Driving LEDs with a Micro Controller

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One of the first experiments people learning about micro controllers usually perform is how to control an LED. Typically they hook an LED in series with a current limiting resistor and connect it to an output pin and write some simple software to make it blink. The Arduino blink sketch shown below is an example:

```
int led = 13;

// the setup routine runs once before the loop() function
void setup() {
  // initialize the digital pin as an output.
  pinMode(led, OUTPUT);
}

// the loop routine runs over and over again forever:
void loop() {
  digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage level)
  delay(1000);               // wait for a second
  digitalWrite(led, LOW);    // turn the LED off by making the voltage LOW
  delay(1000);               // wait for a second
}
```

On Arduinos there is an LED and current limiting resistor on board already (and connected to pin 13) so there is nothing really to hook up for this first experiment. Once this sketch is downloaded onto your Arduino you should see the onboard LED blink on and off until power is removed.

As you might expect the thrill of watching the LED blink wears off pretty quickly and next people might want to try and control the brightness of an LED with software. The Arduino fade sketch below causes the LED connected to pin 9 through say a 470 ohm resistor to ground to go from off to full brightness and then back down, over and over.

```
int led = 9;           // the pin that the LED is attached to
int brightness = 0;    // how bright the LED is
int fadeAmount = 5;    // how many points to fade the LED by

// the setup routine runs once before the loop() function
void setup()  {
  // declare pin 9 to be an output:
  pinMode(led, OUTPUT);
}

// the loop routine runs over and over again forever:
void loop()  {
  // set the brightness of pin 9:
  analogWrite(led, brightness);

  // change the brightness for next time through the loop:
  brightness = brightness + fadeAmount;

  // reverse the direction of the fading at the ends of the fade:
  if (brightness == 0 || brightness == 255) {
```

```
    fadeAmount = -fadeAmount ;
  }
  // wait for 30 milliseconds to see the dimming effect
  delay(30);
}
```

In this sketch an *analogWrite* statement is used to control LED brightness instead of the *digitalWrite* command used to turn the LED off and on as in the previous sketch. Brightness control works using a combination of persistence of vision coupled with Pulse Width Modulation or PWM for short.

Persistence of vision is an effect where our eyes and brain hold onto an image we see for approximately 1/25th of a second before it fades away. We all experience this effect at the movies where we fail to notice that a motion picture screen is actually dark about half the time. Motion pictures project one new frame every 1/24th of a second. Each frame is shown three times during this period. Our eyes retain the image of each frame long enough to give us the illusion of smooth motion. How does this relate to LED brightness? Glad you asked.

An LED, being a semiconductor device, can be switched on and off very quickly. An LED is at full brightness when it is on all of the time over a fixed period of time. If the LED is only on half of the same time period (and off the other half of the time period) and the time period is very short it will appear approximately half as bright. Now if this switching happens at a fast enough rate our persistence of vision will not perceive the LED as being turned on and off or flickering but will perceive it as being on at some brightness level.

PWM divides up the periodic time period into intervals based upon the resolution of the hardware. On most 8 bit micro controllers 8 bit PWM is supported. This means that there are 256 unique durations from always off to always on. Duty cycle is defined as the ratio of on to off times. A PWM output that is on half of the time has a 50% duty cycle. Figure One illustrates various duty cycles of a PWM output. The green lines in this figure show the periodic nature of the PWM output. If a PWM output is used to control LED brightness the frequency of the PWM output becomes important. Flickering of the LED will be visible if the PWM frequency is to low. Most if not all micro controllers allow the frequency of their PWM outputs to be configured.

The *analogWrite* function in the sketch above sets how long the PWM output connected to the LED is on. analogWrite(0) means the output is never on and the LED is dark. analogWrite(255) means the PWM output is always on so the LED is at full brightness. Values between 0 and 255 determine the relative brightness of the connected LED.

We should quickly say a few words about current limiting with LEDs. Current limiting is important to protect both the digital output of the controller driving the LED and the LED itself from burning out. To figure out the value of a current limiting resistor to use with an LED requires three pieces of information. First, the supply voltage used to drive the LED (Vs). Second, the current (I) you want to operate your LED at and third, the forward voltage (Vf) drop of the LED. Forward voltage varies by the color of the LED. A red LED typically drops 1.8 volts whereas a blue LED may drop 3.3 volts.

As an example assume our supply voltage is 5 volts; assume we want 20 mA (0.02 amps) of current for the LED and the voltage drop across the LED is 1.8 volts. Using Ohm's law we can calculate the required resistance with the formula:

$$R = (Vs – Vf) / I$$

Which works out to be around 160 ohms. If the resistor value you calculate turns out not to be a standard value, pick the next larger value to be safe.

OK so now we see how the brightness of an LED can be controlled using PWM. With this information you could control the brightness of a red, green, blue or any single color LED with software. But what if you want variable color output from an LED. In this case you would probably choose an RGB LED for this purpose. RGB LEDs actually contain red, green and blue LEDs internally. This means three PWM channels would need to be used to control the brightness and the color of a single RGB LED. By varying the duty cycle of each of the LEDs inside the RGB LED, many color combinations are possible. If 8 bit PWM is used on all three channels driving an RGB LED, there are theoretically 256 x 256 x 256 or over 16 million possible color combinations. Research has shown the human eye can discern approximately seven million unique colors.

On most Arduino boards (those with the ATmega168 or ATmega328), PWM is available on pins 3, 5, 6, 9, 10, and 11. On the Arduino Mega, it works on pins 2 - 13 and 44 - 46. Older Arduino boards with an ATmega8 only support PWM on pins 9, 10, and 11. On the Teensy 3.1 micro controller that I typically use PWM is available on pins 3, 4, 5, 6, 9, 10, 20, 21, 22, 23, 25, 32.

So as you can see on typical micro controllers there are only a small number of PWM outputs available for driving LEDs. If you only want to drive single color LEDs you may be OK but if you want to drive a large number of RGB LEDs the outlook is bleak.

There a many options available for driving larger number of LEDs using hardware external to but controlled by a micro controller. If you search the Internet you will see many examples. Many designs use 74HC595 shift register chips to drive the LEDs but my current solution of choice is the Adafruit 24-Channel 12-bit PWM LED Driver with SPI Interface; product id number 1429, available for $14.95. With its 24 channels you can control 24 single color LEDs or 8 RGB LEDs with the added advantage of 12 bit PWM giving finer grain control than the 8 bit PWM described previously. An additional advantage is that each PWM output provides constant current so current limiting resistors are unnecessary. In fact, one resistor on this driver board controls the current through all channels which is set at the factory to 15 mA. Up to 30 mA of drive current per channel is possible by changing the resistor. NOTE: this device is a current sink. It sinks current to ground, it cannot source current.

This Adafruit device is really just a breakout board for the TLC5947 controller chip from TI. This breakout board makes all of the TLC5947 signals available in an easy to use configuration without having to deal with surface mount components.

The TLC5947 chip is a cascadeable shift register with built in PWM counters and PWM oscillator. Since each output requires 12 bits of information to control its PWM hardware, a total of 288 bits or 36 bytes of data must be streamed into the chip via SPI to control its 24 PWM outputs. More on how to control the TLC5947 chip in the software section.

For many of my projects a single Adafruit driver board still doesn't have enough outputs to drive large numbers of RGB LEDs. I recently purchase some 8x8 RGB LED matrices for use in a project. Think about it, this is a matrix of 64 RGB LEDs which equates to 64 x 3 or 192 individual LEDs needing PWM control. There were two ways to go on this project. Purchase and connect eight of these boards together somehow so each board controls one row of the display for a total driver cost of $119.60. Or, use one of these boards, eight cheap P Channel power MOSFETs and some clever software to control the entire display. Being frugal, I chose the later. In the discussion to follow I will show you how to use multiplexing of the LED driver to accomplish this feat.

Multiplexing

Multiplexing is a term from the telecom industry which meant to combine multiple channels of data onto a single medium for transmission. Multiplexing reduces the cost of hardware and because of reduced parts count increases reliability. Multiplexing many channels of data onto a single medium required that each channel of data be given its own time slot. This is referred as TDM or Time Domain Multiplexing. We can use the same technique for controlling our LED matrix by assigning each row of the display a different time slot for update. If we update each row of RGB LEDs fast enough, persistence of vision will make it appear that each LED is individually controlled.

I designed some hardware to demonstrate control of an 8x8 RGB LED matrix using multiplexing. The hardware is shown in Figure Two and the hardware's schematic is shown in Figure Four.

The Demonstration Hardware

The 8x8 RGB LED matrix I will control is of the common anode variety. What this means is that each row of the display has the anodes of each red, green and blue LED connected together. See Figure Three. The cathodes of each column of the same color LEDs are also connected together and brought out to a pins on the matrix. By applying a current source to a specific row pin and a current sink to a specific cathode pin a single color LED can be illuminated. I tested the LED matrix I built into the demonstration hardware using a 9 volt battery and a 1K ohm resistor by connecting the + side of the battery through the resistor to a row pin and connecting the – side of the battery to the various column pins. As you move the battery connection from one column pin to another you will see the LEDs change color.

In the demonstration hardware P channel MOSFETs are used as the current source for each row of the matrix. The current flowing from the drain of the device into the row of LEDs is controlled by the

voltage applied to the gate of the MOSFET. As wired, current flows to the LEDs in the row if the gate is driven low by the Teensy 3.1 controller. If the gate is pulled up to the voltage at the MOSFET's source pin, current flow stops. Each row MOSFET is connected to a different pin on the Teensy so that each can be individually controlled.

The current sink side of the equation is handled by the TLC5947 chip on the Adafruit board. The 24 PWM channels provided by the chip are connected to the 24 color column pins of the LED matrix. The data used to control the PWM outputs is streamed serially into the TLC5947 chip via the SPI interface on the Teensy controller. A data and a clock line are used to move the data which flows in one direction only.

Two other control signals are needed for control of the TLC5947 chip. The first is labeled /OE on the Adafruit board but called BLANK on the chip itself. When BLANK is high all of the PWM channels stop sinking current and the chip's internal PWM counters are reset to zero. When BLANK goes back low, the current sinks are enabled and the PWM counters start counting.The second control signal is labeled LAT on the Adafruit board but called XLAT on the chip. The rising edge of this signal causes the data contained in the TCL5947's shift register (loaded via SPI) to be transferred to the individual PWM counters backing each output pin.

I used a Teensy 3.1 controller from pjrc.com for controlling the hardware. It has plenty of RAM and flash memory for coding up any kind of display patterns you can envision. The Teensy is Arduino compatible via the Teensyduino software available from pjrc.com.

The hardware works as follows (under control of the software which will be describe next): data for a row of LEDs is moved from the controller to the TLC5947 chip using SPI. The data is latched into the chip on the rising edge of XLAT and then the appropriate row select output is brought low to enable the LEDs in the row. Next, the BLANK line is driven low which causes the PWM counters to start and the LEDs in the selected row to illuminate. After a precise period of time, data for the next row is loaded and the whole process repeats indefinitely.

The Demonstration Software

The software running on the Teensy 3.1 controller is what makes multiplexing of the LED matrix possible. Multiplexing makes the hardware simpler but the software more complex. The demonstration software sketch is available from the Nuts and Volts website if you would like to duplicate what I have done or use pieces of the software in projects of your own. The sketch requires the TimerOne and the spi4teensy3 libraries to be available in your Arduino build environment. Please refer to the LEDMatrix8x8.ino sketch for the discussion to follow.

The first order of business in the sketch is to define the control signals/pins of the Teensy controller which will control the TLC5947 chip. The assignments are as follows:

```
// PWM driver control pins
```

```
#define LATCH_PIN  9
#define BLANK_PIN 10

// LED Matrix row select pins
#define ROW0_PIN  16
#define ROW1_PIN  17
#define ROW2_PIN  18
#define ROW3_PIN  19
#define ROW4_PIN  20
#define ROW5_PIN  21
#define ROW6_PIN  22
#define ROW7_PIN  23
```

An interrupt on the Teensy 3.1 controller is used to generate the precise timing required to make multiplexing work. The three values below define interrupt timing.

```
// Interrupt period calculations
#define DATA_XFER_TIME_USEC     13
#define ROW_DISPLAY_TIME_USEC 1024

#define INTERRUPT_TIME_USEC (DATA_XFER_TIME_USEC + ROW_DISPLAY_TIME_USEC)
```

`DATA_XFER_TIME_USEC` is the time in micro seconds it takes for the spi4teensy3 library to transfer 36 bytes of row data from the Teensy running at 96 MHz to the TLC5947. The `ROW_DISPLAY_TIME_USEC` is a little more difficult to describe. It is the time it takes the TLC5947 PWM counters to count from zero to 4095 thereby completing the 12 bit PWM cycle. The PWM oscillator internal to the TLC5947 runs at 4 MHz under normal operating conditions. The period of the 4MHz oscillator times 4096 equals 1024 micro seconds.

Since both of these processes must occur for every row of LED matrix data the total time between interrupts is their sum. The TimerOne library is used to cause a periodic interrupt at this frequency.

Finally we define the frame buffer which contains the data used to drive the complete LED matrix.

```
// Frame buffer definition
#define NUMBER_OF_ROWS 8
#define BYTES_PER_ROW 36

// Frame buffer is 2D array of bytes
byte frameBuffer[NUMBER_OF_ROWS][BYTES_PER_ROW];
```

Foreground code in a sketch would put data into the frame buffer that represents the pattern to be displayed and the background code contained in the interrupt service routine (ISR) moves the data from the frame buffer to the hardware continuously. The LED matrix is updated around 122 times per second by the ISR..

From the foreground's code perspective, it just sets pixels to specific colors and these colors magically appear on the LED matrix. It is not necessary to call any kind of show function to force display update,

it all happens automatically and in real time.

With this understanding most of the code in the sketch should now be self explanatory. As a demo I coded a scrolling “Nuts and Volts” text message and a swirling rainbow pattern which alternate. If you build the demonstration hardware and run this sketch you will see a bright, vibrant display without any flicker whats so ever.

Going Further Yet

The demonstration hardware can control 64 RGB LEDs or 192 single color LEDs. If this is still insufficient it ***should be*** possible to add up to eight additional rows of LEDs. It is also possible to chain TLC5947 chips. 16 rows of LEDs combined with two TLC chips would bring the total RGB LED count to 256 with a refresh rate of approximately 60 frames per second. Not to shabby for such a small amount of hardware.

Figure One
Pulse Width Modulation and Duty Cycles

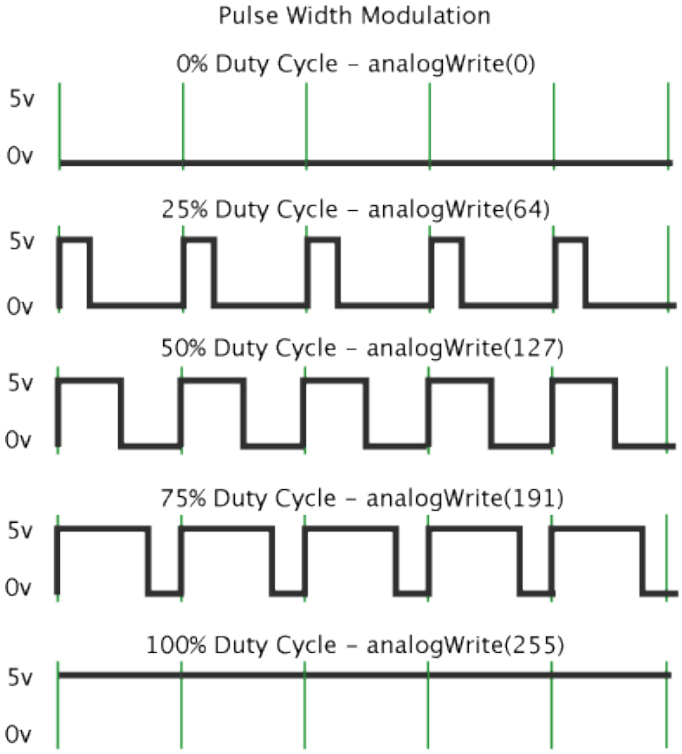

Figure Two
The Demonstration Hardware

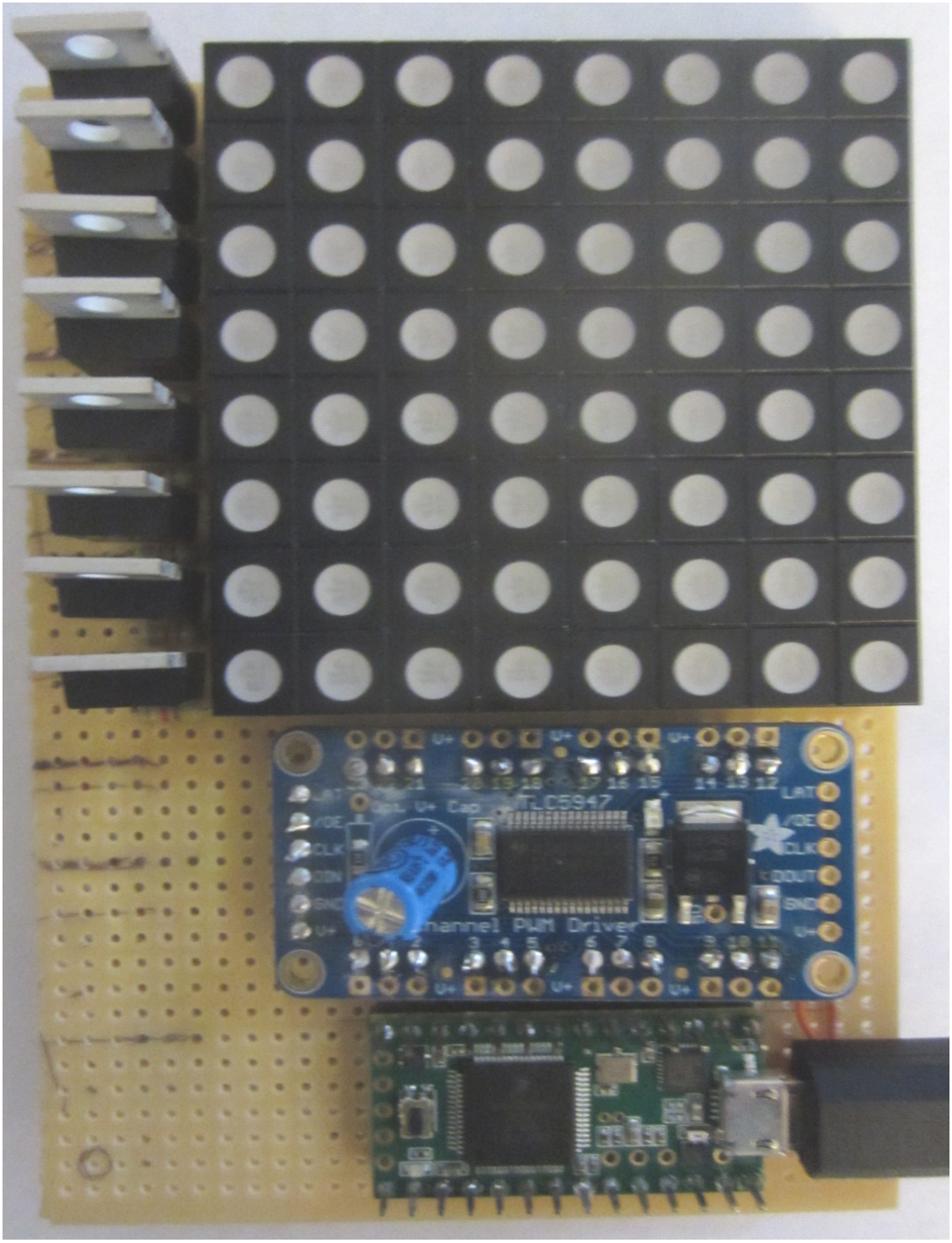

Figure Three
Common Anode RGB LED Matrix Schematic

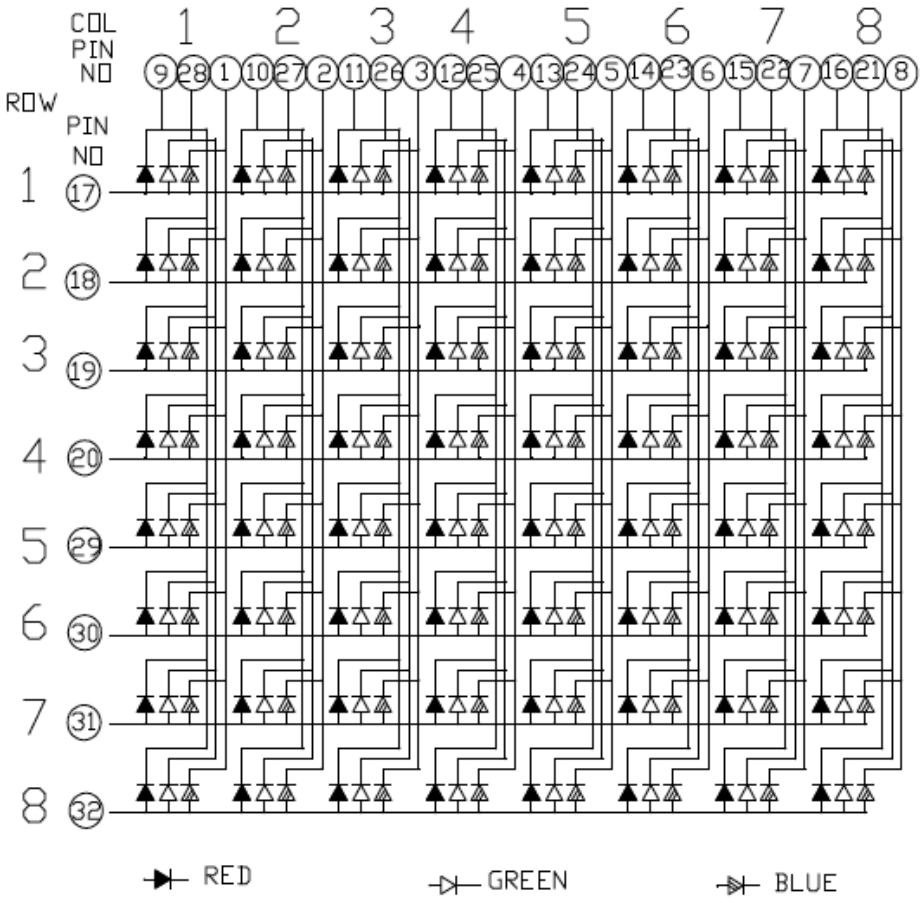

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Figure Four
Demonstration Hardware Schematic

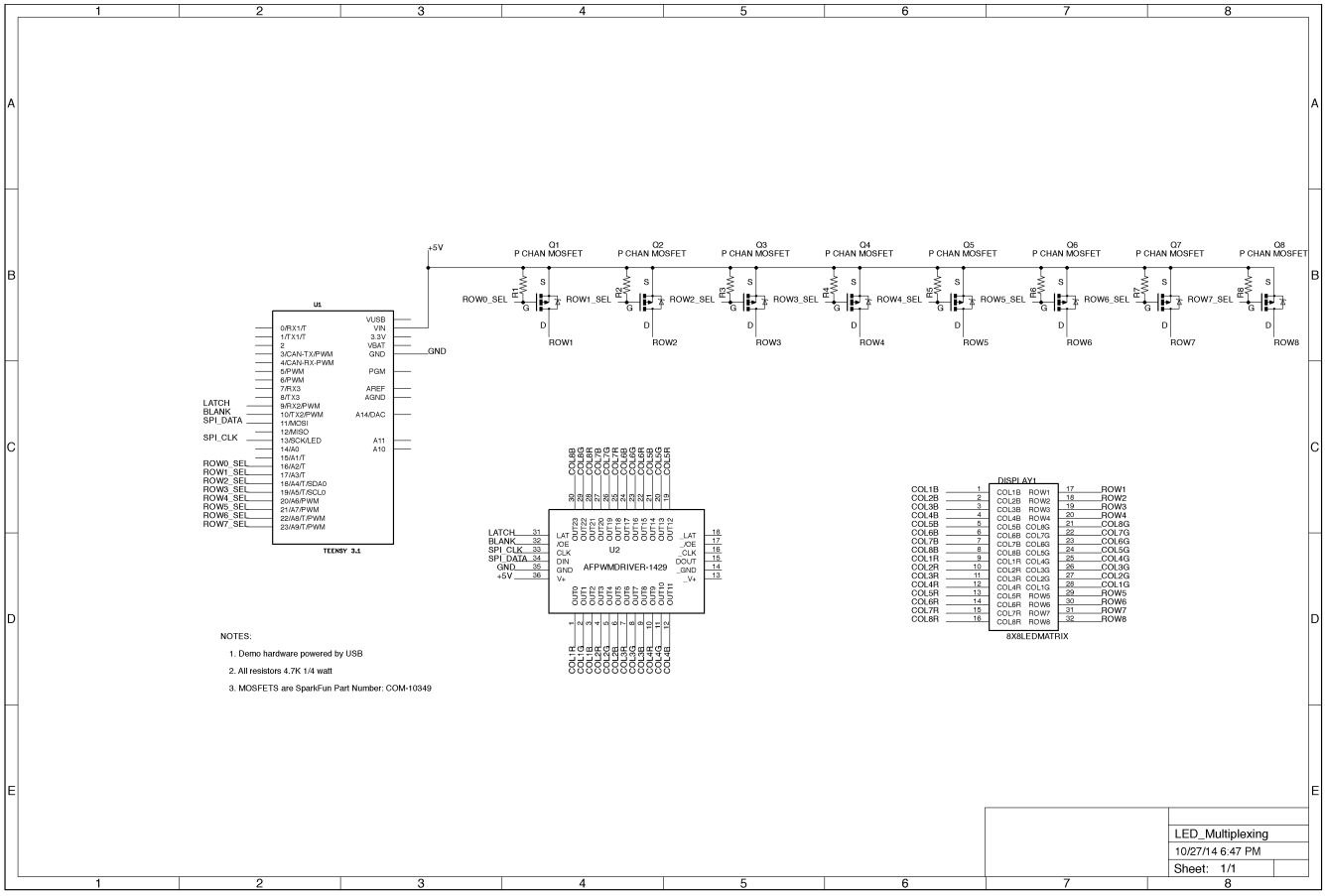

Figure Four
Demonstration Hardware Parts List

Quantity	Part	Description	Source
1	Display 1	Common Anode 8x8 RGB LED matrix	eBay
1	U2	24 channel PWM Controller	Adafruit Product ID: 1429
1	U1	Teensy 3.1 Controller	pjrc.com
8	R1-R8	4.7K ¼ watt resistor	Radio Shack
8	Q1-Q8	P channel power MOSFETs	Sparkfun COM-10349
1		Bread board	Radio Shack
1		USB cable with 5-Pin Micro-B Plug for connecting Teensy to a computer or USB power supply	pjrc.com
1		Optional USB power supply capable of at least 1 amp @ 5 volts	Radio Shack