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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.

Intermediate(/projects?difficulty=intermediate) Work in progress 7

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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 shipping and 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.

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.

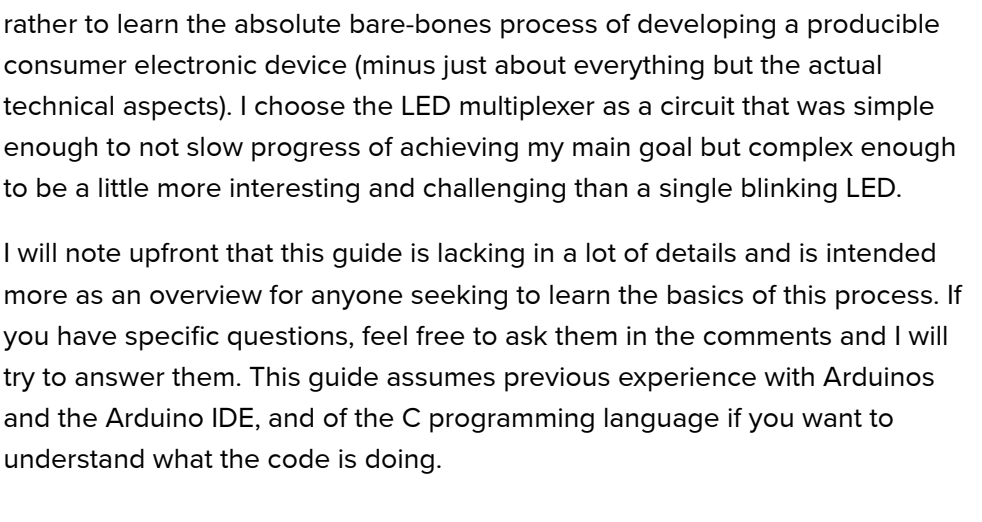
Stages 1A and 1B

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).

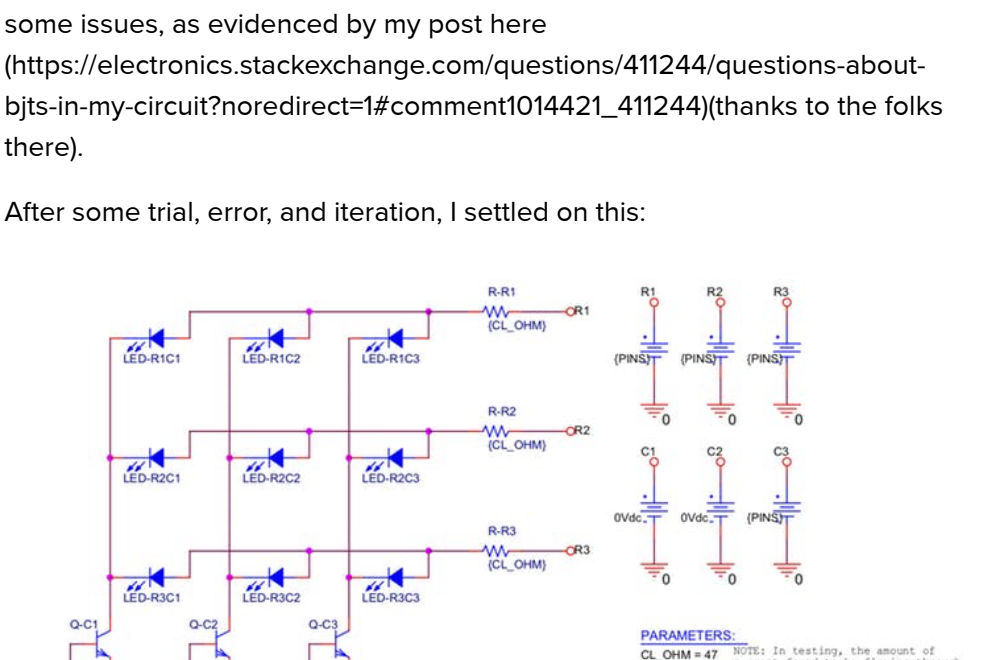
After some trial, error, and iteration, I settled on this:

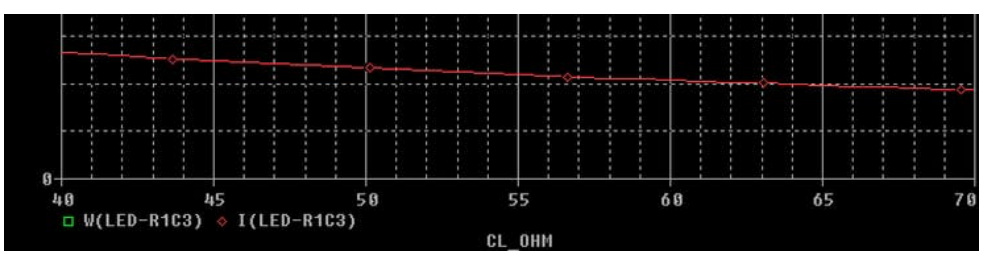


Circuit schematic for LED multiplexer

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:

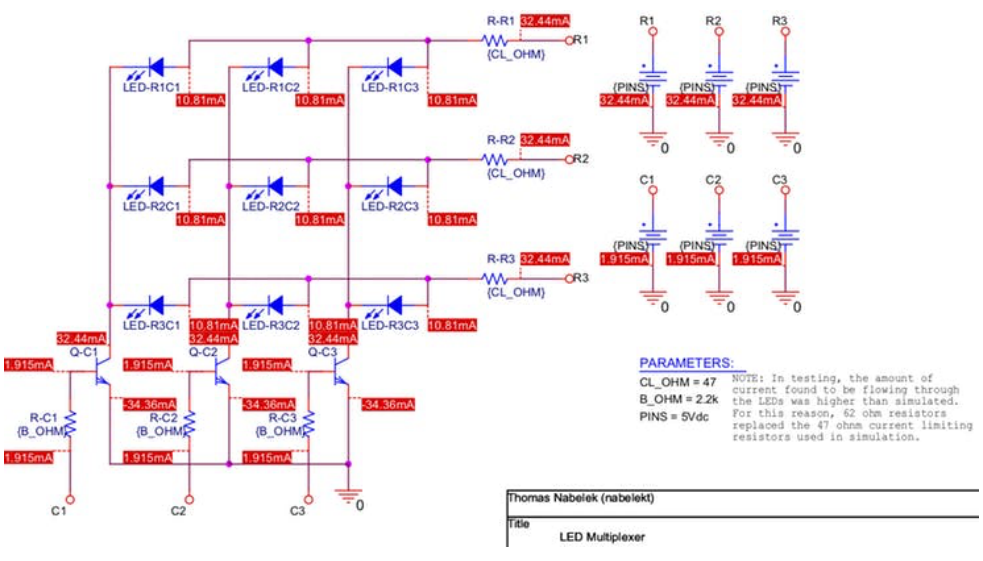




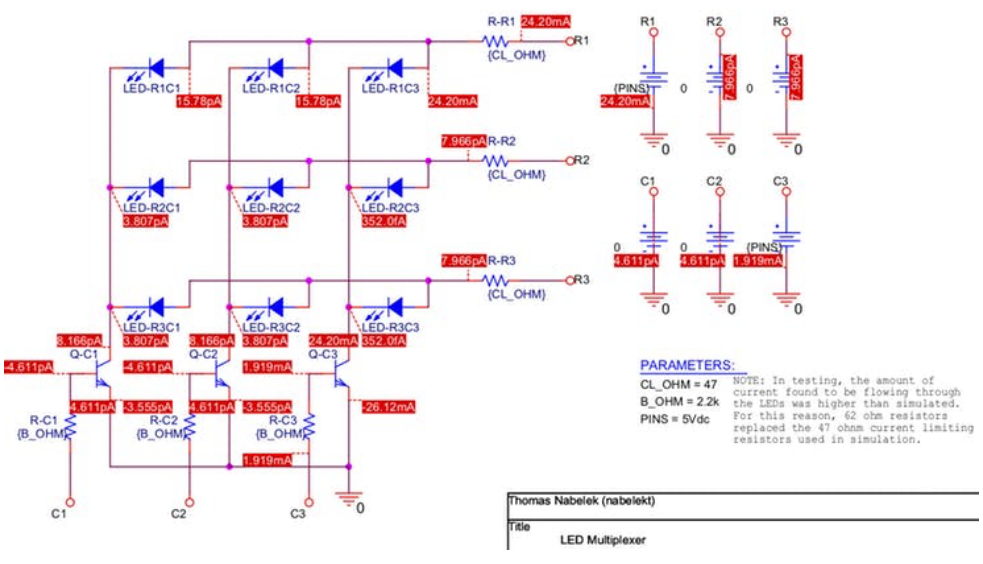
Current (red, mA) and power dissipation (green, mW) through/at LED-R1C3; CL_OHM axis values given in ohms

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.

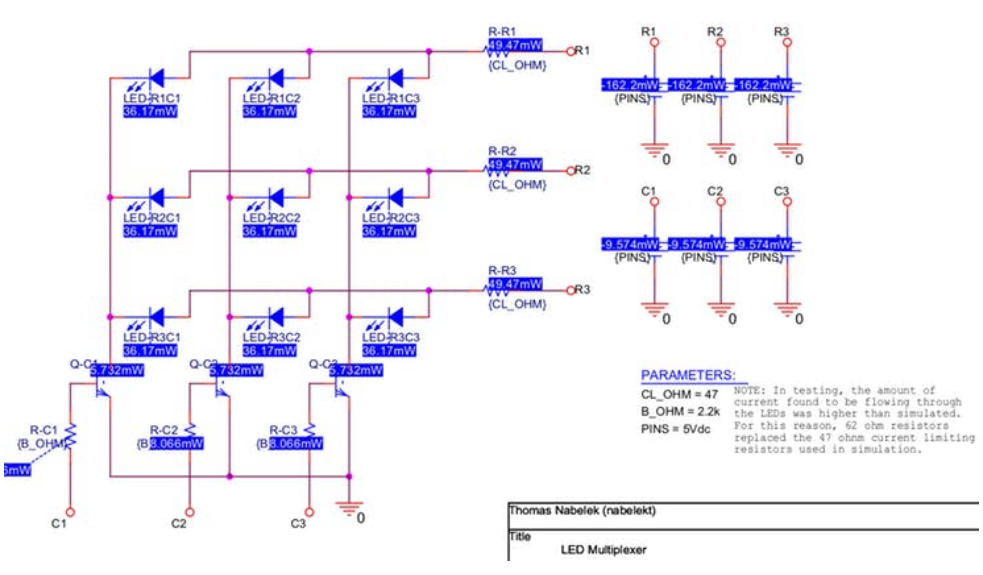
I created the schematic and did the simulation using OrCAD PSpice Designer Lite. (https://www.orcad.com/resources/download-orcad-lite) The software lets you simulate the circuit and get the voltage at any node, current on any branch, and power consumption for any component. Here are a bunch of simulated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



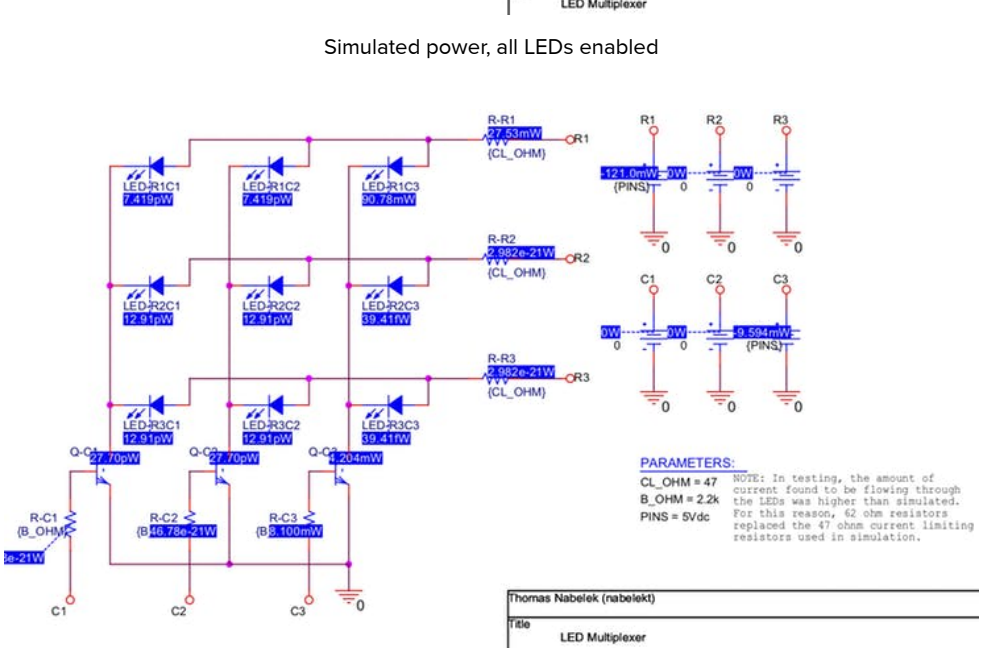
Simulated current, all LEDs enabled



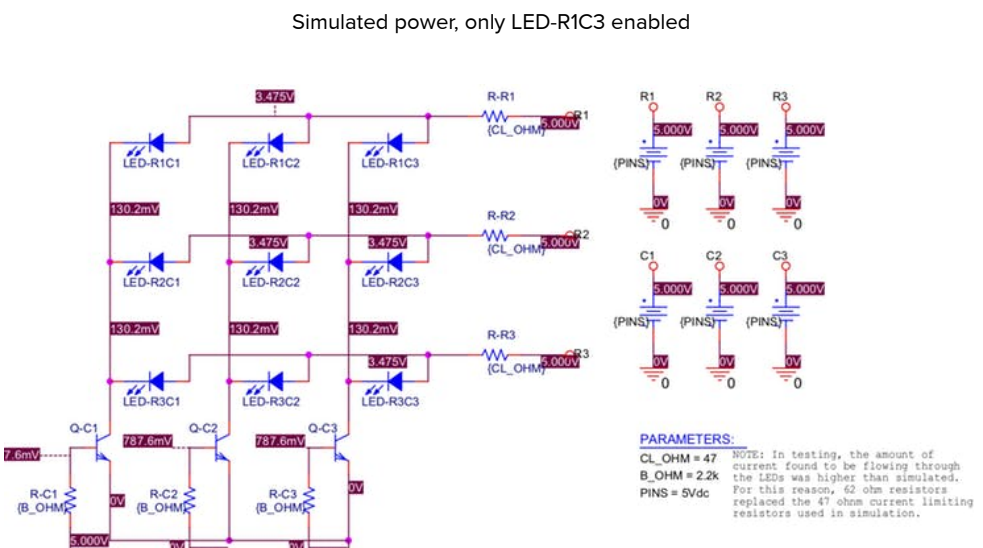
Simulated current, only LED-R1C3 enabled



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."

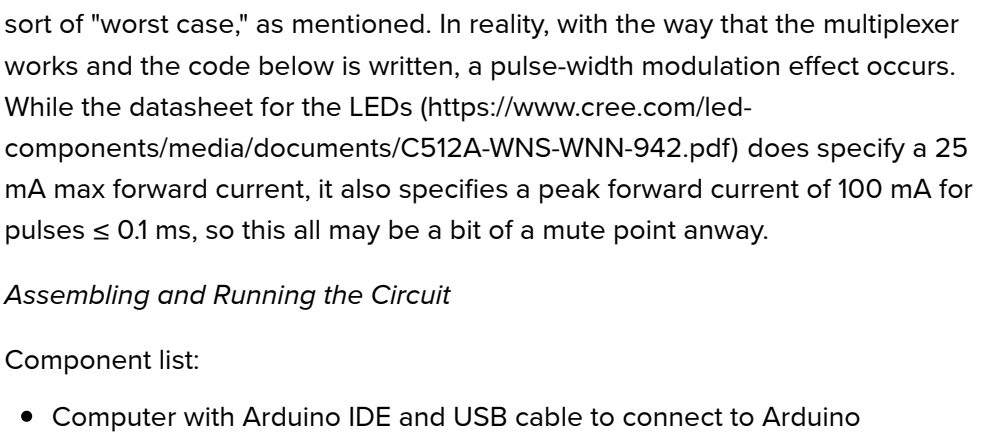
All of this was done enabling both the anode and cathode of only one LED – a sort of "worst case," as mentioned. In reality, with the way that the multiplexer works and the code below is written, a pulse-width modulation effect occurs. While the datasheet for the LEDs (https://www.cree.com/led-components/media/documents/C512A-WNS-WNN-942.pdf) 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.

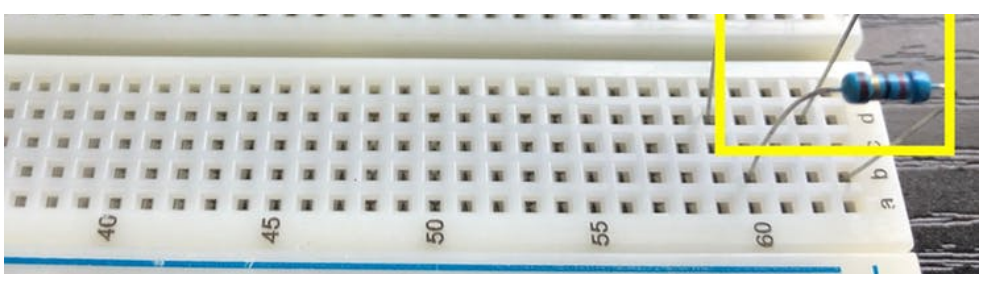
Assembling and Running the Circuit

Component list:

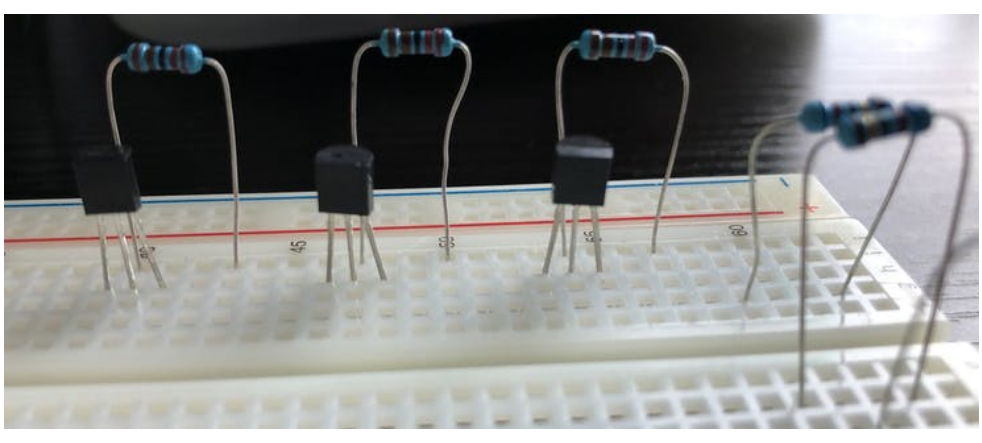
- Computer with Arduino IDE and USB cable to connect to Arduino
- Arduino Uno R3 or cheaper knock-off (these (https://www.amazon.com/gp/product/B01EWOE0UU) have worked very well for me)
- Solderless breadboard (https://www.digikey.com/product-detail/en/adafruit-industries-llc/239/1528-2143-ND/7244929)
- 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 BJT NPN 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.amazon.com/HiLetgo-Breadboard-Prototype-Assortment-Raspberry/dp/B077X7MKHN) – though you only need the male to male, and these (https://www.amazon.com/gp/product/B079FKJ4S3) can help a lot and save you the pain of cutting and stripping wire)

Step 1 : Start with the resistors.

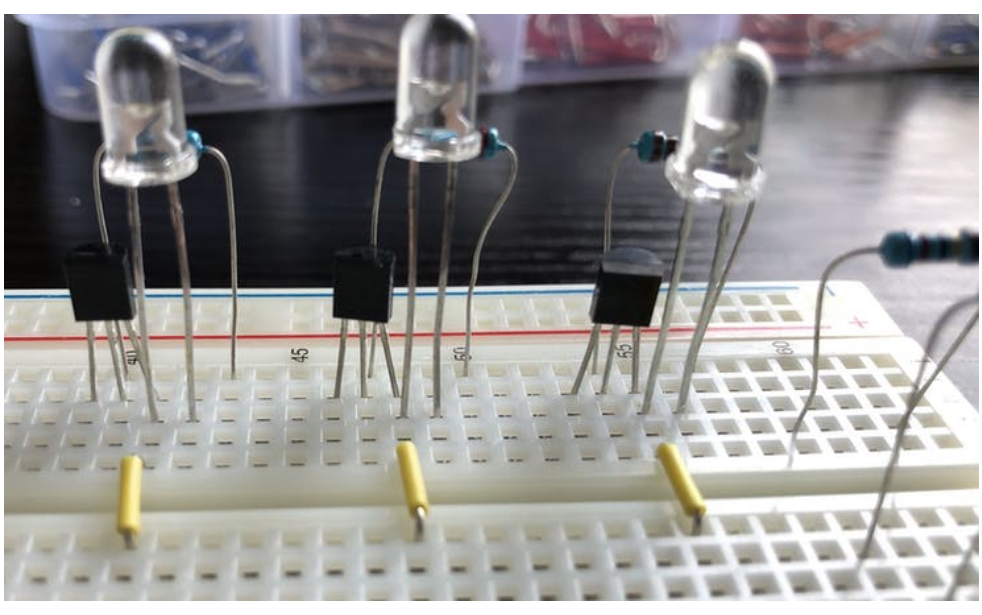




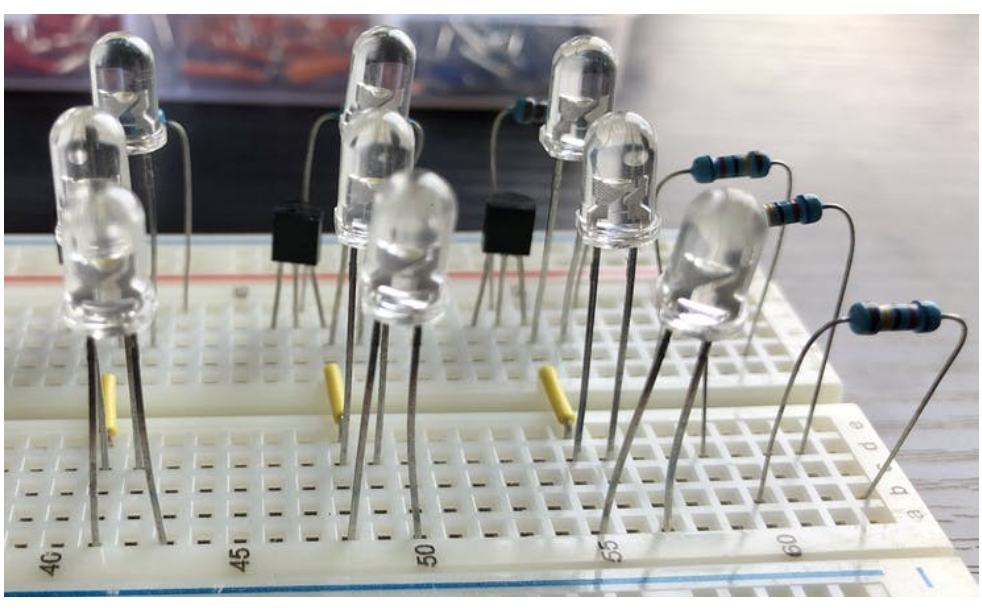
Step 2 : Add the transistors.



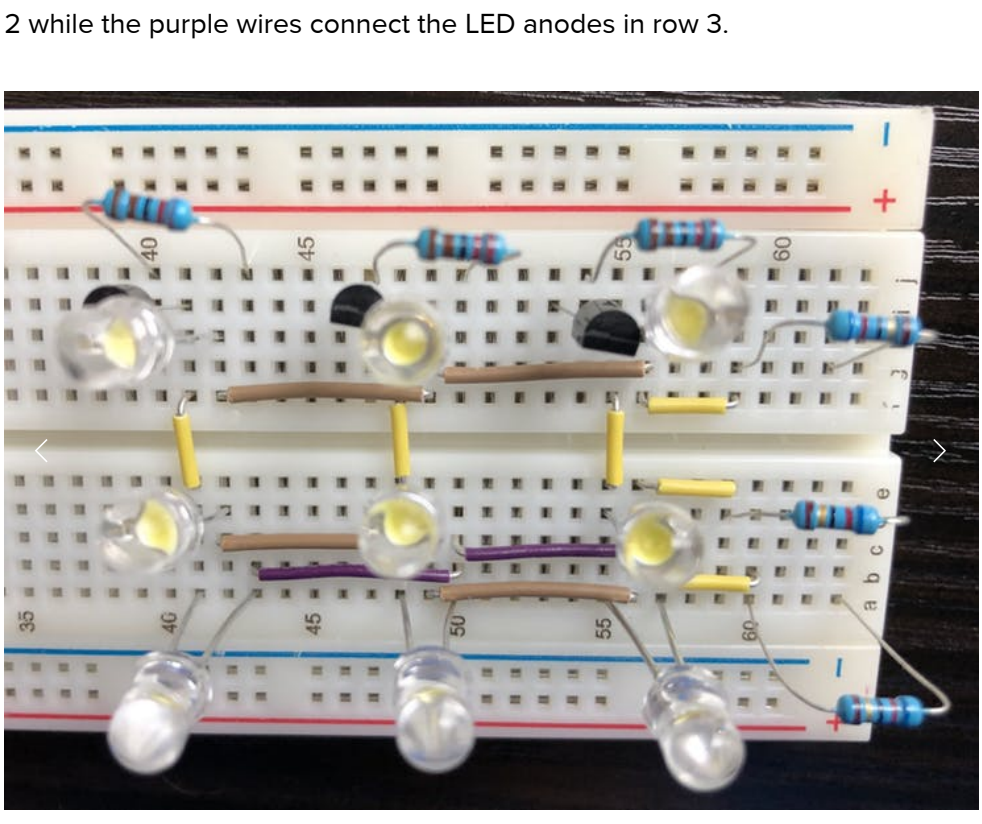
Step 3 : Add bridging wires and Row 1 LEDs.
Pro-tip : Add all of the wires through Step 5 and then go back and add the LEDs. It's way easier.



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.



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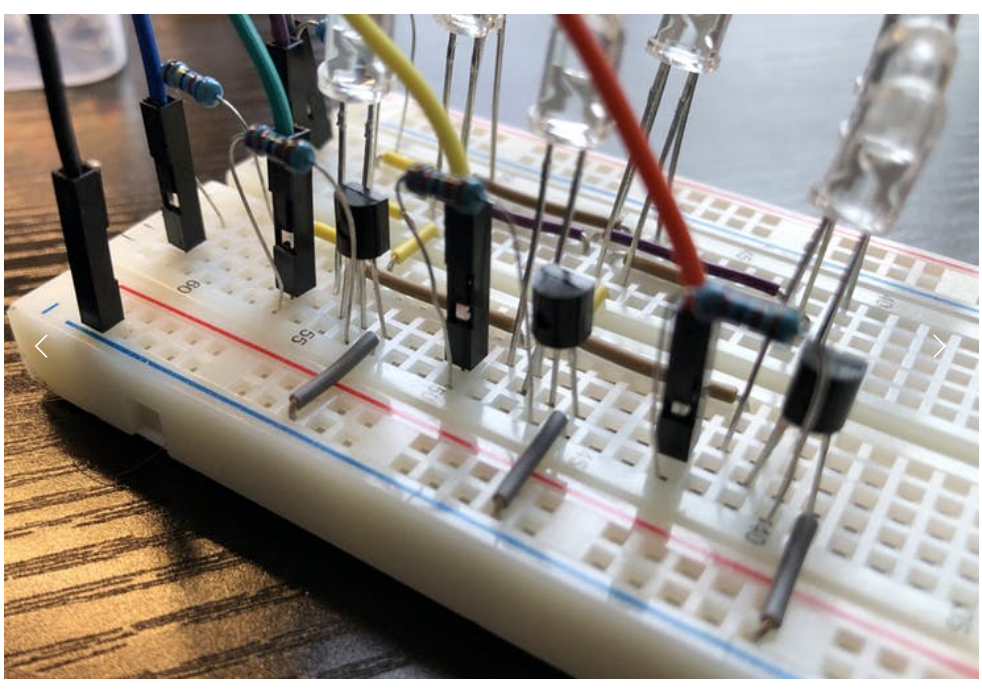
Step 6 : Connect transistor emitters to ground (GND) and wire to Arduino (the second pic is missing GND connection to Arduino - the black jumper in the corner of the breadboard shown in the first image).



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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);
```

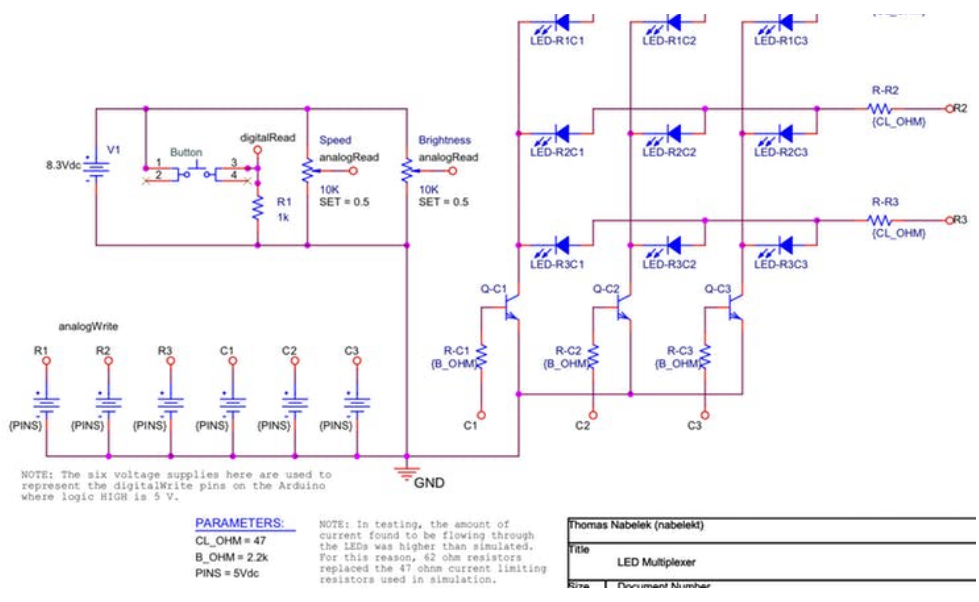
If you want to understand (at least in part) how I am mapping the change in the potentiometer resistance to the speed or brightness in `map_brightness_value()`, take a look at Paul McWhorter's video (https://www.youtube.com/watch?v=QsYcYknKbB0) (most of his videos seem pretty great – very informative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



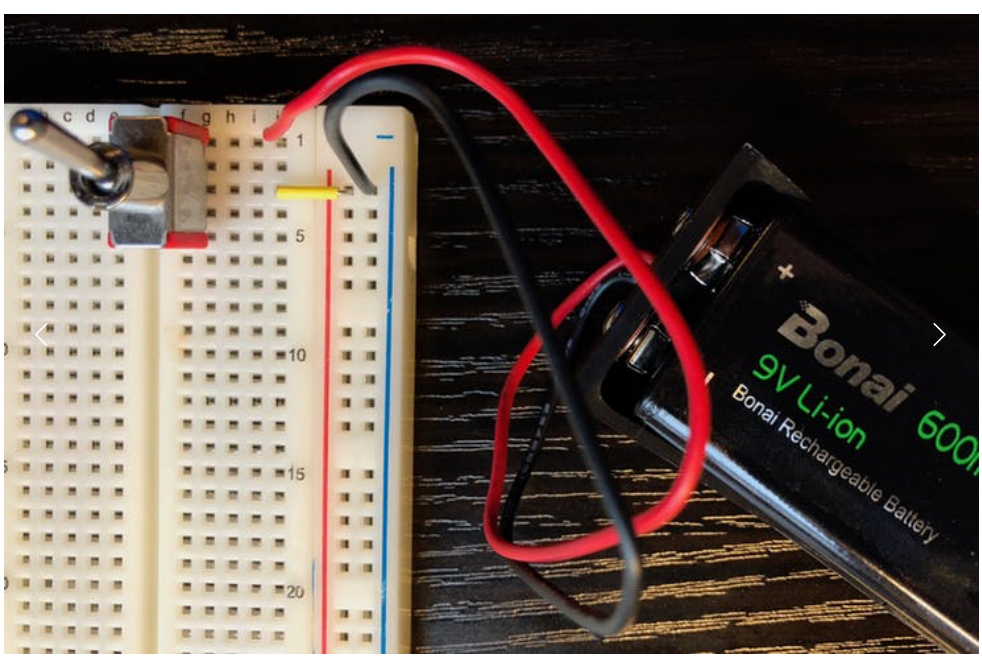
You may notice that the voltage on the positive breadboard rail is unregulated – it comes straight from the battery. Because the only components connected to that node are the switch, button, and potentiometers, this is not concerning. If other components such as the LEDs were also connected to this 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
- 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.amazon.com/HiLetgo-Breadboard-Prototype-Assortment-Raspberry/dp/B077X7MKHN)– though you only need the male to male, and these (https://www.amazon.com/gp/product/B079FKJ4S3)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.



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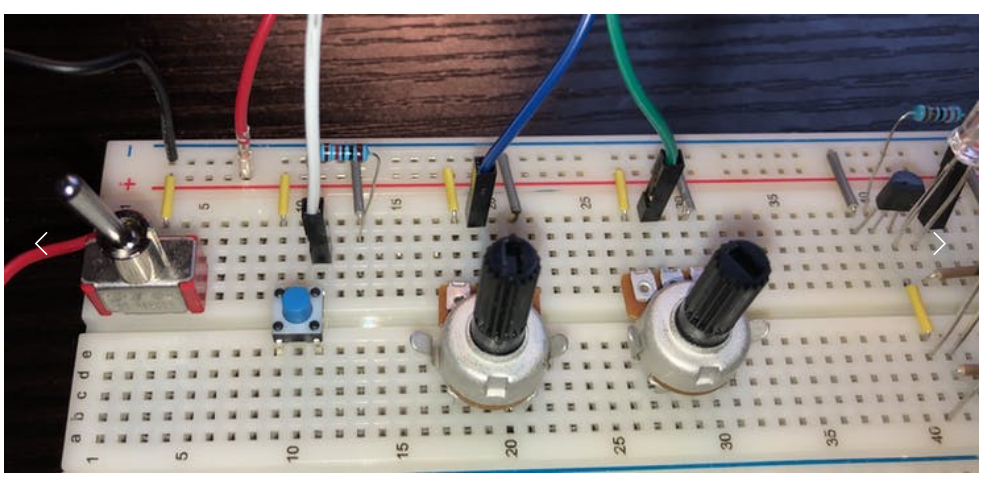
Step 2 : Add the pushbutton. Wire the signal to pin 8 on the Arduino (white jumper in pictures). Put the 10 kΩ resistor between the signal leg of the button and GND.

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 as shown in the pictures. Wire the positive voltage rail to Vin on the Arduino.



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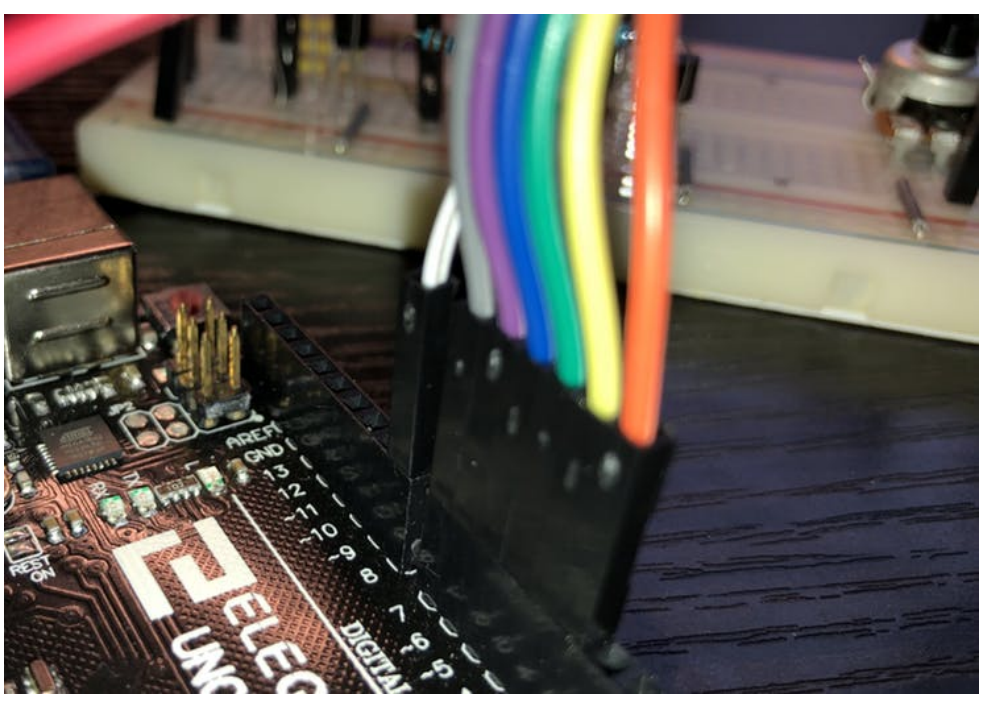


Step 5 : Program the Arduino. The code is made up of three separate files. The directory/file structure on your computer should look something like this:

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

LED_multiplexer.ino is the one that you will need to hit the upload button on in the Arduino IDE.

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.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);
```

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

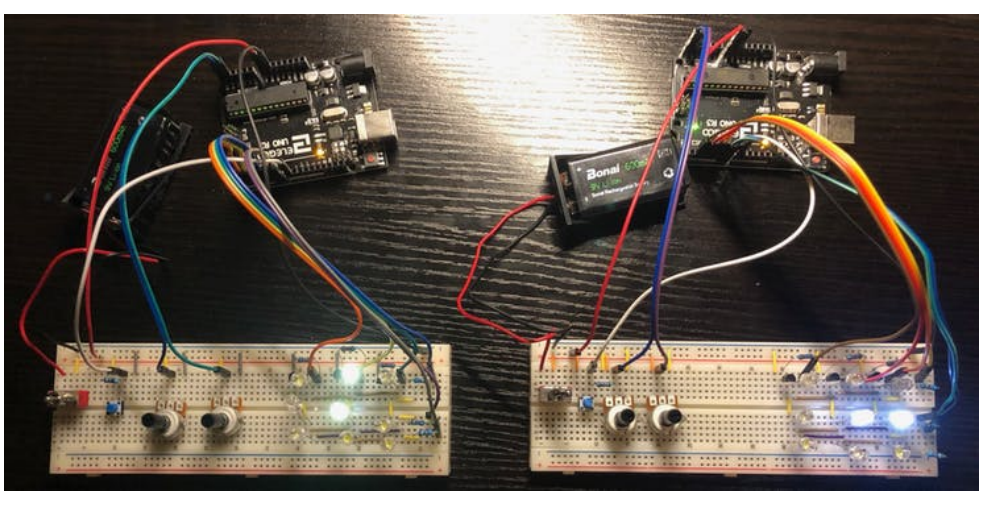
The end goal of this stage is to have the same system of as that at the end of Stage 1 but with the Arduino replaced with only necessary components. However, it is good to test out the second system with an Arduino before replacing the Arduino with a microcontroller and company. Repeat Stage 1 so that you have a duplicate prototype. Alternatively, you can make adjustments to the same 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:

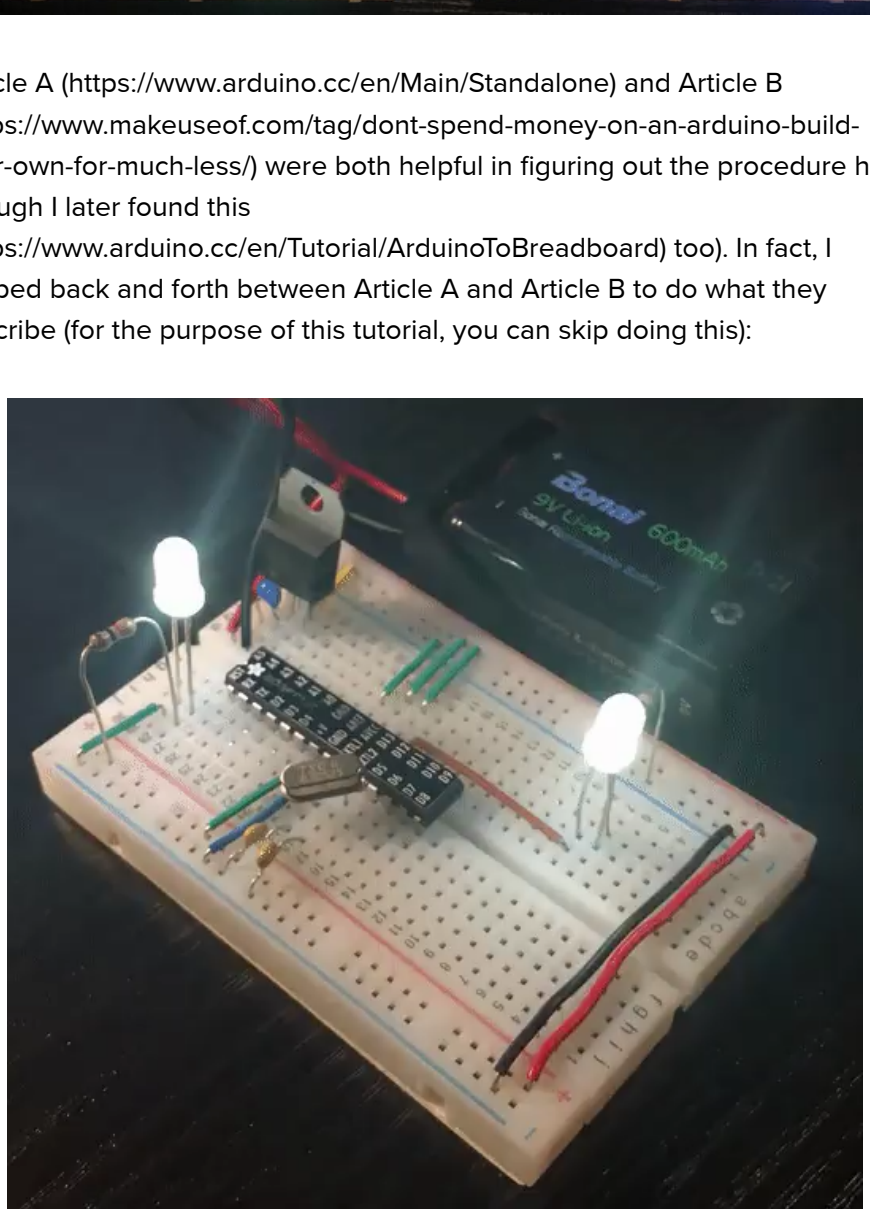
- Everything from the component lists of Stages 1A/B and 1C combined

Steps : Follow same 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 in this stage.

You should now have duplicate systems:



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 the procedure here (though I later found this (https://www.arduino.cc/en/Tutorial/ArduinoToBreadboard) too). In fact, I 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):

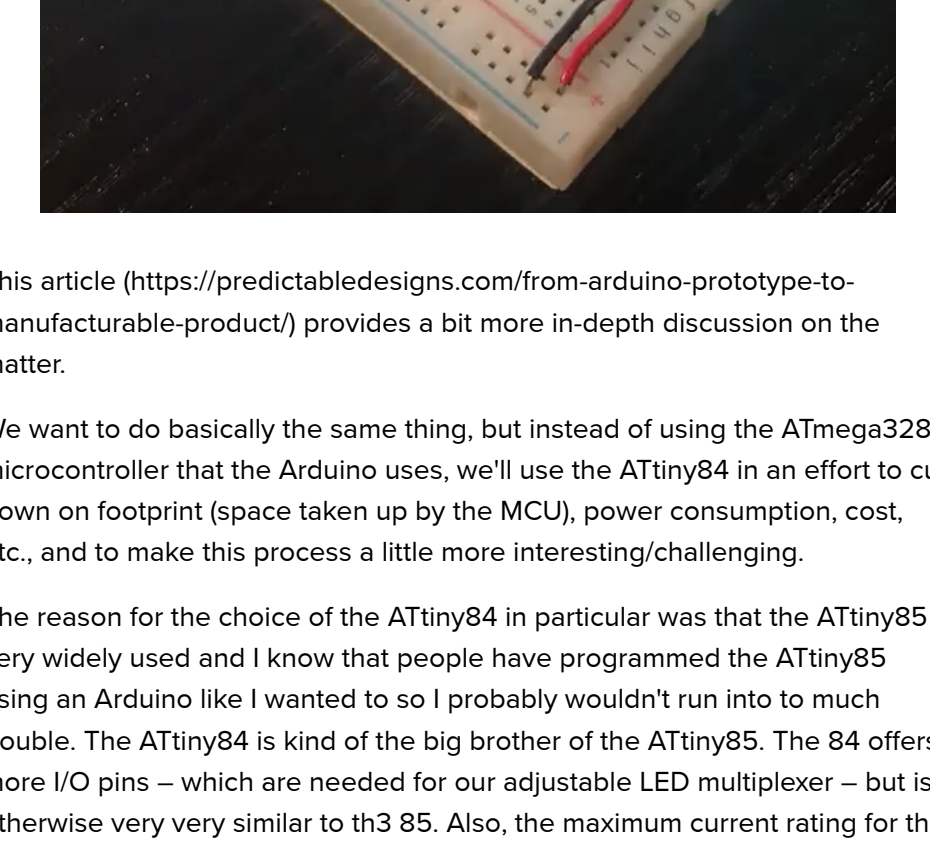


This article (https://predictabledesigns.com/from-arduino-prototype-to-manufacturable-product/) provides a bit more in-depth discussion on the matter.

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 very similar to th3 85. Also, the maximum current rating for the ATtiny84 – listed on page 174 of its datasheet – (http://ww1.microchip.com/downloads/en/DeviceDoc/doc8006.pdf) is 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 this diagram (view it larger here (https://raw.githubusercontent.com/nabelekt/LED_Multiplexer/master/stage_2/ATINY-PinOut-Diagram.png)), and working with a different boards library in the Arduino IDE.



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 (http://ww1.microchip.com/downloads/en/DeviceDoc/doc8006.pdf)).

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

Component List:

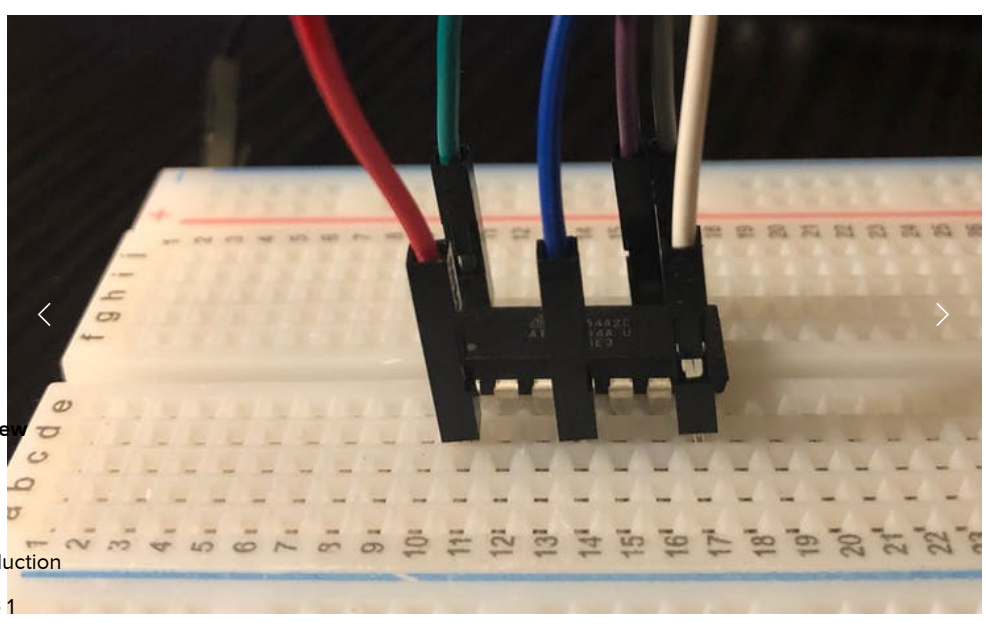
- A smaller solderless breadboard (https://www.digikey.com/product-detail/en/dfrobot/FIT0096/1738-1326-ND/7597069) (not absolutely necessary, but will make initial testing and debugging easier)
- ATtiny84 MCU (https://www.digikey.com/product-detail/en/microchip-technology/ATTINY84A-PU/ATTINY84A-PU-ND/2774082)
- 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)
- 2x 10 µF capacitor
- 6 jumper wires like those used in previous stages
-
- Arduino Uno R3 or cheaper knock-off (these (https://www.amazon.com/gp/product/B01EWOE0UU)have worked very well for me). If you have replicated the

Step 1 : Place MCU on breadboard bridging the gap

Step 2 : Disconnect all wires from the Arduino used in the first part of Stage 2 (your duplication of Stage 1's system). Make sure that your Arduino is disconnected from your computer and not powered.

Step 3 : Refer to the diagram above and use the pin designations closest to the depiction of the MCU. E.g., pin 1 is in the top left corner of the MCU.
Connect pin 14 GND to pin GND 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 1 VCC to 5V on the Arduino.

NOTE: The blue capacitor shown in the pictures below should only be added AFTER completing Step 5.



1 / 2

1 / 3

Step 4 : Plug the Arduino into your computer. Select Tools > Board > Arduino/Genuino Uno. Find and select your board under Tools > Port.

Step 5 : Choose File > Examples > 11.ArduinoISP > ArduinoISP. Upload this sketch to your board.

Step 6 : 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 I needed it).

Step 7 : In the Arduino IDE, open up the Preferences, pop open the Additional Boards Manager URLS 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 is necessary or not).

Step 8 : 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 11 : 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 suggest that you search the interwebs and learn about the pros and cons of internal vs. external oscillators.

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

Step 10 : Select Tools > Burn Bootloader. If successful you should see something like the following:
INSERT BOOTLOADER SUCCESS PICTURE

EXPLAIN Bootloader

EXPLAIN Other methods of programming ATtiny84

Using the internal oscillator means that the only main components that we need 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.

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)

No description — Read More (https://github.com/nabelekt/LED_Multiplexer#readme)

Latest commit to the master branch on 2-4-2019 Download as zip (https://github.com/nabelekt/LED_Multiplexer/archive/master.zip)

Credits

(/thomas-nabelek) **Thomas Nabelek (/thomas-nabelek)**
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