Chapter 4 Sequential Circuits

- Part 1 - Storage Elements and Analysis
  - Introduction to sequential circuits
  - Types of sequential circuits
  - Storage elements
    - Latches
    - Flip-flops
  - Sequential circuit analysis
    - State tables
    - State diagrams
  - Circuit and System Timing

- Part 2 - Sequential Circuit Design
  - Specification
  - Assignment of State Codes
  - Implementation
Intel & Micron 3D X-Point Memory

NVMe with 3D XPoint™ Technology

- SSD NAND technology offers ~100X reduction in latency versus HDD
- NVMe™ eliminates ~20 µs of latency today
- 3D XPoint™ technology reduces NVM latency offering ~10x reduction in latency vs NAND SSD

Source: Storage Technologies Group, Intel

Technology claims are based on comparisons of latency, density and write cycling metrics amongst memory technologies recorded on published specifications of in-market memory products against internal Intel specifications.
Intel & Micron 3D X-Point Memory

WHAT IS 3D XPoint™?

- Crosspoint Structure: Selectors allow dense packing and individual access to bits
- Scalable: Memory layers can be stacked in a 3D manner
- Breakthrough Material Advances: Compatible switch and memory cell materials
- High Performance: Cell and array architecture that can switch states 1000x faster than NAND
Intel & Micron 3D X-Point Memory
Intel&Micron 3D X-Point Memory

Comparison of NAND Based NVMe SSD and 3D XPoint™ Based NVMe SSD:

- **IOPS Performance**:
  - NAND Based NVMe SSD: 13,400 IOPS
  - 3D XPoint™ Based NVMe SSD: 95,600 IOPS
  - 7.13x Improvement

- **Latency Performance**:
  - NAND Based NVMe SSD: 73 Latency
  - 3D XPoint™ Based NVMe SSD: 9 Latency
  - 8.11x Improvement
Intel&Micron 3D X-Point Memory

- DDR4 electrical & physical compatible
- Supported on next generation Intel® Xeon® platform
- Up to 4X system memory capacity, at significantly lower cost than DRAM
- Can deliver big memory benefits without modifications to OS or applications
Overview

- Part 1 - Storage Elements and Analysis
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Sequential Circuits

- The output of a combinational circuit depends **solely** upon the input. The implication is that combinational circuits have **no memory**.

- We need circuits whose output depends upon **both** the input of the circuit and its previous state. In other words, we need circuits that have **memory**.
Three Characteristics

For a device to serve as a memory, it must have three characteristics:

- The device must have two stable states
- There must be a way to read the state of the device
- There must be a way to set the state at least once.
Using Feedback Technique

- So far, the logical flow in the circuits we've studied has been from input to output. Such a circuit is called *acyclic*.

- It’s possible to produce circuits with memory using the digital logic gates we've already seen.

- We introduce a circuit in which the output is fed back to the input, giving the circuit memory.
The NOR gate

- $F = A + B$
- How about we cross-couple two NOR gates?
S-R Latch

- R (reset)
- S (set)

\[ Q^\circ \]
\[ \overline{Q}^\circ \]
Explanation of Last Slide

- The output of a NOR gate is true only when both inputs are false. \( F = X + Y \)
- The output of each NOR gate is fed back to the input of the other.
- S sets the latch, causing Q to become true. R resets the latch.
- This means that if the output of one NOR gate is true, the output of the other must be false.
- Now press the S button. The output of the upper NOR gate, Q is forced to true, allowing the output of the lower NOR to become false.
- Press S again to turn it off. The output of the circuit is unchanged.
- Examine the circuit to understand why. What has happened is that we have stored the value of S. Turning S on and off again does not change the output.
- With S off, turn R on, then off again. What happens? Why.
Introduction to Sequential Circuits

- A Sequential circuit contains:
  - Storage elements: Latches or Flip-Flops
  - Combinatorial Logic:
    - Implements a multiple-output switching function
    - Inputs are signals from the outside.
    - Outputs are signals to the outside.
    - Other inputs, State or Present State, are signals from storage elements.
    - The remaining outputs, Next State are inputs to storage elements.
Introduction to Sequential Circuits

- Combinatorial Logic
  - *Next state function*  
    \[
    \text{Next State} = f(\text{Inputs, State})
    \]
  - *Output function* (Mealy)  
    \[
    \text{Outputs} = g(\text{Inputs, State})
    \]
  - *Output function* (Moore)  
    \[
    \text{Outputs} = h(\text{State})
    \]
- Output function type depends on specification and affects the design significantly
Types of Sequential Circuits

- Depends on the times at which:
  - storage elements observe their inputs, and
  - storage elements change their state

- **Synchronous**
  - Behavior defined from knowledge of its signals at discrete instances of time
  - Storage elements observe inputs and can change state only in relation to a timing signal (*clock pulses* from a *clock*)

- **Asynchronous**
  - Behavior defined from knowledge of inputs at any instant of time and the order in continuous time in which inputs change
  - If clock just regarded as another input, all circuits are asynchronous!
  - Nevertheless, the synchronous abstraction makes complex designs tractable!
Discrete Event Simulation

- In order to understand the time behavior of a sequential circuit we use **discrete event simulation**.

- **Rules:**
  - Gates modeled by an **ideal** (instantaneous) function and a **fixed gate delay**
  - Any **change in input values** is evaluated to see if it causes a **change in output value**
  - Changes in output values are scheduled for the fixed gate delay after the input change
  - At the time for a scheduled output change, the output value is changed along with any inputs it drives
Simulated NAND Gate

- Example: A 2-Input NAND gate with a 0.5 ns. delay:

  - Assume A and B have been 1 for a long time
  - At time t=0, A changes to a 0 at t= 0.8 ns, back to 1.

<table>
<thead>
<tr>
<th>t (ns)</th>
<th>A</th>
<th>B</th>
<th>F(I)</th>
<th>F</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>−∞</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>A=B=1 for a long time</td>
</tr>
<tr>
<td>0</td>
<td>1⇒0</td>
<td>1</td>
<td>1⇐0</td>
<td>0</td>
<td>F(I) changes to 1</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1⇐0</td>
<td>F changes to 1 after a 0.5 ns delay</td>
</tr>
<tr>
<td>0.8</td>
<td>1⇐0</td>
<td>1</td>
<td>1⇒0</td>
<td>1</td>
<td>F(Instantaneous) changes to 0</td>
</tr>
<tr>
<td>0.13</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1⇒0</td>
<td>F changes to 0 after a 0.5 ns delay</td>
</tr>
</tbody>
</table>
Gate Delay Models

- Suppose gates with delay $n$ ns are represented for $n = 0.2$ ns, $n = 0.4$ ns, $n = 0.5$ ns, respectively:
Consider a simple 2-input multiplexer:

With function:
- \( Y = A \) for \( S = 0 \)
- \( Y = B \) for \( S = 1 \)

“Glitch” is due to delay of inverter
Storing State

- What if A connected to Y?
- Circuit becomes:
- With function:
  - \( Y = B \) for \( S = 1 \), and
  - \( Y(t) \) dependent on \( Y(t - 0.9) \) for \( S = 0 \)

The simple combinational circuit has now become a sequential circuit because its output is a function of a time sequence of input signals!

Y is stored value in shaded area.
Simulation example as input signals change with time. Changes occur every 100 ns, so that the tenths of ns delays are negligible.

<table>
<thead>
<tr>
<th>Time</th>
<th>B</th>
<th>S</th>
<th>Y</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Y “remembers” 0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Y = B when S = 1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Now Y “remembers” B = 1 for S = 0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>No change in Y when B changes</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Y = B when S = 1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Y “remembers” B = 0 for S = 0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>No change in Y when B changes</td>
</tr>
</tbody>
</table>

Y represent the state of the circuit, not just an output.
1. In ordinary circumstances, the three inputs A, B, and C would come from other circuits.

2. We've wired them all to one pushbutton to make a point.

3. If you study the circuit, you will see that the output should be zero or false regardless of the input. In Reality?
A circumstance where timing dependencies can briefly cause incorrect output is called a **hazard**.

If the output of this figure were connected to the S input of an S-R latch, the latch could be set to true when it should not be. Storing an incorrect value in this way is called a **glitch**.
Basic (NOR) S – R Latch

- Cross-coupling two NOR gates gives the S – R Latch:
- Which has the time sequence behavior:

<table>
<thead>
<tr>
<th>Time</th>
<th>R</th>
<th>S</th>
<th>Q</th>
<th>( \overline{Q} )</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>?</td>
<td>?</td>
<td>Stored state unknown</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>“Set” ( Q ) to 1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Now ( Q ) “remembers” 1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>“Reset” ( Q ) to 0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Now ( Q ) “remembers” 0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Both go low</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>Unstable!</td>
</tr>
</tbody>
</table>
S-R Latch

<table>
<thead>
<tr>
<th>S</th>
<th>R</th>
<th>Q</th>
<th>̅Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>latch</td>
<td>latch</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
S-R Latch Explanation

○ R (reset) → \( Q \circ \)

○ S (set) → \( \overline{Q} \circ \)
How To Avoid Glitches?

- In order to avoid glitches, we want to design storage elements that only accept input when ordered to do so.
- We will give the order only after the combinational circuits that compute the input to the storage device have had a chance to settle to their correct values.
- One way to do that is to interpose AND gates between the S and R inputs and the latch circuit.
Clocked S - R Latch
Explanation of Last Slide

- Originally, S=R=C=0 and Q=0, Q’=1.
- Click R to turn it on, no change
- Click S to turn it on, no change
- Click R to turn it off, no change
- Click S to turn it off, no change
- Click C to turn it on, now this latch is enabled.
- Click S to turn it on, please note that Q becomes on and Q’ becomes off
- Click S to turn it off, no change
- Click R to turn it on, please note that Q’ becomes on and Q becomes off
- Click R to turn it off, no change
- Click R to turn it on, no change
- Click S to turn it on, please note that both Q and Q’ become off, which means this Clocked S-R latch cannot fix S=R=1 input issue.
A problem with the clocked S-R latch

- Note that clocking does not help with the problem of $S=R=1$. So, we still need an improved latch to overcome this problem.

1. Usually what we want to do with a storage device is store one bit of information.

2. The need for explicitly setting and resetting the latch adds complexity.

3. What we would really like is a circuit that has a data input $D$ and a data output $Q$. When the clock signal is high, whatever appears on $D$ should be stored in $Q$. 
Clocked D-Latch
Explanation of clocked D-Latch

- It has a data input, D, and a control input, C.
- The data input is connected through an AND gate to the S input of an S-R latch. It is also connected through an inverter and an AND gate to the R input.
- The other inputs of the two AND gates are connected to the C input of the circuit.
- If C is false, no signals reach the latch and its state remains unchanged.
- If C is true and D is true, the S input of the latch is true and the latch stores a value of true, which is equal to D.
- If C is true and D is false, the R input of the latch is driven through the inverter and a value of false, which is equal to D, is stored.
Clocked D-Latch Is Level Triggered

- As long as the C input is true, changes to D are reflected in the output of the circuit.

- The clocked D-latch is a *level triggered* device. Whether it stores data depends upon *level* at C.
D Latch

- Adding an inverter to the S-R Latch, gives the D Latch:
- Note that there are no “indeterminate” states!

<table>
<thead>
<tr>
<th>C</th>
<th>D</th>
<th>Q(t+1)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X</td>
<td>0</td>
<td>No change</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Q=0, Reset state</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Q=1, Set state</td>
</tr>
</tbody>
</table>

The graphic symbol for a D Latch is:
Problems with D-Latch

- If D changes while C is true, the new value of D will appear at the output. The latch is *transparent*.

- If the stored value can change state *more than once during a single clock pulse*, the result is a *hazard* that might introduce a *glitch* later in the circuit.

- We must design the circuit so that the state can *change only once per clock cycle*.
Figure 5-3

(a) Block diagram

(b) Timing diagram of clock pulses
How to remove the transparency?

This can be accomplished by connecting two latches together. The left half of the circuit is the clocked D-latch from the previous section. The right half of the circuit is a clocked S-R latch.