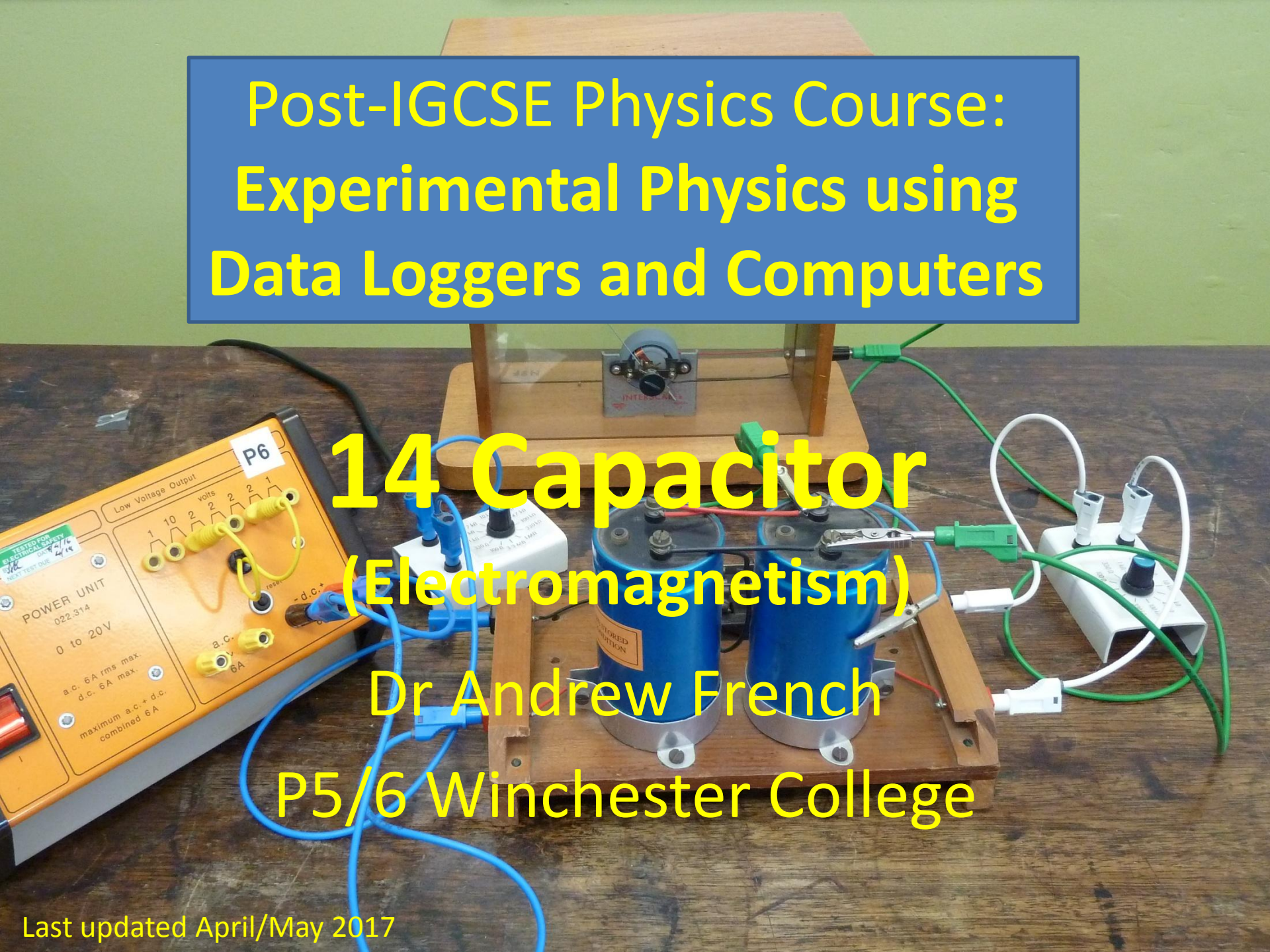
Post-IGCSE Physics Course:

Experimental Physics using Data Loggers and Computers



14 Capacitor

(Electromagnetism)

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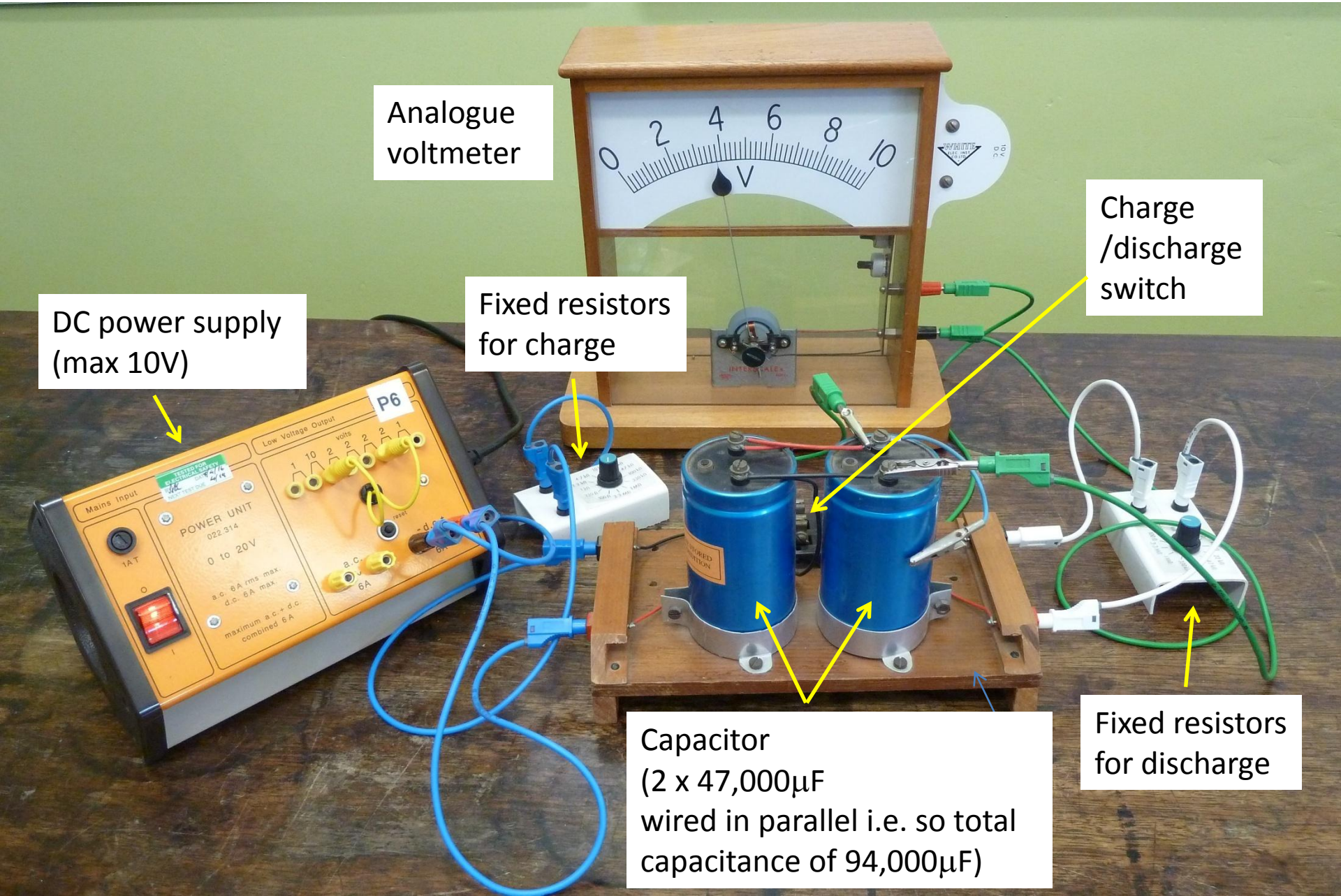
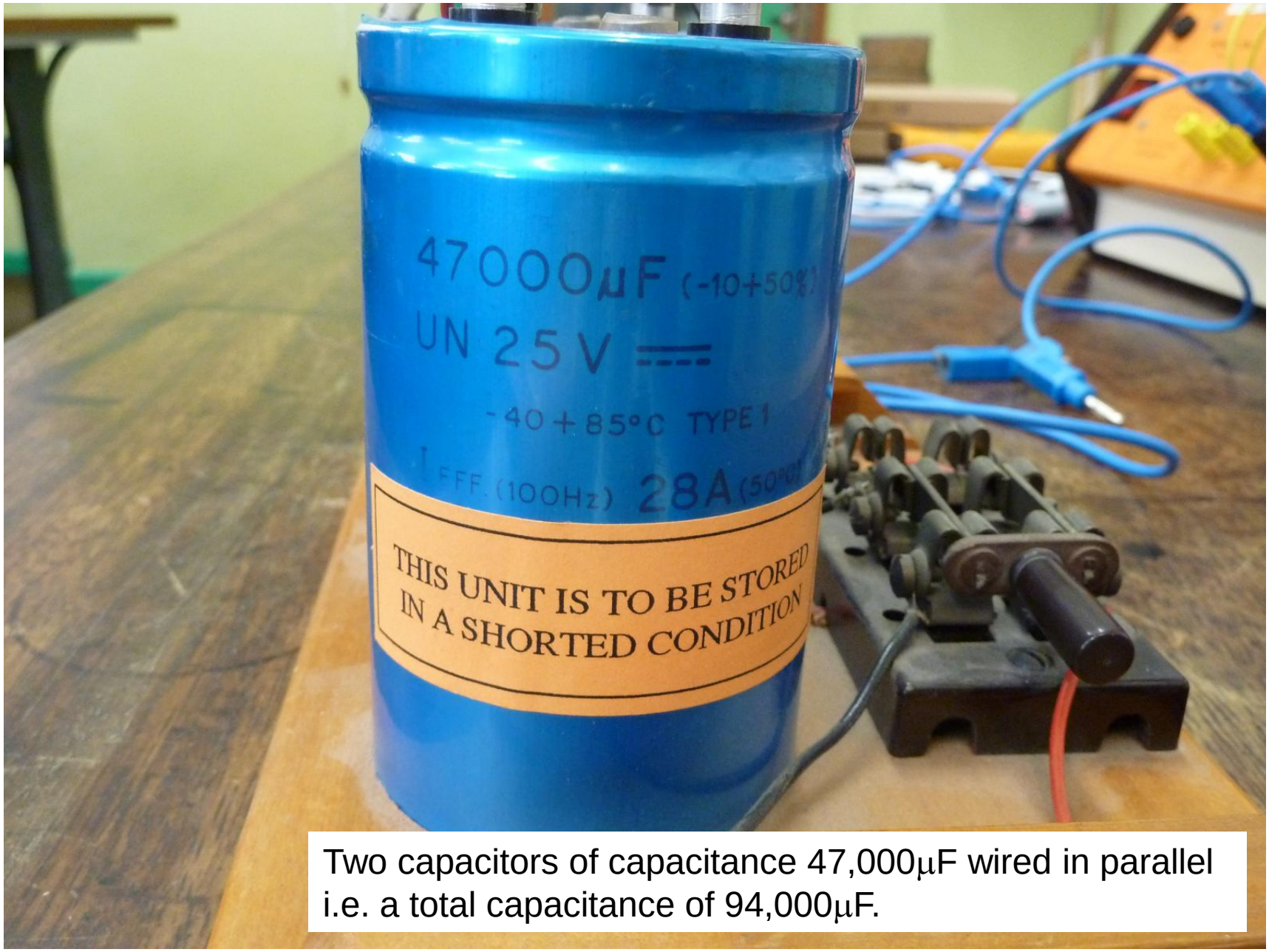
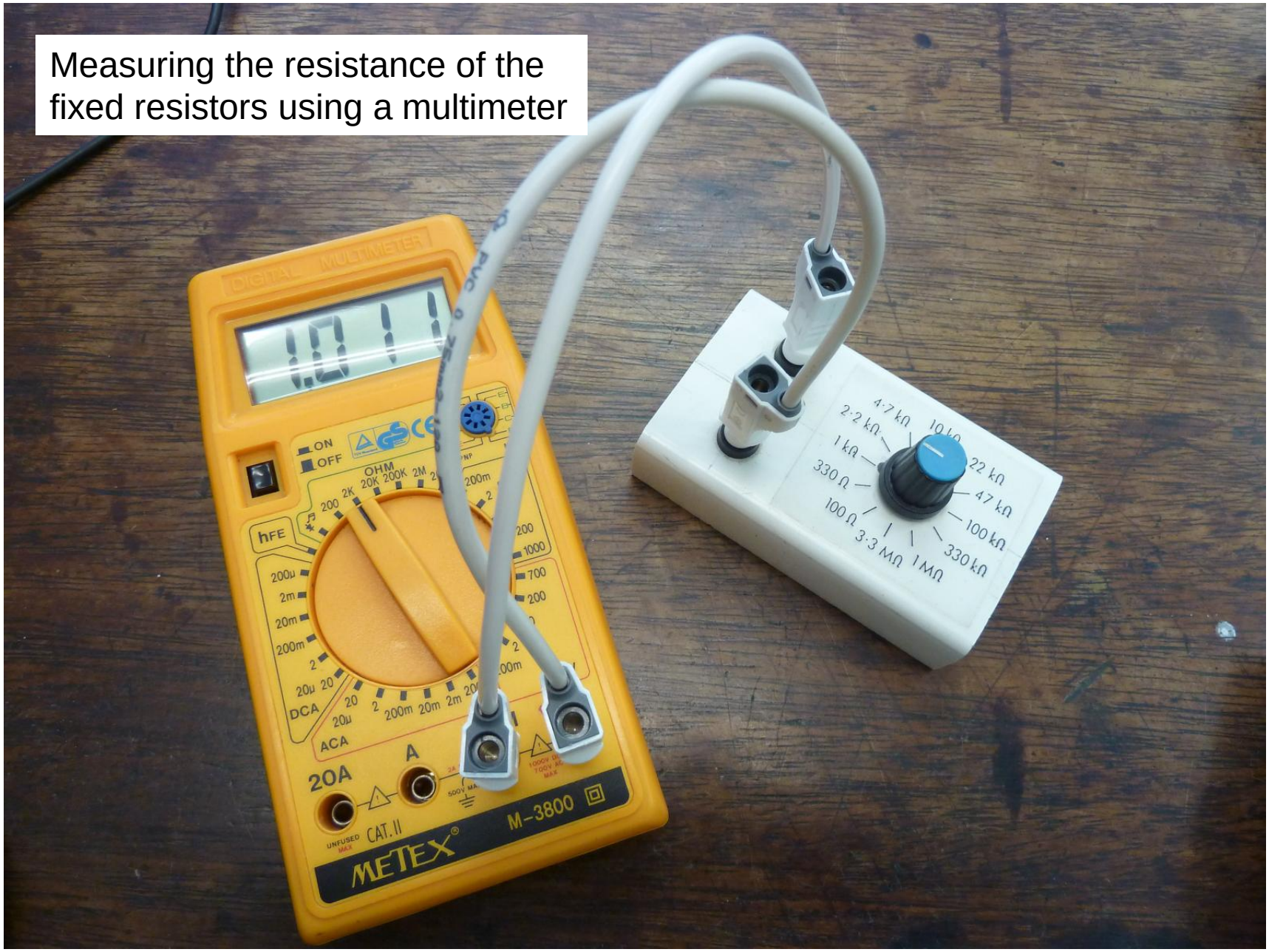
Last updated April/May 2017

Experimental setup





Two capacitors of capacitance 47,000μF wired in parallel i.e. a total capacitance of 94,000μF.


Measuring the resistance of the fixed resistors using a multimeter
DIGITAL MULTIMETER
ON
OFF
OHM
hFE
DCA
ACA
20A
A
UNFUSED
CAT.II
METEX
M-3800
4·7 kΩ
10 kΩ
2·2 kΩ
22 kΩ
1 kΩ
47 kΩ
330 Ω
100 kΩ
100 Ω
330 kΩ
3·3 MΩ
1 MΩ

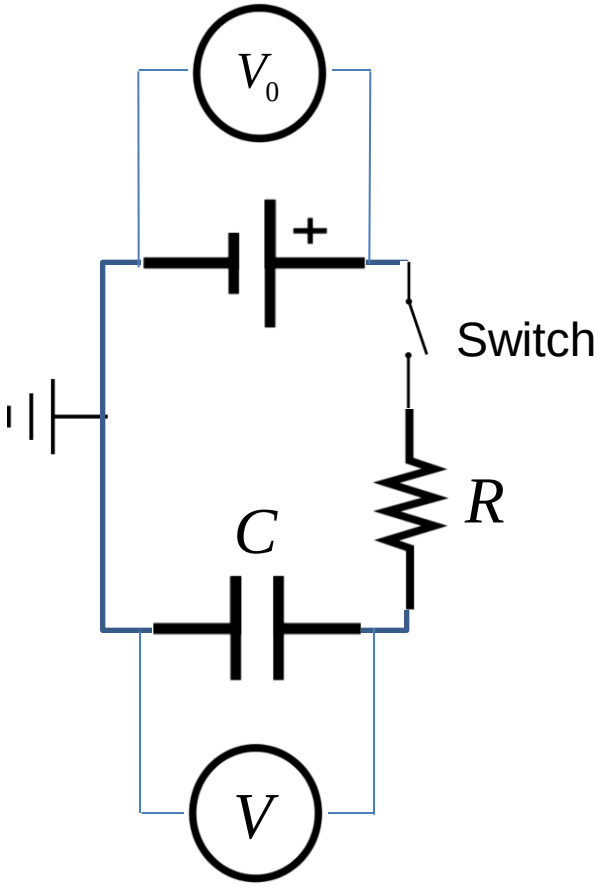
Charging a capacitor using a DC source

1. Switch closed. Current flows through resistor and positive charge builds up on right capacitor plate. An equal amount of negative charge builds up on left plate.

2. *Electrical field* set up between capacitor plates as no current can flow. Voltage V between the plates is $V = Q/C$ where Q is the total charge deposited and C is the *capacitance* ('charge per unit volt')

3. As charge builds up on right plate, potential difference between capacitor and source reduces. This reduces the current flowing onto the plate. Eventually the voltage V becomes V_0 and hence no more current can flow.

3. Note the amount of charge which can be deposited depends on the resulting *electrical field strength* between the plates. Above the breakdown field strength, current will flow between the plates



Dielectric	Breakdown field strength /Vm^{-1}
Air	3×10^6
Mineral oil	15×10^6
Neoprene	16×10^6
Water	65×10^6
Mica	118×10^6

Charging a capacitor using a DC source

$$Q = CV$$

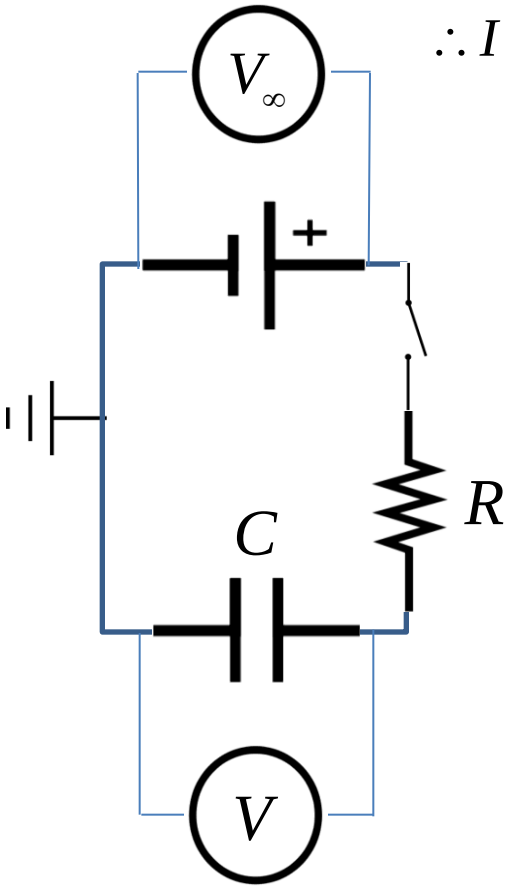
capacitor charge, voltage relationship

$$V_\infty - V = IR$$

Ohm's law

$$I = \frac{dQ}{dt}$$

Definition of current



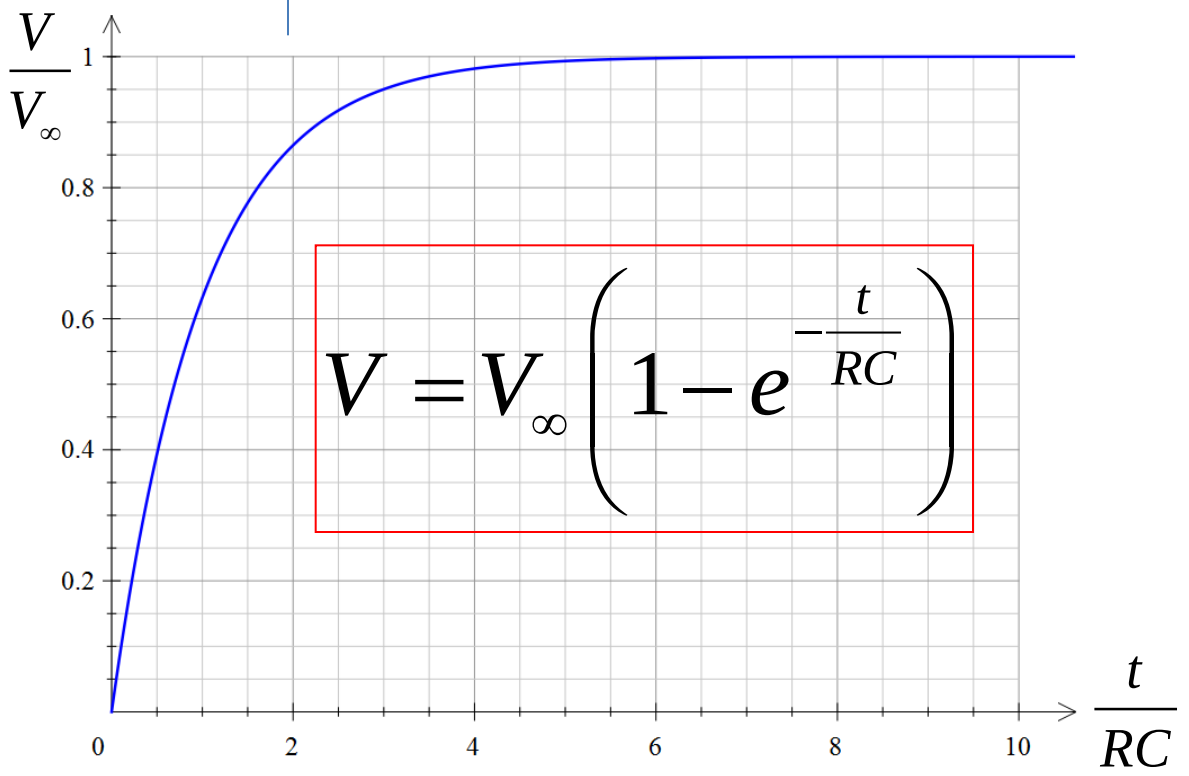
$$\therefore I = \frac{V_\infty - V}{R} = C\frac{dV}{dt}$$

$$\frac{1}{RC}\int_0^t dt = \int_0^V \frac{dV}{V_\infty - V} = -\int_0^V \frac{-dV}{V_\infty - V}$$

$$\frac{t}{RC} = -\left[\ln\left|V_\infty - V\right|\right]_0^V$$

$$-\frac{t}{RC} = \ln\left(V_\infty - V\right) - \ln\left(V_\infty\right) = \ln\left(\frac{V_\infty - V}{V_\infty}\right)$$

$$\frac{V_\infty - V}{V_\infty} = e^{-\frac{t}{RC}}$$



Discharging a capacitor

$Q = CV$

capacitor charge, voltage relationship

$V = IR$

Ohm's law

$I = -\frac{dQ}{dt}$

Definition of current, and negative since charge is discharged from plates

$$\therefore I = \frac{V}{R} = -C\frac{dV}{dt}$$

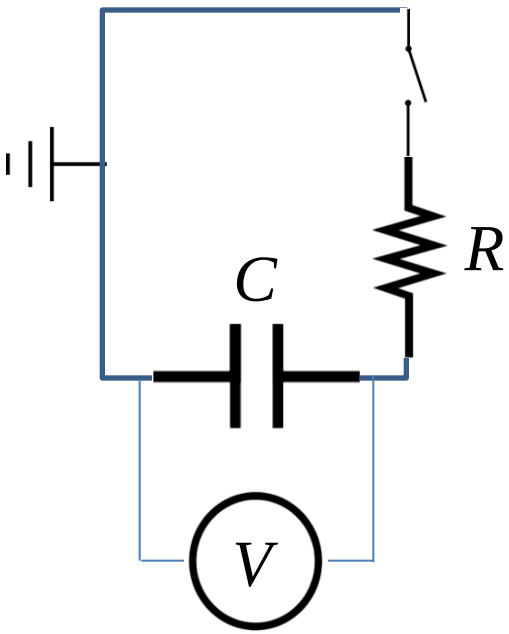
$$\frac{1}{RC}\int_0^t dt = -\int_{V_0}^{V}\frac{dV}{V}$$

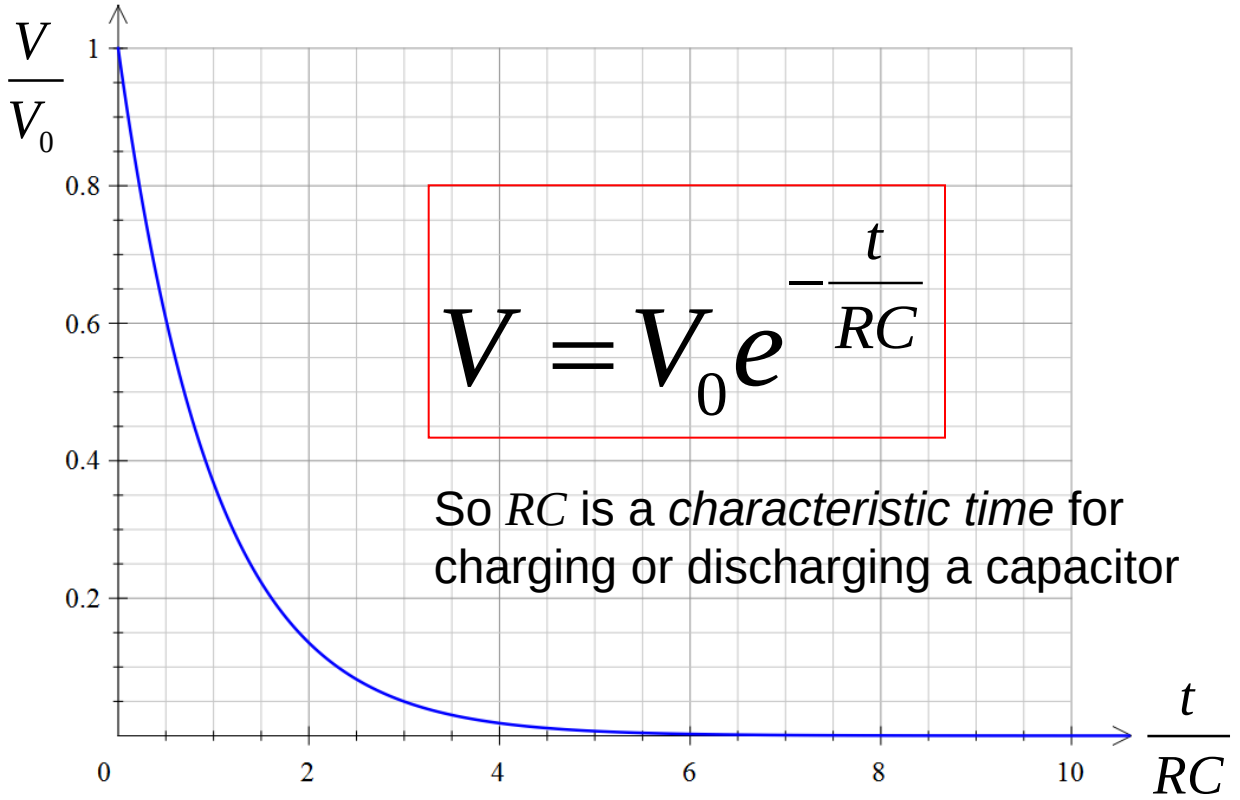
$$\frac{t}{RC} = -\left[\ln|V|\right]_{V_0}^{V}$$

$$\frac{t}{RC} = -\ln\left(\frac{V}{V_0}\right)$$

$$V = V_0 e^{-\frac{t}{RC}}$$

Note $V=V_0$ when $t = 0$





$$V = V_0 e^{-\frac{t}{RC}}$$

So RC is a *characteristic time* for charging or discharging a capacitor

During **charging** phase, MATLAB **`keytime.m`** program is run, and a button on the keyboard is pressed when a fixed voltage is reached. 1,2,3,4,5,6,7,8, 9.5V are an appropriate set.

`keytime.m` stores the times of button presses to high precision. It is essentially a stopwatch with a split time facility.

Once charging is 'complete,' pressing '`q`' and then return will stop the timer and export the timings into an Excel sheet.

The process is repeated for the **discharging** phase.

Charging and discharging is then repeated for the range of fixed resistors.

From the recorded data, both the capacitance and the internal resistance of the circuit can then be calculated.

```
%keytime
% Program which displays the time, and time differences when a key is
% pressed.

function keytime

%Display message to command window
disp(' ');
disp(' %%%%%%%%%%%%%%%%%' )
disp('  Key press timer ' )
disp(' %%%%%%%%%%%%%%%%%' )
disp(' ')
disp(' Press return key to start .... Although note q will quit the program');

%Wait for user input to start the clock
i = input(' ','s');
if strcmp(i,'q')
    return
else
    disp(' Timer started ')
end

%Start clock
t0 = tic;

%Loop timer, checking for user input
stop = 0;
tstart = 0;
t=0;
while stop == 0
    i = input(' ','s');
    if strcmp(i,'q')
        %Save time array to Excel if q key pressed
        finish_time = strrep( datestr(now),':','-' );
        C{1,1} = ['Time data /s finished at ',finish_time];
        C{3,1} = 'Time';
        for n=1:length(t)
            C{3+n,1} = t(n);
        end
        xlswrite( ['Timing ', finish_time],C );
        return
    end
    tstop = toc(t0);
    t = [t,tstop];
    disp([' Time elapsed is ',num2str(tstop),'s']);
    disp([' Time between key presses is ',num2str( tstop - tstart ),'s'])
    tstart = tstop;
end

%End of code
```

MATLAB `keytime.m` program.

Capacitor charge & discharge experiment. 4P1. Winchester College 9-10th May 2017.

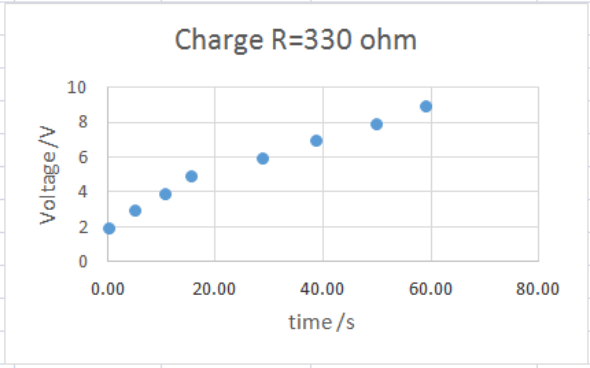
Supply voltage VS /volts	11.34

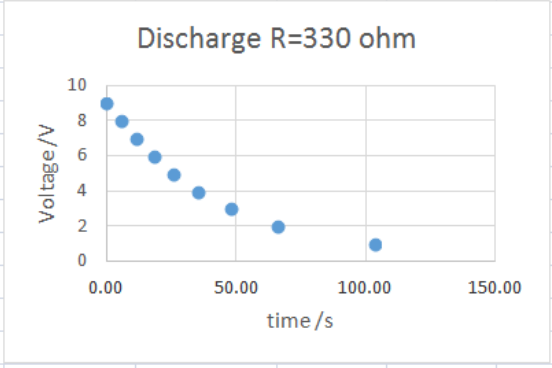
Charging R = 330 ohms

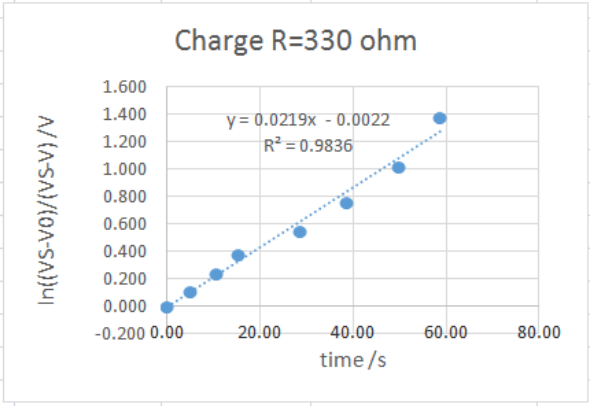
time /s	voltage /V	ln((VS-V0)/(VS-V))
0.00	2	0.000
4.87	3	0.113
10.45	4	0.241
15.22	5	0.387
28.44	6	0.559
38.43	7	0.766
49.56	8	1.028
58.65	9	1.384

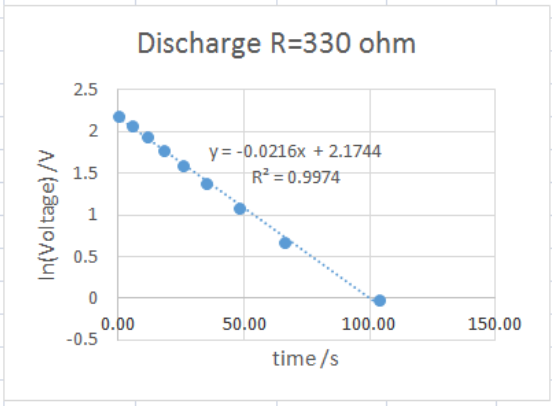
Discharging R = 330 ohms

time /s	voltage /V	ln(V)
0.00	9	2.197225
5.67	8	2.079442
11.41	7	1.94591
18.01	6	1.791759
25.56	5	1.609438
34.96	4	1.386294
47.93	3	1.098612
66.13	2	0.693147
103.38	1	0









RC /s	45.66

RC /s	46.30

Discharge

$$V = V_0 e^{-\frac{t}{RC}}$$

$$\ln V = \ln V_0 - \frac{t}{RC}$$

Obtain RC from gradient of $\ln V$ vs t graph

Charge

Note V_0 is often not zero!

$$V = V_0 + (V_\infty - V_0)\left(1 - e^{-\frac{t}{RC}}\right)$$

$$V = V_0 - V_0 + V_0 e^{-\frac{t}{RC}} + V_\infty - V_\infty e^{-\frac{t}{RC}}$$

$$e^{-\frac{t}{RC}}(V_\infty - V_0) = V_\infty - V$$

$$\frac{t}{RC} = \ln\left(\frac{V_\infty - V_0}{V_\infty - V}\right)$$

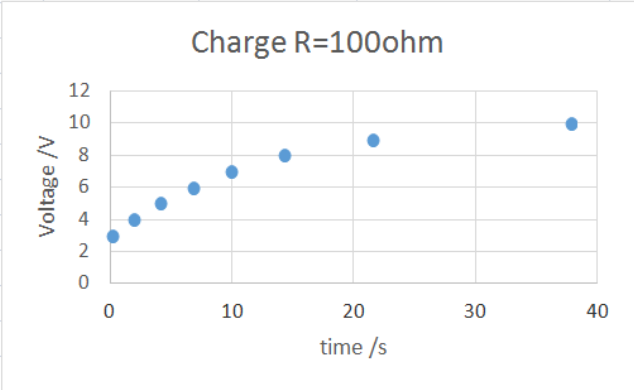
Obtain RC from gradient of $\ln($ ... $)$ vs t graph

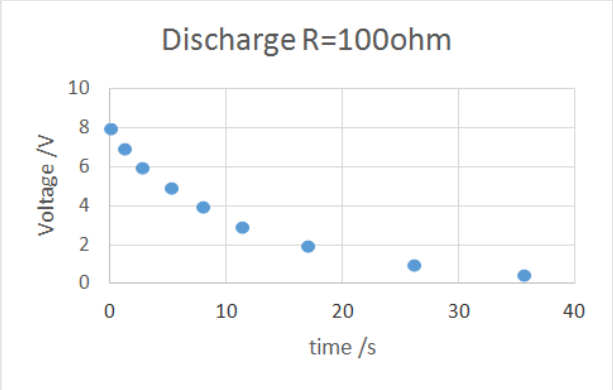
Charging R = 100 ohms

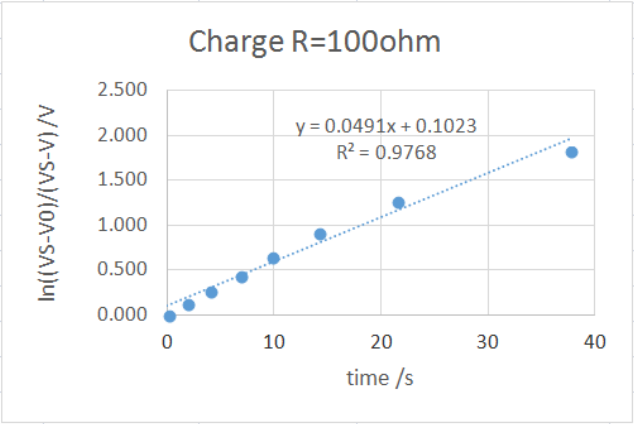
time /s	voltage /V	ln((VS-V0)/(VS-V))
0	3	0.000
1.8479452	4	0.128
3.98388668	5	0.274
6.74392275	6	0.446
9.77592451	7	0.653
14.1917552	8	0.915
21.4638202	9	1.271
37.7117969	10	1.828

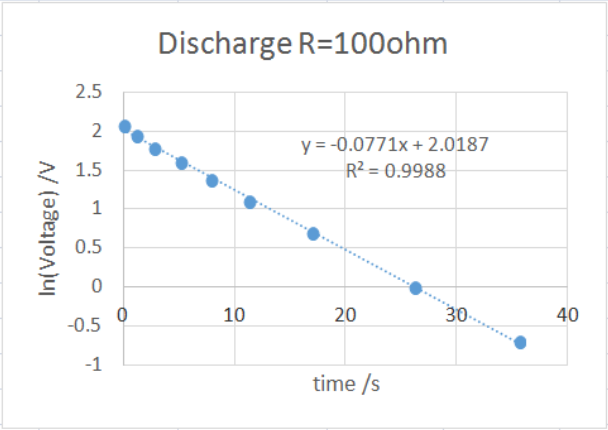
Discharging R = 100ohms

time /s	voltage /V	ln(V)
0	8	2.07944
1.1998906	7	1.94591
2.751837	6	1.79176
5.215849	5	1.60944
7.9038423	4	1.38629
11.343842	3	1.09861
16.959821	2	0.69315
26.199753	1	0
35.591726	0.5	-0.69315









RC /s	20.37

Anomalous!

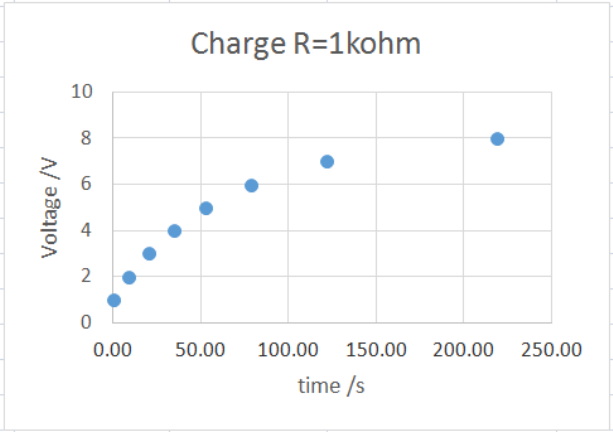
RC /s	12.97

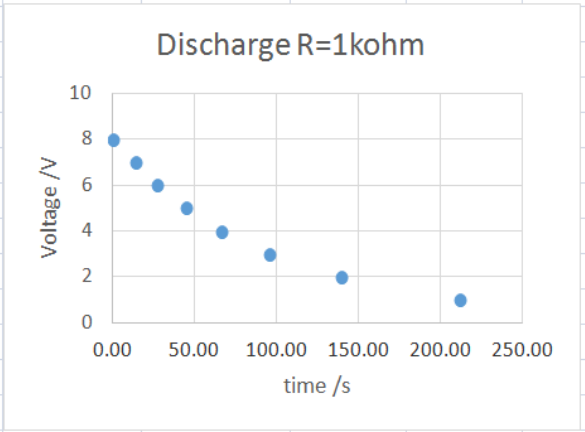
Charging R = 1k ohms

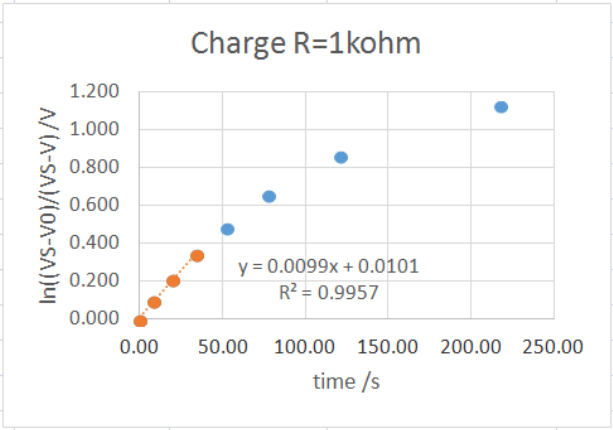
time /s	voltage /V	ln((VS-V0)/(VS-V))
0.00	1	0.000
8.30	2	0.102
20.03	3	0.215
34.27	4	0.343
52.74	5	0.489
78.06	6	0.661
121.08	7	0.868
218.06	8	1.130

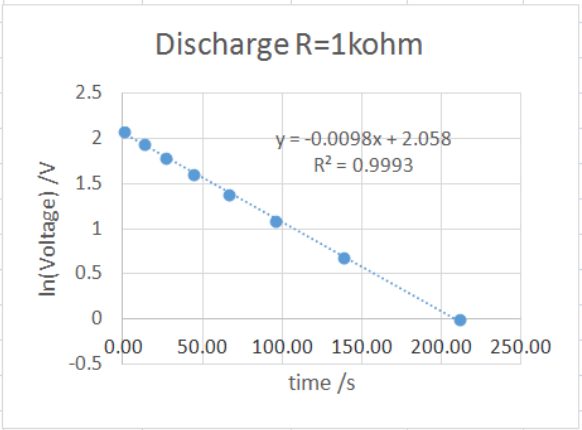
Discharging R = 1kohms

time /s	voltage /V	ln(V)
0.00	8	2.07944
13.46	7	1.94591
26.66	6	1.79176
44.35	5	1.60944
66.12	4	1.38629
95.26	3	1.09861
138.57	2	0.69315
211.19	1	0









RC /s	101.01

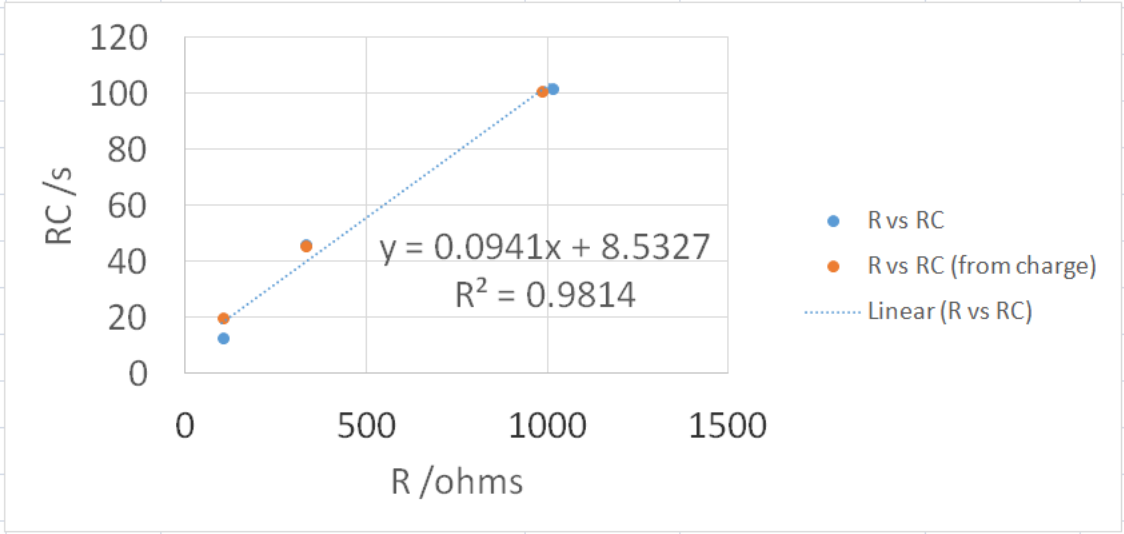
only using first four data points
which are linearly related

RC /s	102.04

R /ohms	RC (from discharge) /s
101.5	12.97
329	46.3
1012	102.04

C /microfarads
94100

Two capacitors connected in parallel.
Rating (printed on capacitor) is 47,000 micro farads each
so expect C = 94,000 microfarads



R /ohms	RC (from charge) /s
102.5	20.37
330	45.66
985	101.01

Only 100ohm result is anomalous!

Significant timing errors?
Might be worth repeating

Resistances measured using an Ohm meter

Calculate capacitance from gradient of resistance vs RC time graph, and internal resistance R_0 from intercept and gradient.

$$0.0941R + 8.533 = (R + R_0)C$$

$$\therefore C = 94{,}100\mu F$$

$$\therefore R_0 = \frac{8.533}{0.0941} = 90.7\Omega$$