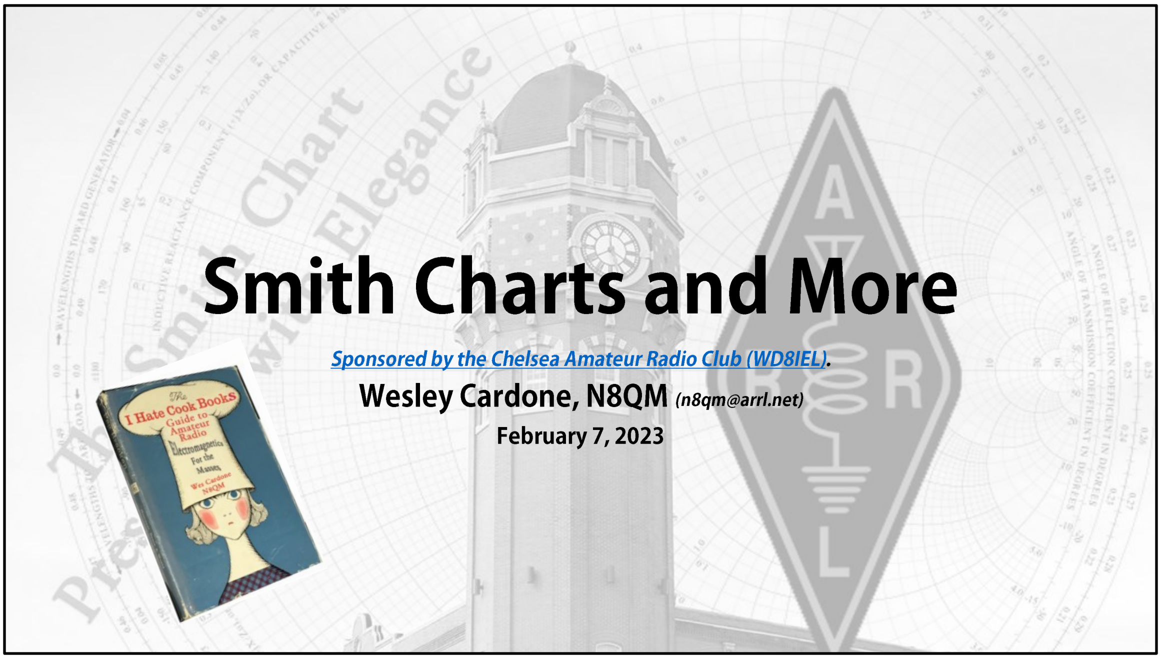

Smith Charts and More

Sponsored by the Chelsea Amateur Radio Club (WD8IEL).

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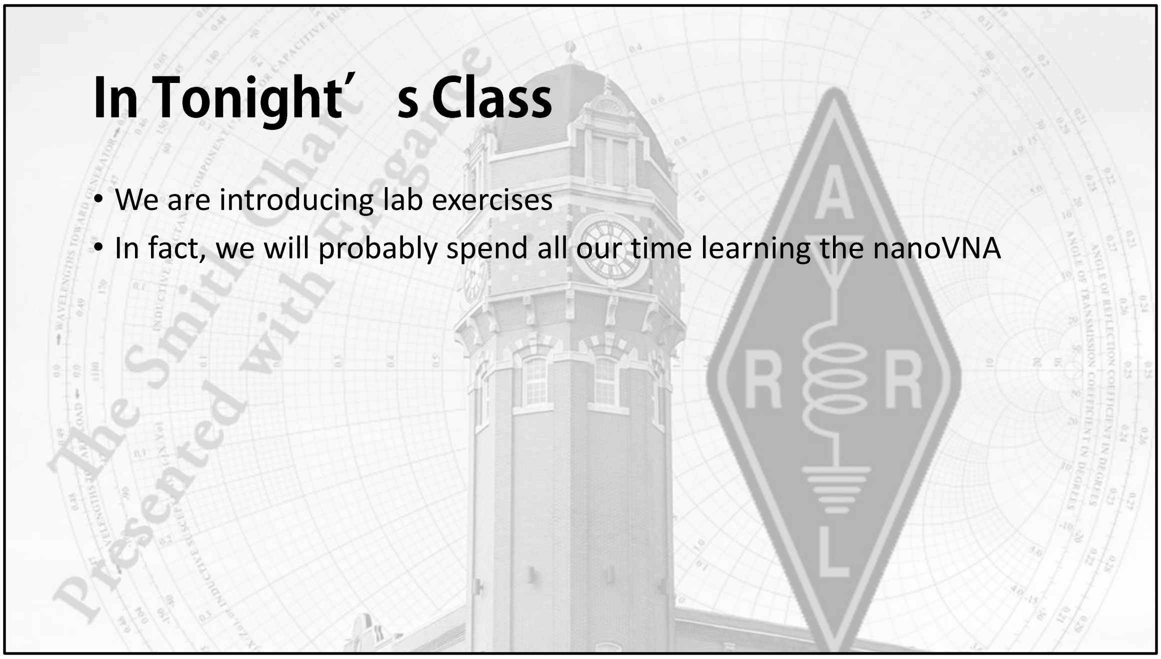
February 7, 2023

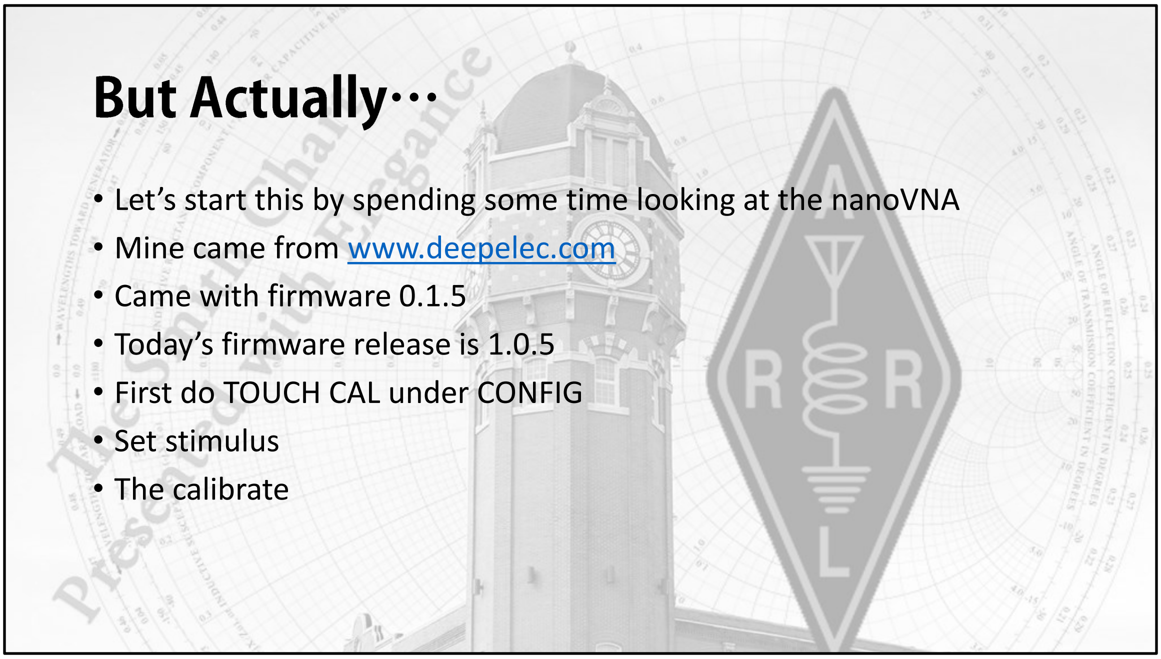
This is the Smith Charts ‘n More training (otherwise known as the I Hate Cookbooks Guide to Amateur Radio Electromagnetics) sponsored by the Chelsea Amateur Radio Club.



In Tonight′s Class

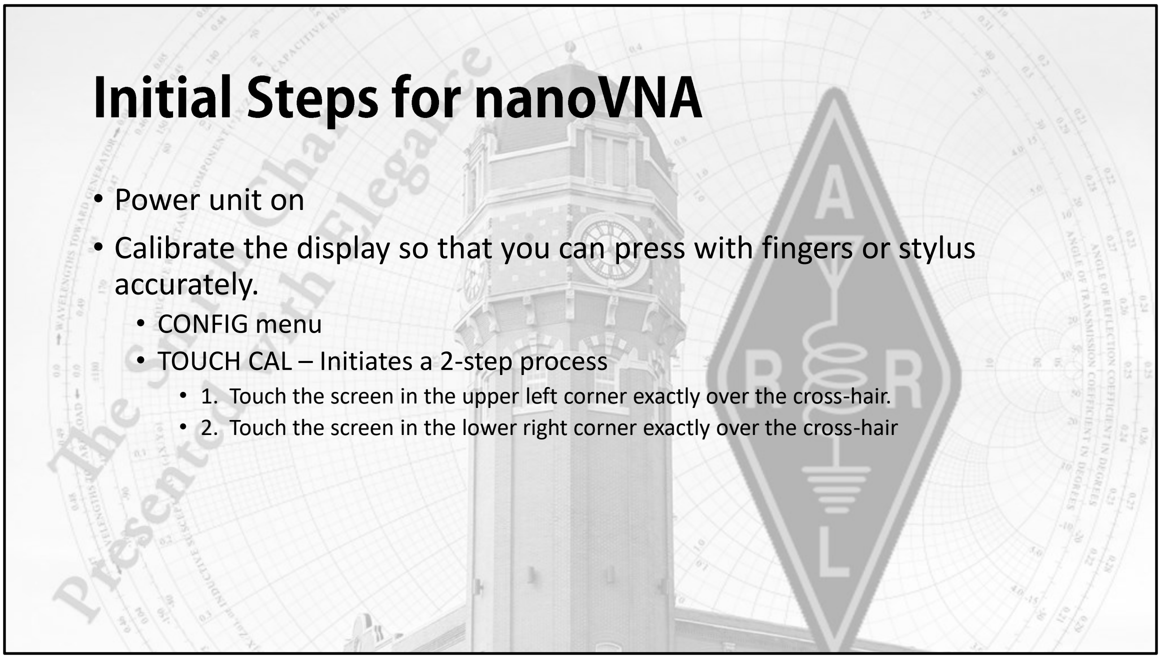
- We are introducing lab exercises
- In fact, we will probably spend all our time learning the nanoVNA

With tonight’s class we are moving in a new direction. We are introducing lab exercises. We will look at the uttermost fundamentals of electromagnetics and relate them to Smith Charts in lab exercises.



But Actually…

- Let’s start this by spending some time looking at the nanoVNA
- Mine came from www.deepelec.com
- Came with firmware 0.1.5
- Today’s firmware release is 1.0.5
- First do TOUCH CAL under CONFIG
- Set stimulus
- The calibrate

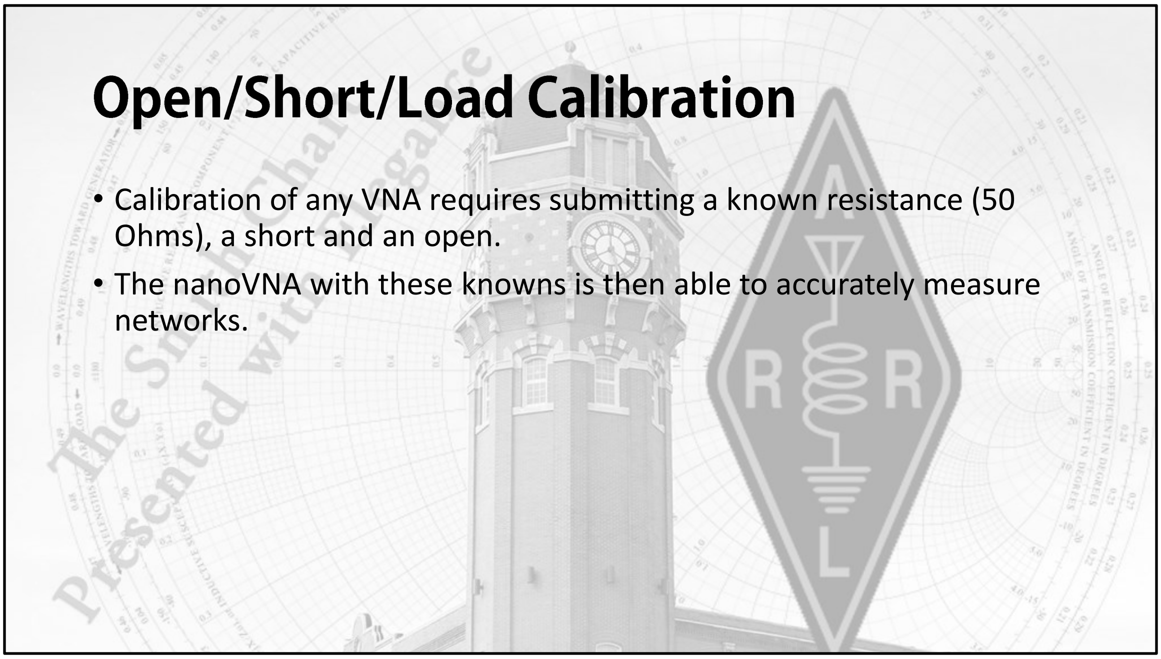


Initial Steps for nanoVNA

- Power unit on
- Calibrate the display so that you can press with fingers or stylus accurately.
  - CONFIG menu
  - TOUCH CAL – Initiates a 2-step process
    - 1. Touch the screen in the upper left corner exactly over the cross-hair.
    - 2. Touch the screen in the lower right corner exactly over the cross-hair

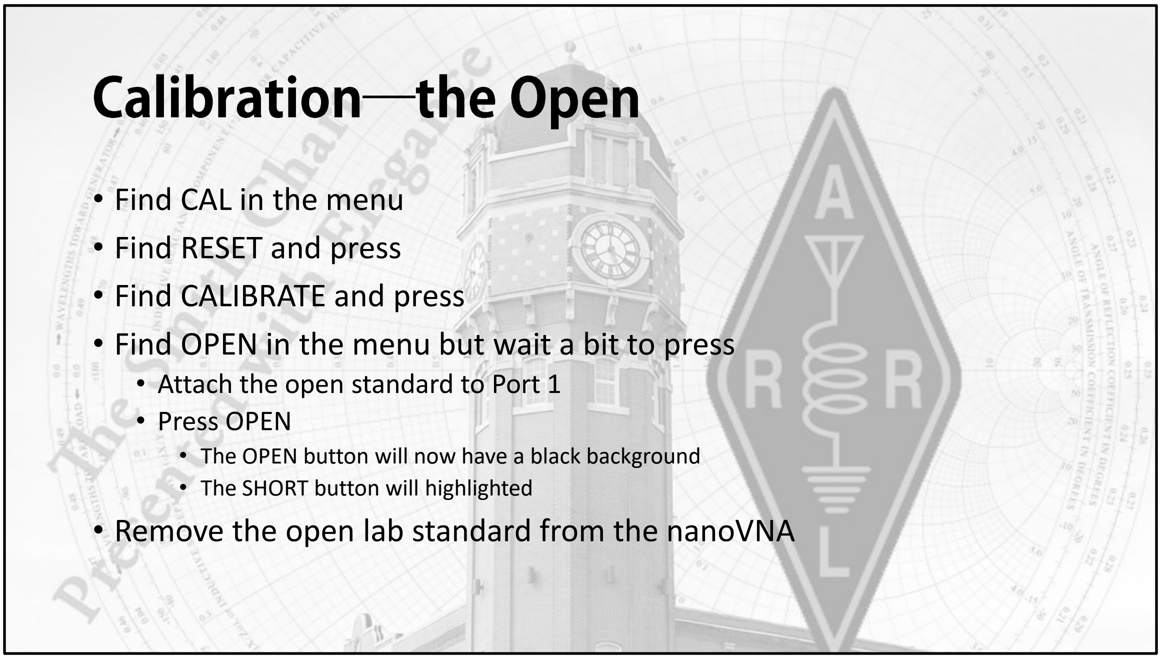
Steps - Sweep Bandwidth - START

- Find STIMULUS and then START – touch bringing up a calculator display
  - Enter 10
  - Touch “M”
  - Verify in lower left screen it says “START 10.000 000 MHz
- In the menu find STOP and press
  - Enter 500
  - Touch M
  - Verify in lower right screen “STOP 100.000 000 MHz
- The number we used here are in preparation for the planned lab exercise. You will want to substitute whatever numbers are otherwise applicable.
- You want to calibrate the nanoVNA every time you change the seep bandwidth such as we did above.



Open/Short/Load Calibration

- Calibration of any VNA requires submitting a known resistance (50 Ohms), a short and an open.
- The nanoVNA with these knowns is then able to accurately measure networks.

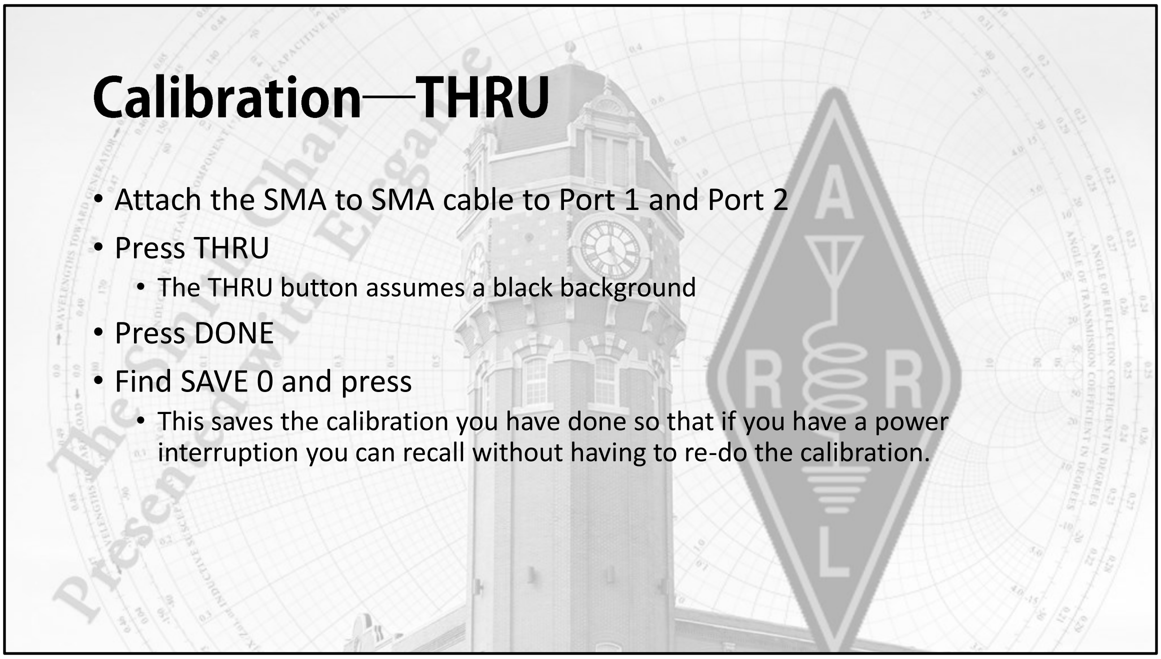


Calibration—the Open

- Find CAL in the menu
- Find RESET and press
- Find CALIBRATE and press
- Find OPEN in the menu but wait a bit to press
  - Attach the open standard to Port 1
  - Press OPEN
    - The OPEN button will now have a black background
    - The SHORT button will highlighted
- Remove the open lab standard from the nanoVNA

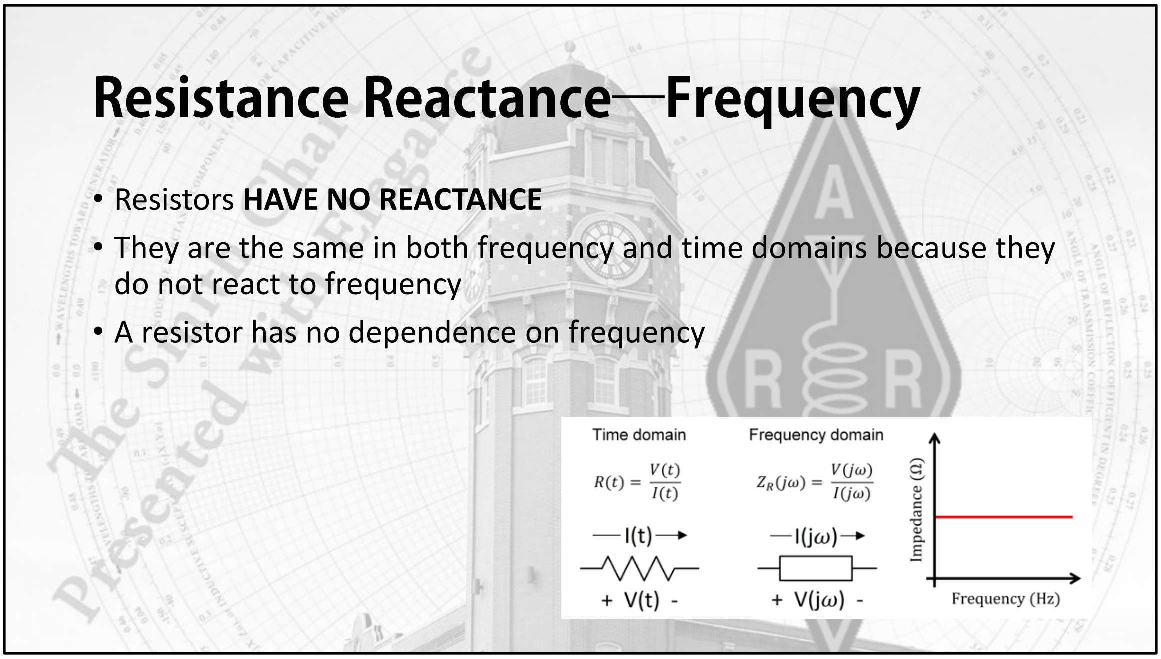
Calibration—the Short and Load

- The SHORT button is already highlighted
- Attach the open lab standard to Port 1
- Press SHORT
  - The SHORT button assumes a black background. If not, get the menu back and press the SHORT button until it shows with a black background.
- Remove the open lab standard
- Attach the 50 Ohm lab standard to Port 1
- Press LOAD
  - The LOAD button assumes a black background
  - Remove the load standard.



Calibration—THRU

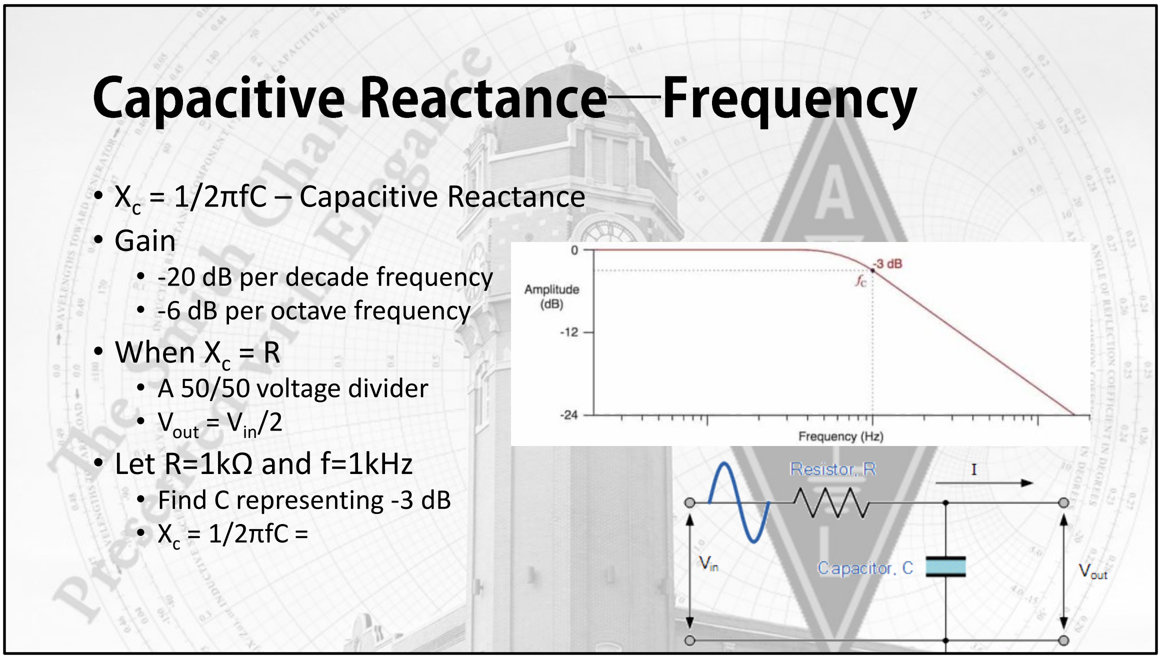
- Attach the SMA to SMA cable to Port 1 and Port 2
- Press THRU
  - The THRU button assumes a black background
- Press DONE
- Find SAVE 0 and press
  - This saves the calibration you have done so that if you have a power interruption you can recall without having to re-do the calibration.



Resistance Reactance—Frequency

- Resistors **HAVE NO REACTANCE**
- They are the same in both frequency and time domains because they do not react to frequency
- A resistor has no dependence on frequency

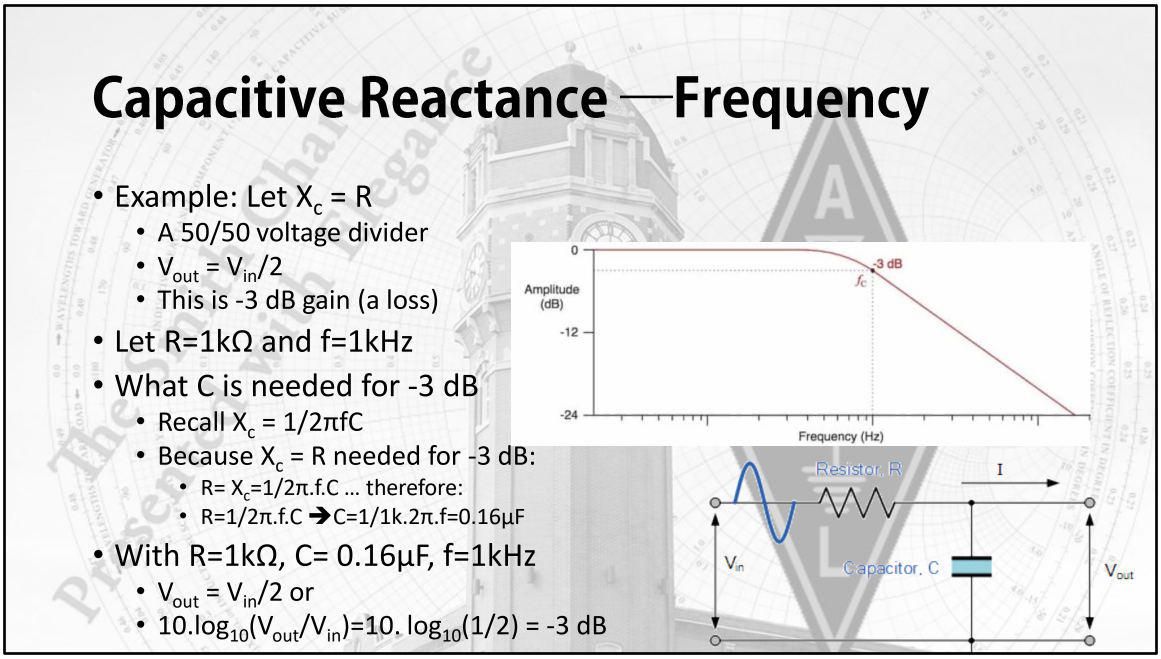
Let’s talk about resistance reactance. Wait a minute… there is no reactance within a resistor other than parasitics. But leave parasitics out. They are hithikers that are something else. We are talking about resistance. A resistance is the same resistance whether it is in DC or ten ga-zillion MegaHertz. Its resistance to the flow of current (Ohms) will always be simply the voltage divided by the current.



Capacitive Reactance—Frequency

- $X_c = 1/2\pi fC$ – Capacitive Reactance
- Gain
  - -20 dB per decade frequency
  - -6 dB per octave frequency
- When $X_c = R$
  - A 50/50 voltage divider
  - $V_{out} = V_{in}/2$
- Let R=1kΩ and f=1kHz
  - Find C representing -3 dB
  - $X_c = 1/2\pi fC =$

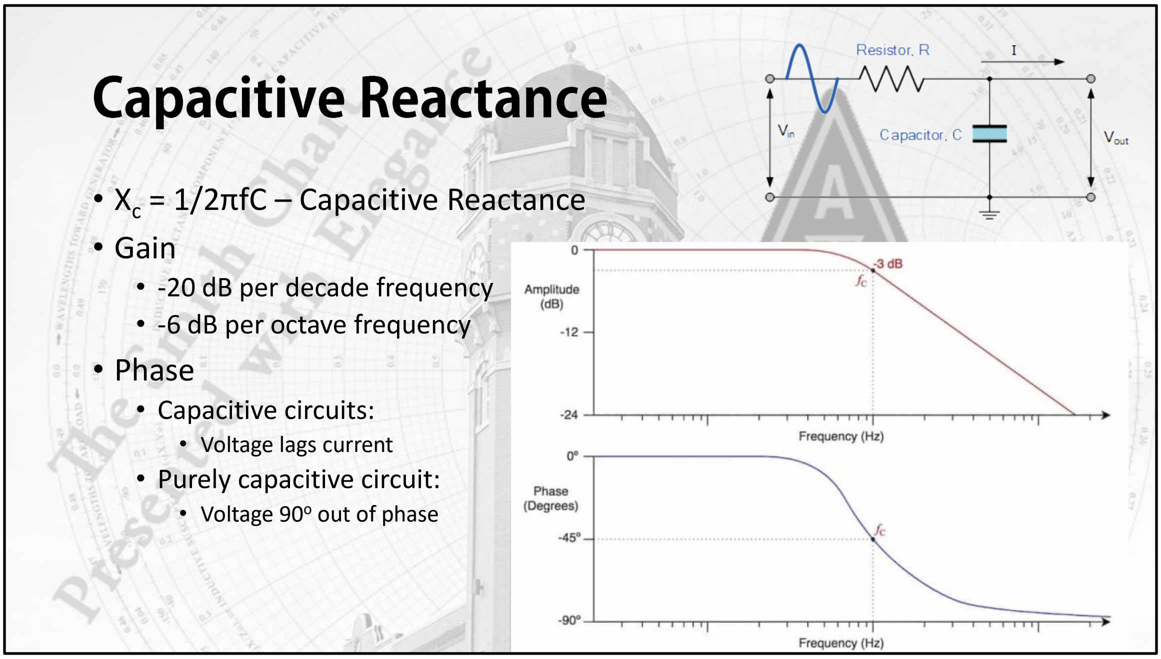
Capacitive reactance is like resistance but, as the name implies, REACTS to frequency. It opposes the flow of electrons but with some unique qualities which depend on frequency. Capacitive reactance is quantified as the reciprocal of 2 pi times the frequency in Hertz times the capacitance in Farads. Therefore, in an RC circuit, while the resistance does not REACT to frequency as the frequency changes, the capacitive reactance does REACT changing its opposition to the flow of electrons. Therefore, a gain plot will reflect this. We are looking at a low pass filter. At low frequencies, the capacitor acts as an open so the voltage out will equal the voltage in. There is no voltage division operative at DC in this circuit. But as the frequency increases, the capacitive reactance DEcreases creating a voltage divider so that now V_{out} no longer equals V_{in}. This is the definition of a gain product. This RC circuit now exhibits so much “gain” as a function of frequency. When X_C equals R, the voltage out is half the voltage in meaning -3 dB. More will be said about that in the next slide.



Capacitive Reactance —Frequency

- Example: Let $X_c = R$
  - A 50/50 voltage divider
  - $V_{out} = V_{in}/2$
  - This is -3 dB gain (a loss)
- Let R=1kΩ and f=1kHz
- What C is needed for -3 dB
  - Recall $X_c = 1/2\pi fC$
  - Because $X_c = R$ needed for -3 dB:
    - $R= X_c=1/2\pi.f.C$ … therefore:
    - $R=1/2\pi.f.C \rightarrow C=1/1k.2\pi.f=0.16\mu F$
- With R=1kΩ, C= 0.16µF, f=1kHz
  - $V_{out} = V_{in}/2$ or
  - $10.\log_{10}(V_{out}/V_{in})=10.\log_{10}(1/2) = -3$ dB

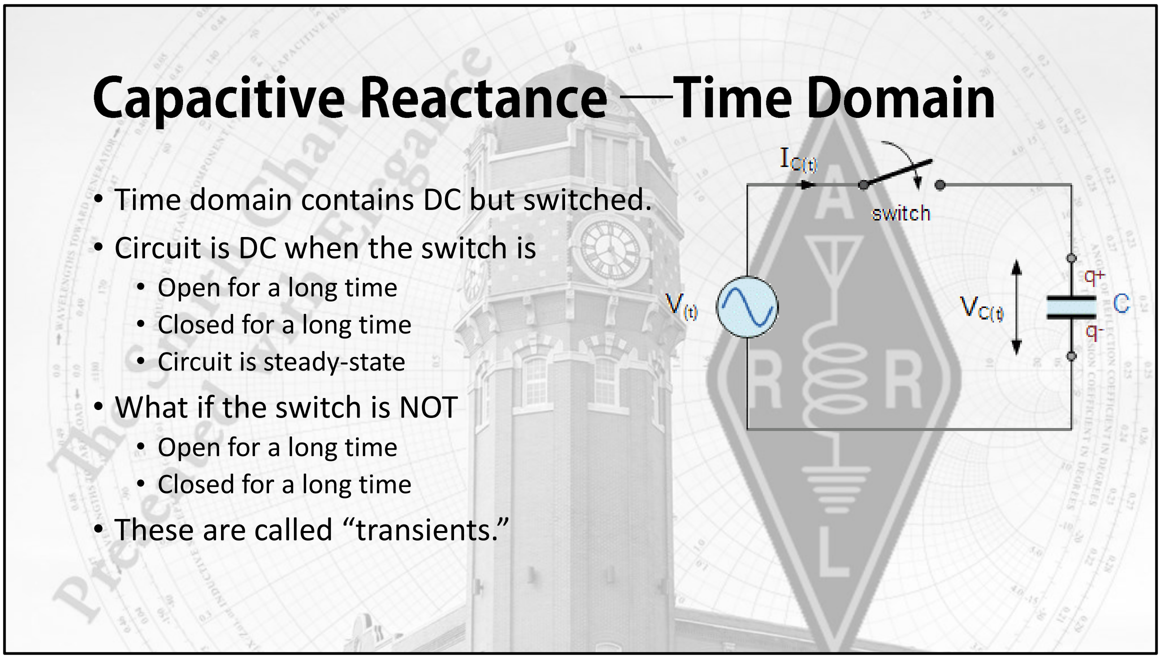
Let's look at this again. Suppose the capacitive reactance, X_c, is equal to the resistance, R. R is so many Ohms and X_c is also so many Ohms. The two have the same opposition to current flow at a particular, and one and only, frequency. This is a voltage divider of one half. V_{out} is half that of V_{in}. Let's talk numbers, now. Let the resistor equal one thousand Ohms. Let the frequency equal 1 kilo-Hertz. What value of capacitance in Farads is required to have a voltage divider such as described here, that is, the voltage out is half the voltage in? Recall that capacitance reactance, X_c, is the reciprocal of 2pi times the frequency in Hertz times the capacitance. Our question asks for a half voltage divider meaning that the resistance, R, equals X_c. Therefore, we substitute R for X_c into the equation. Now, instead of X_c being equal to the reciprocal of 2pi times the frequency in Hertz times the capacitance, R is equal to the same. We can now to some elementary algebraic manipulation of the equation telling us that the capacitance required for a half voltage divider is the reciprocal of 2pi times the frequency in Hertz times the 1kOhm resistance which equates to 0.16uF. So, given a resistor of 1kOhm and capacitor of 0.16uF at a frequency of 1kHz, the voltage out will be half that of the voltage in which is -3 dB.



Capacitive Reactance

- $X_c = 1/2\pi fC$ – Capacitive Reactance
- Gain
  - -20 dB per decade frequency
  - -6 dB per octave frequency
- Phase
  - Capacitive circuits:
    - Voltage lags current
  - Purely capacitive circuit:
    - Voltage 90° out of phase

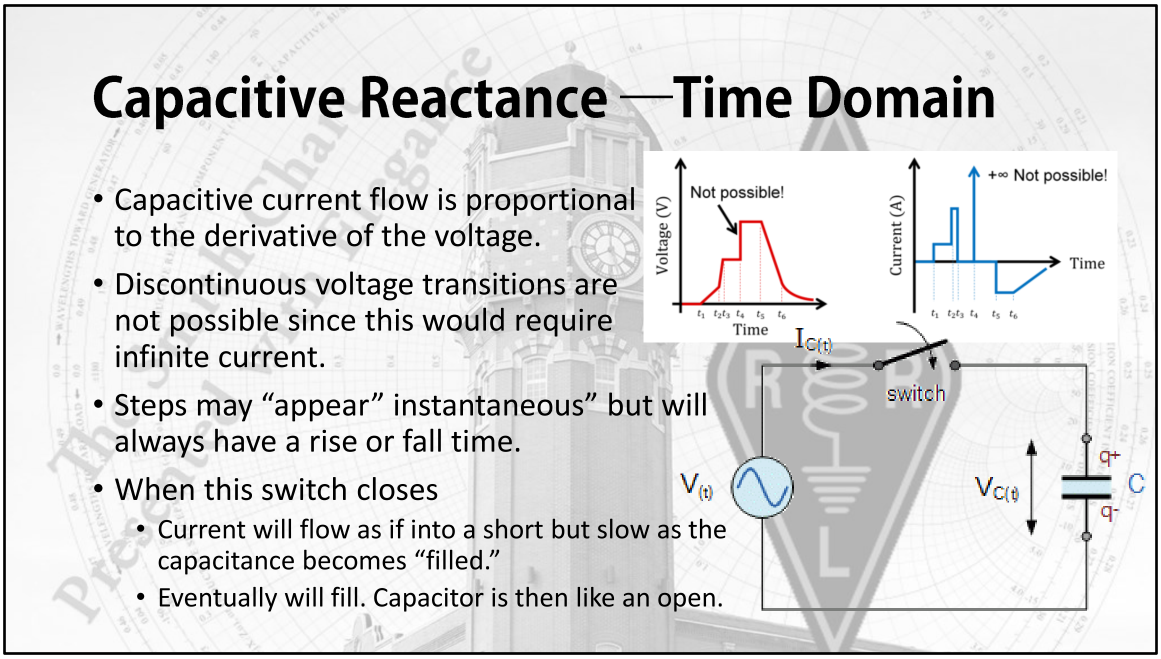
Another aspect of capacitive reactance is its rate of gain. The circuit we looked at in the earlier slide is what we call a “first order” network. There is only one reactive element. “Order” is an important concept to grab a hold of. This is because reactance falls off at a specific rate with frequency. It falls of at 20 dB per decade. Another way of specifying the same thing is to say that it falls off 6 dB per octave. A decade is an order of magnitude such as 10k and 100k.The difference between 10k and 100k is one decade. Likewise for an octave, we can say that the difference between 10k and 20k is one octave. 20 dB per decade and 6 dB per octave are the same thing. But this leads us to phase. I don’t want to say a lot about phase at this point until we can look at it in the upcoming “time domain” discussion a couple of slides down but let us just introduce it for now. At DC and low frequencies, capacitive reactance has zero phase which serves as a datum or reference. Phase is ALWAYS a relative measure, usually relative to zero phase. Consider now infinite frequency. The phase becomes -90°. We will talk in the next couple of slides what -90° means but for now recognize that the phase has moved from zero at DC to minus 90 degrees frequency equals infinity. Now let us consider a half-way point. That is the 3 dB point we looked at earlier. At 3 dB the phase is half-way between zero and -90 with is -45°. That will not make a lot of sense right now but the next couple of slides will flesh it out a little bit.



Capacitive Reactance —Time Domain

- Time domain contains DC but switched.
- Circuit is DC when the switch is
  - Open for a long time
  - Closed for a long time
  - Circuit is steady-state
- What if the switch is NOT
  - Open for a long time
  - Closed for a long time
- These are called “transients.”

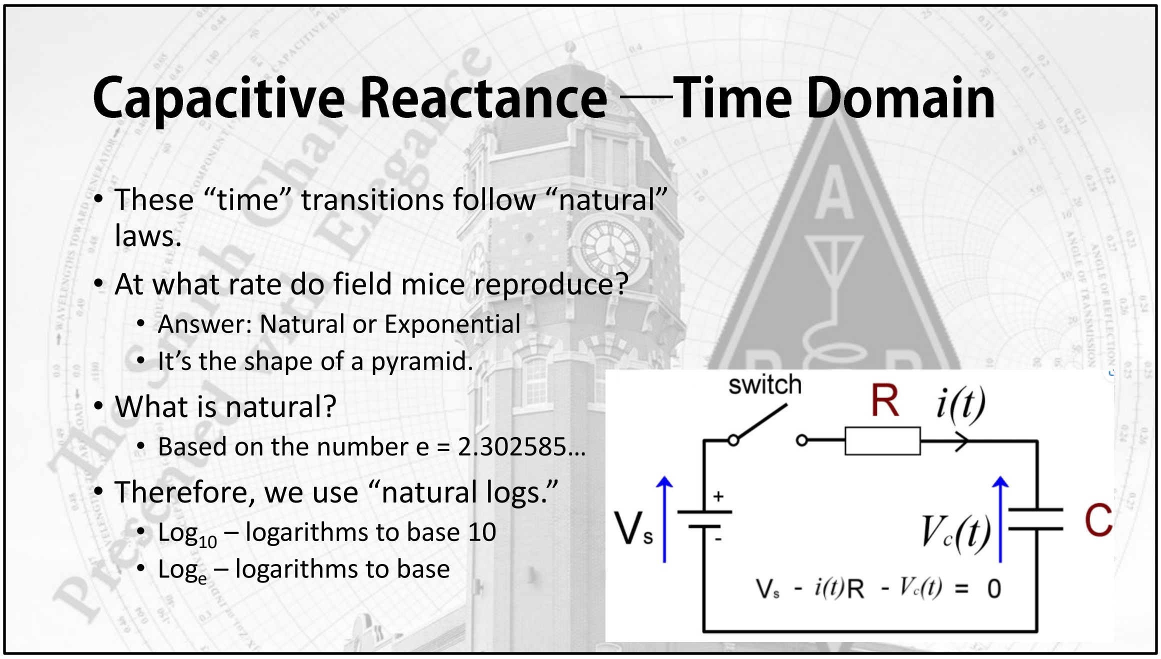
Think of the time domain as controlled DC. It is DC in “steady-state” when all transients have settled. The circuit is NOT in steady-state when the switch has NOT been open or closed for “a long time.” We call these transients.



Capacitive Reactance —Time Domain

- Capacitive current flow is proportional to the derivative of the voltage.
- Discontinuous voltage transitions are not possible since this would require infinite current.
- Steps may “appear” instantaneous” but will always have a rise or fall time.
- When this switch closes
  - Current will flow as if into a short but slow as the capacitance becomes “filled.”
  - Eventually will fill. Capacitor is then like an open.

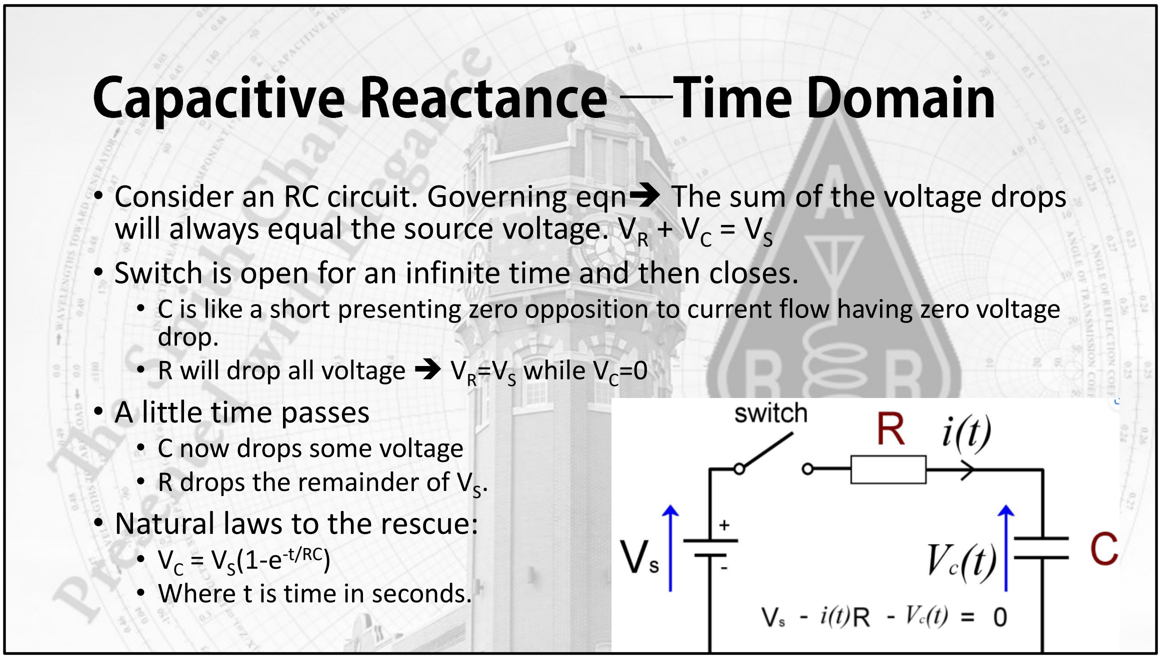
We were talking about the frequency domain up until now. Guess what… frequency contains time. It is so many “cycles per second” which in 1970 we started calling Hertz by international convention. So, in a sense when we were talking within the frequency domain, we were also considering time. In electrical engineering things are simplified if we can dichotomize between frequency and time identifying two domains. Almost always we are either ONLY interested in the frequency domain or we are ALWAYS interested in the time domain. In my entire engineering career, I can recall only one time when I wanted to transition from frequency to time. That was in solving for a skin effect. Skin effect is universally defined as a depth as a function of frequency. Current flow in a wire is limited to only the first so many fractional inches of a wire’s depth as a function of frequency. As the frequency increases, the depth becomes more shallow. At DC there is no skin effect so that current uniformly flows through the entire crossection of a wire. There was one occasion when I wanted to define a skin effect depth as a function of time for a named frequency for a transient perspective. But what I am saying is that it makes sense to have a frequency domain and a time domain because the two normally do not mix.



Capacitive Reactance —Time Domain

- These “time” transitions follow “natural” laws.
- At what rate do field mice reproduce?
  - Answer: Natural or Exponential
  - It’s the shape of a pyramid.
- What is natural?
  - Based on the number e = 2.302585…
- Therefore, we use “natural logs.”
  - Log$_{10}$ – logarithms to base 10
  - Log$_e$ – logarithms to base

Let’s talk about what that time is to transition. Consider a colony of field mice. Suppose you had two mice—a male and a female. Turning them loose into an undeveloped and overgrown field with unlimited food and no predators, how long would it take to produce 1 million mice? It’s a simple pyramid scheme exactly like Social Security. Figure a gestation period of 20 days per mother mouse and an ability to deliver a litter every 25 days. An equation can be written for this based on the natural number e which is 2.302585… and the number goes with on greater precision literally without end. Electrical reactance works the same way.

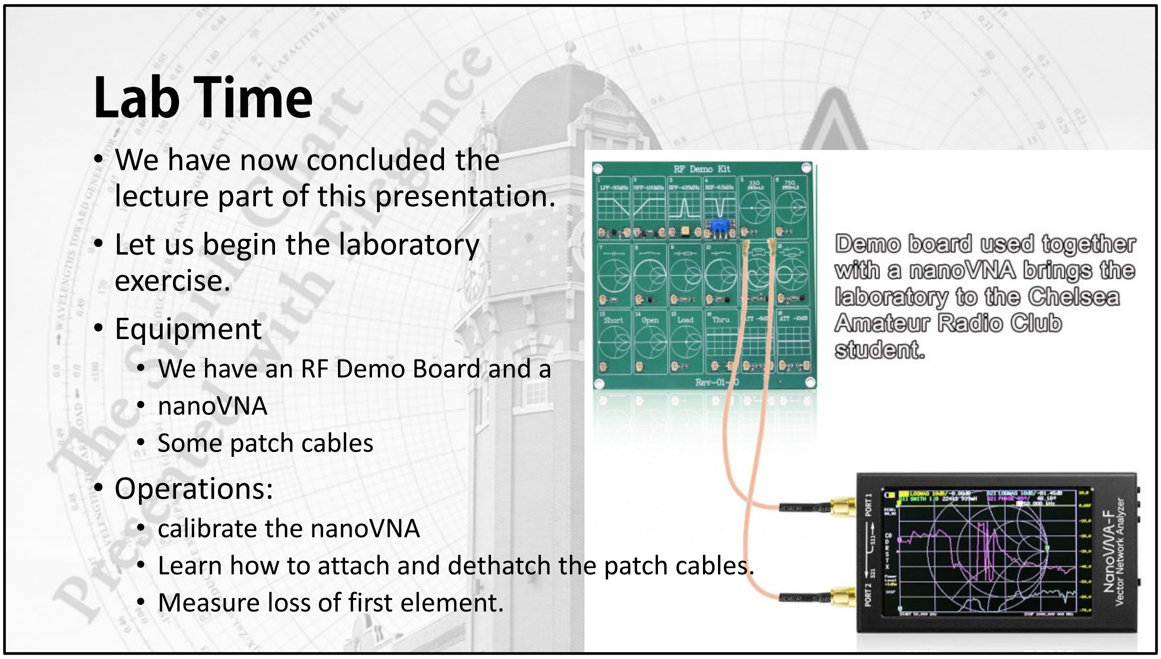


Capacitive Reactance —Time Domain

- Consider an RC circuit. Governing eqn➔ The sum of the voltage drops will always equal the source voltage. $V_R + V_C = V_S$
- Switch is open for an infinite time and then closes.
  - C is like a short presenting zero opposition to current flow having zero voltage drop.
  - R will drop all voltage ➔ $V_R=V_S$ while $V_C=0$
- A little time passes
  - C now drops some voltage
  - R drops the remainder of V_S.
- Natural laws to the rescue:
  - $V_C = V_S(1-e^{-t/RC})$
  - Where t is time in seconds.

$$V_s - i(t)R - V_c(t) = 0$$

Let’s consider our same RC circuit but in a transient set of transitions. Remember that at any time during these changing of states that the voltage of each component within the circuit, that is the resistor and the capacitor, will always sum their voltages to that of the source. In other words, the sum of the resistor and capacitor voltage drops will always equal the constant source voltage. Sometimes the capacitive voltage will be more than the resistor and vise-a-versa. So now, the switch is open for an infinite time but then closes initiation our transient circuit. At that instant, C is like a short dropping zero Volts but passing whatever current is given to it unobstructed. The resistor drops all of the source voltage so that V_s is equal to V_r. But then a little time passes and now the capacitor’s capacitance is beginning to fill up. Capacitance defines a capacity. The capacity is how much charge it can store. It’s now dropping some voltage but slowing down as the seconds pass. The resistor is dropping just that much less voltage but the sum of the two still equals the source voltage. But how much voltage is the capacitor dropping at any one instant of seconds since the switch closed? It depends on the time in seconds. The equation representing this is shown in the slide.

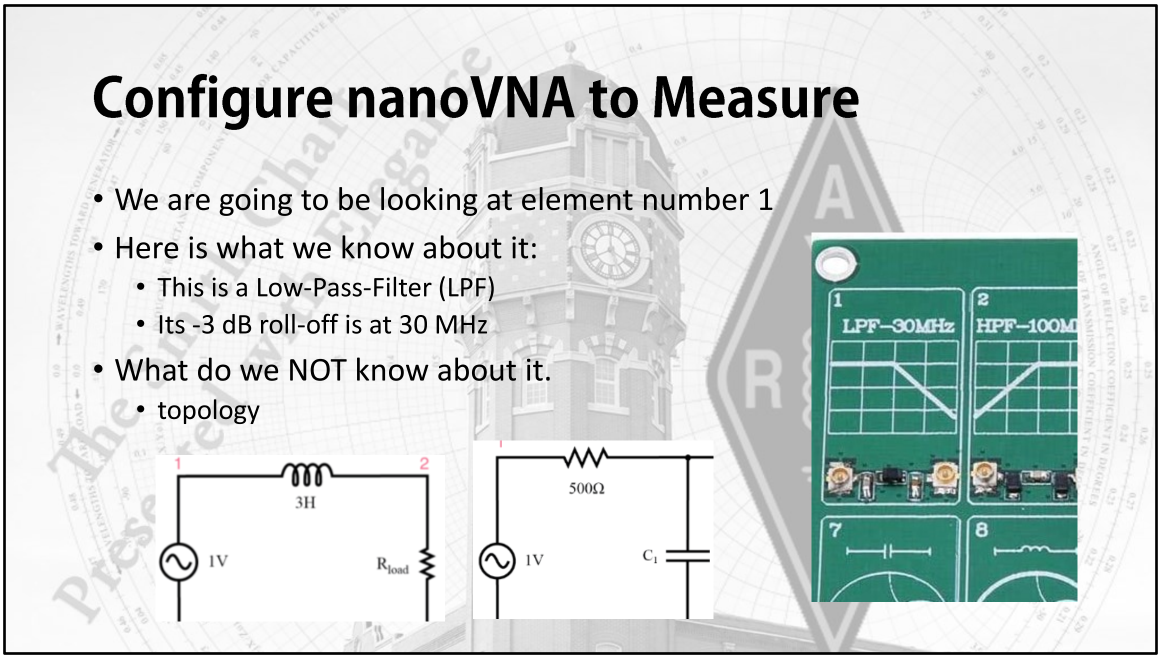


Lab Time

- We have now concluded the lecture part of this presentation.
- Let us begin the laboratory exercise.
- Equipment
  - We have an RF Demo Board and a
  - nanoVNA
  - Some patch cables
- Operations:
  - calibrate the nanoVNA
  - Learn how to attach and dethatch the patch cables.
  - Measure loss of first element.

Demo board used together with a nanoVNA brings the laboratory to the Chelsea Amateur Radio Club student.

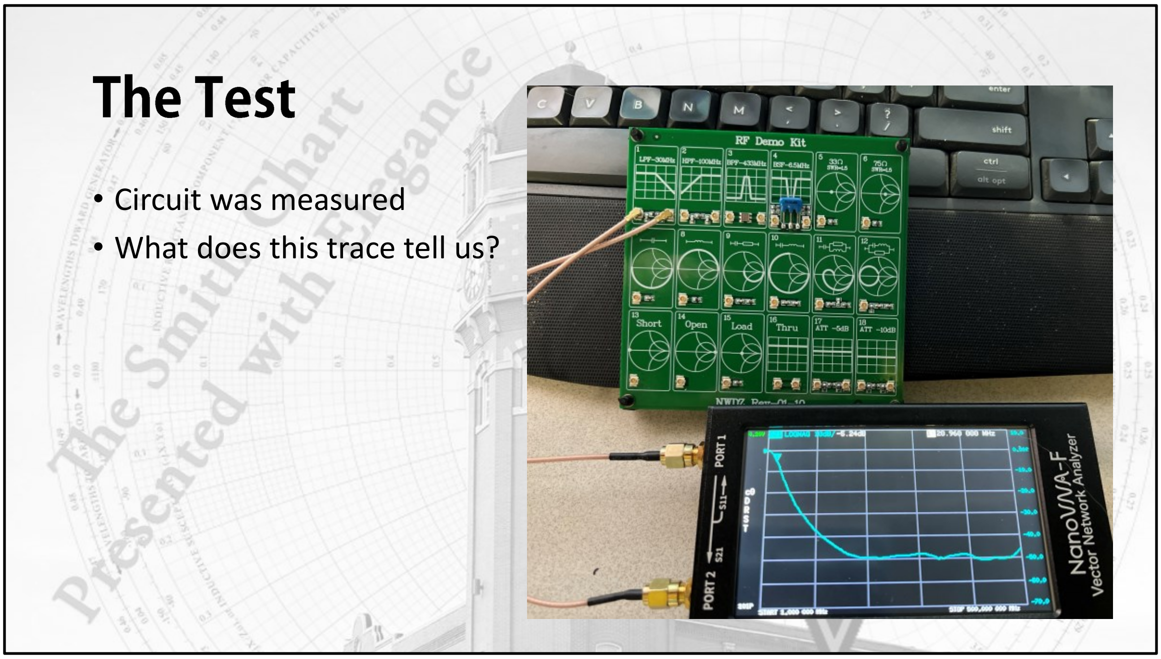
Let us begin the laboratory exercise. You have a nanoVNA, patch cables, and the RD Demo Board. On our list of operations we are going to first calibrate the nanoVNA, then learn how to safely attach and detatch those fragile patch cables, and finally we will measure the first element of the RF Demo Board—its low pass filter.



Configure nanoVNA to Measure

- We are going to be looking at element number 1
- Here is what we know about it:
  - This is a Low-Pass-Filter (LPF)
  - Its -3 dB roll-off is at 30 MHz
- What do we NOT know about it.
  - topology

Let’s look at the RF Demo Board, element number 1—the low pass filter. It is labeled as a 30 MHz low pass filter, but what does that mean? It would ordinarily be safe to say that it means that the low pass filter will be rolling off its gain at -3 dB. But we are going to find out something different in tonight’s exercise. So, here is what we know about this element. It’s a low pass filter that we think rolls off at 30 MHz. However, what we do NOT KNOW about it is its topology. It could be one of two topologies. It could be inductive or it could be capacitive.



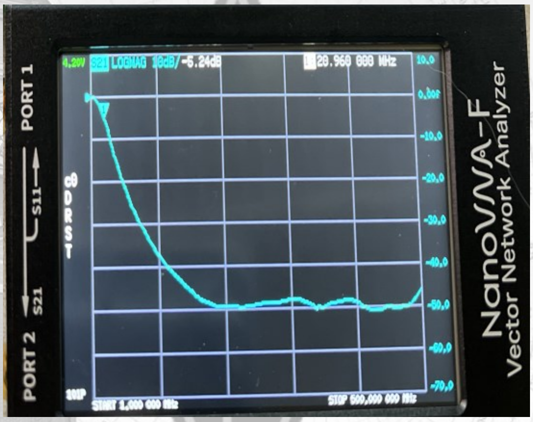
The Test

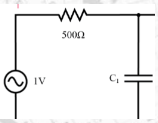
- Circuit was measured
- What does this trace tell us?

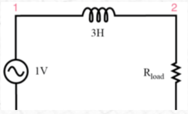
So, we made our measurement but what did we find? We found that -3 dB happened at about 16.5 MHz instead of 30 MHz. Isn't that curious. Let's probe a little deeper in the next slide.

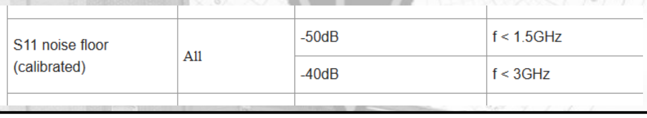
Analytics & Discussion

- -3 dB happens at 16.5 MHZ
  - R = X_c
- -50 dB at infinite freq
  - -50 dB is the NOISE FLOOR of the nanoVNA
- Still Unknowns
  - Topology



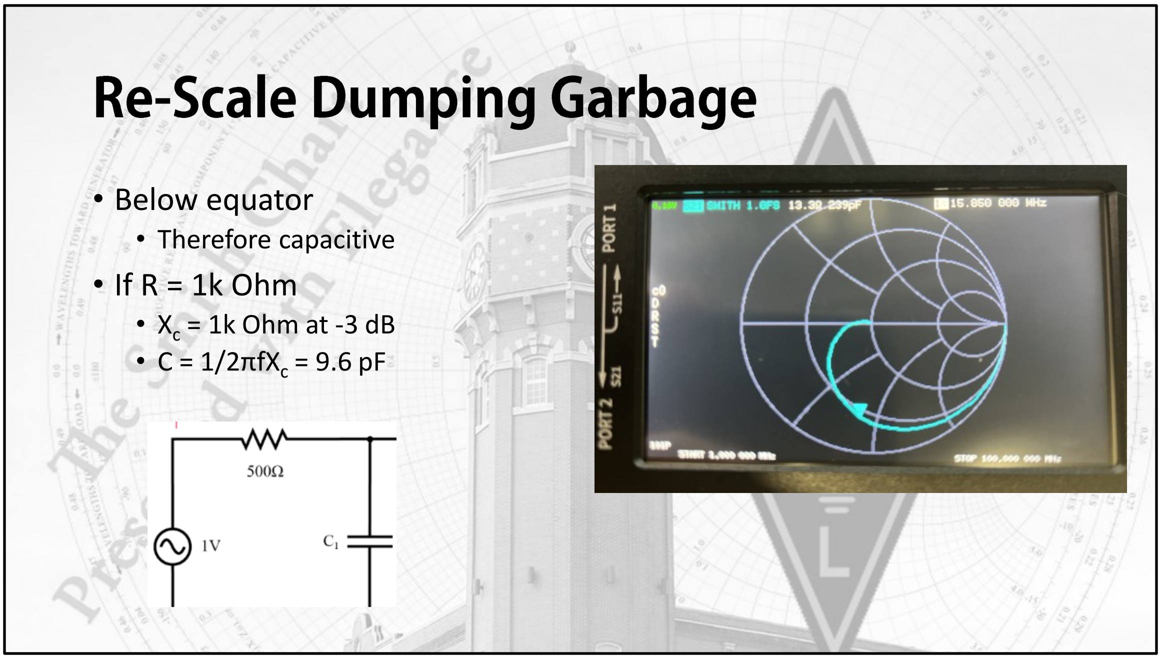






S11 noise floor (calibrated)	All	-50dB	f < 1.5GHz
		-40dB	f < 3GHz

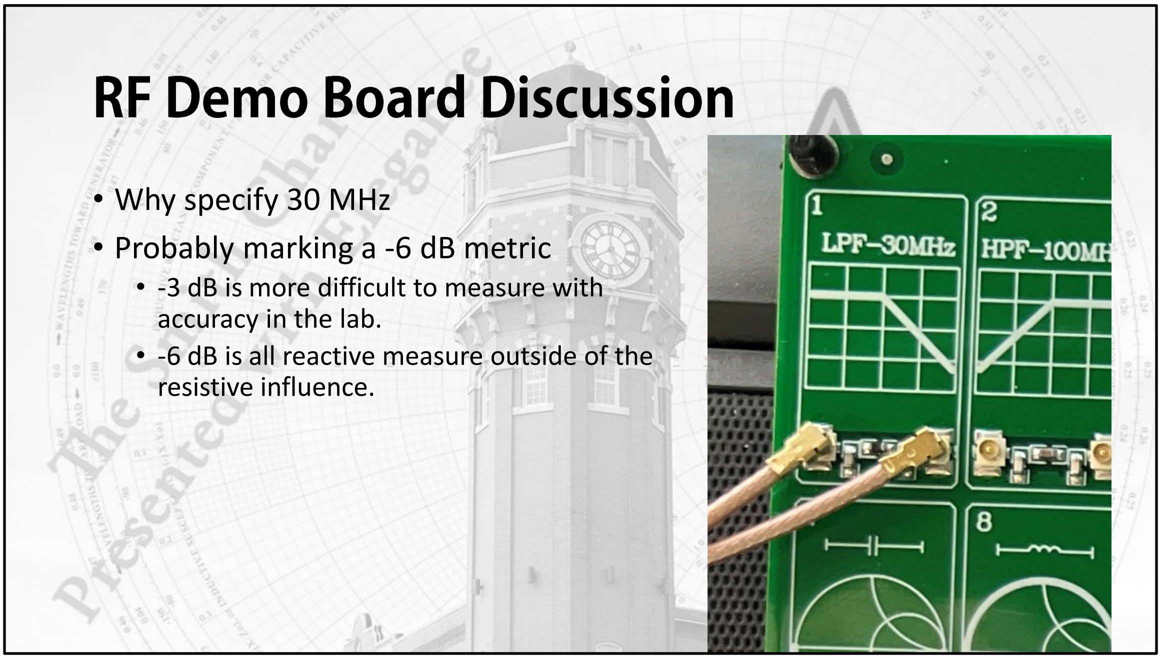
We already noted -3 dB at 16.5 MHz where the resistance equals the reactance. But we also are seeing a maximum gain at about 100 MHz. This is instrumentation error. The nanoVNA is only able to measure a noise floor as low as -50 dB. Know your laboratory instrumentation limitations. But what is still unknown is the topology of the actual circuit of the RF Demo Board. It could be inductive or it could be capacitive. Let us switch to a Smith Chart view in the next slide.



Re-Scale Dumping Garbage

- Below equator
  - Therefore capacitive
- If R = 1k Ohm
  - X_c = 1k Ohm at -3 dB
  - C = $1/2\pi fX_c$ = 9.6 pF

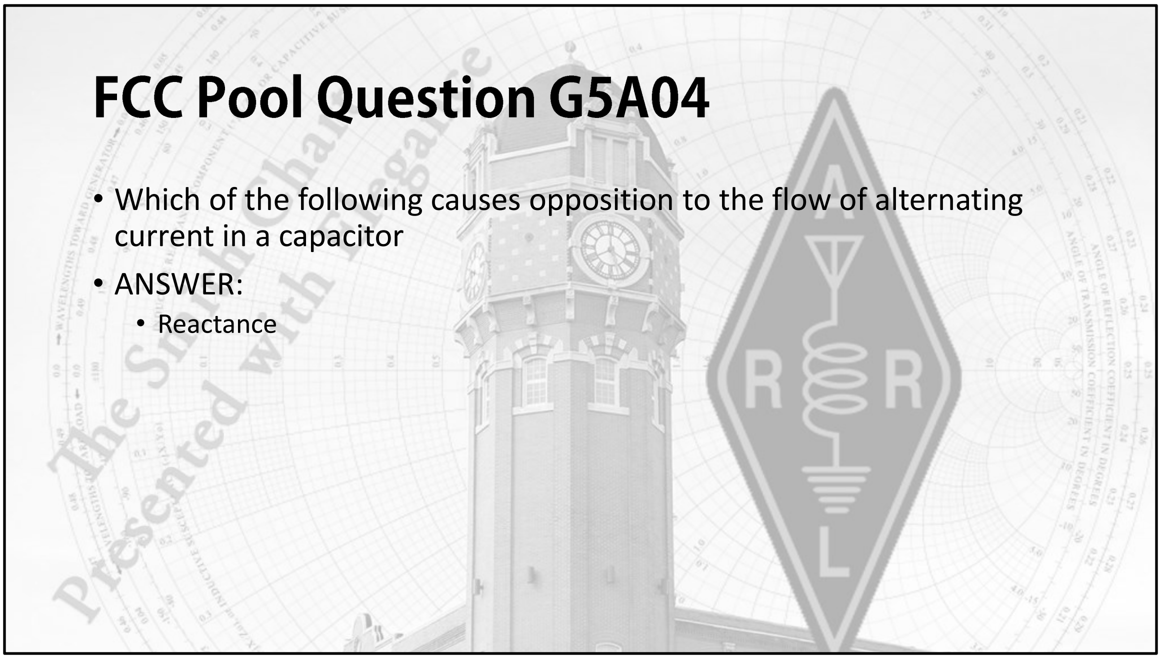
The smith chart shows that the circuit only contains capacitance since there is no trace in the Northern hemisphere. We are showing a quantified capacitance in this slide but we could have done that in the previous slide.



RF Demo Board Discussion

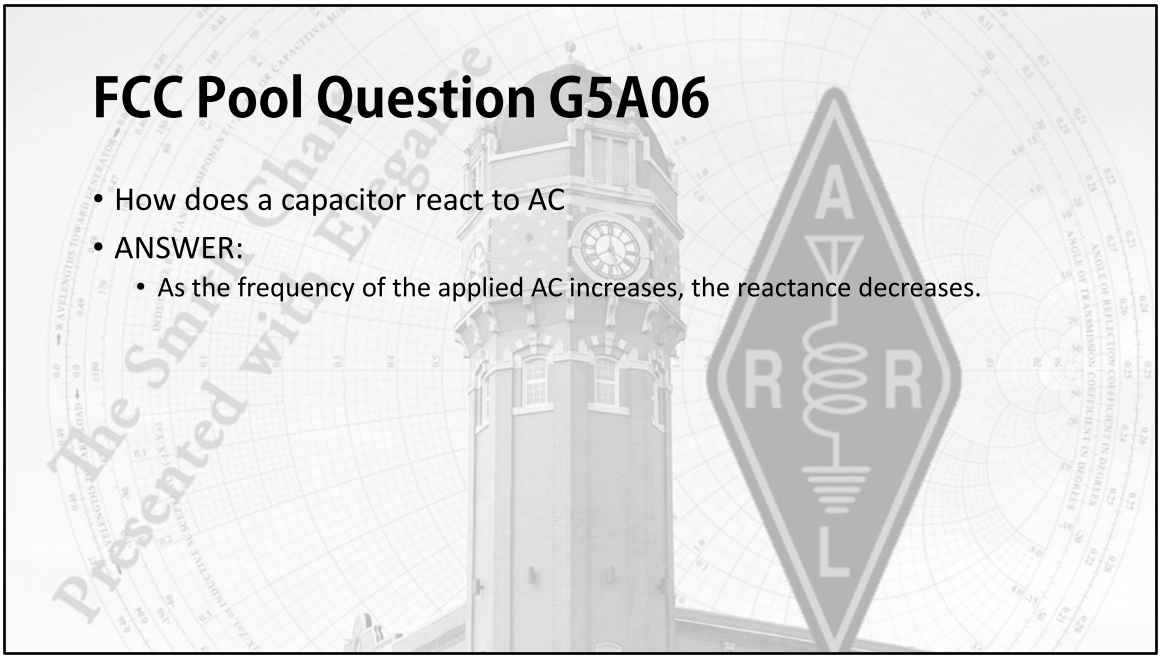
- Why specify 30 MHz
- Probably marking a -6 dB metric
  - -3 dB is more difficult to measure with accuracy in the lab.
  - -6 dB is all reactive measure outside of the resistive influence.

So, now let us entertain the discussion of why 30 MHz. No doubt this is to more precisely locate the roll-off point. At -3 dB the resistance and reactance are equal. But at -6 dB the reactance far outweighs the resistance making its measurement more predictable.



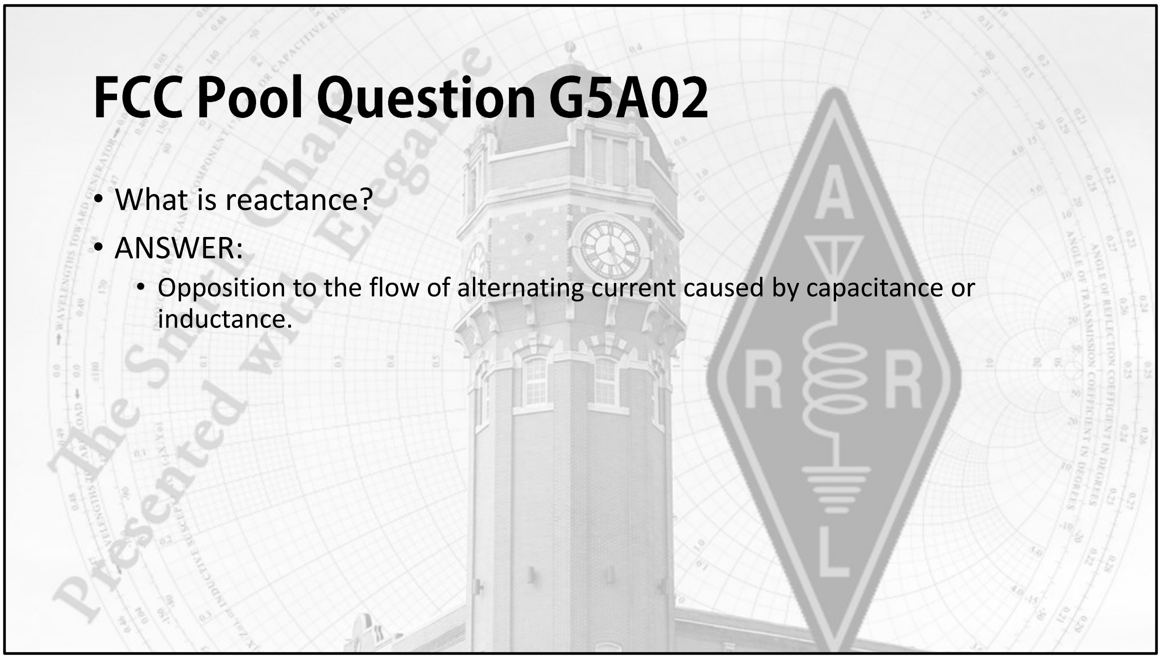
FCC Pool Question G5A04

- Which of the following causes opposition to the flow of alternating current in a capacitor
- ANSWER:
  - Reactance



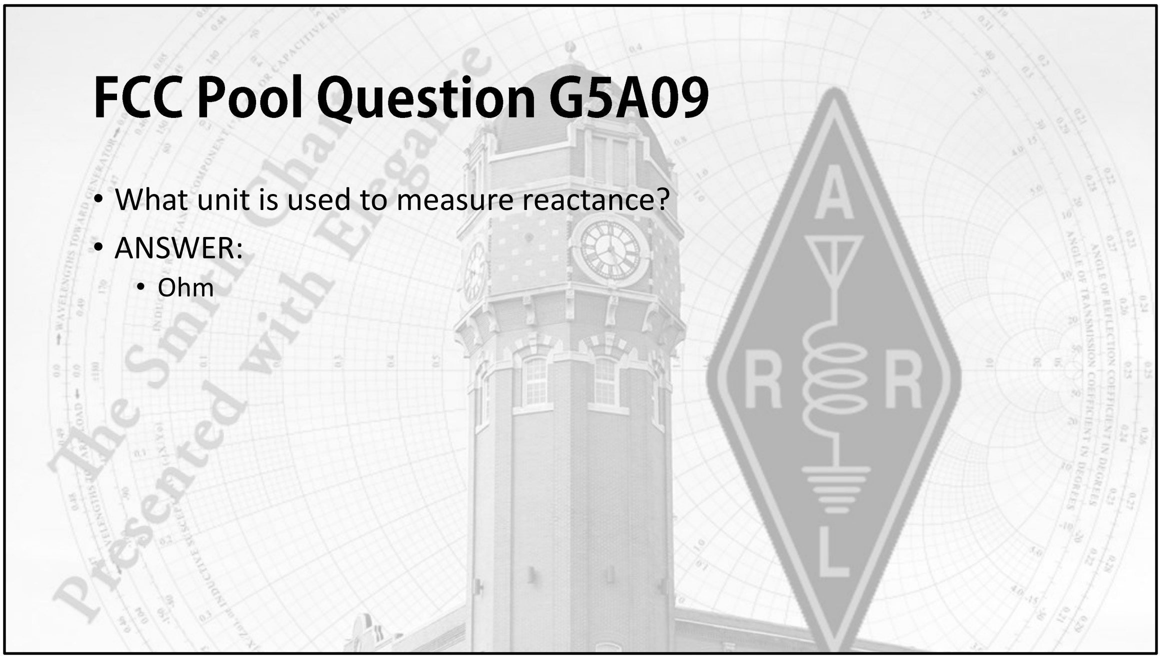
FCC Pool Question G5A06

- How does a capacitor react to AC
- ANSWER:
  - As the frequency of the applied AC increases, the reactance decreases.



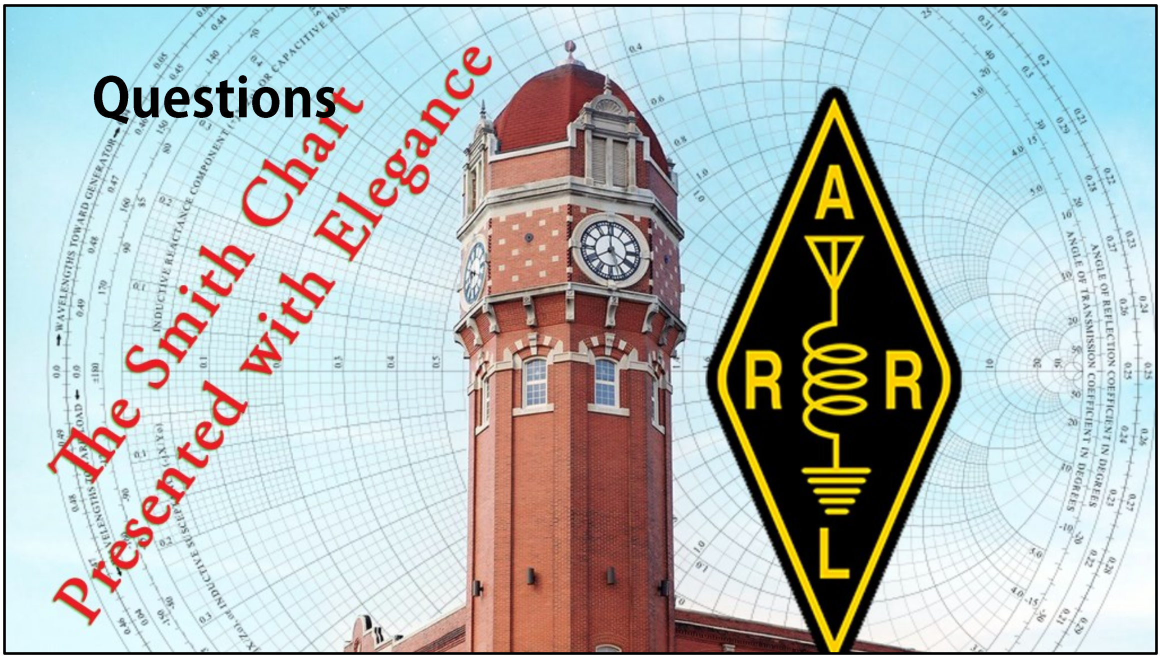
FCC Pool Question G5A02

- What is reactance?
- ANSWER:
  - Opposition to the flow of alternating current caused by capacitance or inductance.



FCC Pool Question G5A09

- What unit is used to measure reactance?
- ANSWER:
  - Ohm



Questions

The Smith Chart
Presented with Elegance