VDD = 12V

R1
10k

R2
10k

C1

1   2

I1
1mA

R3
10k

Figure 1: A bridge circuit.

1 Warm-Up Problems

1. Find the effective resistance seen by the capacitor. (i.e.: the Thevenin resistance across the port between terminals 1 and 2.) Call is R_{12}.

2. Determine the Thevenin equiivalent (i.e.: open circuit) voltage seen from a port between node 1 and ground. Call is V_{oc10}.

3. Determine the Thevenin equiivalent (i.e.: open circuit) voltage seen from a port between node 2 and ground. Call is V_{oc20}.

4. What is the current between terminals 1 and 2? Be sure to explain why.

5. If C_1 is changed to a resistor of 5 kΩ , determine the magnitude and direction of current between terminals 1 and 2. Hint: you already know R_{12}, what other quantity would make this easy to calculate?

6. If I_1 is changed to a dependent current source with a current of $1\text{mS} * v_2$, what is the effective resistance seen by the capacitor?

2   Lab Introduction

In this lab we are examining loading behavior of cabling by making models of different kinds of cables.

1. Deal with Thevenin models in a pracitcal context.

2. Be convinced of the virtue of oscilloscope probes by observing loading effects of different cables.

3. Familiarize yourself our simulator by making Bode and transient plots.

3   Compare the 10X Scope Probe to a BNC Cable

Text Reference: Horowitz and Hill pp1045 to1049, Lab Manual Ref: Hays and Horowitz PP 62, 63
   Capacitive loading is always a consideration when measuring high frequency circuits because capacitance in your cabling can steal your signal from your load. In this section, we are going to measure the capacitance and resistance of oscilloscoope probes and BNC cables in order to build models of them. Probes are two-port devices, so measuring their "impedance" is actually a misnomer, but you are going to be instructed to take measurements in this section whcih allow you to build models of probes ffor which input and output impedance are fairly readily defined.

1. Install ltSpice. Beware that the interface to ltSpice is difficult on Apple computers, and previous students have had better luck running it in a Windows bootcamp environment.

   Consider completing a tutorial. There are many online, including one linked from the class website. You will need to enter schematics and carry out DC, AC and transient simulations to finish the lab.

2. Design a circuit model for a "BNC Probe."

   (a) If you used the RLC meter in lab to measure the resistances and capacitances of of a BNC (coaxial) cable terminated with a pair of hooks or gator clips (and no load impedance), then you would observe $\approx$100mΩ of resistance between the center conductors at either end of the cable, 100pF of capacitance between the center conductor and the shiels, and unmeasurably large resistance (GΩ or greater) between the center pin and the shield. We will refer to this cable (with its termination) as your "BNC Probe." Design a circuit model (i.e.: some arrangement of resistors and capacitors) with two ports that includes all of the measurements described above. Hint: the model is quite simple.

   (b) If you looked at the face of your oscilloscope, you would see the numbers 1MΩ and 11pF written next to each channel. These numbers indicate the input impedance of each oscilloscope channel, so when you connect one port of a probe to an oscilloscope channel you will effectively terminate that port with the parallel combination of 1MΩ and 11pF. Draw a model of a BNC probe connected to an oscilloscope

   (c) The combined model of the BNC probe and the oscilloscope is complicated, and we'd like to replace it with a simpler model. We can do so by finding the input resistance and capacitance of the combined model (i.e.: the Thevenin resistance and capacitance seen from the input port for the combined model). With those parameters, we could simplify the whole model of the probe to a parallel RC circuit with an R value of the input resistance and a C value of input capacitance. We will refer to this model as the "input" model of our probe. Find the input resistance and capacitance and draw the input model for the BNC probe. You may calculate input resistance in a low frequency limit and input capacitance in a high frequency limit.

   Required Data: Model of the BNC probe with numerical values. Input resistance and capacitance of BNC probe when connected to scope.

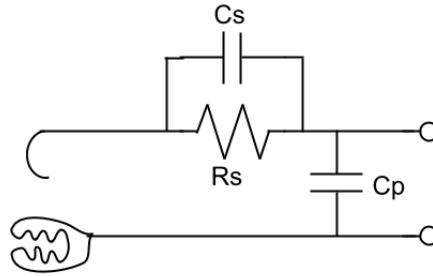3. Calculate the input impedance of a 10x oscilloscope probe.

Figure 2: A schematic model of a 10x oscilloscope probe.

(a) A model of a 10x oscilloscope probe is pictured in Figure 2. The the RLC meter would reveal that to measure the resistances and capacitances in this model are $C_p = 70\text{pF}$, $C_s = 11\text{pF}$, and $R_s = 9\text{M}\Omega$. Draw a model of a 10x probe connected to an oscilloscope, find the input resistance and capacitance of the combined model, and draw an input model for the 10x oscilloscope probe plugged into a scope. When finding the input resistance and capacitance, you may calculate resistance in a low frequency limit and capacitance in a high frequency limit.

(b) The gain of a 10x probe is calculated by comparing the voltage at the input hooks to the voltage across C_p while the probe is connected to an oscilloscope (i.e.: for the full connected model). What is the DC gain of a 10x oscilloscope probe? What is the high frequency gain of a 10x oscilloscope probe? Why is it called a 10x probe? What shape is its frequency response?

(c) The settings of the RLC meter matter when taking these measurements (they basically didn't for the simpler BNC cable). Would you have wanted a high or low probe frequency when measuring resistance? How about capacitance?

Required Data: Model of the 10x probe with numerical values. Input resistance and capacitance of 10x probe when connected to scope. Discussion of low and high frequency gain of 10x probe.

4. Estimate the bandwidthe of these probes when there is a 10kΩ resistance in series with the driving source. Note that 10kΩ is an unusual value for a source resistance, a standard function generator has a 50Ω source resistance, which is a fact you will use in later labs.

(a) Generate two Bode plots using AC simulations: One showing the gain and phase of the combined model of the BNC probe driven through a 10kΩ series resistor, and one showing the gain and phase of the combined model of the 10x probe driven through a 10kΩ series resistor.

(b) Use your input models of each probe to calculate an expected bandwidth for the Bode plots you produced in the previous question. Compare your calculations with your simulations. (These comparisons are crucial in experimental and simulation work becaue they catch mistakes in your models, we will do them extensively in this course, and you are expected to find matches.)

Required Data: Analytical caluclations of corner frequency for each probe type. Bode plot with annotated corner frequency for each probe type.

4   Reverse Engineer Source Impedances

Imagine that you are driving your probes using two mysterious sources that have unknown source impedances. Each source impedance is either completely resistive or capacitive, and neither source

impedance's resistive or capacitive character implies anything about the nature of the other source impedance.

For source A, you observe the following

- When the source is a 1V pulse lasting 10µs, the response of the 10x probe is a rising exponential that peaks at 1V, followed by a falling exponential that stops at 0V.

- When to source is a 1V pulse lasting 10µs, the response of the BNC probe is a rising exponential that peaks at 630mV, followed by a falling exponential that stops at 0V.

For source B, you observe the following

- When the source is a 1V pulse lasting 10µs, the response of the 10x probe is a pulse with a height of 860mV.

- When to source is a 1V pulse lasting 10µs, the response of the BNC probe is a pulse with a height of 375mV.

Note that voltages in both sets of observations are accurate to about 20mV, which is the precision of oscilloscopes in our labs.

Use these measurements to calculate the source impedances Z_A and Z_B. Then simulate those source impedances driving your combined models for each probe to show that your source impedances result in the observations above.