MAE 511

EXPERIMENTAL METHODS I

DIGITAL SAMPLING OSCILLOSCOPE

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Contents

1 Introduction

This paper presents a design for a breadboard based digital sampling oscilloscope, DSO. A digital sampling oscilloscope is a device used to display an electrical signal varying in time. Unlike a voltmeter which displays a time-averaged voltage, an oscilloscope plots the voltage contours such that the waveform's amplitude, frequency, noise and other properties are easily interpreted and can then be further analyzed. In order to display an electrical signal varying in time, the DSO captures a voltage signal from a voltage source, i.e. a signal generator. The voltage signal is then written to memory, which is then read by a micro-controller, i.e. a Teensy. The micro-controller then sends the analog waveform to a computer for display. Our design is more similar to a digitizer than a traditional modern oscilloscope in that the display is not integrated in the breadboard and is instead a computer program which plots the stored signal from the DSO's memory.

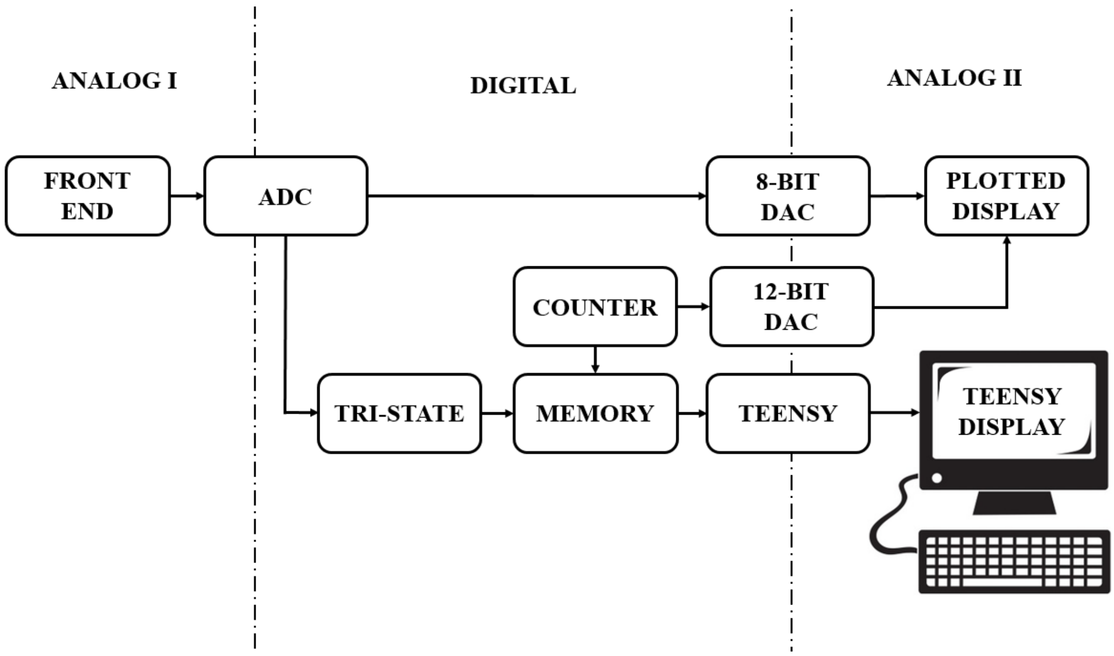


Figure 1: Block diagram illustrating major components of oscilloscope.

In the above block diagram a flow of the major subsystems is depicted. As is shown in the diagram, the DSO can be broken into three regimes, Analog I, Digital, and Analog II. In the first analog regime an input voltage is modified by the front end and sent to the analog-to-digital converter, ADC. The ADC serves as the interface between the first analog regime and the digital regime. In the digital regime the ADC sends a digital signal through the tri-state to the memory in which the storage location is advanced via the counter. The values from the ADC are sent to the 8-bit digital to analog converter, DAC, and the addresses of the memory are sent to the 12-bit DAC. The DAC's serve as the interface from the digital regime to the second analog regime. These analog outputs could be plotted as a waveform. However, the micro-controller instead reads directly from the memory and sends the waveform data to the computer for display.

In the sections that follow the design of the DSO will be discusses by component. The design of the DSO will be followed by a results section and then by a conclusions section.

2 Digital Sampling Oscilloscope Design

In this section an overview of each subsystem's functionality and the manner in which these subsystems relate to one another will be presented.

2.1 Front End

The front end of the DSO consists of three operational amplifiers, op-amps, which serve to convert an input voltage signal ranging from -5V to +5V to a scaled signal ranging from 0 to +5V. This is done to protect the ADC which requires a unipolar voltage input with a maximum of +5V volts.

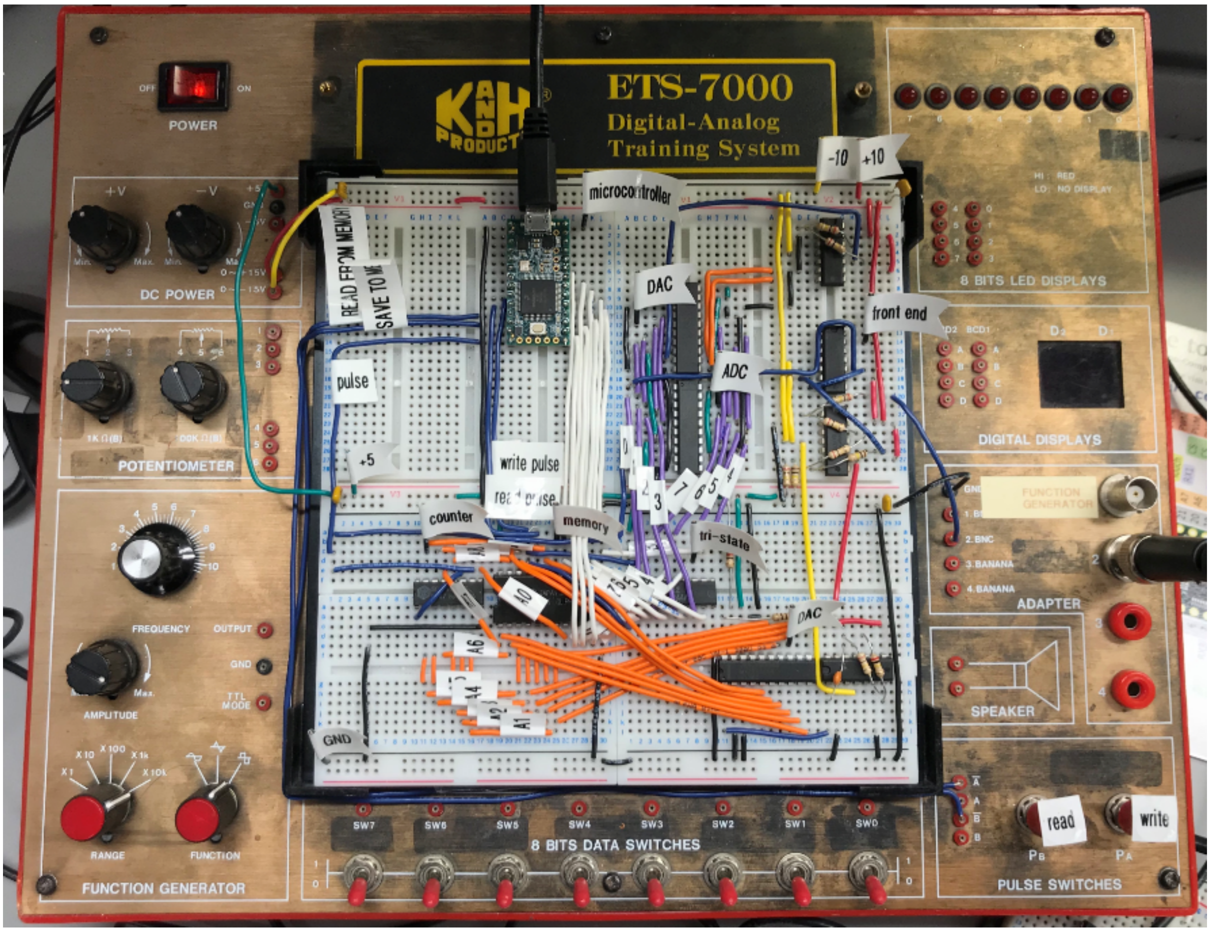


Figure 2: An image of the breadboard configuration with major components and voltage lines labeled.

Inverting Amplifier The first op-amp is configured as an inverting amplifier which inverts the incoming -5V to a +5V signal from the signal generator, V_{in}. Our design uses an R_{in} value of 200kΩ and an R_f value of 200kΩ . V_{out} is then sent to the differential amplifier where,

$$V_{out} = -\frac{R_f}{R_{in}}$$

such that V_{out} is the inverse of V_{in}.

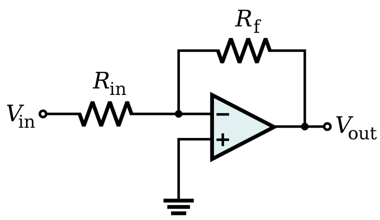


Figure 3: A diagram of an inverting amplifier.

Differential Amplifier The second op-amp is configured as a differential amplifier. The output of the inverting amplifier is received as V_1. The output voltage, V_{out} is calculated as follows,

$$V_{out} = V_R + ((\frac{R_f}{R_1})(V_2 - V_1))$$

where R_1 = 200kΩ, R_f = 100kΩ, V_2 = +5V, and V_R = GND. The output voltage is sent to the voltage follower.

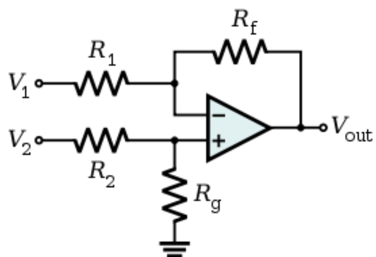


Figure 4: A diagram of a differential Amplifier.

Voltage Follower The third op-amp is configured as a voltage follower. This serves to ensure that the output of the op-amp matches its input ($V_{out} = V_{in}$). The output voltage is then sent to the analog-to-digital converter.

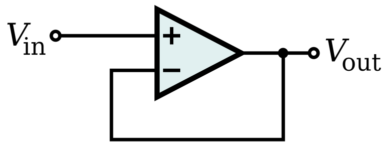


Figure 5: A diagram of a voltage follower.

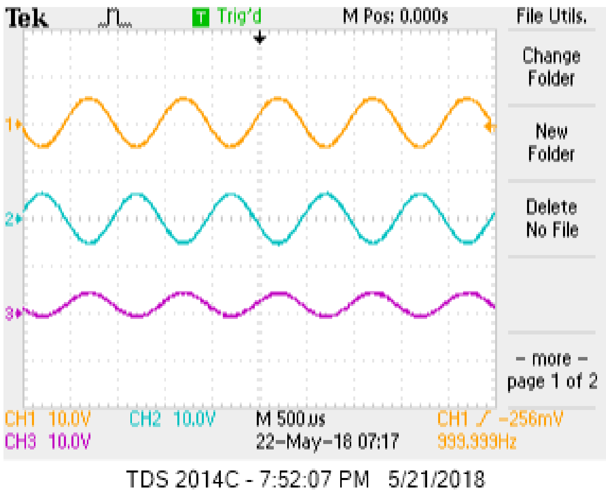


Figure 6: An image of (1) the input signal from-5V to +5V, (2) the signal inverted by the inverting amplifier and (3) the signal inverted and scaled from 0V to +5V by the differential amplifier (to be sent through a voltage follower to the Analog to Digital converter).

2.2 Analog to Digital Converter

The ADC0820 is a high-speed 8-bit analog-to-digital converter with a built in sample-and-hold function. It receives an analog unipolar 0-5 V input from the front end to its V_{IN} pin, and converts it to an 8-bit digital signal. The MODE pin is pulled high, setting the ADC to WR-RD mode. This causes the INT pin to be an output, which is left unconnected. The ADC is run as a stand-alone operation (cf. figure 7).

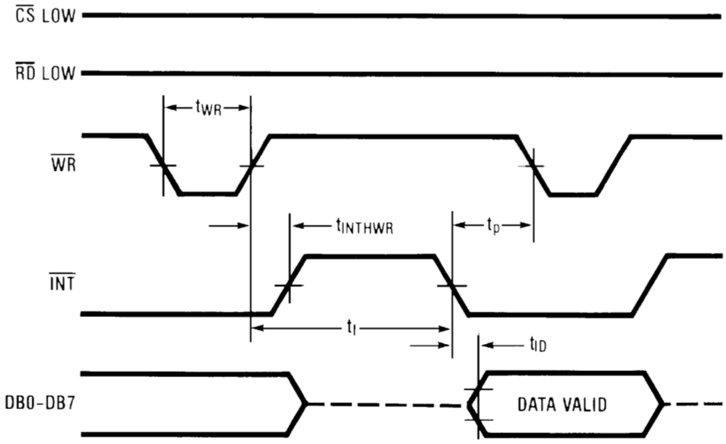


Figure 7: ADC in WR-RD Mode: Stand-Alone Operation

The $\overline{CS}$ pin is grounded, allowing the $\overline{RD}$ and $\overline{WR}$ inputs to be recognized. The $\overline{RD}$ pin is also grounded, and the circuit is therefore controlled by the $\overline{WR}$ pin. To fill the memory once, the Teensy sends 2048 pulses to the write pin $\overline{WR}$ on the ADC. The conversion is initiated upon the falling edge of a pulse. It then takes a certain amount of time for the data on the output lines to be valid. In the figure above, this time is tWR + tI + tID, which according to the datasheet is 1420 nanoseconds. This means that the tri-state should not let the data reach the memory until about 1500 nanoseconds after the conversion has started. We initially wrote our Teensy code such that the time delay was 1500 nanoseconds. However, the data that the Teensy read out of the memory was very noisy. We then increased the time delay, and found that at a delay of about 10 microseconds the noise was smallest. This suggests that the ADC in fact works more slowly than the datasheet claims.

2.3 Tri-State

The tri-state (SN74LS244) controls the data lines running from the ADC to the memory. Each data line from the ADC is connected to an A (input) pin on the tri-state, and the corresponding Y (output) pin is connected to the memory. In this circuit, the tri-state has two functions. First, it ensures that the ADC and the memory do not simultaneously write to the same lines, since this can damage the parts, and inhibits their functionality. The tri-state thus acts as a buffer between the ADC and the memory. The ADC continuously converts data and outputs it to its data lines (purple wires), so in order for the Teensy to read data out of the memory, the tri-state must disconnect the ADC data lines from the memory data lines (white wires). The tri-state is controlled via the gate pins $1\overline{G}$ and $2\overline{G}$. While the Teensy reads data out of the memory, it keeps the gates high, so that the ADC is disconnected from the memory.

During write mode, when the data from the ADC is being saved to the memory, the tri-state serves another purpose: after the ADC receives a pulse from the Teensy to its $\overline{WR}$ pin, it takes a certain amount of time for the data conversion to be completed and the output pins to be stable (cf. section 2.2). Preventing the data from the ADC from reaching the memory until the conversion is complete ensures that the data saved to the memory is correct. We thus want the tri-state gates to open a certain time after the ADC conversion began. We determined this time-frame to be 10 microseconds, and wrote the Teensy code such that the tri-state gates receive a pulse 10 microseconds after the ADC receives a pulse. The ADC conversion is started on the falling edge of a pulse, and the tri-state gates open on the falling edge of a pulse, so by the time the data reaches the memory, the conversion is completed and the data is valid.

Table 1: Truth Table for SRAM

Mode	$\overline{CS}$	$\overline{OE}$	$\overline{WE}$
Standby	LOW	HIGH	HIGH
Read	LOW	LOW	HIGH
Write	LOW	HIGH	LOW

2.4 Memory

The 6116 RAM is a high-speed static RAM with eight data lines and eleven address lines. It operates in two modes, reading and writing, depending on the input signals from the Teensy. The $\overline{CS}$ pin is grounded, so that the write mode is controlled by the write enable pin $\overline{WE}$ and the read mode is controlled by the output enable pin $\overline{OE}$. In either mode, the address lines A0 to A7 receive inputs from the counter, which counts in binary through all possible addresses in the memory and determines which address in the RAM the data is stored to or read from. Since there are 11 address lines, there are $2^{11} = 2048$ addresses in the memory. Therefore, 2048 pulses from the Teensy are required in order to write to or read from the entire memory.

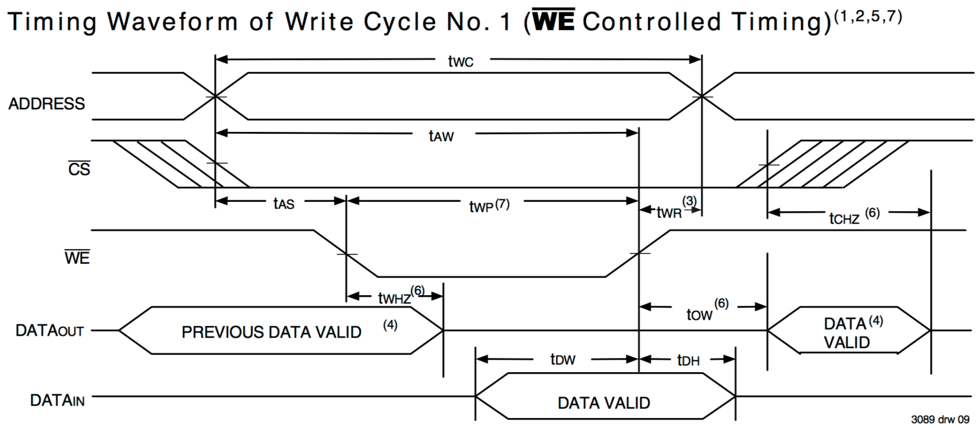


Figure 8: Write timing diagram of the 6116 RAM.

Writing to Memory During write mode, the memory receives inputs from eight data lines from the tri-state that contain the data converted by the ADC, and saves the data to its RAM. This is done as follows: the counter receives a pulse from the Teensy simultaneously with the ADC, causing it to select the next address and to send this as an input to the address lines A0 to A10 on the memory. 10 microseconds later, the write enable pin $\overline{WE}$ receives a pulse from the Teensy. A certain time after the falling edge at $\overline{WE}$, the memory is ready to receive data from its data lines. On the schematic above, this time frame is shown as tWP-tDW, which according to the data sheet of our model is at least 60 nanoseconds. At this time, the ADC has finished the conversion and the tri-state gates are open, so the memory stores the correct data. This process is repeated 2048 times.

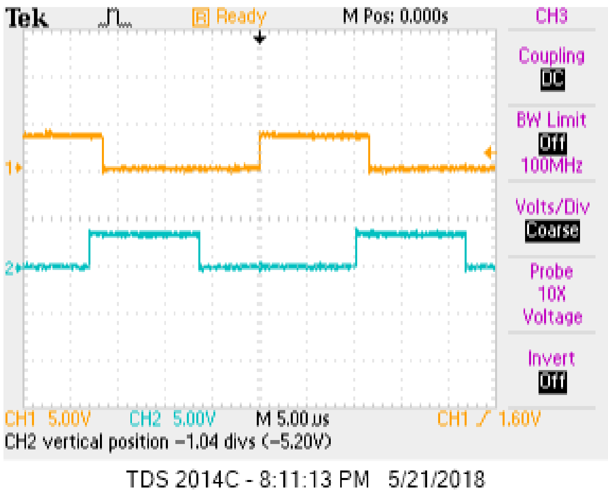


Figure 9: Pulse sent to the ADC and counter (1) and second pulse (2) sent to the tri-state and memory 10 microseconds later.

Reading from Memory During read mode, the memory outputs the content stored in its RAM to the data lines, which are then read by the Teensy. This happens as follows: a pulse is sent from the Teensy to the counter, causing it to select the next address and send this as an input to the address lines A0 to A10 on the memory. 500 nanoseconds later, the output enable pin $\overline{OE}$ receives a pulse from the Teensy. This delay is not necessary, but happens naturally since the Teensy takes 500 nanoseconds to process the command to change the state of each pin. After the falling edge on the $\overline{OE}$ pin, it takes a certain amount of time until the data on the output lines is valid. On the timing diagram above, this time is shown as tOE, and according to the data sheet tOE is at most 120 nanoseconds. This data is then read by the Teensy and can be displayed on the serial plotter.

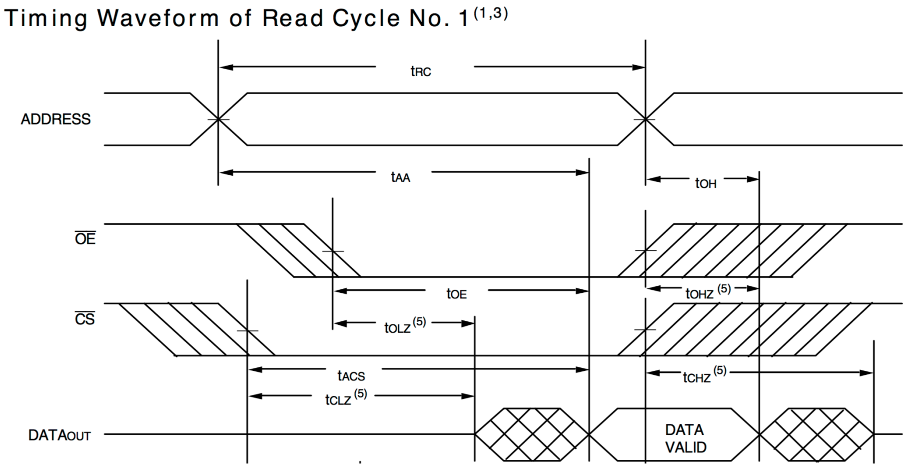


Figure 10: Read timing diagram of the 6116 RAM.

2.5 Counter

The SCL 4040BE is a ripple-carry binary counter. It receives 2048 pulses to its θ pin from the Teensy during both reading and writing modes. On each falling edge of the pulses, it advances one count. The count is expressed in binary on its output pins Q1 to Q12. Since our memory has 11 address lines, we connected Q1 to Q11 to these lines (orange wires). The counter contains a reset pin R. If this pin goes high, the counter is reset to zero. Since we do not need the 12th bit, we connected pin Q12 to the reset pin. Thus, once the counter has counted through the first 11 bits and switches the 12th bit to high, the counter resets.

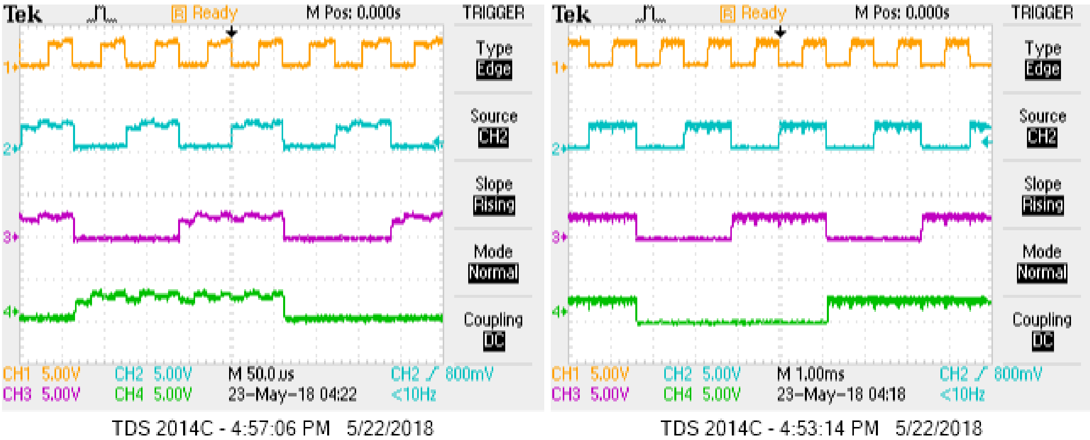


Figure 11: Left: timing diagram for addresses 0 to 3; Right: timing diagram for addresses 4 to 7.

2.6 Digital to Analog Converter

8-bit Digital to Analog Converter The 8-bit digital to analog converter (DAC0830) is used to convert the digital signal coming from the ADC back to an analog signal. Its purpose is primarily to debug and assess the functionality of the ADC without having to interface with the Teensy.

The DAC continuously converts the output of the ADC, which means that the $\overline{CS}$, $\overline{WR_1}$, $\overline{WR_2}$ and $\overline{XFER}$ pins are grounded, and the I_{LE} pin is pulled high. Since the DAC outputs the signal as a current instead of a voltage, we use an op-amp to convert the signal to a voltage signal as shown in figure 12. The I_{OUT1} pin is connected to the positive input of an op-amp, and the I_{OUT2} pin is connected to the negative input of that op-amp. The feedback resistor pin R_{fb} is connected to the output of that op-amp, as this pin provides the connection to a built in feedback resistor that is calibrated to convert the current signal to a voltage signal. The output of the op-amp was then sent through an inverting amplifier in order to retrieve the original voltage scaled to 0V - 5V.

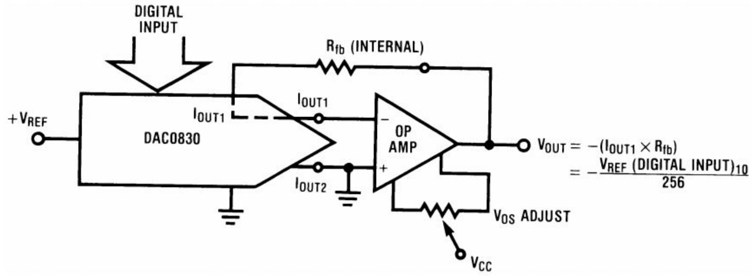


Figure 12: An op-amp connected to the output voltage of the 8-bit DAC to convert the voltage before it is inverted by an inverting amplifier.

12-bit Digital to Analog Converter The 12-bit digital to analog converter (MX7545) is used to convert the digital address signal from the counter into an analog voltage that can be displayed on an oscilloscope or used to plot the 8-bit DAC's output voltage against on an analog display. The counter address lines are connected to the pins DB0 to DB10. Pin DB11 is left unconnected because our address line is only 11 bits. As with the 8-bit DAC, this DAC requires an op-amp at its output, as shown in figure 13. The R_{fB} pin is connected via a 27Ω resistor to the output of the op-amp. The OUT1 pin is connected to the negative input of the op-amp, and via a 33 pF capacitor to the output of the op-amp. As with the 8-bit DAC, the output is put through an inverting amplifier, and can be seen as a ramp when measured with an oscilloscope.

2.7 Teensy

The Teensy is used to send pulses to initiate and to end the processes of writing to the memory and reading from it. The two push switches on the board are connected as inputs to the Teensy. Pressing the right-hand switch initiates the process of writing to the memory, and pressing the left-hand switch initiates reading from the memory. These are pins 10 (write) and 9

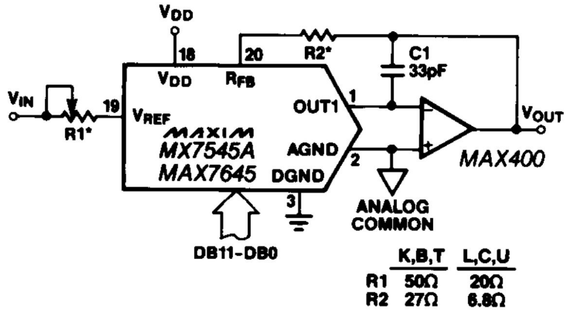


Figure 13: An op-amp connected to the output voltage of the 12-bit DAC to convert the voltage before it is inverted by a voltage follower.

(read) on the Teensy. The Teensy shares a common ground with the circuit board, but 5 V are supplied through the USB cable. The Teensy outputs 0 V as logic low and 3.3 V as logic high, whereas all other components output 5 V as logic high. However, this does not cause any issues because all components that have outputs from the Teensy as their inputs treat values above 2 V as logic high.

Writing to the Memory If pin 10 goes low, the Teensy initiates a timer that sends 2048 pulses to the counter and the ADC via pin 12, and 2048 pulses to the write enable pin ($\overline{WE}$) on the RAM and the gates on the tri-state via pin 7. However, as described in section 2.2 a delay of about 10 microseconds after the ADC conversion is necessary before the converted data is written to the memory to ensure that the conversion has finished and the data is ready. The $delay()$ function cannot be used within a $timer()$ function because interrupts are disabled. Therefore, in order to create the delay, we initiate one pulse, then print a random value to the serial twice, and then initiate the delayed pulse, since we found that the Teensy takes about 5 microseconds to process a command to print to the serial. Therefore, there is a delay of approximately 10 microseconds between when the ADC starts the conversion, and when the memory saves the data. We had initially built a one-shot circuit to create this delay, but then realized that our code could easily generate a sufficient delay.

The time between each pulse is 55 microseconds. This means that our sampling frequency is about 18 kHz. However, the sampling frequency can easily be adjusted in the Teensy code.

Reading from the Memory If pin 9 goes low, the Teensy initiates a timer that sends 2048 pulses to the counter and the ADC via pin 12, and the same number of pulses to the output enable pin ($\overline{OE}$) on the RAM via pin 8. Since the commands are written consecutively in the code, there is a 500 nanosecond delay between the pulses. The pulses to the ADC are not necessary for functionality. The ADC continues to convert data, but the gates of the tri-state are held high by pin 7 on the Teensy. Thus, the data outputs of the ADC (purple lines) are not let through the tri-state, and the memory controls the data lines (white wires). These data lines then run to pins 14 to 21 on the Teensy. The Teensy then reads the inputs from these data lines as bits, and stores them in a byte. This byte captures the voltage, where the values are scaled such that the input of ±5 V is expressed on a scale from 0 to 255.

3 Results

We used the serial plotter in the Teensy software to visualize the data that the Teensy reads out of the memory. Plots of different voltage signals are shown in figures 14 and 15. As mentioned in section 2.7, our results were initially very noisy, and we had to increase the delay between the data conversion in the ADC and the data storage by the RAM in order to reduce noise in the signal. The voltage is plotted on a scale from 0 to 255, since this represents the range of bytes that can be represented with 8 bits, so scaling this range to $\pm 10V$ would retrieve the original voltages.

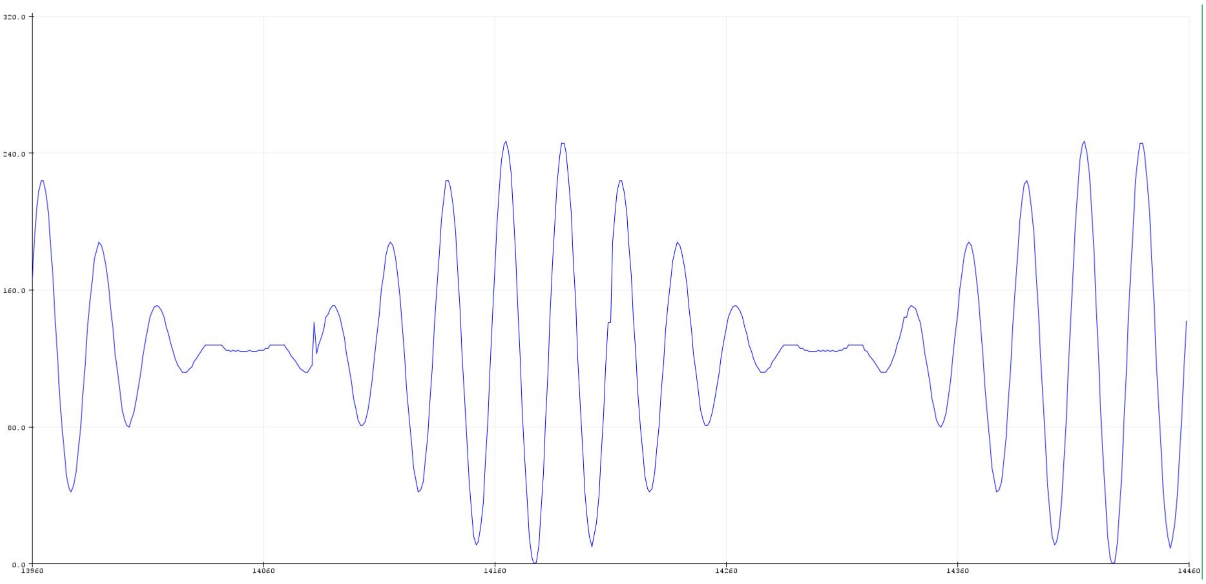


Figure 14: Modulated sine wave saved on the memory and output by the Teensy

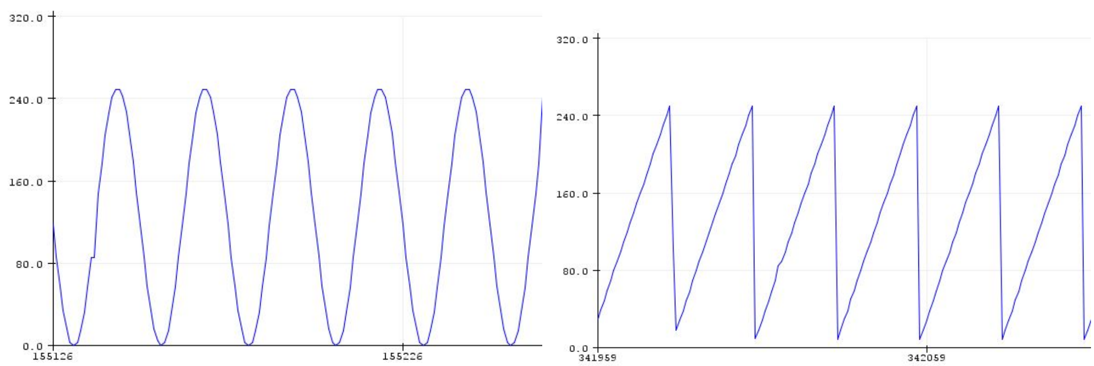


Figure 15: Sine wave and ramp saved on the memory and output by the Teensy

4 Conclusion

Our design produced a fully functional digital sampling oscilloscope. We were tasked with storing and retrieving a -5 V to 5 V input signal. Our oscilloscope was able to convert the analog input voltage to a digital voltage, write the digital data to the memory, read the digital data from the memory, convert the digital data to analog data, and display the analog data. The signal was returned via a Teensy micro-controller and displayed on the serial plotter from the Teensy software package.

Throughout the course of the project we learned a lot more than just how to build a breadboard DSO. We learned how to design a breadboard DSO. We did everything from reading and interpreting data sheets to trouble shooting timing errors. By successfully completing these tasks and producing the functional breadboard DSO we were able to demonstrate fundamental levels of understanding in basic electronic techniques, digital electronics, data acquisition, and data analysis.

5 Appendix

5.1 Components

Table 2: Integrated Circuit Components

Component	Quantity	Part Number
Op-Amp(Package of 2)	4	UA747CN
Analog to Digital Converter	1	ADC0820CCN
8-bit Digital to Analog Converter	1	0830LCN
12-bit Digital to Analog Converter	1	MX7545AKN
Tri-State Buffer	1	SN74LS244
Static Ram	1	HM6116LP-4
Counter	1	SCL 4040BE 8447 844347A
Teensy 3.2	1	-

Table 3: Discrete Components

Component	Quantity	Value
Resistor	2	100 kΩ
Resistor	8	200 kΩ
Resistor	1	220 kΩ
Capacitor	1	33pF

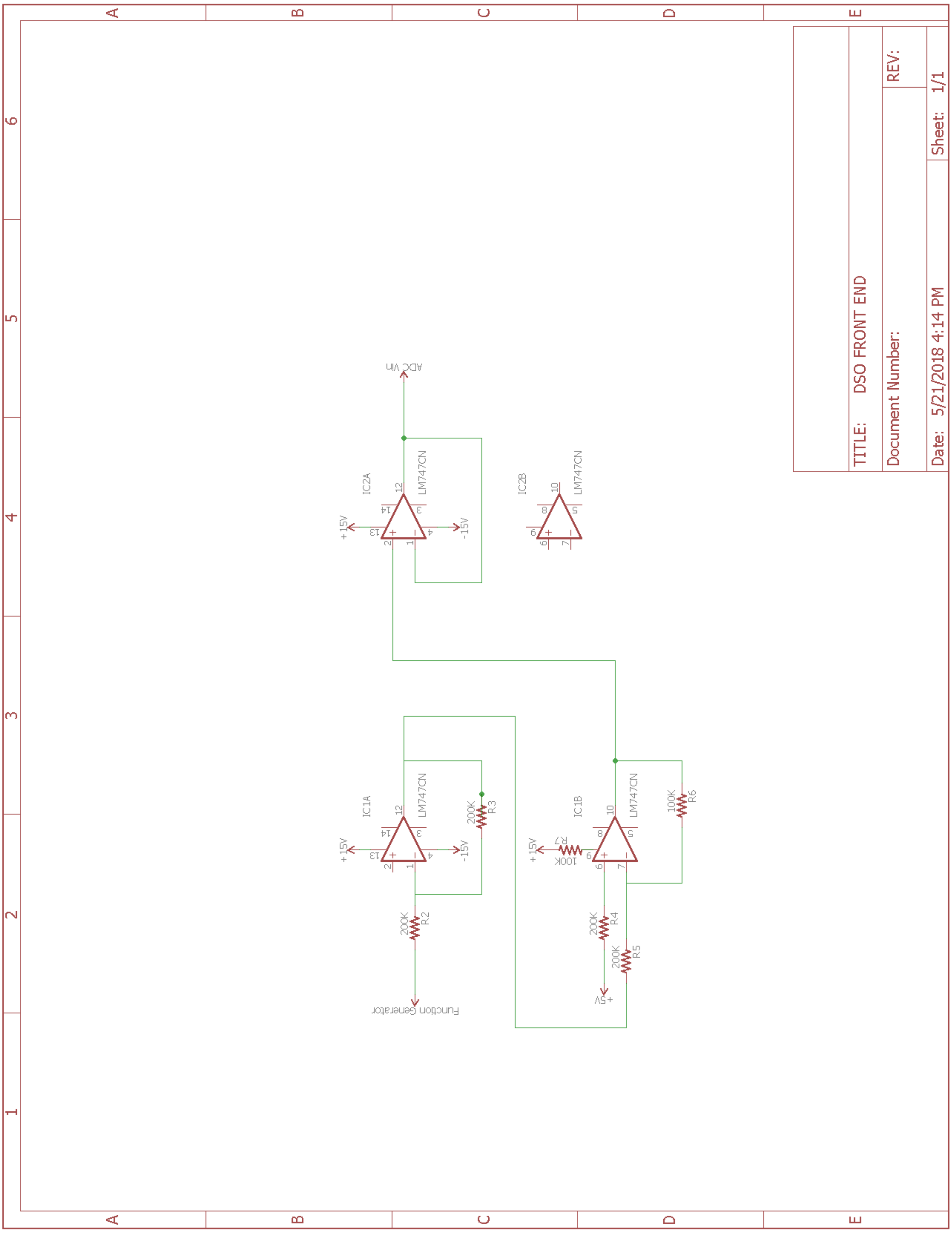
5.2 Teensy Code

```
#include<TimerOne.h>

const int writeRAMpulse = 7;
const int readRAMpulse = 8;
const int readRAMbutton = 9;
const int writeRAMbutton = 10;
const int clockpin = 12;
const int db0 = 14;
const int db1 = 15;
const int db2 = 16;
const int db3 = 17;
const int db4 = 18;
const int db5 = 19;
const int db6 = 20;
const int db7 = 21;
boolean bit0 = 0;
boolean bit1 = 0;
boolean bit2 = 0;
boolean bit3 = 0;
boolean bit4 = 0;
boolean bit5 = 0;
boolean bit6 = 0;
boolean bit7 = 0;
byte dataByte = 00000000;
int incomingByte = 0;
int pulseState = LOW;
int samplingRate = 10;
volatile unsigned long pulseCount = 0;  // use volatile for shared variables

/* The setup function defines the pins on the teensy as inputs or outputs */
void setup(void) {
  pinMode(writeRAMpulse, OUTPUT);
  pinMode(readRAMpulse, OUTPUT);
  pinMode(readRAMbutton, INPUT);
  pinMode(writeRAMbutton, INPUT);
  pinMode(clockpin, OUTPUT);
  pinMode(db0, INPUT);
  pinMode(db1, INPUT);
  pinMode(db2, INPUT);
  pinMode(db3, INPUT);
  pinMode(db4, INPUT);
  pinMode(db5, INPUT);
  pinMode(db6, INPUT);
  pinMode(db7, INPUT);
  Serial.begin(9600);
}

/* The timerWrite function sets up the timer for writing to the RAM */
```

```
void timerWrite(void) {
  Timer1.initialize(samplingRate);
  Timer1.attachInterrupt(sendPulse);   // sends a pulse every 10 microseconds
}

/* The timerRead function sets up the timer for reading from the RAM */
void timerRead(void) {
  Timer1.initialize(samplingRate);
  Timer1.attachInterrupt(readBits);
}

/* The readBits function sends the pulses necessary for reading to the RAM and also reads the data lines */
void readBits(void) {
  if (pulseState == LOW) {

    bit0 = digitalRead(db0);    // LSB
    bit1 = digitalRead(db1);
    bit2 = digitalRead(db2);
    bit3 = digitalRead(db3);
    bit4 = digitalRead(db4);
    bit5 = digitalRead(db5);
    bit6 = digitalRead(db6);
    bit7 = digitalRead(db7);    // MSB

    bitWrite(dataByte,0,bit0);    // LSB
    bitWrite(dataByte,1,bit1);
    bitWrite(dataByte,2,bit2);
    bitWrite(dataByte,3,bit3);
    bitWrite(dataByte,4,bit4);
    bitWrite(dataByte,5,bit5);
    bitWrite(dataByte,6,bit6);
    bitWrite(dataByte,7,bit7);    // MSB
    Serial.println(dataByte);     // this expresses the voltage on a scale of 0 to 255
    pulseState = HIGH;
    pulseCount++;

  } else {
    pulseState = LOW;
    if (pulseCount >= 2047) {       // how many pulses we want to send
      Timer1.detachInterrupt();
      pulseCount = 0;
    }
  }
  digitalWrite(clockpin, pulseState);
  digitalWrite(readRAMpulse, pulseState);
}

/* The sendPulse function sends the pulses necessary for writing to the RAM */
```

```
void sendPulse(void) {
  if (pulseState == LOW) {
    pulseState = HIGH;
    pulseCount++;
    Serial.println(pulseCount);
  } else {
    pulseState = LOW;
    if (pulseCount >= 2047) {       // how many pulses we want to send
      Timer1.detachInterrupt();
      pulseCount = 0;
    }
  }
  digitalWrite(clockpin, pulseState);
  Serial.println(pulseCount);
  Serial.println(pulseCount);
  digitalWrite(writeRAMpulse, pulseState);
}

/* The loop function (main function) waits for an input from the push buttons on the board and initiates reading or writing mode */
void loop(void) {
  //Serial.print("pulseCount = ");
  //Serial.println(pulseCount);
  delay(100);
  if (digitalRead(readRAMbutton) == LOW) {
    Serial.println("READING FROM MEMORY");
    digitalWrite(writeRAMpulse,HIGH);          // this line tells the tri-state to disconnect the ADC from the RAM
    timerRead();
    delay(50);
  } else if (digitalRead(writeRAMbutton) == LOW) {
    Serial.println("WRITING TO MEMORY");
    timerWrite();
    delay(50);                                // this delay stops the loop from running until all the data has been read
  }
}
```

5.3 Front End Schematic



5.4 Body Schematic