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Arduino Prototype to Producible PCB: An LED Multiplexer

Learn the minumum electronic and software aspects of taking an Arduino-based breadboard prototype to producible consumer device.

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Things used in this project

Hardware components

See component list in each stage below. Consider ordering the components from all components lists in this project to save on minimize cost and maximize time. × 1

Story

Introduction

My goal of this project was to teach myself (with the assistance of my helpful folks on the interwebs) how to take an Arduino-based breadboard prototype all the way to mass-producible PCB (printed circuit board). I thought that I would brake it down into five stages:

1) Breadboard circuit linked to an Arduino.

2) Phase 1, but with the Arduino replaced with only necessary components.

3) Phase 2, but soldered together using stripboard. (https://en.wikipedia.org/wiki/Stripboard)

4) A PCB fabricated by a third-party that I would assemble myself.

5) A PCB fabricated and assembled by a third party.

The idea of this project was not to create the adjustable LED multiplexer, but rather to learn the absolute bare-bones process of developing a producible consumer electronic device (minus just about everything but the actual technical aspects). I choose the LED multiplexer as a circuit that was simple enough to not slow progress of achieving my main goal but complex enough to be a little more interesting and challenging than a single blinking LED.

I will note upfront that this guide is lacking in a lot of details and is intended more as an overview for anyone seeking to learn the basics of this process. If you have specific questions, feel free to ask them in the comments and I will try to answer them. This guide assumes previous experience with Arduinos and the Arduino IDE, and of the C programming language if you want to understand what the code is doing.

Throughout this project, I would encourage you to use the same color jumper wires that I use. Doing so will make the pictures more helpful to you.

Stage 1

I broke Stage 1 into there sub-stages: stage 1A, 1B, and 1C. Stages 1A and 1B were dedicated to getting the LED multiplexer down pat. Stage 1C was the point at which I integrated a pushbutton, two potentiometers, a toggle switch, and a battery to make the circuit a bit more interesting and independent of power provided by my computer.

Stages 1A and 1B

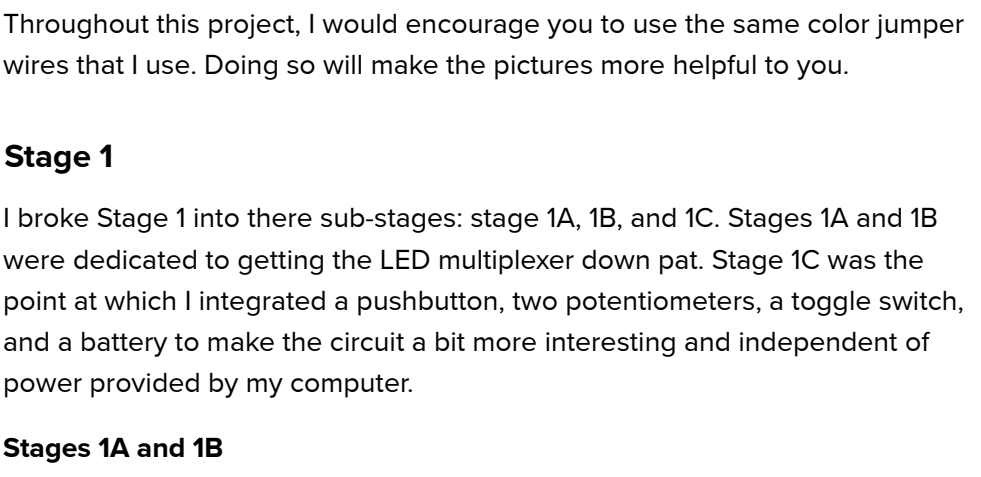
Designing the Circuit

If you don't care much about the circuit theory, feel free to skip down to the *Assembling and Running the Circuit* subsection.

I started with this Instructable by perez1028 (https://www.instructables.com/id/Multiplexing-with-Arduino-Transistors-I-made/)and went from there. I made some heavy adjustments and initially had some issues, as evidenced by my post here (https://electronics.stackexchange.com/questions/411244/questions-about-bjts-in-my-circuit?noredirect=1#comment1014421_411244)(thanks to the folks there).

INSERT discussion about multiplexing.
and this scales so that, assuming a square matrix, the required number of control signals is equal to twice the square root of the total number or LEDs (e.g., 6 = 2*sqrt(9), 10 = 2*sqrt(25))

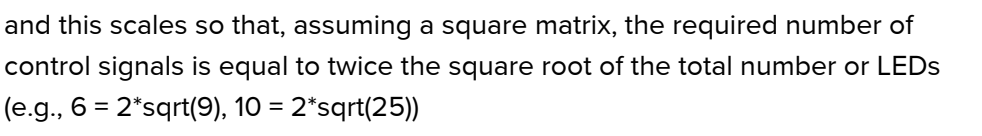
After some trial, error, and iteration, I settled on this:

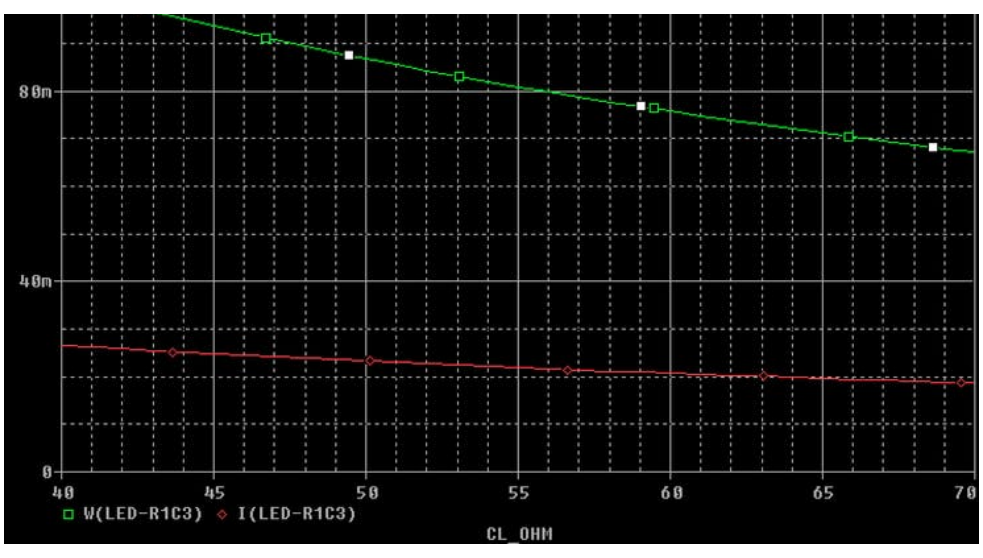


Circuit schematic for LED multiplexer

I used DC voltage sources to simulate the voltage that would be supplied by the Arduino I/O pins.

I wanted the LEDs to be as bright as possible without burning out. I was using Cree C512A-WNS/WNN LEDs, so I took a look at their datasheet (https://www.cree.com/led-components/media/documents/C512A-WNS-WNN-942.pdf)and found the maximum forward current that these LEDs can withstand to be 25 mA and the maximum power dissipation to be 100 mW. Also, on an Arduino, the maximum current output per I/O pin is 40 mA (and 200 mA from Vcc). It is important to make these considerations for all components in the circuit. With these things in mind, I ran various simulations to try to find the optimal resistor values for my design. For instance, I did a sweep of what I have labeled as the CL_OHM resistance value to see the current and power dissipation through/at LED-R1C3:

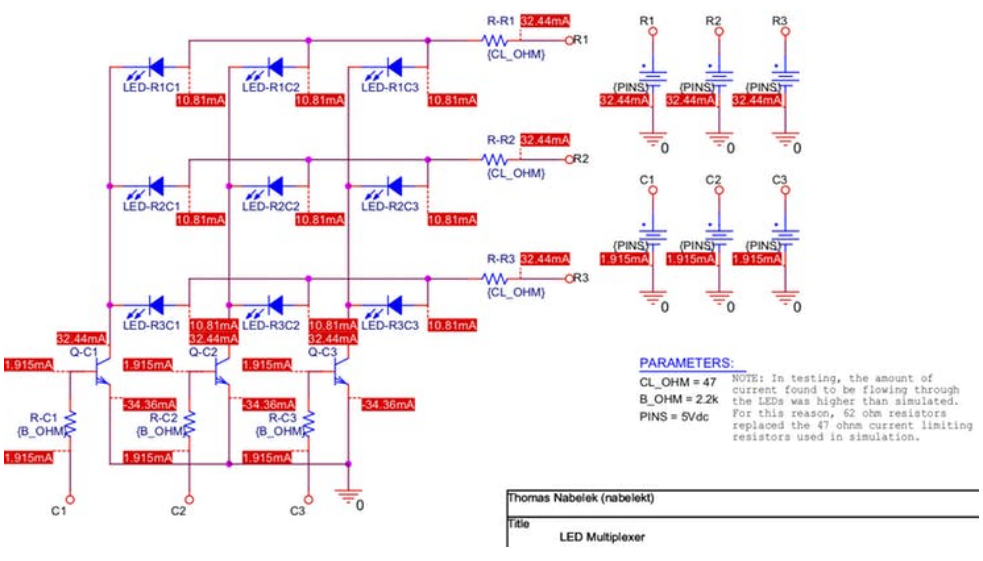




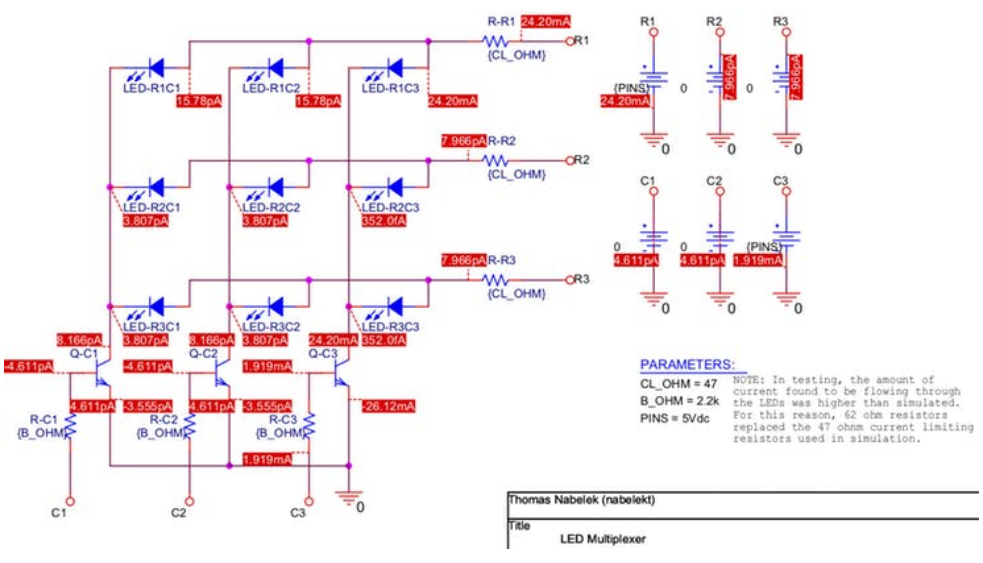
Current (red, mA) and power dissipation (green, mW) through/at LED-R1C3; CL_OHM axis values given in ohms

This was done with only pins R1 and C3 enabled at 5 V and all of the other pins set to 0Vdc – a "worst case" scenario. Given that 47 Ω is a common resistor value, it seemed like a great choice. At 47 Ω, this simulation showed about 24.5 mA of current and 91 mW of power dissipation.

I created the schematic and did the simulation using OrCAD PSpice Designer Lite. (https://www.orcad.com/resources/download-orcad-lite) The software lets you simulate the circuit and get the voltage at any node, current on any branch, and power consumption for any component. Here are a bunch of simulated values:



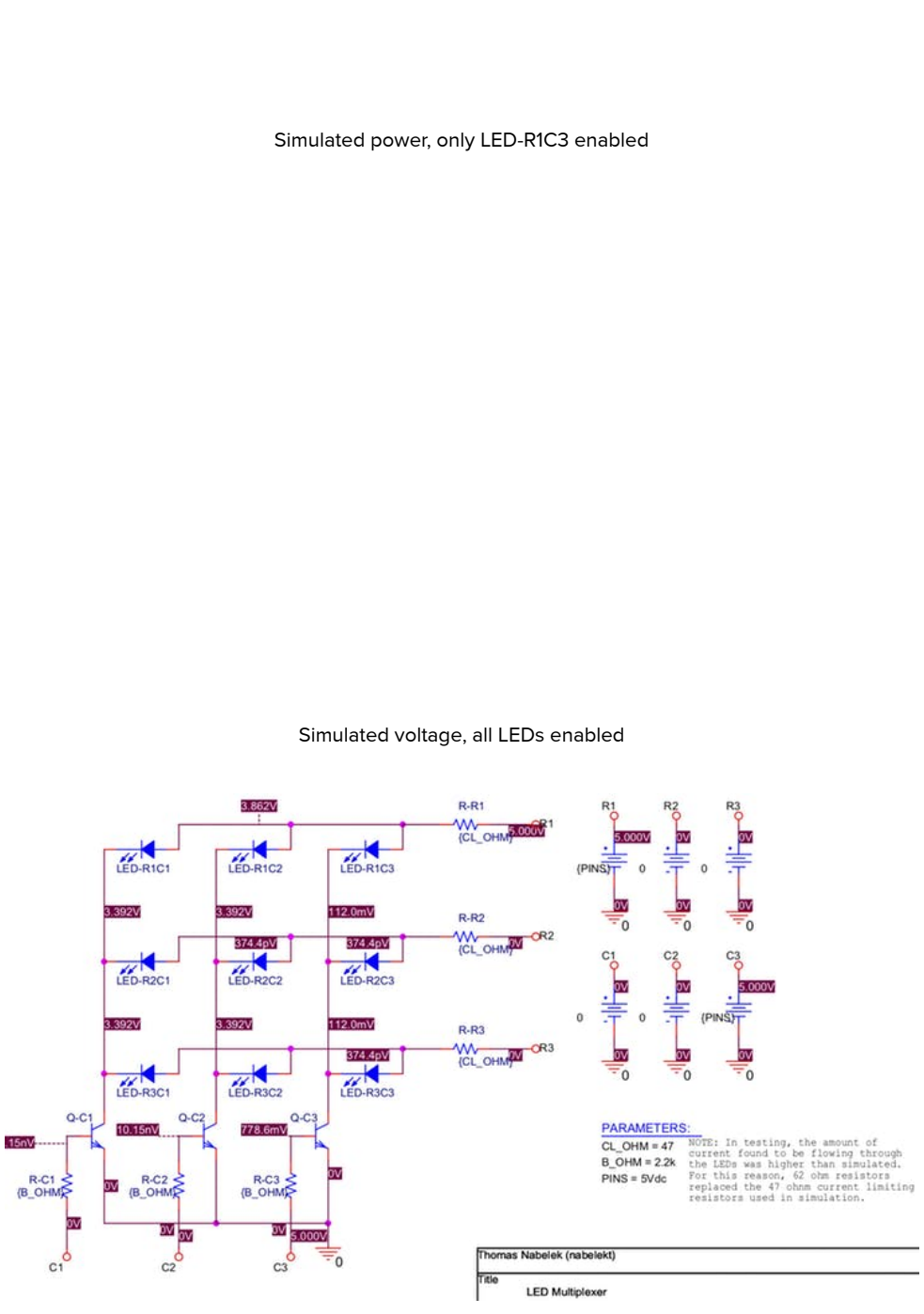
Simulated current, all LEDs enabled



Simulated current, only LED-R1C3 enabled

Simulated power, all LEDs enabled

Simulated power, only LED-R1C3 enabled



Simulated voltage, all LEDs enabled

Simulated voltage, only LED-R1C3 enabled

However, notice the note on the right side of the schematic: "In testing, the amount of current found to be flowing throughthe LEDs was higher than simulated. For this reason, 62 ohm resistors replaced the 47 ohnm current limiting resistors used in simulation."

All of this was done enabling both the anode and cathode of only one LED – a sort of "worst case," as mentioned. In reality, with the way that the multiplexer works and the code below is written, a pulse-width modulation effect occurs. While the datasheet for the LEDs (https://www.cree.com/led-components/media/documents/C512A-WNS-WNN-942.pdf) does specify a 25 mA max forward current, it also specifies a peak forward current of 100 mA for pulses ≤ 0.1 ms, so this all may be a bit of a mute point anway.

Assembling and Running the Circuit

Component list:

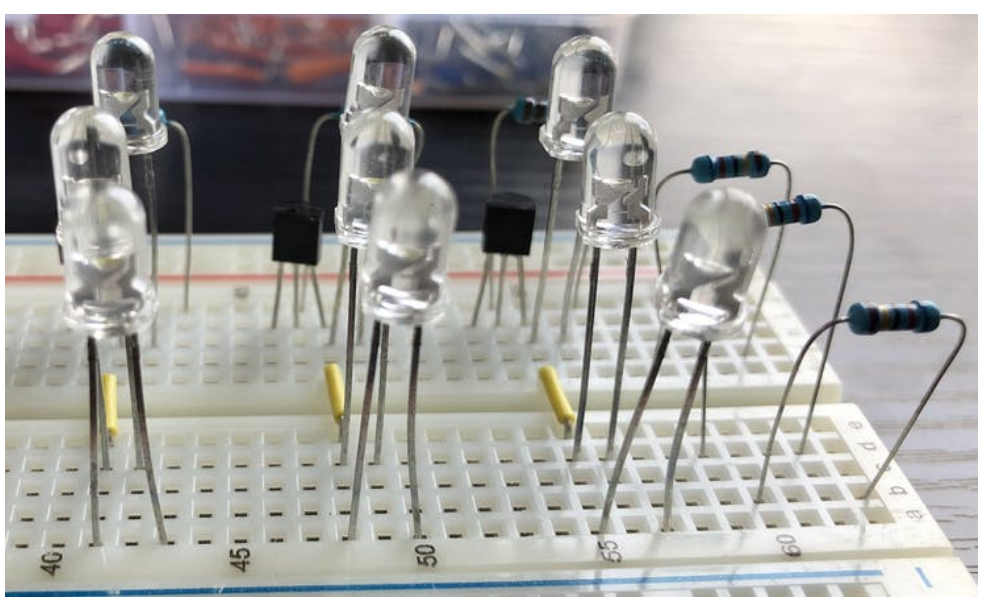
- Computer with Arduino IDE and USB cable to connect to Arduino
- Arduino Uno R3 or cheaper knock-off (these (https://www.amazon.com/gp/product/B01EWOE0UU) have worked very well for me)
- Solderless breadboard (https://www.digikey.com/product-detail/en/adafruit-industries-llc/239/1528-2143-ND/7244929)
- 3x 62 Ω resistors (I used these (http://amazon.com/gp/product/B07J48VNR7) but don't necessarily recommend them – pretty sure the tolerance is much greater than 1%)
- 3x 2.2 kΩ resistors
- 3x 2N3904 NPN BJTs (transistors) (I used these (https://www.amazon.com/gp/product/B06XRBLKDR))
- 9x Cree C512A-WNN-CZ0B0152 LEDs (https://www.digikey.com/product-detail/en/cree-inc/C512A-WNN-CZ0B0152/C512A-WNN-CZ0B0152CT-ND/6138557)
- wire (jumper wires like these (https://www.digikey.com/product-detail/en/PRT-12795/1568-1512-ND), and these (https://www.amazon.com/gp/product/B079FKJ4S3) or these (https://www.digikey.com/product-detail/en/global-specialties/WK-2/BKWK-2-ND/5231341), can help a lot and save you the pain of cutting and stripping wire)

Step 1 : Start with the resistors.

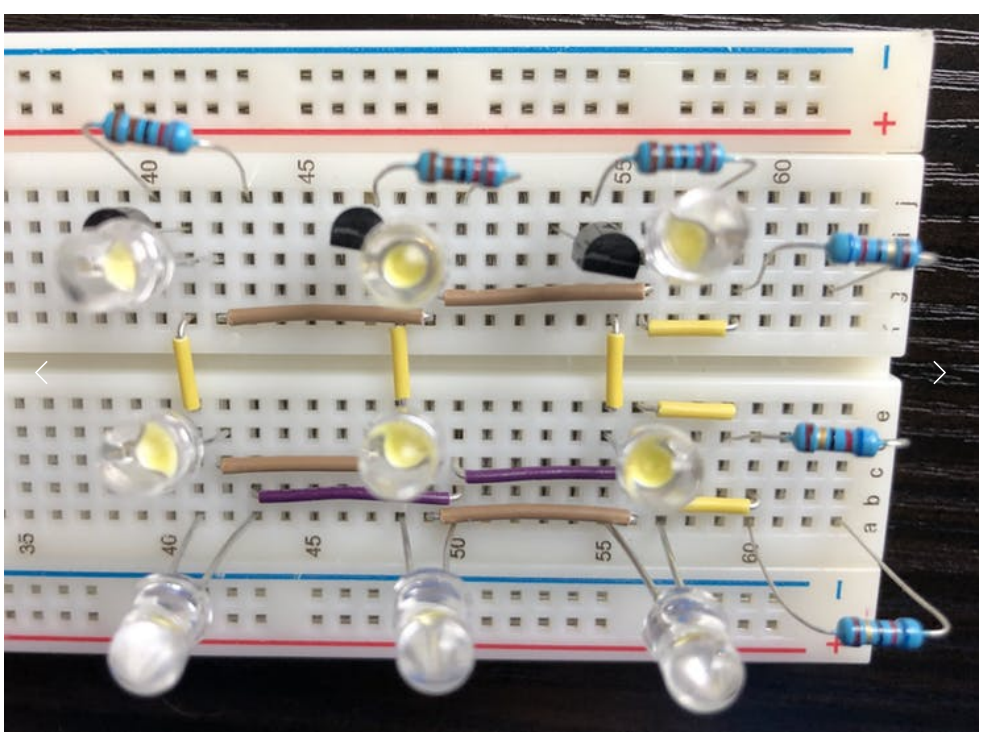
Step 2 : Add the transistors.

Step 3 : Add bridging wires and Row 1 LEDs. Note the politarity of the LEDs. The cathode (shorter leg) should share a node with the collector (right most leg) of the NPN BJT.
Pro-tip : Add all of the wires through Step 5 and then go back and add the LEDs. It's way easier.

Step 4 : Add remaining LEDs.



Step 5 : Add wires connecting LED anodes to each other and to current limiting resistors. The brown wires here connect the LED anodes in rows 1 and 2 while the purple wires connect the LED anodes in row 3.



1 / 2

Step 6 : Wire the transistor emitters (left most pin when looking towards the flat side of the transistors) to the ground rail.
Wire to the Arduino. I will use the resistor designations found in the circuit diagrams above, but it is probably easiest to look at the pictures below.
Connect a jumper from R-R3 to pin 7 on the Arduino.
Connect a jumper from R-R2 to pin 6 on the Arduino.
Connect a jumper from R-R1 to pin 5 on the Arduino.
Connect a jumper from R-C3 to pin 4 on the Arduino.
Connect a jumper from R-C2 to pin 3 on the Arduino.
Connect a jumper from R-C1 to pin 2 on the Arduino.
Connect a jumper from the ground rail to GND on the Arduino (the second pic is missing the ground connection to Arduino - the black jumper in the corner of the breadboard shown in the first image).

1 / 3

Step 7 : Great. Now it's time to program the Arduino. Use the following code and upload it from the Arduino IDE on your computer to the Arduino board.

```
// Code partially based on "Transistor Multiplexing 3x3 LEDs" by Marty Peltz
(https://www.instructables.com/id/Multiplexing-with-Arduino-Transistors-I-ma
de/)
#define COL_1_CATHODE 2
#define COL_2_CATHODE 3
#define COL_3_CATHODE 4
#define ROW_1_ANODE 5
#define ROW_2_ANODE 6
#define ROW_3_ANODE 7
#define LIGHT_LEVEL_INIT 200
#define MAX_BRIGHTNESS 999
#define PATTERN_TIME_INIT 20
int brightness = LIGHT_LEVEL_INIT;
int pattern_time = PATTERN_TIME_INIT;
void setup() {
 Serial.begin(9600);
 // Setup LED/transistor pins digital write pins
 pinMode(COL_1_CATHODE, OUTPUT);
 pinMode(COL_2_CATHODE, OUTPUT);
 pinMode(COL_3_CATHODE, OUTPUT);
 pinMode(ROW_1_ANODE, OUTPUT);
 pinMode(ROW_2_ANODE, OUTPUT);
```

Though the code is severely lacking in comments, I highly suggest that you step through it to understand how an LED multiplexer works. A web search for descriptions in other projects may do some good as well.

If all was successful, your system should look like this:

If one or more LEDs does not come on as it should, debugging can be made easier by enabling all of the LEDs at the same time. To do this, comment out all of the function calls to `multiplex_LEDs()` that are in `loop()` and uncomment the one at the bottom:

```
multiplex_LEDs(0b111, 0b111, 0b111);
```

If you want to understand (at least in part) how I am mapping the change in the potentiometer resistance to the speed or brightness in `map_brightness_value()`, take a look at Paul McWhorter's video (https://www.youtube.com/watch?v=QsYcYknKbB0) (most of his videos seem

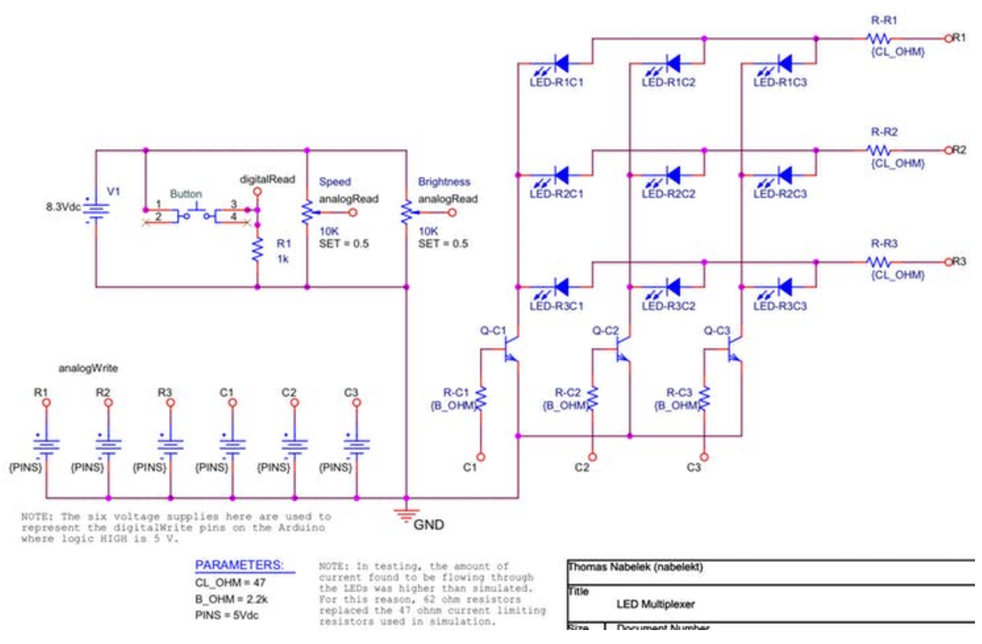
pretty great – very informative and well explained). `map_speed_value()` uses a power equation that I devised rather than a linear equation, but the basic idea is the same.

You may notice that adjusting the brightness can effect the speed of the pattern as well. I believe this is because of the way that the `multiplex_LEDs()` function is written. If the function were instead written to use clock time rather than iteration count for `pattern_time` in determining how long a particular LED configuration is held, I believe this issue would be resolved.

Stage 1C

In this stage we continue with the circuit completed in the last stage and add a pushbutton, two potentiometers, a toggle switch, and a battery to make the circuit a bit more interesting and independent of power provided by the computer via USB.

Here's the full circuit schematic:



You may notice that the voltage on the positive breadboard rail is unregulated – it comes straight from the battery. Because the only components connected to that node are the switch, button, and potentiometers, this is not concerning. If other components such as the LEDs were also connected to this rail, it would probably be advisable to regulate the voltage through the Arduino using the Arduino's Vin and 5V pins (the Arduino accepts 7-12 V and regulates it down to 5 V). One thing I learned in doing this project is that "9V" batteries can range in voltage, typically 7.2-9.6 V depending on its type, when fully charged (see here). I measured one of my Li-ion batteries at 8.33 V when fully charged.

Now let's continue finish the circuit started in Stage 1A/B.

Component List:

- 9 V battery (I'm using one of these (http://www.amazon.com/gp/product/B0746FV8BF))
- Battery connector like these (http://www.amazon.com/gp/product/B00BXX42LQ) or this (https://www.digikey.com/product-detail/en/mpd-memory-protection-devices/BH9VW/BH9VW-ND/221547)
- Toggle switch (https://www.digikey.com/product-detail/en/e-switch/100SP1T1B4M2QE/EG2355-ND/378824)
- Pushbutton (https://www.digikey.com/product-detail/en/te-connectivity-alcoswitch-switches/1-1825910-0/450-1652-ND/1632538)
- 10 kΩ resistor
- 2x 10 kΩ potentiometer (https://www.digikey.com/product-detail/en/tt-electronics-bi/P120PK-Y25BR10K/987-1710-ND/5957454)
- wire (jumper wires like these, (https://www.digikey.com/product-detail/en/PRT-12795/1568-1512-ND) and these (https://www.amazon.com/gp/product/B079FKJ4S3)or these, (https://www.digikey.com/product-detail/en/global-specialties/WK-2/BKWK-2-ND/5231341) can help a lot and save you the pain of cutting and stripping wire)

Step 1 : Add the toggle switch and battery on the left side of the breadboard from Stage 1A/B.

1 / 2

Step 2 : Add the pushbutton. Wire the signal to pin 8 on the Arduino (white jumper in pictures). Put the 10 kΩ resistor between the signal leg of the button and GND.

Step 3 : Add the two potentiometers. The pitch between the potentiometer legs is different that that between the holes of a standard breadboard (0.1" or 2.54 mm), so I had to bend the center leg of each potentiometer a bit to make them fit. The mounting points on the sides can be bent up and out of the way. Wire the left potentiometer (pattern speed adjustment) to pin A5 on the Arduino (blue jumper in pictures). Wire the right potentiometer (brightness adjustment) to pin A4 on the Arduino (green jumper in pictures).

Step 4 : Make sure that the toggle switch is flipped to OFF as shown in the pictures (open circuit). Wire the positive voltage rail to Vin on the Arduino.

1 / 3

1 / 2

Step 5 : Let's program the Arduino. The code is made up of the three separate files given below. Copy and paste them, or just grap them from the GitHub repository (https://github.com/nabelekt/LED_Multiplexer). The three files should be all together in a folder called LED_multiplexer_arduino. The directory/file structure on your computer should look like this:

LED_multiplexer_arduino
|––– LED_multiplexer.h
|––– LED_multiplexer_arduino.ino
|––– patterns.c

LED_multiplexer.h:

```
#pragma once // Prevent cyclic inclusion
#include <stdbool.h>
bool button_pushed;
void multiplex_LEDs(int, int, int);
bool update_rows(int);
void check_button();
int map_speed_value(int);
int map_brightness_value(int);
void pattern_A();
void pattern_B();
void pattern_C();
void pattern_D();
void pattern_E();
void pattern_F();
void pattern_G();
void pattern_H();
```

LED_multiplexer_arduino.ino:

```
// Code partially based on "Transistor Multiplexing 3x3 LEDs" by Marty Peltz
(https://www.instructables.com/id/Multiplexing-with-Arduino-Transistors-I-ma
de/)
#include "LED_multiplexer.h"
#include "patterns.c"
#include <math.h>
#define COL_1_CATHODE 2
#define COL_2_CATHODE 3
#define COL_3_CATHODE 4
#define ROW_1_ANODE 5
#define ROW_2_ANODE 6
#define ROW_3_ANODE 7
#define BUTTON_PIN 8
#define BRIGHTNESS_POT_PIN A4
#define SPEED_POT_PIN A5
#define LIGHT_LEVEL_INIT 100
#define MAX_BRIGHTNESS 1000
#define PATTERN_TIME_INIT 20
#define NUM_PATTERNS 8
// Setup pattern function pointers
void (*patterns[NUM_PATTERNS])(void) =
 {&pattern_A, &pattern_B, &pattern_C, &pattern_D, &pattern_E,
```

patterns.c:

```
#include "LED_multiplexer.h"
void pattern_A() {
 // Single light on around in a circle CW with center light lit
 multiplex_LEDs(0b001, 0b010, 0b000);
 multiplex_LEDs(0b010, 0b010, 0b000);
 multiplex_LEDs(0b100, 0b010, 0b000);
 multiplex_LEDs(0b000, 0b110, 0b000);
 multiplex_LEDs(0b000, 0b010, 0b100);
 multiplex_LEDs(0b000, 0b010, 0b010);
 multiplex_LEDs(0b000, 0b010, 0b001);
 multiplex_LEDs(0b000, 0b011, 0b000);
 button_pushed = false;
}
void pattern_B() {
 // Single light on around in a circle CCW with center light lit
 multiplex_LEDs(0b001, 0b010, 0b000);
 multiplex_LEDs(0b000, 0b011, 0b000);
 multiplex_LEDs(0b000, 0b010, 0b001);
 multiplex_LEDs(0b000, 0b010, 0b010);
 multiplex_LEDs(0b000, 0b010, 0b100);
 multiplex_LEDs(0b000, 0b110, 0b000);
 multiplex_LEDs(0b100, 0b010, 0b000);
```

Open LED_multiplexer_arduino.ino in the Arduino IDE and upload it to your Arduino.

Once the code is uploaded, unplug the USB cable from your computer and/or the Arduino. Flip the toggle switch. If you have been successful, your system should operate like this:

Congrats! Stage 1 and the first prototype adjustable LED multiplexer are complete!

Stage 2

The end goal of this stage is to have the same system as that at the end of Stage 1 but with the Arduino replaced with only necessary components. However, it is good to test out our Stage 2 circuit with an Arduino before replacing the Arduino with a microcontroller and company.

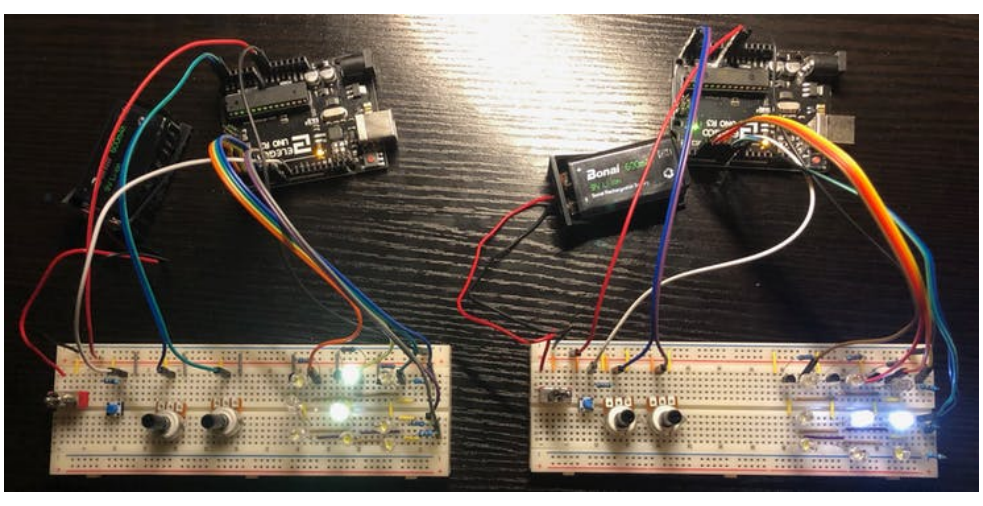
Repeat Stage 1 so that you have a duplicate prototype. Alternatively, you can make adjustments to the Stage 1 circuit and not retain the result of Stage 1. I wanted to keep the result of each stage, so I started Stage 2 by repeating almost exactly what was done in Stage 1, and I will assume here that you do the same.

Component List:

- Everything from the component lists of Stages 1A/B and 1C combined

Steps : Follow the steps from Stages 1A/B and 1C, but note that in this second iteration, the toggle switch, pushbutton, and potentiometers should be a bit more crowded together on the left side in order to make room for the microcontroller unit (MCU) that we are going to replace the Arduino with.

You should now have duplicate systems:



Set your Stage 1 circuit aside. None of the steps below will instruct you to make changes to the Stage 1 circuit.

Article A (https://www.arduino.cc/en/Main/Standalone) and Article B (https://www.makeuseof.com/tag/dont-spend-money-on-an-arduino-build-your-own-for-much-less/) were both helpful in figuring out how to go about replacing the Arduino with minimal components (though I later found this (https://www.arduino.cc/en/Tutorial/ArduinoToBreadboard) too, and this article (https://predictabledesigns.com/from-arduino-prototype-to-manufacturable-product/)provides a bit more in-depth discussion on the matter). I actually jumped back and forth between Article A and Article B to do what they describe (for the purpose of this tutorial, you can skip doing this):

We want to do basically the same thing, but instead of using the ATmega328P microcontroller that the Arduino uses, we'll use the ATtiny84 in an effort to cut down on footprint (space taken up by the MCU), power consumption, cost, etc., and to make this process a little more interesting/challenging.

The reason for the choice of the ATtiny84 in particular was that the ATtiny85 is very widely used and I know that people have programmed the ATtiny85 using an Arduino like I wanted to, so I probably wouldn't run into to much trouble. The ATtiny84 is kind of the big brother of the ATtiny85. The 84 offers more I/O pins – which are needed for our adjustable LED multiplexer – but is otherwise very similar to the 85. Also, the maximum current ratings for the ATtiny84 – 40 mA per pin and 200 mA Vcc and GND as listed on page 174 of its datasheet – (http://ww1.microchip.com/downloads/en/DeviceDoc/doc8006.pdf) are the same as that of the Arduino (and its ATmega328P microcontroller). I initially planned to make use of the ATtiny24 but soon found that it did not have enough program memory (the program memory size, EEPROM size, and RAM size is the only difference that I know of between the ATtiny24, 44, and 84).

I first figured out how to program the Attiny84 by following this ATtiny85 video, (https://www.youtube.com/watch?v=i9WOwDrpRKs&t=150s) remapping the pins using the diagram below (view it larger here (https://raw.githubusercontent.com/nabelekt/LED_Multiplexer/master/stage_2/ATINY-PinOut-Diagram.png), we will use it later), and working with a different boards library in the Arduino IDE, as I will describe.

We will program the ATtiny84 using the SPI protocol (https://www.arduino.cc/en/reference/SPI) (see section 19.5 Serial Programming (page 163) of the ATtiny84 datasheet

Programming (page 165) of the ATtiny84 datasheet (http://ww1.microchip.com/downloads/en/DeviceDoc/doc8006.pdf)) and the Arduino used in the first part of Stage 2. Note that there are other ways to program an AVR MCU like the ATtiny84, such as using a separate programmer like the AVRISP mkII (http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-42093-AVR-ISP-mkII_UserGuide.pdf). I chose to use the method that I will outline in the procedure below because it uses the already familiar Arduino IDE, requires little or no code modification, and does not require any additional hardware.

Enough discussion for now, let's get to it:

Component List:

- A smaller solderless breadboard (https://www.digikey.com/product-detail/en/dfrobot/FIT0096/1738-1326-ND/7597069) (not absolutely necessary, but will make initial testing and debugging easier)
- ATtiny84 MCU (https://www.digikey.com/product-detail/en/microchip-technology/ATTINY84A-PU/ATTINY84A-PU-ND/2774082)
- 10 kΩ resistor
- 1 Cree C512A-WNN-CZ0B0152 LED (https://www.digikey.com/product-detail/en/cree-inc/C512A-WNN-CZ0B0152/C512A-WNN-CZ0B0152CT-ND/6138557) (you could borrow one from the 3x3 LED matrix)
- 2x 10 µF capacitor like this (https://www.digikey.com/product-detail/en/tdk-corporation/FG24X7R1A106KRT00/445-181259-ND/)
- L7805C 5V Linear Voltage Regulator (https://www.digikey.com/product-detail/en/stmicroelectronics/L7805CV/497-1443-5-ND/)
- 6 jumper wires like those used in previous stages

Step 1 : Unplug all jumper wires from the Arduino used in the first part of Stage 2 (your duplication of Stage 1's system).

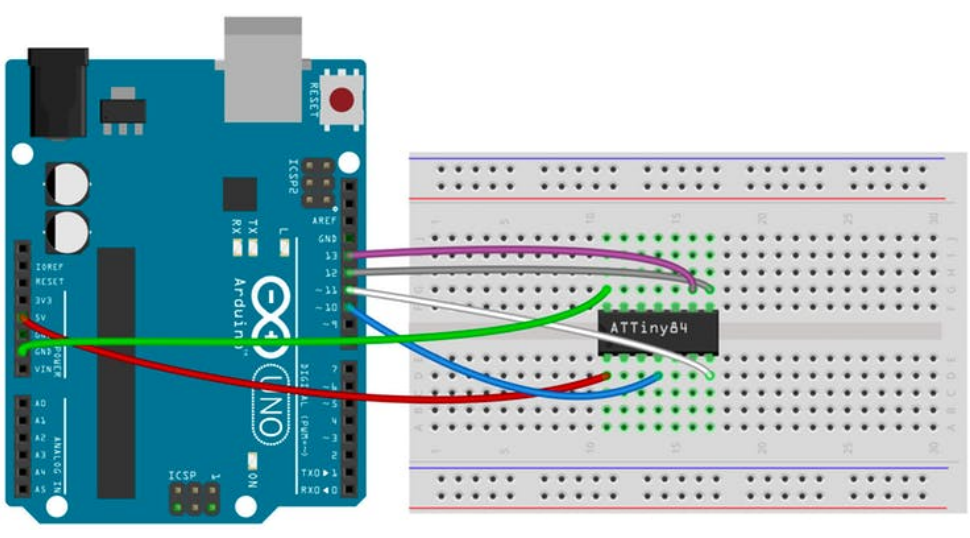
Step 2 : Plug the Arduino into your computer. In the Arduino IDE, select Tools > Board > Arduino/Genuino Uno. Find and select your Arduino under Tools > Port.

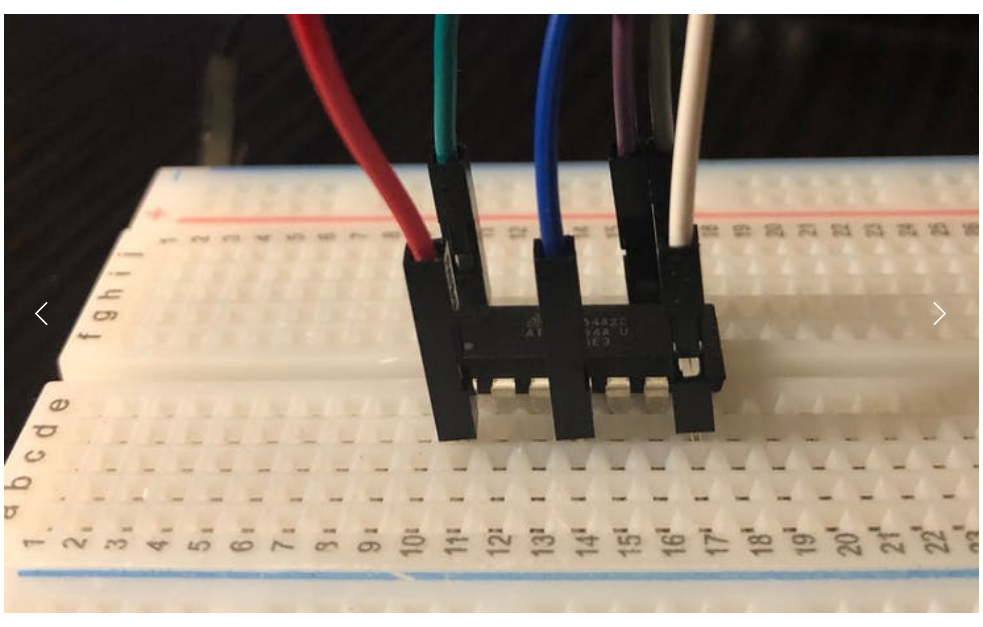
Step 3 : Choose File > Examples > 11.ArduinoISP > ArduinoISP. Upload this sketch to your board. This programs the Arduino to act as an ISP (In-System Programmer) which will allow us to use it to program our MCU.

Step 4 : Place the MCU bridging the gap of the small breadboard (not the same one with your circuit).

Step 5 : Disconnect the Arduino from your computer and make sure that it is not powered.

Step 6 : Refer to the diagram above and use the physical pin designations shown closest to the depiction of the MCU. E.g., pin 1 is in the top left corner of the MCU.
Connect pin 1 Vcc to 5V on the Arduino.
Connect pin 4 RESET to pin 10 on the Arduino.
Connect pin 7 MOSI to pin 11 on the Arduino.
Connect pin 8 MISO to pin 12 on the Arduino.
Connect pin 9 SCK (labeled as "USCK" on the diagram) to pin 13 on the Arduino.
Connect pin 14 GND to GND on the Arduino.





1 / 2

Step 7 : Wire a 10 µF capacitor between RESET and GND on the Arduino (may not be necessary, (https://forum.arduino.cc/index.php?topic=104435.0) but I spent over an hour learning the hard way that it was necessary for me). My capacitors do not have polarity. If yours does (https://learn.sparkfun.com/tutorials/polarity/all#electrolytic-capacitors), make sure that you connect the positive leg to RESET and the negative to GND.

Step 8 : In the Arduino IDE, open up the Preferences, pop open the Additional Boards Manager URLS window, and paste the following on its own line: `https://raw.githubusercontent.com/damellis/attiny/ide-1.6.x-boards-manager/package_damellis_attiny_index.json` . Click OK and then close and reopen the Arduino IDE (I am not sure if this last action is necessary or not).

Step 9 : Go to Tools > Board > Board Manager. Search for "attiny". You should see the “attiny by David A. Mellis” board library (https://github.com/damellis/attiny). (https://github.com/damellis/attiny) Select the latest version (I am using 1.0.2) and install. This adds support for ATtiny microcontrollers to the Arduino IDE. Once the install is complete, you may need to close and reopen the Arduino IDE again.

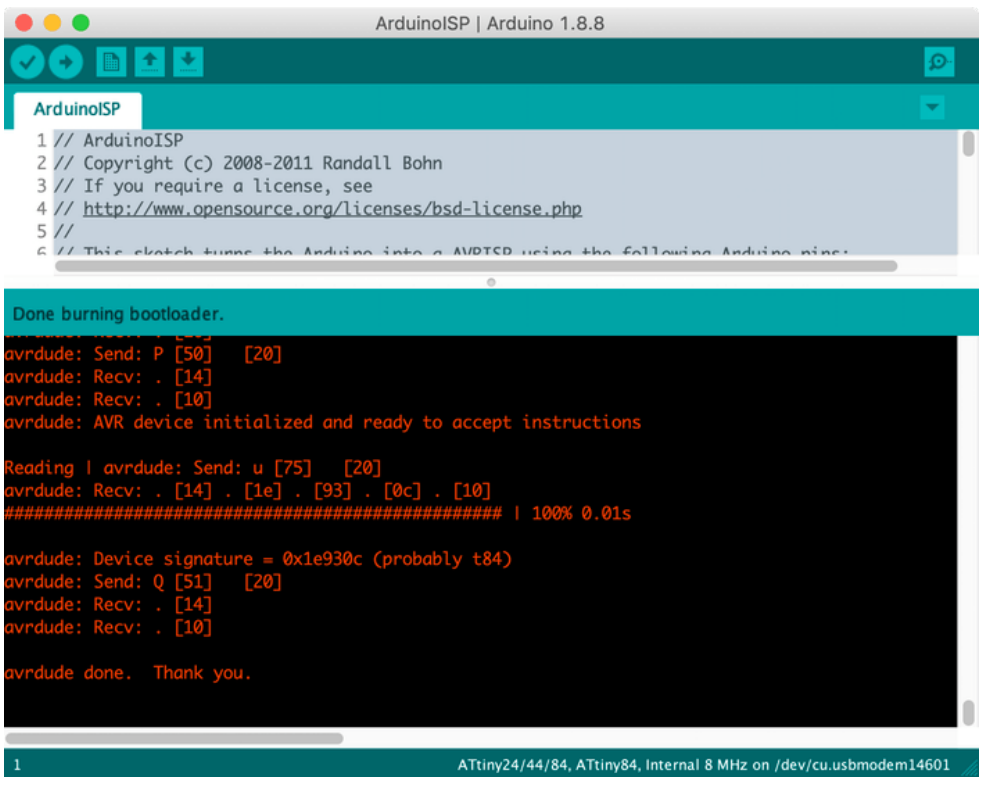
Step 10 : Go to Tools > Board and you should now see a section called "ATtiny Microcontrollers." Select "ATtiny24/44/84". Now, under Tools select Processor > ATtiny84 and Clock > Internal 8 MHz.

Unlike the breadboard Arduino recreation described in Article A and Article B thats I referenced above, we will use the oscillator internal to the ATtiny84 rather than an external clock/oscillator. I highly suggest that you search the interwebs and learn about the pros and cons of internal vs. external oscillators.

Step 11 : Plug the Arduino back into your computer. Find and select your Arduino under Tools > Port.

Step 12 : Select Tools > Programmer > Arduino as ISP.

Step 13 : Select Tools > Burn Bootloader. If successful you should see something like the following (I have verbose output enabled in the Preferences – you probably should too):

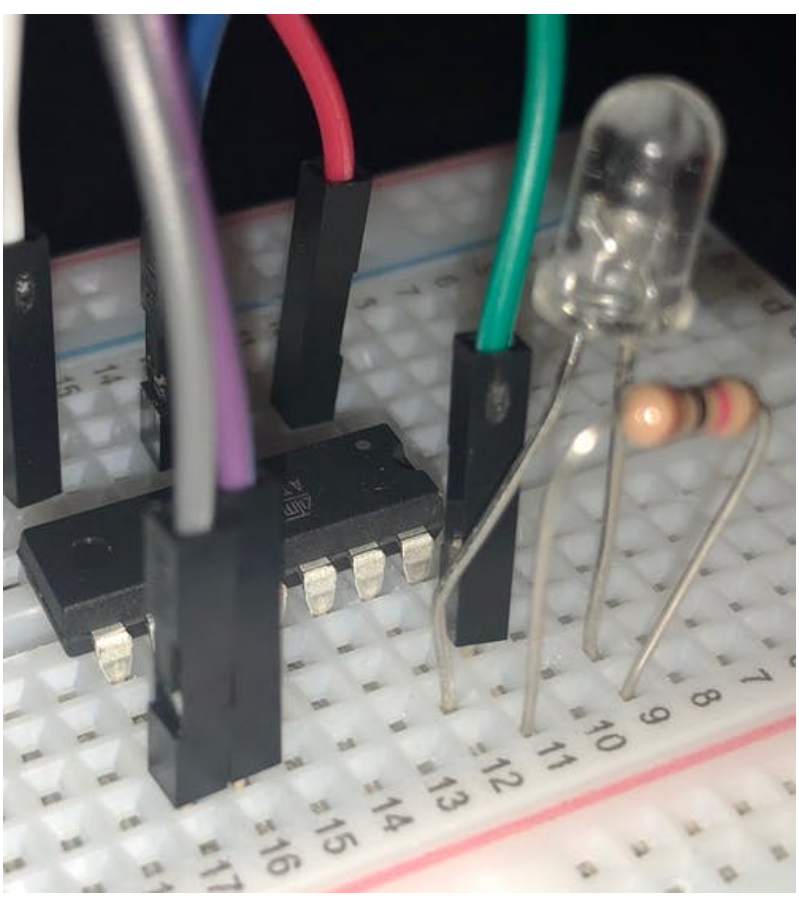


Bootloader successful burned to ATTiny84 MCU

As long as you see "Done burning bootloader," you should be good to go. You have just programmed the MCU with the bootloader that will allow our code to run. You can read more about what the bootloader does here (https://www.arduino.cc/en/Hacking/Bootloader), here (https://www.baldengineer.com/arduino-bootloader.html) and here (https://www.arduino.cc/en/Hacking/Bootloader). If we were using a different programmer, such as the AVRISP mkII (http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-42093-AVR-ISP-mkII_UserGuide.pdf) that I mentioned above, we would not need to burn the bootloader (see second and third post here (https://forum.arduino.cc/index.php?topic=522951.0)).

Step 14 : Disconnect the Arduino from your computer so that it is not powered.

Step 15 : Using the diagram above again, now use the pin designations that I have circled in yellow. These are the pin designations that we will use in our Arduino code. E.g., both pin 0 and pin A0 are what we previously considered to be pin 13. Plug the anode (longer leg) of the LED into the same node on the breadboard as pin 0 and the cathode into a node by itself. Put the 10 kΩ current limiting resistor between the cathode of the LED and GND.



1 / 2

Step 16 : Upload the code below to the ATtiny84 just as you would to the Arduino itself – just make sure that the capacitor described in Step 7 is in place and that "ATtiny24/44/84", "ATtiny84", and "Internal 8 MHz" are still selected for Board, Processor, and Clock, respectively.

```
/*
 modified from http://www.arduino.cc/en/Tutorial/Blink
*/
#define LED_PIN 0
void setup() {
 pinMode(LED_PIN, OUTPUT);
}
void loop() {
 digitalWrite(LED_PIN, HIGH);   // turn the LED on (HIGH is the voltage leve
l)
 delay(500);                       // wait
 digitalWrite(LED_PIN, LOW);    // turn the LED off by making the voltage LO
W
 delay(500);                       // wait
}
```

If you have been successful, you should have the following:

We now know that we can program the ATtiny84. Excellent!

If you have not achieved the desired result, try running through the Troubleshooting List in Step 27 below, but note that some of those items are specific to troubleshooting the programming of the MCU after it has been integrated into our LED multiplexer circuit.

Using the internal oscillator means that the only primary components that we need to replace the Arduino are the voltage regulator – to drop the voltage supplied by the battery to the 5 V that the MCU can accept – and the MCU itself.

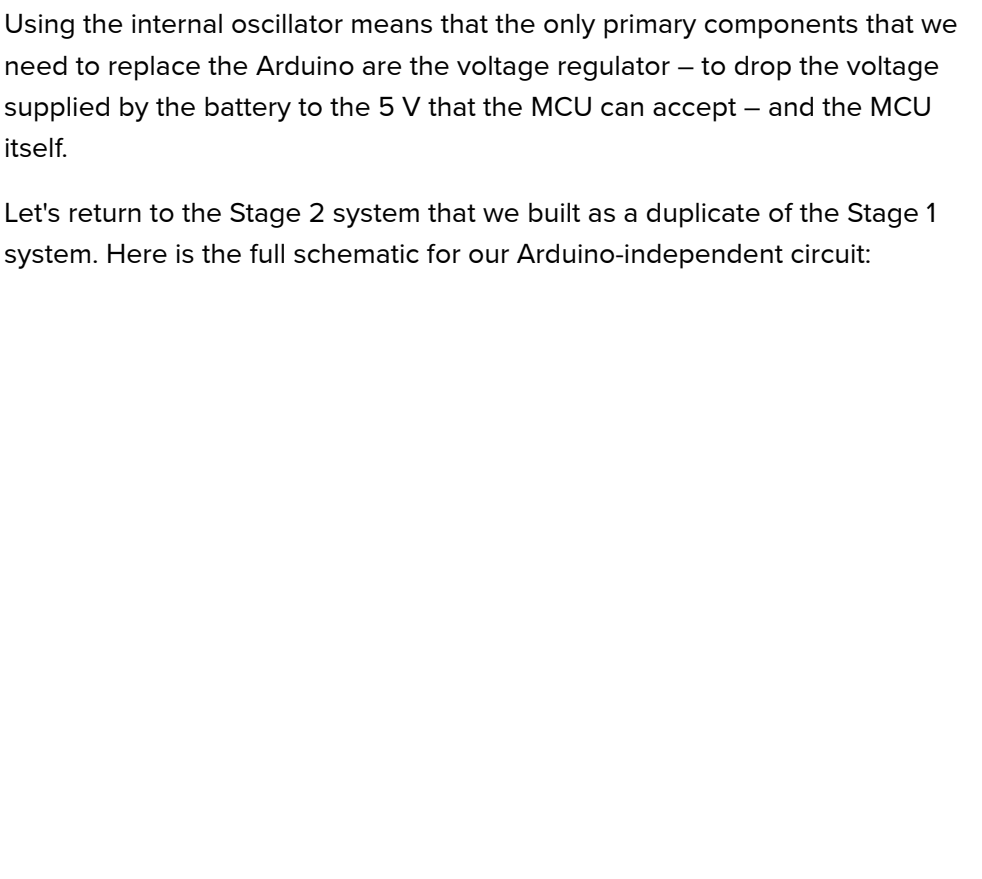
Let's return to the Stage 2 system that we built as a duplicate of the Stage 1 system. Here is the full schematic for our Arduino-independent circuit:

While completing the steps below, refer to the schematic above as it is helpful.

Step 17 : Remove the jumper cables that previously went to GND and Vin on the Arduino.

Step 18 : From the left side of the board, remove the toggle switch, the jumper wire between the toggle switch and positive voltage rail, and the positive battery lead.

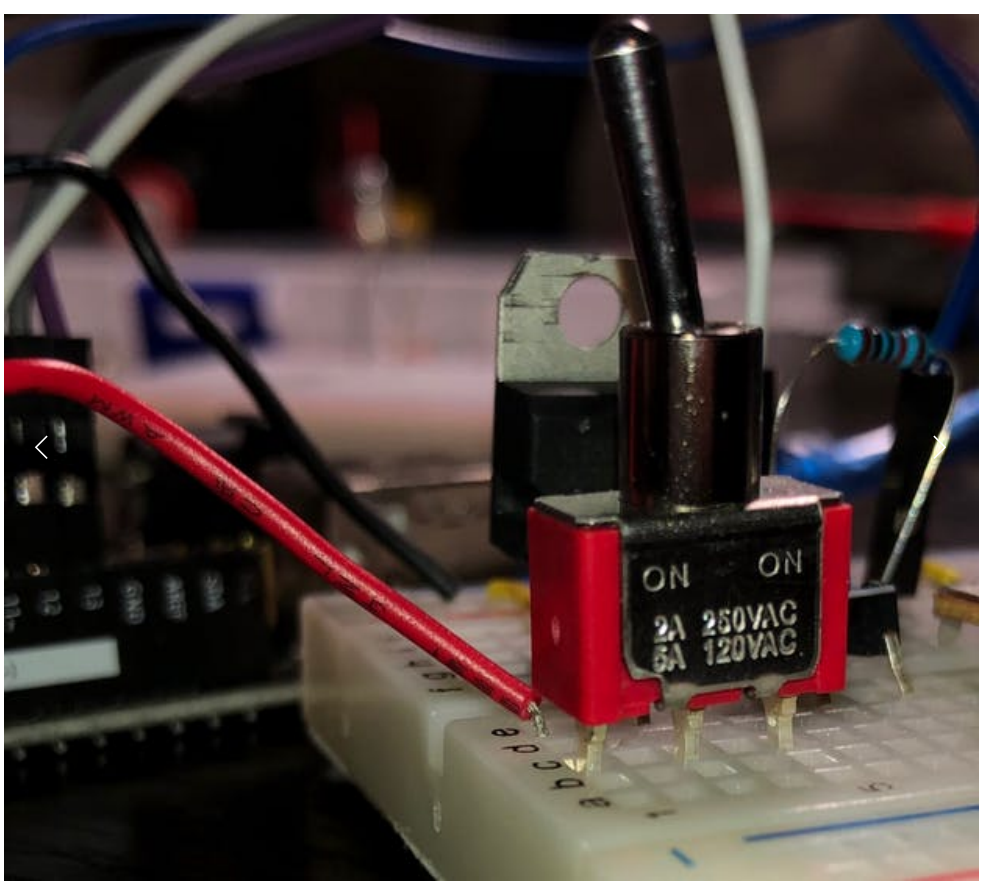
Step 19 : Place the voltage regulator, 10 µF capacitor, positive battery lead, and three wires as shown.



1 / 2

Step 20 : Replace the toggle switch in the new location shown below. Ensure

that the switch it is flipped so that the power is OFF (open circuit).



1 / 2

Step 21 : Place the MCU in the center of the board bridging the gap. Wire physical pin 0 Vcc to the positive voltage rail and physical pin 1 GND to the ground rail.

Step 22 : As in Step 6 above, refer to the pinout diagram and use the physical pin designationsof the MCU. E.g., pin 1 is in the top left corner of the MCU. We are going to rewire the jumper cables that we unplugged from the Arduino in Step 1. I will use the resistor designations found in the diagram at the beginning of Stage 1A/1B, but it is probably easiest to look at the pictures below.
Connect the jumper from R-R3 to pin 8.
Connect the jumper from R-R2 to pin 9.
Connect the jumper from R-R1 to pin 10.
Connect the jumper from R-C3 to pin 11.
Connect the jumper from R-C2 to pin 12.
Connect the jumper from R-C1 to pin 13.
Connect the jumper from the pushbutton to pin 5.
Connect the jumper from the left potentiometer (pattern speed adjustment) to pin 6.
Connect the jumper from the right potentiometer (brightness adjustment) to pin 7.

1 / 4

We now have all of the connections that we need from/to our MCU to/from our circuit.

Step 23 : Let's set the MCU up to be programmed again:
Connect pin 4 RESET to pin 10 on the Arduino.
Connect pin 7 MOSI to pin 11 on the Arduino.
Connect pin 8 MISO to pin 12 on the Arduino.
Connect pin 9 SCK (labeled as "USCK" on the diagram) to pin 13 on the Arduino.
Pin 2 V is already wired to our positive voltage rail on the breadboard, and pin 14 GND is already wired to the ground rail.
Wire the ground rail to pin GND on the Arduino.

1 / 3

Your Arduino should already have the ArduinoISP sketch loaded on to it from earlier, and the MCU already has the bootloader, so we don't need to repeat those steps.

Step 24 : As in Step 5 from Stage 1C, we need to setup our three code files. Either grab the LED_multiplexer_attiny84 folder from the GitHub repository (https://github.com/nabelekt/LED_Multiplexer), or do the following:

a) Duplicate the LED_multiplexer_arduino folder that you have (with its contents). Name the folder LED_multiplexer_attiny84.

b) Rename the LED_multiplexer_arduino.ino file to LED_multiplexer_attiny84.ino so that you have:

LED_multiplexer_attiny84
|––– LED_multiplexer.h
|––– LED_multiplexer_attiny84.ino
|––– patterns.c

c) Open LED_multiplexer_attiny84.ino, delete all of its contents, and copy and pate the following into it:

```
// Code partially based on "Transistor Multiplexing 3x3 LEDs" by Marty Peltz
(https://www.instructables.com/id/Multiplexing-with-Arduino-Transistors-I-ma
de/)
#include "LED_multiplexer.h"
#include "patterns.c"
#include <math.h>
#include <SoftwareSerial.h> // Used for printing to Serial Monitor for debug
#define COL_1_CATHODE 0  // Physical pin 13
#define COL_2_CATHODE 1  // Physical pin 12
#define COL_3_CATHODE 2  // Physical pin 11
#define ROW_1_ANODE 3  // Physical pin 10
#define ROW_2_ANODE 4  // Physical pin 9
#define ROW_3_ANODE 5  // Physical pin 8
#define BUTTON_PIN 8  // Physical pin 5
#define BRIGHTNESS_POT_PIN A6   // Physical pin 7
#define SPEED_POT_PIN A7  // Physical pin 6
#define LIGHT_LEVEL_INIT 100
#define MAX_BRIGHTNESS 1000
#define PATTERN_TIME_INIT 20
#define NUM_PATTERNS 8
// Setup pattern function pointers
void (*patterns[NUM_PATTERNS])(void) =
```

A diff between LED_multiplexer_arduino.ino and LED_multiplexer_attiny84.ino can be found here. (http://www.mergely.com/ymRTCRSr/)There, you can look at the files side by side and see what was changed to support the ATtiny84 rather than the Atmega328p on the Arduino. The primary changes were:

- different pin assignments – as mapped out in that pin diagram given towards the beginning of Stage 2
- swapping the `HardwareSerial` object that is already declared for us as `Serial` for a `SoftwareSerial` object that we declare as `Monitor` to

`Serial` for a `SoftwareSerial` object that we declare as `Monitor` to allow for printing to the Arduino IDE serial monitor. This is only used for debugging, so I have it commented out.

Step 25 : Temporarily disconnect the jumper leading to the brightness (right) potentiometer. I found that having the potentiometer connected to the MCU at the same pin used for MOSI interferes with programming.

Step 26 : Using the switch on the left, toggle the power to the breadboard circuit ON so that the MCU is powered.

Step 27 : Upload the LED_multiplexer_attiny84.ino code to the MCU as in Step 16.

Some of your LEDs will probably blink rapidly while the MCU is being programmed. This blink occurs as a result of the logic HIGH and LOW voltages used to transmit our program code also applying voltage to the anodes/cathode branches of the LED multiplexer.

Assuming that you have verbose output enabled in the Arduino IDE preferences, make sure that your console looks something like the following. There are a number of things here that will indicate success, I have highlighted some of them:

Successful programming of ATtiny84 MCU

If what you have looks like this screenshot, great! Go to step 28.

If instead you have something that looks like the following, go through the Troubleshooting List below:

Unsuccessful programming of ATtiny84 MCU

Troubleshooting List

- ATtiny84 MCU and Arduino are wired as shown in Step 23 pictures
- Brightness potentiometer signal is disconnected from MCU
- Ground rail is connected to GND on Arduino
- Toggle switch is flipped to ON position
- You are using the same MCU used earlier with the bootloader already on it
- The Arduino has the ArduinoISP sketch successfully uploaded to it
- The 10 µF capacitor between RESET and GND is in place, as described in Step 7
- In the Arduino IDE, you have selected "ATtiny24/44/84", "ATtiny84", and "Internal 8 MHz" for Board, Processor, and Clock, respectively
- You have "Arduino as ISP" selected under Tools > Programmer
- Arduino is plugged in to computer and selected under Tools > Port

Step 28 : Toggle the power back to OFF. Reconnect the brightness potentiometer jumper wire to its previous position.

Step 29 : Unplug all jumper wires leading to the Arduino from your breadboard.

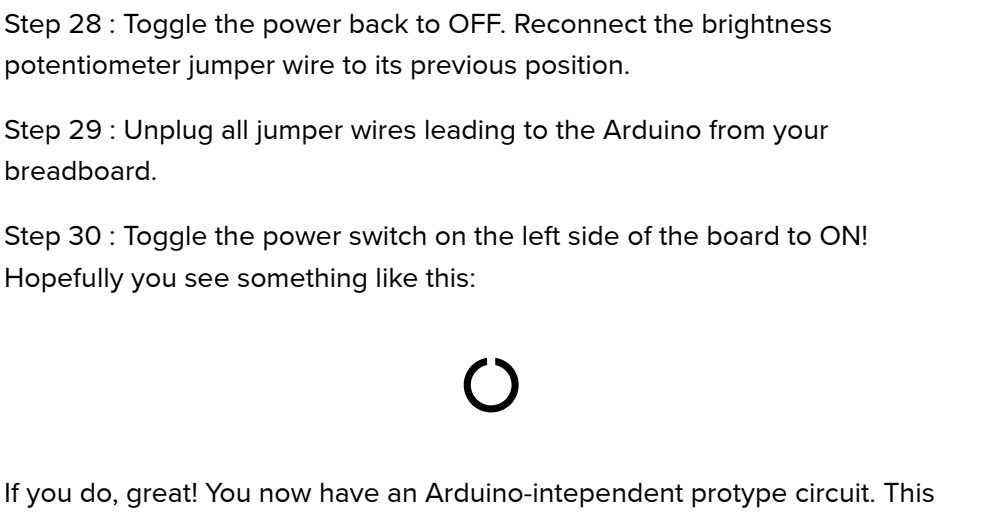
Step 30 : Toggle the power switch on the left side of the board to ON! Hopefully you see something like this:

If you do, great! You now have an Arduino-intependent protype circuit. This step is a big one in the Arduino prototype to manufacturable product process. You are done with Stage 2! *Side note:* Notice that when you flip the power switch on the Stage 2 prototype, the LED pattern beings immediately. However, when you flip the switch on the Stage 1 prototype, there is an almost two second delay before the LED pattern begins. I believe that this has to do with how the bootloader works.

If you do not have a working protype like that shown in the video, but the MCU was successfully programmed as shown in Step 27, and you think that printing messages from the MCU to the Arduino IDE Serial Monitor might be helpful, see the Debug Note below.

Debug Note

Initially, I made the mistake of regulating the voltage only for the MCU:



1 / 2 • Previous setup regulating only the voltage to the MCU

This caused the input voltage on every button press to be unregulated ~8 V at the button pin on the MCU. This too-high voltage would reset the MCU so that I got the following behavior:

Problem with previous setup regulating only the voltage to the MCU

This issue required some debugging to figure out and is the reason why we are regulating the voltage for the whole system. Fortunately, I don't think I fried anything.

To do that debugging, it was helpful to be able to print things out to the Arduino IDE Serial Monitor despite the MCU not having a serial port. This is where the SoftwareSerial Monitor came from in the LED_multiplexer_attiny84.ino code. I am not going to go into detail here about how to set that up, but if you need to do the same, checkout Tom Donnelly's helpful video (https://www.youtube.com/watch?v=9CX4i6rMXS8). Note that the jumper wires that he connects are just those wired in Step 23 above, in addition to the RX/TX jumper(s). If you get stuck on this, feel free to ask for help in the comments at the end.

Stage 3

Moving on to Stage 3, we want to move on from our solderless breadboard to something a bit more condensed and permanent. Optionally, this stage could certainly be skipped in the prototyping process if you as a developer/engineer wanted to move straight to designing a PCB (what we'll do in Stage 4) based off of the a Stage 2-equivalent circuit. In this stage we will use stripboard (https://en.wikipedia.org/wiki/Stripboard) and solder to build our prototype. Completing this process requires a lot of materials and tools:

Component List:

- 22 AWG wire like this (https://www.amazon.com/gp/product/B01180QKJ0) to solder to the board (I generally prefer solid core wire over stranded wire, but that is up to your preference)
- wire to program the MCU (jumper wires like these, (https://www.digikey.com/product-detail/en/PRT-12795/1568-1512-ND)and these o (https://www.amazon.com/gp/product/B079FKJ4S3)r these, (https://www.digikey.com/product-detail/en/global-specialties/WK-2/BKWK-2-ND/5231341)can help a lot and save you the pain of cutting and stripping wire) - whatever you have used in the previous stages
- A smaller solderless breadboard, (https://www.digikey.com/product-detail/en/dfrobot/FIT0096/1738-1326-ND/7597069) or just use the one from Stage 2
- Stripboard like this (https://www.amazon.com/gp/product/B00C9NXP94) - be sure that it it is at least 32 holes wide and 17 holes high so that you can fit your circuit (see images below)
- 3x 62 Ω resistors (I used these (http://amazon.com/gp/product/B07J48VNR7) but don't necessarily recommend them – pretty sure the tolerance is much greater than 1%)
- 3x 2.2 kΩ resistors
- 3x 2N3904 NPN BJTs (transistors) (I used these (https://www.amazon.com/gp/product/B06XRBLKDR))
- ATtiny84 MCU (https://www.digikey.com/product-detail/en/microchip-technology/ATTINY84A-PU/ATTINY84A-PU-ND/2774082)
- 10 kΩ resistor
- 6x header pins (https://www.digikey.com/product-detail/en/adam-tech/PH1-02-UA/2057-PH1-02-UA-ND/9830266) - you need 6 total: 2x1, 2x1, 1x1, and 1x1; see images below. The 2x1 pins can be broken/cut apart to have 2 1x1 pins, but it may just be easier to buy separate 1x1 pins.
- 1x 2-position jumper shunt/connector (https://www.digikey.com/product-detail/en/SPC02SYAN/S9001-ND/76375)
- 9x Cree C512A-WNN-CZ0B0152 LEDs (https://www.digikey.com/product-detail/en/cree-inc/C512A-WNN-CZ0B0152/C512A-WNN-CZ0B0152CT-ND/6138557)
- 2x 10 µF capacitor like this (https://www.digikey.com/product-detail/en/tdk-corporation/FG24X7R1A106KRT00/445-181259-ND/) - 1 of these is to use in the programming process. You can use the same one used in Stage 2.
- 9 V battery (I'm using one of these (http://www.amazon.com/gp/product/B0746FV8BF))
- Battery connector like these (http://www.amazon.com/gp/product/B00BXX42LQ)or this (https://www.digikey.com/product-detail/en/mpd-memory-protection-devices/BH9VW/BH9VW-ND/221547)
- Toggle switch - this time I used this one (https://www.digikey.com/product-detail/en/nidec-copal-electronics/ATE1D-2M3-10-Z/563-1157-ND/1792018) because I don't think I could get the one used in the previous stages through the stripboard holes.
- Pushbutton (https://www.digikey.com/product-detail/en/te-connectivity-alcoswitch-switches/1-1825910-0/450-1652-ND/1632538)
- 2x 10 kΩ potentiometer (https://www.digikey.com/product-detail/en/tt-electronics-bi/P120PK-Y25BR10K/987-1710-ND/5957454)
- L7805C 5V Linear Voltage Regulator (https://www.digikey.com/product-detail/en/stmicroelectronics/L7805CV/497-1443-5-ND/)
- 9 V battery (I'm using one of these) (http://www.amazon.com/gp/product/B0746FV8BF)
- Battery connector like these (http://www.amazon.com/gp/product/B00BXX42LQ) or this (https://www.digikey.com/product-detail/en/mpd-memory-protection-devices/BH9VW/BH9VW-ND/221547)
- Copper tape (https://www.digikey.com/product-detail/en/adafruit-industries-llc/3483/1528-2748-ND/9745247)

You will be soldering in this stage. You should either already know what materials and tools you prefer to use for soldering, or you should take advantage of the abundant resources on the interwebs giving an introduction to soldering. You will at least need:

- solder
- soldering iron and stand

you may also want:

- flux (https://www.digikey.com/product-detail/en/chip-quik-inc/CQ4LF/CQ4LF-ND/6227077)
- solder wick (https://www.digikey.com/product-detail/en/aven-tools/17542/243-1186-ND/2815651)

You should already have:

- Computer with Arduino IDE and USB cable to connect to Arduino
- Arduino Uno R3 or cheaper knock-off (these (https://www.amazon.com/gp/product/B01EWOE0UU) have worked very well for me) - use what you used to program the MCU in Stage 2

Other recommended tools for this stage are:

- Drill with 3/8" drill bit - maybe start smaller
- X-Acto knife or similar
- A circuit board holder like this one (https://www.amazon.com/gp/product/B00Q2TTQEE)
- A wire cutting tool like this one (https://www.amazon.com/Hakko-CHP-170-Stand-off-Maximum-Capacity/dp/B076M3ZHBV)
- Plastic cutter like this one (https://www.amazon.com/Hyde-Tools-45730-Knife/dp/B000C027ZE/)
- A cutting mat like this one (https://www.amazon.com/gp/product/B00251I5P4)

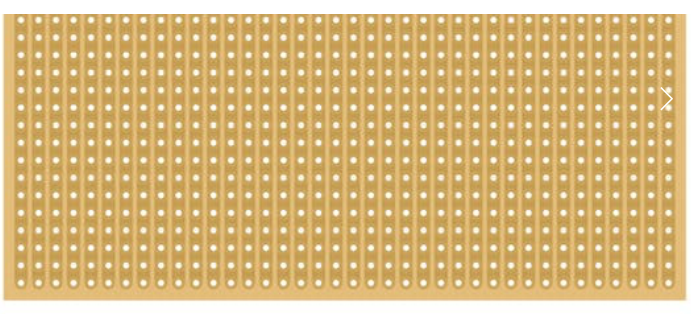
The same circuit diagram as that introduced in Stage 2 Step 16 also applies to our Stage 3 circuit.

We are going to program the MCU (still an ATtiny84) in the same way that we did in Steps 23-30 of Stage 2. I suggest swapping the unprogrammed MCU that you have for this stage with the MCU already programmed and integrated with the Stage 2 circuit. After making this swap, you can follow Steps 23-30 of Stage 2 to program the new MCU (you probably don't have to repeat Step 24) and ensure that it is programmed correctly with an already-proven circuit. Our Stage 3 circuit will provide MCU-programming capability, but it may be easier to address programming issues now than when everything is soldered in place.

Step 1 : Program the MCU as described in the previous paragraph.

Now it's time for us to prepare our stripboard. We need to get the circuit node layout on the stripboard – which currently looks like what is shown in the first image below – to look like what is shown in the second image so that we can solder our components and wires as shown in the third image.

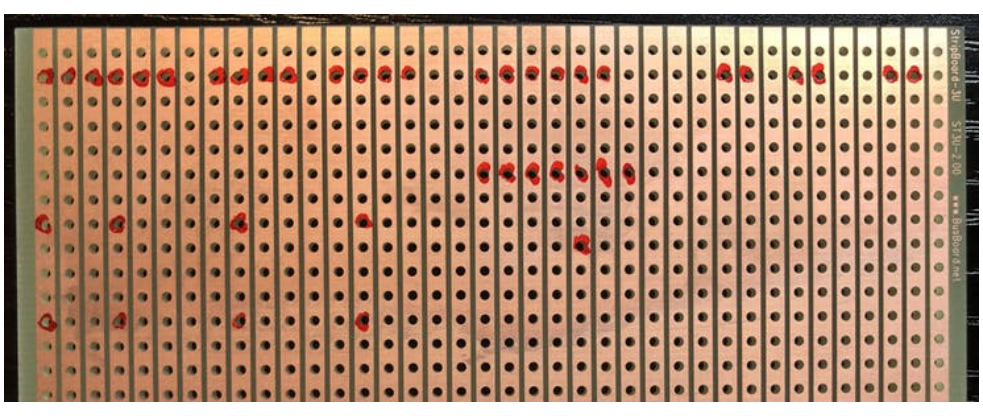
Note that these images are somewhat misleading because they show the copper strips on the same side of the board as the components. We will achieve our desired node configuration by breaking the conductive stripboard paths where necessary and using copper tape to create a GND rail/node across the top.



1 / 3

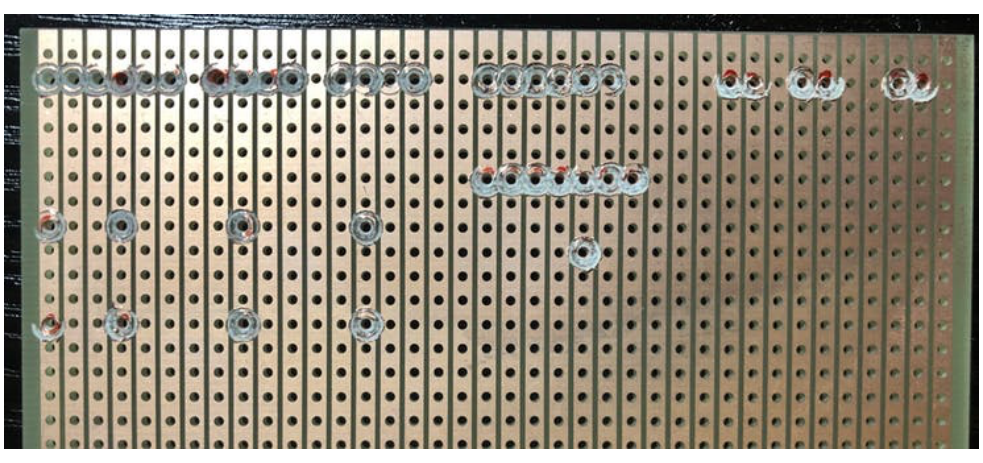
Because the images show the components on the same side of the board as the copper strips, we need to reflect the node layout shown, with the mirror line/axis of reflection running vertically down the center of the board.

Step 2 : Mark the board with a permanent marker as shown in the image below. This gives us our reflected node layout and will tell us where we need to break the conductive copper strips. Refer to the second image given above (but remember that you must reflect the layout).

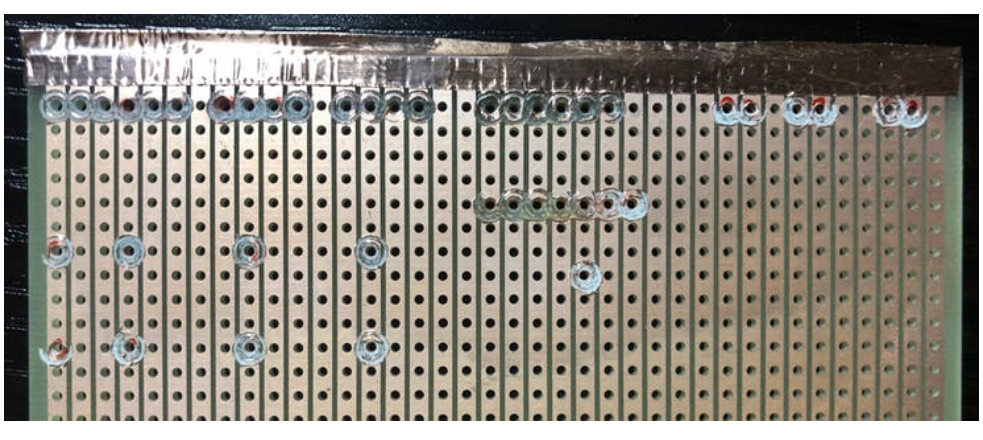


Step 3 : Break the conductive paths where you marked them in the previous step. There are different thoughts on how to go about doing this and tools that people use. (https://electronics.stackexchange.com/questions/94659/how-to-cut-the-tracks-of-a-stripboard) I used a drill. I believe I started with a 1/4" drill bit and moved up to a 3/8" drill bit. You should start smaller as well, and go slow. You don't want to drill any further into the board than it takes to break the conductive path.

You should use your multimeter/ohmmeter to ensure that there is no conductivity (https://www.ifixit.com/Guide/How+To+Use+A+Multimeter/25632#s64987)across the path/strip breaks.



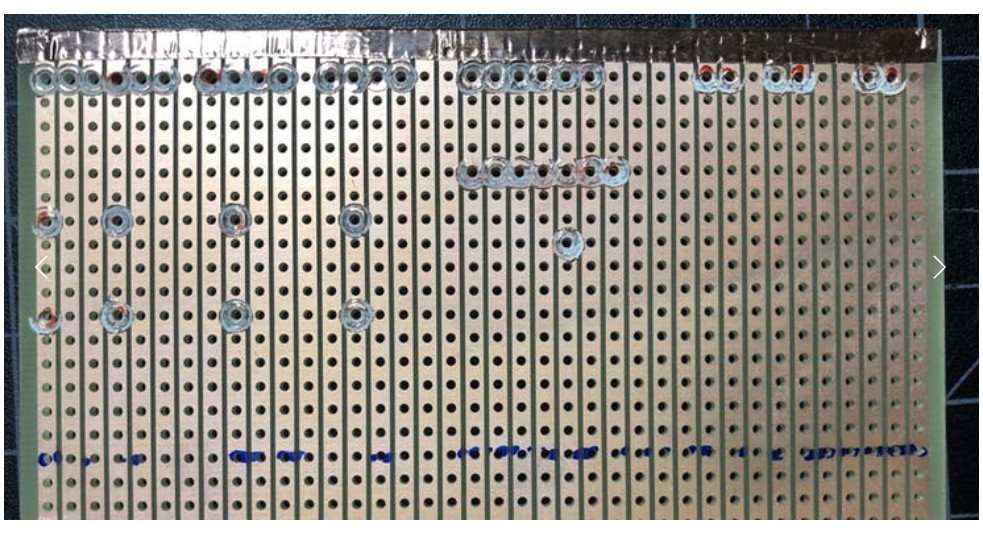
Step 4 : Create a GND rail/node across the top of the stripboard using the copper tape. Run the tape so that it covers the first row of holes, but so that component leads going through the second row holes won't make contact with it.



Flip the board over, place it on a cutting mat, and use an X-Acto knife or similar to trim off the excess copper tape.

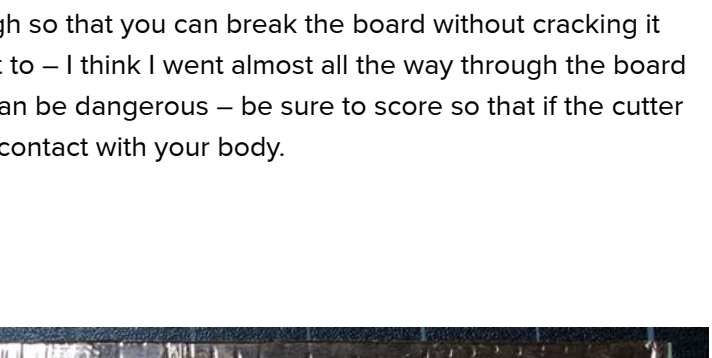
Step 5 : Cut the excess stripboard off to minimize the board's size. We need 16 rows of holes excluding those that we covered with the copper tape. Starting with the row of holes that we covered, count to find the 18th row and mark it with a permanent marker.

Use a tool like the plastic cutter listed above to score the board where you have marked it enough so that you can break the board without cracking it where you don't want to – I think I went almost all the way through the board with the cutter. This can be dangerous – be sure to score so that if the cutter slips, it will not make contact with your body.



1 / 2

Now that our stripboard is prepped, we'll solder our components to the board in the phases:



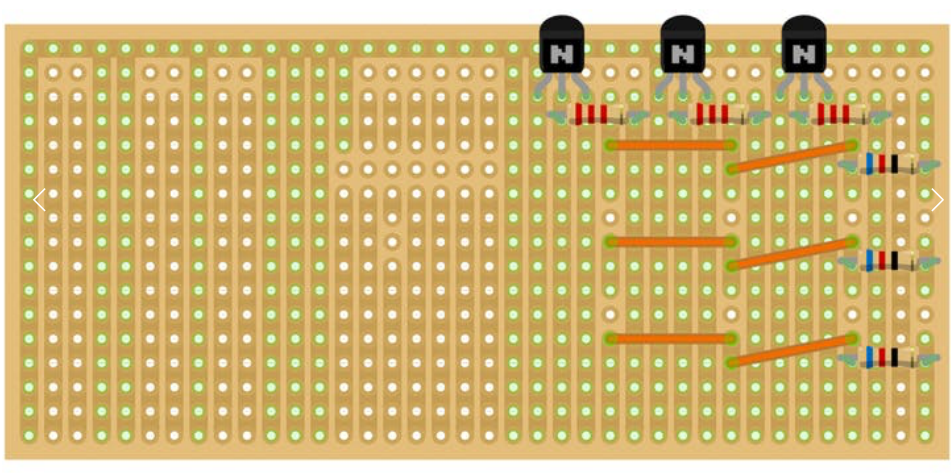
Hopefully this is obvious to you, but be sure to place the components on the side without the copper strips. The above animation and the graphics below are misleading in that they show the components and copper strips on the same side of the board.

Make use of a circuit board holder like I listed above to make this process much easier. I used lightly-placed scotch tape to hold the components in place so that I could flip the board over and solder away.

I am a fairly novice solderer, so excuse the lack of expertise shown in the photos below.

Step 6 : Solder the transistors, 62 Ω resistors, 2.2 kΩ resistors, and wires that will connect the LED anodes in place as shown below.

Because our copper tape is reliably conductive on only one side, in this step I also put solder to ensure good connections between the strip board strips and the copper tape.



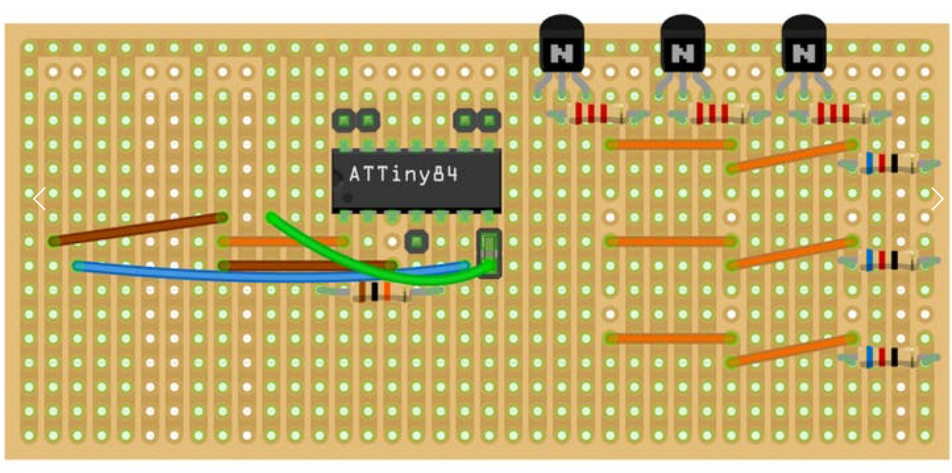
1 / 3

Step 7 : Add the MCU, header pins, 10 kΩ resistor, and wires shown.

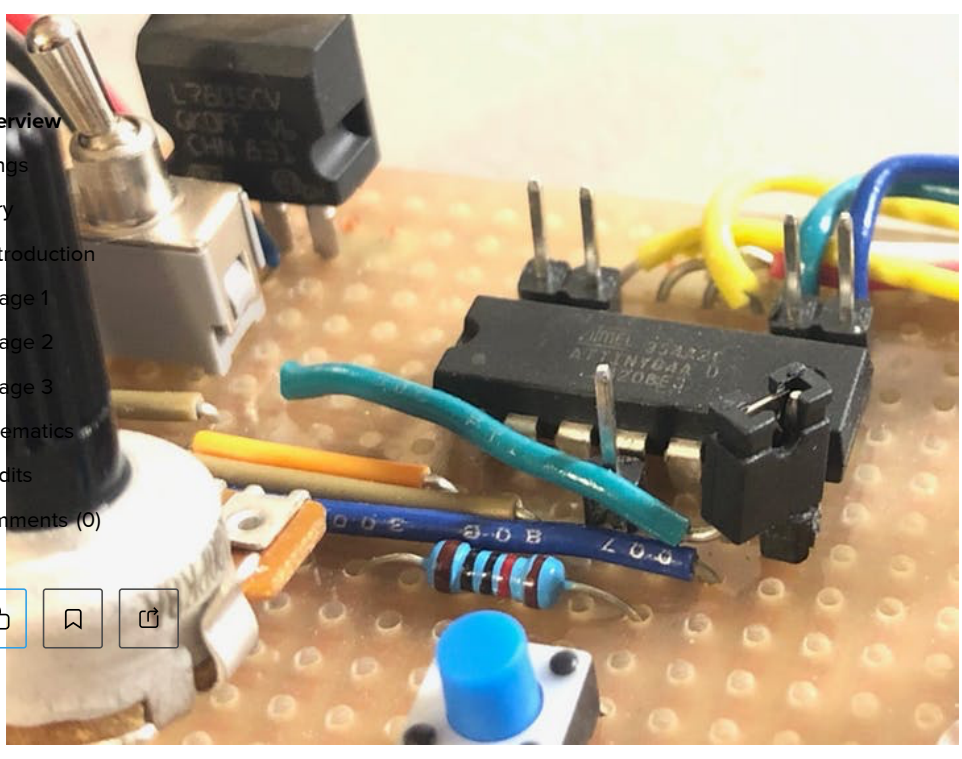
ERRATUM NOTE: In the graphics shown, and in most of the photos below, the green wire is wired to a strip/node with nothing else. This green wire must be soldered one strip to the left – to the same strip containing the variable/output/wiper/middle lead of the right potentiometer (brightness adjustment).

This same wire should not be soldered on its MCU end. Rather, we will connect the potentiometer terminal to the MCU by using a shunt to bridge a header pin at Pin 7 on the MCU to the wire. (The shunt is missing in some of the photos below.) Also, the header pin is missing from the second and third images in the series directly below. In the first image, the header pin is covered by the shunt. The photo below the series of three shows what you should end up with.

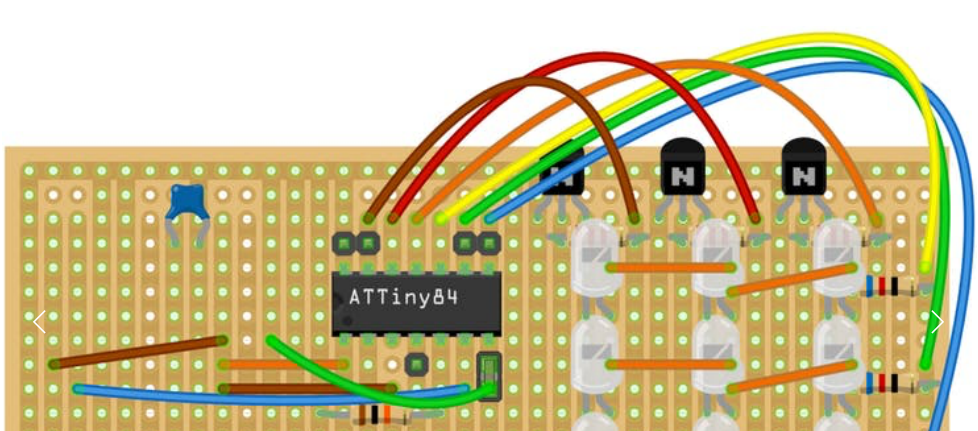
The whole purpose of this shunt business is the same as that of Step 25 in Stage 2 – having the potentiometer connected to the MCU at the same pin used for MOSI interferes with programming. When we want to program the MCU again, we must be able to temporarily disconnect the potentiometer from that pin. Using the shunt instead of soldering the connection allows us to do that.



1 / 3

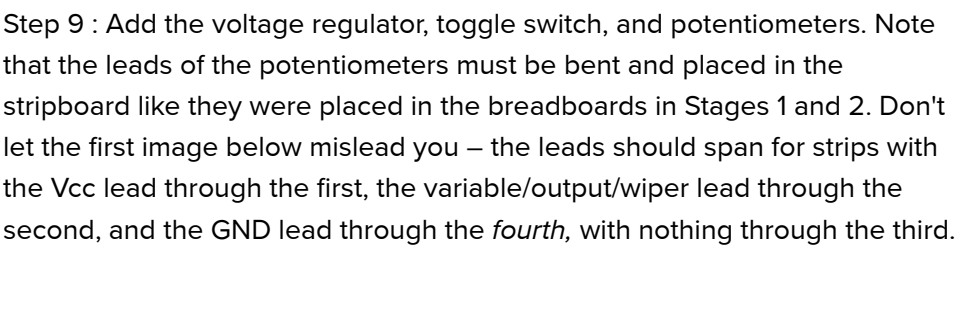


Step 8 : Solder into place the capacitor, pushbutton, and LED multiplexer control signal wires.



1 / 3

Step 9 : Add the voltage regulator, toggle switch, and potentiometers. Note that the leads of the potentiometers must be bent and placed in the stripboard like they were placed in the breadboards in Stages 1 and 2. Don't let the first image below mislead you – the leads should span for strips with the Vcc lead through the first, the variable/output/wiper lead through the second, and the GND lead through the *fourth,* with nothing through the third.



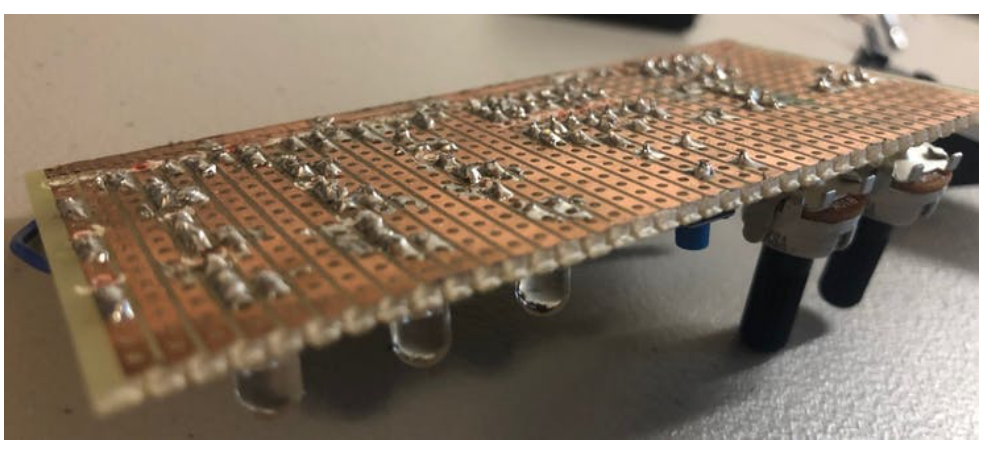
1 / 3

In this layout, the strip with the output pin of the voltage regulator functions as a 5 Vcc rail.

Step 10 : Finally, connect the battery terminals.

1 / 2

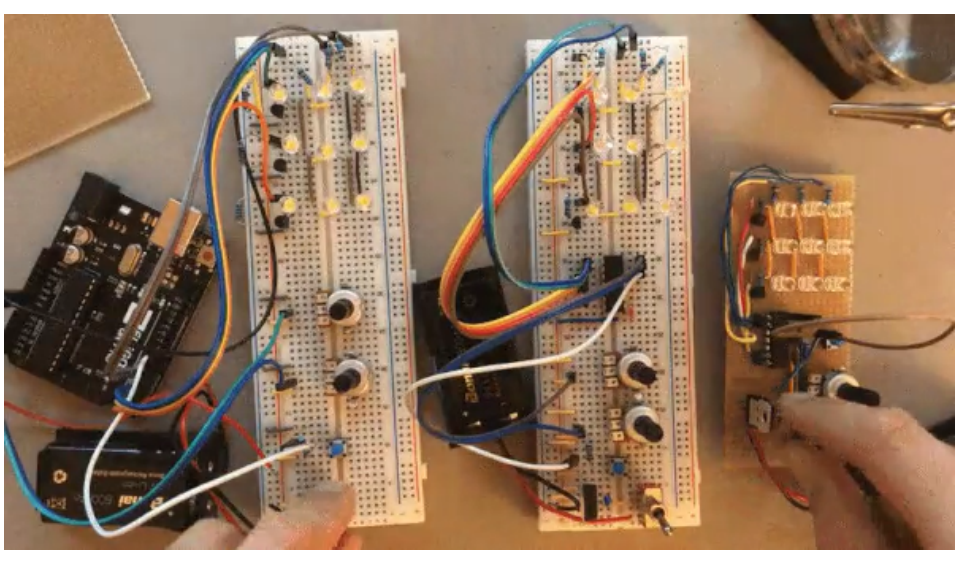
Step 11 : Using something like the wire cutting tool listed above, trim the component and wire leads off the underside of the board to clean it up a bit and help it to sit a bit flatter. I suggest disconnecting the battery for this so that you don't short any components, and wearing safety glasses is a great idea here as well – the pieces that you cut off are likely to want to fly.



Reconnect the battery and there you have it! Because we programmed the MCU previously, we don't need to do so now. You should now have a fully functioning Stage 3 circuit.

Completed video here.

If you do have a reason to reprogram the MCU, we built in the ability to do that with the header pins. Just follow Steps 23-29 of Stage 2.



https://learn.sparkfun.com/tutorials/switch-basics/all#poles-and-throws-open-and-closedhttps://learn.sparkfun.com/tutorials/switch-basics/all#poles-and-throws-open-and-closed

Schematics

Project Repository (https://github.com/nabelekt/LED_Multiplexer)

0 (https://github.com/nabelekt/LED_Multiplexer/watchers) nabelekt (https://github.com/nabelekt) / LED_Multiplexer (https://github.com/nabelekt/LED_Multiplexer)
0 (https://github.com/nabelekt/LED_Multiplexer/forks)

Code, circuit schematic files, pictures, and screenshots related to project at "Arduino Prototype to Producible PCB: An LED Multiplexer" project — Read More (https://github.com/nabelekt/LED_Multiplexer#readme)
https://www.hackster.io/nabelekt/arduino-prototype-to-producible-pcb-an-led-multiplexer-30f1eb (https://www.hackster.io/nabelekt/arduino-prototype-to-producible-pcb-an-led-multiplexer-30f1eb)

Latest commit to the master branch on 2-3-2019 **Download as zip (https://github.com/nabelekt/LED_Multiplexer/archive/master.zip)**

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Thomas Nabelek (/nabelekt)
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