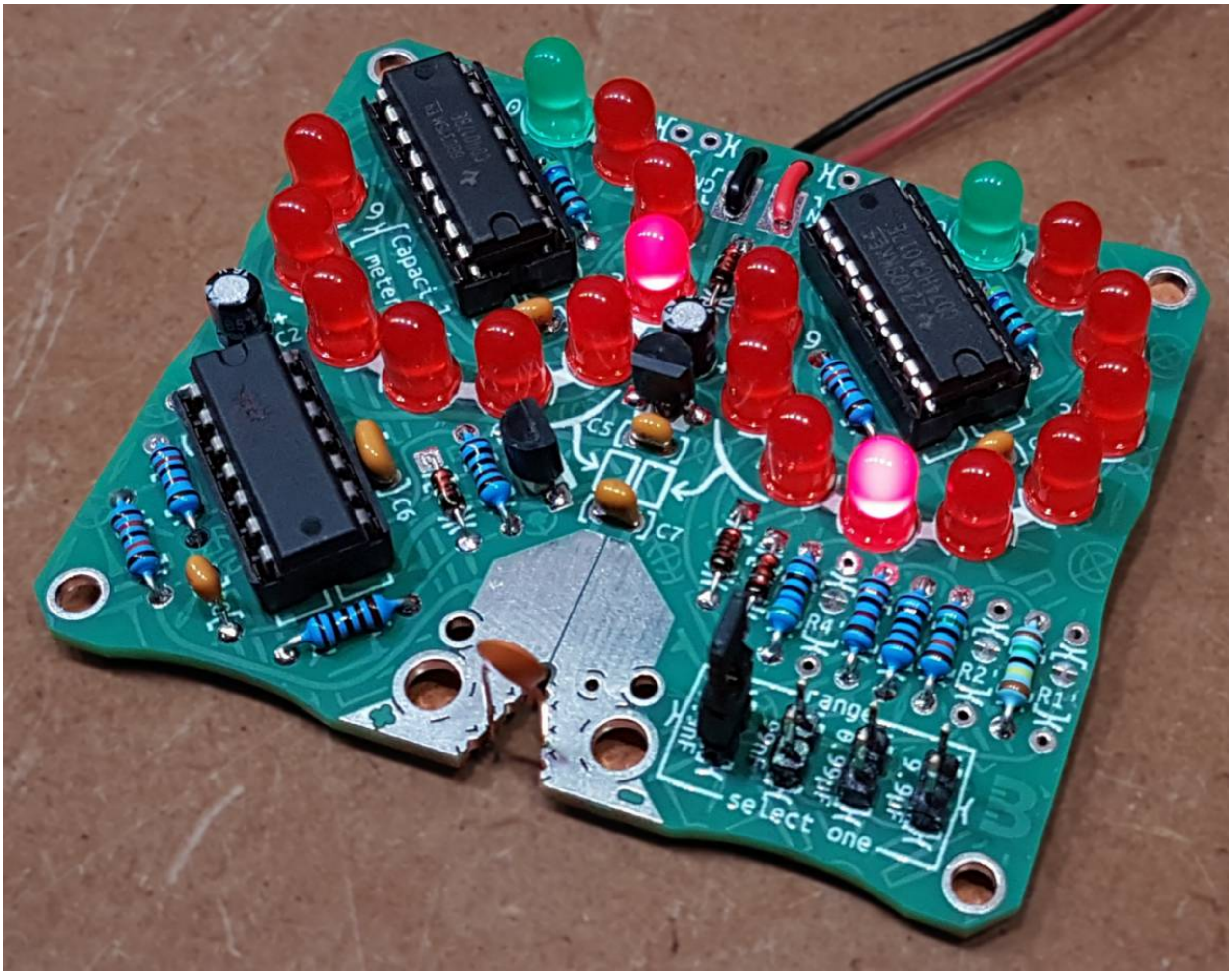
How it works



Capaci-Meter

A Boldport Project by

Jez Siddons, Stephen Bernhoeft and Boldport.

Introduction

This Capaci-Meter is based on a design that I created in 1984/1985 to submit for my UK O'Level Technology course project, I was 15/16 years old.

That original project used an almost identical measurement principle to this Boldport project. However, instead of the 3 digit 7-segment counter system that was used on the original version, I've opted for a more retro-style "Dekatron"-type arrangement of LEDs to represent 2 measurement digits.

With two digits for display, this is not designed to be an accurate measurement instrument, rather it is aimed at enabling the user to establish if a capacitor is close to the desired value, especially if the user has any difficulty reading the values printed on the capacitor itself.

Typical accuracies are in the order of ±5%, but this can be improved for each of the 4 measurement ranges by means of some fine-tuning resistors, space for which is provided on the Boldport PCB.

Bear in mind however that the 2 "digit" display can only provide a maximum theoretical accuracy of ±1% of full scale for each range. Furthermore, measurement quantization and jitter can add a further ±1 digit of error on any reading. So you could realistically yield a best possible accuracy of ±2% at full scale if all 4 ranges are fine tuned.

This project provides 4 measurement ranges, which should suit many of the capacitors that you're likely to be interested in testing.

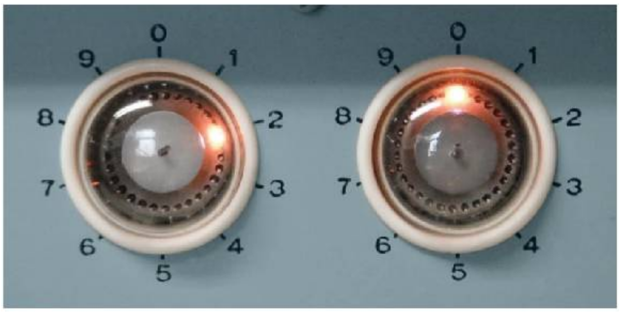
Range	Capacitance Minimum	Capacitance Maximum	Capacitance Resolution
1	0.2nF (200pF)	9.9nF	0.1nF (100pF)
2	2nF	99nF	1nF
3	0.02µF (20nF)	0.99µF (990nF)	0.01µF (10nF)
4	0.2µF (200nF)	9.9µF	0.1µF (100nF)

If a capacitance is too big for the currently selected range then the display will max-out at "99", indicating a possible over-range. If you see the reading "99" then, if possible, try a higher range to see if the capacitance was really over-range or perhaps sitting exactly on "99".

The minimum capacitance for each range is really a limit of the counter resolution (as well as jitter), hence the minimum is typically twice the measurement resolution.

✓ As with any measurement system, it's good to select a measurement range that gives you a reading that is as close as possible, but not over, the maximum full scale value.

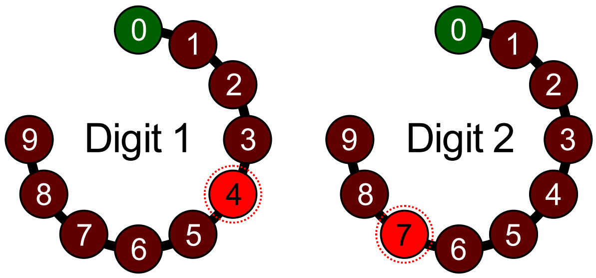
The Display



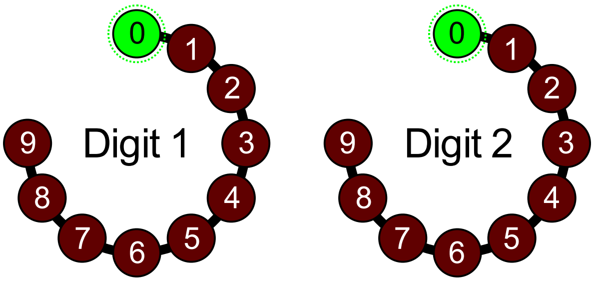
The display for the Capaci-Meter comprises of 2 digits that are each formed by circles of 10 LEDs. These circles are reminiscent of Dekatrons that were used for counter/displays long before the advent of chips, LEDs and even transistors.

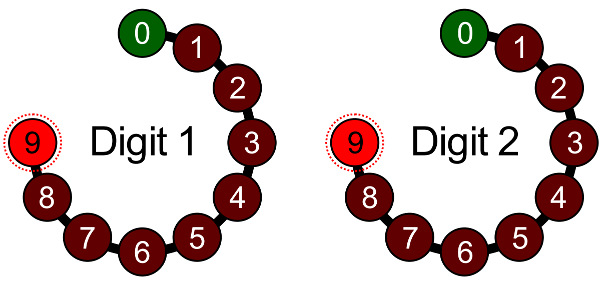
The Dekatron scheme for this project is useful because it's easy to get standard off-the-shelf chips that can count to 10 that also provide 10 individual outputs that can directly drive LEDs. The chips we use are the CD4017 type from the hugely varied CMOS 4000-series.

Unlike the original Dekatrons, the LEDs here are arranged in the same way as the hours on a clock, so it becomes more intuitive to read the display. For example, here is a value of "47" being displayed. So if the currently selected measurement range was 0.0-9.9µF then this display would represent 4.7µF.



In the following examples, the displays are showing zero and "99" respectively. The display may show "99" if the value being measured is exactly full-scale, or perhaps over-range.

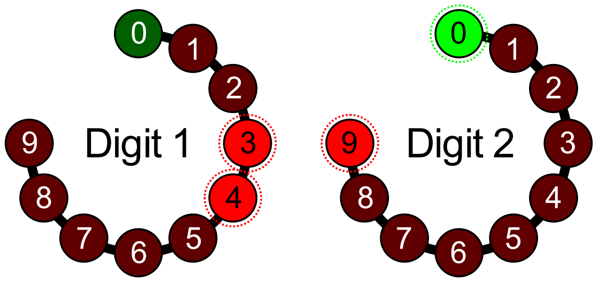




Jitter

Occasionally, it is possible that the display may be jittering between 2 values. This can happen if the capacitance is just on the border between two measurement steps, or perhaps there is some electrical noise that causes some small variations. In most circumstances it is easy to see what value is being displayed even if there is some jitter. However it can be trickier to interpret if Digit2 is jittering between 9 and 0 which would also cause Digit1 to jitter.

Here we can see that the display is jittering between "39" and "40". It can appear confusing to start with, but just remember that jitter typically occurs between adjacent values (such as 39 and 40). This means that we can be sure that the display is not showing "30" and "49" because they are not adjacent values.



✓ Remember that the LEDs in this project are arranged just like the hours on a clock face. Also, to make it easier to recognise "at-a-glance", the zeros are green LEDs.

The measurement principle

The overall principle relies on measuring the time it takes for the capacitor-under-test to charge up by a certain amount through a known resistor. This is done repeatedly and the amount of time is measured using a simple square wave generator and a counter.

The circuit comprises of 3 main sections:

"Cx dependent" Astable Multivibrator (where Cx is the capacitor under test)

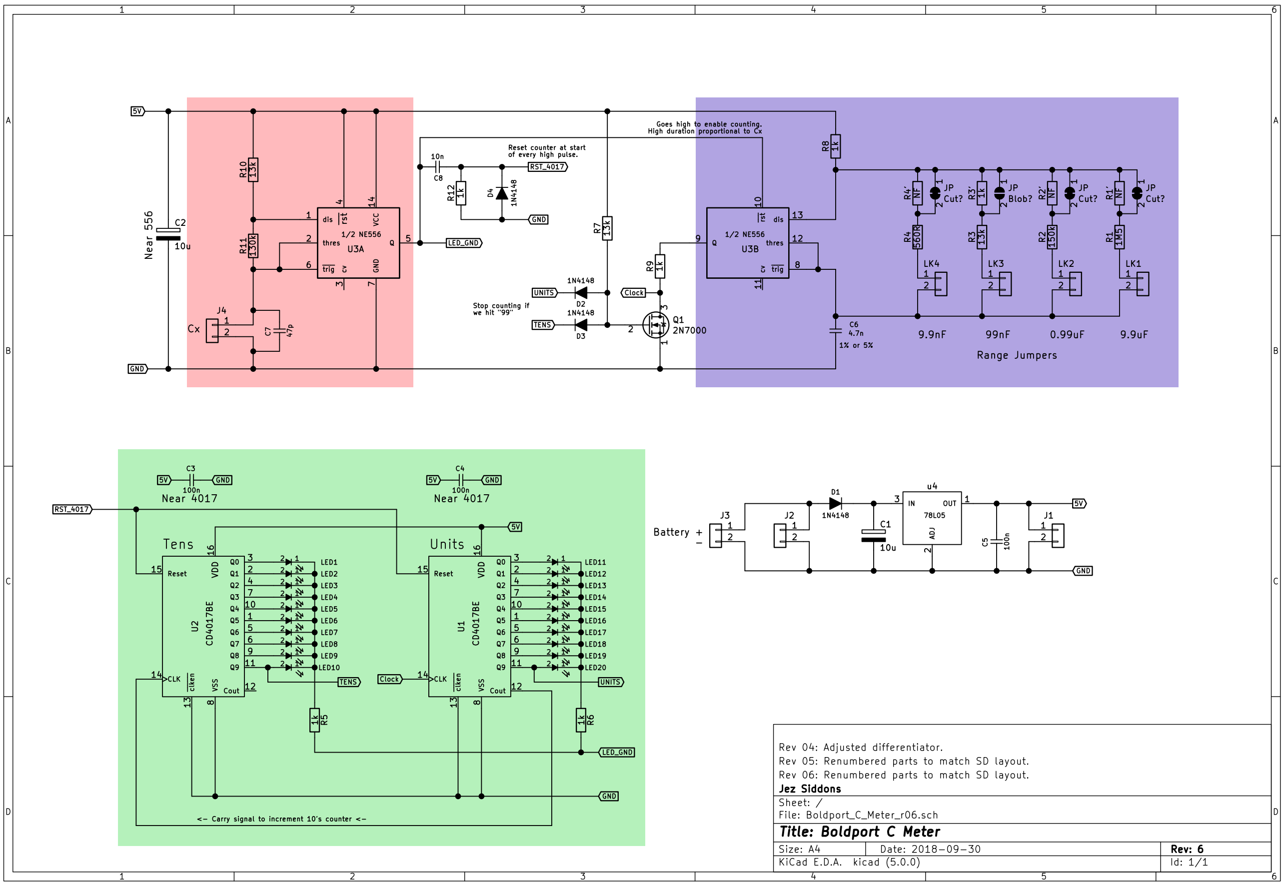
This generates continuous pulses that are proportional in duration to the size of the capacitor being measured.

"Master Clock" Astable Multivibrator

This generates a square wave that is used by the counter for measuring time. By changing the frequency of the square wave, we can change the effective measurement range of the whole instrument.

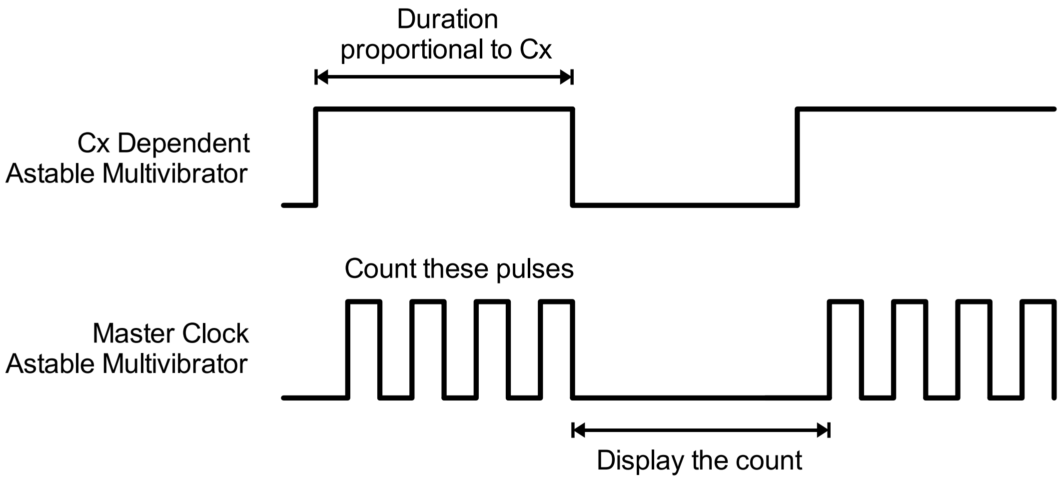
Counter/Display

The counter is responsible for counting the rising edges that come out of the "Master Clock". By doing so it can measure time. The counters also drive the LEDs which form the display.



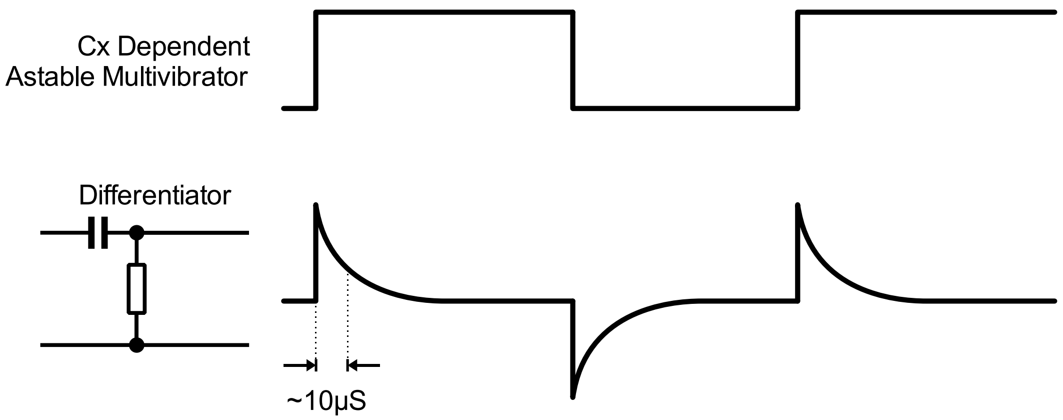
The "Cx dependent" Astable Multivibrator is a simple 555-based oscillator (actually half of a 556 dual-timer chip). It produces a rectangular signal of high and low pulses. The duration of the high and low pulses are proportional to the capacitance Cx. In this application, we're making good use of the high pulses. When the output of this stage is high then we want to enable the master clock (which is formed with the other half of the 556 dual-timer chip).

The "Master Clock" Astable Multivibrator is responsible for generating pulses that are fed into the counter/display. So when the "Cx dependent" astable multivibrator is producing a high level signal, the counter is counting the pulses from the "master clock". When the "Cx dependent" astable multivibrator is producing a low level signal, the counter no longer counts the "master clock" pulses, and at the same time, the LEDs are switched on so we can see the counted value.



Starting the count at zero

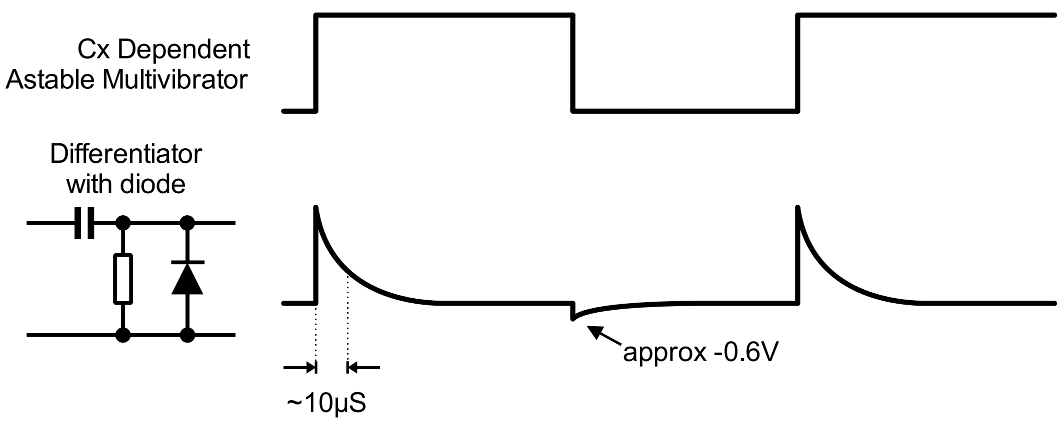
To make sure that the counter starts from zero every time the counting starts, we need to reset the counter on the rising edge of the signal coming out of the "Cx dependent" astable. We do this using a simple differentiator which gives very narrow pulses from each rising and falling edge of the rectangular signal.



The differentiator (as its mathematical name implies), gives a positive pulse when it experiences a rising edge on its input and gives a negative pulse when it sees a falling edge on its input.

The values of the capacitor and resistor in the differentiator circuit determine the rate of decay of the differentiated signal. Here we've chosen values that give about ⅔rds decay in 10μS, determined simply by T=RC.

It's only the positive pulses (from the rising edges) that we want to use for resetting the counters, so a diode is added to remove the negative pulses that are produced during the falling edges, that ensures that the counters don't experience signals that they are not designed to handle.

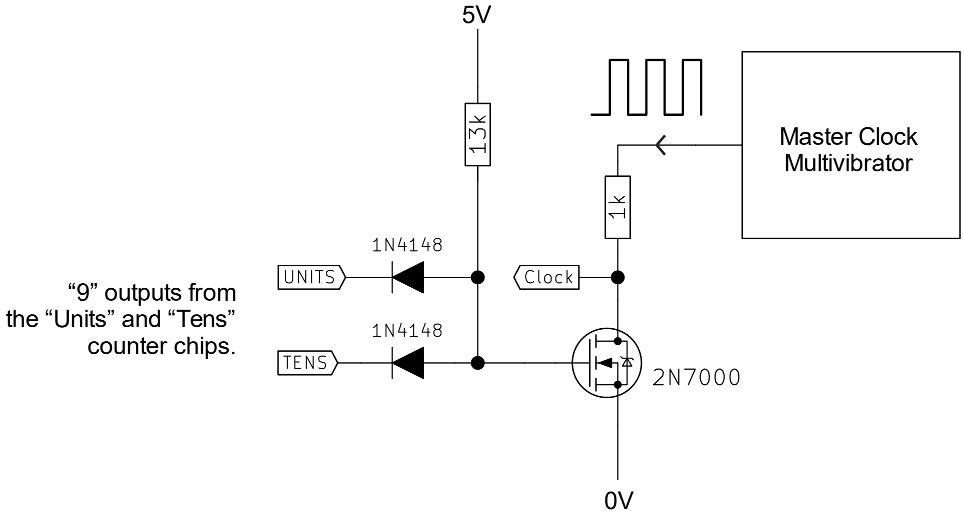


Preventing Roll-Overs

Another feature of the circuit that we haven't mentioned so far is the part that ensures that counting is stopped if it hits 99. Although not strictly necessary, if we didn't limit the count to 99 then the resultant count could be ambiguous if the number of counts exceeded 99 and rolled round.

From a logical point of view, we want to stop the count if the "units" count is 9 AND the "tens" count is also 9. So it's an AND gate that we need. We could use a logic gate chip to achieve that, but as it's only a single gate that is required then a whole chip is a waste (chips tend to typically provide four 2-input logic gates, and we only need one).

For just a single AND gate, we could use a pair of diodes and a MOSFET. When both the counters are outputting a high signal on the "9" outputs then we want to hold the master clock signal low to prevent further counts occurring.



The MOSFET will be off (and therefore completely open-circuit) if its gate voltage is below about 2V (the gate threshold voltage). In that situation, the MOSFET won't affect the clock signal coming out of the master clock.

Ignoring the diodes for now, the gate is held close to 5V by means of the 13k pull-up resistor, so the MOSFET would turn on and will effectively hold the master clock signal to ground, thereby preventing any counts.

Now consider the diodes. The MOSFET gate will only be allowed to get to 5V if neither diode is pulling the gate voltage down. This can only happen if both the "9" outputs from the counters are high (so the diodes cannot conduct and pull the gate voltage down). So when both "9" outputs are high then the MOSFET switches on and holds the master clock down thereby preventing any further counts.

If either (or both) of those lines were low then the MOSFET would be turned off and the master clock would happily feed through the 1k resistor and onwards to the counter clock input.

Master Clock Frequencies

We want the counter to count up to 99 for a capacitance that is “full-scale” for the relevant range that we’re currently on. As an example, testing a capacitor of 9.9µF on the top range (0-9.9µF), we want the count to reach exactly 99.

In our circuit, the duration of the high pulse coming out of the “Cx dependent” astable multivibrator is determined by the values of R10, R11 and Cx using the following formula:

$T_{HIGH} = 0.693 \times (R10 + R11) \times Cx$

We have values of 13k for R10, 130k for R11 and, in this example, 9.9µF for Cx. That gives us a high pulse duration of:

$T_{HIGH} = 0.693 \times (13000 + 130000) \times 9.9 \times 10^{-6}$

$T_{HIGH} = \underline{0.981 \text{ Seconds}}$

During that time we want to count 99 pulses from the master clock. So the frequency of the master clock (for this particular measurement range) can be calculated:

$f_{CLOCK} = 99 / 0.981$

$f_{CLOCK} = \underline{100.9 \text{ Hz}}$

That’s the frequency required for the 9.9µF range. If we reduce the capacitance range by a factor of 10 (to a full scale of 0.99µF) and we still want to count to 99, then the master clock frequency needs to go up by a factor of 10, and so on.

So here are the frequencies needed for each range and the associated resistor references that can be adjusted to control each frequency:

Range	T_{HIGH} at full scale	Master frequency	Range Resistor Pair
0.0nF to 9.9nF	981µS	100.9kHz	R4 and R4’
0nF to 99nF	9.81mS	10.09kHz	R3 and R3’
0.00µF to 0.99µF	98.1mS	1.009kHz	R2 and R2’
0.0µF to 9.9µF	0.981 Secs	100.9Hz	R1 and R1’

The frequencies above are the theoretical target values for each range, the actual frequencies may differ slightly due to the component tolerances of the timing components around U3B and also tolerances of the timer chip itself. If desired, the frequencies generated for each measurement range can be fine-tuned by adjusting the values of the relevant pairs of resistors R1 & R1’, R2 & R2’, R3 & R3’ and R4 & R4’.

✓ You can force the “master clock” astable multivibrator to generate a signal continuously by shorting the Cx test points together. During that time, the LEDs will be extinguished, but the master clock will be operating and can be checked on an oscilloscope or frequency counter.

Master Clock - Fine Adjustment Guide

Without making any adjustments, the accuracy is likely to be within ±5% of full scale, possibly better, so don't feel compelled to adjust anything unless you really want to. However, if desired, you can adjust the frequency of the Master Clock for each range to improve accuracy of the relevant range. Measure the master clock frequency by monitoring pin 9 of the 556 chip (U3) while the capacitor test leads are shorted. Then determine what percentage error you have compared to the theoretical target frequency for that range.

Target frequency	Range Resistor Pair
100.9kHz	R4 and R4'
10.09kHz	R3 and R3'
1.009kHz	R2 and R2'
100.9Hz	R1 and R1'

$$error\% = \frac{(f_{measured} - f_{target})}{f_{target}} \times 100$$

R1 Adjustments		
R1	**R1'**	**Freq. Adj.**
1.3M	110k	+6%
1.2M	220k	+5%
820k	620k	+4%
1.3M	150k	+3%
1.2M	270k	+2%
1.1M	390k	+1%
1.5M	**0**	**0.0%**
1.5M	15k	-1%
1.5M	30k	-2%
1.5M	47k	-3%
1.5M	62k	-4%
1.5M	75k	-5%
1.5M	91k	-6%

R2 Adjustments		
R2	**R2'**	**Freq. Adj.**
130k	11k	+6%
120k	22k	+5%
82k	62k	+4%
130k	15k	+3%
120k	27k	+2%
110k	39k	+1%
150k	**0**	**0.0%**
150k	1.5k	-1%
150k	3.0k	-2%
150k	4.3k	-3%
150k	6.2k	-4%
150k	7.5k	-5%
150k	9.1k	-6%

R3 Adjustments		
R3	**R3'**	**Freq. Adj.**
13k	160Ω	+6%
13k	300Ω	+5%
13k	430Ω	+4%
13k	560Ω	+3%
13k	680Ω	+2%
13k	820Ω	+1%
13k	**1k**	**0.0%**
13k	1.1k	-1%
13k	1.3k	-2%
12k	2.4k	-3%
13k	1.6k	-4%
12k	2.7k	-5%
13k	1.8k	-6%

R4 Adjustments		
R4	**R4'**	**Freq. Adj.**
510Ω	16Ω	+6%
510Ω	22Ω	+5%
510Ω	27Ω	+4%
510Ω	33Ω	+3%
510Ω	39Ω	+2%
510Ω	43Ω	+1%
560Ω	**0**	**0.0%**
560Ω	5.6Ω	-1%
560Ω	11Ω	-2%
560Ω	16Ω	-3%
560Ω	22Ω	-4%
560Ω	27Ω	-5%
560Ω	33Ω	-6%

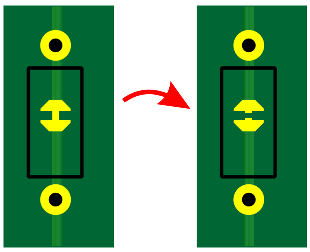
When you've worked out the percentage error for a particular range, use the tables here to work out the new resistor values.

The nominal values are highlighted in green.

For example:
If your frequency error for a particular range is +2.2% (too high) then you need to adjust the frequency by about -2% to get closer to the target frequency.

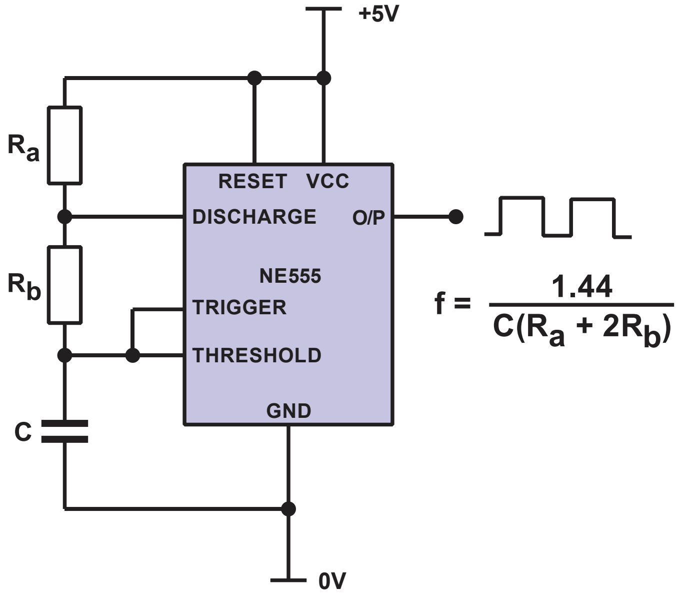
These tables assume you're using resistors with 1% tolerance or better.

Remember, if the resistor position that you want to place a resistor has a "shorted pad" then make sure you carefully cut the short with a craft knife before you fit the resistor.



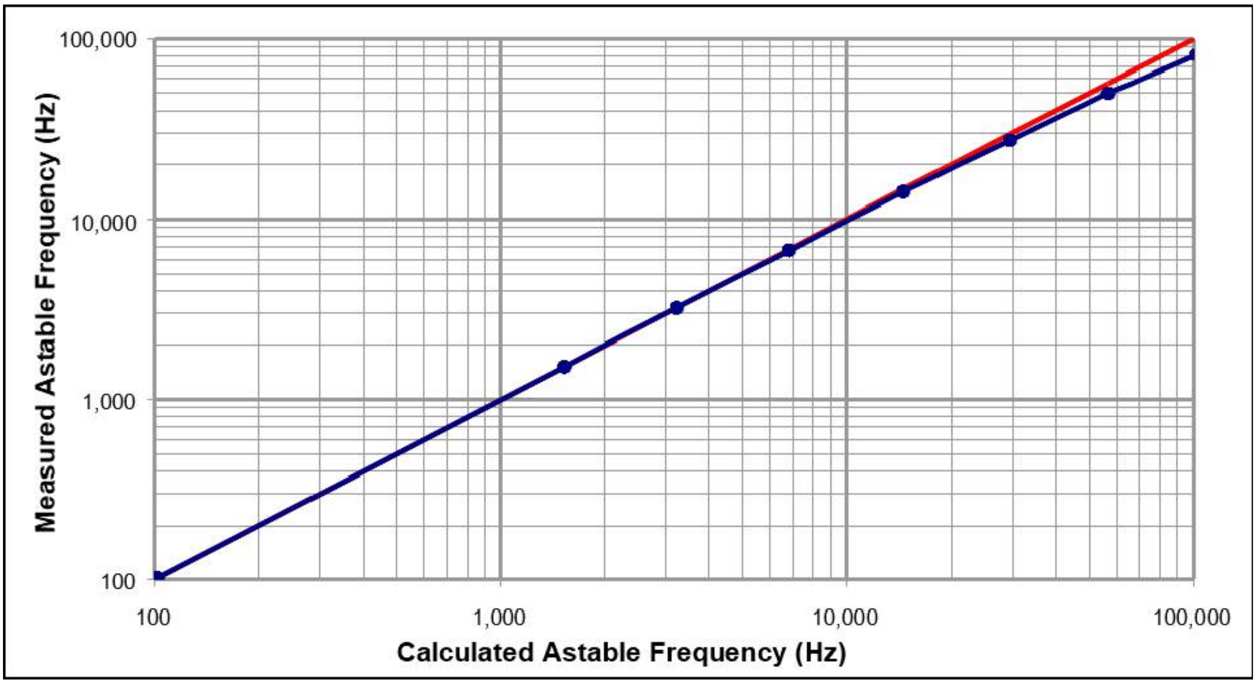
Master Clock - Deviation from theoretical values

For all 4 measurement ranges, the astable multivibrator that is used for the master clock will be generating a frequency over quite a wide range, from around 100Hz to around 100kHz. Here's the standard 555 astable multivibrator configuration along with the theoretical frequency formula:



As we approach higher frequencies, the actual output frequency will deviate from the theoretically calculated frequency.

I've observed this deviation when taking some measurements using a real 556 chip in the same configuration as used in this project:



This observed deviation away from the calculated frequency has been taken into account for the selected values of the range setting resistors in this project. However, there may be some benefit of further fine tuning as detailed earlier.

Troubleshooting

Problem	Possible Cause
A red and green LED are lit at the same time on the right-hand circle.	That is normal when the capacitance is low or there is nothing connected to the test leads. It's not possible to resolve low values when the applied capacitance is less than about 2% of the selected full scale.
LEDs completely dead.	Test terminals are shorted together. Capacitance is much bigger than 9.9µF. Something other than a capacitor is on the test terminals. Testing in-circuit. PSU problem, check battery and regulator.
LEDs are flashing.	This is expected for capacitances over around 0.15µF (150nF), the "Cx Dependent" astable will oscillate at a fairly low frequency. The LEDs are only powered up during the low output levels of the astable, so the LEDs will blink when the frequency is low.
Readings are not stable.	The input impedance of the circuit is quite high. Keep test leads as short as possible and avoid touching the connections as you will induce your own 50Hz (or 60Hz) mains interference.
Reading is showing "99".	It's possible that the capacitance is too high for the currently selected range. Select a higher measurement range.
Reading is showing "00" or "01".	Capacitance is too low for the currently selected range or perhaps no capacitor is connected at all.
I'd like the LEDs to be brighter.	The LED current limiting resistors, R5 and R6, are 1kΩ by default which gives an approximate peak LED current of 2mA. The value of 1kΩ was chosen to minimise the number of different resistor values in the "Bill of Materials" and also to ensure that the current was well within the maximum recommended for the 4017 counter outputs. The circuit has been tested with 470Ω however (yielding about 4mA peak) and the 4017 chips suffer from no problem.

Specifications

Parameter	Typical Value
Minimum measurable capacitance	~0.2nF (200pF)
Maximum measurable capacitance	9.9µF
Open circuit test voltage	~3.3V
Maximum allowed voltage on the test probes	-0.6V to +5.6V
Input impedance	~130kΩ
Accuracy (unadjusted)	±5% of full scale
Accuracy (range resistors fine tuned)	±2% of full scale
Current consumption	~15mA
Supply voltage range	7.5V to 15V

Acknowledgements

I would like to thank my friend Stephen Bernhoeft for his critical eye, advice and clarity with refining and testing this circuit and also for drafting it into the superb KiCAD software and helping me get up to speed with it. On that particular point, KiCAD is a superb CAD package and I urge you to give it a try if you haven't already.

Thanks also to Saar and Ben of Boldport for their superb creative and practical input and for "*working the Boldport magic*" that has become their trademark.

Finally

I am happy to help with any questions regarding this project. The best way to contact me is via the Capaci-Meter project channel on the Boldport Club Server on Discord.

You can find more information on the Boldport website: boldport.com/capaci

I hope you enjoy building and using this project as much as I have.

Jez Siddons

E&OE