# UMass ECE 210 – Fall 2023

## Lab 7: RLC circuit with NMOS switch

**GOALS:**

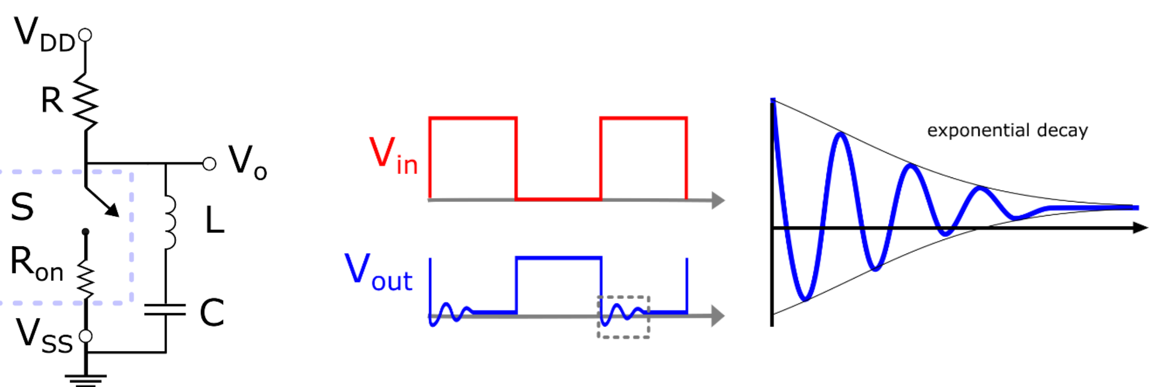
- Study RLC circuit oscillations
- Introduction to inverters

**DATA required for Lab report:**

| |
|---|
| PLOT – Rise time of gate capacitance |
| PLOT – Output of NMOS inverter with capacitor |
| PLOT – Output of NMOS inverter with capacitor and inductor ringing |

**CD4007 Datasheet: https://www.ti.com/lit/gpn/cd4007ub**

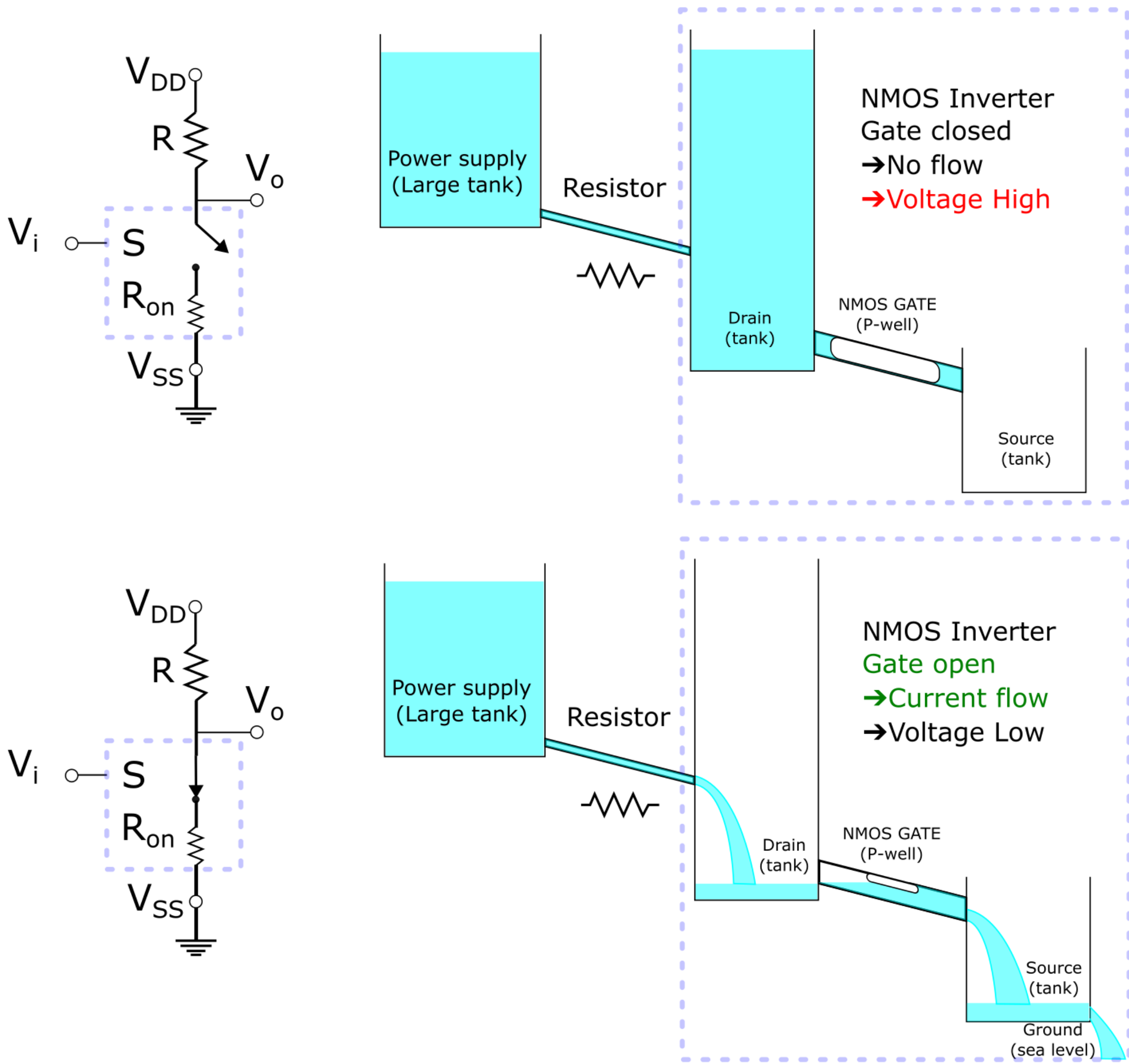
NMOSFETs can be used as switches to control circuits and in the SR (switch resistor model) can be included in the subsequent circuit as a resistance. We will see how when wired up with an inductor and capacitor we can induce ringing from the fast switching and measure the Q factor of the oscillations.




The time dynamics of NMOS switching is critical for logical operations as the switch must drive the next NMOS device as fast as possible (without ringing) to increase the speed of the calculations. One speed limit is the finite capacitance of the next NMOS device's gate, which must be charged before the "Field Effect" can create a path for the current (as the NMOS device switches on). This charging delay from gate capacitance is the main speed limit for CPUs and motivates the entire field of Very Large-Scale Integration (VLSI) nanofabrication layout.

## MOSFET Switch (Inverter)

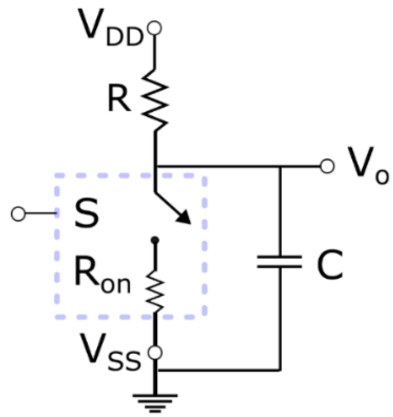
In this lab we will investigate the time response of circuits with capacitors and inductors when they are excited by step changes in voltage from a switch. We will use a Negative MOSFET as our voltage-controlled switch. This creates a digital circuit often called an inverter (Fig 1). When the input (Vi) is at a low voltage, the output is at a high voltage ($V_{DD}$), and when the input is at a high voltage, the switch is turned on, and the output drops to a low voltage, thus inverting!




The MOSFET can be modeled as a switch in series with a resistance, $R_{ON} = 300\Omega$.
The switch is controlled by $V_{input}$: if $V_{input}$ is low, the gate is closed and the switch is open. Therefore, there is no current in R and $V_{output} = V_{DD}$.
When $V_{input}$ is high, the gate is open and switch is closed, and a voltage divider is formed with R and $R_{ON}$, dividing $V_{DD}$ to a small value close to zero.
To get the output low voltage to be less than 0.25V we will set R greater than 5k Ohm.

## Inverter Transient Response

Inverter circuits often drive other logic circuits or transmission lines. Anything connected to the inverter output is said to "load" the inverter. We will add a capacitor to the output as a load and measure the transient response. When the switch opens, current flows through R into C and $V_o$ increases until the capacitor is charged to $V_{DD}$. When the switch closes, C discharges through $R_{on}$ until $V_o$ approaches zero. If $R_{on}$ is zero, C discharges until $V_o$ approaches 0V. If $R_{on}$ is **not** zero, C discharges until $V_o$ matches the output without a capacitor.



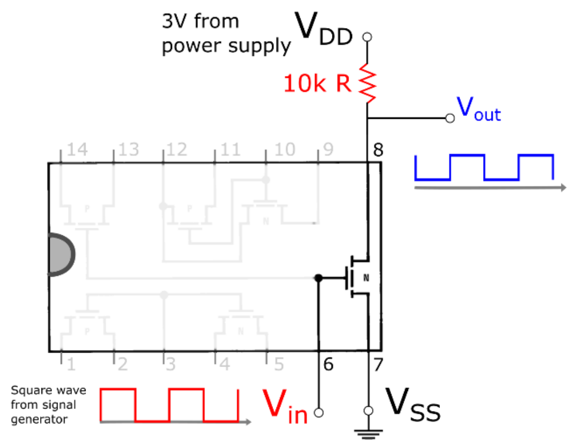

## NMOS Inverter (fast switch):

1. Find a CD4007 MOS integrated circuit at the front of the lab and place in breadboard
   **CD4007 Datasheet:**
   **https://www.ti.com/lit/gpn/cd4007ub**

2. Connect a 10k Ohm resistor to **PIN 8**

3. Supply 3V ($V_{DD}$ = 3V) to the resistor
   *The notation VDD indicates the 'Drain' for all MOSFETs in the IC, not just one.*

4. Set the signal generator to **Square Wave:**
   a. **Period** = 100 µs, 50% duty cycle
   b. **$V_{MAX}$** = +5.0V, **$V_{MIN}$** = 0.0V
   *Verify the OFFSET voltage is 2.5V*




5. Monitor the square wave from the signal generator on oscilloscope CH1

6. Split the input signal and connect it to the NMOS gate on **PIN 6**

7. Ground **PIN 7** and make sure ground is common for all devices!

8. Measure and RECORD the output from **PIN 8** with CH 2 of the oscilloscope

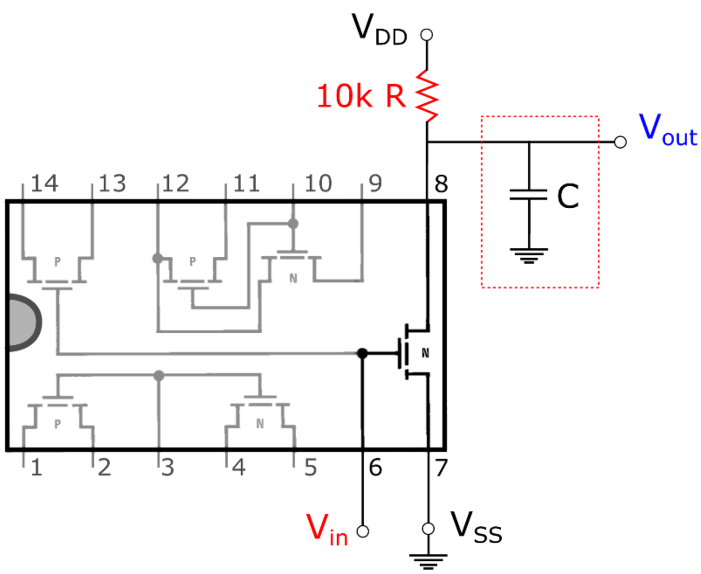
   *Verify your output is a square wave oscillating between 3V and some low voltage. That is the inversion of the input signal on CH1.*

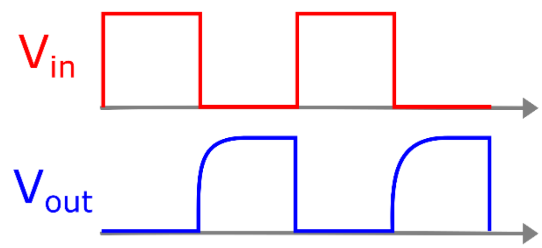
9. RECORD the low voltage of the output signal manually
   (The Oscilloscope 'Minimum' won't be precise enough due to overshoot)

10. Calculate $R_{on}$ from this low voltage assuming a voltage divider with R=10kΩ

**Measure the rise/fall time driving a capacitor:**

1. Insert a 0.5nF capacitor between the drain (PIN 8) and ground (PIN 7).
2. Measure and RECORD the rise time, $T_{rise}$ and fall time, $T_{fall}$ of $V_{out}$.
3. Calculate the rise and fall time expected given R and C
4. Compare your calculated times and measured times

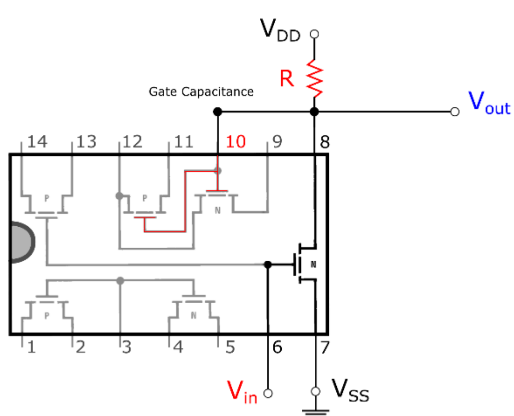


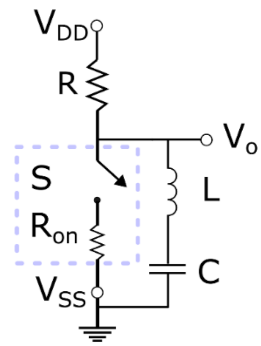

**Try measuring the internal gate capacitance:**

1. Remove the external 0.5nF (500pF) capacitor
2. Look up the gate capacitance in the data sheet: [https://www.ti.com/lit/gpn/cd4007ub](https://www.ti.com/lit/gpn/cd4007ub)
3. Add a wire to connect pin 8 to pin 10 (and/or pin 3)
   (This will drive the gate of other MOSFETs on the IC)
4. Try measuring the difference of $T_{rise}$:
   a. Pin 8 and pin 10: connected
   b. Pin 8 and pin 10: disconnected

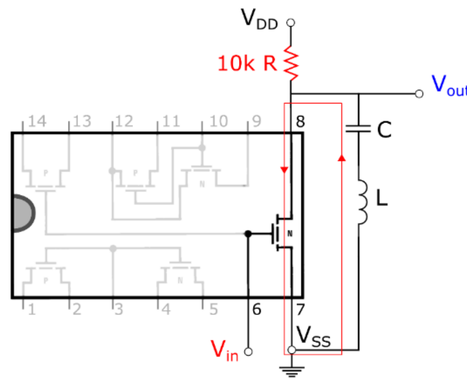
   *You will only see a small difference.*
   *That is expected.*
5. For your lab report:
   a. Estimate the small internal gate capacitance from the difference in rise times with the extra gate capacitance.
   b. Compare to the data sheet specification for gate capacitance.



**Measure the Oscillations of RLC circuit:**

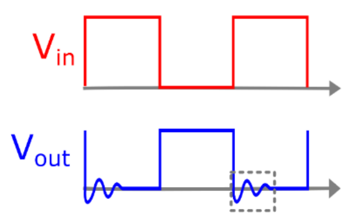



1. Disconnect PIN 10 from PIN 8
2. Connect a 0.5nF capacitor to the output (PIN 8)
3. Set the signal period back to 100us.
4. Use a large 1mH inductor to connect the capacitor to ground (PIN 7)
5. Trigger on the <u>falling</u> edge of Ch2
   (or the rising edge of CH1)




6. RECORD the output voltage ringing
7. Measure the period of the ringing
8. Calculate the period of the ringing

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad 2\pi f = \omega \left[\frac{rad}{s}\right] \qquad T = 2\,\pi\,\sqrt{LC}$$



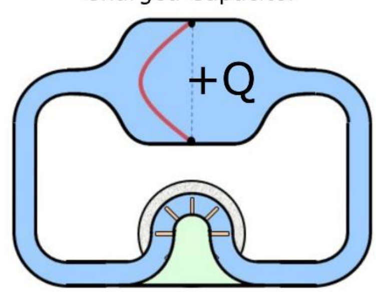

9. Compare your calculated and measured values
10. <u>**For your lab report:**</u>
    Work out the KVL for the RLC circuit
    *With R being $R_{on}$ of the MOSFET plus L and C*

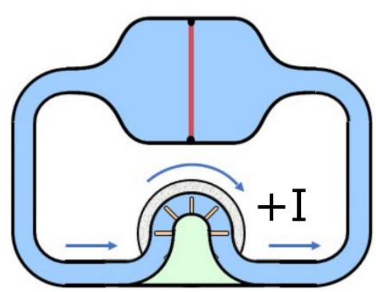
$$\Delta V_R + \Delta V_L + \Delta V_C = 0$$
$$R \cdot i + L \cdot \frac{di}{dt} + \frac{1}{C}\int i\,dt = 0$$
$$\frac{d^2}{dt^2} i + \frac{R}{L}\frac{di}{dt} + \frac{1}{LC} i = 0$$
$$\frac{d^2}{dt^2} i + 2\alpha\frac{di}{dt} + \omega^2 i = 0$$

$$2\alpha = \frac{R}{L} \left[\frac{radians}{second}\right]$$

$$\omega = \frac{1}{\sqrt{LC}} \left[\frac{radians}{second}\right]$$

Charged Capacitor



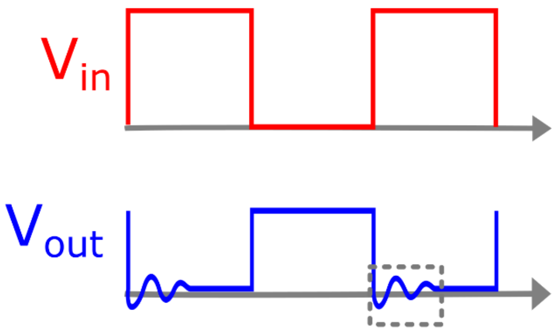

Paddlewheel Spinning

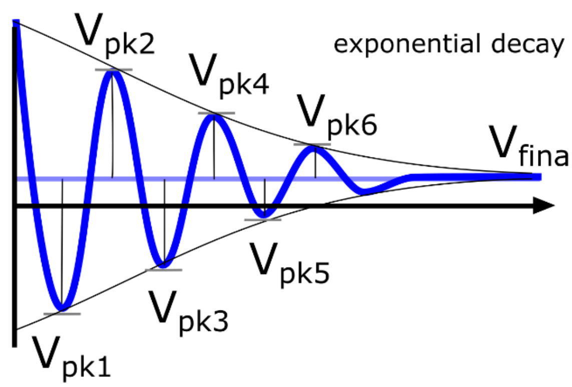
**Measuring the Q factor:**

1. Turn on the cursor of your oscilloscope to measure voltage and time (Cursor>Tracking>Ch2)

2. Measure the final voltage after the ringing damps out completely (This is the small but not zero voltage of the voltage divider from R and $R_{on}$)

3. Measure the voltage of the first few peaks of the ringing
   a. $V_{pk1}$ $V_{pk2}$ , $V_{pk3}$ , $V_{pk4}$ , $V_{pk5}$ , …
   b. Time of each peak ( $t_1$, $t_2$, $t_3$, …)
4. RECORD and PLOT the table of voltages relative to the final voltage (not zero!)




5. Estimate the Q factor from when the amplitudes decay to ~4% of their maximum
6. Calculate the Q factor from R, L, and C: $Q = \frac{1}{R}\sqrt{\frac{L}{C}}$
7. **For your lab report:**
   a. Fit the voltage vs. time to an exponential curve
   b. Record the decay time constant of the fit ($\tau_{decay} = ?$)
   c. Calculate the Q factor from this exponential curve fit:
   $$Q = \frac{\omega_0}{2\,\alpha}\,, \qquad 2\alpha = \frac{1}{\tau_{decay}}$$
   d. Calculate the damping attenuation $\alpha$ from RLC values
   e. Calculate the Damping factor $\zeta = \frac{\omega_0}{\alpha}$
   f. Is the ringing: under, over or critically damped?

**LAB REPORT DUE NEXT WEEK**

Start outlining report. Do you have all the data you need?
Do you need to take pictures of your circuits?

# Lab Report 7 – Rubric

**2,000-word limit 1 report/group**

| | | Points | Grade |
|---|---|---|---|
| | Introduce and define concepts (with citations) | 5 | |
| | Motivation for experiment | 5 | |
| **1** | Experimental Diagram (drawing + PICTURE with labels) | 5 | |
| | PLOT – **Output of NMOS Inverter** (with input) | 5 | |
| | Analysis (remember to show your work for calculations) | 5 | |
| **2** | Experimental Diagram (drawing + PICTURE with labels) | 5 | |
| | PLOT – **Rise time of charging capacitor** (with input) | 5 | |
| | Analysis (remember to show your work for calculations) | 5 | |
| **3** | Experimental Diagram (drawing + PICTURE with labels) | 5 | |
| | PLOT – **RLC circuit damped oscillations** (with input) | 5 | |
| | Analysis (remember to show your work for calculations) | 5 | |
| | Conclusion | 5 | |
| | | 60 | |

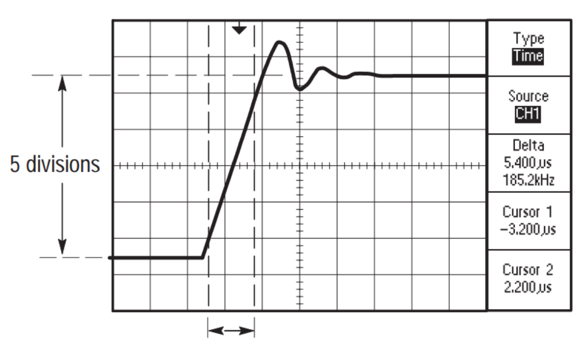
# Taking Cursor Measurements

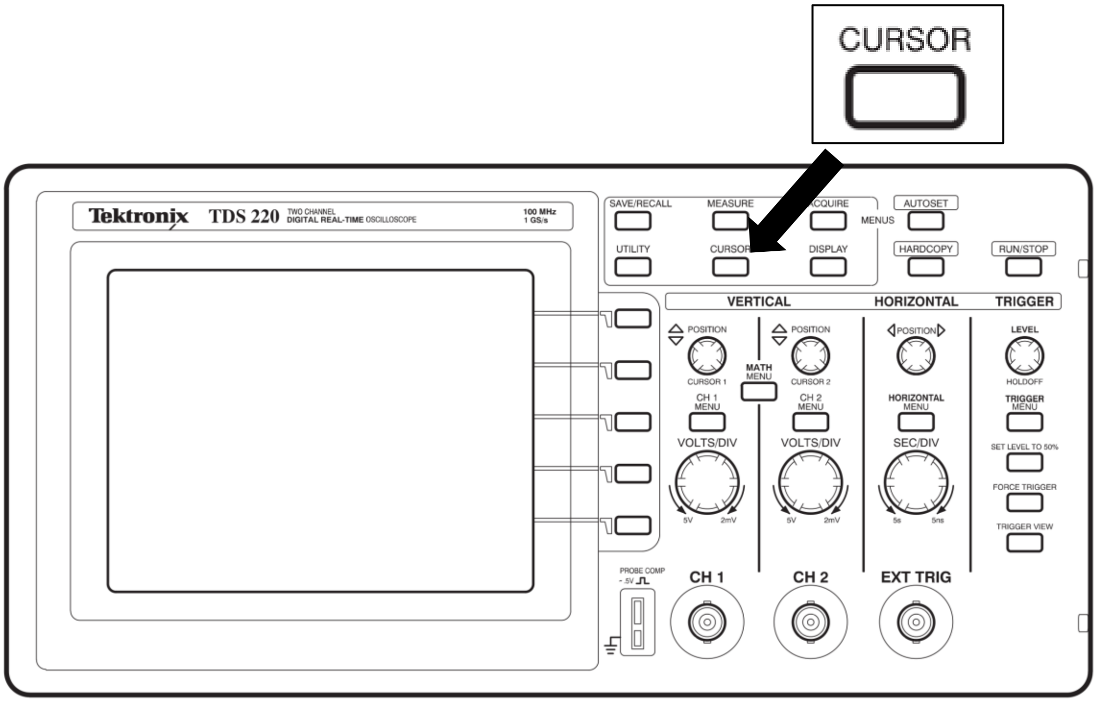
You can use the cursors to quickly take time and voltage measurements on a waveform.

### Measuring Rise Time

After measuring the pulse width, you decide that you need to check the rise time of the pulse. Typically, you measure rise time between the 10% and 90% portion of the waveform. To measure the rise time, do these steps:

1. Adjust the **SEC/DIV** knob to display the rising edge of the waveform.
2. Adjust the **VOLTS/DIV** knob to set the waveform amplitude to about five divisions.
3. Push the **CH 1 MENU** button to see the CH1 menu if it is not displayed.
4. Push the **Volts/Div** button to select **Fine.**
5. Adjust the **VOLTS/DIV** knob to set the waveform amplitude to exactly five divisions.
6. Use the VERTICAL **POSITION** knob to center the waveform; position the baseline of the waveform 2.5 divisions below the center graticule.
7. Push the **CURSOR** button to see the Cursor menu.
8. Push the top menu box button to set the type to **Time**.
9. Use the **CURSOR 1** knob to place the cursor at the point where the waveform crosses the second graticule line below center screen. This is the 10% point on the waveform.
10. Use the **CURSOR 2** knob to place the second cursor at the point where the waveform crosses the second graticule line above center screen. This is the 90% point on the waveform.
11. The delta readout in the cursor menu is the rise time of the waveform.



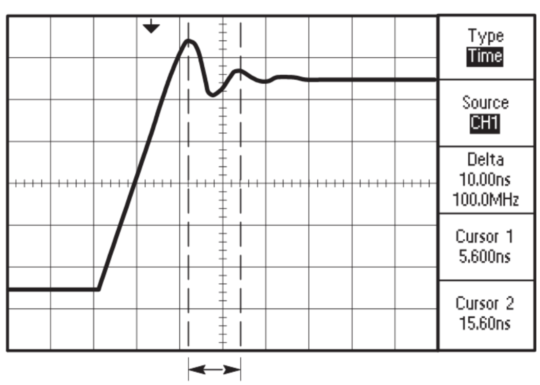



### Measuring Ring Frequency

To measure the ring frequency at the rising edge of a signal, do these steps:

1. Push the **CURSOR** button to see the Cursor menu.
2. Push the top menu box button to select **Time**.
3. Use the **CURSOR 1** knob to place a cursor on the first peak of the ring.
4. Use the **CURSOR 2** knob to place a cursor on the second peak of the ring.

You can see the delta time and frequency (the measured ring frequency) in the Cursor menu.



### Measuring Ring Amplitude

You measured the ring frequency in the previous example. Now you want to measure the amplitude of the ringing. To measure the amplitude, do these steps:

1. Push the **CURSOR** button to see the Cursor menu.
2. Push the top menu box button to select **Voltage**.
3. Use the **CURSOR 1** knob to place a cursor on the highest peak of the ring.
4. Use the **CURSOR 2** knob to place a cursor on the lowest point of the ring.

You can see the following measurements in the cursor menu:

- The delta voltage (peak-to-peak voltage of the ringing)
- The voltage at Cursor 1
- The voltage at Cursor 2