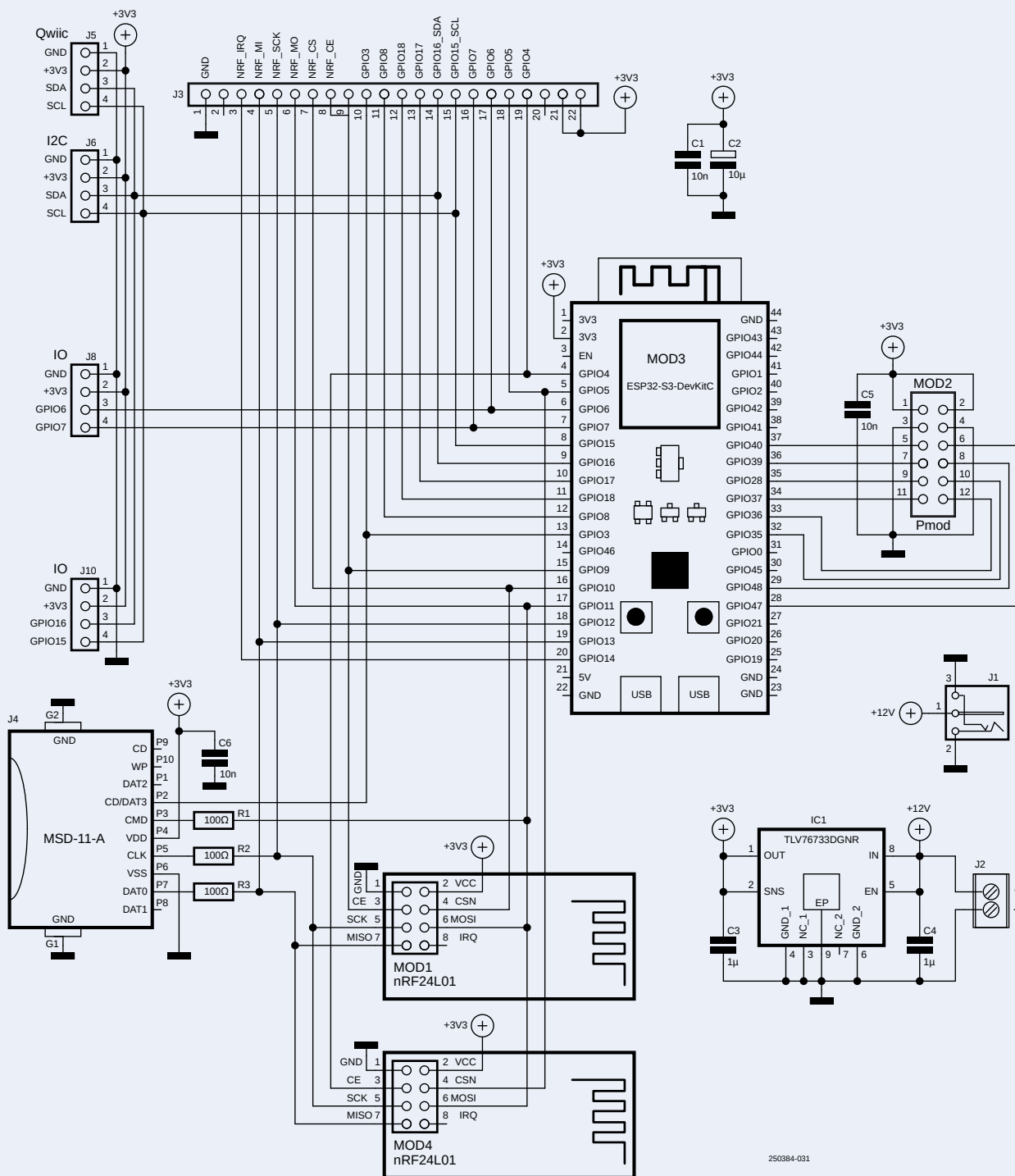


Figure 3: The circuit diagram with another 2x4 connector for a second nRF24 radio module.

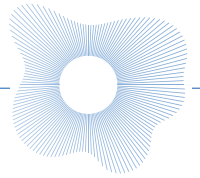
Receiver Software

Let's now turn to the receiver software. The `setup()` function is very similar to last time. Interesting is the `loop()` function (see **Listing 1**). You can see the algorithm I described earlier in this article, with the naive timing (directly outputting the samples when a packet has arrived) and the switch of the active radio module, as well as the symmetry concerning both radio modules.

We start retrieving the time in microseconds and polling both radio modules, if a packet has arrived. For the active module, it is then investi-

gated if the packet arrived in time; if not, we switch to the other module. In case we had already switched the active module directly before that, we assume that both modules were not able to receive packets in time any more. After that, the I2S interface is restarted.

After that, we tell `Output.h` to visualize the radio module which is currently active. This software module will then put the LED off for the radio module 1 being the active one, and on for radio module 2. With that, you can get feedback when a single radio receiver would have had problems, and some hints about interferences or the maximum range.



Listing 1: Dual Radio Receiver Loop.

```
void loop() {

    TimeReceived = micros(); // current time in microseconds

    if( Radio1_DataReceived() )
    {
        PacketReceived1 = 1; // flag: packet from radio module 1
        LastTimeReceived1 = TimeReceived;
    }

    if( Radio2_DataReceived() )
    {
        PacketReceived2 = 1; // flag: packet from radio module 2
        LastTimeReceived2 = TimeReceived;
    }

    if ( ActiveModule == 1 )
    {
        if ( TimeReceived - LastTimeReceived1 > TimeOut ) // packet not arrived in time
        {
            if (ActiveModuleHasChanged1 == 1) // have we just changed to module 1?
            {
                I2S_Restart();
            }
            ActiveModule = 2; // change to module 2
            ActiveModuleHasChanged2 = 1; // flag: we just changed to module 2
        }
        else
        {
            ActiveModuleHasChanged1 = 0; // clear flag that we just changed to module 1
        }
    }
    else
    {
        if ( TimeReceived - LastTimeReceived2 > TimeOut ) // packet not arrived in time
        {
            if (ActiveModuleHasChanged2 == 1) // have we just changed to module 2?
            {
                I2S_Restart();
            }
            ActiveModule = 1; // change to module 1
            ActiveModuleHasChanged1 = 1; // flag: we just changed to module 1
        }
        else
        {
            ActiveModuleHasChanged2 = 0; // clear flag that we just changed to module 2
        }
    }

    Output_ShowValue(OCHAN_ACTIVE_MODULE, ActiveModule); // visualize active module
                                                           // (will switch LED on or off)
```

```

if (PacketReceived1 == 1 && ActiveModule == 1 ) // packet received by module 1
{
    Radio1_ReadSamplesInBuffer(mBuffer, PACKET_LENGTH_SAMPLES);
    I2S_WriteSamplesFromBuffer(mBuffer, PACKET_LENGTH_SAMPLES);

    PacketReceived1 = 0; // clear flag
    PacketReceived2 = 0;
}

if (PacketReceived2 == 1 && ActiveModule == 2 ) // // packet received by module 2
{
    Radio2_ReadSamplesInBuffer(mBuffer2, PACKET_LENGTH_SAMPLES);
    I2S_WriteSamplesFromBuffer(mBuffer2, PACKET_LENGTH_SAMPLES);

    PacketReceived2 = 0; // clear flag
    PacketReceived1 = 0;
}

...
}

```



In the next part of the `loop()` function, the active radio module gets read out and the samples are put to the I2S interface. For now, we don't need any ring buffer here. At the end of the `loop()` function (not shown in Listing 1), the `Input_Loop()` function of the *Input.h* module is called, to poll button presses. A short press will trigger the first radio module switching to the next channel, a long one controls the second radio module.

A Look Ahead

It goes without saying that you can also build more than one receiver. Consider the two transmitters broadcasting the same music on two different radio channels, as two radio stations you would have in your house. With a receiver in each of your rooms, you will get everywhere the same music playing, without wires, a digital quality, and a latency of some milliseconds. However, if we want to build an independant receiver for the left loudspeaker and one for the right loudspeaker, we need a better synchronization, and we are not speaking any more of milliseconds, but microseconds. We will come back to that in one of the next editions! ◀

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About the Author

Jens Nickel studied physics and was further educated as an editor for professional tech/science magazines. In 2005, he started working for Elektor, and for the past several years, he has served as the Editor in Chief of the magazine. Jens has liked programming since the early days of the C64. No wonder that he is also fascinated by the flexible and powerful options of good microcontroller platforms. Over the last few years, the ESP32 has become his favorite controller for personal projects. Jens's hobbies include music videos, digital audio, and studio control projects.

Questions and Comments?

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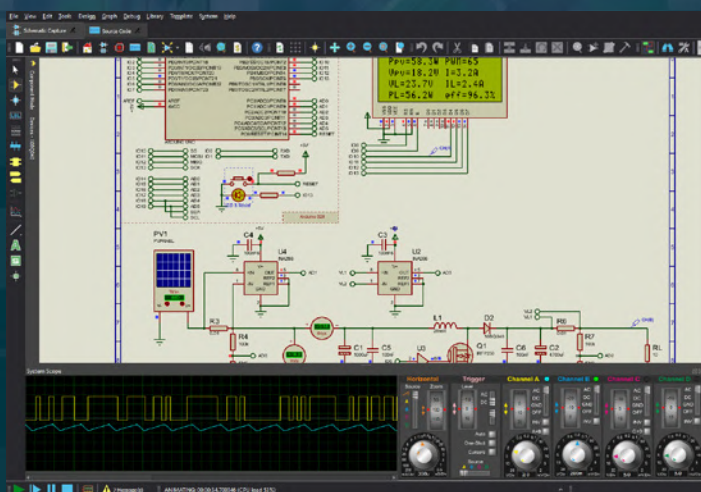
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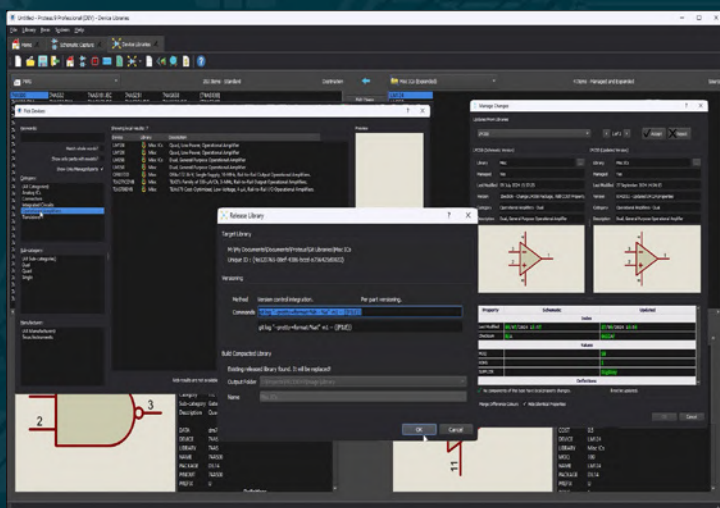
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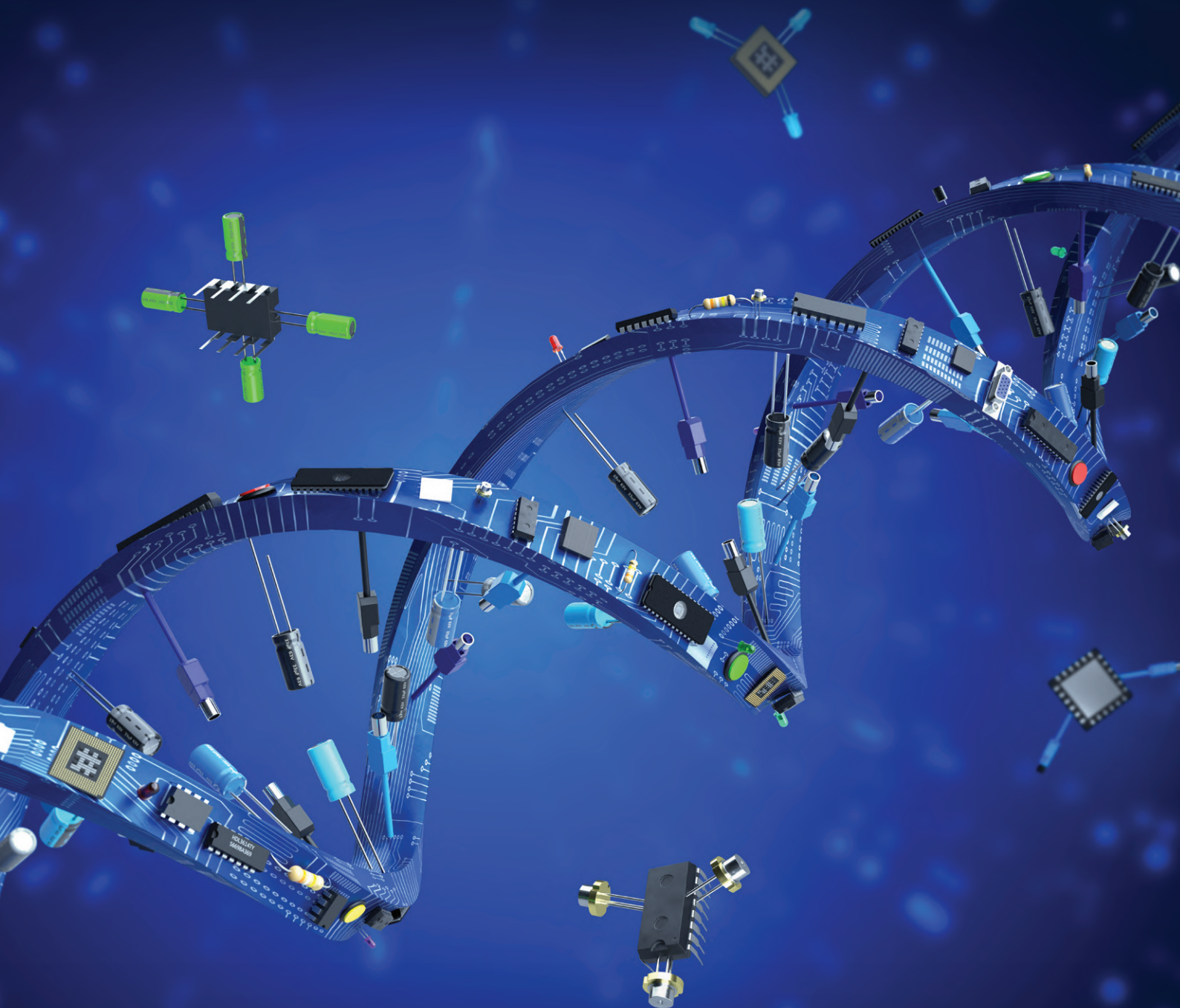
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