ECET 3410

High Frequency Systems

Introduction

1

What are "High Frequency" Systems

The concept of what constitutes a "**high frequency**" system can be vary different depending on one's point of view…

- A power-system (50-60Hz) engineer may consider any waveform above 1000Hz as a "high-frequency"
- An audio engineer that works with 20-20kHz signals may consider ultra-sonic signals (>20kHz) as "high frequency"
- Both of the above engineers would probably consider anything above 100kHz as "high frequency"
- An Rf engineer working at an AM Radio Station (~1Mhz) might consider anything above 100MHz as "high frequency"
- But a microwave engineer that designs >10Ghz circuits might consider all of the above-mentioned frequencies as "low frequency"

2

What are "High Frequency" Systems

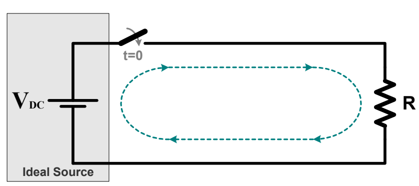
All of the previous examples provide subjective (and greatly varying) definitions of what constitutes a "**high-frequency**" system based upon the respondent's background.

Thus, to truly characterize what constitutes a high-frequency system, we need to discuss a fundamental concept that is often neglected in traditional circuits, electronics, and digital courses:

Travel Velocity

3

Traditional Circuit Theory



Consider the simple DC circuit shown above, what will happen when the **switch closes at time t=0**?

Based on traditional circuit theory, **when the switch closes** at time t=0, **current will "instantaneously" begin to flow** out of the positive terminal of the source and around the closed-loop path provided by the circuit.

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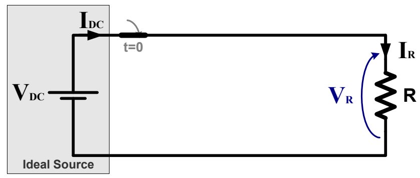
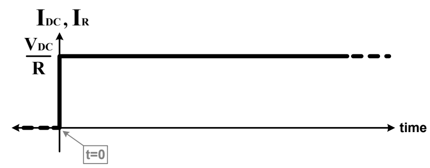
Traditional Circuit Theory



Additionally, the **magnitude of the current** will instantaneously rise up to the value (based on Ohm's Law) that results in an equal but opposing voltage across the resistor:

$$I_{DC} = I_R = \frac{V_{DC}}{R}$$



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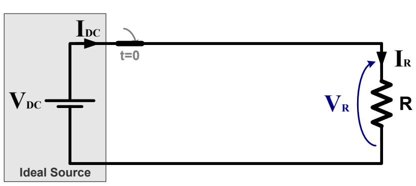
What About Travel Velocity?



$$I_{DC} = I_R = \frac{V_{DC}}{R}$$

But this doesn't take into account "**travel velocity**"…

What is the <u>fastest</u> rate that anything can physically travel???

Speed of Light (in a vacuum)

$$c = 3x10^8 \ \frac{\text{meters}}{\text{second}}$$

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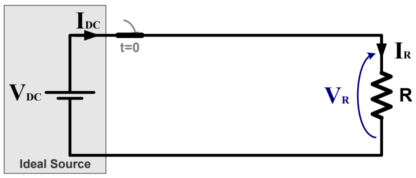
What About Travel Velocity?



Current represents the flow of charge* in a circuit.

*** - remember that, although current denotes positive charge flow, electrons actually flow in the opposite direction around the circuit.**

And like everything else in the universe, those charged particles have a **maximum velocity** that is bounded by the **speed of light**.

But what affect will that have on the current flowing in the circuit?

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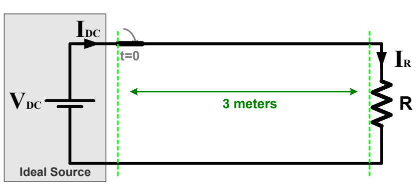
What About Travel Velocity?

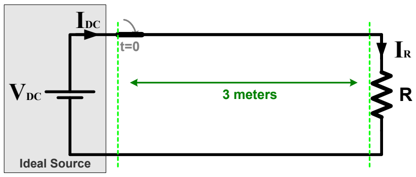


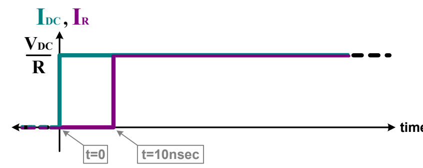
Let us consider the system if the **wires** connecting the source to the resistor are **3 meters in length**.

Furthermore, let's assume that the charged particles will travel at the **speed of light**.

8

When Does the Current Reach the Load?





If the wires are 3 meters in length, then…

When the switch closes at time t=0, the **time** that it takes for the **current** leaving the source **to reach the load** (assuming maximum travel velocity) is:

$$time = \frac{distance}{velocity} = \frac{3 \text{ meters}}{3x10^8 \ \frac{\text{meters}}{\text{second}}} = 10^{-8} \text{ seconds} = \boxed{10 \text{ nsec}}$$

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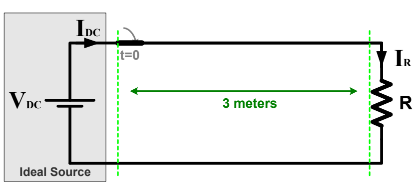
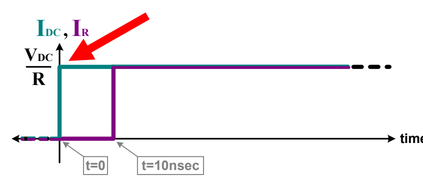
What Determines the Initial Current?





So, it takes 10nsec for the source current to reach the load. This seems reasonable… except that we determined the initial source current magnitude based on Ohm's Law:

$$I_{DC} = I_R = \frac{V_{DC}}{R}$$

and Ohm's Law provides the relationship between the voltage developed by a resistor and the **current flowing in the resistor**.

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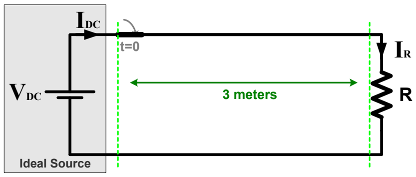
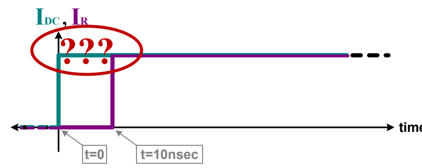
What Determines the Initial Current?





So, it takes 10nsec for the source current to reach the load. This seems reasonable… except that we determined the initial source current magnitude based on Ohm's Law:

If the current doesn't reach the load until 10nsec after the switch closes, then what determines the initial magnitude of the current when the switch first closes?

Note that, if it takes 10nsec for the current to reach the load, then it also takes 10nsec for a voltage to appear across the load.

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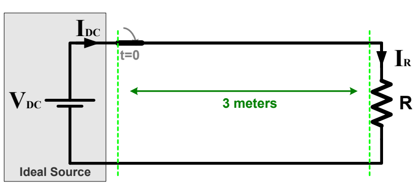
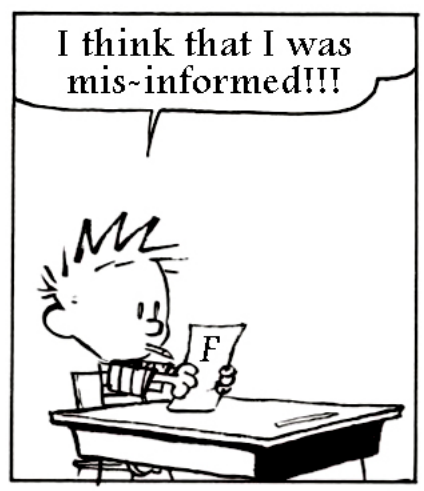
Am I Missing Something???





Obviously, **something** happens when the switch first closes, but if travel velocity is considered, exactly what happens can't be determined solely by traditional circuit theory.

(Note that under **steady-state conditions**, the Ohm's Law solution will thankfully hold true!)

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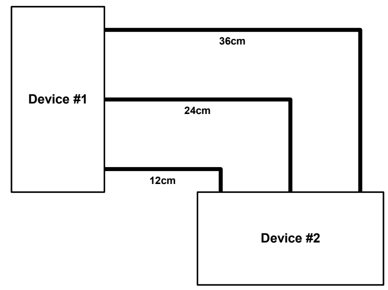
Let's Look at a “Fast” Digital System

Consider the digital system shown to the right that contains two devices that are connected together by three parallel signal lines.

What will happen if device #1 begins to output a 1GHz clock signal on each of the three signal lines?

Note – assume that the clock signal is a square-wave with a 50% duty-cycle



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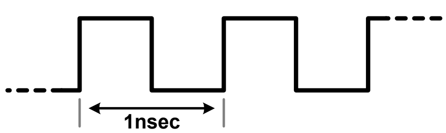
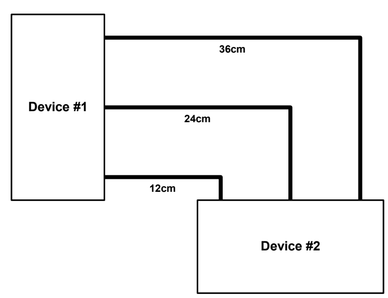
Let's Look at a “Fast” Digital System

If the signals are 1GHz square-waves with a 50% duty-cycle, then the outputs will repetitively transition “high” for ½nsec and then back “low” for ½nsec.





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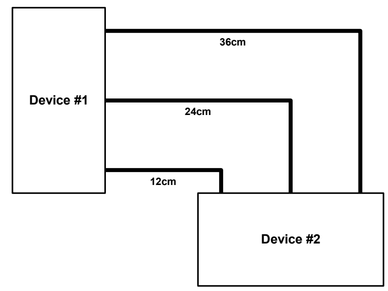
Let's Look at a "Fast" Digital System

When neglecting travel velocity, it can be assumed that whenever an output on device #1 goes high, that voltage will instantaneously be seen at the associated input of device #2.

And based on that assumption, the same voltage potential would be present at every point on the wire that connects the output to the input.



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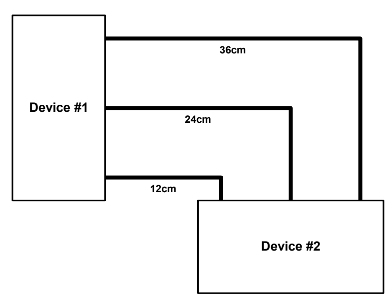
But what if we Account for Travel Velocity?

Assuming maximum travel velocity, the voltages will travel 15cm every ½nsec, which is the length of time that the inputs will remain "high".

But, as shown in the figure, the lines that connect the two devices together are of different lengths…



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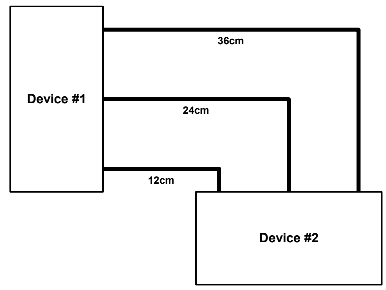
Travel Distance is Important!

And since the wires all have different lengths, if all three outputs transition "high" at the same time, and all of the voltages travel at maximum velocity (15cm every ½nsec)…

Then the output voltages from device #1 will reach the inputs of device #2 at different times.



But, beyond any timing issues that might arise, a less obvious effect will occur that might make you question your circuits knowledge!

17

Notice Something Strange???

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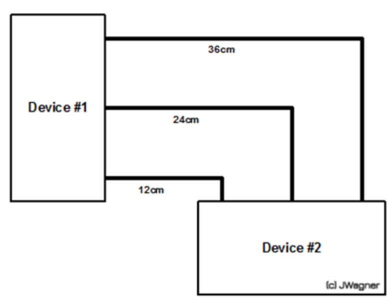

But, beyond any timing issues that might arise, a less obvious effect will occur that might make you question your circuits knowledge!

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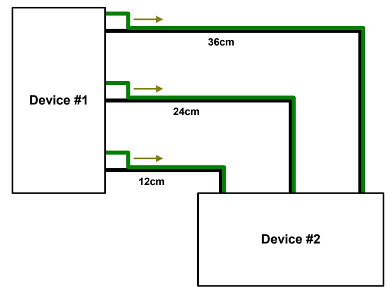
Let's Take A Closer Look

When the outputs of device #1 transition to a "high" state, the voltages will be applied to ends the three lines.

And the applied voltage waveforms will immediately begin to propagate down the lines toward device #2.



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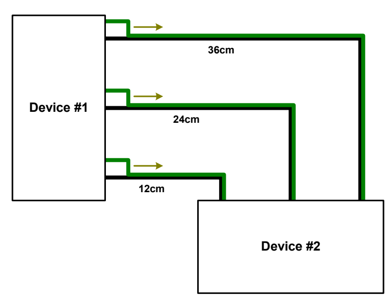
Timing Becomes a Problem

Assuming a maximum travel velocity of $3x10^8$ m/s, the voltages will travel 15cm during the first ½nsec that the outputs remain "high".

$$t = \frac{d}{v} = \frac{0.15\ \text{m}}{3x10^8\ ^{\text{m}}/_{\text{sec}}} = 0.5x10^{-9}\ \text{sec} = 0.5\ \text{nsec}$$



20

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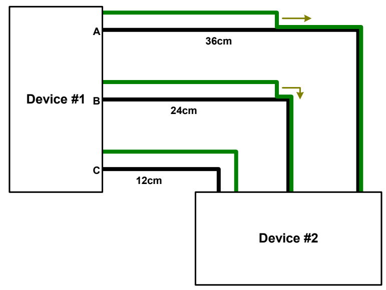
Thus, in ½nsec, the waveform on line **C** will have reached device #2 while the waveforms on lines **A** and **B** will still be traveling towards device #2.

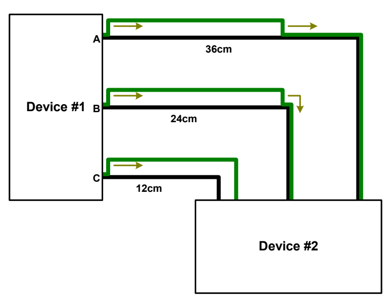


21

Let's Confuse the Issue Even More!

But, after the first ½nsec has passed, the outputs will transition back to a "low" state.

Note that this occurs <u>before</u> the initial pulses on lines **A** and **B** have even reached the inputs of device #2.

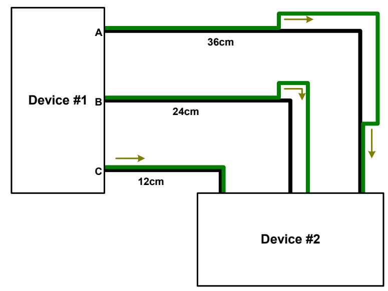


22

Let's Confuse the Issue Even More!

During the time that the outputs remain "low" (½nsec):

- The voltage pulse applied to line **A** will continue traveling towards device #2
- The voltage pulse applied to line **B** will finally reach device #2
- The 0-volt "low" state being applied by the outputs of device #1 will actually reach device #2 on line **C**.



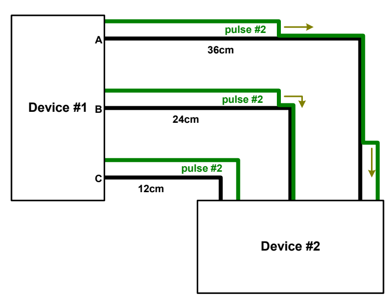
23

Let's Confuse the Issue Even More!

After a total of 1nsec, the outputs will transition "high" again for another ½nsec …

Thus, after a total of 1.5nsec:

Pulse #2 has reached device #2 on line **C** despite the fact that pulse #1 is still being seen by device #2 on line **A**!



And, there are two independent voltage pulses traveling down line A at the same time!

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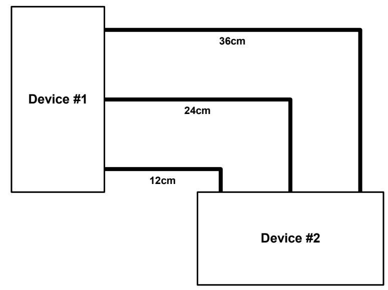
Let's Look at a “Fast” Digital System

Once again, let’s watch the animation, but this time with pauses at the critical moments in time.

Note: the animation assumes that the inputs of device #2 are matched to the impedances of the lines.

We’re not yet ready to discuss this concept, but if the inputs weren’t matched, we would see reflections occurring on the lines when the pulses reach device #2.



25

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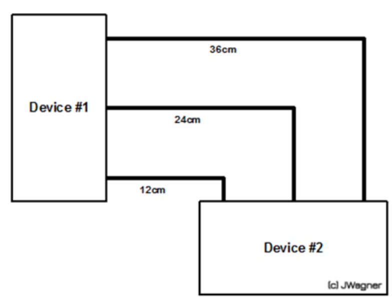

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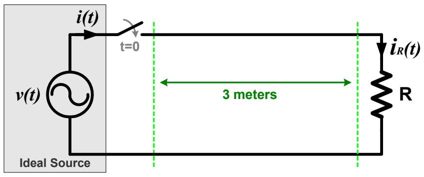
Am I Missing Something???



What about **steady-state AC systems**?

The same issues will also arise with high-frequency AC systems.

And thus… **the fun begins!**

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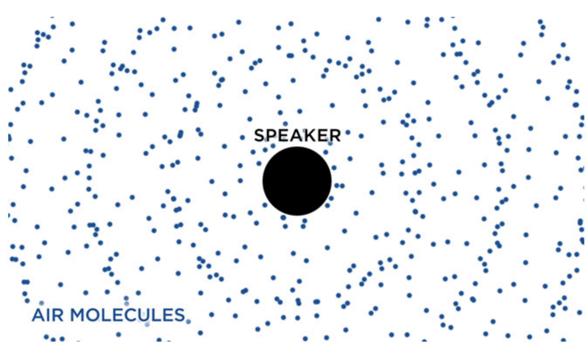
Traveling Waves

A **traveling wave** is an oscillation accompanied by a transfer of energy that travels through a medium with no associated mass transport, such as the sound (pressure) waves that are emitted from a speaker.



28

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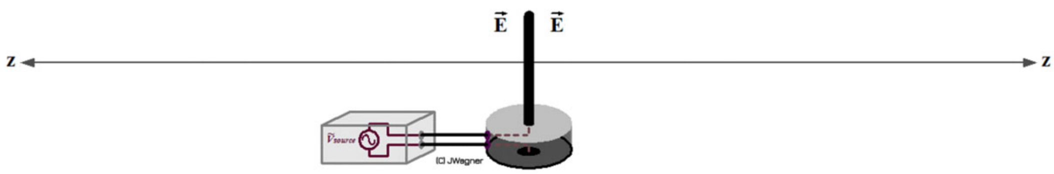

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Frequency, Velocity, and Wavelength

The **wavelength** of a periodic traveling waveform is:

$$\lambda = \frac{\nu}{f}$$

where: λ is wavelength,
ν is velocity, and
f is frequency.

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Wavelength vs. Frequency

The following table shows wavelength as a function of frequency for waves traveling at the speed of light.

Frequency (f)	Period (T)	Wavelength (λ)
60 Hz	16.67 msec	5000 km
1000 Hz	1 msec	300 km
1 MHz	1 μsec	300 m
100 MHz	10 nsec	3 m
1 GHz	1 nsec	30 cm
10 GHz	100 psec	3 cm

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High Frequency Systems

With respect to AC systems:

When a transmission line's length becomes greater than 10% of the wavelength of an applied waveform, high frequency effects should be considered.

With respect to digital systems:

When a transmission line's length becomes greater than 10% of the distance that a signal can travel in one "clock-cycle", high frequency effects should be considered.

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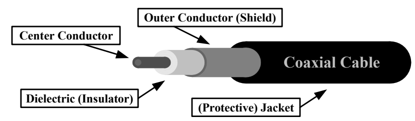
Methods of Transmission

- **Transmission Lines**

  Cables or other structures consisting of two (or more) conductors that are designed to carry electrical signals over "large" distances



- **Waveguides**

  Hollow metal structure within which electromagnetic waves are able to propagate

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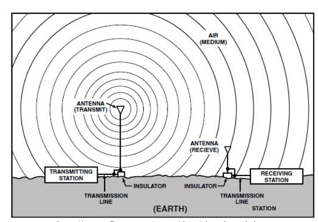
Methods of Transmission

- **Wireless Communication** (Antennas)

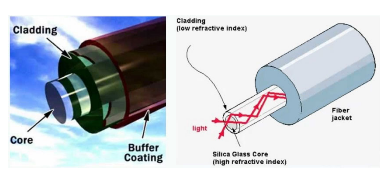
  Utilizing electromagnetic wave propagation to transfer information between two or more points that are not connected by electrical conductors.



http://www.firerescue1.com/data/signalgraph.jpg

- **Optical Fibers**

  Transmitting information from one place to another by sending pulses of light through an optical (glass) fiber



https://www.youtube.com/watch?v=7h2xr-pi5VQ

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