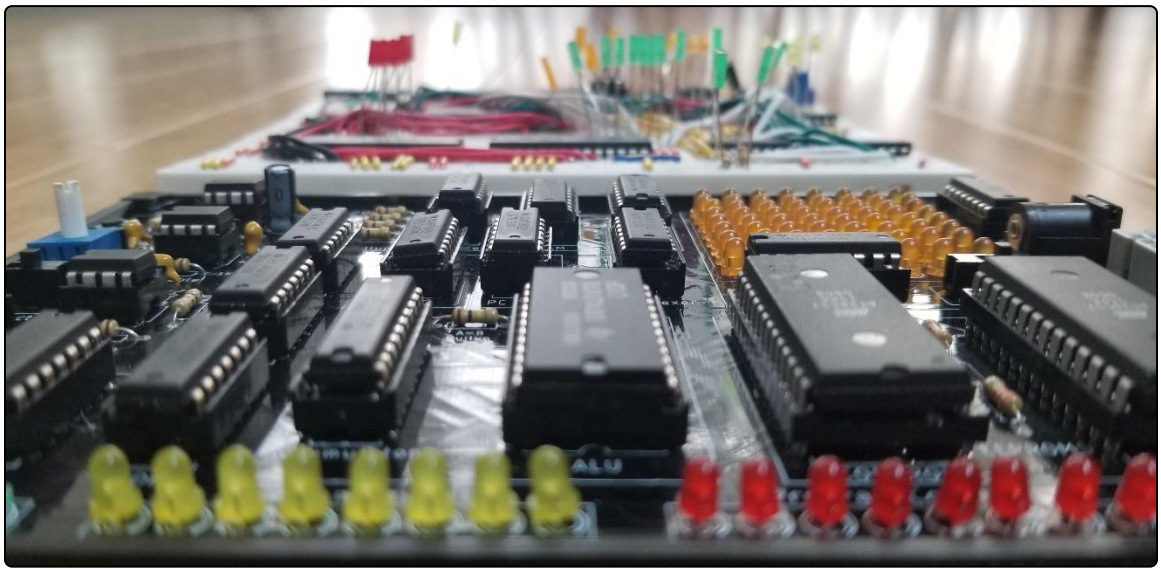
Design Engineering Report



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Date: Friday, July 3, 2020

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Royal St. George's College

High School

Project 1. POV: Dual 7 Segment Display

Purpose

The purpose of this project was to maximize the hardware capabilities by alternating signals on the same wire. This took the form of lighting up two seven-segment displays with only eight Arduino pins and an input for it to display.

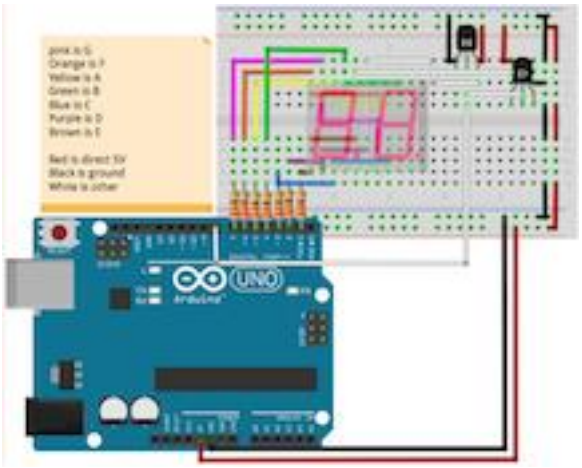
Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/Tasks.html#POV1
IR Sensor Datasheet: https://www.sparkfun.com/datasheets/Sensors/Infrared/gp2y0a02yk_e.pdf

Procedure

Parts	Quantity
602MK2 Dual seven-segment display	1
Arduino board (ATMega328p)	1
USB 2.0 a to b cable	1
2Y0A02 Distance sensor	1
NPN 3904 Transistor	1
PNP 3906 Transistor	1
220Ω Resistor network	2
10KΩ resistor	3

The pins of the dual seven-segment display are connected so that 'a1' is connected to 'a2', 'b1' is 1connected to 'b2', and so on. The pins are then resisted and attached to Arduino pins one to seven so that they correspond to segments 'g', 'f', 'a', 'b', 'c', 'd', and 'e' respectively. The ground of one of the seven-segment displays is connected to the collector pin of an NPN transistor, and the other ground is connected to the emitter pin of a PNP. Both base pins of each of the transistors are connected to a pin that emits a square wave so the two oscillate with alternate signals. This turns each seven-segment display on and off in an alternating pattern so that, when one is on the other is off.



Fritzing Diagram

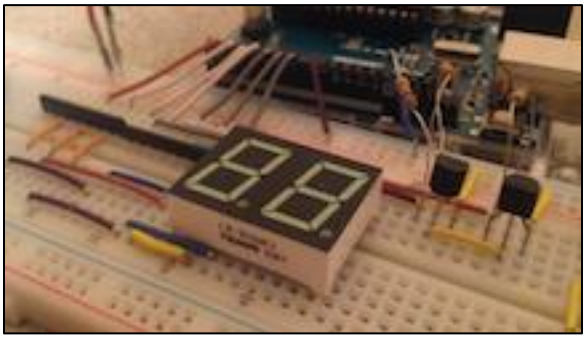
An infrared distance sensor is wired to ground, voltage, and an analog input pin to provide the data that is displayed on the display. The specific IR sensor that was selected measures from 20cm to 150cm.

An array of bytes is configured in such a way that each bit will light up a certain LED in the seven-segment display, and each byte shows a digit. A value is read in by the IR sensor and is converted to centimetres, then restricted to a two-digit maximum. When the information is sent to the displays, the code turns one display off so that only one of them shows the resulting number. Different information is sent, and immediately the other display is turned on to show that information. This oscillation occurs so rapidly that there is a "persistence of vision" effect where it appears both displays are on at the same time but displaying different digits.

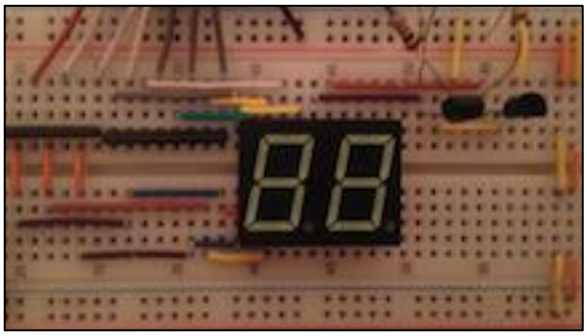
Code

```
// Purpose: To display the distance coming from a IR sensor in centimeters on
   two seven-segment displays.
// Name   : Distance Display
// Author : Daniel Raymond
// Status : Functional

// Global variable setup here
uint8_t dist;       // Converted analog input
uint8_t cnst;       // Constrained dist
uint8_t sensePin = A3;    // Sensor pin
uint8_t tens;       // Left digit displayed
uint8_t ones;       // Right digit displayed
uint8_t base = 10;  // Current base (in base 10)
uint8_t totP = 50;  // Total Period: in milliseconds
uint8_t osiP = 5;   // Oscillation Period: must be lower than totP

  // gfabcde.
uint8_t display[10] = {
  0b01111110,  // zero
  0b00011000,  // one
  0b10110110,  // two
  0b10111100,  // three
  0b11011000,  // four
  0b11101100,  // five
  0b11101110,  // six
  0b00111000,  // seven
  0b11111110,  // eight
  0b11111000,  // nine
};

void setup() { // Runs once at the beginning
  DDRD = 0xFE; // pinMode for the 7 segment pins
  DDRB =  0x21;// pinMode for the oscillating pin and the power pin
}

void loop() { // Loop that makes the cycle continue forever
  dist = 9462 / (analogRead(sensePin) - 18);  // Converts analogRead to cm
  delayMicroseconds(1);
  cnst = constrain(dist, 20, 99);        // Constrains dist

  tens = cnst / 10;                 // Isolates the tens digit
  ones = cnst % 10;                 // Isolates the ones digit
                                // Loops oscillating #'s for
                                // totP regardless of osiP
  for (int x = 0; x < totP*2/osiP; x++) {
    PORTB = 0x00;         // Turn off left 7-segment
    PORTD = display[ones];     // Sends information for right 7-segment
    delay(osiP);
    PORTB = 0x20;         // Turns off right 7-segment
    PORTD = display[tens];     // Sends information for left 7-segment
    delay(osiP);
  }
}
```

Media

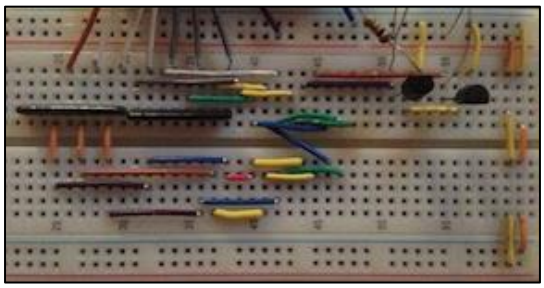


'Trimetric Display View



Top Wiring View

Circuit in Action



'Under the Dual 7-segment display

Reflection

Overall, this project was a huge success. The oscillation of the ground pins on the dual seven-segment display was a very clever and unique way to reduce pin usage. It has taught the class to be mindful of how their Arduino is wired and to help raise the potential limit of what can be achieved. Mid-level programing was also introduced in this project and is another great advantage for coders to understand as it allows direct access to the data that is stored.

Project 2. DIY 8x8 LED Matrix

Purpose

The purpose of this project is to create an LED matrix with anything on it. This is very open ended, so in this design the matrix acts as a timer in which the user can enter a time in seconds, and the LED matrix will begin to light up row by row. When it is completely lit up, the time is finished, and it will start blinking until you turn it off via a button.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/Tasks.html#DIY
Timer Interrupt Library: http://playground.arduino.cc/Code/Timer1

Theory

Since LED matrices have all the anode legs of each row connected, and all the cathode legs of each column connected, creating diagonal lines are impossible to do at the same time. To achieve this however, rows must be alternated incredibly fast using a persistence of vision trick so that the illusion of a diagonal line is created. This trick can be used to show the individually incrementing line, and then the previously filled rows which can be all displayed at the same time. Using this technique, the desired visual output can be achieved. To create the correct intervals of time, timer interrupt statements are used to determine how long each LED should be on for and when to execute the next command.

Parts	Quantity
DIY 8x8 LED Matrix (3mm)	1
Arduino board (ATmega328p)	1
USB 2.0 a to b cable	1
PBNO	1
Shift Register (SN74HC595)	2

Procedure

To begin this arduous task, 64 three-millimetre LEDs are bent so that their anode and cathode legs make a right angle perpendicular to the LED head. After doing this for all the LEDs, rows of eight LEDs are soldered together using a previously 3D printed rig to ensure the correct spacing. Once eight rows are created, the remaining cathode legs are soldered from each of the rows to form the eight by eight matrix (See figure 1). Heat shrink is used on each connection to ensure that none of the anode wires touch any of the cathode wires. After this, a cover is 3D printed to keep the correct spacing of the LEDs during use and to improve the aesthetic of the design.

To wire up the matrix, two shift registers are used; one for the cathode legs and one for the anode legs. The data, clock, and latch pins are separately wired to the Arduino board. Since the pins of the board are internally resisted, the outputs of the shift registers of do not need to be tied to resistors. As per usual, the grounds are connected to the Arduino pin and power is applied.

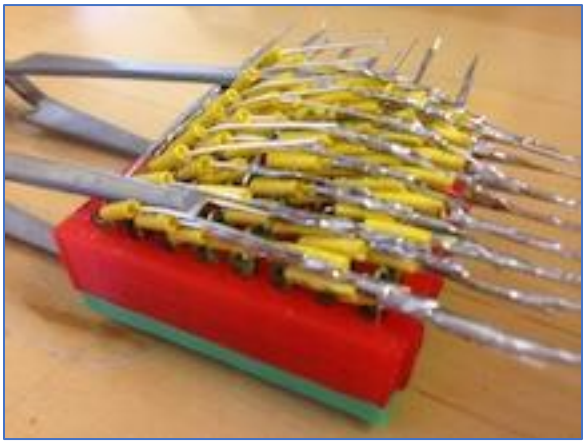
Code

```
// Name   : Custom Matrix Timer
// Author : Daniel Raymond
// Status : Functional

// Pins
uint8_t rowLatch = 2;
uint8_t rowData = 3;
uint8_t rowClk =  4;
uint8_t colLatch = 5;
uint8_t colData = 6;
uint8_t colClk = 7;

uint8_t btn = 13;

// Global variable setup
uint8_t cRow = 0; // Current changing row
uint8_t bRows = 0; // How many rows below should be lit up

uint16_t timer = 0;
double input;

#include <TimerOne.h>

void setup() {
  Serial.begin(9600);
  DDRD = 0b11111100; // Sets up the shift register pins

  // Timer that interrupts the code 1/100th of a second to add one to timer
  Timer1.initialize(10000);
  Timer1.attachInterrupt(second);
}
```

```
void loop() {
  if (Serial.available() > 0) {
    input = Serial.parseInt(); // Reads in time in seconds

    for (uint16_t row = 0; row < 7; row++) {
      for (uint16_t col = 0; col < 7; col++) {
        // Changes led only when time is 1/49th of the way done
        while (timer < ((input / 49) * 100)) {
          for (uint8_t cycle = 0; cycle < 7; cycle++) {
            display(cRow, ~(1 << row)); // Displays the running row
            display(255, ~(bRows)); // Displays rows below the running row
          }
        }
        timer = 0; // Resets timer
        cRow <<= 1;
        cRow++; // Adds one to the current row
      }
      bRows += 1 << row; // Creates one more full row below the current
      cRow = 0; // Resets the current row
    }
    while (digitalRead(btn) == 0) { // Flashes when timer is done
      display(255, 0);
      delay(250);
      display(0, 0);
      delay(250);
    }
    bRows = 0; // Resets full row
  }
  display(0, 0); // Wipes screen
} // End Loop

void display(uint8_t rowInfo, uint8_t colInfo) {
  PORTD = 0; // Closes the latch
  shiftOut(rowData, rowClk, LSBFIRST, rowInfo);
  shiftOut(colData, colClk, LSBFIRST, colInfo);
  PORTD = 0xFF; // Opens the latch
}

void second() {
  timer++; // Timer increments
}
```

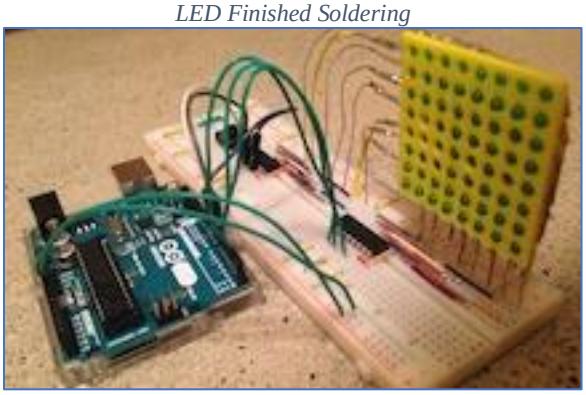
Media

Video: https://www.youtube.com/watch?v=3lzKODT3Jx8



LED Finished Soldering

Trimetric LED View



Completed Circuit

Circuit in Action

Reflection

This project took up a lot of time. The ambitious idea to solder the 8x8 instead of the 4x4 was, while enjoyable, very intensive. I was in the Design Engineering Studio after school four of the five days outside of class adding up to a total of eight hours, not including work at home. While I enjoyed the project, most of the time was spent soldering. After all the time spent on the project, it is disappointing that one row and one column didn't work even though none of the LEDs were burnt out and all of them were facing the correct way. It remains a mystery. Overall, it was a fun project that showed the complexity of even the simplest parts we've used. It makes me appreciate the parts and the fact that we don't have to make them ourselves.

Project 3. Frequency Spectrum Analyzer

Purpose

The goal of this project is to wire an 8x8 LED matrix to display the decibel level of seven unique frequency spectrums using the ATtiny84 microcontroller off board and the MSGEQ7 frequency analyzing chip.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/Tasks.html#FSA
Equalizer Datasheet: https://www.sparkfun.com/datasheets/Components/General/MSGEQ7.pdf

Procedure

To begin this project, the ATtiny84 is wired to two shift registers using three output pins. The clocks of the shift registers are wired together as well as the two latches. For the data pins, the overflow pin of one of the shift registers goes into the data of the other. In this way, we can use two functioning shift registers while only using three pins of the microcontroller. One of the shift registers' output pins are wired to each of the cathode column pins and the other is connected to the anode row pins. To test that this setup works properly, data is hardcoded into an array which is then shifted out using the persistence of vision method (POV).

Parts	Quantity
8x8 LED Matrix (3mm)	1
ATtiny84	1
Pocket AVR Programmer	1
Shift Register (SN74HC595)	2
7 Band Graphic Equalizer (MSGEQ7)	1
Electret Microphone (MAX9814)	1
TRS audio jack (3.5mm)	1
Capacitor	4
Resistor	1

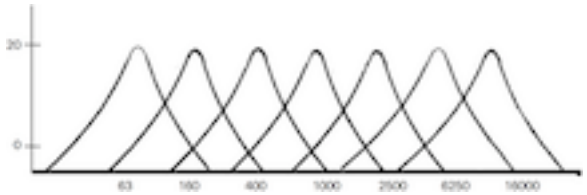
The next iteration of this project is the addition of the dual inputs. For this, a microphone and a TRS audio jack are used with a switch to determine which of the inputs is to be in use. Since the audio jack has left audio (tip) and right audio (ring) but only one input is needed, the two can be wired together and sent to the switch. To interpret the sine wave of voltage that either of the two inputs are sending, an equalizer chip is used. This chip converts its input into seven discrete 'bands' of data that correspond to seven different frequencies (See *MSGEQ7 Frequency Response*). To send this serial data, a strobe, reset and output pin are used. The data pin of the equalizer chip must be sent to an analog-input pin of the microcontroller.

Code is written to read in the data sent from the equalizer chip by manipulating the reset and strobe pins. Since the data that is read is either from 0 to 1023 due to the 10 bit analog to digital converter within the microcontroller, and a total of eight possible decibel levels for the LEDs is required, the raw data can be bit shifted right seven times to give eight possible outcomes. This means that any other bits other than the top three most significant ones are useless. This value from one to eight is than used as the index for another hardcoded array which has eight incrementing values that are all one less than a power of two. This then is shifted onto the column pins of one of the shift registers using POV. This displays our required seven bands.

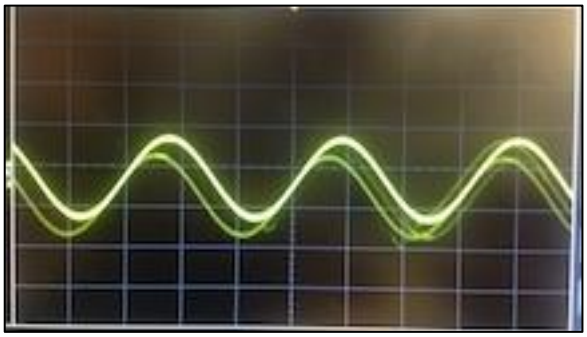
Code

```
// Name   : Frequency Spectrum Analyzer
// Author : Daniel Raymond
// Status : Functional

// Global variable setup here
const uint8_t data = 0;
const uint8_t ltch = 1;
const uint8_t clk = 2;

const uint8_t strb = 8;
const uint8_t reset = 9;
const uint8_t inPin = A7;..

uint8_t spectrum [8];
const uint8_t values [8] = {0x01, 0x03, 0x07, 0x0F, 0x1F, 0x3F, 0x7F, 0xFF};

void setup() { // Runs once at the beginning
  DDRA = 0x07;
  DDRB = 0x06;
}

void loop() { // Loop that makes the cycle continue forever
  // Reset input for the MSG
  digitalWrite(reset, HIGH);
  digitalWrite(reset, LOW);

  for (uint8_t i = 0; i < 7; i++) {
    // Sets MSG latch to be able to read in
    digitalWrite(strb, LOW);
    // Uses 3 most significant bits to tell how many LEDs to turn on
    spectrum[i] = values[analogRead(inPin) >> 7];
    digitalWrite(strb, HIGH); // Sends info

    digitalWrite(ltch, LOW);
    shiftOut(data, clk, LSBFIRST, spectrum[i]); // V+ data (col)
    shiftOut(data, clk, MSBFIRST, ~(1 << i)); // GND data (row)
    digitalWrite(ltch, HIGH);
  }
}
```

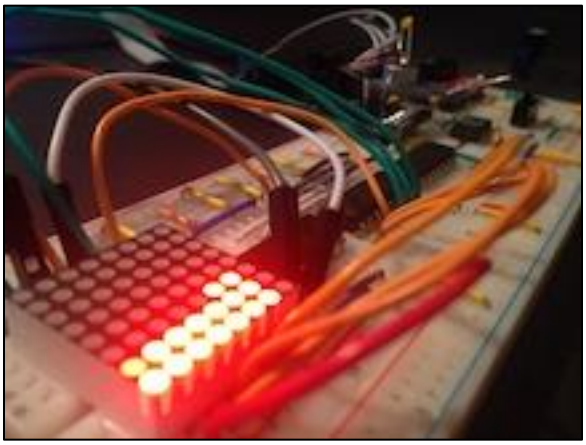
Media



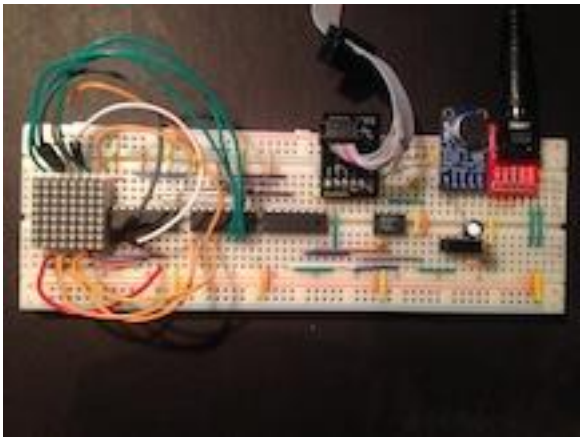
MSGEQ7 Frequency Response



Audio-in Sine Wave



Trimetric LED View



Complete Circuit

Reflection

I have learned a lot about audio to voltage conversion and its simplicity. Taking the sine wave of the physical audio vibrations and converting it to a sine wave of voltage is deceptively simple. This project was a supposed to be a simple concept for learning about audio devices and letting us work on our ISP, but this was not the case. The class spent quite a long time trying to create this device. Although I feel as though I learned a lot from this project, it was also quite frustrating to wire it.

Project 4. Light-Based Alarm Clock

Purpose

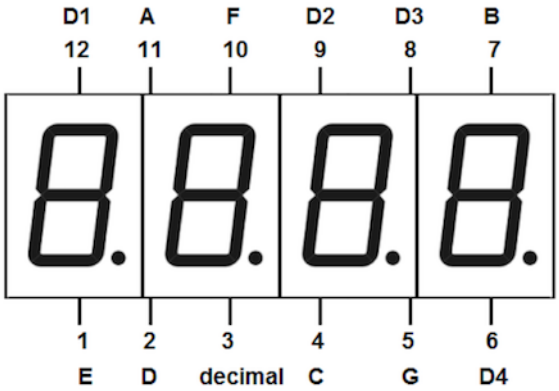
This independent study project (ISP) is designed to wake the user up using light with a settable alarm, all while showing the time. The clock must have a 3D printed case, ensuring the final design has the aesthetic of an actual product.

Reference

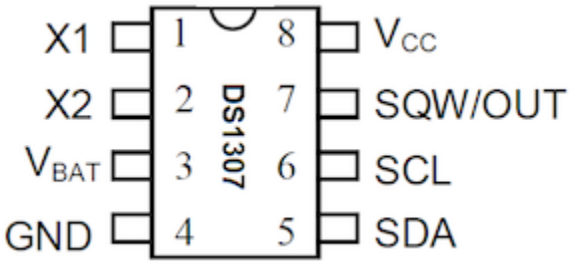
Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/ISPs.html
RTC Datasheet: https://cdn.sparkfun.com/datasheets/BreakoutBoards/DS1307.pdf

Theory

There are two unique parts to this project. The first is the four-digit seven-segment display. There are 12 pins on this device and 32 LEDs. To make this physically possible, eight of the pins are anodes, and four are cathodes. The cathodes control which digit is being grounded, while the anodes determine which segment of all the digits are being powered. This means that if you grounded all four digits and put power to one of the anode pins, four LEDs would come on. In order to achieve maximum capability with this display, the data that is sent to the anode pins must sync with one ground being turned on. If this is done for all four digits in a row, incredibly fast, the persistence of vision effect (POV) will come into play and it will appear as though all four digits are displaying different numbers simultaneously.



The next component is the real time clock (RTC) or specifically, the DS1307 chip. The goal of this real time clock is to, one flashed with the appropriate time, keep track of the number of milliseconds that have passed since January 1st, 1970. This Unix time allows the RTC to feed real time data to the microcontroller. The chip itself has eight pins, seven of which are essential.



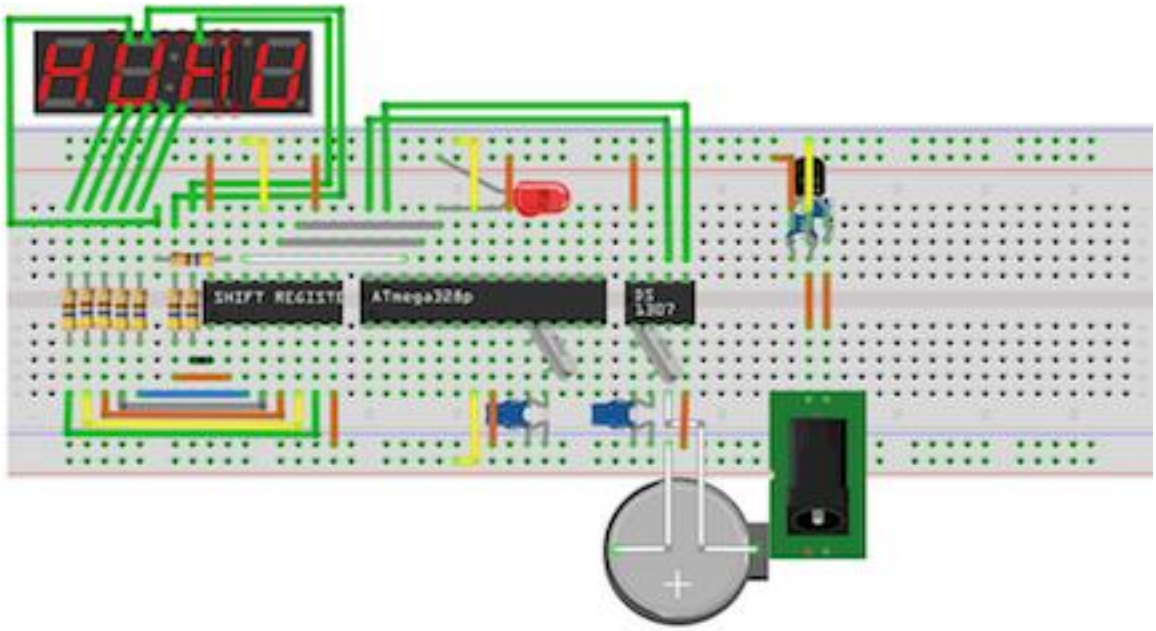
Firstly, there are rail and battery power pins that simply decide how the chip will be powered. Because of the onboard battery, the chip doesn't have to be flashed again if the rest of the breadboard circuit loses power. Of course, there is also a ground. Next, X1 and X2 are in charge of using a crystal in case the user wants an alternate clock speed. Finally, the Serial Clock Line (SCL) and the Serial Data Line (SDA) communicate with the microcontroller, with the data line sending the information and the clock line synchronizing the data transfers. To handle all the resistors, crystals, and capacitors for this chip, a board can be purchased. Once the RTC is fully installed, a library can be used to retrieve information from it.

Procedure

To start of this design, the microcontroller is hooked up to an 8MHz crystal, given power and wired to a programmer. Next, the anode pins of the display are wired through a 470Ω resistor network and into the output pins of a shift register. The cathode pins are connected directly to the off board ATmega328p microcontroller. For the final step of wiring the display, the clock, latch, and data pins of the shift register are also connected to the controller. Two normally closed push buttons (PBNC) are wired with pull down resistors and connected to the ATmega. These buttons take user input to either snooze the alarm or set the time.

Parts	Quantity
4 Digit 7 Segment Display	1
ATmega328p	1
Pocket AVR Programmer	1
Shift Register (SN74HC595)	1
Real Time Clock (DS1307)	1
5V Voltage Regulator (LM78L05)	1
470Ω Resistor Network	2
1KΩ Resistor	4
100uF Capacitor	6
Super Bright LED (YSL-R1042WC-D15)	1

Next, the two switches are wired to power, a pin on the microcontroller, and ground. These switches give the user control over when the clock is displaying the alarm and when they are setting the alarm. For the RTC, the SDA and SCL pins are hooked up to A4 and A5 on the microcontroller and it is given power and ground. A DC jack with a 5V voltage regulator is wired to allow the clock to run off a battery or an electrical plug. For the final component of the breadboard prototype, an LED is simply wired from an output pin of the ATmega to ground. Since this is the alarm of the circuit, the brighter the LED, the better. Once this product is all wired up, a case is 3D printed with holes for all the switches, buttons and LEDs. Code is written to POV the seven segments, take inputs from the buttons and switches, and to light up the LED when the alarm time is equal to the current time.



Code

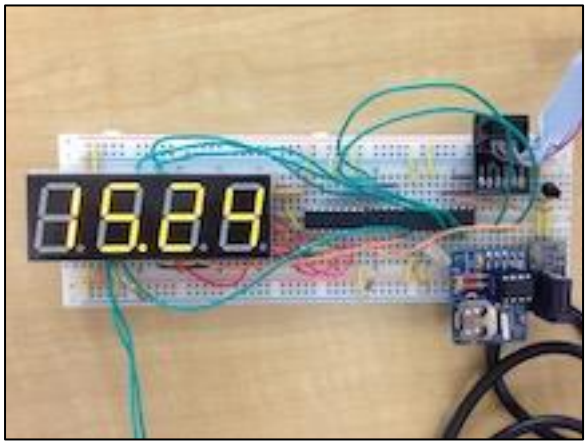
```
// Name   : Light Based Alarm Clock
// Author : Daniel Raymond
// Status : Functional

// Global variable setup here
// Time Variables
volatile uint8_t alrmHr = 11;
volatile uint8_t alrmMin = 45;
// Switch & Button Variables
volatile uint8_t btnWork = 1; // See if button variable can be re-pressed

// Libraries
#include <TimerOne.h>
#include <Wire.h>
#include "RTClib.h"
#include <EEPROM.h>
RTC_DS1307 rtc;

// Pins
// Shift register pins
const uint8_t Data = A3;
const uint8_t Ltch = A2;
const uint8_t Clk = A1;
// All 7 segment ground pins
const uint8_t Seg1 = 4;
const uint8_t Seg2 = 5;
const uint8_t Seg3 = 6;
const uint8_t Seg4 = 7 ;
// Button pins
const uint8_t setBtn = 3;
const uint8_t offBtn = 2;
// Switch pins
const uint8_t setSwtch = 8;
const uint8_t alrmSwtch = 9;
// LED pins
const uint8_t LED = A0;
```

```
void setup() { // Runs once at the beginning
  if (! rtc.begin()) {
    while (1);
  }
  rtc.adjust(DateTime(F(__DATE__), F(__TIME__))); // Updates RTC

  DDRD = 0xF0;
  DDRC = 0x0F;
  // Allows button to be reactivated every 8th of a second
  Timer1.initialize(125000);
  Timer1.attachInterrupt(sec);
}

// Main Loop
void loop() {
  check();
  // Snoozes
  if (digitalRead(offBtn) == 0)
    digitalWrite(LED, LOW);
  // Checks switches for display
  if (digitalRead(alrmSwtch) == 0)
    tmDsply();
  else {
    if (digitalRead(setSwtch) == 0)
      alrmDsply();
    else
      setAlrm();
  }
}
// Displays the Time
void tmDsply() {
  DateTime now = rtc.now();
  // Shows time from the RTC
  segment(Seg1, EEPROM.read(now.minute() % 10));
  segment(Seg2, EEPROM.read(now.minute() / 10));
  segment(Seg3, EEPROM.read(now.hour() % 10) | 1); // Turns decimal on
  if (now.hour() >= 10)
    segment(Seg4, EEPROM.read(now.hour() / 10));
}
// Displays what the alarm is
void alrmDsply() {
  segment(Seg1, EEPROM.read(alrmMin % 10));
  segment(Seg2, EEPROM.read(alrmMin / 10));
  segment(Seg3, EEPROM.read(alrmHr % 10) | 1);
  if (alrmHr >= 10)
    segment(Seg4, EEPROM.read(alrmHr / 10));
}
```

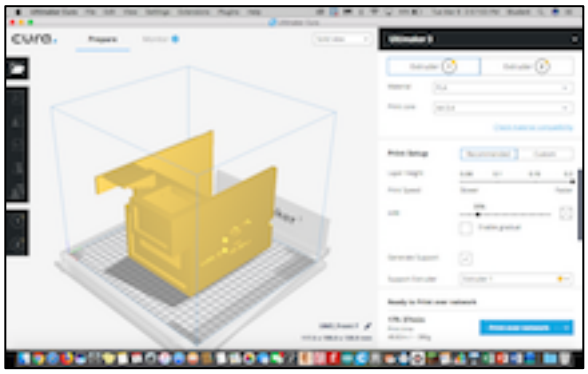
```
void setAlrm() { // Displays set mode for Alarm
  // Sets display
  for (int i = 0; i < 70; i++) {
    segment(Seg1, EEPROM.read(alrmMin % 10));
    segment(Seg2, EEPROM.read(alrmMin / 10));
    segment(Seg3, EEPROM.read(alrmHr % 10) | 1);
    if (alrmHr >= 10)
      segment(Seg4, EEPROM.read(alrmHr / 10));
  }
  if (digitalRead(setBtn) == 0 && btnWork == 1) { // Increases alarm
    alrmMin++;
    if (alrmMin == 60)
      alrmHr++;
    alrmMin %= 60;
    if (alrmHr == 25)
      alrmHr = 1;
    btnWork = 0;
  }
  blanked();
  delay(100);
}
void blanked() { // Blanks screen
  digitalWrite(Seg1, HIGH);
  digitalWrite(Seg2, HIGH);
  digitalWrite(Seg3, HIGH);
  digitalWrite(Seg4, HIGH);
}
void segment(uint8_t seg, uint8_t data) { // Shows data on one segment
  // Stops sending data
  digitalWrite(Ltch, LOW);
  shiftOut(Data, Clk, MSBFIRST, 0);
  digitalWrite(Ltch, HIGH);
  // Ground config
  blanked();
  digitalWrite(seg, LOW);
  // Data sending
  digitalWrite(Ltch, LOW);
  shiftOut(Data, Clk, MSBFIRST, data);
  digitalWrite(Ltch, HIGH);
  delay(1);
}
void sec() { // Re-allows button to increase variables every 1/8 second
  btnWork = 1;
}
void check() {
  DateTime now = rtc.now();
  // Checks if alarm should go off
  if (now.minute() == alrmMin && now.hour() == alrmHr && now.second() < 3)
    digitalWrite(LED, HIGH);
}
```

Media

Circuit Version 1 – Arduino



Circuit Version 2 – RTC + Off-board



1D Print Model

Final Product

Reflection

I have never put more hours into a school project. I am very proud of the outcome, and love it show it off every chance I get. The fact that something I have made is something I want to use is fantastic. One thing that I love about ISPs is that whenever you decide your idea, you never have any idea of how to make it or how it will work. For instance, when I was first told about the RTC, I was very confused. Now, I feel as though I could wire one up in seconds (to be honest, I probably could). Overall, I am overjoyed by the whole experience.

Project 5. Printed Circuit Board: RTC Clock

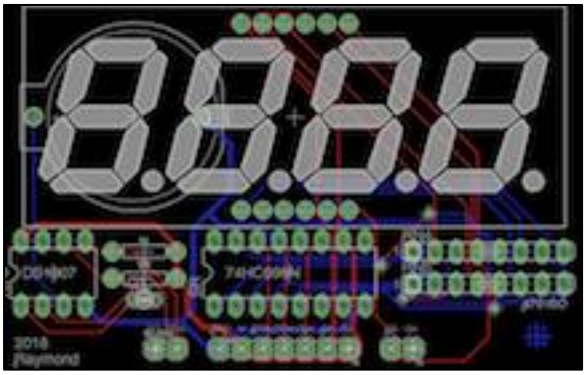
Part A. Design

Purpose

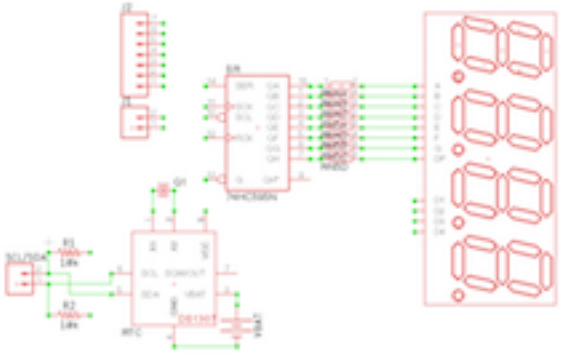
This project is an introduction to Eagle and designing printed circuit boards (PCB). For this, a board is designed with a four-digit seven segment display that is hooked up to a shift register. All the required control pins are wired to pins that can be hooked up to an Arduino. On top of this, a prewired RTC can be connected to the Arduino. With this project, a user can extract data from the RTC and then show it on the display.

Parts	Quantity
Printed Circuit Board	1
4 Digit 7 Segment Display	1
Real Time Clock (DS1307)	1
8MHz Crystal	1
Shift Register (SN74HC595)	1
470Ω Resistor Network	2
10kΩ Resistor	2

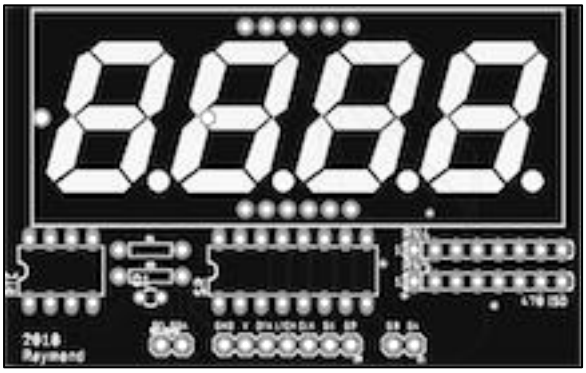
Media



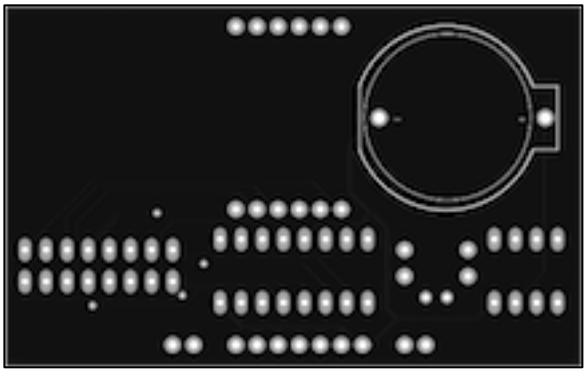
Finished Eagle Design



Schematic



Rendered Top



Rendered Bottom

Part B. Implementation

Purpose

The purpose of this project is to complete the PCB design project by soldering, testing, and coding. This product is designed for grade 11 ACES who are learning how to use real time clocks (RTC), specifically the DS1307. The quad 7 segment display gives the user a finished product, as well as another component to use alongside the RTC.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/Tasks.html#PCB2
RTC Datasheet: https://cdn.sparkfun.com/datasheets/BreakoutBoards/DS1307.pdf
DirtyPCBs: https://dirtypcbs.com/store/pcbs

Theory

The theory for this PCB is quite simple. Like my previous ISP, the Light-Based Alarm Clock, a microcontroller reads a DS1307 RTC and sends the data directly to a quad 7 segment display. Since this RTC is I2C compatible device, only four wires are needed to communicate with it: SCL, SDA, power, and ground. Since there are four digits on the display and only two numbers, hours and minutes, modulo and integer division are used to separate the high digit from the low one. Once the microcontroller has read in the time from the flashed RTC, it sends the data to the display using an eight-bit serial in parallel out shift register. Since this specific display only has 12 pins, the four grounds for each of the 7 segments are used to show all the digits using POV.

Procedure

After designing the PCB in eagle, the layers of the board are separated using a CAM processor and sent to a PCB manufacturer, in this case DirtyPCBs. Once the boards arrive two chip seats are soldered on: one for the RTC and one for the shift register. The two 10KΩ resistors, resistor networks, capacitor, and battery holder are soldered in as well. Finally, the display and headers pins are soldered in. The RTC and shift register are inserted into the chip seats. To connect the board to the Arduino, the PCB is inserted on the digital pin side of the board with 'G4' being inserted into digital pin six. Finally, code is written to read the data of the RTC and deliver it to the display using POV.

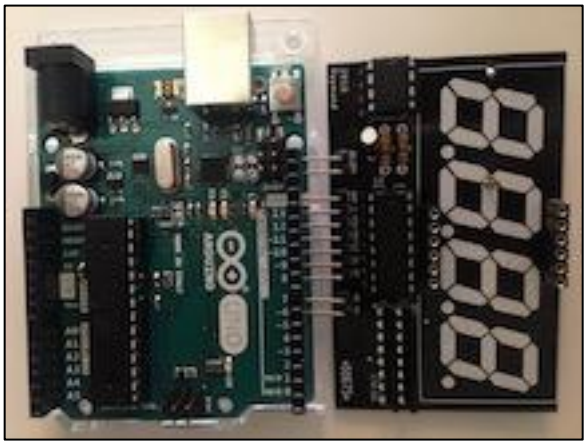
Parts	Quantity
PCB	1
4 Digit 7 Segment Display	1
Arduino UNO	1
Shift Register	1
Real Time Clock (DS1307)	1
5V Cell Battery & Holder	1
Chip Seat	2
470Ω Resistor Network	2
10KΩ Resistor	2
100uF Capacitor	6
Male Header Pins	11

Code

```
// Name   : PCB RTC Clock
// Author : Daniel Raymond
// Status : Functional

// abcdefg.

#include <EEPROM.h>
#include <TimerOne.h>
#include <Wire.h>
#include "RTClib.h"

RTC_DS1307 rtc;
const uint8_t Pwr = 13;
// Shift register pins
const uint8_t Data = 12;
const uint8_t Ltch = 11;
const uint8_t Clk = 10;
// All 7 segment ground pins
const uint8_t Seg4 = 9;
const uint8_t Seg3 = 8;
const uint8_t Seg2 = 7;
const uint8_t Seg1 = 6 ;

void setup () {
  pinMode(13, OUTPUT);
  digitalWrite(13, HIGH);

  if (! rtc.begin())
    while (1);
  if (! rtc.isrunning())
    rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));

  for (int i = 6; i < 14; i++)
    pinMode(i, OUTPUT);
  digitalWrite(Pwr, HIGH);
}

// Main Loop
void loop() {
  DateTime now = rtc.now();
  // Shows time from the RTC
  segment(Seg1, EEPROM.read(now.minute() % 10);
  segment(Seg2, EEPROM.read(now.minute() / 10);
  segment(Seg3, EEPROM.read(now.hour() % 10);
  //  // if (now.hour() >= 10)
  segment(Seg4, EEPROM.read(now.hour() / 10);
}
```

```
// Shows data on one segment
void segment(uint8_t seg, uint8_t data) {
  // Stops sending data
  digitalWrite(Ltch, LOW);
  shiftOut(Data, Clk, LSBFIRST, 0);
  digitalWrite(Ltch, HIGH);
  // Ground config
  digitalWrite(Seg1, HIGH);
  digitalWrite(Seg2, HIGH);
  digitalWrite(Seg3, HIGH);
  digitalWrite(Seg4, HIGH);
  digitalWrite(seg, LOW);
  // Data sending
  digitalWrite(Ltch, LOW);
  shiftOut(Data, Clk, LSBFIRST, data);
  digitalWrite(Ltch, HIGH);
  delay(1);
}
```

Media



PCB Pin layout

Clock in Action

Reflection

Receiving a PCB that I had made for their first time in my life was exhilarating. Seeing physical boards that were very professional made me see the potential for future projects and ISPs. Soldering the board was nerve-racking, as I thought there was no way it was ever going to work first try; to my surprise, it did. I was so excited to solder it that I forgot to take video of the process! After that, coding it was a breeze because I had done a project like this for my ISP. Overall, I am thrilled with how my design turned out; I love its compact design and professional style.

Project 6. I²C Velocity Data Logger

Purpose

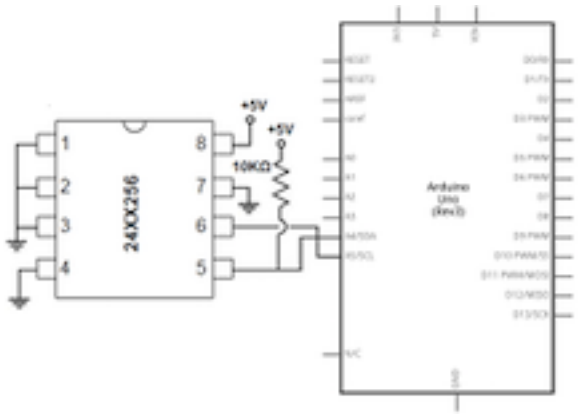
The goal of this project is to develop an understanding of the Inter-Integrated Circuit (I2C) protocol. This is achieved by creating a circuit which logs data onto an external electrically erasable programmable read-only memory (EEPROM) chip. This data is then presented on the serial plotter by reading off said chip. An RTC is also used to time stamp each byte of data. The data that is going to be logged is the velocity of a hand that is using a computer.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/Tasks.html
EEPROM Datasheet: http://www.advanide.com/wp-content/uploads/products/contact_memories/24LC256.pdf

Theory

To calculate the velocity of the hand, first the coordinates of it are measured. These values are then subtracted from its previously measured coordinates to figured out the total distance travelled over a given period. From these two lengths, x and y, Pythagorean theorem is used to calculate the total distance the object travelled. This distance value is divided by the period and then logged onto an external I2C EEPROM chip. EEPROM chips have what is essentially an array of bytes, that can be read and written to. To measure the period in j distance recordings, an RTC is used. The RTC has a square wave, which emits a 1Hz, 4KHz, 8kHz, or 32KHz waves. This allow frequency allows us to determine how often we sample from our sensors.



EEPROM Wiring

Procedure

A DS1307 RTC chip is connected to the SDA and SCL pins of an Arduino UNO. Pull up resistors are tied to both lines, as the Arduino can only pull them down. An 24LC256 EEPROM chip is also wired as shown in *EEPROM Wiring* so that the microcontroller can read and write to it. The sensors that are used for this project are two IR distance sensors. This allows for two-dimensional distance tracking of an object. Using this information, the velocity can be calculated. This is the data that is sent to the EEPROM to be stored. Finally, the data is read off the EEPROM chip and displayed on a serial plotter.

Parts	Quantity
Arduino UNO	1
Real Time Clock (DS1307)	1
I2C EEPROM (24LC256)	1
IR Distance Sensor (GP2Y0A41SK0F)	2
10KΩ Resistor	2

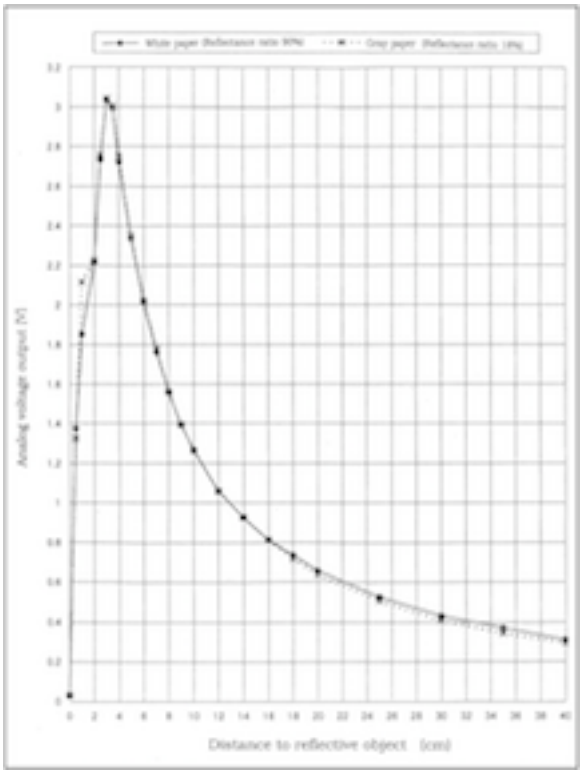
Code

```
// Name   : I2C Speed Graphing Program
// Author : Daniel Raymond
// Status : Functional

#include <Wire.h>
#define RTC_ADDRESS 0x68
#define EEPROM_ADDRESS 0x50 // Stores 32KB
#define INT0 2
#define SQWE 4
#define controlReg 0x07
#define RS0 0
#define RS1 1
#define Hz4 (1 << RS0)
#define smth 3 // Smoothing factor

uint16_t averaging = 0;
uint8_t incr = 0;
volatile uint16_t count = 0;
volatile bool triggered = false;

double distance = 0;
double tmDif = 0;
double avVels[smth];
double avVel = 0;

struct prevRec {
  double seconds;
  double minutes;
  double distX;
  double distY;
  double mills;
} pr
struct  currRec {
  double seconds;
  double minutes;
  double distX;
  double distY;
  double mills;
} cr;

void setup() {
  Serial.begin(9600);
  Wire.begin();
  Wire.beginTransmission(RTC_ADDRESS);
  Wire.write(controlReg);
  Wire.write((1 << SQWE) | Hz4); // Sets the Hz at which we receive data
  Wire.endTransmission();

  PORTD |= (1 << PD2); // Enable pullup resistor (Input Mode + writing HIGH)
  attachInterrupt(digitalPinToInterrupt(INT0), pulse, FALLING);
}
```

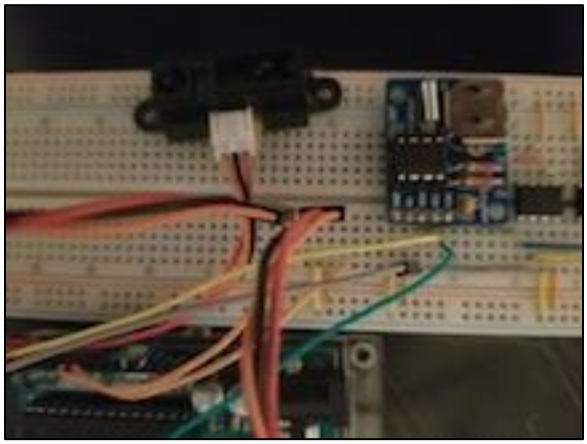
```
void setup() {
  Serial.begin(9600);
  Wire.begin();

  Wire.beginTransmission(RTC_ADDRESS);
  Wire.write(controlReg);
  Wire.write((1 << SQWE) | Hz4); // Sets the Hz at which we receive data
  Wire.endTransmission();

  PORTD |= (1 << PD2); // Enable pullup resistor (Input Mode + writing HIGH)

  attachInterrupt(digitalPinToInterrupt(INT0), pulse, FALLING);
}
void loop() {
  if (triggered) { // Runs  times a second
    triggered = false;

    avVels[incr] = calcVel(); // Smooth out the data
    incr = (incr + 1) % smth;

    avVel += avVel[incr];

    if (incr == (smth-1)) {
      Serial.println((avVel/smth);
      avVel = 0;
    }
  }
} // End loop
void readDist() {
  uint8_t rawX = analogRead(PC0);
  uint8_t rawY = analogRead(PC1);

  pr.distX = cr.distX;
  pr.distY = cr.distY;

  cr.distX = constrain(2076 / (rawX - 11), 4, 30);
  cr.distY = constrain(2076 / (rawY - 11), 4, 30);

  double lngthX = abs(cr.distX - pr.distX);
  double lngthY = abs(cr.distY - pr.distY);

  distance = sqrt(lngthX * lngthX + lngthY * lngthY);
}
double calcVel() {
  readDist();
  pr.mills = cr.mills;
  pr.seconds = cr.seconds;
  pr.minutes = cr.minutes;
  Wire.beginTransmission(RTC_ADDRESS);
  Wire.write(0);
  Wire.endTransmission();
  Wire.requestFrom(RTC_ADDRESS, 2);
while (!Wire.available());
  cr.seconds = bcd2dec(Wire.read());
  cr.minutes = bcd2dec(Wire.read());
  cr.mills = count;
  tmDif = ((cr.minutes - pr.minutes) * 60) + (cr.seconds - pr.seconds) + ((cr.mills -
pr.mills) / 4096);
  return (distance / tmDif) / 100;
}
```

```
void pulse() {
  count++;
  triggered = true;
  PORTB ^= (1 << PB5); // Flicker the LED (Alternates between 0 & 1)
}

uint8_t bcd2dec(uint8_t bcd) {
  return 10 * (bcd >> 4) + (bcd & 0x0F);
}
```

Media



Distance Sensor Distance to Voltage Graph



Circuit

Reflection

Although it was disappointing not to get the EEPROM chip working, I still learned a lot about I2C. I liked the idea of incorporating physics concept into hardware, because it feels as though this project has a real-world application. Once again, for the last time, I've realized how inconsistent the distance sensors are. Although this project was late, rushed, and didn't work, I still feel as though I put way too many hours into this project, especially with this ISP coming up.

Project 7. Bluetooth Photo Frame

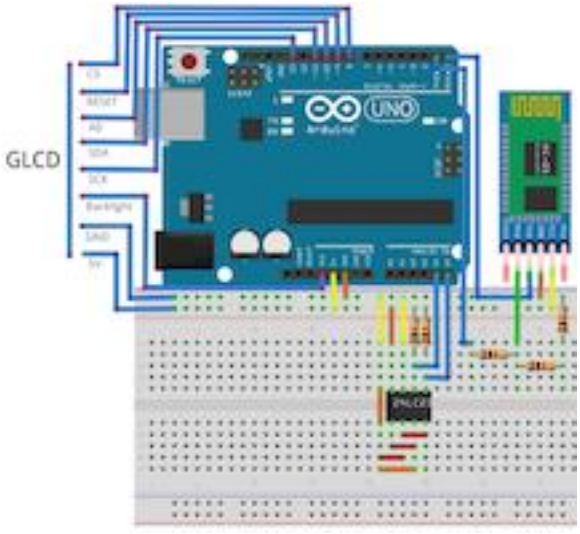
Purpose

The purpose of this project was to design and create a device that would receive photos using Bluetooth and display them on a graphical liquid crystal display (GLCD). The photos would be sent from a phone that has a personally designed app to transfer the data.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI3M/1718/ISPs.html
GLCD Datasheet: https://www.buydisplay.com/download/manual/ER-TFTM050-2
MIT App Inventor: http://ai2.appinventor.mit.edu/#

Theory



The HC05 module itself handles most of the difficult aspects of Bluetooth. It transmits data via low power radio wave frequencies, specifically around 2.45 gigahertz (GHz). This frequency is an internationally agreed upon standard. Since Bluetooth data is transfer through radio waves, this means that it must either use amplitude modulation (AM) or frequency modulation (FM). As it turns out, Bluetooth uses FM. If the phone wants to send a 0 to the module, it sends out a frequency of 2.402 GHz, and if it wants to send out a one, it sends out 2.480 GHz. Bluetooth wiring and coding, however, is quite simple. There are two communication pins for transmitting and receiving data. The transmitter of the HC05 is connected to the receiver of the Arduino, and the reverse is true for the other communication pins. Since this is serial communication, the Arduino pins used are zero and one. Whenever, the Arduino receives data from the outside world, all the code must do is state that when the serial in line has something on it, read it.

The GLCD has three main components: vertical sync (vsync), horizontal sync (hsync), and colour. The hsync chooses the column in which the colour is going to be displayed on. To do this, it scrolls along the screen horizontally. The vsync is coordinating with it in such a way that, whenever the hsync finishes scrolling through a row, the vsync shifts down by one. This creates a unique point in time for each pixel to be told what colour to be. All the microcontroller has to do is tell the GLCD what colour to display at any given point in time.

The phone application development software is very high level. It uses block code and along with drag-and-drop interfacing. All the app does is connect with the HC05 and have a button to tell it which image to display. When the button is pushed, it sends the appropriate data.

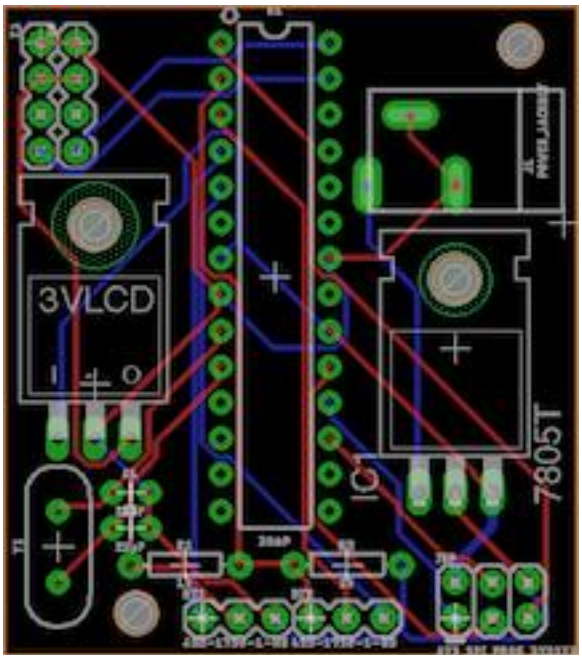
Parts	Quantity
Arduino UNO	1
HC05 Bluetooth Module	1
I2C EEPROM (24LC256)	1
ILI9163C Graphic LCD	1
4.7KΩ Resistor	5

Procedure

To start off the project, the RX and TX pins of the HC05 Bluetooth module are connected to the TX and RX pins of the Arduino (respectively). This allows the Arduino to transmit data using Bluetooth, as well as receive data from the transmitting HC05. Since the logic level of the Bluetooth module is 3.3V, a voltage divider is used on the RX pin. 5V and ground are also connected to the HC05.

When the ER-TFTM0D0-2 is purchased, the decision must be made of what kind of communication to use. Since the class is most familiar with it, I^2C is chosen. This means that the SDA and SCL pins need to be connected, as well as power and two ground. This is a beast of a machine due to its onboard microcontroller, so it requires 300mA of current. For this, a PCB is designed to provide enough power to the GLCD, as well as an offboard ATmega328p microcontroller to run it. This specific display does not have a backlight pin, so registers need to be manipulated in order to turn it on. Unfortunately, the difficultly of this display was underestimated, so a new display is purchased that is much, much simpler. The new display is the ILI9163C graphic LCD. It uses SPI communication on top of having a dedicated power, ground, and backlight pin.

After the entire device is wired up and programmed, an app is developed for Android that connects to the HC05, selects an image, and sends it to the Arduino. Unfortunately, there is no feasible way to transfer image data over Bluetooth; it can only send and receive text. This means that the data transfers would have to be simple. To work around this distinct problem, external EEPROM chips are used to store pre-set images. When the app sends a string, the Arduino receives it and determines which image is to be shown on the GLCD screen. The specific EEPROM chip that is the 24LC256 I2C EEPROM chip, which have been used (unsuccessfully) in a previous project. Once the EEPROM is in place, the prototype is finally complete.



PCB for the ER-TFTM0D0-2

If one were to go a step further in this process, a new PCB would be designed to accommodate the new parts and a case would be 3D printed to store the project. Unfortunately, time constraints did not allow for these extremities.

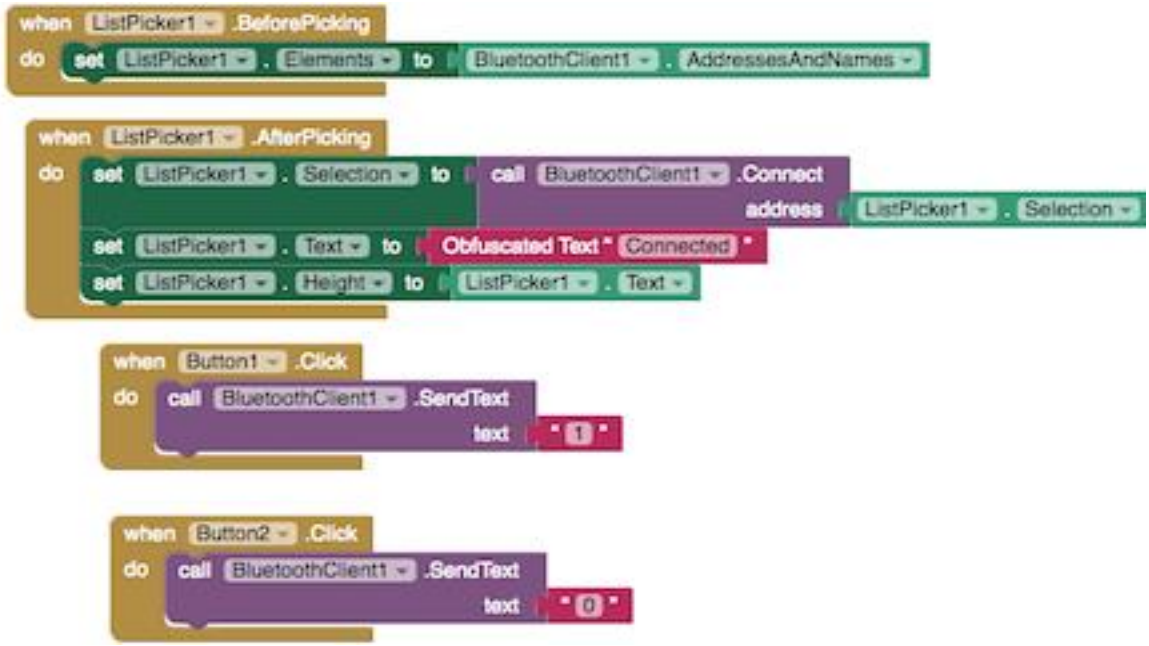
Code

```
// Name: Bluetooth Photo Frame
// Author: Daniel Raymond
// Description: Receives photos using Bluetooth and then displays then on a GLCD.

#include <Wire.h>
#include <SPI.h>
#include <Adafruit_GFX.h>
#include <TFT_ILI9163C.h>

#define EEPROM_ADDRESS 0x50
#define CSelect 10
#define DC 9
#define a0 8
#define BLACK 0x00
#define baud 9600
#define LCD_W 128
#define LCD_H 128
uint8_t state = 0;

TFT_ILI9163C tft = TFT_ILI9163C(CSelect, a0, DC);

void setup() {
  tft.fillScreen(BLACK); // Start of with a black screen
  Wire.begin(); // Begin wire library
  tft.begin(); // Begin tft library
  Serial.begin(baud); // Default communication rate of the Bluetooth module
}

void loop() {
  if (Serial.available() > 0) { // Checks whether data is coming from the serial port
    state = Serial.read(); // Reads the data from the serial port
    for (uint8_t x = 0; x < LCD_W; x++)
      for (uint8_t y = 0; y < LCD_H; y++) // Read colour data from EEPROM
        tft.drawPixel(x,y,convClr(readIIC(EEPROM_ADDRESS,(x*12+y)+(state-48)*16834)));
        // state is a character: subtracting 48 converts to an int and multiplies by
        // 16834 to determine which image
    state = 0; // Reset state
  }
}
uint16_t convClr(uint8_t clr) {
  uint8_t red = clr >> 5;            // 3 bits
  uint8_t green = (clr >> 2) & B00111; // 3 bits
  uint8_t blue = clr & B11;           // 2 bits
  return (map(red, 0, 8, 0, 0xF) << 8) | (map(green, 0, 8, 0, 0xF) << 4) | map(blue,
0, 4, 0, 0xF); // Maps 8bpp to 16bpp
}

uint8_t readIIC(int adrs, unsigned int eeaddress) {
  uint8_t rdata = 0xFF;//sets a uint8_t for data
  Wire.beginTransmission(adrs);//begins communicating with eeprom address
  Wire.write((int)(eeaddress >> 8)); // sends the MSB to the eeprom address
  Wire.write((int)(eeaddress & 0xFF)); // sends the LSB to the eeprom address
  Wire.endTransmission();//end transmission
  Wire.requestFrom(adrs, 1);//request one uint8_t from that address
  while (!Wire.available());
  rdata = Wire.read();//if the data is available read it
  return rdata;//return the data at specified address
}
```

Media

ER-TFTM0D0-2

Display Prototype



MIT App Inventor 2 Block Code

Reflection

I underestimated the difficulty of this project. The Bluetooth is finicky, the graphic LCDs are infinitely more complex than LED matrices, and phone applications are limiting. This is the first time an ISP of mine has not gone to plan in any sort of capacity. Failure is something that, while uncomfortable at first, has shown me to appreciate the knowledge gained more than the final project. I fully believe that I will be using these parts in the future, and the skills I have gained from this ISP will most likely help me in my future endeavors.

Project 8. CHUMP

Part A. The Code

Purpose

This project is an introduction to machine code, assembly, and the future project of the four-bit computer. The assignment is to come up with a series of machine code commands that performs a task. Since this project is only based on the code, the mechanics of the four-bit computer will be explained in a later report.

Theory

There are seven general commands, all of which have two flavors: memory and constant. If the constant version is chosen, the lower nibble acts as the number in which the command uses. If the memory version is chosen, it acts as the address for the register in RAM. The data in this register is the number that the command uses. All the commands alter data in registers; it is their function. Figure 1 demonstrates each command and what register they change.

```
    LOAD  .Accumulator
     ADD  .Accumulator
SUBTRACT  .Accumulator
 STORETO  .........RAM
    READ  .....Address
    GOTO  ..........PC
  IFZERO  ..........PC
```

Figure 1

The goal of this specific series of commands is to check if the accumulator register is equivalent to the second register (register 1) in random access memory (RAM). To do this, it first sets register 1 to a random value; in this case, two. Then it loads the accumulator with the value it wants it to be compared to. Once all of this preparation is done, the computer subtracts three (the value from register 1) from the accumulator. If this is then equal to zero, the two numbers are equivalent. To signify this equivalency, the computer places a one in register five. If they are not equivalent, it leaves it at zero. Finally, it resets the accumulator back to its original value of two.

Code

```
0000:   00000010      LOAD        2       ;accum = 2
0001:   10000001      READ        1       ;addr = 1
0002:   01100001      STORETO     1       ;memory[1] = 2
0003:   00000011      LOAD        3       ;accum = 3
0004:   01010001      SUBTRACT    2       ;accum -= mem[1]
0005:   10101000      IFZERO      8       ;accum == 0? pc = 8
0006:   00000001      LOAD        1       ;accum = 1
0007:   01110101      STORETO     5       ;mem[5] = 1
0008:   00000001      LOAD        2       ;accum = 2
```

Reflection

This project was complex and mind-bending. Although all the registers, loading, and arithmetic was challenging itself, I found the most difficult part about this entire project was finding an end goal with a level of appropriate difficultly. The processor was so limited that I didn't fully understand what purpose it served, and thus it took me a while to come up with broken code.

Part B. The Clock

Purpose

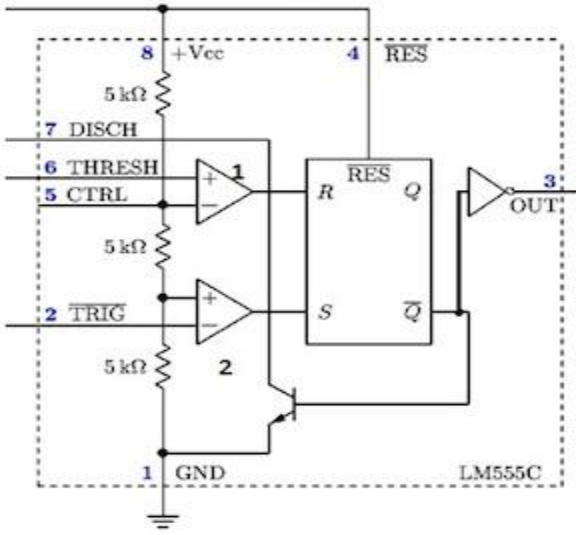
The clock is the heartbeat of a computer. It synchronizes all the data transmission and coordinates components of a computer. In this report, multiple timer ICs will be used to create this clock.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/4BitComputer/index.html#tasks
555 Explained: https://youtu.be/kRlSFm519Bo?t=2m59s
Logic Gate Combination: https://youtu.be/SmQ5K7UQPMM?t=45s

Theory

This circuit has four main components: astable, monostable, and bistable oscillators, as well as a few logic gates that connects everything. All three oscillators use the 555 timer as their core IC. The 555 has a threshold and a trigger voltage that turn the output off and on respectively. When current is applied to pins six and two, comparators check to see if it is above 3.3V or below 1.7. If it is above, it will reset the SR Latch (See diagram to the right) and if it is below the chip will set the output to on. When the output is high, pin seven of the 555 is connected to ground. This is meant to drain the external capacitor, cycling the process. The 555 can be repurposed in many ways by changing the external components. It can even be used for its SR latch alone.

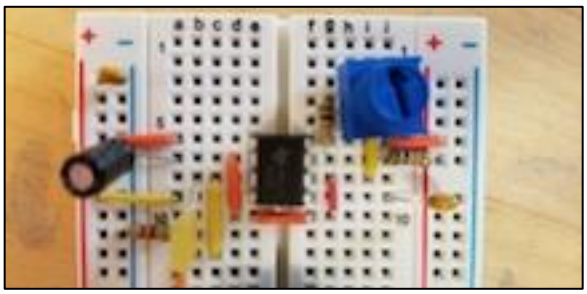


Procedure

First, an isolated astable oscillator is built around one of the 555 timer ICs. This circuit is designed to have a defined pulsing output with its duty cycle controlled by a potentiometer. Next, the monostable oscillator is built. This is not so much an oscillator as it is a debounced button using a 555. Then the bistable oscillator is built using a switch and yet another 555 IC. This is practically a switch that turns an output on and off; the 555 is again for debouncing. Finally, to combine all three oscillators, a switch along with a series of 'and' and 'or' gates are used to determine the final output: an automatic or manual pulse.

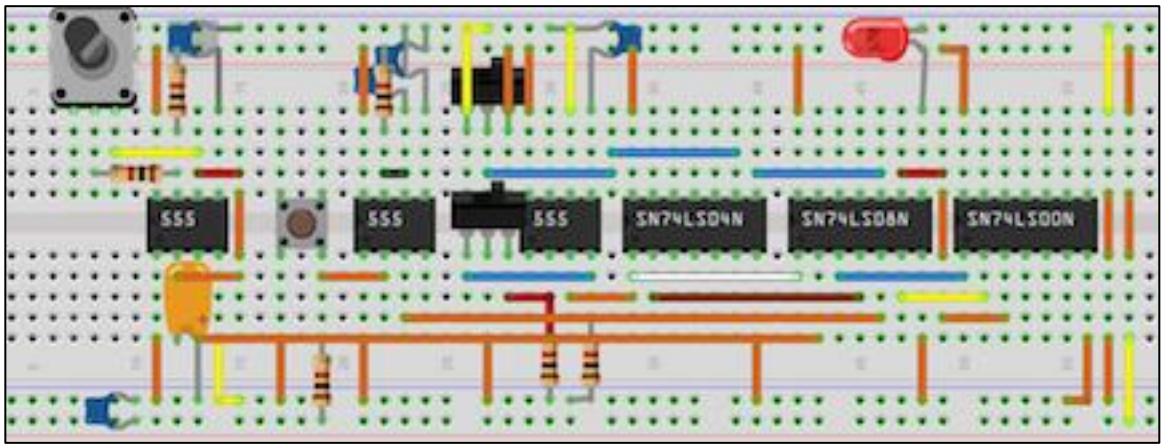
Parts	Quantity
555 Timer IC	3
SN74LS00N	1
SN74LS04N	1
SN74LS08N	1
1K Ω Resistor	6
Toggle Switch	2
PBNO Button	1
100nF Capacitor	4
1uF	1
3mm LED	3

Media



Astable Oscillator

Bimetric view



Final Circuit

Reflection

This project was satisfying, partially because I finished it without too many hitches, but also because it seems like such a simple idea. If I showed the outcome of the LED (perhaps if this were a product of some kind), they wouldn't be impressed in the slightest. I mean, we made an LED blink, and switch to a button activated LED. Congratulations. Now, this may seem like a disappointment, but it is because of hardware that I have gained an appreciation for just how complex these things can be. Resistors and potentiometers all affect the outcome, one wrong wire and the entire thing is dysfunctional. Overall, I'd say this is the coolest way to run the blink sketch so far.

Part C. ALU: The Arithmetic and Logic Unit

Purpose

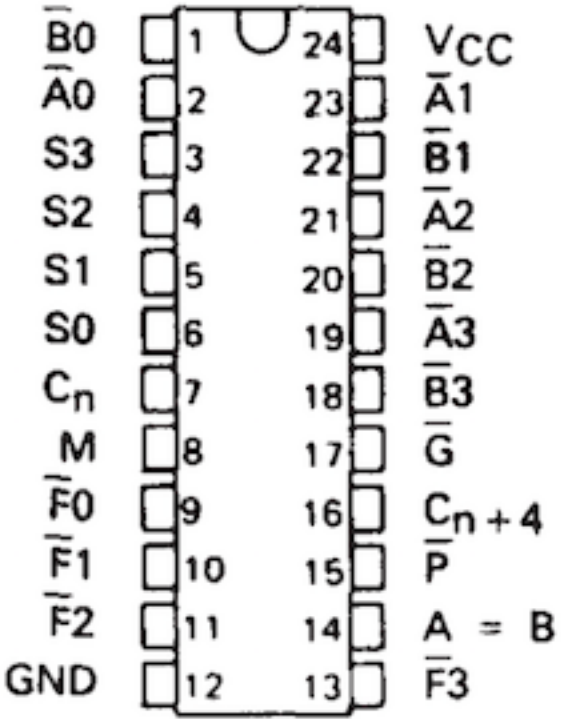
This project is all about learning how to use an arithmetic logic unit (ALU). Specifically, the purpose of this project is to learn how the select pins and other inputs are used to manipulate the functions of the ALU and thus the output.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/4BitComputer/index.html#ALU
ALU Datasheet: https://source.z2data.com/2016/10/12/6/26/26/577/639651/sn54ls181.pdf

Theory

There are five main categories of pins that are used: select, carry, 'A', 'B', and output. On top of this there is a mode pin as well. The mode pin changes whether the ALU is performing logical or arithmetic operations. Since there are 16 logical and 32 arithmetic, the C_n pin is used to create the addition 16 arithmetic operations. C_{n+4} is the carry pin and is used to chain these processors together, creating a more powerful eight-bit ALU. Finally, there is the pin 'A' = 'B' which sets the constants used in the function equal.



ALU Pinout

This ALU is a four-bit processor. Because of this, all the remaining categories are split into groups of four pins. The select pins for example, determine which function to use. Since mode and C_n decide which group of 16 function to choose from, the select pins finish the job and choose the specific function to perform.

'A' and 'B' pins make up two separate constants that are manipulated by a function to create the final output. Since there are four pins for each constant, the numbers they can create are limited from zero to 15. 'A0' and 'B0' control the least significant bit of the nibble that makes up the constants, and 'A3' and 'B3' make up the most significant.

The final category of pins that are used in the core assembly of this ALU are the output pins. There are four pins to produce a four-bit output. Again, zero to 15. If the output from a given function was 13, then the 'F3', 'F2', 'F1', and 'F0' would show high, high, low, and high. It is important to note that there is no overflow with a single ALU; it will simply cut off the output at a maximum value of 15.

Procedure

To begin wiring the ALU for testing purposes, pins 24 and 12 are connected to voltage and ground respectively. Pin 14 (see ALU Pinout) is wired to ground as the constants should be separate.

Parts	Quantity
SN74LS181N (ALU)	1
220Ω Bussed Resistor Network	1
LED Bar Graph	1
5V Power Supply	1
Jumper Wire	14

The select pins (S_0-S_3) are attached to jumper wires. This allows for the user to have flexibility and easy access when testing the functions of the ALU. The same goes for the Mode and C_n pins as they also affect the type of functions that are used. Jumper wires are again used for 'A' and 'B' pins to easily change the constants used in the functions. To simplify the use of the circuit, the rail connections of select, 'A', and 'B' are separated. They are also colour-coded so that each category of pins can be easily identified.

The output pins (F_0-F_3) are wired to the anode pins of an LED bar graph. A 220Ω bussed resistor network is connected to each pin used in the bar graph, with its common pin attached to ground.

Five volts are applied to the circuit. To test it, the select pins are maneuvered to match the function table. The 'A' and 'B' pins are moved from power to ground and back again to ensure that the entire circuit is functional.

SELECTION				ACTIVE-HIGH DATA		
				M = H	M = L; ARITHMETIC OPERATIONS	
S3	S2	S1	S0	LOGIC FUNCTIONS	$\overline{C_n}$ = H (no carry)	$\overline{C_n}$ = L (with carry)
L	L	L	L	$F = \overline{A}$	F = A	F = A PLUS 1
L	L	L	H	$F = \overline{A + B}$	F = A + B	F = (A + B) PLUS 1
L	L	H	L	$F = \overline{A}B$	$F = A + \overline{B}$	$F = (A + \overline{B})$ PLUS 1
L	L	H	H	F = 0	F = MINUS 1 (2's COMPL)	F = ZERO
L	H	L	L	$F = \overline{AB}$	$F = A$ PLUS $A\overline{B}$	$F = A$ PLUS $A\overline{B}$ PLUS 1
L	H	L	H	$F = \overline{B}$	$F = (A + B)$ PLUS $A\overline{B}$	$F = (A + B)$ PLUS $A\overline{B}$ PLUS 1
L	H	H	L	$F = A \oplus B$	F = A MINUS B MINUS 1	F = A MINUS B
L	H	H	H	$F = A\overline{B}$	$F = A\overline{B}$ MINUS 1	$F = A\overline{B}$
H	L	L	L	$F = \overline{A} + B$	F = A PLUS AB	F = A PLUS AB PLUS 1
H	L	L	H	$F = \overline{A \oplus B}$	F = A PLUS B	F = A PLUS B PLUS 1
H	L	H	L	F = B	$F = (A + \overline{B})$ PLUS AB	$F = (A + \overline{B})$ PLUS AB PLUS 1
H	L	H	H	F = AB	F = AB MINUS 1	F = AB
H	H	L	L	F = 1	F = A PLUS A[1]	F = A PLUS A PLUS 1
H	H	L	H	$F = A + \overline{B}$	F = (A + B) PLUS A	F = (A + B) PLUS A PLUS 1
H	H	H	L	F = A + B	$F = (A + \overline{B})$ PLUS A	$F = (A + \overline{B})$ PLUS A PLUS 1
H	H	H	H	F = A	F = A MINUS 1	F = A

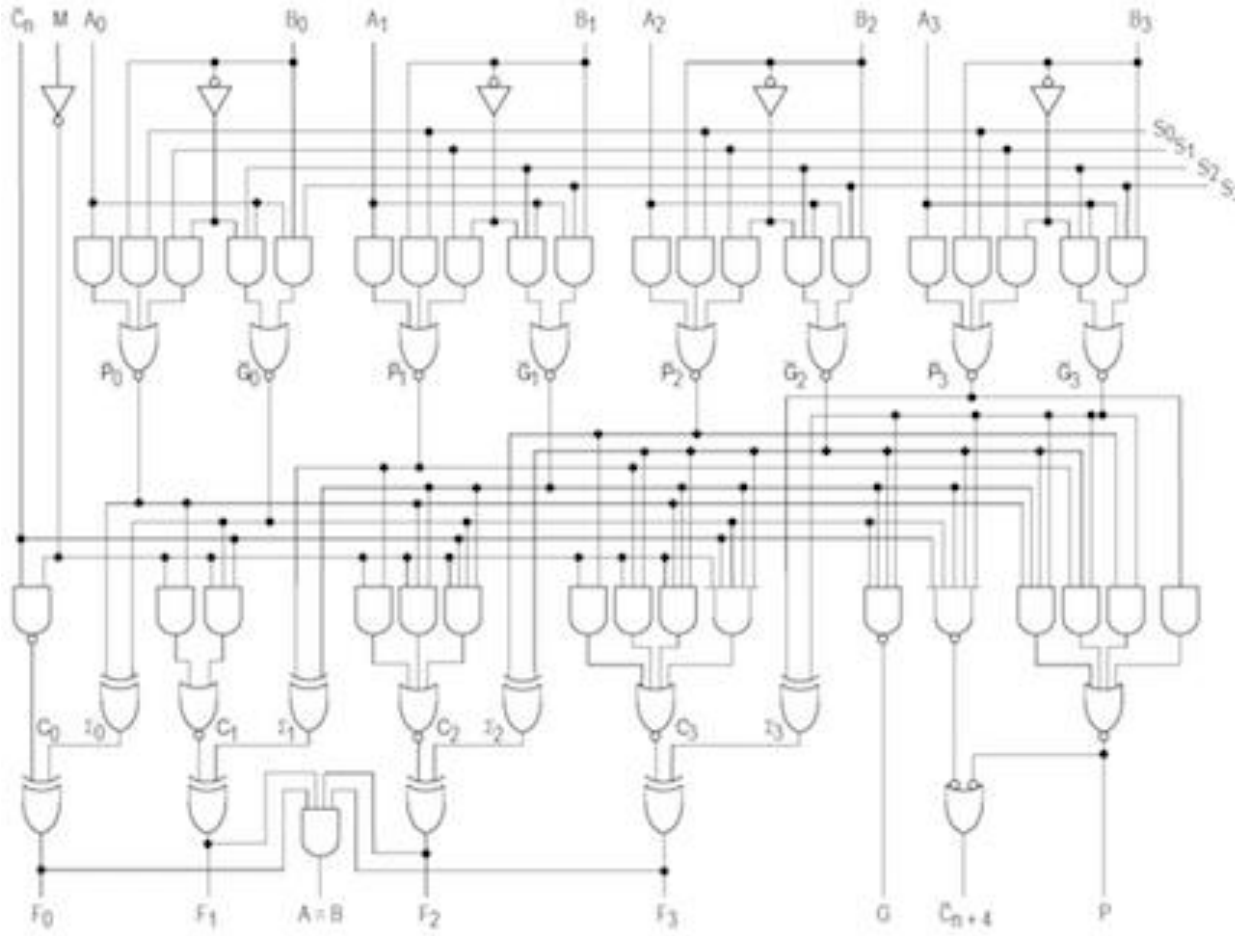
Function Table

Media

Video: https://youtu.be/wKXTI73b1jg

Mode, C_n, and Select Pins

ALU – Trimetric View



SN74LS181N Schematic

Reflection

This project was not as difficult as I thought it would be. The ALU itself is relatively simple to understand if you have the correct table and data to look at. However, while this ALU is easy to understand, I feel that we will find it much more difficult to use the logic gates to perform an actual task.

Part D. The ROMs

Purpose

This project is the initial wiring of the complete CHUMP. In it the clock, program counter (PC), program EEPROM, and the input to the control EEPROM are wired together to create an LED output that displays the relevant data.

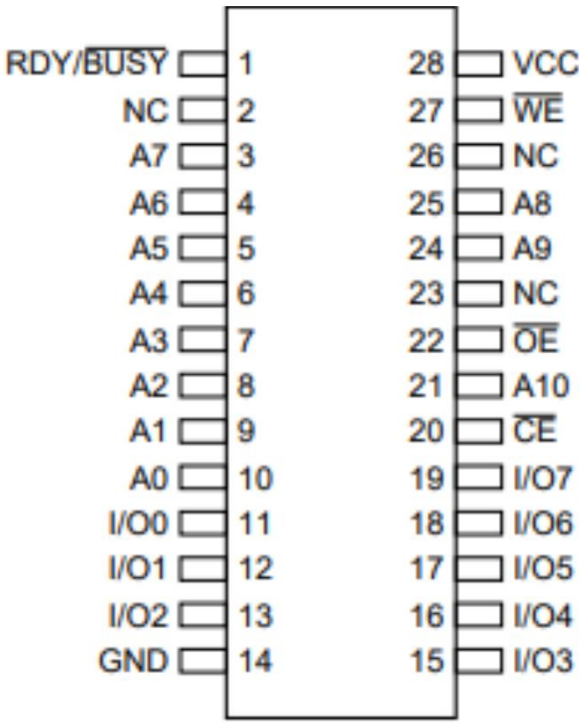
Reference

Home Page: http://darcy.rsgc.on.ca/ACES/TEI4M/4BitComputer/index.html#Processor
PC Datasheet: http://mail.rsgc.on.ca/~cdarcy/Datasheets/74LS161.pdf
ROM Datasheet: http://mail.rsgc.on.ca/~cdarcy/Datasheets/AT28C17.pdf

Theory

The program counter is simply a four-bit counter with an option to load another number into it. It receives a square wave and for each pulse it adds one to its output. This chip uses its four output pins to send a four-bit number, Q_A being the LSB and Q_D being the MSB. Its load pin is active low, so whenever it is grounded, the PC's register changes to match four input pins: A, B, C, & D (see Program Counter Pinout). Clear is an active low pin, and it resets the counter register.

The remaining three pins, ENT, ENP, and RCO, are for chaining these PCs together. RCO is an output pin that goes high only when its PC is at nine. This is then fed into the ENT of the next PC, creating a 2-digit binary coded decimal. However, this is not used for this project.



EEPROM Pinout

The next chip in the circuit is the AT28C17 EEPROM chip (ROM). It has 2048 eight-bit registers. To access each individual register, 11 address pins are used: A_0-A_{10}. This chip has two main modes: reading and writing. When writing is enabled, the output pins become input pins and change the register at the address specified by A_0-A_{10}. If output is enabled, these pins become the output that displays the data inside the addressed register and can be read. The only other unique pin on this chip is pin 1. It is an output pin that tells the reader whether this chip is ready to be used, or busy performing an internal operation.

Procedure

Parts	Quantity
74LS161 (Program Counter)	1
AT28C17 (ROM)	2
Square wave source (Clock)	1
LEDs (R/Y/G)	4/9/8

To begin wiring this computer, power and ground are connected to all the rails and all the chips. The output of the clock is connected to the clock pin of the PC. This clock, in the future, will be synchronizing multiple components of the CHUMP, but for now it only connects to the PC. The load pin is connected to power as it is an active low pin. The ALU will be connected to the input pins of the PC in the future, but for now they remain unconnected.

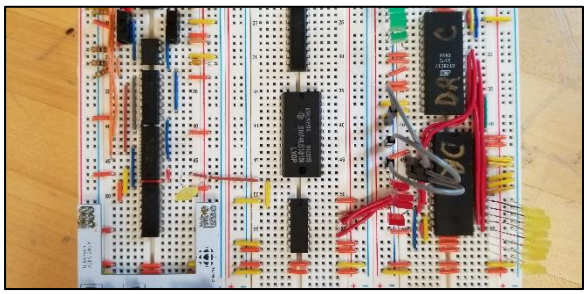
The four output pins (Q_A-Q_D) are wired to the first four address pins of the program ROM with A_0 being the LSB. LEDs are connected for debugging and demonstrative purposes. Since the PC can only count to fifteen, the rest of the address pins cannot be controlled within the computer, so they are connected to ground. However, it is possible to access the higher addresses by connecting optional jumper wires to the remaining address pins instead of grounding them, leaving manual control to the operator. To make the ROM functional, the outputs and chip are enabled by their respective pins. Since the output pins of this chip can also act as inputs, write enable is inhibited. The output of this is displayed by LEDs, but is also wired to another ROM chip: the control ROM.

This chip is not programmed correctly (currently), but is wired nearly identically to the program ROM. The only difference is that the eight output pins of the first ROM connect to the first eight address pins of the control ROM. In the future, this chip will be connected to the rest of the of the processor and will distribute data, but for now it will remain a blank slate. LEDs are inserted on the output pins to display the outgoing data, and the first section of the circuit is finished.

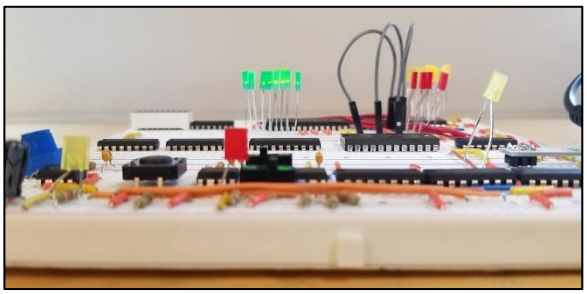
Address	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	ASCII
000000:	00	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F	.....
000010:	FF	FE	FD	FC	FB	FA	F9	F8	F7	F6	F5	F4	F3	F2	F1	F0	.....
000020:	FF	00	FF	00	FF	00	FF	00	FF	00	FF	00	FF	00	FF	00	.....
000030:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
000040:	AA	55	AA	55	AA	55	AA	55	AA	55	AA	55	AA	55	AA	55	.U.U.U.U.U.U.U.U
000050:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
000060:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
000070:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
000080:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
000090:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
0000A0:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
0000B0:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
0000C0:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
0000D0:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
0000E0:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....
0000F0:	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	FF	.....

Program EEPROM Registers

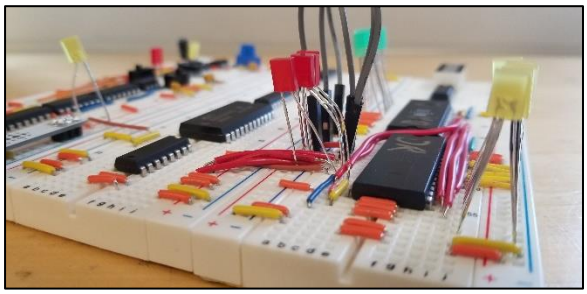
Media



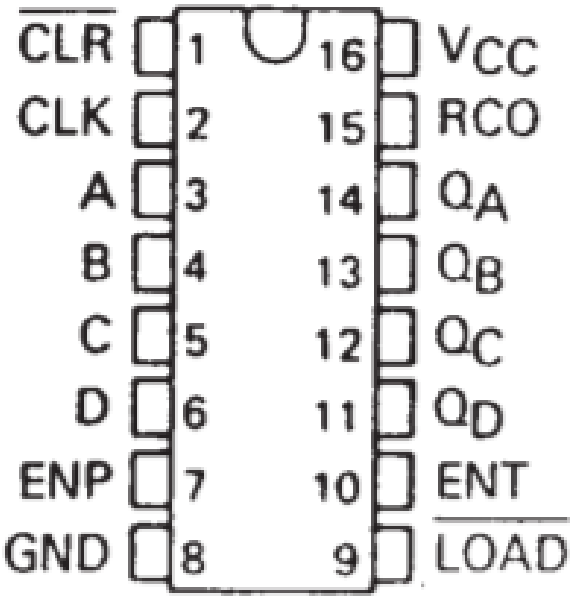
Full Processor



Bimetric View



Trimetric View - EEPROM



Program Counter Pinout

Reflection

After this project, this computer seems a whole lot less daunting. The first time we were told that in two weeks we would be finished the entire CHUMP, I panicked a little bit. I understood the general logic behind the computer, but when it came down to the actual wiring, I was at a loss. Now, I understand the reasoning behind each wire. This is most likely the easy part of the CHUMP, but now I feel a lot more under control than I did a week ago.

Part E. The Completed Processor

Purpose

This is the final circuit of the CHUMP. The purpose of it is to bring everything together and create a completely working four-bit computer made entirely of chips and wires.

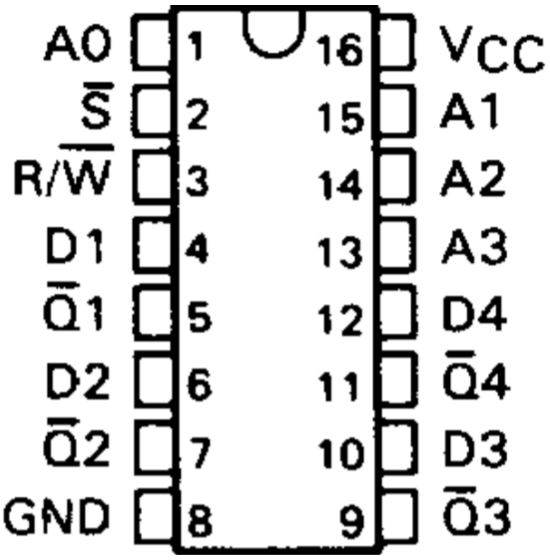
Reference

Home Page: http://darcy.rsgc.on.ca/ACES/TEI4M/4BitComputer/index.html#Individual
RAM: https://www.silicon-ark.co.uk/datasheets/sn74ls189an-datasheet-texas-instruments.pdf
Accumulator: http://www.ti.com/lit/ds/symlink/sn74ls377.pdf
Address: http://www.ece.sunysb.edu/~dima/74ls174.pdf
Multiplexer: http://www.ti.com/lit/ds/symlink/sn74ls157.pdf

Theory

The control ROM receives the opcode from the program ROM. This opcode is the instruction for the entire computer. Using this information and its eight output pins, the control ROM distributes the proper ALU instruction, which function the RAM should be performing (read or write), and the inhibiting pin of the accumulator chip (Accum). It knows this based on the previously agreed upon interpretation/language inside the registers of the ROMs. For example, the current opcode for an addition operation is 0010. This number becomes the address for the control ROM. It looks inside that specific register and outputs whatever it sees. In this case, it would set the ALU to addition and enable the Accum. Since we aren't using the RAM, it is set to read as a precaution.

The RAM that is used in this project is the SN74LS189N. It has 16 four-bit registers. As a result, it has four address pins, four data input pins, and four output pins. It works similarly to the EEPROMs as previously discussed, the main difference being that in this project we are writing to it in certain scenarios. To write to this chip, the R/W pin is grounded.



RAM Pinout

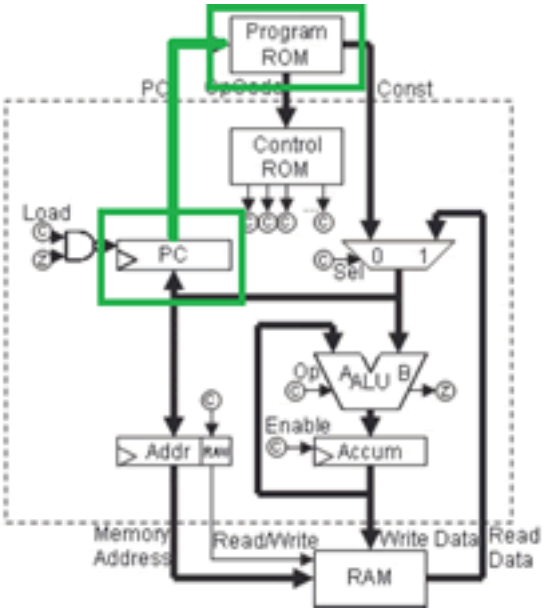
The address chip is a hex flip-flop. It has eight inputs and eight corresponding outputs. When an input is given power, even for an instant, its respective output is set to high. In this way, it acts as a single register that holds the address for the RAM. Once its clock pin completes one full cycle, all its outputs are set low. The Accum is the exact same chip, but it is an octal flip-flop with an inhibitor.

The multiplexer has two primary inputs comprised of four pins each: A and B. Based on the input of a select pin, it decides to output either all the A inputs or all the B inputs. This is used in the CHUMP to determine whether to use the constant provided by the program ROM or the output of the RAM.

Procedure

To begin, the control ROM is flashed to contain the correct opcode translations (as this was not the case previously). For example, the addition instruction needs the ALU set to add and the Accum enabled. This means the select pins are, in order, high, low, low, and high. Mode is also set to low and C of n is set to high. This creates the control code 1001 0101. As shown by the control table, R/W is set to read, not because reading is necessary to this computation, but because the RAM should not be written to at this time. This table shows the outputs of all the control ROM address, so this is the information that is flashed to each address, with the opcode indicating the address for each register.

Parts	Quantity
AT28C17 (EEPROM)	2
SN74LS189N (RAM)	1
SN74LS181N (ALU)	1
(PC)	1
SN74LS377 (Accum)	1
(Multiplexer)	1
(Flip-Flop)	1
2.2KΩ resistors	5



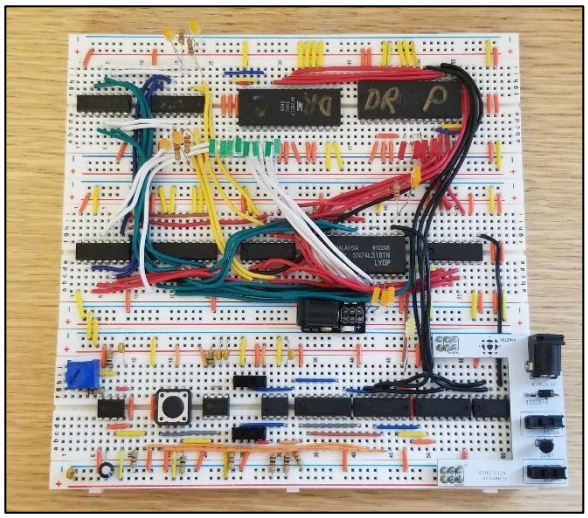
This all works, but there is one problem: other chips need to be told what to do. The multiplexer needs to select which input to display on its output, so it is wired on the LSB of the opcode; if it is a zero it chooses the constant and if it is 1 it chooses the RAM. This only works because of the way the opcodes are arranged. The PC also needs a control pin to tell it when to load in a new value. For this, logic gates are used. Specifically, the middle bits of the opcode are OR'd together and AND'd with the MSB of the opcode. This tells the computer whether it is performing a GOTO or an IFZERO command. This is then NAND'd with the 'A=B' pin of the ALU. This pin, despite its name, does not compare the inputs. "The A = B output from the device goes HIGH when all four F outputs are HIGH" (ALU Datasheet). Knowing this, the ALU is told to output all ones when performing a GOTO, and 'Not A' when performing an IFZERO. If 'A' is zero, it will set the 'A = B' pin high, loading the PC like originally intended.

Once all the EEPROMs are flashed correctly, the chips are laid out onto three breadboards. By studying the block diagram, it is possible to determine which chip connect, so the chips with the most connections are as close to the center as possible. The lower nibble of the program ROM output is wired to the A input of the multiplexer, as this has the possibility of being used in the ALU's computation. The output of the multiplexer is wired to three chips: the PC, the address register, and the B-input of the ALU. The ALU uses these four bits for the computation. The address register changes to match this output in case the RAM is read from and this is to be used as an address for a register in RAM. Finally, the PC is wired to this output in case there is a GOTO or an IFZERO and a new value needs to be loaded to it. The output of the RAM is wired to the B input of the multiplexer. The control ROM is wired in order of the control table. The RAM control, however, is wired through the hex flip-flop to stick with the clock cycle.

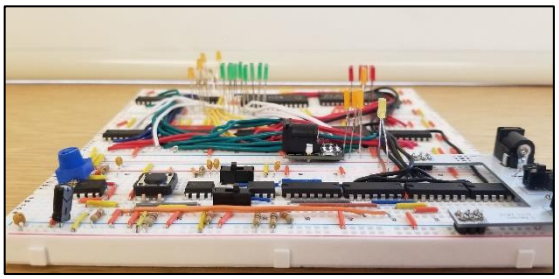
Media

Instruction	OpCodes	ALU	S_3	S_2	S_1	S_0	M	Cn	Acc	R/W
LOAD const	0000	B	1	0	1	0	1	X	0	X
LOAD IT	0001	B	1	0	1	0	1	X	0	1
ADD const	0010	A PLUS B	1	0	0	1	0	1	0	X
ADD IT	0011	A PLUS B	1	0	0	1	0	1	0	1
SUBTRACT	0100	A MINUS B	0	1	1	0	0	0	0	X
SUBTRACT IT	0101	A MINUS B	0	1	1	0	0	0	0	1
STORETO	0110	ignore	X	X	X	X	X	X	1	0
STORETO IT	0111	ignore	X	X	X	X	X	X	1	0
READ const	1000	ignore	X	X	X	X	X	X	1	1
READ IT	1001	ignore	X	X	X	X	X	X	1	1
GOTO const	1010	Logic 1	1	1	0	0	1	X	1	X
GOTO IT	1011	Logic 1	1	1	0	0	1	X	1	X
IFZERO const	1100	Not A	0	0	0	0	1	X	1	X
IFZERO IT	1101	Not A	0	0	0	0	1	X	1	X

Control Code Table



Complete CHUMP



CHUMP - Bimetric

Reflection

I loved this project; The wiring was intense and stressful, but also fun and meditative. The block diagram for the CHUMP contains the minimal amount of information required to completely wire this circuit up; there was no paint-by-numbers, but it still showed the flow of information perfectly. It has been a thrill ride of a project and guaranteed my favourite project we have ever done in hardware. The moment it worked, I was up in the clouds. Thanks to the chump club, I have a memory I will treasure for ever. The boys and the coursework here are truly nothing short of spectacular. I can't wait to see what's in store for us next.

Project 9. Video Turntable

Purpose

This photographic turntable is made to allow for 360 videos of projects for the entire Design Engineering Studio (DES). It also serves a secondary purpose as a rotary display for students to view projects on, complete with a character LCD to show the name of the current project atop the turntable.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/ISPs.html#logs
Colour Sensor Datasheet: https://www.mouser.com/catalog/specsheets/TCS3200-E11.pdf
Barcode Reference: https://www.barcoderesource.com/code128_barcodefont.html

Theory

To determine what is displayed on the LCD, the colour sensor acts as a barcode scanner. The motor spins the platform, allowing the barcode to pass by the sensor. In this process there are multiple different techniques being used.

Barcodes themselves have multiple different ways of storing information for their various uses, all with many pros and cons. In this project, the encoding font of choice is barcode 128B. This font is perfect for many reasons. Firstly, 128 is an international standard, so finding barcode generators online is incredibly easy. Secondly, it has the entire range of alphanumeric characters, as well as 32 other punctuation symbols. It is essentially the entire ASCII table without all the low-level commands. This makes is easy and efficient while still maintaining all the required functionality. Finally, it lines up perfectly with the ASCII table, allowing for easy conversion.

To scan the barcode, there are a few different options. IR sensors, colour sensors, and barcode scanners themselves can all tell the difference between black and white. While a barcode scanner is most likely the best solution for gathering this specific information, they are expensive. By taking advantage of the rotating platforming we can use any device that can read the difference between black and white. For this, a TCS32000 colour sensor is used. It can read the three primary colours: red, green, and blue (as well as clear). It has a total of eight pins: power and ground, an enable, four select pins, and one output pin. Two of the select pins determine which colour it is analyzing. The other two tell the sensor how sensitive it should be. The output pin, however, is a little strange. The output of the TCS3200 is not a linear colour reading, but rather a wavelength that encodes the intensity of a specific colour. Because of this, a simple `analogRead()` will not be used, but rather another function called `pulseIn()`. This tracks the length in times in milliseconds that a voltage is either high or low (depending on one of the parameters).

Colour Sensor Photodiodes

The TCS3200 colour sensor has an eight-by-eight array of light sensitive photodiodes, each which a specific colour filter. Each colour it can detect uses 16 of the photodiodes (red, green, blue, and clear).

The motor chosen for this project is rather tall and would be better if it were parallel to the ground. To fix this problem, bevel gears are used. There are just like normal gears with the minor difference that they are used at a 90-degree angle to one another. These gears also allow for slight tweaking in the balance of speed vs torque, which is useful tool to have.

The motor used is a 0.79 Nm brushed DC motor with a 4mm D-shaft. Newton-meter is a measurement of torque; in other words, this component can lift nearly eight kilograms one centimeter away from its axis of rotation. This is evidently enough power to spin the platform with nearly anything that can fit on it. The D-shaft allows for easy design, as a bevel gear can be designed to friction fit onto it without any extra components.

Procedure

To begin, the 3D design for the prototype is made. It has a platform connected to a bevel gear system that is driven by the motor. The motor is screwed into the base which holds these two parts together with a disk joint. The base is also designed to hold the LCD as well as the colour sensor, which needs to be close to the edge of the platform.

Parts	Quantity
ATtiny84	1
0.79 Nm Motor	1
I2C 16x2 Character LCD	1
TCS3200 Colour Sensor	1
ON-OFF-ON Toggle Switch	1
10KΩ Potentiometer	1
Voltage regulator	1
Disk joint	1

Once the design is printed, the motor is screwed in and connected to a tristate toggle switch. This acts as a physical half H-bridge**,** allowing current to flow through the motor in either direction, depending on the state of the switch. The power of the switch is connected to a potentiometer which is then connected to 12 volts. This is the maximum recommended voltage for the motor.

To keep this circuit on one power supply, a 5V voltage regulator is used to power the ATtiny84. This is the microcontroller that is used as it has the perfect number of pins for this project. There are two main devices attached to the MCU: a character LCD and a colour sensor. These are the devices that read and display the barcode information. Since a normal LCD requires way too many pins that the ATtiny84 simply does not have, an LCD with I2C is used. Thus, the LCD is connected to power, ground, SDA, and SCL. The colour sensor is hard-wired to have a sensitivity of 20%. The other two selects and the output pin are connected to the MCU. This allows the user to take control over which colour is being read.

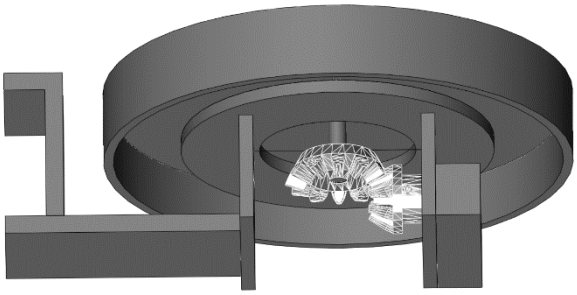
Unfortunately, there is no datasheet for the I2C LCD, so a library must be used. However, all the libraries are for the old form of I2C, so some of the libraries are edited. The colour sensor is made to calculate the rotary speed of the barcode (and the platform), and then scan a barcode that has 0.8326mm per bar. It then concatenates all the information into a string that is then displayed on the LCD.

Code

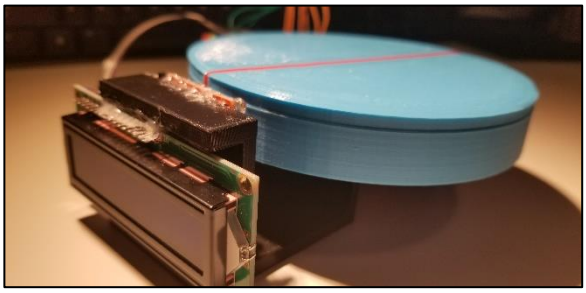
```
// Author: Daniel Raymond
// Date: September 14, 2018
// Description: Code for the display of the turntable. It reads a barcode
// and displays the result on an I2C LCD.

#include <TinyWireM.h>
#include <LiquidCrystal_I2C.h>

#define SDA A6 // 7:PA6
#define SCL A4 // 9:PA4

#define S2 A1 // 12: PA0
#define S3 A0 // 13: PA1
#define clrPin A2 // 11:PA2
#define scanBtn A3 // 10: PA3

#define adrs 0x3F
#define radius 60
#define pi 3.14159
#define codeSize 187 // barcode length in mm
#define bitWidth 0.8326

LiquidCrystal_I2C lcd(adrs, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);

uint8_t asciiChar = 0;
String text = "";
uint8_t lngth = 0;
uint8_t clr = 0;

void setup() {
  pinMode(S2, OUTPUT);
  pinMode(S3, OUTPUT);
  lcd.begin(16, 2); // Dimensions of the LCD
}

void loop() {
  if (scanBtn) {
    scanCode();
    printName();
  }
}

// Calculates the outer speed of the disk in mm/s
unsigned long rotationSpd() {
  unsigned long startTm = millis();
  unsigned long endTm;
  unsigned long rotationSpd;

  while (!readFreq(LOW, HIGH, 0, 1)); // Wait for red line to appear
  delay(50); // Wait for red line to pass

  while (!readFreq(LOW, HIGH, 0, 1)); // Wait for red line to appear again
  endTm = (millis() - startTm) << 1; // Timing a full rotation

  rotationSpd = 2000 * pi * radius / endTm; // platform speed in mm/s
  return rotationSpd; // gives circumference speed in mm/s

}
```

```
// Reads in the barcode
void scanCode() {
  text = "";
  unsigned long rSpd = rotationSpd();
  unsigned long startTm = millis();
  unsigned long endTm = millis + (codeSize / rSpd);
  float bitTime = bitWidth / rSpd; // time per each bit

  // Wait for barcode
  while (!readFreq(LOW, HIGH, 0, 1)); // Waits for red to spike

  // Scan barcode
  while (millis != endTm) {
    for (uint8_t x = 0; x < 8; x++) { // Read in 8 bits for a character
      asciiChar += readFreq(HIGH, HIGH, 0, 1) << (7 - x); // create a byte
      delay(bitTime);
    }

    text += (char)(asciiChar + 32); // Using barcode font 128B
    asciiChar = 0;
  }
}

void printName() {
  lcd.clear(); // Resets lcd
  lngth = text.length();
  lcd.setCursor((16 - lngth) >> 1, 0); // Centers text
  lcd.print(text); // Prints name
}

// Reads in an intensity from the colour sensor
int readFreq(uint8_t p2, uint8_t p3, uint8_t minimum,  uint8_t maximum) {
  int tempFreq = 0;
  // Setting RED (R) filtered photodiodes to be read
  digitalWrite(S2, p2);
  digitalWrite(S3, p3);

  // Reading the output frequency
  tempFreq = pulseIn(clrPin, LOW);

  // Remapping the value of the frequency to white or black
  tempFreq = constrain(tempFreq, 17, 260); // Measured max and min
  tempFreq = map(tempFreq, 17, 260, maximum, minimum);

  return tempFreq;
}
```

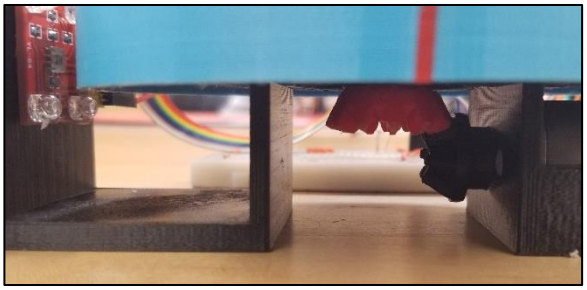
Media



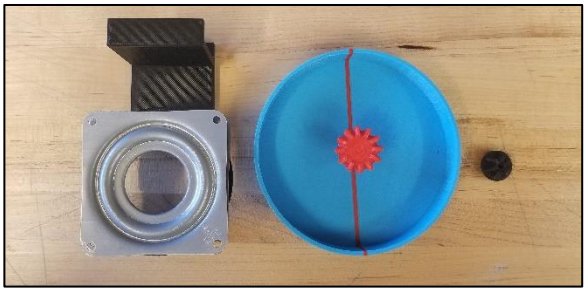
Complete CAD Design



I2C LCD Display



Sensor & Gears



3D Printed Parts

Reflection

Although there were times where it seemed impossible to complete, I am proud of what I've managed to accomplish. The core problem with it seems to be that the gears do not mesh well enough to provide a consistent enough rotational speed. This affects the primary usage, as well as the colour sensor. Despite this, I did learn a surprising amount. The colour sensor is a very consistent and useful part that I can see myself using in the future.

Project 10. Keypad Storage Unit

Purpose

This project is a storage unit that limits access to one compartment at a time. It is a personal vending machine, of sorts, that places a primary role on the use of the telephone keypad.

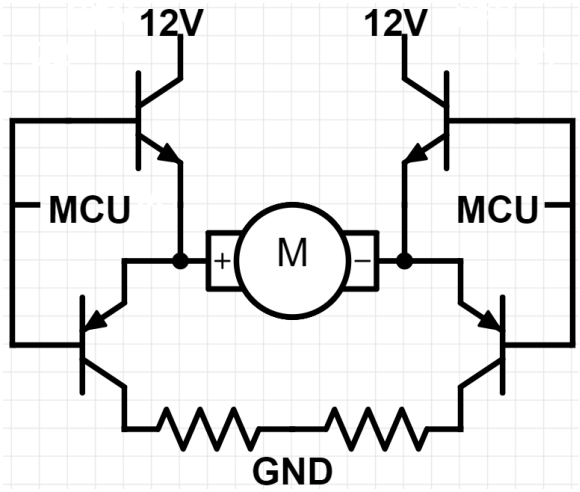
Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/Tasks.html#TelephoneKeypad
H-Bridge Datasheet: http://www.ti.com/lit/ds/symlink/sn754410.pdf

Theory

A software solution is used to debounce the keypad. The keypad itself does not have a power supply, but simply connects corresponding row and column pins together. To measure a button press, the rows are continually outputting low. When a button is pressed, the corresponding column pin, along with the common, is pulled low. Once this is detected, a timer waits for the bouncing to end. At this point in time the button is still pressed so it reads all the column pins, which reside in port B. To determine which column was pressed, a switch case statement is used. When the column is found to be grounded, it is the correct one. Next, the row pin must be determined. To do this, a loop runs which grounds each row pin individually. When the correct row pin is grounded, it triggers an if statement which returns the correct button value. Finally, when the button is released, another delay runs, ignoring the debouncing period. Since the bouncing interval when being released is longer than the press, the interval is made twice as long.

To control the motor, an H-bridge is used. This controls the direction the current travels, causing the motor to spin in either direction. When a single side of the circuit is powered, the NPN on its side is turned on while the PNP is turned off. This forces the current to flow through the motor. Doing this for the other side causes the current to flow through the motor in the opposite direction. When both pins are turned off, the motor is stationary.



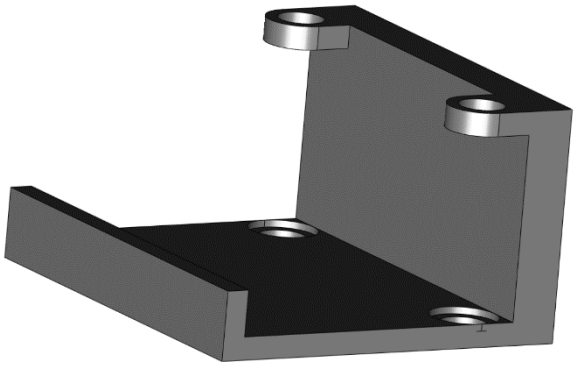
H-Bridge Schematic

The motor that is used to shift the canvas is a brushed DC motor. This component works in a very interesting way. When the motor is powered, there is a brush that contacts a metal plate that is connected to an electromagnet. This causes the magnet to become magnetic and be attracted to a ferromagnet that lines the exterior of the motor. This causes the shaft to rotate. This act disconnects the brush from the metal plate and connects it with a plate on the opposite side. This reverses the poles of the two internal electromagnets, causing it to be attracted to the opposite side of the motor. This cycle continues until power is disconnected.

Procedure

Parts	Quantity
Arduino UNO	1
0.36 Nm Motor	1
H-Bridge	1
DC Jack	1
Canvas Cover	1
3D Printed Components	18
M3 Screws	2

This project is heavily design centric. There are six main components to the tower: levels, inserts, upper supports, the bottom support, the roller, and the inverter stand. The levels comprise the main build of the design, being the landings for each stored item. This component, along with the inserts, create a modular design to increase the height of the build. The only special floor is the top, which has a curved roof. This helps with the movement of the belt. The upper supports are to protect the stored items inside as well as provide structural support. The bottom support, however, is special. It provides the connection between the tower and the motor. There are holes for M3 screws to connect the motor, and an insert to hold the roller as it rotates. Unfortunately, the is too much resistance to pull the canvas using the roller; no amount of tension helps this problem. The resulting solution is the inverter stand. The idea is to allow gravity to help with the problem, not add to it. By flipping the entire tower, the friction primarily resides on the roller. The motor is connected to an external power source. The Arduino controls an H-bridge IC that allows for bidirectional control of the motor. The debounced keypad is read an compared with the current level of the opening. The motor then shifts the canvas cover accordingly, opening the correct storage compartment.



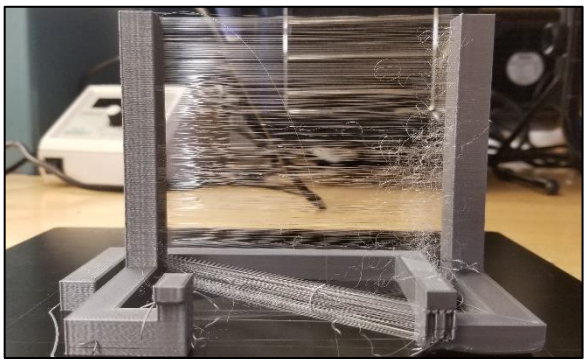
Level Module

Code

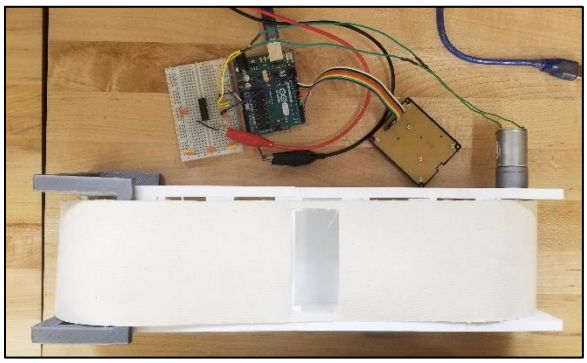
```
//  Author: Daniel Raymond (Keypad Code provided by Chris D'Arcy)
// Project: Sectional Storage Unit
//    Date: 2019-11-31
uint8_t keys[4][3] = {{1, 2, 3},  // There are only 6 floors
                      {4, 5, 'x'},
                      {'x', 'x', 'x'},
                      {'x', 0, 'x'}
};
uint8_t colPins[] = {9, 10, 11};
uint8_t numCols = sizeof(colPins);
uint8_t rowPins[] = {4, 5, 6, 7};
uint8_t numRows = sizeof(rowPins);
uint8_t row, col;          // Looped variables
#define INTERVAL 10L       // Debouncing wait period
#define COMMON 2
unsigned long detect;      // Keeps track of time during debounce
uint8_t input;             // Stores column values when read
uint8_t level = 0;         // Current floor the opening is on
uint8_t destination;       // Floor that needs to be open
#define FRWDPIN 12         // Motor pins
#define BACKPIN 13
#define TMCONSTANT 1500    // Scaling the motor's duration
```

```
void setup() {
  pinMode(COMMON, INPUT_PULLUP);          // Connected to every column
  for (col = 0; col < numCols; col++)
    pinMode(colPins[col], INPUT_PULLUP);  // Every column starts high

  for (row = 0; row < numRows; row++) {
    pinMode(rowPins[row], OUTPUT);        // For 'scanning' each row with grounds
    digitalWrite(rowPins[row], LOW);
  }
  pinMode(FRWDPIN, OUTPUT);
  pinMode(BACKPIN, OUTPUT);
}

void loop() {
  while (bitRead(PIND, COMMON));          // Waits until common pin is turned low
  detect = millis();                      // Reads time
  while ((millis() - detect) < INTERVAL); // Waits until interval has passed
  input = PINB;                           // Reads columns pins
  destination = getTelKey(input);         // Record key input

  // Do nothing if * or # is pressed, or if it is already at the correct floor
  if (!(destination == 'x') && (level!= destination)
    moveMtr();                            // Move the motor the corresponding amount

  while (!bitRead(PIND, COMMON));         // Waits until any button is released
  detect = millis();                      // Reads time
  while ((millis() - detect) < INTERVAL << 1);// Waits for bouncing interval to pass
}
char getTelKey(uint8_t input) {
  switch (input & 0b00001110) {         // Masks every pin but the columns
    case 0b00000110: col = 2; break;    // Checks which column is being grounded
    case 0b00001010: col = 1; break;
    default: col = 0;                   // If it isn't the other 2, it must be this
  }
  for (row = 0; row < numRows; row++) {
    digitalWrite(rowPins[row], HIGH);   // Ignores every row...
    if (digitalRead(colPins[col])) {
      digitalWrite(rowPins[row], LOW);
      return keys[row][col];
    }
    digitalWrite(rowPins[row], LOW); // ...Except for this one (ground each row pin)
  }
}

void moveMtr() {
  int8_t dist = destination - level;// Determine # of floors to travel (signed)

  if (dist > 0)                     // Determine direction for the motor to spin
    digitalWrite(FRWDPIN, HIGH);
  else
    digitalWrite(BACKPIN, HIGH);

  delay(abs(dist)*TMCONSTANT);      // Wait for the motor to move the right distance

  digitalWrite(FRWDPIN, LOW);
  digitalWrite(BACKPIN, LOW);
  level = destination;             // destination has now arrived
}
```

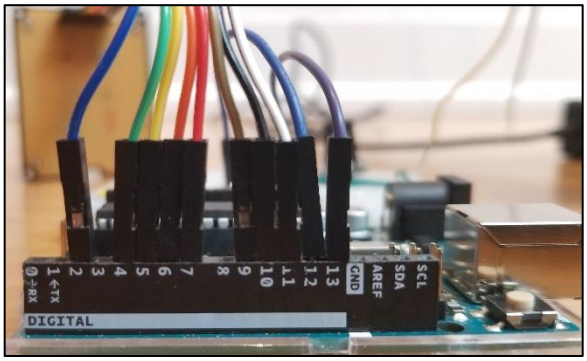
Media



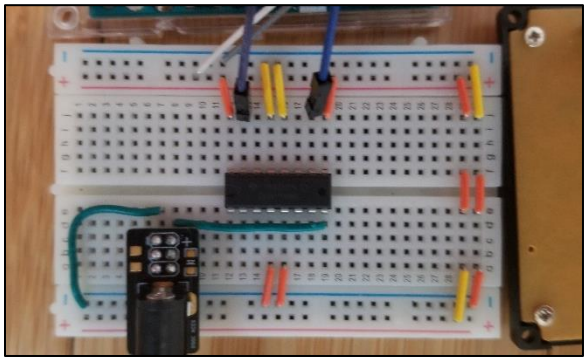
Inverter Stand



Complete Design



Arduino Pinout



H-Bridge Circuit

Reflection

This project has increased my design capabilities immensely. I have always had a difficult time knowing where to start, and this storage unit has shown me that it is better to start to build the general concept first. Having multiple iterations of a design is important; the finer details of a project can always be changed but starting and noticing problems early is crucial. The keypad is an interesting component and it confused me for a good while. I found myself writing my own keypad code simply to better understand the device, even if it wasn't used in the final design. In the end, I am disappointed that the canvas roller was not as predictable as I'd like, but some additional modifications might fix the issues.

Project 11. Rotary BCD Switch

Purpose

This is the first major assembly project. In it, a hexadecimal rotary BCD switch (rBCD) determines the output of a seven-segment display, entirely programmed in AVR Assembly. For example, if the rBCD is turned to six, a six will appear on the display.

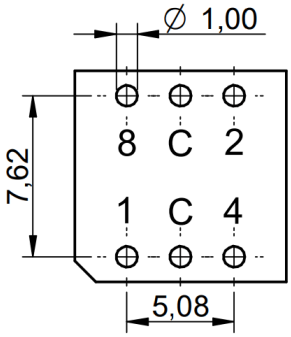
Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/Tasks.html#Rotary
AVR Assembly Instructions:
https://www.microchip.com/webdoc/avrassembler/avrassembler.wb_instruction_list.html

Theory

Rotary BCD

The new component involved is the rBCD. As the name implies, it encodes a number in four of its pins to make a nibble of data. To do this the rBCD as six pins: four-bit pins and two power pins (presumably for symmetries sake). When a hexadecimal value is pointed to, its binary equivalent is connected to power. This alone cannot be read from, as there is no current flow. Instead, there is a resistor tying these pins to ground. This current is then read in by the Arduino.



Rotary BCD Pinout: LSB-MSB

Arrays

To light up the correct segments, an array is used. In each of its cells, it contains a byte of information that, when put to the output register of the correct port, will light up the seven-segment display. The information corresponds to its address in the array. To program this in assembly, there are a few requirements. First, it needs to know where you are storing the information, whether it is in program flash or in RAM. While program flash is plentiful, it is slower for the microcontroller to access (three cycles versus one). Next, it needs to have a name assigned to the array. This simply allows the programmer to reference the first address of the array, as it would otherwise be unknown. To access this information, a pointer is used. Pointers a 16-bit words comprised of two accumulators. When given to the 'lpm' (load from program memory) or the 'lds' command (load from SRAM), they are treated as an address that a value should be loaded from.

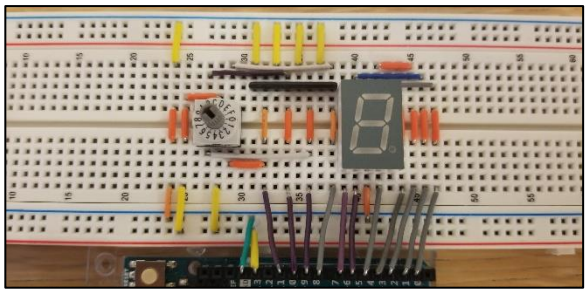
Procedure

The circuit itself is relatively simple. To begin, the rBCD is connected to power. Its bit pins have pulled down resistors and are wired to the MCU in order of significance. It is important that they are all tied to the same port of the Arduino, in this case it is port B. Since the seven-segment display is a common cathode component, pins three and eight are grounded. The rest of the display's pins are connected to port D of the microcontroller.

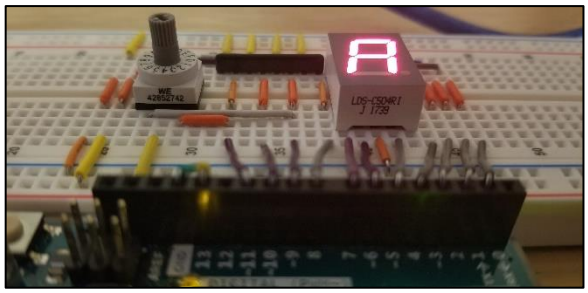
Parts	Quantity
Arduino UNO	1
Rotary BCD Switch	1
10K Ω Resistor Network	1

To develop a general idea for the coding of the device, a working program is made using mid-to-high-level techniques. In this iteration, port manipulation is used to allow for an easier conversion to assembly. The program holds an array, and when the rBCD is read, the value given is used as the address for the array. The value in each cell corresponds to the segments that should light up on the display for that value. For example, if the value read in by the rBCD was *1000*, then the data in cell eight is used. In this case, eight should light up all the segments, so it would contain *0xFF*, or *255*. Each bit in this byte triggers a specific pin of the display. After programming the project in C, converting AVR Assembly is quite easy, as it uses the exact same concepts and framework.

Media



Completed Circuit



Working Circuit with Pin Numbers

Reflection

This project has demonstrated to me the power of assembly language. This is something that I have been looking forward to learning for a long time. I always had a feeling that it would be something that I would enjoy, but now it is finally here. While assembly might not have an immediate application, I love knowing how things work 'under the hood.' It is fantastic this opportunity is given to me in the first place.

Code

```
#include <avr/io.h>

  a = (1 << PD3)            ; Segment pins
  b = (1 << PD4)
  c = (1 << PD5)            ; Each control a respective bit
  d = (1 << PD6)            ; in a byte
  e = (1 << PD7)
  f = (1 << PD2)
  g = (1 << PD1)

  pwr   = PB5             ; Power for the rotary BCD
  sPins = a|b|c|d|e|f|g   ; Direction Register for the 7-Segment
  sDDR  = DDRD-0X20       ; Direction for the 7-Segment
  sOUT  = PORTD-0x20      ; Out port for the 7-Segment
  rDDR  = DDRB-0x20       ; Direction for the Rotary BCD (rBCD)
  rIN   = PINB-0x20       ; In port for the rBCD
  rOUT  = PORTB-0x20      ; Out port for the Power pin

digits: .byte  a | b | c | d | e | f      ; 0
        .byte      b | c                  ; 1
        .byte  a | b |     d | e |     g  ; 2
        .byte  a | b | c | d |         g  ; 3
        .byte      b | c |         f | g  ; 4
        .byte  a |     c | d |     f | g  ; 5
        .byte  a |     c | d | e | f | g  ; 6
        .byte  a | b | c                  ; 7
        .byte  a | b | c | d | e | f | g  ; 8
        .byte  a | b | c |         f | g  ; 9
        .byte  a | b | c |     e | f | g  ; A
        .byte          c | d | e | f | g  ; B
        .byte  a |         d | e | f      ; C
        .byte      b | c | d | e |     g  ; D
        .byte  a |         d | e | f | g  ; E
        .byte  a |             e | f | g  ; F

.global setup
setup:
  ldi   r16,  sPins       ; Prep every pin in port D to output
  out   sDDR, r16         ; Set Direction Register to all output

  sbi   rDDR, pwr         ; Set every pin to input except pin 13
  sbi   rOUT, pwr         ; Set pin 13 high (but nothing else)
ret


.global loop
loop:
  in    r29,  rIN         ; Read the entire port that the rBCD is on - put it on ZL
  andi  r29,  0x0F        ; Only read the lower nibble (4 pins of rBCD)

  ldi   ZL,   lo8(digits) ; Set initial pointer to base value of the array
  ldi   ZH,   hi8(digits) ; Set upper byte just in case the array is stored in a
high location
  add   ZL,   r29         ; Increment pointer by the address

  lpm r16, Z              ; Load the value of SRAM at Z into r17
  out   sOUT,  r16        ; Output value on the 7-segment
ret
```

Project 12. Assembly Shift Registry

Purpose

The goal of this project is to program a shift register in assembly. Its output leads to an LED bar graph. Specifically, the bar graph is supposed to follow an incrementing pattern, adding the next LED to all the previous ones. The second animation is a binary decrementing pattern. A switch decides which animation to show.

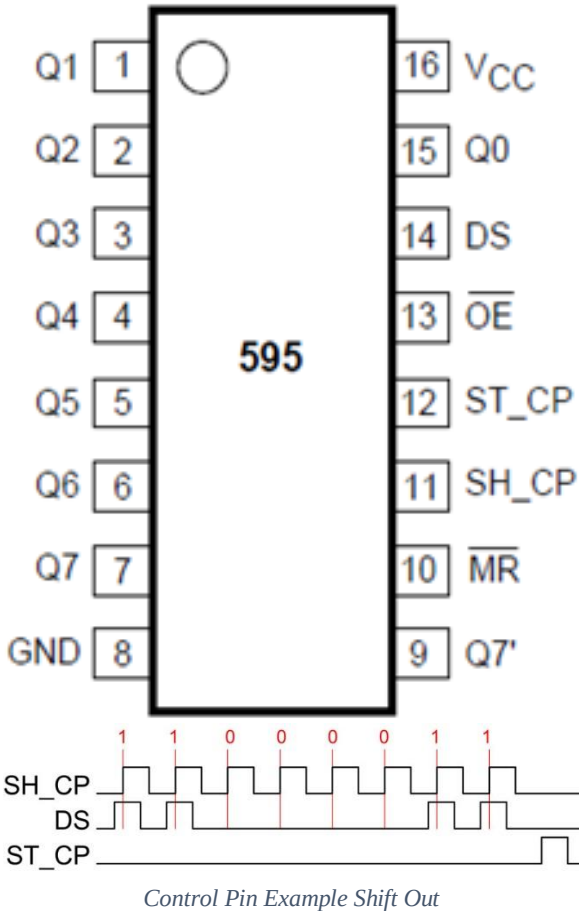
Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/Tasks.html#KnightRider
Tim Morland's PCB: http://darcy.rsgc.on.ca/ACES/PCBs/index.html#ShiftBar
Personal Website: dan.raymond.ch

Theory

The shift register is a serial-to-parallel IC with three main control pins: latch, data, and clock. The latch controls whether the chip is reading or presenting the data. To beginning reading, this pin is set low. After this, a value of either high or low is presented on the data pin. When the clock pin goes high (on a RISING edge) the shift register reads the data pin and 'loads' that value into the byte. After this process cycles eight times (or more when daisy chaining) the latch is pulled high, displaying the byte on the shift register's eight output pins.

The data byte presented by the shift register is made to follow the pattern $2^n - 1$, so all the LEDs stay on as a new one is added onto it. To present this data, as mentioned before, the data pin needs to present each bit individually. To accomplish this, a 1-bit mask cycles through and is AND'd with the data. If the result is zero, the data pin is grounded; otherwise it is pulled high. To create this data byte there are two registers involved. The first starts at one and then, through every iteration of the loop, shifts left one bit. At each cycle this value is AND'd with the data byte that is sent out to the shift register.



Control Pin Example Shift Out

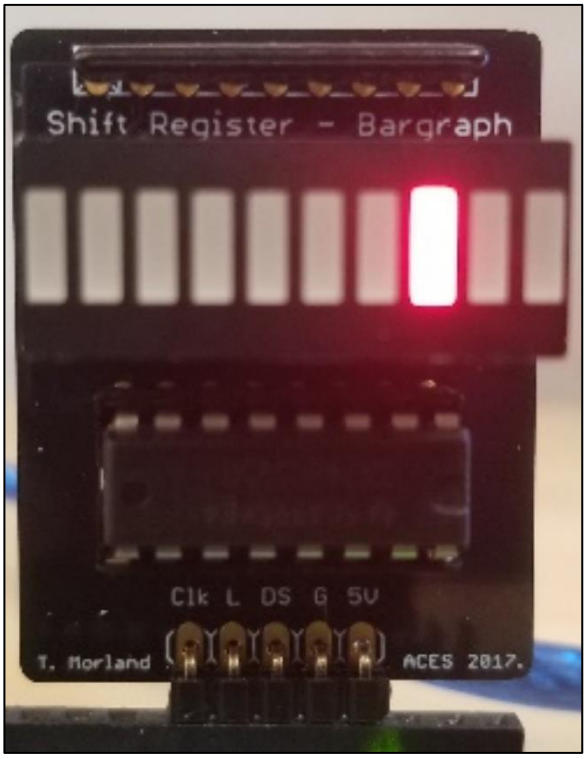
The final piece is the switch. It is connected to `PC0-2` of the Arduino, with its outer pins tied to power and ground respectively. The middle pin simply reads the value that it is connected to and sets the animation.

Procedure

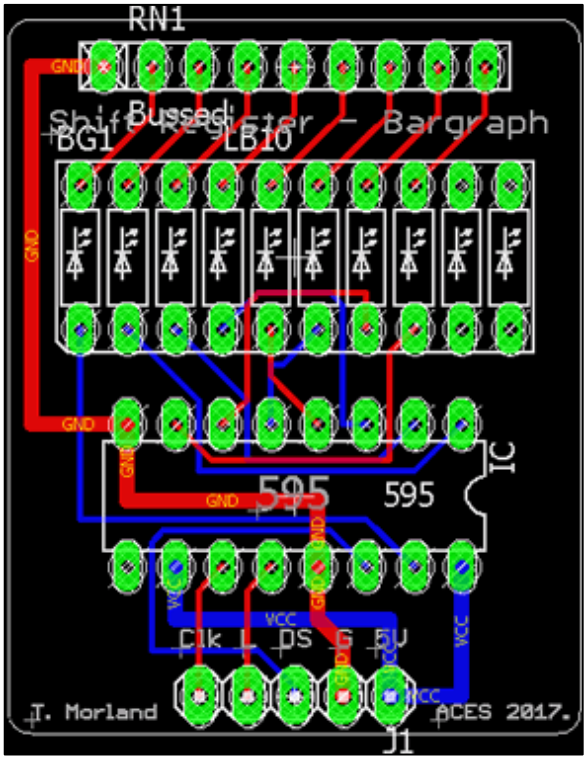
The creation of this device is incredibly simple. It uses Tim Morland's Arduino Appliance to attach the shift register to the LED bar graph. Everything is soldered (either through a chip seat or directly), and then the PCB is inserted into the Arduino. Power and ground are applied to their respective pins, and the appliance is programmed to shift out data that is displayed on the LEDs, as described in the Theory section.

Parts	Quantity
Arduino UNO	1
T. Morland PCB	1
LED Bar Graph	1
220 Ω Resistor Network	1
74HC595	1
Right Angle Header Pin	5

Media



Working Shift Register Bar Graph



PCB Board Design

Reflection

I love assembly. There are very few aspects of it that inhibit use; you are free to build anything because literally every part of the MCU is at your disposal. Having access to each register and being able to change individual bits is a skill that I did not realize I wanted, but now am glad I have. This project has demystified lots of the high-level functions that I once took for granted (shiftOut, SPI, etc); I can't wait for the next.

Code

```
; PROJECT:    Knight Rider (shift register animations)
; PURPOSE:    To manipulate a shift register (SR) in AVR Assembly
; DEVICE:     Arduino (ATmega328p)
; AUTHOR:     Daniel Raymond
; DATE:       2019-02-01

.org          0x0000        ; Tells PC that reset is the 1st instruction
      rjmp    reset

.equ    DDR           = DDRD
.equ    POUT          = PORTD

.equ    clock         = PD7
.equ    latch         = PD6
.equ    data          = PD5
.equ    gnd           = PD4
.equ    pwr           = PD3
.equ    outPins       = (1<<clock | 1<<latch | 1<<data | 1<<gnd | 1<<pwr)

.equ    swtchPwr      = PC0
.equ    swtchRead     = PC1
.equ    swtchGnd      = PC2
.equ    DDRS          = DDRC
.equ    POUTS         = PORTC
.equ    PIN           = PINC
.equ    outPinSwtch   = (1<<swtchPwr | 1<<swtchGnd)
.equ    onPos         = (1<<swtchPwr | 1<<swtchRead)

.def    util    = r16         ; r16 is a general-purpose register
.def    read    = r17         ; Reading in the value of the switch port
.def    incr    = r18         ; Incrementing register for the # of LEDs that are on
.def    leds    = r19         ; The register that holds the final output of the SR
.def    mask    = r20         ; Mask to isolate which LEDs need to be on
.def    bit     = r21         ; The bit in focus (when shifting out)

reset:
      ldi util,     outPins       ; Set pins on the SR to output
      out DDR,      util          ; Change data direction to match outputPins
      ldi util,     outPinSwtch   ; Sets up power and ground for the switch
      out DDRS,     util          ; Makes data direction match
      sbi POUT,     pwr           ; Set the power pin to high
      sbi POUTS,    swtchPwr      ; Give the switch power

      ldi incr,     1             ; Set the first LED on
  loop:
   anim1:
      in  read,     PIN           ; Read the switch
      cpi read,     onPos         ; If the read pin is high
      brne          anim2         ; If the switch is low, go to the 2nd Animation
      ldi incr,     1             ; Revert the increment register
      clr leds                    ; Turn off all LEDs (LSB will be turned on)
      rcall         rowLEDs       ; Otherwise, it will run the row anim
      rjmp          anim1         ; Once it is done, it will run the row anim again
   anim2:
      ldi leds,     0xFF          ; Start the leds as all on
      rcall         decr          ; Run the animation
  rjmp loop
rjmp    reset
```

```
decr:
       dec leds
       rcall         shiftOut      ; Sending out the LED data
       rcall         delay250ms    ; Wait
       in  read,     PIN           ; Read the switch
       cpi read,     onPos         ; If the read pin is high
       breq          loop          ; If switch state has changed, it will go to loop
       rjmp          decr          ; Otherwise, it will continue to flash
ret

rowLEDs:
       or  leds,     incr          ; Set another LED high while keeping the others on
       rcall         shiftOut      ; Shift out the data
       rcall         delay250ms    ; Wait for 1s
       rcall         delay250ms

       in  read,     PIN           ; Read the switch
       cpi read,     onPos         ; If the read pin is high
       brne          anim2         ; Go the other animation if it is low

       lsl incr                    ; Move on to the next LED
       cpi leds,     0xFF          ; See if we've reached all 8 LEDs
       brne          rowLEDs       ; Continue the loop w/o reverting all the variables
       ldi incr,     1             ; Revert the increment register
       clr leds                    ; Turn off all LEDs (LSB will be turned on)
ret

shiftOut: ; Shift out function
       ldi mask,     1             ; Dealing with the first bit
       cbi POUT,     latch         ; Pull latch low to be able to send in data
 cycle:                                      ; Loop for all 8 bits
       cbi POUT,     clock         ; Pull clock low
       mov bit,      leds          ; We're going to be destroying the info
       and bit,      mask          ; Clear all except the bit in question
       breq          out0          ; If mask is 0, set the data pin to 0, else it's 1
       sbi POUT,     data          ; Setting the data pin
       rjmp          wrapUp        ; jumping to the end
  out0:
       cbi POUT,     data          ; Setting the data pin
  wrapUp:
       sbi POUT,     clock         ; Send out data by pulling the clock high
       lsl mask                    ; Shift the bit in question over by 1
       cpi mask,     0             ; See if a full byte has passed
       breq          leave         ; Get out if a full byte has been sent
       rjmp cycle                  ; Continue if it's not done
 leave:
       sbi POUT,     latch         ; Release the data
ret

delay250ms: ; A delay for 250ms
       ldi  r29, 21
       ldi  r30, 75
       ldi  r31, 191
L1:    dec  r31
       brne L1
       dec  r30
       brne L1
       dec  r29
       brne L1
       nop
ret
```

Project 13. The 4-Wire DC Fan

Part A. Research

Purpose

This is the beginnings to a four-stage project: programming a four wire PWM fan in assembly. This part will focus on how the PF80251B1-000U-S99 fan is controlled and its operation requirements.

Reference

Fan Datasheet: http://mail.rsgc.on.ca/~cdarcy/PDFs/Sunon12VDCFanSpec.pdf
Four Wire PWM Fan Control: http://mail.rsgc.on.ca/~cdarcy/PDFs/4WirePWMFans.pdf

Theory

Characteristics

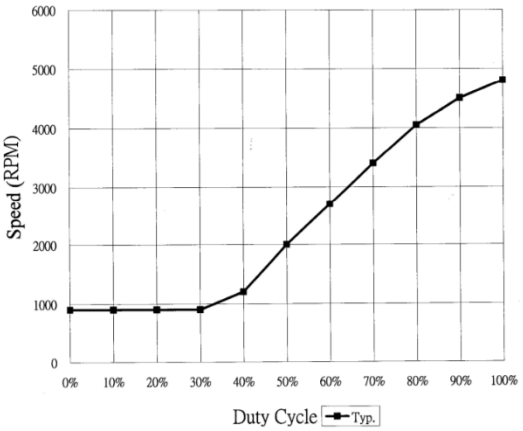
This 2-ball fan operates with a 12V DC power supply, allowing it to rotate at 4800±10% RPM. This results in a 28.3L/s air flow. The max current the fan will ever draw is 2A. When facing the front of the fan, the blades rotate counter clockwise, causing the air to flow back through the fan.

Wire Functions

This fan has four wires: 12V power, ground, control, and feedback. The first two wires are relatively simple, sourcing power to the device. To control the fan's motor voltage the control wire is used. This is done by varying the duty cycle of the square wave pulse on this wire; the higher percentage the duty cycle, the more voltage applied to the motor. Specifically, altering the duty cycle from 30% to 100% alters the RPM approximately linearly from 900 to 4800. If the duty cycle is less than 30%, the speed will rest at its 900 RPM minimum.

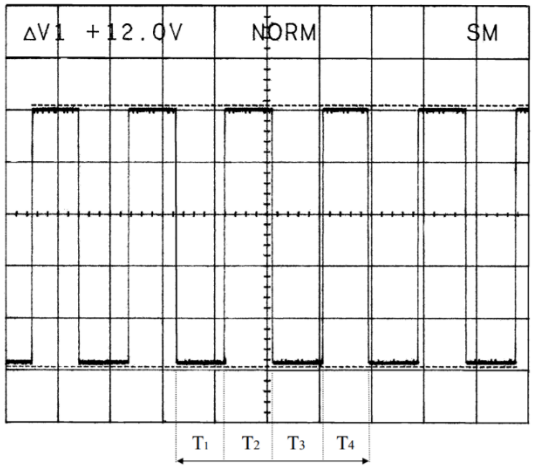
Wire Colours	
Red	Power (12V)
Black	Ground
Yellow	3rd Wire (Feedback)
Blue	PWM (Control)

The PWM square wave has very specific requirements in order to work properly. Firstly, the frequency of each cycle must be between 23 kHz and 28 kHz, preferably at 25 kHz. Because of this, the `analogWrite()` function cannot be used, as it only provides a frequency of 980 Hz with the Arduino Uno. Next, a high voltage on the control wire ranges from 2.8V to 6V. The maximum voltage that is considered ground is 0.4V. These voltages are compared with the ground wire. If the applied voltage happens to lie between 0.4V and 2.8V, then the fan will consider it to be floating, defaulting to the maximum RPM.



Duty Cycle vs RPM

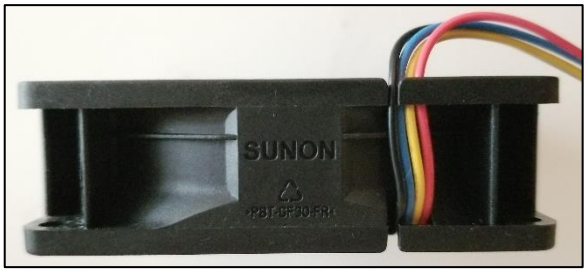
Sometimes however, there are external factors that affects the RPM in unwanted ways. For this, the feedback wire measures the physical output and reports it to the controller. The feedback wire uses a tachometer output a hall-effect sensor that is mounted on the PCB in the core of the fan. This tachometer creates two pulses per single rotation of the fan (2Hz:1 Rotation). The pulses always have a 50% duty cycle regardless of RPM, so by measuring the amount of time T_1 from the rising edge of a pulse to the falling edge, we can calculate how long it will take for the fan to complete one rotation. This is represented by the equation $RPM = 4 \cdot T_1 \div 60$. If the RPM is far of its expected value, the fan's built-in protection will shut of the motor until the resistance is reduced. This feedback wire is open collector, so a pullup resistor must be attached to prevent floating.



Feedback Wire Pulsing Output

Media

PF80251B1-000U-S99



Wire output of the fan: Ground, PWM, Feedback, & Power

Reflection

This project was not very interesting to me at a cursory glance. However, after researching the part I was surprised by how complex the simplest parts of a computer can be. My most notable reason for liking this fan is that it is a real-life component used in current computers. I even opened my desktop PC to find a four-wire DC fan working the way depicted in the datasheets.

Part B. Execution

Purpose

This project has two core components: a 4-wire fan with speed control and character LCD showing various pieces of data about the current state of the fan. It is all programmed in assembly and wired to an Arduino.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/AssemblyTasks.html#40b
Waveform Descriptions:
https://www.sparkfun.com/datasheets/Components/SMD/ATMega328.pdf#page=99&zoom=100,0,760
LCD Library: https://github.com/rsgcaces/AVROptimization/blob/master/LCDLib.asm

Procedure

Parts	Quantity
Arduino (ATmega328p)	1
Four-Wire Fan	1
Character LCD	1
Potentiometer	1

The LCD is wired to display the fan data. Since the default pin layout of the LCD library interferes with compare match pins of the timers, the library pins are redefined. The fan is wired to 12 V, ground, OC2B (control), and ICP1 (feedback). While the feedback is not implemented in this project, the potential for it exists. The final component is a potentiometer wired to the first analog read pin of the Arduino.

The code first initializes the LCD using Weinman's library and sets up Timer 2, as wells as the ADC conversion. Timer 2 is made to have a 25 kHz square wave output on OC2B, controlling the RPM of the fan. Whenever the counter reaches the value of `OCR2B`, the pin will be cleared and whenever it overflows it will set it. Every time an analog conversion is complete, the eight most significant bits will be read in. This data is then sent to two different places: the LCD and the fan. For this raw reading to be displayed onto the LCD, the data must first be converted into binary encoded decimal, which packs numbers from 0 to 9 into each nibble. This allows for an easy way to convert from binary to ASCII. This is then displayed on the LCD. To send the data to the fan, this eight-bit value must be converted to a percentage of the top value of timer 2. This top value creates the 25 kHz, and the certain value of `OCR2B` creates a specific duty cycle. The top value is 80, so the reading must be mapped from 0-255 to 0-80. Since $\frac{val}{255} = \frac{OCR2B}{80}$ we can determine that $OCR2B = 80val \ll 8$. This creates incredibly simple arithmetic, as our input is simply multiplied by 80, and then the upper byte is put into `OCR2B`. This will give the proper duty cycle for the fan.

When it is all put together, the LCD displays the raw potentiometer reading, the duty cycle and theoretical RPM. The fan changes speed as the user turns the potentiometer.

Theory

Timers: Overview

Timers are simply counters that can cause an action, such as an interrupt, when a specific requirement has been met. Typically, this is when the counter overflows. This, by itself, is not too great; a lot of their functionality can be done in software very easily. What makes them great is they run solely using hardware within the microcontroller. This can offload some of the code to the hardware capabilities of the MCU and reduce some of the power required to execute a program.

There are six important registers, five of which need to be adjusted for the timer to function properly. The `TCCR#A`[1] register holds the *Compare Match* (COM) bits and half of the *Waveform Generation Mode* (WGM) bits. On the ATmega328p, there are two COM pins for each timer, named *OC#A* and *OC#B*. By default, these COM bits are cleared, meaning the *OC#A/B* pins are unaffected by the timers. However, by setting these four bits these pins can be toggled, cleared, or set through a timer control software-less interrupt. To tell these pins when to be altered there are two comparison registers, `OCR#A` and `OCR#B`. When the timer has incremented to a point where it is equivalent to one of these registers, it will trigger the compare match interrupt, causing their respective pin to either toggle, set, or clear.

There is another control register, `TCCR#B`. This holds the rest of the WGM bits as well as the prescaler. For the ATmega328p, Timer 0 and 2 have eight different waveforms whereas Timer 1 has 16. Since waveform generation is a complex topic, there is a dedicated theory section to it. Prescalers on the other hand, are relatively simple. Without a prescaler, every timer will increment once per clock cycle. For the Arduino UNO, this is 16 million times a second. To slow this down, prescalers act as mini timers, incrementing a set number of times before telling the main timer to increment. This, again, is purely done in hardware and its value is controlled by the Clock Select bits in `TCCR#B`.

There are three interrupts associated with each timer. First, there is the Timer overflow interrupt. When the timer reaches its maximum value, it will roll over to zero and cause this interrupt. The next to, as previously mentioned, are the comparison interrupts. When the timer register is equal to `OCR#A/B`, these interrupts will trigger. In order to use any of these interrupts their respective enable bit must be set. All of these enable bits are in `TIMSK#`.

The final register is the `TCNT#` register. This the place where the incrementing value is stored. Depending on the timer and the MCU, this can be a one- or two-byte register. Because of this, `OCR#A` and `OCR#B` can also be full words instead of a single byte, as depicted in the table.

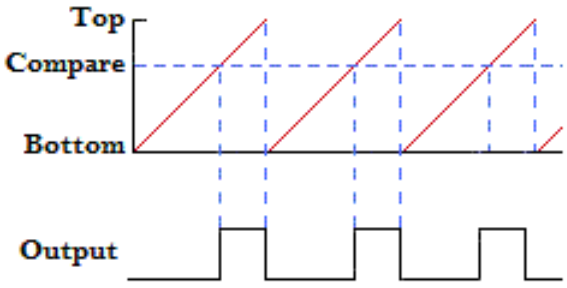
	7	6	5	4	3	2	1	0
TCCR#A	COM#A1	COM#A0	COM#B1	COM#B0	–	–	WGM#1	WGM#0
TCCR#B	DOT[2]	DOT[2]	–	–/WGM13	WGM#2	CS#2	CS#1	CS#0
OCR#A	Comparison Register(s)							
OCR#B	Comparison Register(s)							
TIMSK#	–	–	–	–	–	OCIE#B	OCIE#A	TOIE#

[1] # represents the timer in focus. For example, TCCR1A is the Timer Control Register for Timer 1.
[2] Depends on Timer: Bits are not reserved but are irrelevant for this project.

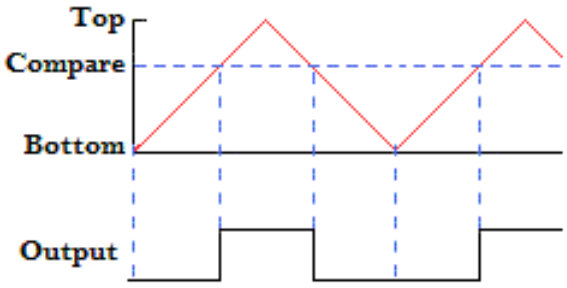
Waveforms

Timers can increment in two main ways: Fast PWM and Phase Correct (PC) PWM. When Fast PWM is used, the counter will increment to the top value and reset back to zero. CTC and Normal modes also use fast PWM but are named differently in the datasheet for their typical usage. PC PWM begins to decrement once it reaches the top value. For both incrementing patterns, by adjusting the top value (or prescalers) the frequency can be adjusted. This is because the counter will reach the top sooner if the limit is lower. When the comparison register is adjusted, the duty cycle is altered in a predictable pattern. For flexibility with frequency, modes with OCRA as the top should be chosen.

When the COM bits of `TCCR#A` are used in conjunction with different waveforms, the output of the OCRA/B pins behave differently. For some, when the timer has a value of zero, OCRA/B would be cleared. Others, it will toggle, or be set, or be ignored. To view the specifics, see the ATmega328p datasheet.



Fast PWM



Phase Correct PWM

MODE	TYPE	TOP	UPDATE OCRA/B AT:	OVF INT. FLAG SET AT:
0	Normal	MAX	Equivalence	MAX
1	Phase Correct PWM	MAX	MAX	0
2	CTC	OCRA	Equivalence	MAX
3	Fast PWM	MAX	0	MAX
4	Reserved	-	-	-
5	Phase Correct PWM	OCRA	MAX	0
6	Reserved	-	-	-
7	Fast PWM	OCRA	0	MAX

Timers: Application

Only one of the three timers are used in this project, with the other two having the potential to be used as well. To control the fan, timer 2 is put on waveform mode seven and `COM2A1` bit is set. This clears OC2B on compare match, sets it when it overflows. The overflow limit of this waveform is `OCR2A`. This allows for control of the frequency and duty cycle with variations in `OCR2A` and `OCR2B` respectively. The fan requires a 25 kHz frequency, while the RPM is controlled by the duty cycle. The other timers can be used to schedule LCD updates as well as input capture, but these have not been implemented.

Analog Reading

The ATmega328p uses a 10-bit Analog to Digital Converter. To achieve this, a series of OP-Amp comparators checks if the input voltage is above or below half of the reference voltage (RFV). If it is, it sets the most significant bit of the ADC register and then subtracts half of the RFV. It then repeats this process, comparing the subtracted input voltage to a further division of the RFV, until 10 bits of precision has been reached.

To complete this process, multiple registers must be set up. First, the `ADMUX` register is used to determine which pin is performing the read. Also, within this register is the `ADLAR` bit, which determines whether the most significant eight bits are grouped together in the upper byte or right aligned like normal. Next, there are two control registers, `ADCSRA` and `ADCSRB`. These hold important enable bits, prescalers and flags. The ADC clock speed should be reduced to 125 kHz to maintain accuracy using the `ADPS#` bits. To trigger an analog reading, the ADC Auto Trigger Enable (`ADATE`) bit is set. This causes the ADC to be triggered by an external event depending on the `ADTS#` bits in control register B. For continuous conversions, these three bits are cleared. To enable the interrupt, the ADC Interrupt Enable bit is set. The final register is `DIDR0` which allows each of the analog pins digital use be disabled in order to reduce power consumption.

To ensure proper conversion, the ADC should be run once to 'warm' it up. The first conversion tends to be inaccurate and should be avoided. Once the user would like to read the ADC value, the 10-bit data will be stored in `ADCH` and `ADCL`.

	7	6	5	4	3	2	1	0
ADMUX	REFS1	REFS0	ADLAR	–	MUX3	MUX2	MUX1	MUX0
ADCSRA	ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0
ADCSRB	–	ACME	–	–	–	ADTS2	ADTS1	ADTS0
DIDR0	–	–	ADC5D	ADC4D	ADC3D	ADC2D	ADC1D	ADC0D

LCD

Most character LCDs have a backpack on them. In this case, the driver chip used in the backpack is the HD44780U. This chip is a generic driver IC that can be used for Character LCDs of up to 64×2. Although the specifics of controlling the LCD are masked behind a library, the general concepts are clear. The driver has to 8-bit registers that it uses to control the LCD: the instruction register (IR), and the data register (DR). First, the cursor must be set, telling the LCD which segment to write on. To do this, the IR is set to *Cursor Shift*. As the name suggests, this shifts the cursor over to the next character slot. Then the IR is set to *Set DDRAM Address*. This chooses the character from DDRAM, with a *Read Data* putting it into the DR. Then, when the LCD is ready, it displays the data register onto the screen at the specified location.

Code

```
;PROGRAM      :LCDfromADCinClass
;PURPOSE      :Obtains ADC of POT readings and configures it for LCD presentation
;AUTHOR               :C. D'Arcy
;DATE         :2019-04-30
;DEVICE               :Arduino (ATmega328p)
;NOTES        :DD stands for Double Dabble (Shift/Add3) algorithm that converts binary
(8 or 16) to packed BCD (3 or 5)
#include      <prescalers.inc>
#define       TOP           80            ;16MHz/8/25000 = 80 = TOP (OCR2A)
.equ          cTHREE        =0x03  ;DD: CONSTANTS for Double Dabble algorithm
.equ          cTHREEZERO    =0x30  ;DD: ditto
.equ          POTAddress    =0x00  ;LCD cursor addresses for labels
.equ          DCAddress     =0x08  ;      "
.equ          RPMAddress    =0x40  ;      "
.equ          TACHAddress   =0x48  ;      "
.def          index         =r14   ;used as a Z register address offset into the arrays
.def          temp          =r15   ;temporary usage
.def          util          =r16
.def          count         =r17   ;countdown support for various activities
.def          bin0          =r18   ;DD: binary LOW byte
.def          bin1          =r19   ;DD: binary HIGH byte
.def          BCD10         =r20   ;DD: BCD: 2 Least significant BC Digits
.def          BCD32         =r21   ;DD: BCD: Middle BC Digits
.def          BCD4          =r22   ;DD: BCD: 1 Most Significant BC Digit
.def          three         =r23   ;DD Registers: assigned the constant 0x03
.def          threeZero     =r24   ;DD Registers: assign the constant 0x30
; ***** INTERRUPT VECTORS ********************************************
.org          0x0000                      ;start of vector jump table
      rjmp    reset                       ;lowest interrupt address => highest priority!
.org          ADCCaddr                    ;
      rjmp    ADC_vect                    ;
.org          INT_VECTORS_SIZE
; ***** LCD STRING LABELS *********************************************
POTLabel:
.db           "POT:",0,0                  ;must be null-terminated (with even padding)
DCLabel:
.db           "DUTY:",0                   ;      ”
RPMLabel:
.db           "RPM:",0,0                  ;      ”
TACHLabel:
.db           "TCH:",0,0                  ;      ”
DUTYTable:
      ;p.11:http://mail.rsgc.on.ca/~cdarcy/PDFs/Sunon12VDCFanSpec.pdf
.db                   " 0102030405060708090 10"
RPMTable:
      ;p.11:http://mail.rsgc.on.ca/~cdarcy/PDFs/Sunon12VDCFanSpec.pdf
.db                   " 900 900 900 900120020002700340040504500 4800"

reset:                                    ;PC jumps to here on reset interrupt...
      ldi     util,  low(RAMEND)          ;initialize the stack pointer
      out     SPL,   util                 ;
      ldi     util,  high(RAMEND)         ;
      out     SPH,   util                 ;

      ldi     three, cTHREE               ;DD Support
```

```
       ldi    threeZero,cTHREEZERO        ;      "

       call          ADCSetup             ;Configure the ADC peripheral
       call          LCD_init             ;initialize devices and MCU peripherals
       call          T2Setup
       sei
   wait:
       rjmp   wait                        ;repeat or hold...
ret                                              ;unreachable

ADCSetup:
       ldi    util,  1<MUX0               ;turn off digital use of A0 tp save power
       sts    DIDR0, util                 ;disable digital use of A0 (pin 14)
       ldi    util,  1<<ADEN              ;enable the A/D peripheral
       sts    ADCSRA,util                 ;
       ori    util,  1<<ADPS2 | 1<<ADPS1 | 1<<ADPS0    ;divide down AD clock to 125kHz
(recommended for accuracy)
       sts    ADCSRA,util                 ;set it

       clr    util                        ;Ignore the ACME bit
       sts    ADCSRB,util                 ;free running, for now

       ldi    util,  1<<REFS0 | 1<<ADLAR  ;AVCC reference (5V) and Left Adjust
       sts    ADMUX, util                 ;

       lds    util,  ADCSRA               ;prepare for a dummy conversion (recommended)
       ori    util,  1<<ADSC              ;set the SC flag
       sts    ADCSRA,util                 ;tstart your covnversion
   dummy:
       lds    util,  ADCSRA               ;read the register
       sbrc   util,  ADSC                 ;
       rjmp   dummy                       ;
       lds    util,  ADCSRA               ;
       ori    util,  1<<ADSC|1<<ADIE      ;Start first conversion and enable interrupt
       sts    ADCSRA,util          ;
ret

T2Setup:
       sbi    DDRD,  PD3                  ;PWM on pin 3 (OC2B)
       ldi    util,  1<<COM2B1 | 1<<WGM21 | 1<<WGM20
       sts    TCCR2A,util                         ;
       ldi    util,  1<<WGM22 | T2ps8             ;
       sts    TCCR2B,util                         ;
       ldi    util,  TOP                          ;
       sts    OCR2A, util                         ;
       clr    util                                ;
       sts    OCR2B, util                         ;
       ldi    util,  OCIE2B                       ;
       sts    TIMSK2,util                         ;
ret

ADC_vect:
       lds    temp,  ADCH                         ;Grab the most significant 8 bits
       mov    util,  temp                         ;let's determine the duty cycle...
       clr    r17                                 ;
       ldi    r18,   TOP                          ;
```

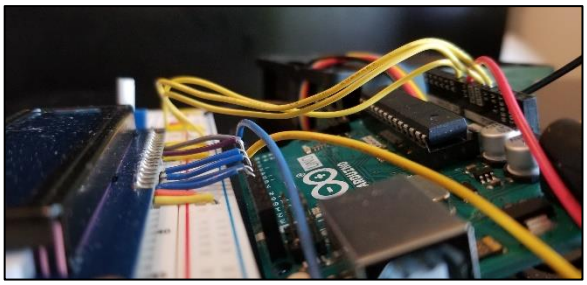
```
       clr    r19                                ;
       mul    r18,   util                        ;
       sts    OCR2B, r1                          ;set the duty cycle

       clr    index
       mov    util,  temp
   again:
       subi   util,  25
       brlo          continue
       inc    index
       rjmp   again
   continue:
;perform the Double Dabble algorithm on the ADC value
       mov    bin0,  temp                        ;restore ADCH value and prepare for DD
       clr    bin1                               ;prepare bin1 (bin0 is already to go)
       call          bin16BCD                    ;convert to BCD
       call          LCDUpdate                   ;update the LCD
       lds    util,  ADCSRA                      ;start the next conversion
       ori    util,  1<<ADSC                     ;
       sts    ADCSRA,util                        ;
reti

LCDUpdate:
       ldi    ZH,    high(POTLabel)              ;point to the base address of POT Label
       ldi    ZL,    low(POTLabel)               ;      "
       ldi    util,  POTAddress                  ;set the target address on the LCD
       call          lcd_write_string_4d         ;display it
       mov    util,  BCD32                       ;obtain the hundreds & thousands digits
       andi util,    0x0F                       ;we only want BCD2 (low nibble)
       ori    util,  48                          ;add 48 to get the ASCII value
       call          LCDWriteCharacter           ;write it
       mov    util,  BCD10                       ;obtain the units and tens digits
       swap   util                               ;work with the tens digit first

       andi   util,  0x0F                        ;mask it
       ori    util,  48                          ;add 48 to get the ASCII value
       call          LCDWriteCharacter           ;write it
       mov    util,  BCD10                       ;reload
       andi   util,  0x0F                        ;mask off the tens digit
       util,  48                                 ;add 48 to get the ASCII value
       call          LCDWriteCharacter           ;write it

       ldi    ZH,    high(DCLabel)
       ldi    ZL,    low(DCLabel)
       ldi    util,  DCAddress
       call          lcd_write_string_4d
       lsl    index
       call          DisplayDuty
       ldi    ZH,    high(RPMLabel)
       ldi    ZL,    low(RPMLabel)
       ldi    util,  RPMAddress
       call          lcd_write_string_4d

       lsl    index
       call          DisplayRPM
       ldi    ZH,    high(TACHLabel)
```

```
        ldi     ZL,     low(TACHLabel)
        ldi     util,   TACHAddress
        call            lcd_write_string_4d
ret

LCDWriteCharacter:
        call            lcd_write_character_4d          ;display the character
        ldi     util,   80                              ;40uS delay (min)
        call            delayTx1uS
ret

DisplayDuty:
        ldi     ZH,     high(DUTYTable)<<1
        ldi     ZL,     low(DUTYTable)<<1
        add     ZL,     index

        lpm     util,   Z+
        call            LCDWriteCharacter
        lpm     util,   Z+
        call            LCDWriteCharacter
        ldi     util,   '%'
        mov     count,  index
        cpi     count,  20
        brne    bypass
        ldi     util,   '0'
    bypass:
        call            LCDWriteCharacter
ret

DisplayRPM:
        ldi     ZH,     high(RPMTable)<<1
        ldi     ZL,     low(RPMTable)<<1
        add     ZL,     index

        lpm     util,   Z+
        call            LCDWriteCharacter
        lpm     util,   Z+
        call            LCDWriteCharacter
        lpm     util,   Z+
        call            LCDWriteCharaacter
        lpm     util,   Z+
        call            LCDWriteCharacter
ret

; ****************************** End of Main Program Code ******************

#define             LOCALLCD            ;This allows user code to override default
(Appliance) wiring
.equ    lcd_D7_port         = PORTB             ;lcd D7 connection
.equ    lcd_D7_bit          = PORTB4
.equ    lcd_D7_ddr          = DDRB

.equ    lcd_D6_port         = PORTB             ;lcd D6 connection
.equ    lcd_D6_bit          = PORTB3
.equ    lcd_D6_ddr          = DDRB
```

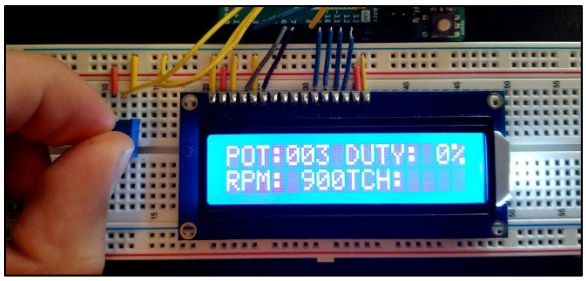
```
.equ    lcd_D5_port         = PORTB             ;lcd D5 connection
.equ    lcd_D5_bit          = PORTB2
.equ    lcd_D5_ddr          = DDRB

.equ    lcd_D4_port         = PORTB             ;lcd D4 connection
.equ    lcd_D4_bit          = PORTB1
.equ    lcd_D4_ddr          = DDRB

.equ    lcd_E_port          = PORTD             ;lcd Enable pin
.equ    lcd_E_bit           = PORTD7
.equ    lcd_E_ddr           = DDRD

.equ    lcd_RS_port         = PORTD             ;lcd Register Select pin
.equ    lcd_RS_bit          = PORTD6
.equ    lcd_RS_ddr          = DDRD

#include      <LCDLib.asm>                      ;Weinman's LCD library code
#include      <DoubleDabble.asm>
```

Media

Video: https://youtu.be/ec6GigbML2w



Wiring Close Up



LCD in Action

Reflection

This project was intense, but I feel as though I understood. It is kind of shame that it has been squeezed into a busy time with so many other school projects, but I'm glad we did it. However, I think the most enjoyable part for me was learning about the LCD. I'd love to further my knowledge of character and graphic LCDs in university.

Project 14. Sound Controlled Power Bar

Purpose

This is project initially started off as a voice recognition module that could tell the time and control a remote power bar. As it evolved however, the emphasis was placed on the power bar itself, and controlling it remotely. The final product has two components: a recognition module and a control module. The recognition module uses radio frequencies to tell a PCB when a clap occurs. This PCB then alters the outlets on a relay-controlled power bar. The PCB uses surface mount technology (SMT) and is encased in a slim 3D printed housing.

Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/ISPs.html
Voice Control: https://cdn.sparkfun.com/datasheets/Sensors/Sound/EasyVR_Datasheet_2.3.pdf
Regulator: https://www.analog.com/media/en/technical-documentation/data-sheets/3638fa.pdf

Procedure

To begin, two prototypes are made; one to control the power bar, and another to tell it when a sound has been recognized. The former has a PCB made with an NRF, MCU, and a voltage regulator, along with their concurrent parts. This allows it to receive data, interpret it, and control the outlets accordingly.

Parts	Quantity
ATmega328p	2
MSGEQ7	1
Electret Microphone	1
NRF24L01	2
LTC3638 Voltage Regulator	1
1 µF Capacitor	2
22 pF Capacitor	2
10K Ω Resistor	1
2K Ω Resistor	1
1K Ω Resistor	1
220 µH Inductor	1
16 MHz Crystal	2
Schottky Diode	1
1 mm Pitch FFC Converter	1

A large component of this project is finding an efficient way to source 5 V. Since the PCB is mounted onto a power bar, there are plenty of options. A USB could be added to directly plug into one of the outlets, but this doesn't provide a satisfying user experience as it takes some of the utility away. Instead, the decision is made to source power from the internal PCB of the power bar. Various AC and DC power sources are found with different voltages levels, but in the end a switching regulator, sourced from 100 VDC, is used to generate the PCB's 5 V.

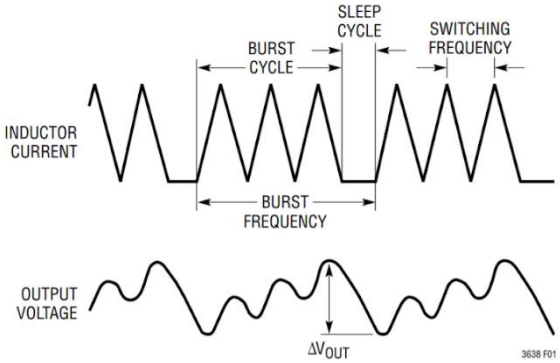
Initially, a voice control module is purchased to perform the recognition, lessening the load on the Arduino. However, the device was not able to function in time for this ISP. Another potential solution is to use the Üspeech Arduino library, but it is too cumbersome and imprecise to be useful. Instead, the MSGEQ7 chip is used to detect claps. By only analyzing the amplitude of high frequencies, a clap can be detected. Once this occurs, a signal is sent through the NRFs to the PCB. Unfortunately, the pitch for the FFC converter was incorrectly chosen. This means that code is not able to be uploaded to the onboard ATmega328p.

Theory

Audio Recognition

To recognize audio, there are several different techniques, all with varying capabilities and challenges. Devices that can detect phrases generally compare the audio input with five-to-seven pre-recorded messages. If there is a comparison with over a 90% similarity, it will trigger an output than can be read by the main microcontroller. This signal can come in many forms, such as I2C, SPI, UART, or simply GPIO. Certain techniques, such as the Üspeech library or the MSGEQ7 circuit detect frequencies and can be used to decipher consonants.

Step-Down Converters

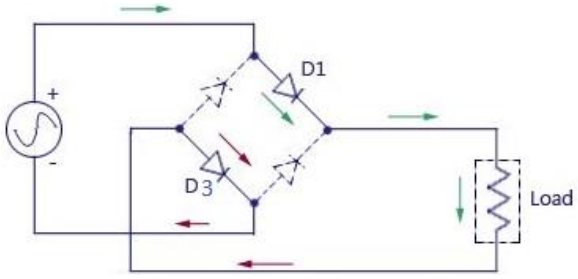


A step-down converter (also known as a buck converter) is a type of switching regulator that decreases a DC input voltage efficiently. Instead of converting the unwanted power into heat, it uses a pulsing technique, similar to PWM, to decrease the voltage. To achieve a proper output there are two components: a burst and a sleep cycle. The burst cycle rapidly increases and decrease the output current, creating a triangle wave. The frequency of this wave is determined by the inductance and capacitance of external components. This cycle continues until the feedback pin, V_{FB}, detects the peek expected voltage. One this occurs, the output moves onto the sleep cycle. During this phase, the main source of power is from the external capacitor and inductor. Once the output voltage drops below 0.8 V, the feedback pin resets the entire process. When the LTC3638 decreases the voltage from 140 V to 5 V, the expected efficiency is 76%.

Alternating Current

Alternating current, as opposed to direct current, switches the current back and forth between two wires. This has two main uses: motors and voltage reduction. While most hobby motors are brushed DC motors, they essential convert the power to AC. This is because as the motor rotates, the brush connects to a different plate, switching the current. When using an AC motor, this doesn't need to be a part of the interior, so as a result they are more compact and efficient. The main reason AC is used in power lines is because of the high voltage that is used in them. When this high voltage reaches a house, it must be reduced. Historically, DC has not been able to provide efficient methods of power reduction. AC, on the other hand, can use transformers to drop voltage levels with a 99% efficiency! This is the only reason AC is used in North American power grids; lots of the United Kingdom simply uses high voltage DC (HVDC), as new methods for decreasing DC voltage are being introduced.

To convert AC to DC, a full bridge rectifier can be used. As the current alternates, the frontward diodes take turns providing the source for current, and the back diodes provide a path to ground. A capacitor can be used between DC power and ground for smoothing.

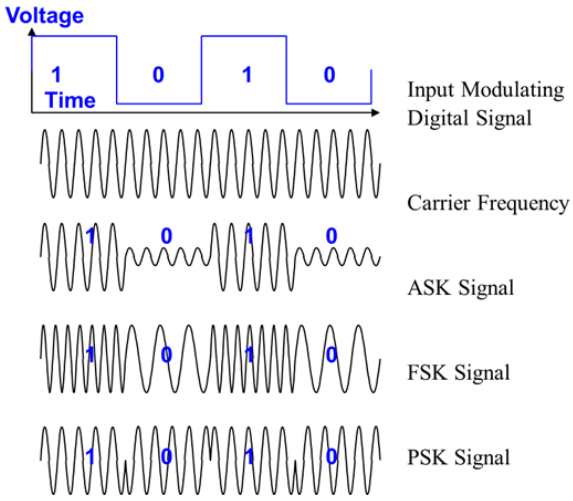


Full Bridge Rectifier

NRFs

The two NRFs in the project are used to communicate information from the recognition module to the control module. NRFs, like most forms of wireless communication, uses radio frequencies to transmit data. To distinguish it from other techniques, it uses a 2.4 GHz – 2.525 GHz frequency range.

There are three different variables to account for when using an NRF: data rate, bandwidth, and channel frequency. The data rate is analogous to the clock cycle; It tells the NRF how quickly to move to the next bit when transmitting or receiving data. The options for the NRF24L01 are 250 kb/s, 1 Mb/s, and 2 Mb/s. At first glance the higher bit rate seems like the preferred option, but it comes with a cost. As the data rate increases, so does the bandwidth. The bandwidth is the range of acceptable frequencies an NRF can output, before being ignored by the receiver. When choosing a bit rate, both factors must be considered. Finally, there is the channel frequency. To make two NRFs communicate with each other, they must be on the same frequency range.



Radio frequencies can typically transmit data in two different ways: AM (ASK) or FM (FSK). AM, or amplitude modulation, varies the amplitude of the signal being transmitted. A high amplitude represents a high bit and a smaller amplitude represents a low bit. FM, or frequency modulation, varies the frequency (as the name suggests). In this case, a high frequency represents a high bit. NRFs use a specific type of FM known as Gaussian Frequency Shift Keying (GFSK). GFSK is a simple form of FM radio frequencies; it has no representation for a new bit (such as PSK), but it does provide a smoothing between bits. This increases the likelihood of having a bit be mistaken for another, but reduces interference with neighbouring channels, allowing for a decreased bandwidth.

Reflection

This project has evolved so much since its beginning. The simple decision of where to source the PCB's power changed the focus of the ISP in a way I never anticipated. Learning about AC, inductors, and voltage regulation was always something that provoked my curiosity, but I never thought it would work its way into a project. I'm disappointed the voice recognition failed so early in the process, but it has finally taught me a lesson that has taken me two years to learn; I enjoy delving into the complexities of known parts more than I like debugging new ones. My next ISP will hopefully reflect this.

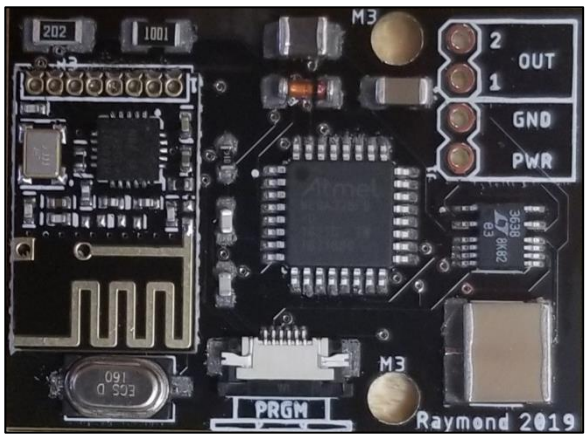
Code

```
// PROJECT: NRF Transmitter
// DEVICE:  ATmega328p
// AUTHOR:  Daniel Raymond
// DATE:    2019-02-05

#include <RF24.h>

// Global variable setup here
#define strb  A1
#define reset A0
#define inPin A2
#define CE    7
#define CSN   8
#define WAIT  2000

RF24 radio(CE, CSN);
const byte address[6] = "00001";          // Channel Freq = 2400 + address [MHz]
uint8_t data = 0;

uint16_t freq;
long tmDelay = millis();
boolean allowRead = false;

void setup() {
  DDRC = 0x06;                            // Sets up pin
  DDRD = 1<<PD5;

  pinMode(CSN,OUTPUT);
  pinMode(CE,OUTPUT);
  _SPI.begin();                           // Sets up the NRF
  digitalWrite(CE,LOW);
  digitalWrite(CSN,HIGH);
  radio.openWritingPipe(address);         // Give channel to communicate on
  radio.setPALevel(RF24_PA_MIN);          // Set Power Amplifier Level
  radio.stopListening();                  // Set to be the transmitter
}

void loop() { // Loop that makes the cycle continue forever
  // Reset input for the MSG
  digitalWrite(reset, HIGH);
  digitalWrite(reset, LOW);

  for (uint8_t i = 0; i < 7; i++) {
    digitalWrite(strb, LOW);                // Sets MSG latch to be able to read in
    if (i == 6)
      freq = analogRead(inPin);             // Only reads the high frequency
    digitalWrite(strb, HIGH);               // Moves on to the next frequency
  }

  if (freq >=30 && allowRead) {
    radio.write(&data, sizeof(data));       // Write the data to the NRF
    tmDelay = millis();
    allowRead = false;
  }

  if (millis()-tmDelay > WAIT)
    allowRead = true;
}
```

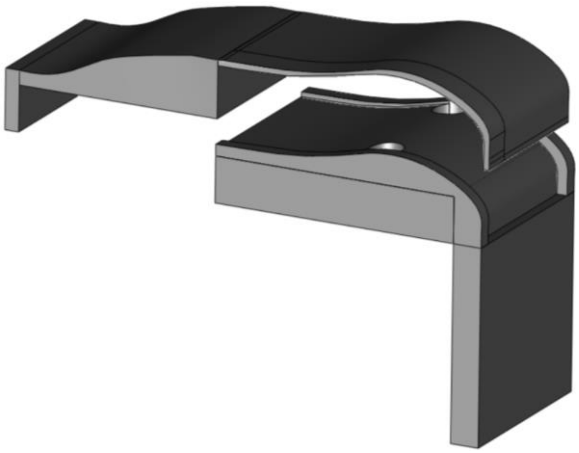
```
// NRF Receiver
#include <RF24.h>

#define CE  7
#define CSN 8
RF24 radio(CE, CSN);
const byte address[6] = "00001";
uint8_t data;

void setup() {
  radio.begin();
  radio.openReadingPipe(0, address);  // Give channel to communicate on
  radio.setPALevel(RF24_PA_MIN);      // Set PA level
  radio.startListening();             // Set to be receiver
  DDRD = 0x0F;                        // Set direction of OUTPUT Pins
}
void loop() {
  if (radio.available()) {
    radio.read(&data, sizeof(data));  // Read in the data when it is available
    PORTD = data;                     // Output the values onto the power bar
  }
}
```

Media

Video: https://youtu.be/b-euUTvDf28

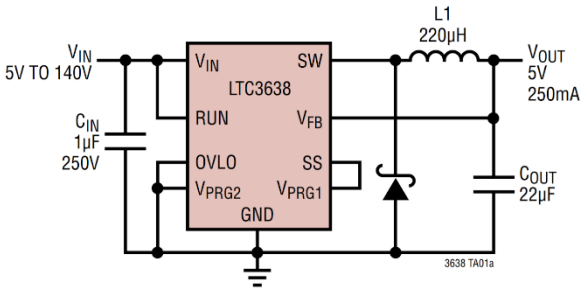


Power Bar PCB



2-Piece Case for the PCB

Relay Controlled Power Bar (IoT Relay 2)



Buck Converter Schematic

Project 15. CHUMP Extended

Purpose

This project is a continuation of the 4-bit programmable computer built in September. Numerous components have been added to the design, including a Program Counter (PC) extension, LED matrix, and a coding input system (CIS). This is a partner project with James Corley; he primarily focused on the input and case whereas I focused on the output and the PCB.

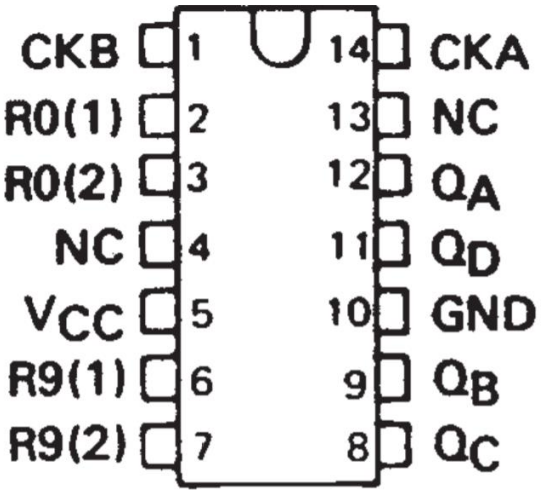
Reference

Project Page: http://darcy.rsgc.on.ca/ACES/TEI4M/1819/ISPs.html
PC Ext. Datasheet: http://www.ti.com/lit/ds/symlink/sn74ls93.pdf

Theory

PC Extender

Since the original CHUMP had a four-bit PC, only 16 total lines of code could be used. Considering that two daisy-chained shift registers requires a minimum of 33 lines, this isn't practical. Instead of completely overhauling the current PC, a four-bit counting IC is used to extend it, allowing for 256 possible lines of code.



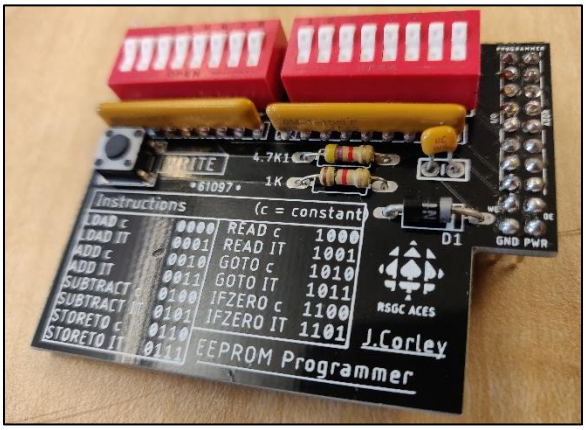
The chip used is the *SN74LS93N*. It has three core components: a clock input, reset, and a four-bit output. This chip takes in the falling edge of a pulse, incrementing its output by one. Since we only want these bits to increment when the PC overflows, the MSB of the PC becomes the clock input. There is no load functionality to the IC, but it can be cleared by two reset pins; when both are high, the output will be cleared immediately. When performing a jump, this reset pin must be pulled high. This allows jumps anywhere from 0 to fifteen. However, there is one subtle problem. When the PC load is grounded, it will load in a new four-bit value on the next clock cycle, whereas this IC will clear itself immediately. To work around this, the reset is first sent through the extra flip-flop of the address register. The flip-flop will store the data, resetting it on the next clock cycle.

Output

The output of the computer is the three LSBs of the accumulator. In ascending order (0→2), the pins tied to the accumulator are the latch, data, and then the clock. To control the 8x8 LED matrix on the board, there are two daisy chained shift registers. Their latch and clock pins are tied together, reducing the total number pins required to control them down to three. To transmit data, the latch is grounded, and the clock pin is pulsed. This will cause the shift register to read in the data line. This clock signal is pulsed 16 times: enough to fill both registers. Then, the latch is pulled high, outputting the data onto the shift registers. Unfortunately, outputting a value from RAM to the ALU will affect the pins of the shift registers, so using RAM is not viable

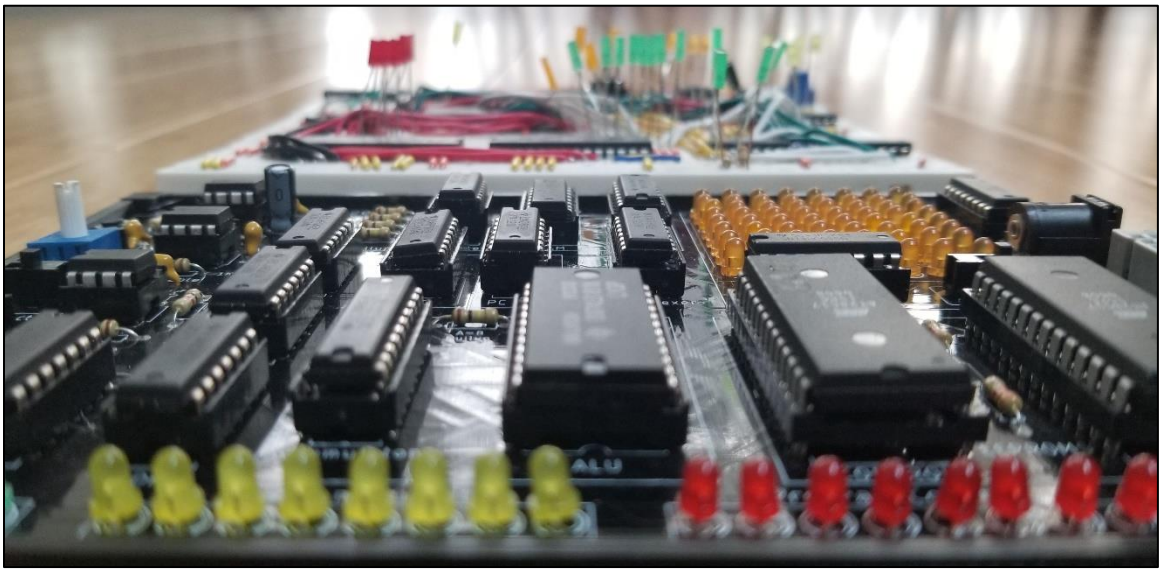
CIS

Although James is the head engineer for the CIS, it is important that everyone knows a broad overview of every component. The EEPROM that contains the code is the *AT28C17* EEPROM. To write to it there are two control pins, as well as a byte of address pins and a byte of data pins. The control pins are Write Enable (WE) and Output Enable (OE); they are both active-low. On the central PCB WE is pulled high and OE is pulled low. This sets the EEPROM into output mode, where it can be used by the computer. To program it, OE is pulled high. The two switch banks can be used to control the state of each bit. Although this EEPROM has 1024 bytes of possible storage the computer is only able to access 256 of them.



Programmer PCB

Once the 8/10 address pins determine what line of memory the byte is being store in, the data pins can be toggled to control the byte that is being inserted. When all the appropriate switches have been made, WE is pulsed, flashing that specific line of code into the EEPROM.



PCB & Breadboard Together

Operation Codes

In this project we have continued to use the same operation codes as in the breadboard version, with one small edit. As a brief refresher, the upper nibble of each program line details which instruction the computer will execute while the lower nibble acts as a constant. The operation code (Op Code) is given to the control EEPROM, which determines the state of certain chips.

The change is because a logical *AND* operation has been added. However, adding this instruction to the end of the instruction table was not viable. To determine whether the PC should be loaded to, the middle bits of the Op Code were OR'd and then that result was AND'd with the MSB. This told the computer that it was doing either a *GOTO* or an *IFZERO*, both of which had the possibility of the jumping. This was then NAND'd with the *A=B* pin of the ALU to allow for the *IFZERO* to function. This was fine for the breadboard, but with the introduction of a new operation, the system breaks. If the new operation is performed and the result happens to be 15, then the computer would perform a *GOTO*. A solution to this would be to XOR the middle bits instead of simply ORing them, but this would require massive restructuring of the device.

Instead, the jump commands are shifted down in the instruction table. This changes the resulting logic, but it is simpler than the original. To determine if there is a possibility of jumping, the two MSBs are AND'd together. The slot where the *GOTO* used to be is then filled up by the new instruction and won't trigger any accidental jumps.

Instruction	Op Codes	ALU	S_3	S_2	S_1	S_0	M	Cn	Acc	R/W
LOAD const	0000	B	1	0	1	0	1	X	0	X
LOAD IT	0001	B	1	0	1	0	1	X	0	1
ADD const	0010	A PLUS B	1	0	0	1	0	1	0	X
ADD IT	0011	A PLUS B	1	0	0	1	0	1	0	1
SUBTRACT	0100	A MINUS B	0	1	1	0	0	0	0	X
SUBTRACT IT	0101	A MINUS B	0	1	1	0	0	0	0	1
STORETO	0110	ignore	X	X	X	X	X	X	1	0
STORETO IT	0111	ignore	X	X	X	X	X	X	1	0
READ const	1000	ignore	X	X	X	X	X	X	1	1
READ IT	1001	ignore	X	X	X	X	X	X	1	1
AND const	1010	AND	1	0	1	1	1	X	0	X
AND IT	1011	AND	1	0	1	1	1	X	0	1
GOTO const	1100	Logic 1	1	1	0	0	1	X	1	X
GOTO IT	1101	Logic 1	1	1	0	0	1	X	1	X
IFZERO const	1110	Not A	0	0	0	0	1	X	1	X
IFZERO IT	1111	Not A	0	0	0	0	1	X	1	X

Procedure

This is the most complex PCB designed in this entire Design Engineering Report. However, the working breadboard version is used as a reference to make the schematic creation process much easier. Each component of the CHUMP is designed discretely and wired together after thorough checking. Since there are some unusual parts used, an order is placed on Digikey for chip seats, multiplexors, headers, and other parts the were low in stock. The CIS PCB is designed to attach to the central PCB via a 20-pin header. This allows for communication of the address, data, control pins, as well as supplying power and ground to the external board.

Once the board arrives, the clock is soldered onto the PCB. This is where the first problem was encountered: since the clock was designed separately, there is a different naming convention for the power. This is fixed using a simple wire, connecting the power traces. Then the program counter and its eight LEDs are soldered, working as intended. Next, the EEPROMs seats are soldered and tested. They are functional, but the CIS programmer short circuits the computer. This is because its output is tied to the PC output. When they output different signals, a short occurs. To fix this, an eight-bit multiplexor is added to decide between the two signals. Since the rest of the board is incredibly interconnected, the entire board is soldered up except for the shift registers and the LED matrix. The third problem: the multiplexor input that is connected to the program ROM was improperly labeled. On the ROM the pins were labeled from zero to three, whereas the multiplexor was labelled from one to four. While not detrimental, this is considered when performing load commands. The ROM is programmed to match the code of the breadboard, which works flawlessly. For a comprehensive parts list, see the CHUMP.

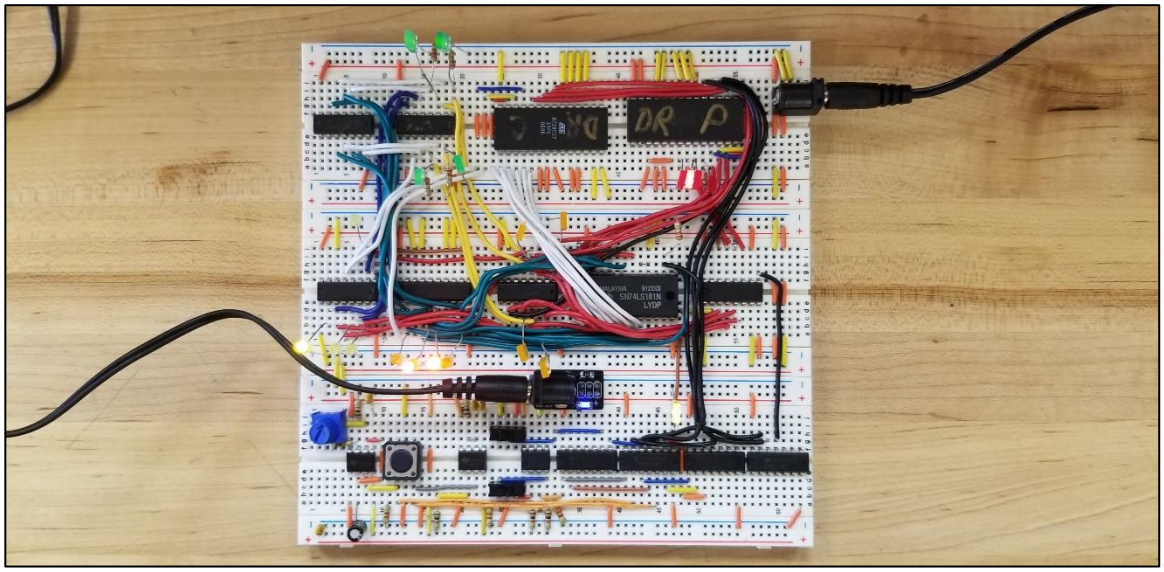
Code

Since this is a programmable computer, the code can literally be anything. Below is simply a way of turning on all the LEDs. To see the code that is running in the video, see project 17.

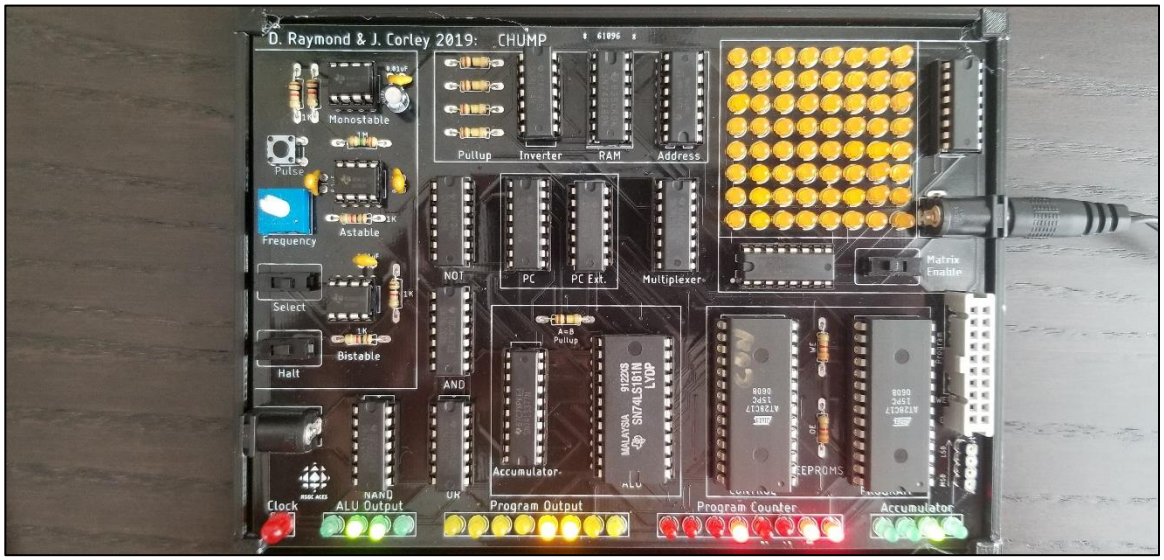
Line	***Ground Data***		***Line***	***Power Data***	
0	LOAD	0000	17	LOAD	0110
1	LOAD	0100	18	LOAD	0010
2	LOAD	0000	19	LOAD	0110
3	LOAD	0100	20	LOAD	0010
4	LOAD	0000	21	LOAD	0110
5	LOAD	0100	22	LOAD	0010
6	LOAD	0000	23	LOAD	0110
7	LOAD	0100	24	LOAD	0010
8	LOAD	0000	25	LOAD	0110
9	LOAD	0100	26	LOAD	0010
10	LOAD	0000	27	LOAD	0110
11	LOAD	0100	28	LOAD	0010
12	LOAD	0000	29	LOAD	0110
13	LOAD	0100	30	LOAD	0010
14	LOAD	0000	31	LOAD	0110
15	LOAD	0100	32	LOAD	0001
16	LOAD	0010	33	GOTO	0000

Media

Personal Video: https://youtu.be/vZ13xud0qBc
James' Video: https://youtu.be/C6ym7kKK5XI



Bread Board



PCB

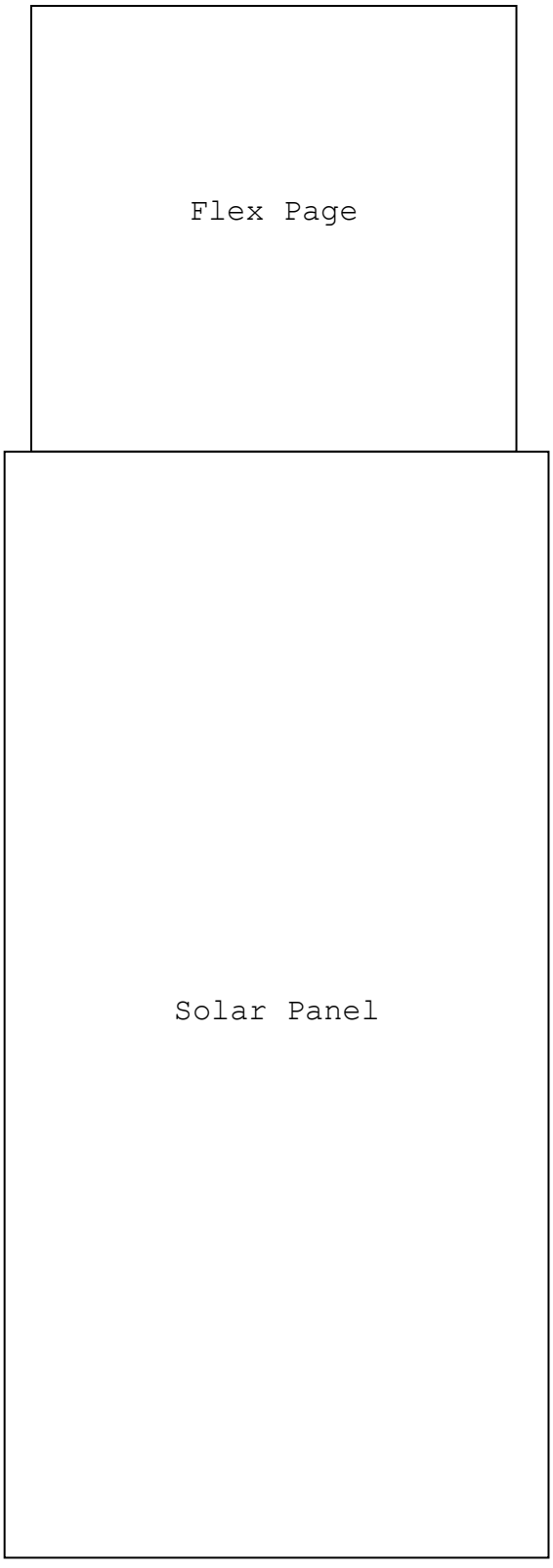
Reflection

We've gone out with a bang. I loved this project so much and it is nice to have something physical to bring to university and be proud of. Even though the project is officially finished, I'm glad we are bringing it through the finish line and getting version II. It will be a nice conversation starter and reminder of my time in the DES. In grade 9, I dreaded doing hardware, but simultaneously knew that I would go through the entire program. I was destined for it. Thanks to Hardware, I've finally found something I'm passionate about.

Project 16. Flex PCB: Snake Video Game

Purpose

This is the game *Snake* played on an SMT eight by eight LED matrix. The goal of the game is to direct your snake into apples. If you eat one, your snake will grow in length. If you hit the edge of the screen or the body of the snake, the games ends. To execute the code, a surface mount flexible circuit board is made, powered by a flexible solar panel. This is what is laminated into this report.



Reference

Project Page:
darcy.rsgc.on.ca/ACES/TEI4M/1819/Task.html#FP1
Github Repository:
https://github.com/draymond63/Snake

Procedure

To start, the PCB is designed in Eagle. The circuit is relatively simple; it contains a generic ATmega328p, two shift registers, an LED matrix and some buttons. Since the shipping time is quite lengthy, a board is sent out as soon as possible. It is designed with two pads on opposite ends of the board that are to be connected to the power rails of the solar panel. There is a programming finger designed to fit into a 1mm pitch FFC connector. This is then chained into a laptop to allow for programming.

To begin programming as soon as possible, a prototype is made with through-hole versions of the PCB. Since this is one of my most ambitious AVR assembly projects, the code is first written in Arduino C. Once the entire C code is fully functional, it is fully converted to AVR assembly.

Things such as arrays and variables take quite some time to port over. All the accumulators are used for data manipulation and storage of key variables. Booleans, lesser variables, and arrays are stored in SRAM. Once the PCB and Digikey parts arrive, the circuit is soldered. The code is altered slightly to function on the PCB.

Theory

Shifting an Array

Parts	Quantity
ATmega328p	1
SNCH595	2
PBNO	4
10K Ω Resistor	5
Diode	14
LED	64

In SRAM, eight bytes are allocated to holding the status of each LED in the matrix. Each byte corresponds to a different row and each bit in that byte corresponds to a different LED. Two shift registers control the anode and cathode pins of the matrix. To output this data, a full byte is applied to the power register. The index of this byte in the array becomes the row that is grounded. This process cycles through the array, creating the familiar POV effect.

Snake Tracking

Four main pieces of data are kept track of in order to maintain control of the snake's position: the coordinates of head, the coordinates of the tail, the direction the head is going, and the direction the tail is going. Using these pieces, we can ensure the snake is always the correct length and moving in the proper manner.

The head starts off at the top left of the screen, represented by `(0,0)`. Based on the direction of the head at the given time, one of the coordinates will increment or decrement accordingly. For example, if the head direction is `down`, then the Y component will increment by one. This coordinate is then set on the LED array and is lit up when the timer is triggered.

The tail's coordinates behave in the exact same manner as the head, but instead of setting a bit in the LED array, it clears it. The tail behaves as an "inverse head", moving along, turning off LEDs as it goes. To keep determine which direction the tail is going to move, an array of directions is made; it holds all the previous moves that the head has done. This length of this array needs to match the length of the snake. However, the length of the snake is dynamic, so to ensure enough space is allocated for the array, it is given 64 bytes: the amount of space needed to track a snake that has filled the screen. On every timing triggered event, a movement index tells the tail which direction from the array to grab. The tail moves, then the used cell is replaced with the current direction of the head. This ensures that when the snake has moved the length of the snake, the tail will be at the old coordinates and will move in the same direction the head did. When the length of the tail increases, the tail skips a turn and all the data in the directions array above the movement index is shifted up to fill the new available slot.

Timing

The screen is continually refreshing, using POV to display all the proper LEDs. However, timer 1 is used to schedule when the screen updates with new information. Whenever timer 1 overflows it will change a boolean value. On the next cycle of the loop it will alter the LED array that is outputted on the matrix. Since timers overflow incredibly quickly, a prescaler is used. This counts the overflows using hardware, then interrupts the MCU once it has counted the specified amount. The specifics to setting up a timer interrupt are discussed in detail in the fan project

Collisions

Collisions can occur when the snake's head goes off the screen (hitting a boundary) or trying to cross over its own body. When this happens, the player loses the game. Detecting these occurrences is surprisingly simple. While checking if the coordinates of the snake are greater than 7 would do (since negatives on an unsigned integer result in 0xFF), this would cause a frame where the player has gone off the screen but hasn't lost. This is fine, but easily solved. Instead, the code checks if the player is at a boundary and trying to go past it. To check if the snake is attempting to cross itself, the `moveHead` function checks to see if the LED it is trying to turn on is already on. If that bit in the array is zero, then it is not going to crossover with itself. The only thing to be wary of is the apple, which sets an LED on that is not a part of the snake. To work around this, the code first checks if the head is going to be on the apple. If it is, it ignores the lose function and sets the `appleEaten` boolean to true.

Button Detection

There are four buttons paired with each possible direction. Instead of polling each button to see if anything action has occurred, all the inputs have been tied to an external interrupt pin with diodes. This allows the MCU to know instantly when an input has occurred. Then, on the next iteration of the loop, the `btnPress` boolean will be true, and it runs a function to poll the buttons and change the head direction accordingly. Each direction is tied to a certain bit position, so the raw reading can be put into the `headDir` register without needing to convert it in any way. To check if this new direction is attempting to backtrack, it is compared with to the previous direction using a clever algorithm. If the sum of the new and old directions equal to the sum of two opposing directions, it is attempting to backtrack. For example, $LEFT + RIGHT = 1$. If the sum of the new and old direction also equals one, then the snake must be backtracking. If this happens the new direction is scrapped, and the head direction is reverted.

Apple Spawning

Apples generate at random coordinates. To achieve this, an analog read is performed. This creates a ten-bit conversion value, but since it doesn't matter what the actual reading is, the lower byte is masked to show only the three least significant bits. These bits have the most variability and are stored into the apple's coordinates (operation occurs twice; once for X, once for Y). This spawn function is called once at the beginning, and then whenever the `appleEaten` boolean is set.

Reflection

This project was lots of fun for me. I've finally learned that I love intense coding challenges. Most of my previous project have involved complex parts, but this was simply an LED matrix and some buttons; the only challenge was the code. I loved solving the problems in C, and then porting my solutions over into assembly. This is my biggest software undertaking yet: 600 lines of AVR assembly code. Designing circuit boards is a fun, but stressful process. I enjoy it and wish to continue making boards through university. Surface mount PCBs are scary and had me worried that nothing would work. The idea of a flexible circuit is still crazy to me. As of writing this report, it does not work on the PCB, but I honestly think I still have a shot if I solder another (the LED matrix on the current one seems like a fluke to me).

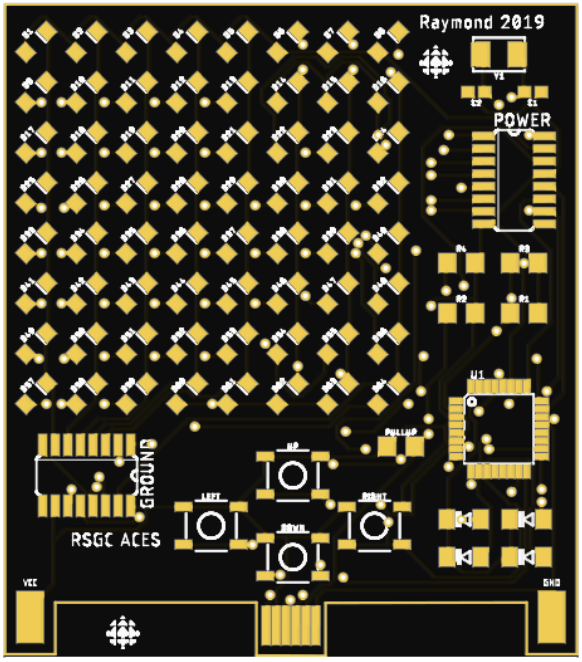
Code

This is the main function of the ASM. See my Github for the C and the full ASM programs.

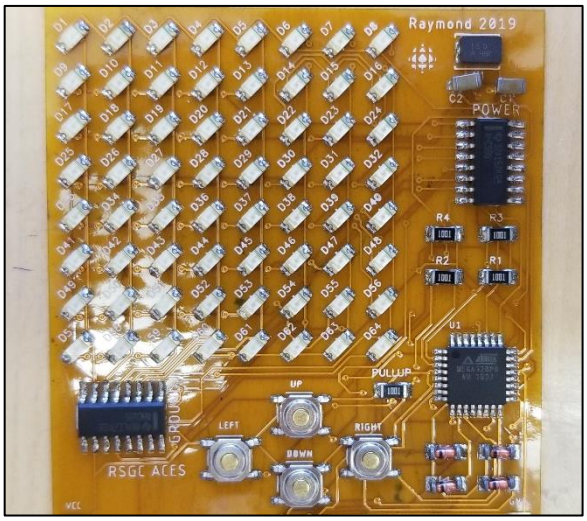
```
reset:
      ldi    util,  (PLtch | PData | PClk | Gltch | GData | GClk)
      out    DDRB,  util                        ; Sets all of the SR pins to output
      call   initVar
      call   initArray

      cli                                       ; Disable global interrupt system
      call   T1Setup                            ; Sets up the hardware and timer ints.
      call   INT0Setup
      sei                                       ; Re-enable global interrupt

      call   spawnApple                         ; Spawn the first apple in the game
  loop:
      ldi    ZH,    high(btnPress)              ; if INT isn't triggered, don't poll
      ldi    ZL,    low(btnPress)               ;      "
      ld     data,  Z)                          ;      "
      tst    data                               ;      "
      breq   skipChangeDir
             call   changeDir                   ; Otherwise, change the direction
      skipChangeDir:
      ldi    ZH,    high(snakeMove)             ; Check if the timer has triggered
      ldi    ZL,    low(snakeMove)              ;      "
      ld     data,  Z                           ;      "
      tst    data                               ;      "
      breq   skipUpdate                         ;      "
      ldi    ZH,    high(gameOver)              ; if the game is over, don't update
      ldi    ZL,    low(gameOver)               ;      "
      ld     data,  Z                           ;      "
      tst    data                               ;      "
      brne   skipUpdate                         ; If not, it's time to update the page!
             ldi    util,  FALSE                ; Set the snakeMove boolean to false
             ldi    ZH,    high(snakeMove)
             ldi    ZL,    low(snakeMove)
             st     Z,     util
             call   moveHead                    ; Move the head in the correct dir

             ldi    ZH,    high(appleEaten)     ; If an apple is eaten, skip the tail
             ldi    ZL,    low(appleEaten)      ;      "
             ld     data,  Z                    ;      "
             tst    data                        ;      "
             brne   skipTail                    ;      "
             ldi    ZH,    high(gameOver)       ; If the game is over don't move tail
             ldi    ZL,    low(gameOver)
             ld     data,  Z
             tst    data                        ; If the game is over, skip the tail
             brne   skipTail
             call   moveTail                    ; Function that moves the tail
         skipTail:
             call   updateLength                ; Update the position variables
                                                ; (Movement index, snake length, etc)
      skipUpdate:
      call          shiftArray                  ; Constantly displays LEDs array
  rjmp loop
rjmp   reset
```

Media

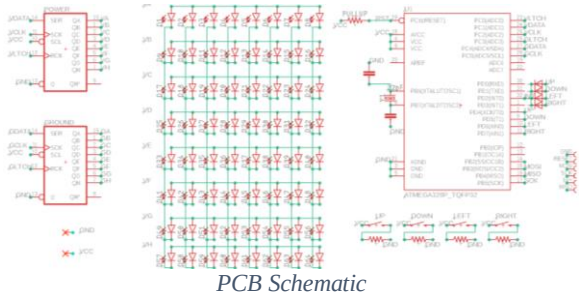
Video: https://youtu.be/lHQrBdLFWxc



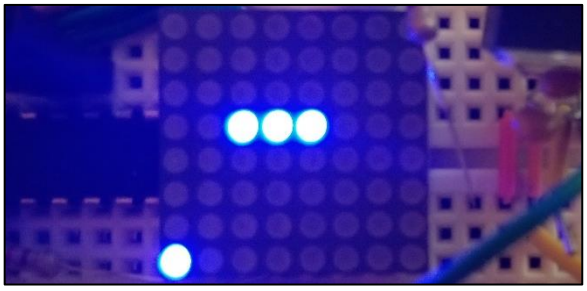
PCB Board in Eagle



Soldered PCB



PCB Schematic



Snake in action

University of Waterloo

System's Design Engineering

Project 17. Vibeify: A Personalized DJ

Purpose

This is a frontend project that allows users to control the music that they play based on the mood of the room. The camera tracks motion and the more people move, the more hype music gets played. The creation of this project took place at QHacks 2020 with Cameron Raymond, Ross Hill, and Aaron Jiang.

Reference

Github Repository: https://github.com/rosslh/vibeify
Devpost: https://devpost.com/software/vibeify
Posenet: https://www.tensorflow.org/lite/models/pose_estimation/overview

Theory

User Experience

The user is first shown a login page. This website uses Spotify to find music and as a result the user must have an account for it to function. This passes complete control over to the Spotify API until the login is successful. The user is then presented with a live video of themselves with the Posenet figure superimposed on their body, and the current energy level of the room. The user can choose what music should play by selecting the music icon, and control the music using the panel at the bottom of the screen.

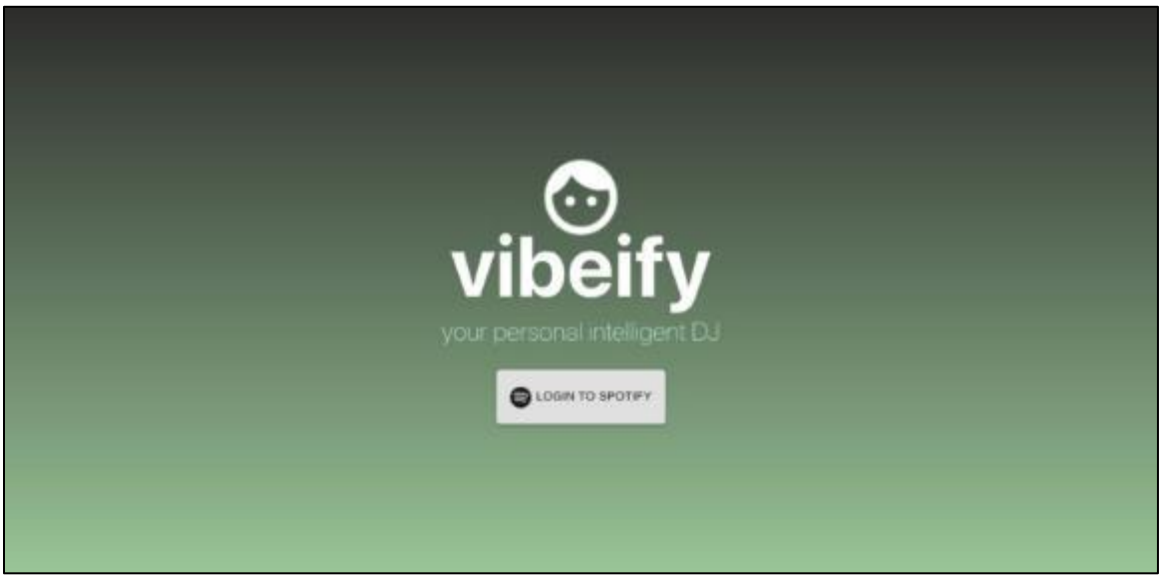
Motion Tracking

The first step is to be able to track the position and the ultimately speed of multiple users in a room. This is achieved using the device's camera and a pretrained neural network made by Google called Posenet. This model places up to eight nodes on an image of human body: four for the torso and one for each limb. The wonderful thing about this model is that it can handle multiple people at a time. To calculate the speed of everyone, a vector is made for each person that is comprised of all the node coordinates. At each timestep, the cosine similarity is computed which gives an estimation for the change in body position. The amount of change is recorded for each person recorded by the camera and a rolling average is computed; this is the total energy of the room.

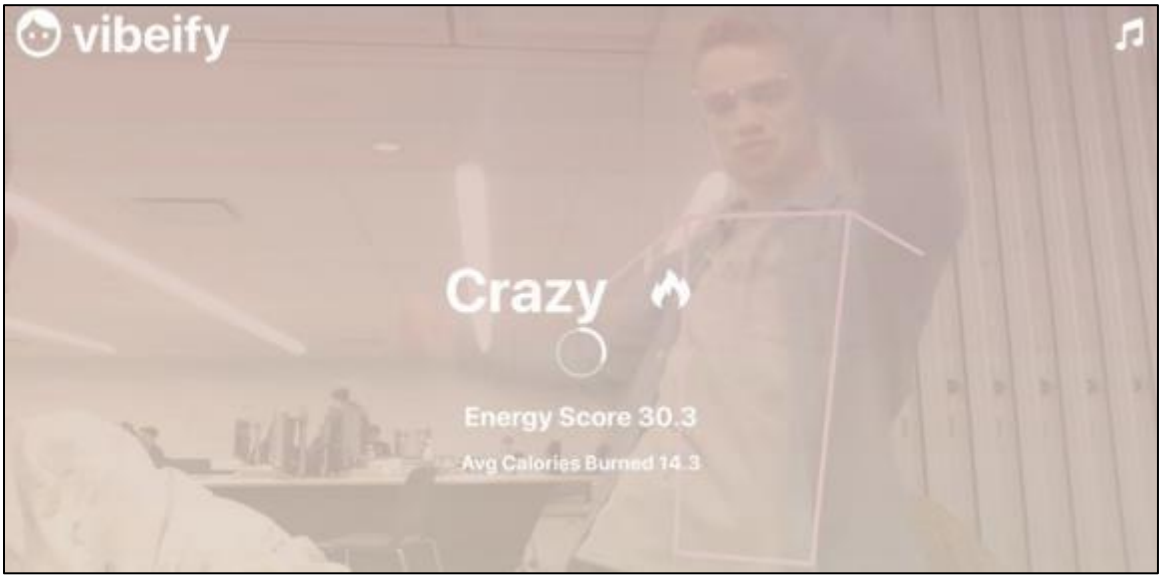
Spotify API

Once the user logs in, an API call is made to retrieve all their playlists. This is then displayed to the user so they can select which playlists can contribute to the pool of songs that could be played during the session. Thanks to Spotify, each song comes with metadata about its dance-ability, energy, and more. The vibe of the room is linearly compared to the energy of the song and the best match is chosen to play next.

Media



Spotify login page



Reaching the highest energy state: Crazy

Reflection

Although I have endeavoured to build other frontend and full stack projects, this was the first that aimed at creating a real-life product. This incorporated many different concepts and overall was a huge success. The unlikely team of Cameron, Ross, Aaron, and me was very well coordinated and wonderful to work with.

Code

For a full outline of the code, view the Github repository. Below is a React/JavaScript snippet that controls the cosine similarity, comparing the previous position to the current one.

```
cosinesimilarity(prevPoses, currentPoses) {
    if (prevPoses == null || currentPoses == null) {
      return 1;
    }
    // A list of lists - each element is a vector of an individual's position
    let prevPosesMatrix = [];
    prevPoses.forEach(({ score, keypoints }) => {
      let prevVec = [];
      if (keypoints !== undefined) {
        keypoints.forEach(({ score, part, position }) => {
          prevVec.push(position.x);
          prevVec.push(position.y);
        });
        prevPosesMatrix.push(prevVec);
      }
    });
    let currentPosesMatrix = [];
    currentPoses.forEach(({ i, keypoints }) => {
      let currentVec = [];
      if (keypoints !== undefined) {
        keypoints.forEach(({ i, j, position }) => {
          currentVec.push(position.x);
          currentVec.push(position.y);
        });
        currentPosesMatrix.push(currentVec);
      }
    });
    let cosinesimilarities = 0;
    for (let ind = 0; ind < prevPosesMatrix.length; ind++) {
      if (ind < currentPosesMatrix.length) {
        cosinesimilarities += similarity(
          prevPosesMatrix[ind],
          currentPosesMatrix[ind]
        );
      }
    }
    let avg = cosinesimilarities / prevPosesMatrix.length
    return Number.isNaN(avg) ? 1 : avg
  }
```

Project 18. Andro: A Breadboard AI Processor

Part A. Training & Simulation

Purpose

This is the first step in creating an independent piece of circuitry that can compute the output of a neural network. The model and input data are loaded onto the memory of the device and the multiplication and addition are performed without a single line of code. There are a few restrictions to this device to reduce the complexity; it only accepts sequential models, only dense layers, no biases or activation functions, and every input and weight must be one bit (-1 or 1). This part focuses on training a model using the MNIST dataset that can be used to test the device and simulating the full structure of the device so a parts list can be made.

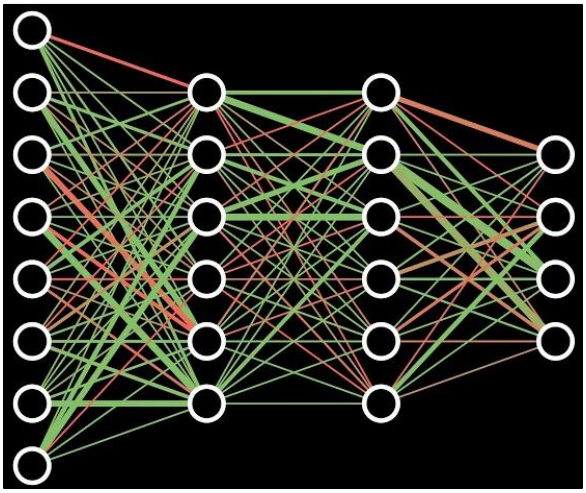
Reference

Github Repository: https://github.com/draymond63/Andro
Quantization: https://www.tensorflow.org/model_optimization/guide/quantization/training

Theory

Sequential Dense Layered Networks

Sequential neural networks are generally comprised of a sequence of layers. The layers take a vector (or matrix) of inputs and perform a computation to compute a new vector (or matrix). The goal is for the final layer to produce an output with a tangible meaning. For example, this could be a classification model, where each node corresponds to the likelihood of the input belonging to a given class.



Sequential Dense Layered Network (courtesy of 3Blue1Brown)

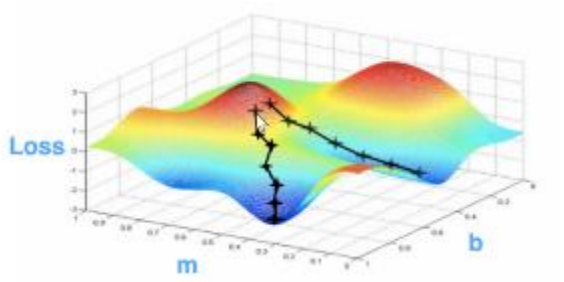
Dense layers are comprised of a series of nodes which can store the result of a computation. Each node in a given layer is connected to every node of the previous layer. The vector of inputs is dotted with a vector of weights. Weights are unique to every node-input connection but remain constant once the model is finished training. Biases are constants that are optionally added to each node after the weight multiplication to control the strength of a given node. Because of this vector-like representation, dense layers are often thought of as a matrix multiplication that transforms the input vector.

Quantization

Typically, weights and biases are 32- or 64-bit floats. When a model has thousands of these, its footprint quickly grows. Quantization is the process of reducing the size and increasing the speed, at the expense of accuracy. It can affect the input data, the weights, or even the nodes after they are calculated (or all three). 8-bit quantized models can typically perform the same computation with comparable accuracy of a 64-bit float model, but as the bits decrease the accuracy takes even more of a toll. In the extreme, every number is represented with one bit only; these are binarized neural networks (BNNs). For reasons that are beyond the scope of this report, BNNs have better accuracy when zero represents negative one instead of zero. The circuit that is being implemented requires a 1-bit quantized input and model (weights). After the computation of a single node, the value is converted to zero (negative one) or one depending on its sign.

Training

The type of optimizer used in this project is called stochastic gradient descent. This involves giving the model a sample of inputs and comparing its outputs to the correct answers. The goal now is to reduce the error as much as possible. To do this a scalar function is created with every single piece of trainable data (weights, biases, etc.) as the independent variables and the error as the dependent variable. Increasing the model accuracy involves trying to minimize this function. So, all the partial derivatives are taken (called the gradient) and the weights are changed slightly in the negative direction: in essence, descending towards a local minimum of error. Since there are many multiple local minimums and we would like to find the best one, a bit of randomness is thrown into the mix.



Error function visualized with 2 weights (m & b)

Most quantized neural networks involve training the model with full precision floats and then converting all the values after, aptly named post-quantization. However, BNNs are so drastic in their reduction that often the model is rendered completely useless by the process. To fix this, the training is made aware of the post-quantization and runs tests for quantized accuracy.

Simulation

The final phase of part A involves simulating the circuit to determine the correct parts to buy. Online resources such as TinkerCAD and Falstad are too restrictive, so a custom python library is made. This gives complete control over the chip designs; there are classes for each chip and one special one names "pins." When a pin is wired to an input, the input will always update to reflect it. Pins have two main internal variables, *value* and *raw*. *Value* is an array of the bits made up by each wire in the pins, whereas *raw* is the decimal value. The setter functions cause both to update so they are always consistent. Multiplexors, EEPROMs, logic gates, binary counters, up down counters, and much more are all simulated in this library.

Code

This is a snipper from "AndroD4" which uses the bitwise operators and data to predict the image. For more detail or other deconstructions, see the Github Repository or the procedure.

```
# Functional model that takes in an image and guesses the number (mnist)
def model(image):
    input_layer = image
    num_layers = len(shape) - 1
    for l_index in range(num_layers): # One less: not including the input layer
        prev_size = shape[l_index]
        # Keep track of current layer
        curr_size = shape[l_index + 1]
        curr_layer = []
        curr_packed_nodes = 0
        # Last layer isn't quantized
        last_layer = True if curr_size == shape[-1] else False

        for node in range(curr_size):
            accum = 0
            for w_index in range(prev_size):
                EEPROM_addr = w_index >> 3  # 3 LSBs are for bit selection
                bit_index = w_index & 0b111 # Mask away all but lowest three bits

                # Select bit weight and input data
                # print(bin(weights[l_index][node][EEPROM_addr]))
                weight = weights[l_index][node][EEPROM_addr] & ( 1 << bit_index )
                data = input_layer[EEPROM_addr]              & ( 1 << bit_index )
                # Multiply and add
                mult = XNOR(weight, data)
                accum = UpDown(accum, mult) # * Breakpoint here to match D5
            # Save node in some form
            if not last_layer:
                # Quantize (Grab MSB)
                MSB = getMSB(accum)
                val = NOT(MSB)
                # Store value by bit packing again
                curr_packed_nodes |= val
                # If 8 nodes have gone by, packed weights together
                if (node + 1) % 8 == 0: # Don't start with appending
                    curr_layer.append(reverseByte(curr_packed_nodes))
                    curr_packed_nodes = 0
                else:
                    # Shift bits to make room for the next node
                    curr_packed_nodes <<= 1
```

```
            # Last layer is not quantized
            else:
                curr_layer.append(accum)

        # Make sure size is appropriate
        if not last_layer:
            EEPROM_size = curr_size >> 3
            # Current layer is going into the previous
            input_layer = curr_layer
        else:
            EEPROM_size = curr_size

    # Return actual guess instead of encoded logits vector
    # print(curr_layer)
    answer = curr_layer[0] # Start off guessing it is zero
    index = 0
    for i, challenger in enumerate(curr_layer):
        if challenger >= answer:
            answer = challenger
            index = i
    return index
```

Procedure

The model files are setup to gradually deconstruct the neural network into bitwise operators and eventually hardware. There are five in total:

1. Trains the neural network and saves all its weights into a 2D python list.
2. Confirms that a Tensorflow model can be reconstructed from the saved weights.
3. Uses pure NumPy to perform all the model calculations.
4. Uses the fully quantized, bit-packed weights along with bitwise operations.
5. A full-blown simulation of the circuitry with the custom library.

There are also files a few extra files to help with processing. One is made that perform the bit-packing, since all the bit weights and MNIST images are packed into bytes to be stored on the EEPROM. Another visualizes the input images using matplotlib.

Reflection

This is the first project where I am building a custom processor from the ground up. The idea started as inspiration from my time working at Untether AI. I have never made such a complicated block diagram before and I am excited to implement the circuitry. This project has also inspired me to invest in many personal tools, so the bank account has taken a significant hit.

Part B. Circuit Design

Purpose

This section explains the block diagram in much more detail, showing how the overall circuit will function. This is all theory; for the implementation of the design and the specific of the ICs used, view later sections. For a simpler explanation, visit my website.

Reference

Website: https://danielraymond.me/#/bnn

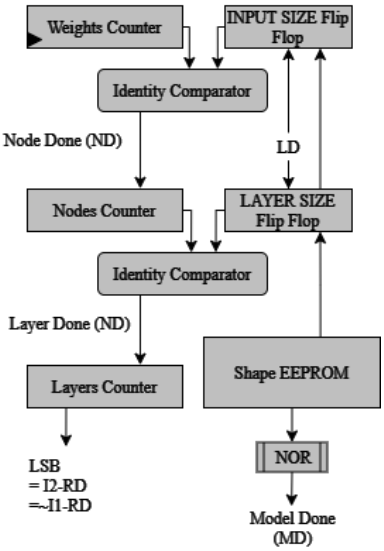
Theory

Overview

To begin there is a model that is stored on an EEPROM. Each bit represents one weight and thus are packed into bytes. At each clock cycle a single bit (weight) is parsed out and multiplied by a bit of input data, which is also packed into bytes on another EEPROM. These results of this multiplication are added together until a single node has been computed. The sign is taken and stored into a 3rd EEPROM for use in the next layer. Once every node in the layer is computed, the input switches to this third EEPROM and the next layer of weights is used. This result gets stored into the previous input EEPROM. On the last layer, the output is not quantized but is instead stored in a different and final chunk of memory. This circuitry activates after everything else is done, selects the largest node output and stores its value and index into two flip flops.

Program Counters

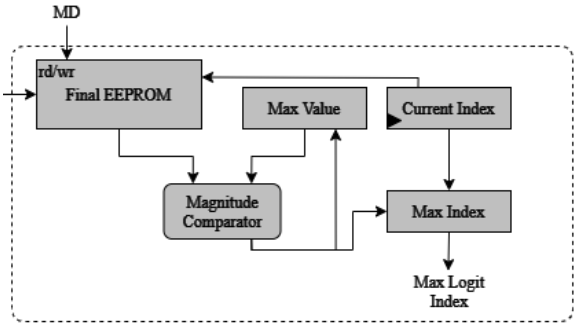
There are three main counters in this circuit which all follow a similar structure. The weight counter increments every clock cycle, indicating that a new weight has been added to the current node. The entire circuit knows that this computation is finished when the weight counter (*WC*) is equal to the length of the input vector. When this is signaled by the output of a comparator, named *Node Done*, going high. This signal is tied to the clock of the node counter (*NC*), which causes it to increment. The exact same setup is for *NC*, except it is compared to the current layer size. The layer counter increments when *Layer Done* goes high. The layer size and input size are chained to yet another EEPROM that contains the shape of the model. When the output of this is all 0's, we raise *Model Done* to signal that the final logits have been calculated.



Memory-Multiplier

There are three EEPROMs involved in the computation of the model. For the weight EEPROM, a certain number of address lines are dedicated to cycling through the weight bytes of a given node, then a few more to cycle through the nodes, and then more still to cycle through the layers. Each byte, containing eight weights, is held for eight clock cycles so an 8-1 multiplexor can cycle through each bit. Similarly, the two input EEPROMS have their own 8-1 mux's, except their output is decided between with a 2-1 mux. The selected input and weight are XNOR'd together; this simulates multiplication of -1 and 1, where 0 represents -1. This value is then connected to an up down counter to implementing incrementally adding and subtracting by one. The MSB of this counter, which represents its sign, is NOT'd (since a 1 means it's negative which is the inverse of needs to be stored) and sent to a shift register where it is packed into eight bits and loaded into the next available EEPROM byte.

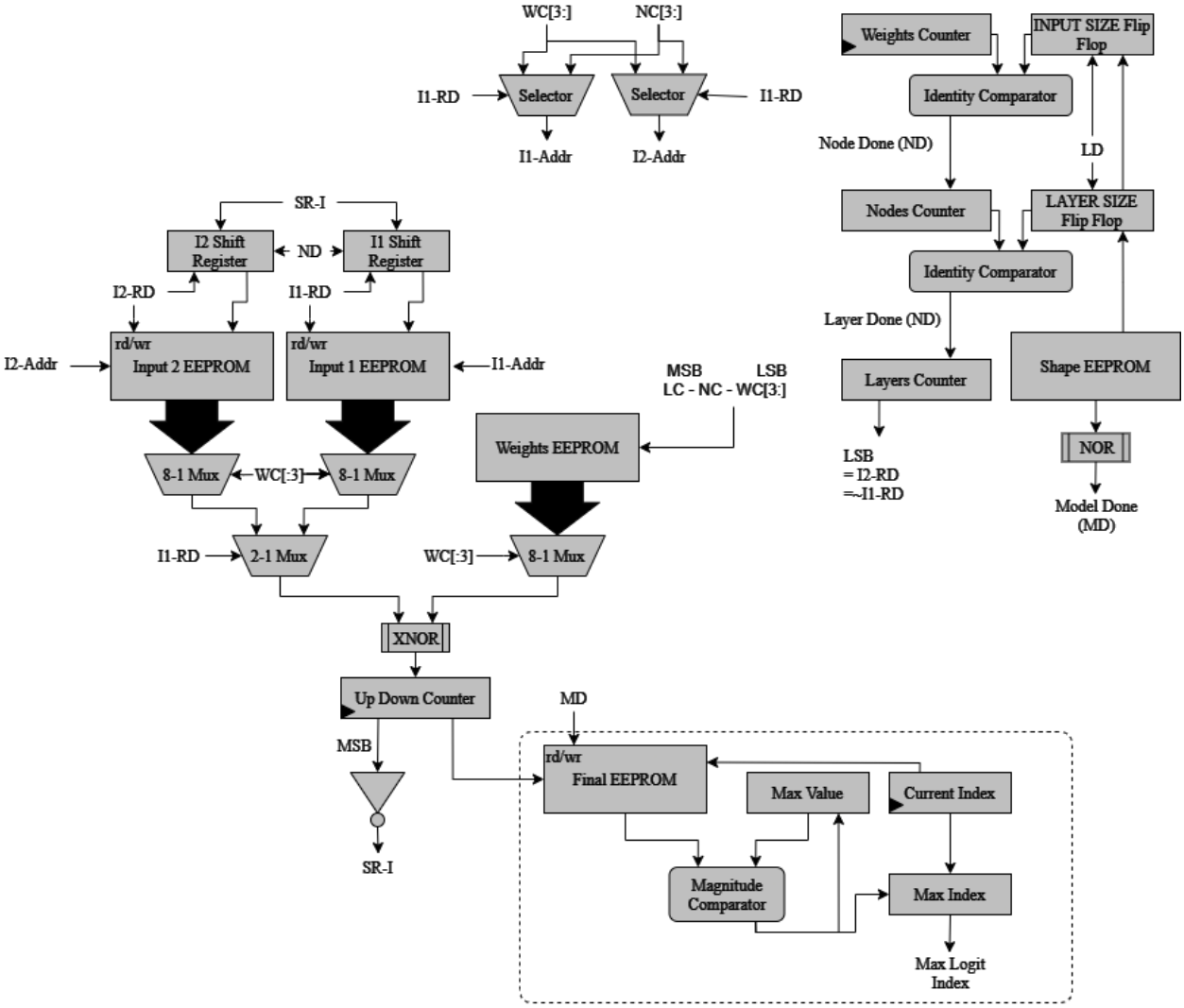
Max Logit Selectors



This circuit begins reading from the final EEPROM once the model is finished its calculation. On each clock pulse the current index counter increments and the next logit is displayed. This is compared with the maximum value; if it is larger, the magnitude comparator sends a signal to the max value & index registers to update. This is iterated until the current index is equal to the layer size. The final maximum index is going to be displayed on a seven-segment display which, for the MNIST dataset will be the prediction of the neural network.

Media

Putting all together, this is the final block diagram:



Total Block Diagram

Reflection

This is the result of many iterations of design. While the result may seem lackluster, there is already some very complex circuitry that is at play. I hope that this design will be successfully implemented sometime soon!