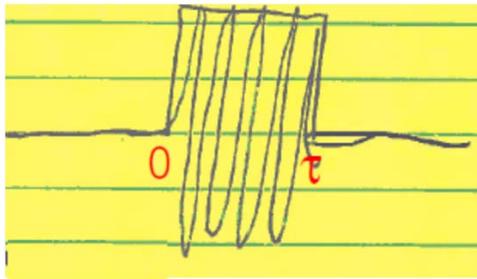
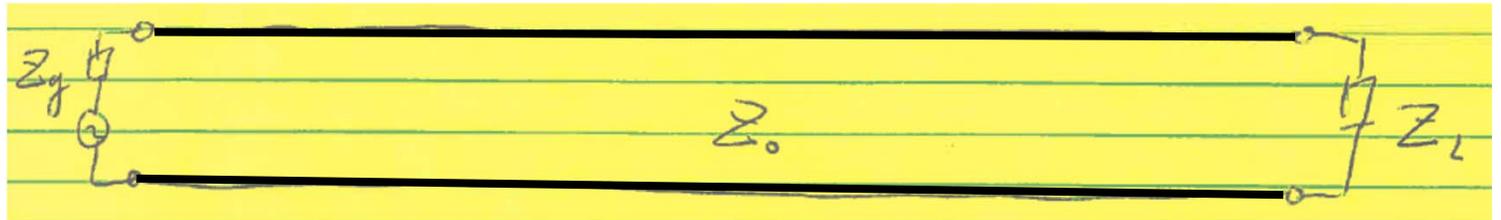


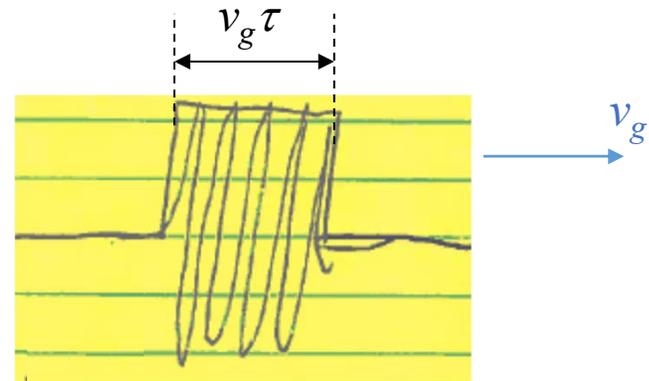
## Propagation of Pulses on Transmission Lines

So far we have been talking about single-frequency (harmonic) “signals”, which carry no information.

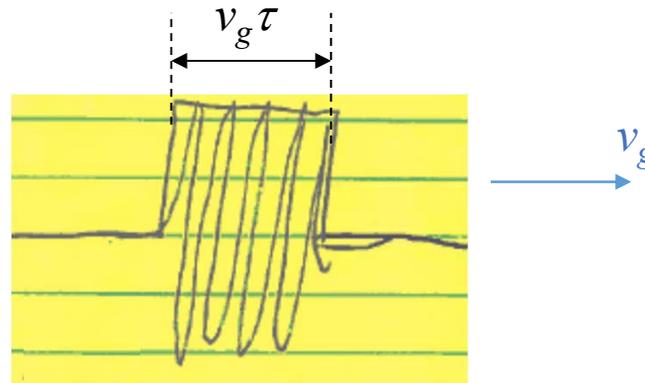
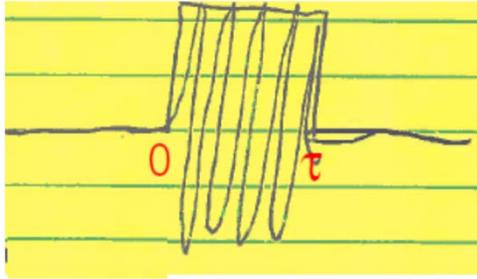
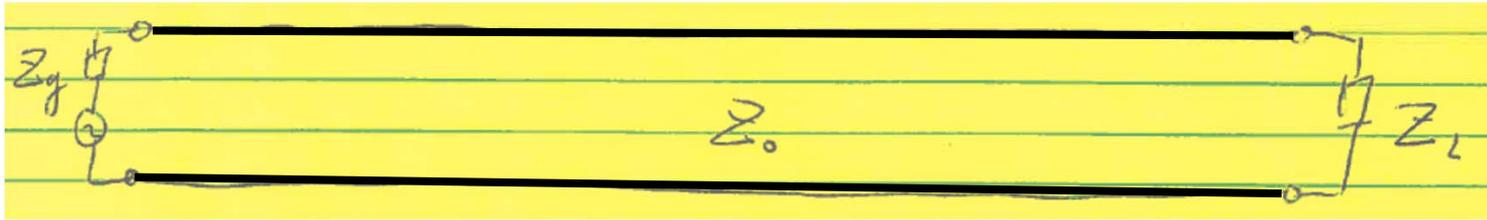
To transmit information, we must **modulate** the signal.



For example, we modulate a microwave carrier to send a bit down the line.



This envelope travels along the line at speed  $v_g$ , the “**group velocity**,” which is usually a little different from  $v_p$ , due to **dispersion**.

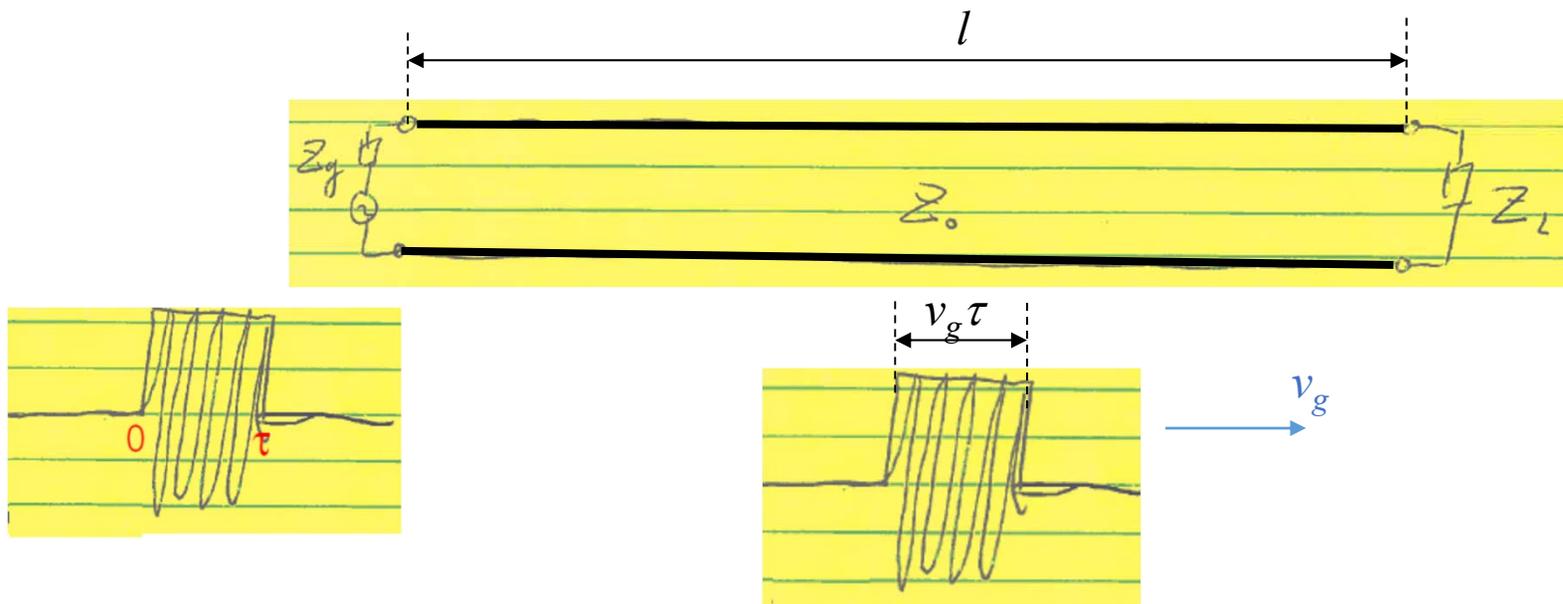


For simplicity, we ignore dispersion and assume  $v_g = v_p$ .

If  $Z_L = Z_0$ , this pulse is totally absorbed upon arrival at the load.  
This is what we want.

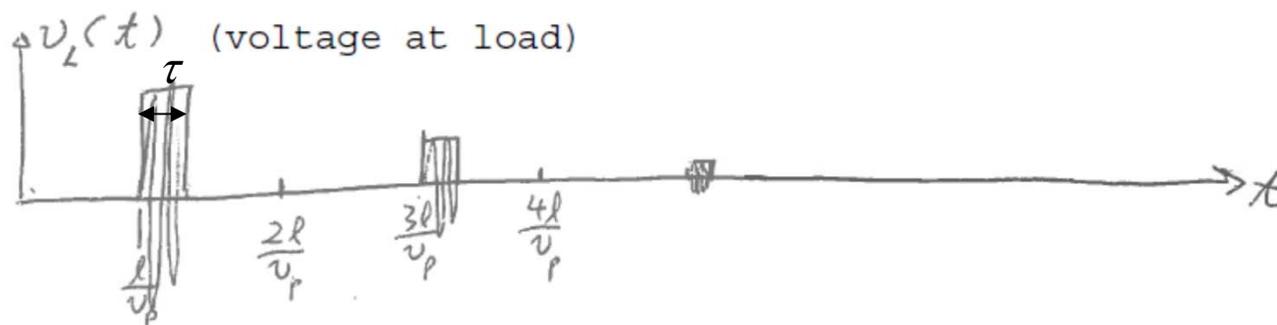
For a lossless line,  $Z_0$  is real.

If  $Z_L$  is purely resistive, this match is (assumed to be) frequency-independent.

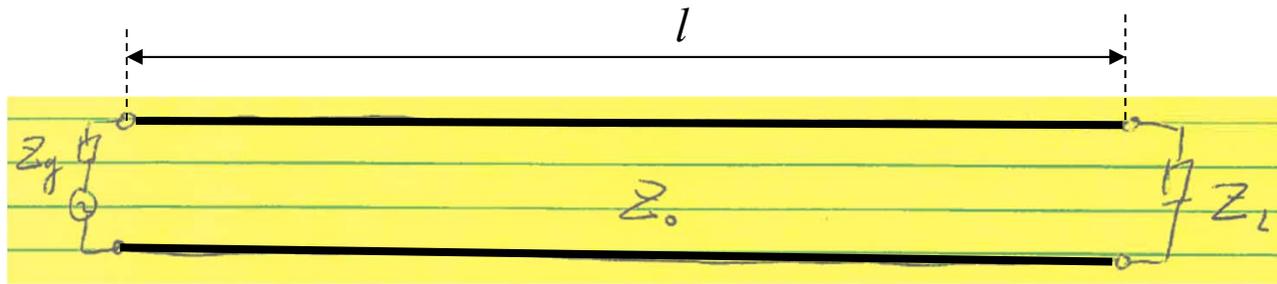


If  $Z_L \neq Z_0 \neq Z_g$ , things become complicated.

We first look at the case,  $\tau < l/v_p$ :

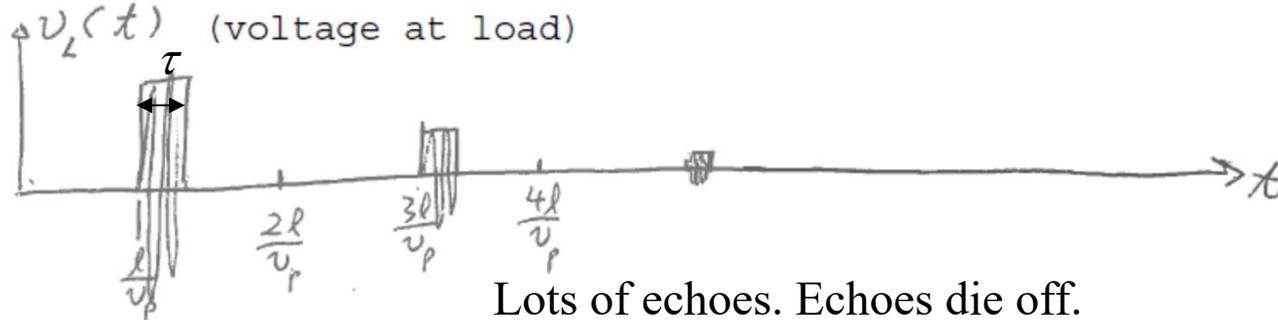


Lots of echoes. Echoes die off.



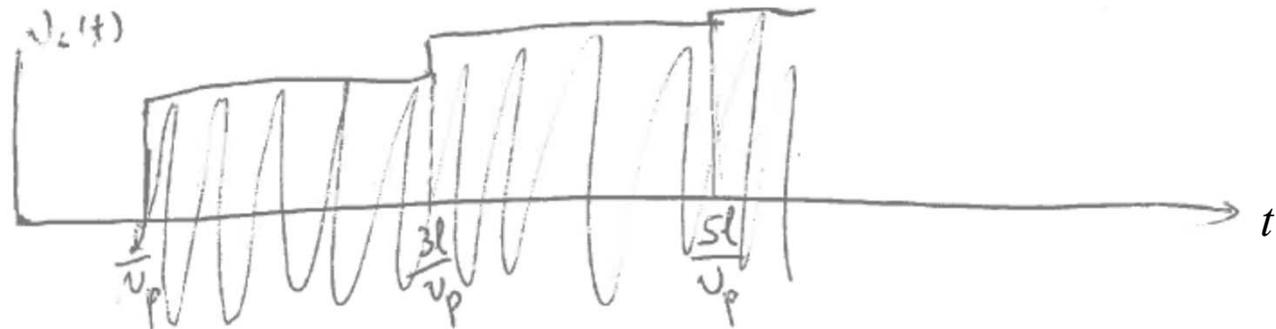
$$Z_L \neq Z_0 \neq Z_g$$

First case,  $\tau < l/v_p$ :



Lots of echoes. Echoes die off.  
May corrupt other bits

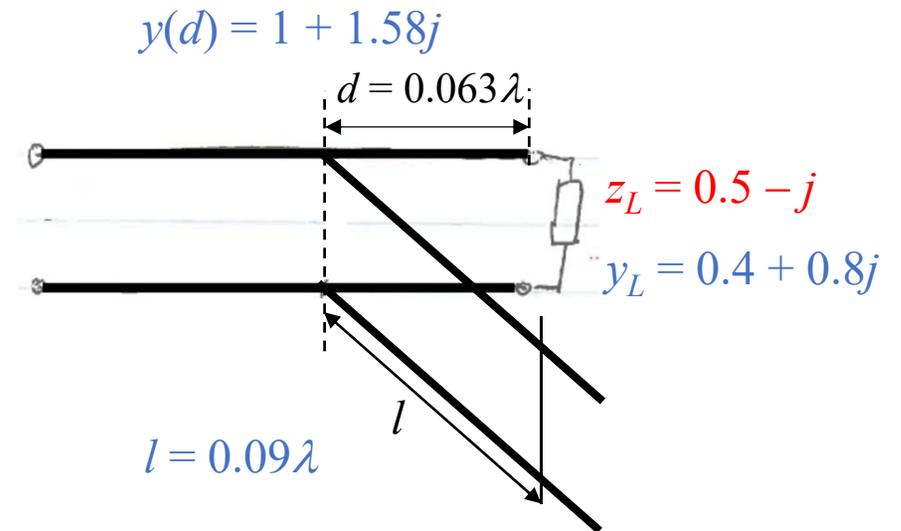
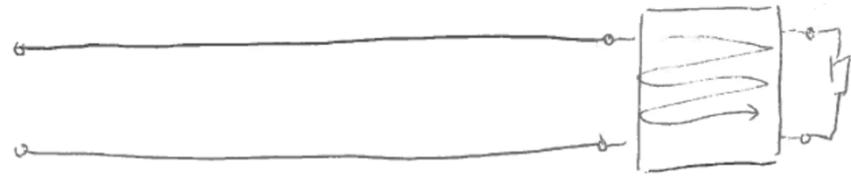
Second case,  $\tau > l/v_p$ ,  
i.e.,  $l < v_p \tau$ :



The bit is distorted and  
broadened.

Recall that we always have multiple reflections inside any matching network.

Does impedance matching really help us?  
Why?



Single stub matching example

Recall that we always have multiple reflections inside any matching network.

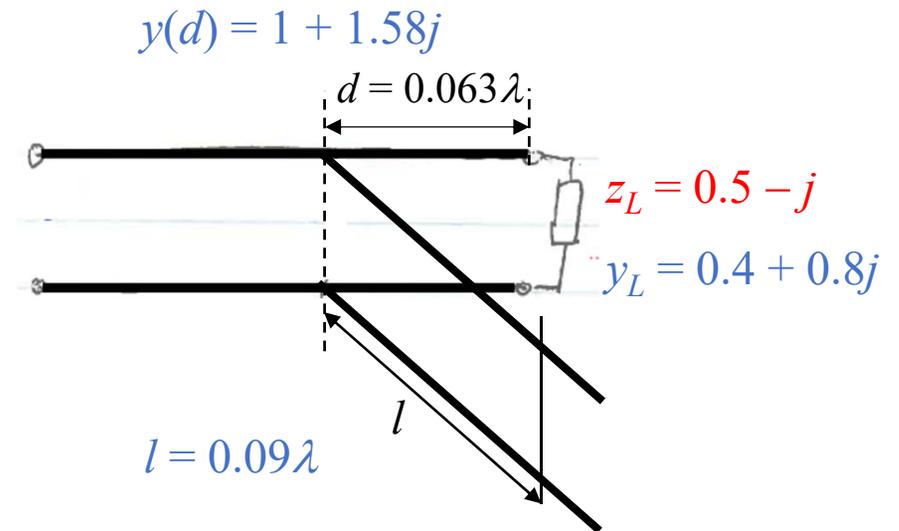
Do impedance matching really help us?  
Why?

Notice that we can always choose to have  $d < \lambda/2$  and  $l < \lambda/2$ .

The time to travel  $\lambda/2$  is  $1/(2f)$ .

Thus the bit is broadened only by several  $1/(2f)$ , at most.

Without matching, we have echoes.



Single stub matching example

The modulated case is quite complicated. We now look into a simple case quantitatively.

## Several Things to Talk about

### Homework

Previous student comments:

I prefer HW assignments to be mandatory. That way I'm forced to do it and learn. I was good about doing the **optional** HW at the beginning of the semester, but lost steam towards the end.

I realize that he uses the homework as a self study and trusts the student to do it on their own time, but as a **Junior** semester class, having no graded assignments between exams makes it very easy to prioritize other classes. If it is important that the students really learn your material, you need to provide **incentive** to do the homework. Simply giving a grade for it would suffice.

At the junior year, you need to make the transition.

### Test 1

Thu 10/18/2018. Chapters 1 & 2.

### Reading to prepare for the Field Theory

Chapter 3: vector analysis.

Sections 4-1, 4-2, 4-3, & 4-4

**First, let's list the basic assumptions to be used:**

1. Lossless line.  $Z_0$  is purely real.
2. Purely resistive load  $Z_L = R_L$ .
3. Therefore,  $\Gamma$  is frequency-independent.  
(If  $R_L = Z_0$ , impedance matched for all frequencies)
4. Dispersionless:  $v_g = v_p$  for all frequencies.

Know the simplifying assumptions. Know the limitations.

## Propagation of a voltage step on a transmission line

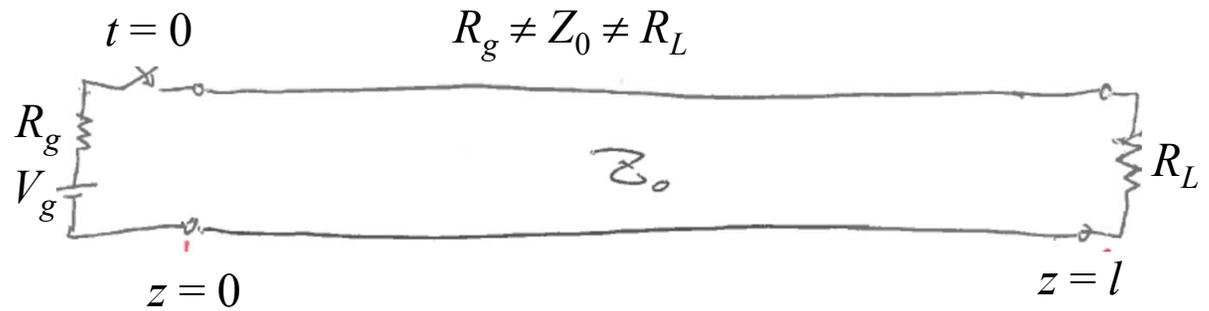
For  $0 < t < T = l/v_p$ ,

Time of a single trip

The “turn-on” event has not reached the load yet. It does not know about  $R_L$ .

The transmission line feels like infinitely long. In other words, no reflection yet.

What is the equivalent input impedance at  $z = 0$ ?



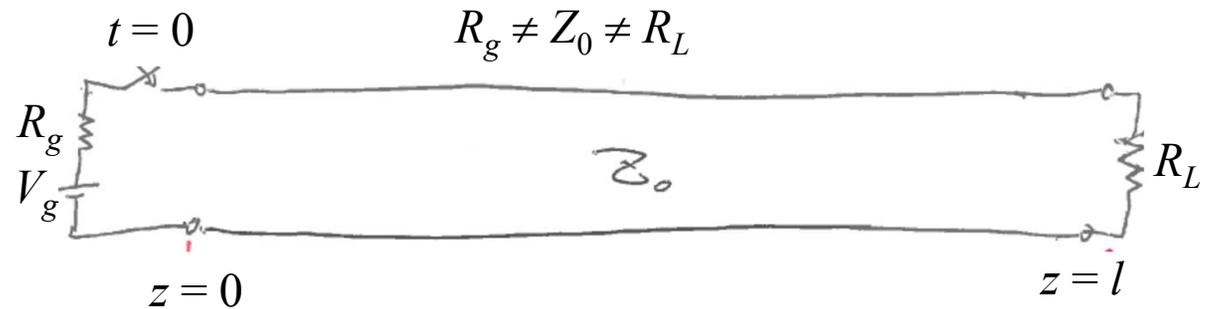
Notice change in convention. Generator at  $z = 0$ , load at  $z = l$ .



# Propagation of a voltage step on a transmission line

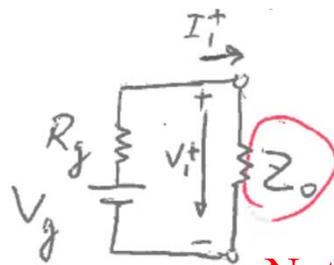
For  $0 < t < T = l/v_p$ ,

Time of a single trip



The “turn-on” event has not reached the load yet. It does not know about  $R_L$ .

The transmission line feels like infinitely long. In other words, no reflection yet.



The equivalent input impedance at  $z = 0$  is  $Z_0$ .

Not  $Z_{in}$ !

$$V_1^+ = \frac{V_g Z_0}{R_g + Z_0}$$

$$I_1^+ = \frac{V_g}{R_g + Z_0}$$

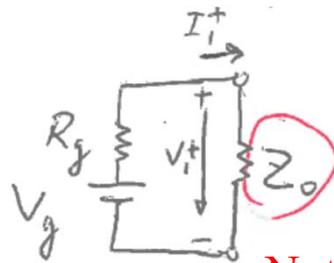
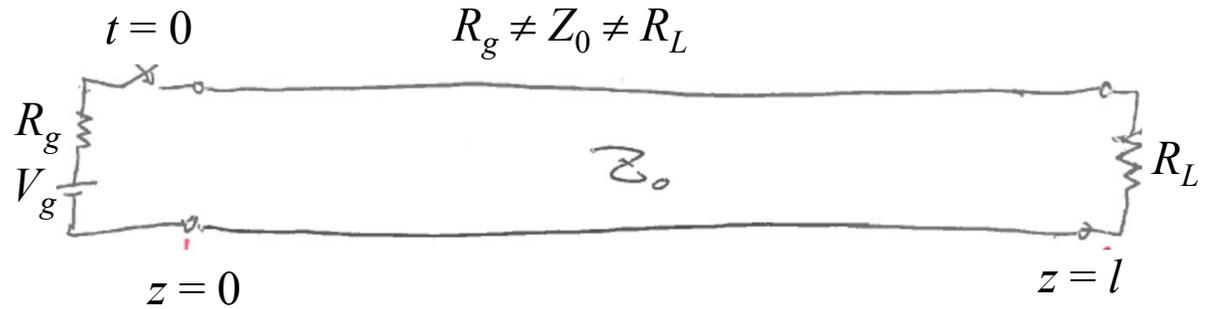
Subscript “1” means the first round trip.

Superscript “+” means the incident direction.

# Propagation of a voltage step on a transmission line

$$V_1^+ = \frac{V_g Z_0}{R_g + Z_0}$$

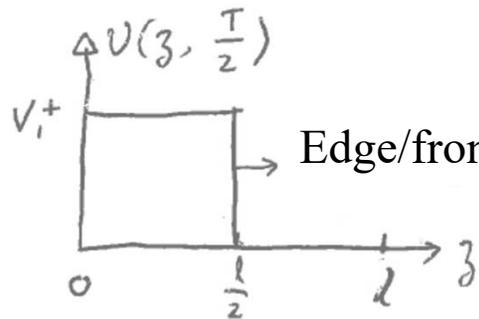
$$I_1^+ = \frac{V_g}{R_g + Z_0}$$



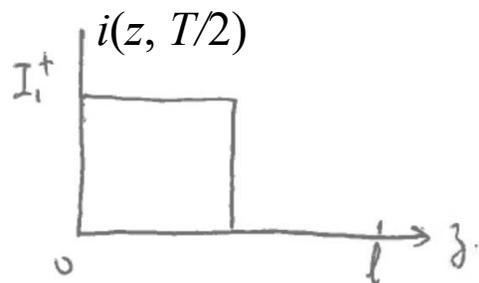
The equivalent input impedance at  $z = 0$  is  $Z_0$ .

Not  $Z_{in}$ !

Snapshots at  $t = T/2$



Edge/front moving at  $v_p$  (actually  $v_g$ )



The leading edge reaches the load at  $t = T$ . Reflection.

$$V_1^- = \Gamma_L V_1^+$$

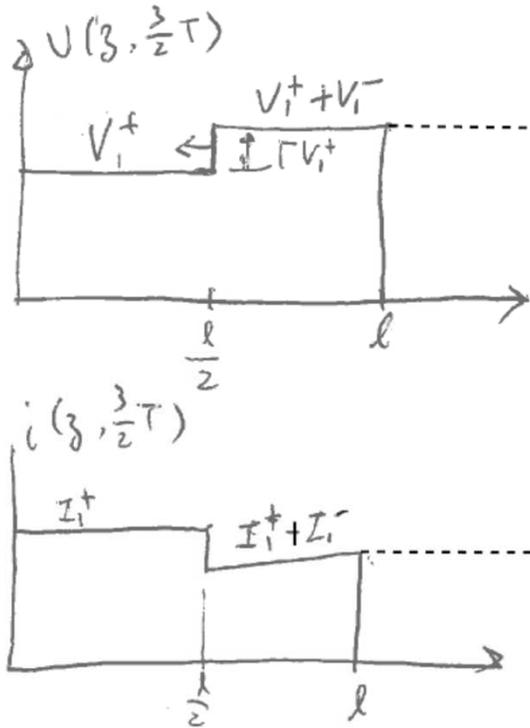
$$I_1^- = -\Gamma_L I_1^+$$

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0}$$

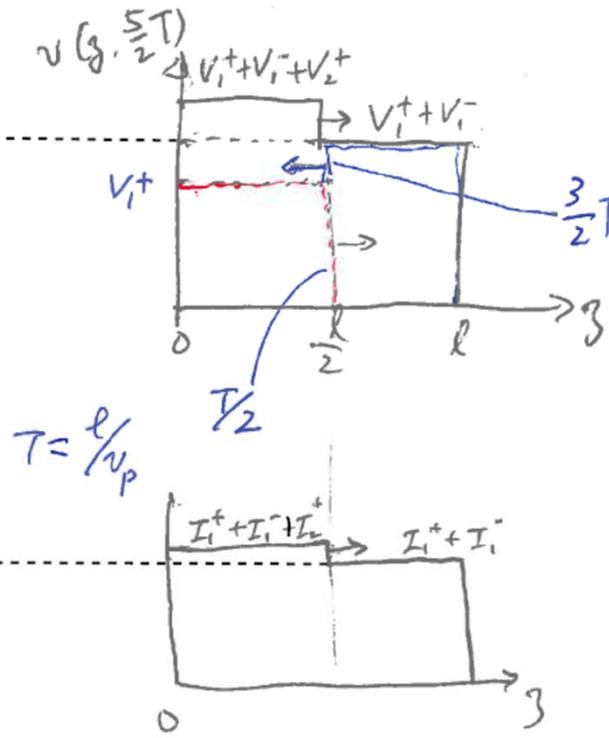
What is the voltage at the load at  $t = T$ ?

What is the voltage at the load at  $t = T$ ?  $V_1^+ + V_1^-$

Snapshots at  $t = 3T/2$



Snapshots at  $t = 5T/2$



Assuming

$$\Gamma_L > 0$$

$$\Gamma_g > 0$$

At  $t = 2T$ , the front hits the source. Reflection.

$$\Gamma_g = \frac{R_g - Z_0}{R_g + Z_0}$$

$$V_2^+ = \Gamma_g V_1^- = \Gamma_g \Gamma_L V_1^+$$

$$I_2^+ = -\Gamma_g I_1^- = \Gamma_g \Gamma_L I_1^+$$

At  $t = 3T$ , the front hits the load again.

$$V_2^- = \Gamma_L V_2^+$$

$$I_2^- = -\Gamma_L I_2^+$$

Again, notice the sign.

$$V_2^+ + V_2^- = V_2^+ (1 + \Gamma_L)$$

$$I_2^+ + I_2^- = I_2^+ (1 - \Gamma_L)$$

Again, notice that reflection happens instantaneously.

It goes on and on. For the  $i$ th round trip,

$$V_i^+ + V_i^- = V_i^+ (1 + \Gamma_L)$$

$$I_i^+ + I_i^- = I_i^+ (1 - \Gamma_L)$$

$$v(z = \infty) = V_1^+ + V_1^- + V_2^+ + V_2^- + V_3^+ + V_3^- + \dots$$

$$= \sum_{i=1}^{\infty} (V_i^+ + V_i^-)$$

$$= V_1^+ (1 + \Gamma_L) + V_2^+ (1 + \Gamma_L) + \dots = (1 + \Gamma_L) [V_1^+ + V_2^+ + \dots]$$

$$= (1 + \Gamma_L) \sum_{i=1}^{\infty} V_i^+$$

Note: At the steady state,  $v$  is the same at all  $z$ , therefore we do not specify  $z$ .

$$v(t=\infty) = V_1^+ + V_1^- + V_2^+ + V_2^- + V_3^+ + V_3^- + \dots$$

$$= \sum_{i=1}^{\infty} (V_i^+ + V_i^-)$$

$$V_i^+ + V_i^- = V_i^+ (1 + \Gamma_L)$$

$$= V_1^+ (1 + \Gamma_L) + V_2^+ (1 + \Gamma_L) + \dots = (1 + \Gamma_L) [V_1^+ + V_2^+ + \dots]$$

$$= (1 + \Gamma_L) \sum_{i=1}^{\infty} V_i^+$$

$$V_2^+ = \Gamma_g \Gamma_L V_1^+ \quad V_{i+1}^+ = \Gamma_g \Gamma_L V_i^+$$

$$v(t=\infty) = V_1^+ (1 + \Gamma_L) [1 + \Gamma_g \Gamma_L + (\Gamma_g \Gamma_L)^2 + \dots]$$

$$= V_1^+ (1 + \Gamma_L) \sum_{i=0}^{\infty} (\Gamma_g \Gamma_L)^i$$

Use

$$1 + x + x^2 + \dots = \sum_{i=0}^{\infty} x^i = \frac{1}{1-x}$$

with  $x = \Gamma_g \Gamma_L$

We get:

$$v(t=\infty) = V_1^+ (1 + \Gamma_L) \cdot \frac{1}{1 - \Gamma_g \Gamma_L}$$

$$v(t = \infty) = V_1^+ (1 + \Gamma_L) \cdot \frac{1}{1 - \Gamma_g \Gamma_L}$$

$$V_1^+ = \frac{V_g Z_0}{R_g + Z_0}$$

$$\Gamma_g = \frac{R_g - Z_0}{R_g + Z_0}$$

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0}$$

$$\Rightarrow v(t = \infty) = \frac{V_g R_L}{R_g + R_L}$$

Surprising?

Similarly,

$$i(t = \infty) = I_1^+ (1 - \Gamma_L) \sum_{i=0}^{\infty} (\Gamma_g \Gamma_L)^i$$

$$= I_1^+ \frac{1 - \Gamma_L}{1 - \Gamma_g \Gamma_L}$$

$$= \frac{V_g}{R_g + R_L}$$

We have traced  $v(t)$  and  $i(t)$  all the way to  $t = \infty$ .

That's quite tedious.

We have a graphical tool to trace this bouncing back and forth.

It's called the bounce diagram.