PREDICTABLE DESIGNS
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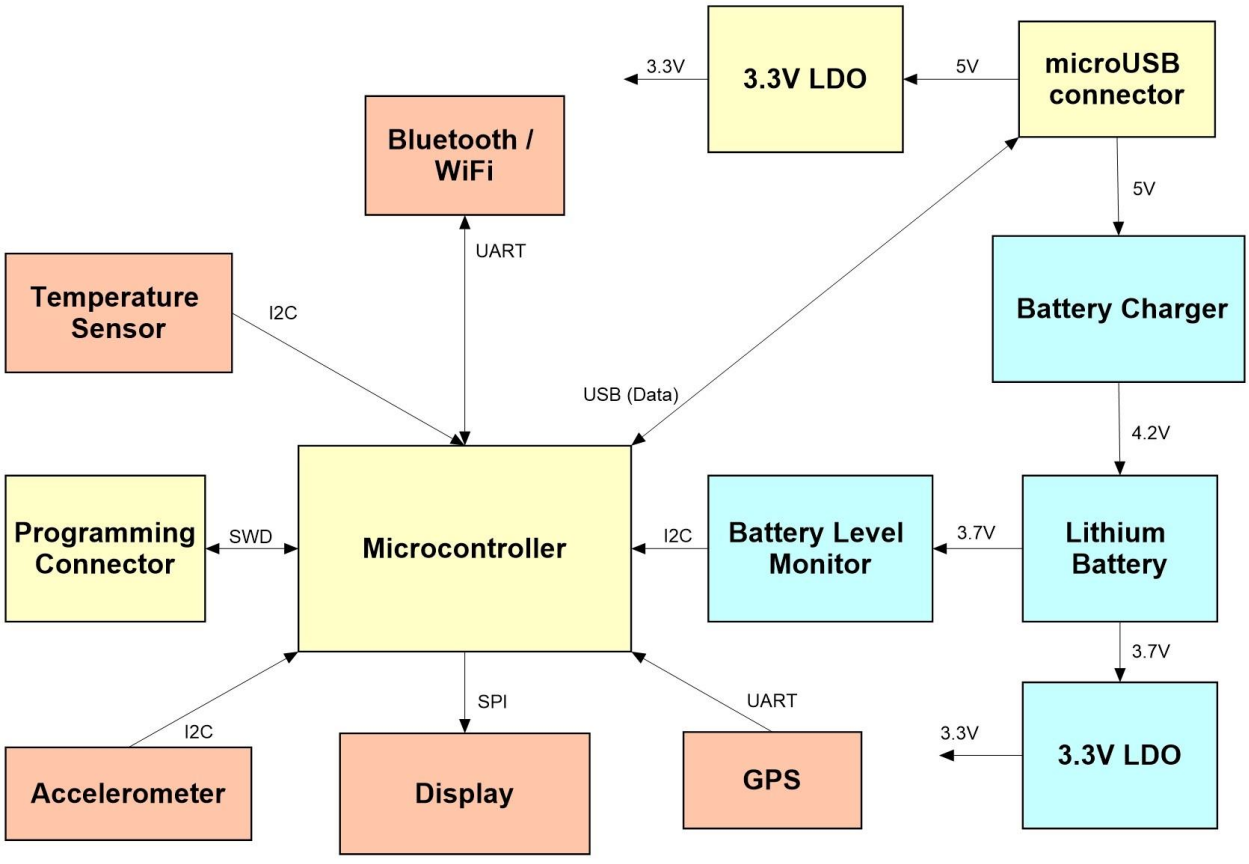
# - Complete Tutorial (Part 1) -

# How to Design Your Own Custom Microcontroller Board (with Video)



***Article Technical Rating: 7 out of 10***

This is the first in a series of tutorials where you'll learn how to design your own custom microcontroller board. To get the most out of this tutorial it's critical that you read the article and watch the included video.

Initially, we're going to focus on just the microcontroller itself so you can more easily understand the design process without getting overwhelmed with circuit complexity.

I'll break down the design process into three fundamental steps:

**Step 1 - System Design**

**Step 2 - Schematic Circuit Design**

**Step 3 - PCB Layout Design**

You're going to learn how to design the system and the schematic circuit in this first tutorial. Then, in part two you'll learn how to lay out the Printed Circuit Board (PCB) and order prototypes.

This will be an ongoing tutorial series and in the future we'll greatly expand the capabilities of the design by adding advanced features such as: a rechargeable battery, a display, Bluetooth, WiFi, USB data, GPS, and an accelerometer.

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# System / Preliminary Design

When developing a new circuit design the first step is the high-level system design (which I also call a preliminary design). Before getting into the details of the full schematic circuit design it's always best to first focus on the big picture of the full system.

Designing the system consists mainly of two steps: creating a block diagram and selecting all of the critical components (microchips, sensors, displays, etc.). A system design treats each function as a black box

In engineering, a black box is an object which can be viewed in terms of its inputs and outputs but without any knowledge of its internal workings. With a system-level design the focus is on the higher level interconnectivity and functionality.

## Block Diagram

Below is the block diagram that we'll be working from in this tutorial series. As I mentioned, for this first tutorial we'll focus just on the microcontroller itself. In future tutorials we'll expand the design to include all of the functionality shown in this block diagram.

A block diagram should include a block for each core function, the interconnections between the various blocks, specified communication protocols, and any known voltage levels (input supply voltage, battery voltage, etc.).

Later, once all of the components have been selected and the required supply voltages are known I like to add the supply voltages to the block diagram. Including the supply voltage for each functional block it allows you to easily identify all of the supply voltages you'll need as well as any level shifters.

In most cases when two electronic components communicate they need to use the same supply voltage. If they are supplied from different voltages then you'll usually need to add in a level shifter.

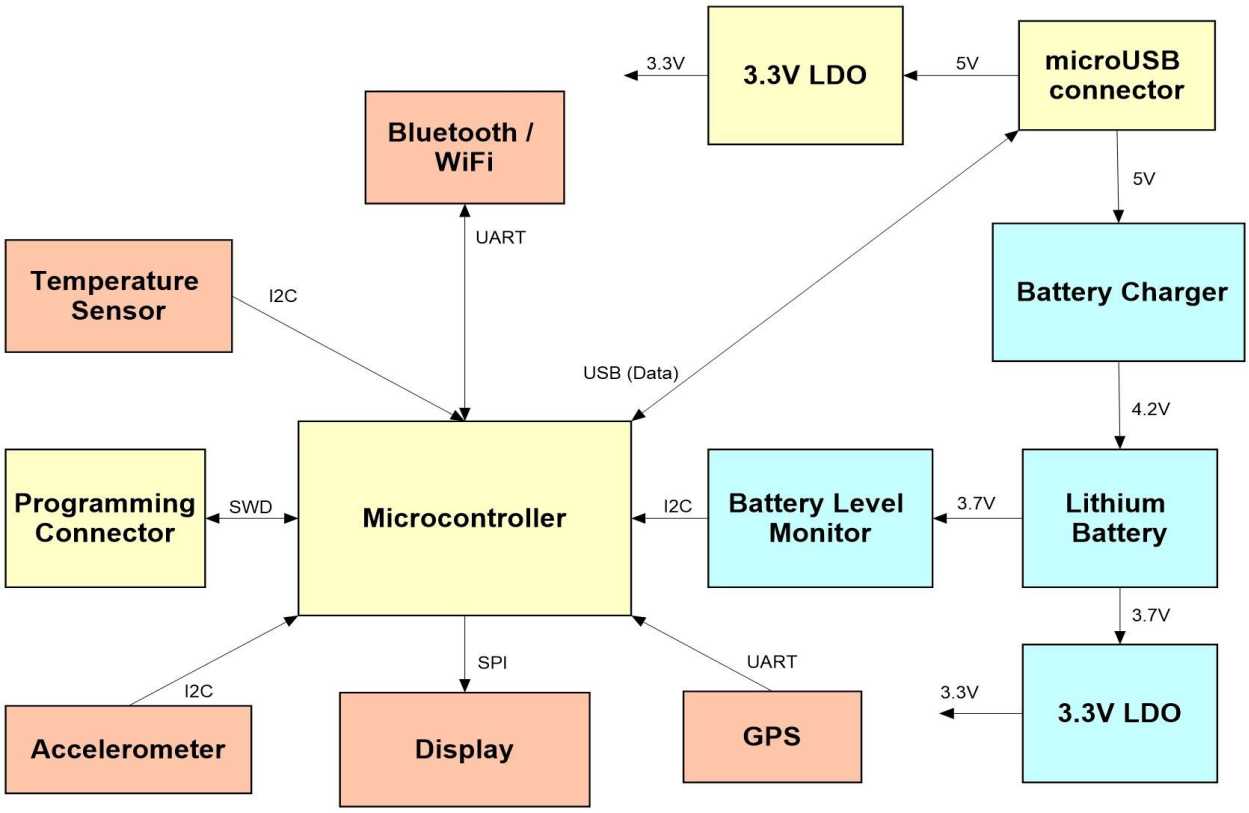


*Figure 1 - System-level block diagram. Blocks in yellow are included in this initial tutorial. Other blocks/functions will be added in future tutorials.*

Now that we have a block diagram we can better understand the necessary requirements for the microcontroller. Until you've mapped out everything that will connect to the microcontroller it's impossible to select the appropriate microcontroller.

## Select Microcontroller

When selecting a microcontroller (or just about any electronic component) I like to use an electronics distributor's website like Newark.com. Doing so allows you to easily compare various options based on a variety of specifications, pricing, and availability. It's also an easy way to quickly access the component's datasheet.

If you regularly read this blog you'll know that I'm a big fan of ARM Cortex-M microcontrollers. Arm Cortex-M microcontrollers are easily the most popular line of microcontrollers used in commercial electronic products. They have been used in tens of billions of devices.

Microcontrollers from Microchip (including Atmel) may dominate the maker market but Arm dominates the commercial product market.

Arm doesn't actually manufacture the chips directly themselves. They instead design processor architectures that are then licensed and manufactured by other chip makers including ST, NXP, Microchip, Texas Instruments, Silicon Labs, Cypress, and Nordic.

The ARM Cortex-M is a 32-bit architecture that is fantastic choice for more computationally intensive tasks compared to what is available from older 8 bit microcontrollers such as the 8051, PIC, and AVR cores.

Arm microcontrollers come in various performance levels including the Cortex-M0, M0+, M1, M3, M4, and M7. Some versions are available with a Floating Point Unit (FPU) and are designated with an F in the model number such as the Cortex-M4F.

One of the biggest advantages of Arm Cortex-M processors is their low price for the level of performance you get. In fact, even if an 8-bit microcontroller is sufficient for your application you should still consider a 32-bit Cortex-M microcontroller.

There are Cortex-M microcontrollers available with very comparable pricing to some of the older 8-bit chips. Basing your design on a 32-bit microcontroller gives you more room to grow should you want to add additional features in the future.


*Figure 2: The STM32 from ST Microelectronics is my favorite line of ARM Cortex-M microcontrollers*

Although numerous chip makers offer Cortex-M microcontrollers, my favorite by far is the STM32 series from ST Microelectronics. The STM32 line of microcontrollers is quite expansive with just about any feature and level of performance you would ever need. The STM32 line can be broken down into several subseries as shown in Table 1 below.

| **STM32 Series** | **Cortex-Mx** | **Max clock** (MHz) | **Performance** (DMIPS) |
|---|---|---|---|
| F0 | M0 | 48 | 38 |
| F1 | M3 | 72 | 61 |
| F3 | M4 | 72 | 90 |
| F2 | M3 | 120 | 150 |
| F4 | M4 | 180 | 225 |
| F7 | M7 | 216 | 462 |
| H7 | M7 | 400 | 856 |
| L0 | M0 | 32 | 26 |
| L1 | M3 | 32 | 33 |
| L4 | M4 | 80 | 100 |
| L4+ | M4 | 120 | 150 |

*Table 1: Comparison of various STM32 microcontroller variants*

The STM32F subseries is their standard line of microcontrollers (versus the STM32L subseries which is specifically focused on lower power consumption). The STM32F0 has the lowest price but also the lowest performance. One step up in performance is the F1 subseries, followed by the F3, F2, F4, F7, and finally the H7.

For this tutorial I have selected the STM32F042K6T7 which comes in a 32-pin LQFP leaded package. I selected a leaded package primarily because it simplifies the debugging process because you have easy access to the microcontroller pins. Whereas with a leadless package, like a QFN, the pins are hidden away underneath the package making access impossible without test points.

A leaded package also allows you to more easily swap out the microcontroller if it were to become damaged. Finally, leadless packages cost more to solder on to the PCB so they increase both the prototyping and manufacturing costs.

I selected the STM32F042 because it offers moderate performance, a good number of GPIO pins, and various serial protocols including UART, I2C, SPI and USB. This is a fairly entry-level STM32 microcontroller with only 32 pins, but with a wide variety of features. More advanced versions come with as many as 216 pins which would be quite overwhelming for an introductory tutorial.

In this first video we won't be using most of these features, but we will take advantage of them in future videos in this series.

## Schematic Circuit Design

Now that we have selected the microcontroller it's time to design the schematic circuit diagram. For these tutorials I'll be using a PCB design tool called DipTrace.

There are dozens of PCB tools available but when it comes to ease of use, price, and performance I find that DipTrace is hard to beat, especially for beginners.

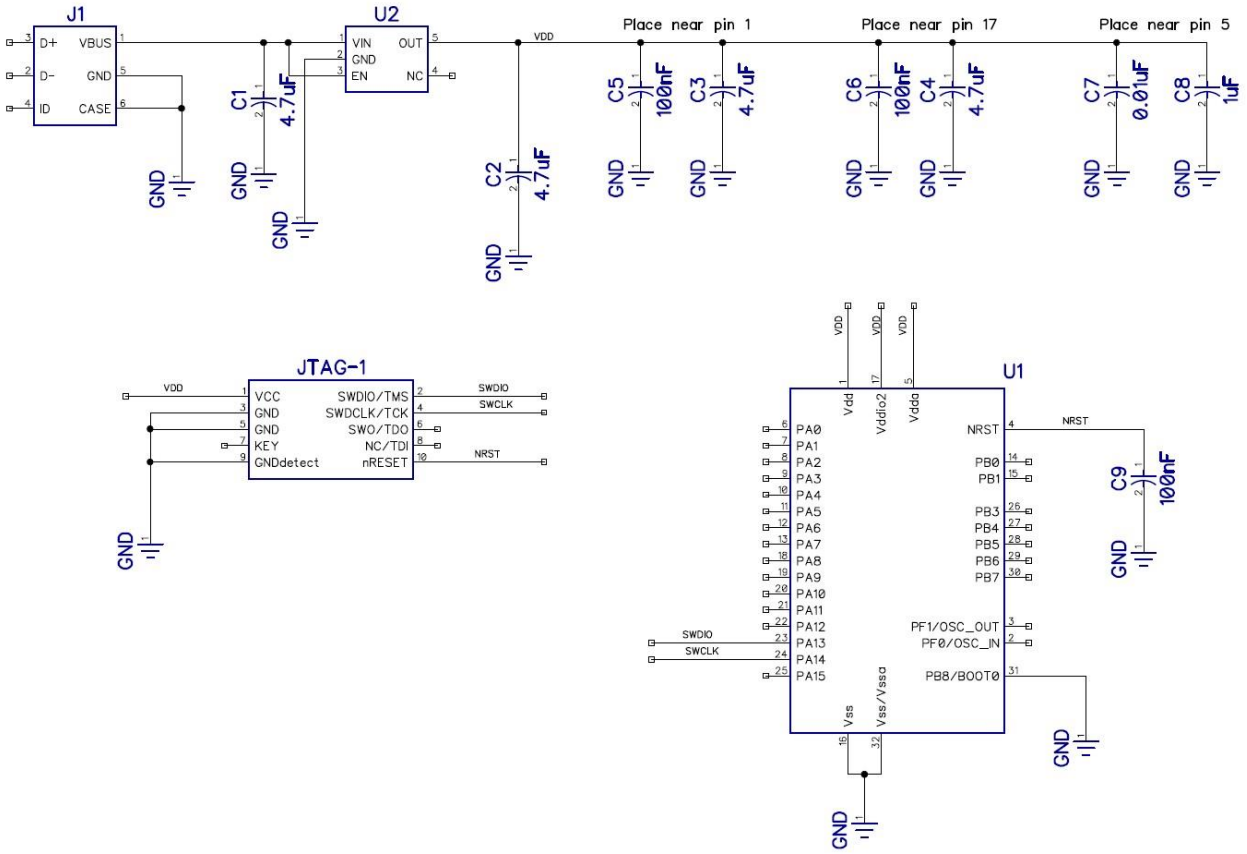


*Figure 3: Schematic circuit diagram for this first tutorial showing the STM32 microcontroller, linear regulator, USB connector, and programming connector.*

If you don't have a PCB design package then you may want to consider downloading the free version of DipTrace so you can follow along closely with this tutorial. The best way to learn something is always to actually do it.

For this initial tutorial the free version of DipTrace is sufficient, but as we expand the functionality of this circuit in future tutorials you'll need to upgrade to a paid version of DipTrace or their 30-day free trial.

**DISCLOSURE:** I'm an affiliate for DipTrace, but only after I used it to successfully design dozens of products. I've been using it now for almost 4 years, and I still love it. If you do decide to purchase DipTrace, I would really appreciate it if you would use this link so I get a commission at no extra cost to you.

Nonetheless, this tutorial will be focusing on the process for designing a custom microcontroller board, and not on how to use any specific PCB design tool. So regardless of which PCB software you end up using you'll still find these tutorials are just as useful.

The first step in designing a schematic is to place all of the key components. For this initial design this includes the microcontroller chip, a voltage regulator, a microUSB connector, and a programming connector.

For more complex designs it usually makes more sense to completely design each sub-circuit first, then merge them all together. Depending on the design complexity (and personal preference) you may also want to place each sub-circuit on its own separate sheet. This keeps the schematic from becoming a huge, overwhelming monster on a single sheet.

## Capacitors

Next, we'll place all of the various capacitors. For the most part you can think of capacitors as tiny little rechargeable batteries that hold electrical charge and help to stabilize the voltage on a supply line.

We'll start by placing a 4.7uF capacitor on the input pin of the linear regulator. This is the 5VDC input voltage supplied by an external USB charger. This voltage is fed into a TLV70233 linear regulator which steps the voltage down to 3.3V since the microcontroller can only be supplied by a maximum of 3.6V.

Another 4.7uF capacitor is placed on the output of the regulator as close to the pin as possible. This capacitor serves to store charge to supply transient loads and it acts to stabilize the internal feedback loop of the regulator. Without an output capacitor most regulators will begin to oscillate.

Decoupling capacitors must be placed as close as possible to the microcontroller supply pins (VDD). It's always best to refer to the microcontroller datasheet in regards to their recommendations for decoupling capacitors.

The datasheet for the STM32F042 recommends a 4.7uF and a 100nF capacitor be placed next to each of the two VDD pins (input supply pins). It also recommends 1uF and 10nF decoupling capacitors be placed near the VDDA pin.

The VDDA pin is the supply for the internal analog-to-digital (ADC) converter and must be especially clean and stable. We're not using the ADC in this first tutorial but we will in a future one.

Note that you'll commonly see two capacitor sizes specified together for decoupling purposes. For example, 4.7uF and 100nF capacitors.

The larger 4.7uF can store more charge which helps stabilize the voltage when large spikes in load current are required. The smaller capacitor serves mainly to filter out any high-frequency noise.

## Microcontroller pinout

Although the STM32F042 offers a wide variety of functions such as UART, I2C, SPI, and USB communication interfaces, you won't find any of these functions labeled on the microcontroller pinout. This is because most microcontrollers assign a variety of functions to each pin so as to reduce the number of pins required.

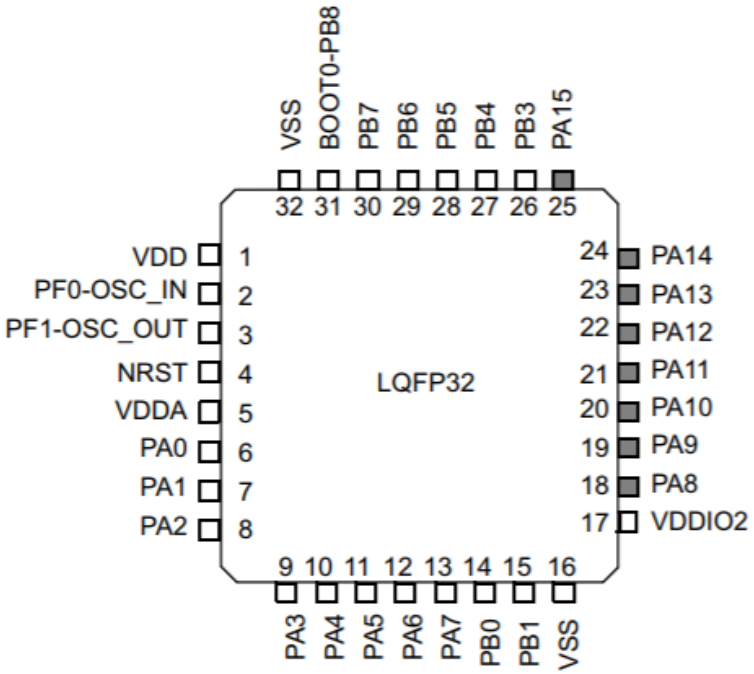


*Figure 4: Pinout for the STM32F042 microcontroller in a 32-pin LQFP leaded package.*

For example, on the STM32F042 pin 9 is labeled as PA3 which means it is a GPIO pin. Upon startup this function is automatically assigned to this pin. But it also has alternative functions that can be specified in the firmware program.

Pin 9 can be programmed to serve the following functions: receive input pin for UART serial communication, an input to the Analog-to-Digital Converter (ADC), a timer output, or an I/O pin for the capacitive touch sensor controller.

Refer to the pin definition table in the microcontroller datasheet (page 33 for the STM32F042) which shows all of the various functions available for each pin.

Always be sure to confirm that two functions required for your product don't overlap on the same pins.

## Clock

All microcontrollers require a clock for timing purposes. This clock is just an accurate oscillator. Microcontrollers execute programmed commands sequentially with each tick of the clock.

The simplest option, if available on the selected microcontroller, is to use the internal clock. This internal clock is known as an RC oscillator clock because it uses the timing characteristics of a resistor and capacitor.

The major downside to an RC oscillator is accuracy. Resistors and capacitors (especially those embedded inside a microchip) vary significantly from unit to unit causing the oscillator frequency to vary. Temperature also significantly impacts the accuracy.

An RC oscillator is fine for simple applications, but if your application requires accurate timing then it won't be sufficient. For this initial tutorial we're going to use the internal RC clock to keep things simple. In future tutorials we'll improve the design by adding a much more precise, external crystal-based oscillator.

## Programming Connector

Programming an STM32 is done via one of two protocols: JTAG or Serial Wire Debug (SWD). More advanced versions of the STM32 (STM32F1 and higher) offer both JTAG and SWD programming interfaces. The STM32F0 subseries offers only the simpler SWD programming interface so that is what we will focus on for this tutorial.

The SWD interface requires only 5 pins. They are SWDIO (data input/output), SWCLK (clock signal), NRST (reset signal), VDD (supply voltage) and ground.

Unfortunately the ST-LINK programmer device that you'll use to program the STM32 uses a 20-pin JTAG connector (with SWD functionality). This connector is quite large and is not practical for smaller board designs.

Instead, you can use a 20-pin to 10-pin adapter board such as this one from Adafruit so you can use a smaller 10-pin connector on your board.

For this tutorial we will use the 10-pin connector. If that is still too large for your project then you can always use a 5-pin header and jumper wires from the 20-pin programmer output to connect only the 5 lines required for SWD programming.

## Power

The last part of the schematic we'll cover is the power section. The STM32 microcontroller can be powered with a supply voltage from 2.0 to 3.6V. Unless you have a variable power supply, you'll need an on-board regulator to provide the appropriate supply voltage.

For this design we'll power the board using an external USB charger which outputs 5 VDC. This voltage will then feed into a linear voltage regulator (TLV70233 from Texas Instruments) which steps it down to a stable 3.3V.

The STM32 requires a maximum of only 24mA assuming none of the GPIO pins are sourcing any current (each GPIO pin can source up to 25mA). The absolute maximum current the STM32 will ever require is 120mA assuming various GPIO pins are sourcing current.

The TLV70233 is rated for up to 300mA which should be more than sufficient for this initial design. In future tutorials, as we add additional functions, we may need to revisit this to ensure the regulator can handle the required system current.

In future tutorials we'll significantly improve the power circuit design by adding in a rechargeable lithium battery that can be recharged via the USB port.

## Electrical Rules Check

The final step of designing the schematic circuit diagram is to perform a verification step called an Electrical Rules Check (ERC). This verification step checks for errors such as shorts between nets, nets with only one pin, superimposed pins, and unconnected pins.

You can also setup various pin type errors. For example, if an output pin is connected to another output you will get an error. Or if an output pin is connected to a power supply line you will get an error. DipTrace uses a colored grid matrix that allows you to define which pin type connections will give you errors or warnings.

## Summary

In this first tutorial we've designed the system block diagram, selected all of the critical components, and designed the full schematic circuit diagram.

In part 2 of this tutorial series we'll focus on designing the actual printed circuit board (PCB) layout and ordering board prototypes.