ESE 1500 – Lab 08: Machine Level Language

LAB 08

In this lab we will gain an understanding of the instruction-level implementation of computation on a microprocessor by:

1. Using ItsyBitsy to perform the Fourier Transform on sampled data in the time domain, converting it to the frequency domain.
2. Timing your Fourier Transform to see how long the operation takes to perform.
3. Calculating number of cycles each instruction takes and calculating the time of execution using the assembly file.

Background:

Let us learn first what an .elf file and a .hex file are.
ELF is an acronym for Executable Linking Format. Files that contain the .elf file format are system files that store executable programs, shared libraries and memory dumps.
A HEX file is a hexadecimal source file typically used by programmable logic devices.
.elf and .hex files are both generated in the process of uploading Arduino code to the device.

In this lab you will be compiling Arduino code, which generates a .elf file. We will then generate assembly code from the .elf file to observe how your code works at the processor instruction level. You will see which instructions get executed in what order and how many times. This will give you an idea of which instructions take longer time and how to reduce your execution time.

In previous labs we've performed DFT for various applications without thinking about the implementation. We have had programs which run for several seconds and sometimes minutes!
Now we will look deeper at how the machine executes your program and how much time that takes.
From your lecture, you know what processor instructions are and how to read them. Let's work with them to understand the execution time of your program.

Prelab: Obtaining the Assembly code

- In this section, we'll compile our Arduino code and obtain the location of a temporary .hex file
- We'll convert the .hex file to assembly code.
- As a note, we highly suggest you to use your personal computer for the lab, Detkin computers did not work well when we were testing the lab out.

Optimizing our code requires that we view the generated machine code (hex) in assembly language. This allows us to know how things work at the instruction level. When we review assembly code we understand how the computer's hardware works and functions on a low-level. This allows us to calculate how many clock cycles each instruction takes and how to optimize our code/logic to achieve faster execution. Make sure to read the entire lab as a part of the pre-lab (including the description of ARM instructions in the Appendix).

1. We assume you have already downloaded the Arduino IDE and configured it for the Itsy Bitsy. Instructions are in Lab 1, Prelab, Step 3. Or you can run the Arduino IDE on the workstations in Detkin.

2. We will be compiling the code to compute the Fourier Transform of a discrete sample data and detect the peak frequency present in it. Go over the code (listed in next step) and understand the math behind it.

3. Paste the following code in the Arduino IDE and name your file FT_PeakDetection or open the file provided from the syllabus:

```
#define FFT_ABS_THRESHOLD 200
// may need to lower FFT_ABS_THRESHOLD if input magnitude is low
#define MAX_SAMPLES 256 //make it a power of 2
#define SAMPLING_TIME 0.00002 //Amount of time between samples
#define pi 3.1416
#define scale_factor 100
#define ADC ADC0
int samples[MAX_SAMPLES];
boolean samplesReceived = false;
int sineref[MAX_SAMPLES];
int cosref[MAX_SAMPLES];
long ask;
long ack;
double freq[MAX_SAMPLES];
double samp_freq;
```

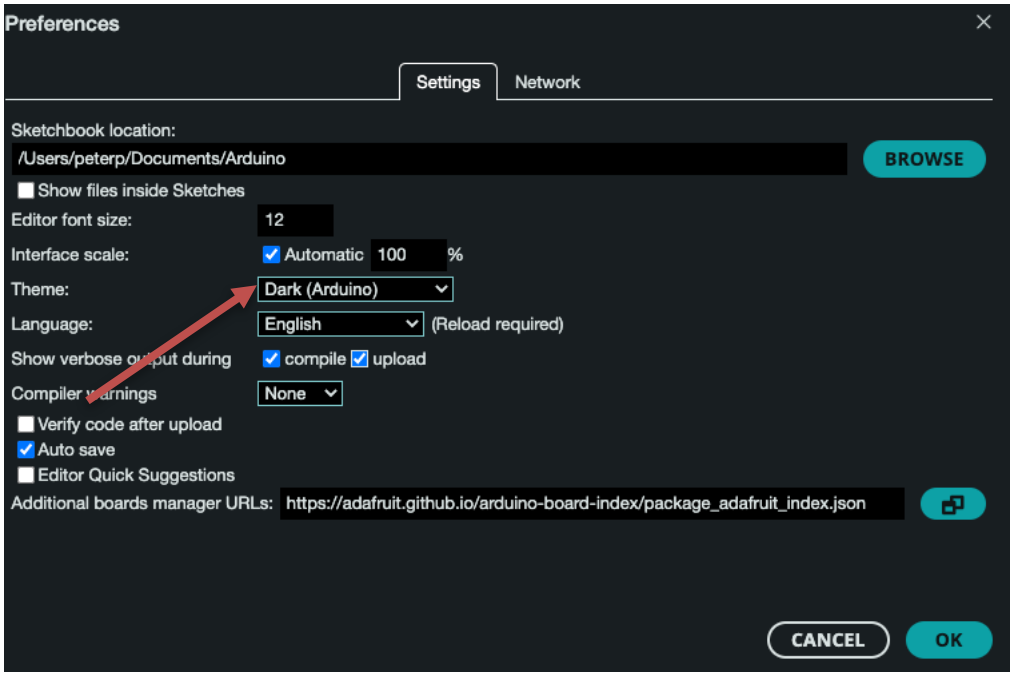
```
int i;
int k;
double fft_abs;
void setup() {
  Serial.begin(9600); // setup serial monitor speed
  while (!Serial); // wait for serial to be ready
  Serial.println("Hello World;");
  pinMode(A0, INPUT_PULLUP);
  ADC -> CTRLA.reg &= 0b1111100011111111; // mask PRESCALER bits
  ADC -> CTRLA.reg |= ADC_CTRLA_PRESCALER_DIV16; // divide Clock by 16 (original was 64)
  // this PRESCALAR does appear to impact sample rate...smaller divider ... faster sample
  ADC -> AVGCTRL.reg = ADC_AVGCTRL_SAMPLENUM_1 | // take 1 sample
  ADC_AVGCTRL_ADJRES(0x00ul); // adjusting result by 0
  ADC -> SAMPCTRL.reg = 0x00;
  samp_freq = 1 / (SAMPLING_TIME + 0.0000185); // Includes ~analogread delay
}
long dotproduct(int length, int * a, int * b) {
  long sum = 0L; // Initializing long
  for (int i = 0; i < length; i++) {
    sum += (long) a[i] * (long) b[i]; //type casting
  }
  return (sum);
}
void loop() {
  for (int i = 0; i < MAX_SAMPLES; i++) {
    samples[i] = analogRead(A0); // read input from A0
    delayMicroseconds(SAMPLING_TIME * 1000000);
    samplesReceived = true;
  }
  if (samplesReceived) {
    for (int i = 0; i < MAX_SAMPLES; i++) {
      Serial.println(samples[i]);
    }
    for (k = 0; k < (MAX_SAMPLES/2); k++) {
      for (i = 0; i < MAX_SAMPLES; i++) {
        sineref[i] = (int)(sin(2 * pi * k * i / MAX_SAMPLES) * (1 << 10)); //sine and cosine samples will be
            between -1 and 1, so multiply those by 2^10 and round
        cosref[i] = (int)(cos(2 * pi * k * i / MAX_SAMPLES) * (1 << 10));
      }
      ask = (dotproduct(MAX_SAMPLES, samples, sineref)) / (MAX_SAMPLES * scale_factor); //scaling it
      ack = dotproduct(MAX_SAMPLES, samples, cosref) / (MAX_SAMPLES * scale_factor);
```

```
    freq[k] = k * samp_freq / (MAX_SAMPLES - 1);
    fft_abs = abs(ask) + abs(ack); // abs returns the modulous

    if (fft_abs > FFT_ABS_THRESHOLD) {
      Serial.println("Peak found at ");
      Serial.println(freq[k]);
      Serial.println("  peak absolute value: ");
      Serial.println(fft_abs);
    }
   }
   while (1); //Run code once
  }
}
```

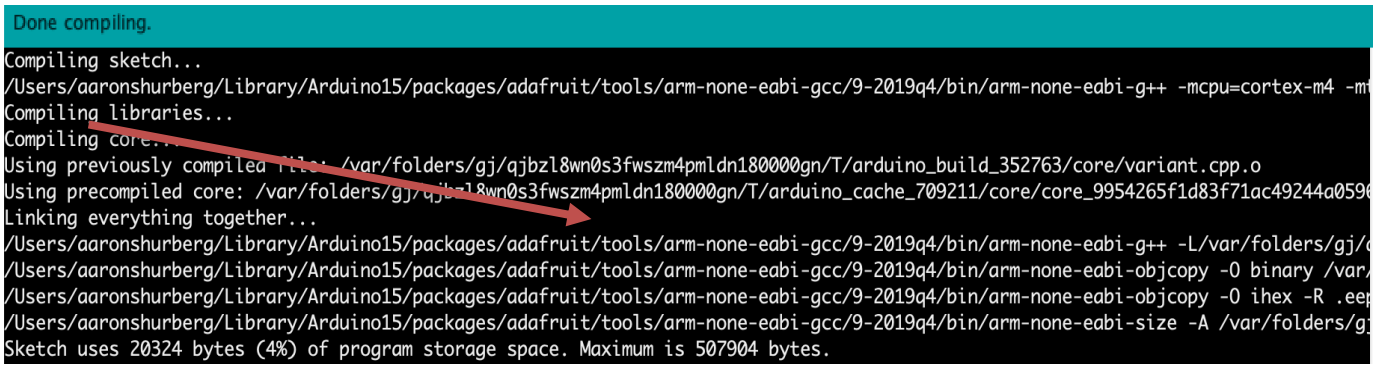
In the next few steps (5-12 or 13—20), we will be (a) finding the binary elf file produced by compilation, (b) finding where the objdump binary is on your system, and (c) running objdump on your elf file to produce machine-level assembly code. The resulting assembly code is the assembly version of the Fourier Transform function you pasted into the Arduino IDE.

4. For MacOs follow steps 5 through 12.
   For Windows (including Detkin Windows machines) skip to step 13.
   Before compiling, make sure to select the Arduino ItsyBitsy M4 (SAMD51) in the Tools bar of the Arduino IDE
5. Now to see compiler outputs, do the following to change the settings of the Arduino IDE:



6. Enable “Show Verbose Output during Compilat1 ion and Upload”.

7. Now, compile (verify) your code to see the output files (ELF, BIN, HEX files).
8. Once you compile you will see something like this:



The directory referenced in the first photo, /Users/aaronshurberg/Library/Arduino15/packages/adafruit/tools/arm-none-eabi-gcc/9-2019q4/bin/ contains a file called **arm-none-eabi-objdump** which will be used in step 9. Scroll right to see the .elf file's location. This location will be specific to your machine (Aaron Shurberg is the name of a previous TA).

The directory referenced in the second photo, /var/folders/gj/qjbzl8wn0s3fwszm4pmldn180000gn/T/arduino_build_352763/FT_PeakDetection.ino.elf, is where the elf file is stored. This one is again specific to your machine. Please check your Arduino IDE output to check exactly where it is.

   a. If you have trouble finding either path it may be easier to copy the output to a text editor and search around for it.
   b. Click anywhere on your desktop that is empty. Find "Go" in the menu bar and "Go to Folder".
      i. For finding arm-none-eabj-objdump, type /Users/YOUR USERNAME/Library/Arduino15/packages/adafruit/tools and search from there.
      ii. For finding FT_PeakDetecdtion.ino.elf, type /var/folders/ and manually follow the path from here from what your Arduino output says.

9. Now navigate to your desktop (cd ~/Desktop) or wherever you choose to store the lab files in terminal.
   a. Create a new directory: `mkdir lab8`
   b. Change into that directory: `cd lab8`

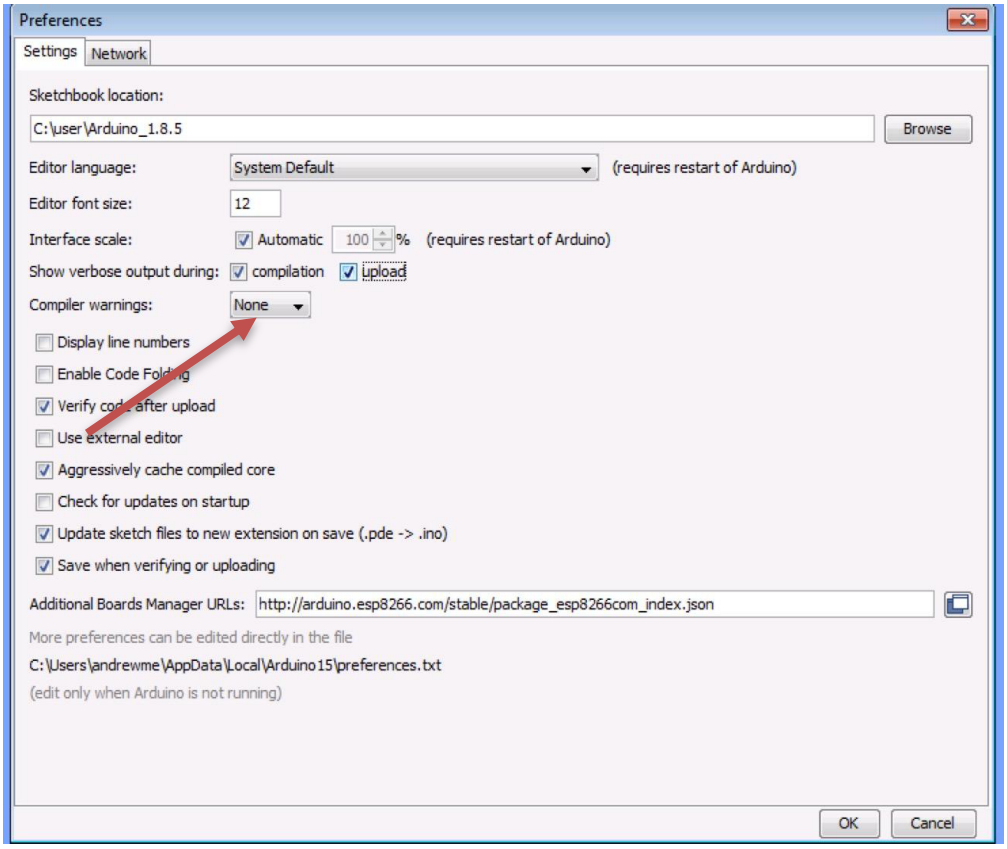
10. Now, generate the assembly file. You want to call the objdump binary that you found with the elf file you found as one of the arguments. Type the following (one long command line) in the terminal press enter: /Users/aaronshurberg/Library/Arduino15/packages/adafruit/tools/arm-none-eabi-gcc/9-2019q4/bin/arm-none-eabi-objdump **-S** /var/folders/gj/qjbzl8wn0s3fwszm4pmldn180000gn/T/arduino_build_352763/FT_PeakDetection.ino.elf **> d.txt**

    Here you should replace the location with the specific locations you obtained from the Arduino console. You are able to drag the file, from its location into the terminal window and it should put the file's path in console. Also observe here, d.txt is the text file you're storing the assembly code in, and FFT_ ESE150Lab8.ino.elf is the name of your Arduino file.

    This command (">") is redirecting stdout to a text file called "d.txt".

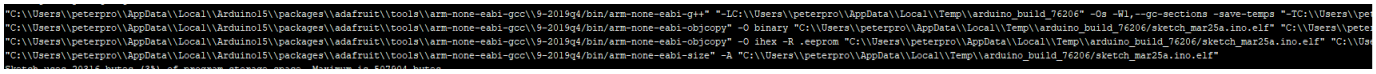
Note: There are other ways to generate the assembly code, and some applications do it for us by taking in the elf file. For more information on this you can refer to the link below as an example.
https://sourceforge.net/projects/arduino-to-assembly-converter/

    a. Note if either of your paths contain spaces, then wrap the entire line of text in quotes (‘’).

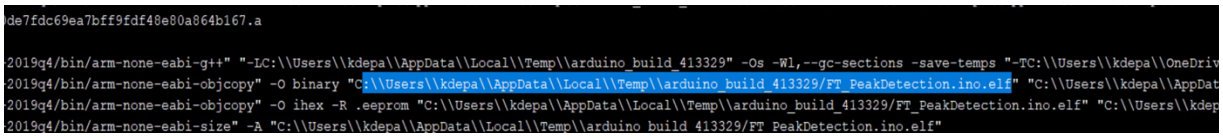
11. The file d.txt should now be saved in the directory from step 8.
    a. This file should be included in the prelab canvas submission
12. You can now skip to step 21.
13. 

    Go to File->Preferences and then enable "Show Verbose Output during Compilation and Upload".
14. Now, compile your code to see the output files (ELF, BIN, HEX files).

15. Once you compile you will see something like this:

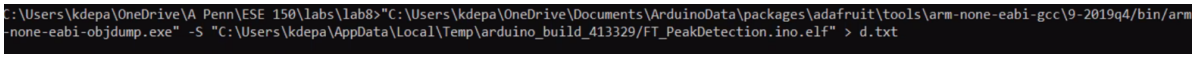


16. The directory "C:\Users\peterpro\AppData\Local\Arduino15\packages\adafruit\tools\arm-none-eabi-gcc\9-2019q4\arm-none-eabi\bin/" contains a file called arm-none-eabi-objdump which will be used in step 19. The .elf's location is to the right. This location is specifc to your machine. Look in the output carefully to find the location.
17. Note the directory ("C:\Users\kdepa\AppData\Local\Temp\arduino_build_413329") where the FT_PeakDetection.ino.elf is stored highlighted below:



    a. If you have trouble finding either path it may be easier to copy the output to a text editor and search around for it.

18. Now navigate to your Documents (cd C:\Users\kdepa\Documents) or wherever you choose to store the lab files in a Command Prompt terminal (search in the Start Menu if you don't know where to find it)
    a. Create a new directory: `mkdir lab8`
    b. Change into that directory: `cd lab8`
19. Now let's generate assembly code from the .elf file generated. You want to call the objdump binary that you found with the elf file you found as one of the arguments. Run the following (one long command line) in the command prompt:
    C:\Users\kdepa\OneDrive\Documents\ArduinoData\packages\adafruit\tools\arm-none-eabi-gcc\9-2019q4/bin/arm-none-eabi-objdump.exe **–S**
    "C:\Users\kdepa\AppData\Local\Temp\arduino_build_413329/FT_PeakDetection.ino.elf" **> d.txt**



    Here you should replace the location with the specific locations you obtained from the Arduino console. You can drag your file into the console window and it will put the file's location into the terminal. Also observe here, d.txt is the text file you're storing the assembly code in, and FFT_ ESE150Lab8.ino.elf is the name of your Arduino file.
    This command (">") is redirecting stdout to a text file called "d.txt".

Note: There are other ways to generate the assembly code, and some applications do it for us by taking in the elf file. For more information on this you can refer to the link below as an example.
https://sourceforge.net/projects/arduino-to-assembly-converter/

20. The file d.txt should now be saved in the directory from step 18
    a. This file should be included in the prelab canvas submission
21. **Now you have created d.txt with your assembly code in it!**
    Familiarize yourself with the assembly code.
    The more you look through it, the easier the lab will be.
    Include this code in your Prelab Canvas submission.
22. Go over the code and identify the sections associated with a line of Arduino C code.
    a) Search for third instance of the following (e.g. in the text editor Press CTRL+F and enter)

sineref[i] = (int)(sin(2 * pi * k * i / MAX_SAMPLES) * (1 << 10));
to see how this command is executed.

b) You will obtain something like this:

```
439e:      4630          mov    r0, r6
43a0:      f003 fdf2     bl     7f88 <__aeabi_i2d>
43a4:      a342          add    r3, pc, #264    ; (adr r3, 44b0 <loop+0x178>)
43a6:      e9d3 2300     ldrd   r2, r3, [r3]
…
```

Recall we looked at instructions like add in lecture. Going line by line:

i) "mov r0,r6" instruction moves r0 to r6.
ii) "bl 7f88 <__aeabi_i2d >" instruction sets PC to 0x00007f88 (calls subroutine)
iii) "add r3,pc, #264" instruction computes r3=pc+264
iv) "ldrd r2, r3, [r3]" instruction writes two words to memory simultaneously. That is address= signextend(r3), r2=Mem[address], and r3=Mem[address+4]

c) Look up the dotproduct:

int dotproduct(int length, int *a, int *b)

Hint: For the branch to the top of the loop, look for a branch that branches back to the code near the beginning of dotproduct().

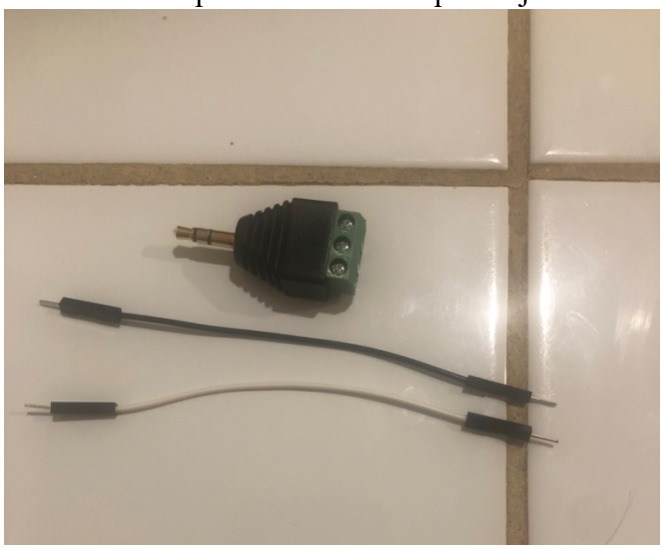
23. You will need these in Section 3 (and your report). Submit your raw code (10 or 19) and extracted code (dot product from 20c) to the Prelab assignment on Canvas.

Lab Procedure:

Lab – Section 1: Fourier Transform using Itsy Bitsy

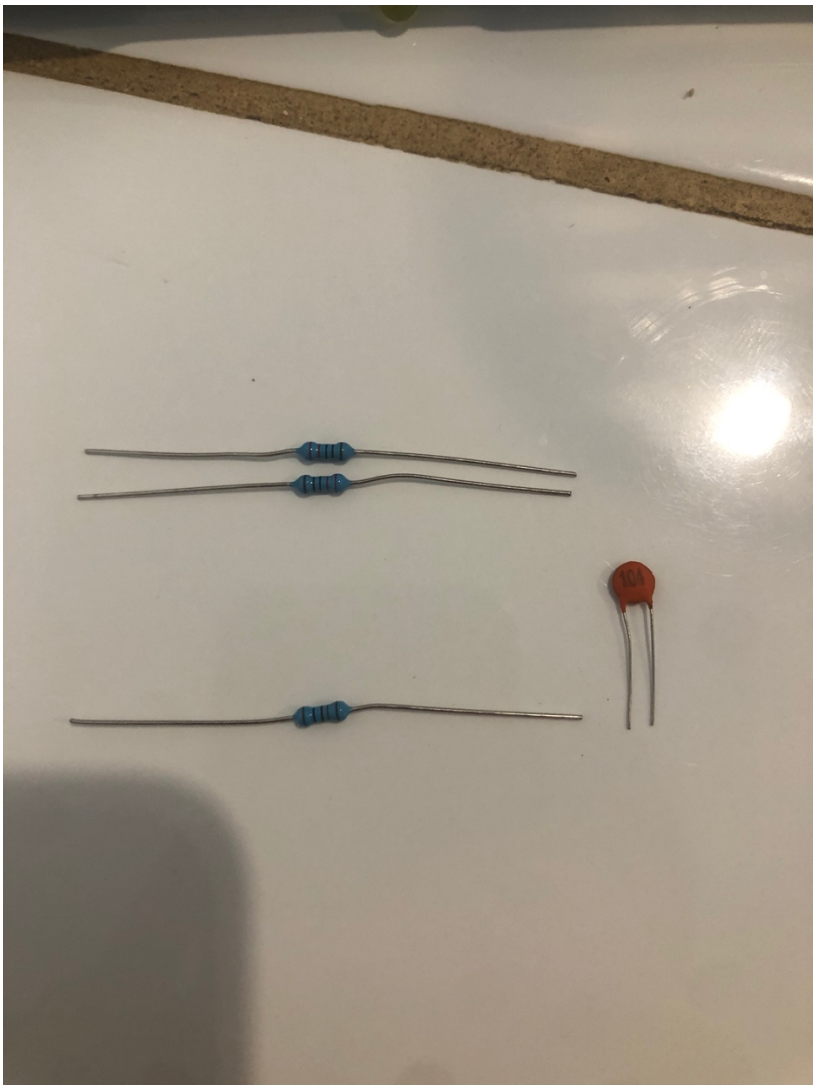
- In this section we'll use the Itsy Bitsy to compute the Fourier Transform of a signal and recheck the most prominent frequency.
- We will use the same circuit from Lab 1 as follows:

1. Grab the male headphone jack, a black wire (common convention used for ground) and any other wire of your choosing:
    a. We will use this headphone jack to sample audio that comes from your computer or phone.
    b. ***If your computer or phone does not have a standard female headphone jack, please let a TA know.***
    c. Below is a picture of the headphone jack and some wires.

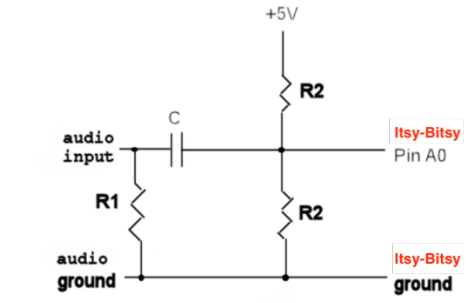


    d. Connect the black wire into the green socket on the headphone jack. This is the socket that is neither Left (L) or Right (R). The symbol you see is often used for ground. Ground is a reference point for any voltage reading. All readings are relative to ground.
    e. Next, connect the non-black wire into either the Left or Right socket. It shouldn't matter which one you choose. This wire will be considered as the audio input.
    f. Finally, connect the headphone jack to your audio source. This could either be your computer or your phone.
    g. So far, you should have something similar to the following picture:

2. Next, grab **2x 10K Ohm**, **1x 1K Ohm** resistor and **1x 100nF** capacitor:
    a. The resistors are the blue objects in the plastic bag. You can determine the value of the resistances by looking at the stamp near the bottom of the holding bands. It is important that you do not lose track of which resistors are which, so that you can reuse them in the future.
    b. The 100nF (aka 0.1uF) capacitor is the red object in the plastic bin with a 104 label.
    c. Here is a picture of the components:



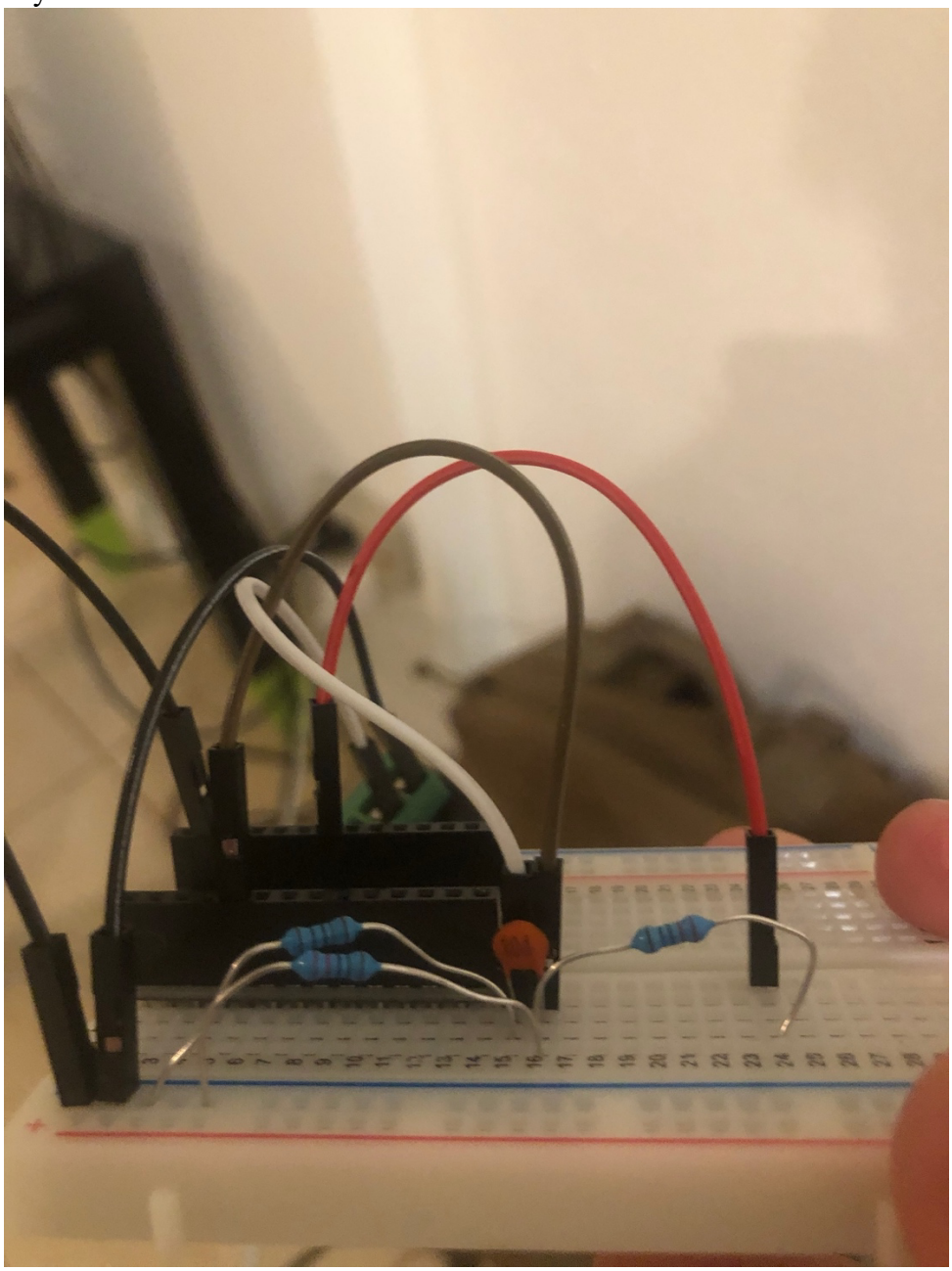
3. A diagram of the circuit you will build:



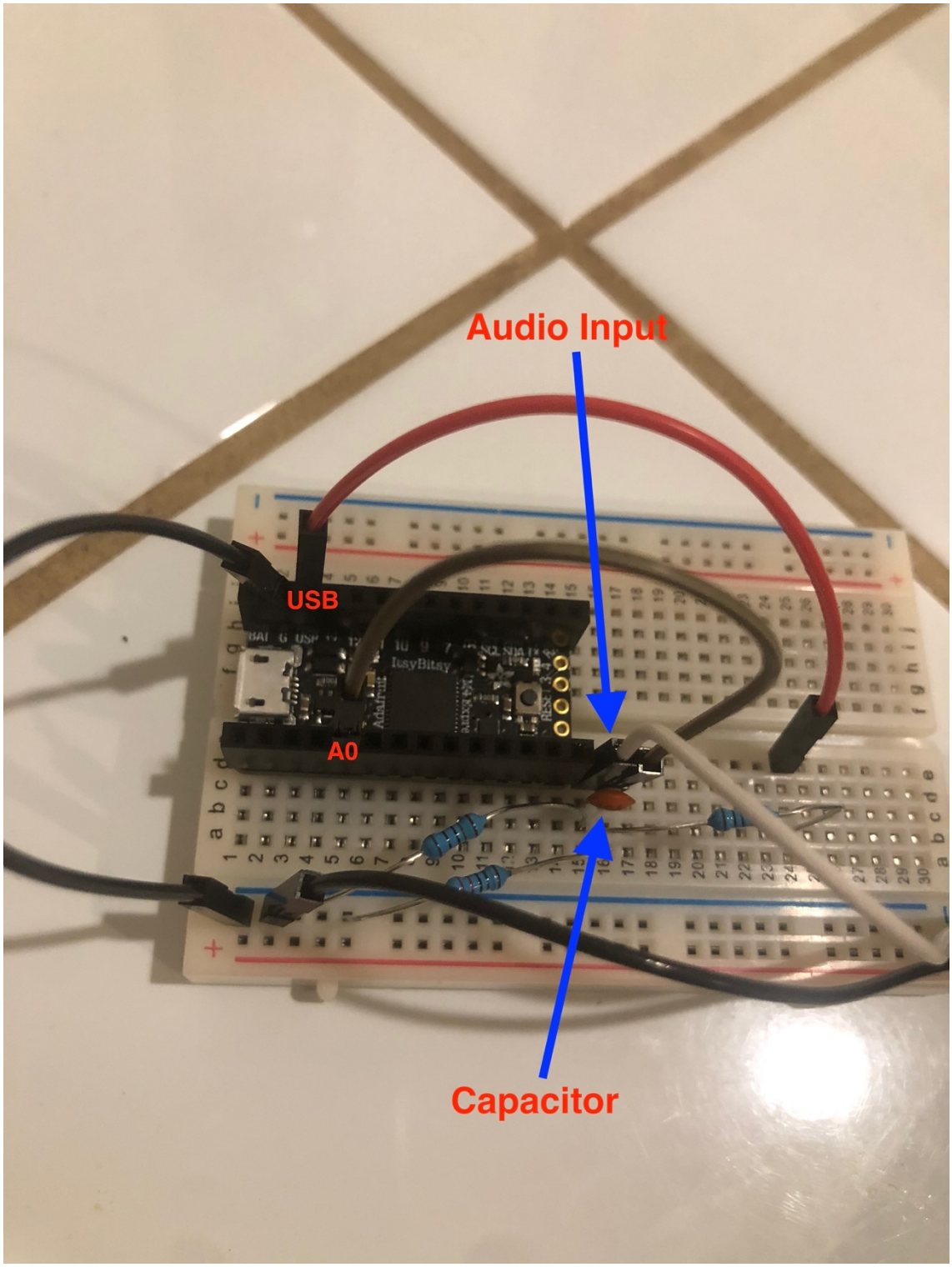
R1 = 1K ohms
R2 = 10 k
C = 0.1uF

4. The next step is to connect the resistors and the capacitors. Both the 1K Ohm and one of the 10K Ohm resistors will connect to the common ground above, but they will go to different ends of the capacitor. It is best to have the capacitor away from any Itsy-Bitsy pins. The other 10K Ohm

resistor will connect into the same side of the capacitor as its identical twin. This resistor can go to any other row on the breadboard.



5. Finally, connect the audio input wire into the same row of the capacitor as the 1kOhm resistor. Connect the other side of the last 10K Ohm resistor to the USB pin of the Itsy-Bitsy, and connect the other side of the capacitor to pin A0. The final product should look like this:



6. Download the provided 300 Hz MP3 from syllabus link.
7. Play the provided 300 Hz MP3 file. (Note that the file only runs for 1 minute; restart as necessary.)
8. Run the code from the prelab to sample the audio input and compute the Fourier Transform and print the most prominent frequencies.

9. Identify which of the frequencies printed is the frequency of your signal and what the others could be. (Note: we haven't performed any calibration calculations to identify which frequency corresponds to each k.)

Lab – Section2: Timing the Dot Product

- In this section, you'll time the dotproduct using the in-built micros() command.
- Finally, you'll calculate different size dotproducts and time taken for each.

1. Take a look at the micros() function in the Arduino library by clicking on the link below.

https://www.arduino.cc/reference/en/language/functions/time/micros/

2. Initialize two variables that will be used to calculate the time in micro seconds at two different points in your program to calculate how much time the Arduino takes to execute that section.

```
unsigned long microseconds1;
unsigned long microseconds2;
unsigned long time_elapsed;
```

3. Call the micros() function **before and after the calculation** of the dot product as shown below.

```
long dotproduct(int length, int *a, int *b) {
  microseconds1 = micros();
  long sum=0L;      // Initializing long
  for(int i=0;i<length;i++) {
    sum+=(long)a[i]*(long)b[i]; //type casting
    }
          microseconds2 = micros();
          time_elapsed = (microseconds2 - microseconds1);
          Serial.println(time_elapsed);
  return(sum);
}
```

4. The variable time_elapsed will contain the execution time in microseconds.
5. Now let's repeat the process for different size dotproducts and measure the execution time.
6. Replace the value of MAX_SAMPLES with different sizes (in powers of 2, like 128, 256, 512, 1024,2048,4096) as shown below.

```
#define MAX_SAMPLES 256
```

7. Try increasing the number of samples to 16384 and run the program. Report the console message and reason behind it.
8. Tabulate and plot the values in Excel (time vs MAX_SAMPLES).
9. Show the TA the plot before you continue.
10. Review the plot and identify an equation that approximates the curve.

Lab – Section 3: Computing the runtime for the Dot Product

- In this section we will go through the assembly code generated and check the number of cycles each instruction takes
- Finally, you'll calculate the runtime of the dotproduct

1. Refer to the dotproduct Assembly code generated and extracted in the pre-lab.
2. Now refer to the Appendix to see how many clock cycles each instruction takes (For example, add, mla, ldr, mov).
3. Next we will calculate the total clock cycles that the assembly code takes:
    a. Total Cycles is defined by the following:

$$\Sigma_i (IC_i)(CC_i)$$

Where IC_i is the number of instructions for a given instruction type i, and CC_i is the clock-cycles for that instruction type. The summation sums over all instruction types for a given benchmarking process.

    b. Make a spreadsheet table with one line for each instruction in dotproduct
        i. Each instruction from the dot product should get one row each.
        ii. Now to the right, we're going to add 4 columns and name them max_total_cycles_run_max_samples_time, min_total_cycles_run_max_samples_time, max_total_cycles_run_once, min_total_cycles_run_once, MAX_SAMPLES.
        iii. Here is how it breaks down.
            1. Two columns to the table for cycles for each of the instructions. (max_total_cycles_run_once, min_total_cycles_run_once)
                a. One column for the maximum number of cycles the instruction takes
                b. One column for the minimum number of cycles the instruction takes
                (Look at the format of the appendix with the 2 columns)
            2. Now the remaining two columns max_total_cycles_run_max_samples_time, min_total_cycles_run_max_samples_time.
                a. These two columns are used to calculate the number of cycles that they will execute based on MAX_SAMPLES and the number of cycles for one execution.
                b. Reference the appendix for how many cycles each instruction takes.
    c. Put MAX_SAMPLES in a separate spreadsheet cell.
    d. Add an equation that uses the table values to calculate total cycles.
    Make the equation use the MAX_SAMPLES cell so you can get it to compute a Total Cycles estimate for each of the different MAX_SAMPLES values you previously measured. In other words, produce an equation that will vary depending on the value you input into the MAX_SAMPLES cell.
    (Note: This equation is known as dp_cycles(MAX_SAMPLES) in the postlab.)
4. Add an equation using the above to calculate the Execution time using the formula below:

Execution Time = $Total\ Cycles\ \times clock\ time$

Here the clock frequency is 120MHz.

5. Compare the time obtained in this to the time obtained from Section 2.

6. Show the TAs the value and explain your discrepancy.

    a. Request a TA come view your calculated values.
    b. The TA will ask you a few questions.
    c. This is your exit check off.

Postlab

1. For what MAX_SAMPLE window sizes can you sample data and compute the Fourier Transform in real time?
    - For our 50000 samples per second rate, calculate how many clock cycles the Arduino could compute between samples. Call this number of clock cycles ctime.
    - Be sure to take care of the difference between cycles and time. ctime represents clock cycles and not time.
    - From the lab (Section 3, 3d), you know how many clock cycles it takes to compute the dotproduct for a particular values of MAX_SAMPLES. Call this function dp_cycles(MAX_SAMPLES). You should get your dp_cycles function directly through your spreadsheet results (use the max cycles version).
    - Further, you know it takes roughly 2×MAX_SAMPLES×dp_cycles(MAX_SAMPLES) to compute the Fourier Transform.
    - For what values of MAX_SAMPLES is 2×MAX_SAMPLES×dp_cycles(MAX_SAMPLES) < ctime×MAX_SAMPLES?
    - How does the maximum MAX_SAMPLES window size change if we sample at 16000 samples per second?

HOW TO TURN IN THE LAB

- Each student should assemble an individual writeup and upload as a PDF document to canvas, containing:
    - dotproduct\extracted code from prelab
    - Console message and explanation from Section 2, step 7
    - Arduino C code for time calculations
    - Table and plot of different DFT MAX_SAMPLES vs time taken for execution
    - Calculation of your Total Cycles with spreadsheet table and any assumptions made
    - Calculation of Execution time and inference from the comparison
    - Answers to any other highlighted questions in the lab
    - Answers to post-lab

Appendix: Armv7-M Microcontroller Instructions

Section I:

To run code that is written in the Arduino IDE on the actual Itsy Bitsy Processor processor (ARM Cortex M4), a series of steps need to be taken. These will all be covered in more detail in later classes, starting with CIS240.

The processor cannot execute high level Arduino code that we write; what it executes is machine code, a series of bits that represent instructions telling the machine what to do. Each processor has a specific set of instructions that it "knows" what to do with; these are defined in the Instruction Set Architecture (ISA) of the device. In this lab we are using the ARM ISA of the Itsy Bitsy's processor, but the concepts are extensible to any other device.

In between the high level code and the machine code is assembly. In assembly each line is a direct translation of the machine code but is human readable. In a high level code it's not immediately clear what instructions correspond to complex structures such as a for loop, or an if statement. However, in assembly, those logical structures are already broken down into single lines of code that each reference one instruction. Each instruction may either reference a memory address, i.e. to jump to a subroutine stored at the address, or load data from that address, or it may reference "registers". Registers are special locations in memory that can be used to store values when we want to do mathematical operations on them. (Additionally, there are certain special registers that are used to store information such as "C" the carry flag. Similarly, there is a status register that contains bits for N, Z, and V. These bits refer to negative, zero, and overflow, and are set by certain comparison, move, and arithmetic instructions. You can read more about these in the full datasheet linked below). To understand the assembly, we need to understand each instruction that the processor supports. Section II of this appendix details the instructions necessary for the lab; more details, as well as all the supported instructions can be found in the datasheet linked below.

A typical line of assembly could look like this:

```
43a4:        a342            add     r3, pc, #264    ; (adr r3, 44b0 <loop+0x178>)
```

Here 43a4 is the memory location, represented in hexadecimal, where this instruction is stored in the Arduino. The a342 is the actual string of bits (machine code), represented in hex, that are the instruction. The "add r3, pc, #264" is the human readable version of that instruction.

In assembly anything after a semicolon (;) is a comment, here the comment is letting us know that the memory location 43a4 that the assembly command is equivalent to the form address (adr) and putting 44b0 in r3 where 44b0 is <loop+0x178>. <loop+0x178> says the address 0x178 bytes after the loop label.

Section II:

Below are the instructions that you will find in this lab and the relevant information for each. For the purposes of the lab, while it will be helpful to have a basic understanding of what each instruction does when identifying what parts of the Arduino code they refer to, you do not need to fully understand how to translate the Arduino code to assembly or vice-versa. This will be covered more in CIS240 and beyond. You should focus most on tracing through the execution of the assembly code and figuring out how many cycles each instruction takes.

Note that some instructions can take a variable number of cycles, indicated in the chart by the 2 columns for min and max cycles (depending on various things, such as if a condition is true or false when the instruction is executed). For the lab, this is what is meant by maximum and minimum number of cycles. For example, b might take 2 cycles if the branch prediction is correct but 4 if it is not. Note that whether the condition is true or not will affect what code runs, which further affects how long the entire program will take (i.e. in the high level code an if block might take a lot longer to run than the corresponding else block). For this lab we just want to look at the maximum and minimum number of cycles of each individual instruction, ignoring the effects taking a certain branch might have on the logical runtime of the code.

Instruction Semantics	Instruction Description	Min Number of Cycles	Max Number of Cycles
ldr <c><q> <Rt>, [<Rn>, <Rm> {, LSL #<shift>}]	Load a value in memory into a register: <Rt>=Memory[<Rn>+(<Rm> << <shift>]	1	2
b<c><q> <label>	Branch based on condition <c> or unconditional if omitted. PC=PC+<label>	1 (not taken if conditional)	4
bl<c><q> <label>	Branch based on condition <c> or unconditional if omitted to a subroutine. PC=PC+<label>	2	4
mov{s}<c><q> <Rd>, #<const>	<Rd>=#<const> {s}-optionally updates flags with s set	1	1
cmp <q> <Rn>, <Rm> {,<shift>}	Computes Rn-Rm and updates the flags based on the result optionally	1	1

mla <q> <Rd> <Rn> <Rm>	Multiply and accumulate. Rd=Rn*Rm+Rd	2	2
add{s} <Rd> <Rn> #<const>	Does the following addition Rd=Rn+const. {s}- optionally updates flags with s set	1	1
Push <registers>	Push registers onto the stack potentially including LR	1+N (where N is number of registers including LR)	1+N (where N is number of registers including LR)
Pop <registers>	Pop values off the stack into the list of registers potentially including PC	2+N	4+N

Notes:
b<c> stands for branch based on certain conditions, for example bge (where the condition replacing <c> is ge for "greater than or equal")
<q> is either N or W with N meaning narrow (16-bit) encoding and W meaning wide (32-bit) encoding
N = number of register to process in list including PC/LR
LR = link register which contains the address to return when function call finishes
This appendix should suffice for our lab. To see more details of the ARMv7-M ISA see https://developer.arm.com/documentation/ddi0403/latest/ and https://developer.arm.com/documentation/ddi0439/b/Programmers-Model/Instruction-set-summary/Cortex-M4-instructions?lang=en