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## EE273 Lecture 4 Wires Concluded RC Lines and Measurement Techniques

October 5, 1998

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1

## Today's Assignment

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- Reading
  - Sections 6.1 through 6.3
  - Complete before class on Wednesday

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2

## A Quick Overview

- Balanced lines
  - differential (odd) and common-mode (even) propagation
  - rise on signal is accompanied by fall on return
- Modeling wires
  - build a model to capture relevant electrical properties
  - ignore inessential elements
  - depends on rise time
- Time-Domain Reflectometer

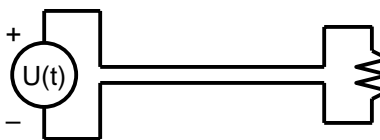
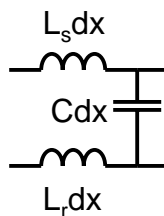
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3

## Balanced Transmission Lines

- All transmission lines have inductance in the return path
  - leads to a shift in return voltage across line
- In a balanced line, return inductance equals signal inductance
- Suppose we put a 1V step into a balanced line
  - 0.5V drop across signal inductor
  - 0.5V drop across return inductor



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4

### Even and Odd Mode Impedance

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e.g., pair of strip guides  
between ground planes

- M and  $C_d$  represent coupling between lines
- L and  $C_c$  represent coupling to other conductors

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5

### Even and Odd Mode (Command and Differential Mode) Impedance

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- Any excitation can be described as the superposition of a differential or odd-mode signal and a common-mode or even-mode signal
- e.g. 1V step:  $V_c = 0.5V$ ,  $V_d = 0.5V$

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### Even and Odd Mode (Command and Differential Mode) Impedance

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$$Z_D = \frac{V_D}{I_1} = \left( \frac{L - M}{C + C_D} \right)^{1/2}$$

$$Z_C = \frac{V_C}{I_1} = \left( \frac{L + M}{C - C_D} \right)^{1/2}$$

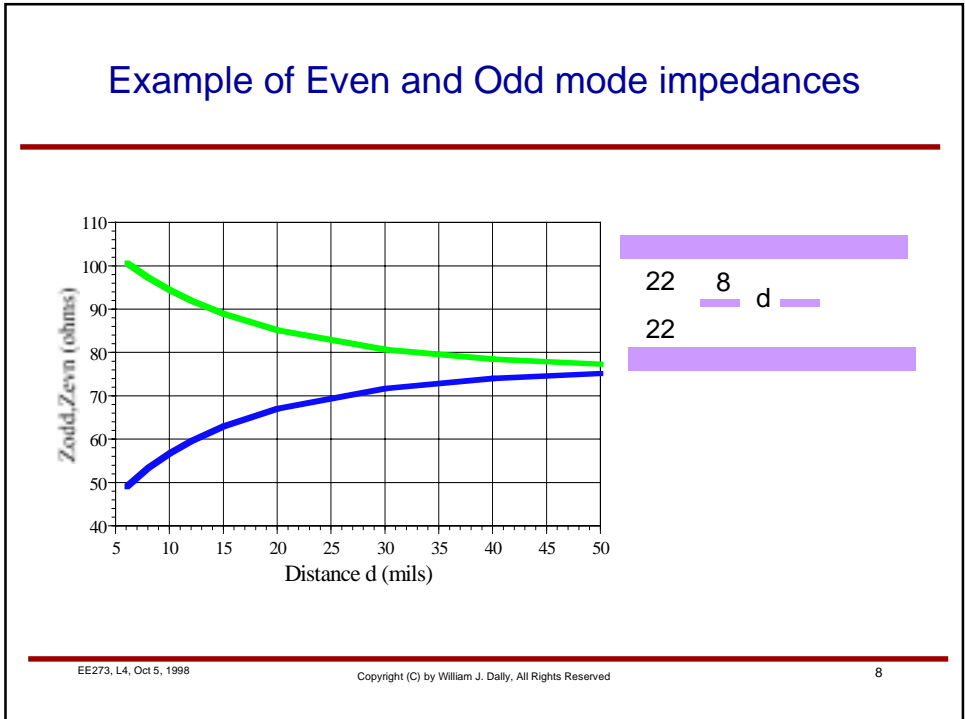
$$C = C_c + C_d$$

$$\frac{L}{M} = \frac{C}{C_d}$$

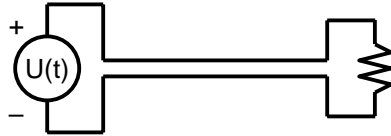
• Even and odd-mode signals see different impedance

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## Terminating Even and Odd Modes



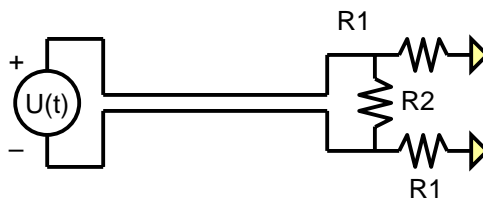
- Suppose  $Z_D=50\Omega$  and  $Z_C=100\Omega$ .
- What happens to a 1V step on the line above?
- How should the line be terminated?

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9

## Terminating Even and Odd Modes



$$R1 = Z_{\text{odd}}$$

$$R2 = 2 \left( \frac{Z_{\text{even}} Z_{\text{odd}}}{Z_{\text{even}} - Z_{\text{odd}}} \right)$$

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10

### Modeling of Wires

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- Given a real system
  - chips, packages, boards, connectors, backplanes, cables
- Need to develop a *model* of the signaling medium
  - for hand calculation of key properties
  - for SPICE simulations
- Model must
  - capture all *relevant* wire properties
    - transmission line properties
    - major discontinuities
    - terminations
  - ignore those that are not relevant
    - e.g., short discontinuities

The diagram shows a cross-section of a system. At the top, a grey chip is mounted on an orange package. Below this, a green PC board contains an orange connector. To the right, a vertical green backplane is connected to the connector. Labels with arrows point to 'package', 'chip', 'PC board', 'connector', and 'backplane'.

- A good model captures the *relevant* behavior while being as simple as possible

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### Example Model

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The diagram is identical to the one in the previous slide, showing a chip on a package, a connector on a PC board, and a backplane.

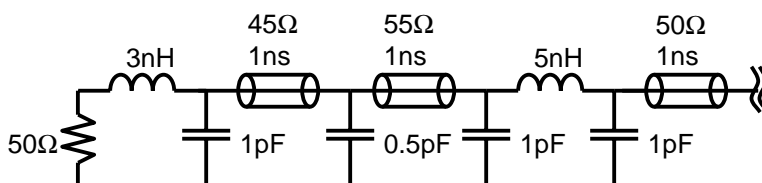
The equivalent circuit model consists of a series of components connected in a line. From left to right: a 50Ω resistor, a 3nH inductor, a 45Ω transmission line segment, a 1pF capacitor, a 55Ω transmission line segment, a 0.5pF capacitor, a 5nH inductor, a 1pF capacitor, a 50Ω transmission line segment, and finally a 1pF capacitor followed by a double-line symbol indicating the circuit continues.

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## Deriving a Model

- How do we make a model of a signal path?
  - hand calculation
  - assemble models from component, connector, and package vendors
  - CAD programs
  - measurements of the actual system



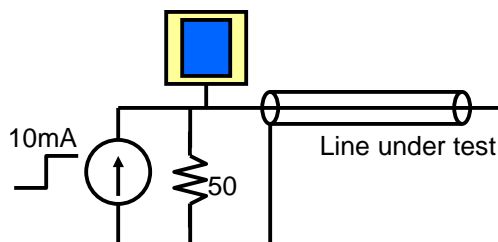
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13

## Meet the Time-Domain Reflectometer

- A time-domain reflectometer is a fast step generator and a high-speed oscilloscope.
- To characterize a line
  - inject a fast (usually 20ps) step into the line
  - observe the reflected waveform
  - what does it mean?

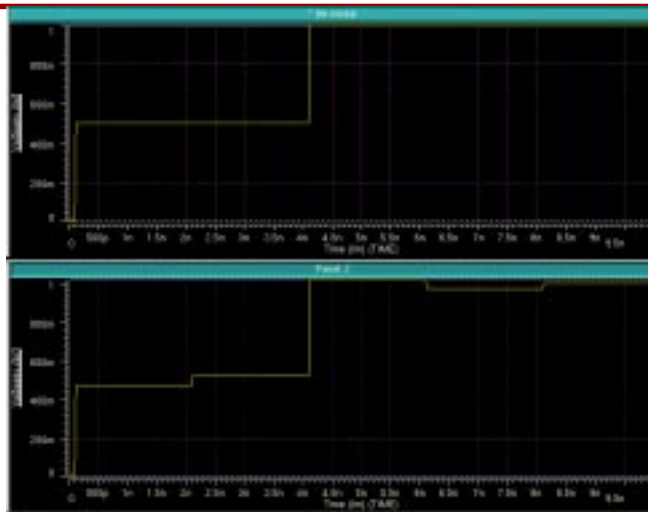


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14

### What made these waveforms?



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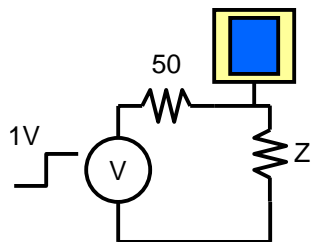
15

### Calculating Impedance from Voltage

$$V = \frac{Z}{Z + Z_0}$$

$$(Z + Z_0)V = Z$$

$$Z = Z_0 \left( \frac{V}{1 - V} \right)$$



V	Z
0.50	50.0
0.47	44.3
0.53	56.4

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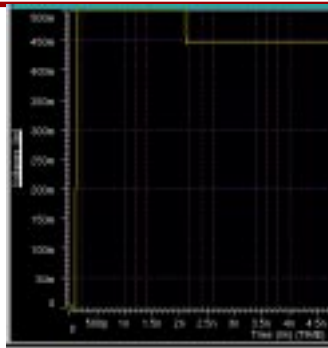
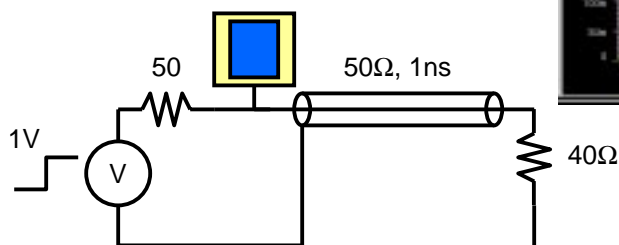
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16



### Time of Observation is Round Trip

$$Z(x) = Z_0 \left( \frac{V(2x/v)}{1 - V(2x/v)} \right)$$



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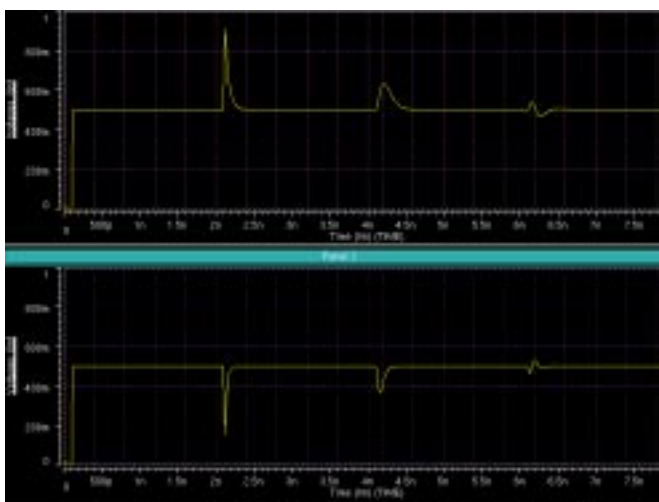
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### What About Inductors and Capacitors?

$$L = 2Z_0\tau_L$$

$$C = \frac{2\tau_C}{Z_0}$$



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18

## Rise-Time Degradation

- Upstream elements (Ls & Cs) low-pass the signal resulting in a longer rise-time
- This affects the reflections from down-stream elements
  - slow rising edge
  - spread out response (convolution with slow edge)
  - L & C responses don't go full swing
- This makes it
  - hard to extract exact L and C values
  - impossible to measure very small discontinuities
    - but if the TDR can't see them, neither can the signal

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19

## Extraction Procedure

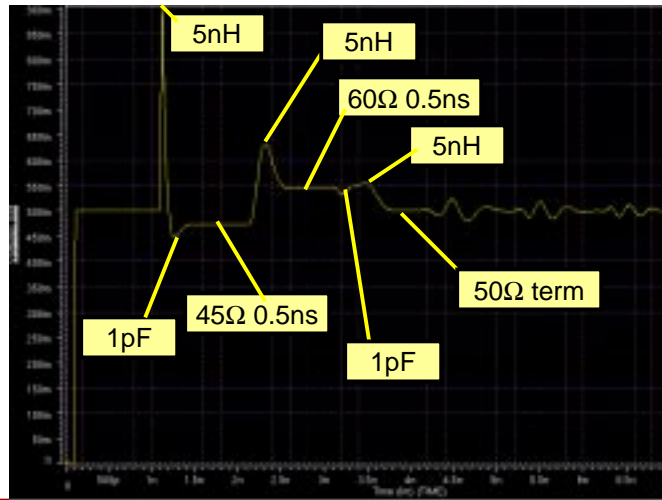
- Identify regions of the TDR plot as
  - flat region - transmission line
  - bump up - inductor
  - bump down - capacitor
- Starting at source
  - determine value of Z & t, L, or C for nearest element
  - simulate to validate and determine new  $t_r$ 
    - iterate as needed to get value right
  - move on to next element
- Don't need model with more resolution than your fastest rise time

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20

### Example TDR Trace

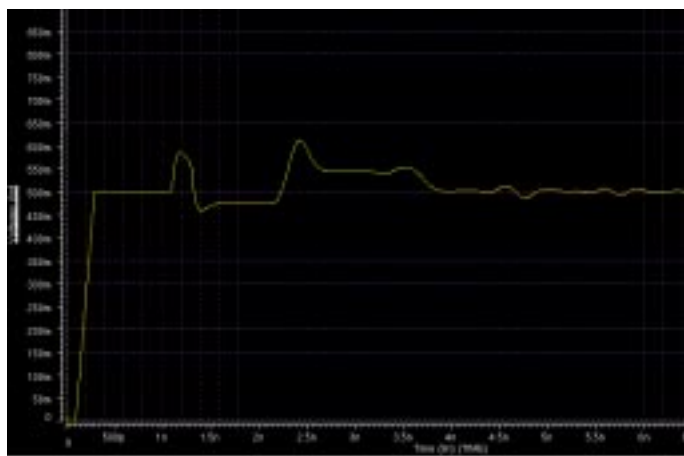


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21

### Same waveform with 200ps edge



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22

## Next Time

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- Noise
  - what disturbs digital signals
  - fixed and proportional noise
- Power Supply Noise
  - single supply and differential
  - sources
- Cross Talk
  - capacitive crosstalk
  - transmission lines