

# Adafruit Metro Express Capacitance Meter

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## 1 Introduction

This week, you will build a capacitance meter to measure the capacitance of unknown capacitors. In addition, you will study the equivalent capacitance of capacitors in series and in parallel. The lab can be open-ended and you are encouraged to find ways to improve the circuit and code to make a more versatile instrument.

## 2 Materials

The materials below were assembled earlier to display a brief message from the Adafruit on the LCD. Check to ensure that the board is still assembled and that the display still works. If it does not, your first job is to fix it.

- PC with Mu IDE installed.
- Adafruit Metro Express board and power cable
- Half-size breadboard
- LCD display module
- 220  $\Omega$  resistor ( $\Omega$  is Ohm)
- 10 k $\Omega$  potentiometer
- Jumper wires

The materials here are the new parts needed for completion of this weeks project.

- Jumper wires
- Resistors (various sizes)
- Capacitors, also various sizes

## 3 Background

A parallel plate capacitor was introduced earlier to describe a device that generated a uniform electric field. A simple schematic of such a capacitor is shown in Figure 1. While a uniform electric field is a useful thing, this is not why capacitors are found in many electronic circuits. Rather, capacitors are useful because they can be charged, store electrical energy, and discharged faster than a chemical battery. For example, the flash on a camera requires a large electric current in a short pulse. A battery is unable to produce enough current to create a bright flash, so the battery is used to charge a capacitor which then discharges the stored energy quickly (*... in a flash!*). Another common use is in electric motors. It takes more work to initially start the

motor than it takes to maintain the rpm once it is moving. Capacitors can provide an initial burst of energy to accelerate the motor.

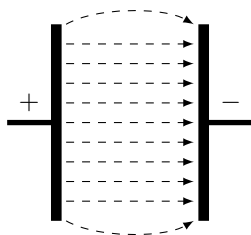


Figure 1: Parallel Plate Capacitor

Unlike a battery, which is charged and discharged according to the rate of a chemical reaction, a capacitor can be charged or discharged very quickly – especially useful when powering a camera flash, an AED, or a taser. The factor that limits how quickly a capacitor charges or discharges, besides its size, is the resistance in the circuit, which limits the current and how quickly charge can build up on the capacitor. If a capacitor is initially uncharged, the charge builds rapidly at first, but as the voltage on the capacitor approaches the potential of the source, the rate of charging slows down. A plot of charge vs. time is shown in Figure 2.

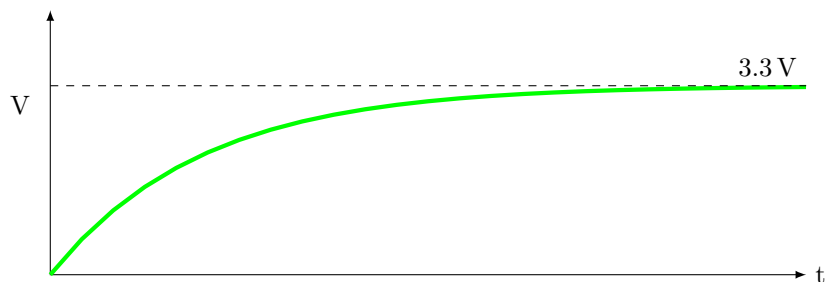


Figure 2: Capacitor charging

Similarly, the rate at which the capacitor discharges depends on the resistance in the circuit. In Figure 3 below, three discharge curves are shown, the red illustrates the discharge in a circuit with little resistance, and the blue a circuit with a large resistance.

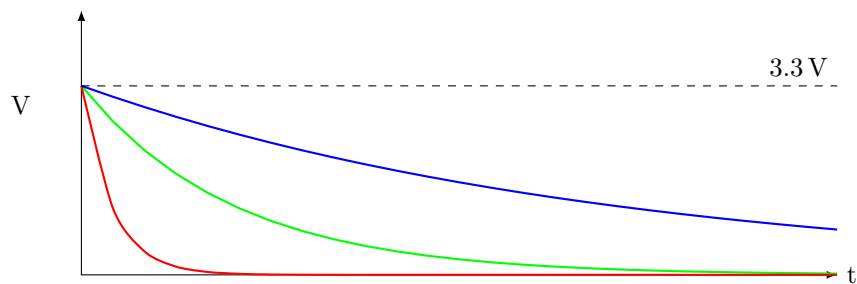


Figure 3: Capacitors discharging

These charge and discharge curves are modeled by the equations:

$$q = q_0 \left[ 1 - e^{-t/(RC)} \right] \quad \text{Charging the Capacitor}$$

and

$$q = q_0 e^{-t/(RC)} \quad \text{Discharging the Capacitor}$$

where  $q_0$  is the maximum voltage,  $R$  is the resistance in the circuit and  $C$  is the capacitance of the capacitor in Farads. The product  $RC$  is called the time constant, which is  $\tau$ :  $\tau = RC$ . This equation provides a way to measure the capacitance of any capacitor. If a fully discharged capacitor is charged, when  $t = \tau$ ,  $q = q_0 \times [1 - e^{-1}]$ , or  $q = q_0 \times 0.632$ . Note that the time constant depends on the capacitance of the capacitor *and* the resistance in the circuit.

## 4 The Circuit

Figure 4 is a simple schematic of the circuit you will build this week. The Adafruit provides the voltage to charge the capacitor and controls the three switches. In addition, it measures the charge on the capacitor (the voltage) as a function of time, using its built in timer. When the program starts, the charging switch is in the ‘closed’ position, allowing current to flow to the capacitor while the Adafruit monitors the voltage as a function of time. The  $10k\Omega$  resistor limits the current and slows the charging, otherwise the capacitor may charge too quickly to measure. (You will choose the resistor in the circuit and modify the Adafruit program to reflect the resistance used.) When the voltage reads 2.086 volts ( $2.086V = 3.3V \times 0.632$ ), the Adafruit calculates the capacitance from  $t = \tau = RC$ :

$$C = \frac{t}{R} = \frac{t}{10000}$$

To discharge the capacitor, the Charging switch is opened and the ‘Discharge through LED’ switch is closed. Only one discharge circuit is needed, but the second is helpful since we are inserting an LED into the discharge circuit. The initial discharge directs the current through the LED, which will glow briefly. When the voltage drops below a minimum voltage for the LED, the current essentially stops, and the capacitor discharges only very slowly. The final discharge switch is then closed to allow the capacitor to finish discharging quickly. The  $1k\Omega$  resistor in this part of the circuit also limits the current and allows the LED to remain lit for a longer period of time. You can change this resistor to see how it affects the LED brightness.

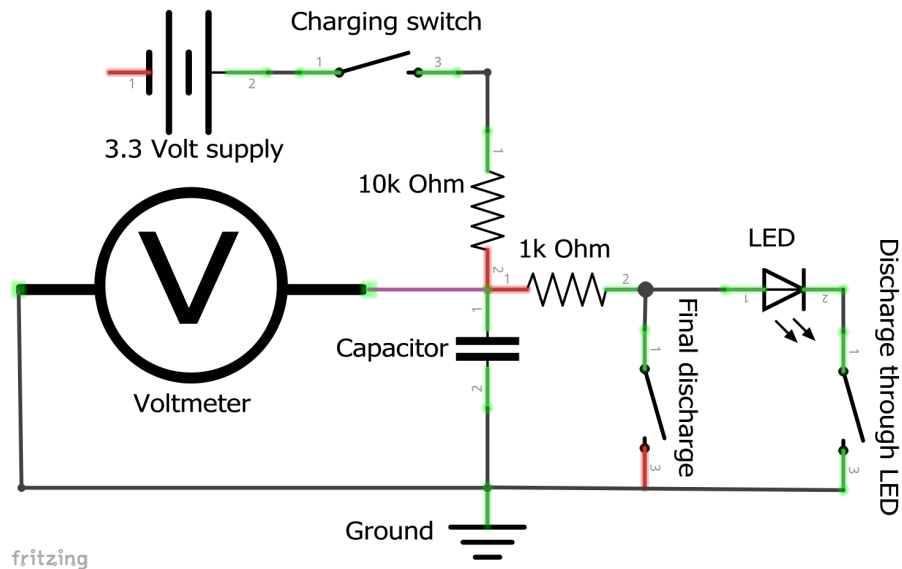


Figure 4: Capacitance Schematic

## 5 Adafruit Pinout

The LCD display you built earlier will not be changed. The circuit may be easier to work with if you use a second small breadboard for the new circuit, but it is not necessary (Figure 5).

First, attach the wire that will provide 3.3 V to the capacitor. Rather than drawing this from the 3.3 V power pin we have been using, we will use one of the digital pins so we can turn it on and off. It doesn't matter which one, but the code specifies pin # 4 (if you use a different pin, you must also change the given code). The ground does not need to be turned on and off, so we connect the ground end of the capacitor to the ground we have been using.

When you insert the capacitor, note that one pin is shorter than the other and may be marked with a (–) sign. Many capacitors are electrolytic capacitors and cannot be inserted backwards. The (–) pin must be connected to the ground and the other (longer) pin is connected to the 3.3 V power supply. If it is inserted backwards, the capacitor may be damaged or ruined.

You will notice that the LED also has one short pin. The LED is a diode: a semiconductor device that allows current to flow only in one direction. Diodes must be inserted so that the current flows from high potential source through the long pin and out the short pin; like the capacitor, the short pin goes to ground. If this is inserted backwards, the LED won't light, but it also won't be damaged unless the voltage is quite large.

Since the discharging of the capacitor must be controlled, the discharge wires are connected to the Adafruit digital pins. In this sketch, we are using pin # 6 for the discharge through the LED and pin # 5 for the final discharge.

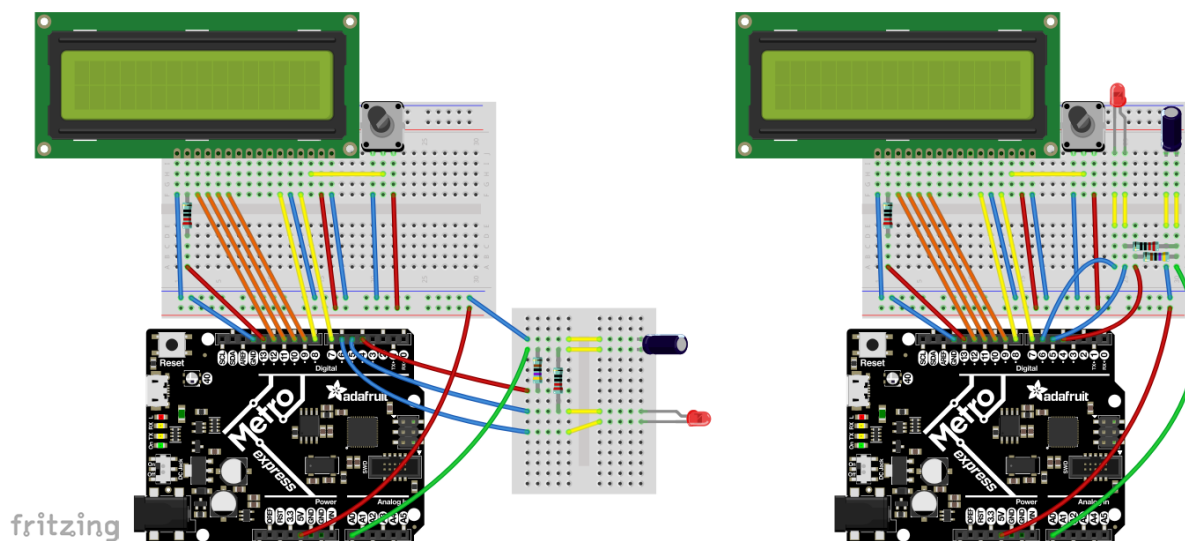


Figure 5: Pin-out Diagrams for the Capacitance Meter

The resistors are suggested values. As you experiment with the capacitance meter, you will be able to replace these resistors with others and see how the results are affected. If the  $10\text{ k}\Omega$  resistor is replaced, you will have to update the code and reload it to the Adafruit. The resistor in the discharge circuit has no effect on the operation of the meter and can be changed at any time. You will note that this resistor affects how long the LED remains lit during discharge and how bright it is.

## 6 Code for the Adafruit

The code for this lab is reproduced below, but is also available in a separate .py file. Note that the value of the resistor is set to 10,000  $\Omega$  (# define resistorValue). If your time constant is too long or too short you will need to replace the resistor with a different one, and this line of code will also have to be changed. You must upload the new code to the Adafruit before it takes effect.

Remember that anything after # is a comment. It gets messy, but read them. If you have programming experience, you may feel that this is some ugly code – feel free to improve it!

```
"""
* This code is included with the files for Adafruit Labs Capacitance Meter by
* Matthew Riehl and is in the public domain. I have only modified the
* code to better support the laboratory exercise. Several Capacitance Meters
* are described online. The original inspiration for this project is from
* https://www.arduino.cc/en/Tutorial/Foundations/CapacitanceMeter and
* https://www.circuitbasics.com/how-to-make-an-arduino-capacitance-meter/ and
* https://electronoobs.com/eng_arduino_tut10_1.php.
*
* Perhaps the hardest part was translating the code from C++ into Python.
*
* Note that the pin assignments for the LCD are NOT the same as found on many
* projects. They have been moved around to make the wiring more
* intuitive and easier to troubleshoot.
```

The LCD circuit:

```
* LCD RS pin to digital pin 7
* LCD Enable pin to digital pin 8
* LCD D4 pin to digital pin 9
* LCD D5 pin to digital pin 10
* LCD D6 pin to digital pin 11
* LCD D7 pin to digital pin 12
* LCD Backlight (pin 15 on LCD) to pin 13 on (might
need to add a 220 ohm series resistor)
* LCD R/W pin to ground
* LCD VSS pin to ground
* LCD VCC pin to 5V
* 10K potentiostat:
- ends to +5V and ground
- wiper to LCD V0 pin (pin 3)
```

Additional circuit elements for the Capacitance Meter:

```
* pin 4 charges the capacitor
* pin 5 is ground as the final discharge pin
* pin 6 is ground for the initial discharge pin (lights the LED)
* pin A5 monitors the voltage across the capacitor
"""
```

```
import time
import board
import digitalio
import adafruit_character_lcd.character_lcd as characterlcd
from analogio import AnalogIn
```

```

# Define variables and constants
ResistorValue = 5000    # This is the known resistor -- this value must be
# changed to the actual value of R1.

VoltagePin = AnalogIn(board.A5) # Analog to Digital data -- read at A5
ChargePin = digitalio.DigitalInOut(board.D4)
dischargePin = digitalio.DigitalInOut(board.D6)
dischargePin2 = digitalio.DigitalInOut(board.D5)
microFarads = 0
nanoFarads = 0
average = 0
count = 0
volt = 0
elapsedTime = 0

def get_voltage(pin):
    return ((pin.value / 65536) * 3.3)

# Modify this if you have a different sized character LCD
lcd_columns = 16
lcd_rows = 2

# Metro M0/M4 Pin Config:
lcd_rs = digitalio.DigitalInOut(board.D7)
lcd_en = digitalio.DigitalInOut(board.D8)
lcd_d7 = digitalio.DigitalInOut(board.D12)
lcd_d6 = digitalio.DigitalInOut(board.D11)
lcd_d5 = digitalio.DigitalInOut(board.D10)
lcd_d4 = digitalio.DigitalInOut(board.D9)
lcd_backlight = digitalio.DigitalInOut(board.D13)

# Initialise the LCD class
lcd = characterlcd.Character_LCD_Mono(
    lcd_rs, lcd_en, lcd_d4, lcd_d5, lcd_d6, lcd_d7, lcd_columns, lcd_rows, lcd_backlight
)

lcd.clear()
lcd_backlight = True
ChargePin.direction = digitalio.Direction.INPUT
dischargePin2.direction = digitalio.Direction.OUTPUT
dischargePin2.value = False
lcd.message = "Capacitance \nMeter!!!"
time.sleep(3)
lcd.message = ("R1 Resistance \n{} Ohms ".format(int(ResistorValue)))
time.sleep(3)
volt = get_voltage(VoltagePin)
while volt > 0:
    time.sleep(0.1)
    volt = get_voltage(VoltagePin)

```

```

lcd.clear()
dischargePin2.direction = digitalio.Direction.INPUT
dischargePin.direction = digitalio.Direction.INPUT

# now = time.monotonic()    # the time now (in seconds)

while True: # This loop continues forever.

    lcd.message = "Charging...."
    ChargePin.direction = digitalio.Direction.OUTPUT
    ChargePin.value = True
    start = time.monotonic()      # start counting time.
    while volt < 2.067:
        volt = round(get_voltage(VoltagePin), 3)
        lcd.message = ("\nV = {} Volts ".format(float(volt)))

        elapsedTime = time.monotonic() - start
        microFarads = (elapsedTime / ResistorValue) * 1000000
        lcd.clear()
        if microFarads > 1:
            lcd.message = ("{} uF \n{} seconds" .format(float(microFarads), float(elapsedTime)))
            time.sleep(3)
            # lcd.clear()
        else:
            lcd.message = ("{} seconds \n {}nF" .format(float(microFarads/1000), float(elapsedTime)))
            time.sleep(3)
            lcd.clear()
        while volt < 3.000:
            volt = round(get_voltage(VoltagePin), 3)
            lcd.message = ("\nV = {} Volts ".format(float(volt)))
            lcd.clear()
            while volt > 1.65:
                volt = round(get_voltage(VoltagePin), 3)
                lcd.message = ("Discharging... \n{} Volts" .format(float(volt)))
                ChargePin.direction = digitalio.Direction.INPUT
                dischargePin.direction = digitalio.Direction.OUTPUT
                dischargePin.value = False
                while volt > 0:
                    volt = round(get_voltage(VoltagePin), 3)
                    lcd.message = ("Discharging... \n{} Volts" .format(float(volt)))
                    dischargePin.direction = digitalio.Direction.INPUT
                    dischargePin2.direction = digitalio.Direction.OUTPUT
                    dischargePin2.value = False
                    lcd.clear()
                    average = ((average * count) + microFarads) / (count + 1)
                    count += 1
                    lcd.message = ("Count = {} times \nAvg = {} uF" .format(int(count), float(average)))
                    time.sleep(3)
                    lcd.clear()
            dischargePin2.direction = digitalio.Direction.INPUT

```

When you have a working capacitance meter, ask your lab instructor for permission before continuing...

Two .py files are included on GitHub. The code above is a simple meter that cycles through charging and discharging, keeping track of the number of cycles and the average measured capacitance. The second file prints the voltage as a function of time on the Mu serial plotter. It is possible to write the output to a file for additional analysis.

## 7 Optimization of your Capacitance Meter

Keep track of what you do and take notes on the results. You will turn these in with your lab report.

You will optimize your capacitance meter by adjusting the resistance of the charging resistor so that the time constant,  $\tau$ , is more than one second, but not so long that you get bored waiting for the capacitor to charge (5 to ten seconds is ideal). You will also adjust the discharge resistor to maximize either the length of time the LED is lit or the intensity of the light. You should have at least a  $240\Omega$  resistor here at all times, otherwise you may damage the LED.

The accuracy of the capacitance meter necessarily depends on how accurately the resistance of the charging resistor is known. You may wish to measure this resistance with a commercial multi-meter and input the measured resistance.

A few other variables can be adjusted:

The program continues to charge the capacitor until the voltage is nearly 3.3 volts. As we saw above, the rate of charging becomes quite slow as  $q$  approaches  $q_0$ . If  $C$  is large, you may wish to lower the voltage at which the program switches from charging to discharging the capacitor.

The program discharges the capacitor through the LED until a pre-set voltage is reached, and then it switches to the secondary discharge circuit which bypasses the LED. Since LEDs are semiconductor devices, they do not obey  $V = IR$ ; when  $V$  falls below a certain threshold voltage, the current essentially ceases. The threshold voltage depends on various things, including the color of the LED: red and other long wavelengths of LEDs have lower threshold voltages than shorter wavelength LEDs like green and blue. You should adjust this pre-set voltage so that the LED is very dim, but not extinguished, when the switch occurs.

NOTE: The voltage is read by one of the analog pins on the Adafruit. The Adafruit then digitizes the voltage by assigning it a number between 0 ( $= 0V$ ) and 65536 ( $= 3.3V$ ). The voltage value that corresponds to the time constant,  $\tau$ , is a digital reading of  $65536 \times 0.632 = 41419$  or an analog voltage of  $0.632 \times 3.3 = 2.086$  Volts.

## 8 Capacitors in Series and in Parallel

Again, please keep a record of your work and calculations on a separate page to turn in.

In this section, you will investigate the capacitance of a circuit that contains multiple capacitors in series or in parallel. The Adafruit will measure the capacitance of the circuit and you will compare this to the expected results, calculated from the known capacitance's.

As we saw earlier, the equivalent capacitance of two or more capacitors in parallel is the sum of the individual resistances.

$$C_{Parallel} = C_1 + C_2 + \cdots = \sum_i C_i$$



When capacitors are in series, however, it can be shown that the equivalent capacitance is:

$$\frac{1}{C_{series}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots = \sum_i \frac{1}{C_i}$$

1. Construct circuits that contain at least two or three capacitors in series and measure the capacitance with your new meter. If necessary, replace your charging resistor with one suitable for the capacitance you are measuring.
2. Draw each circuit, label each capacitor with the known capacitance, and calculate the expected capacitance of the circuit.
3. Calculate the percent error.
4. Repeat steps 1-3 with circuits that contain at least two or three capacitors in parallel.
5. Repeat steps 1-3 with circuits that contain at least three or four capacitors with both parallel and series components.