Flip-Flops

Outline:

1. **Timing noise**
   - Signal races, glitches
   - FPGA example ("assign" → bad)

2. **Synchronous circuits and memory**
   - Logic gate example

3. **Flip-Flop memory**
   - RS-latch example

4. **D and JK flip-flops**
   - Flip-flops in FPGAs

5. **Synchronous circuit design with FPGAs**
   - FPGA example ("always" → good).
   - Parallel circuit design with FPGAs.
Amplitude Noise

A digital circuit is very immune to amplitude noise, since it can only have two values (Low or High, True or False, 0 or 1). Digital electronics circuits typically have error rates smaller than 1 part in $10^9$.

Timing Noise

Just like an analog circuit, a digital circuit can experience timing noise. Fortunately, good clocks are cheap and easily available, and a good design will eliminate the effects of timing noise.

If attention is not paid to timing issues can easily produce amplitude noise (bit errors).
Signal Race

The timing delays produced by wires and logic gates can produce unwanted (illogical) outputs.

Example: 3-input NAND gate
The timing delays produced by wires and logic gates can produce unwanted (illogical) outputs.

Example: 3-input NAND gate

If gate delays are too long output pulse could disappear.
Signal Race

The timing delays produced by wires and logic gates can produce unwanted (illogical) outputs.

Example: 3-input NAND gate

The pulse is shorter than expected and delayed.

Pulse is shorter than expected and delayed.
Signal Race with Glitch

[diagram courtesy of Altera Inc.]

Inverter delay + component differences

Resulting $\overline{A}B$

Resulting $\overline{A}B$

Resulting $Y$

[Figure adapted from *Principles of Electronics: Analog & Digital* by L. R. Fortney]
Signal Race with Glitch

[diagram courtesy of Altera Inc.]

XOR

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
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<td>H</td>
<td>H</td>
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<td>H</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>L</td>
</tr>
</tbody>
</table>

[Figure adapted from *Principles of Electronics: Analog & Digital* by L. R. Fortney]
Glitches with FPGAs

Quartus II will simulate glitches

```
module adder_assign(input1, input2, result);
  input [3:0] input1;
  input [3:0] input2;
  output [4:0] result;
  assign result = input1 + input2;
endmodule
```
Asynchronous design requires very careful attention to signal delays to avoid producing glitches and other spurious signals.

Glitches will produce false data and can produce very wrong results
e.g. a glitch on the most-significant-bit will produce a factor of 2 error.

Asynchronous design can produce very fast digital circuits, but is generally avoided due to more difficult design.
The use of **memory** and a **clock** can eliminate signal races and glitches.

**Basic flip-flop operation**

The flip-flop will record and output the value at the input if the **clock** is HIGH. If the **clock** goes LOW, then the flip-flop does not change its value or output.

Glitches are eliminated if

1. The clock HIGH and LOW times are longer than any gate delays.
2. The inputs are synchronized to the clock.
Synchronous Timing

A

B

C

Y

Flip-flop AB

resulting Y

Flip-flop C

Guaranteed minimum signal pulse

Time
Generally, the flip-flop is changes state on a clock signal “edge”, not the level. The flip-flop takes the value just before the clock “edge”.

For 74LS74: minimum $t_s = 20$ ns
minimum $t_h = 5$ ns

Note: A flip-flop saves information (i.e. 1 bit); it does not modify it.
Generally, the flip-flop is changes state on a clock signal “edge”, not the level. The flip-flop takes the value *just before* the clock “edge”.

Note: A flip-flop saves information (i.e. 1 bit); it does not modify it.
Synchronous Timing (revisited)

A B C
Flip-flop AB
resulting Y

A B C
Flip-flop C
resulting Y

clock

Time
How does a flip-flop work?

Basic flip-flop: the SR latch

![SR latch diagram]

Logic table

<table>
<thead>
<tr>
<th>S</th>
<th>R</th>
<th>Q</th>
<th>Q̅</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Q₀</td>
<td>Q₀</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>1</td>
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<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Q₀ = value before S&R changes

R = 0 & S = 0:

- S = 0 & assume Q = 0 → Q = 1.
- S = 0 & assume Q = 1 → Q = 1.
- R = 0 & assume Q = 0 → Q̅ = 1.
- R = 0 & assume Q = 1 → Q̅ = 1.
How does a flip-flop work?

Basic flip-flop: the SR latch

\[ \overline{S} \] \quad Q

\[ \overline{R} \] \quad \overline{Q}

Logic table

<table>
<thead>
<tr>
<th>S</th>
<th>(\overline{R})</th>
<th>Q_0</th>
<th>\overline{Q}_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>(Q_0)</td>
<td>(\overline{Q}_0)</td>
</tr>
<tr>
<td>0</td>
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<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

\(Q_0 = \text{value before S&R changes}\)

\[ \overline{R} = 0 \quad \text{&} \quad \overline{S} = 0: \]

\[ \overline{S} = 0 \quad \text{&} \quad \text{assume } \overline{Q} = 0 \rightarrow Q = 1. \]

\[ \overline{S} = 0 \quad \text{&} \quad \text{assume } \overline{Q} = 1 \rightarrow Q = 1. \]

\[ \overline{R} = 0 \quad \text{&} \quad \text{assume } Q = 0 \rightarrow \overline{Q} = 1. \]

\[ \overline{R} = 0 \quad \text{&} \quad \text{assume } Q = 1 \rightarrow \overline{Q} = 1. \]
How does a flip-flop work?

Basic flip-flop: the SR latch

How does a flip-flop work?

Basic flip-flop: the SR latch

Logic table

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<th>$\bar{S}$</th>
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<tr>
<td>1</td>
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<td>$Q_0$</td>
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$Q_0 = \text{value before S&R changes}$

$\bar{R} = 0 \& \bar{S} = 1$: 

- $\bar{S} = 1 \& \text{assume } \bar{Q} = 0 \rightarrow Q = 1$.  
- $\bar{S} = 1 \& \text{assume } \bar{Q} = 1 \rightarrow Q = 0$.  
- $\bar{R} = 0 \& \text{assume } Q = 0 \rightarrow \bar{Q} = 1$.  
- $\bar{R} = 0 \& \text{assume } Q = 1 \rightarrow \bar{Q} = 1$.  

$\bar{S}$

$\bar{R}$

$Q$

$\bar{Q}$

$\bar{S}$

$\bar{R}$

$Q$

$\bar{Q}$
How does a flip-flop work?

Basic flip-flop: the SR latch

![Diagram of the SR latch]

Logic table

<table>
<thead>
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</table>

$Q_0 =$ value before S&R changes

$\overline{R} = 0 \& \overline{S} = 1:$

- $\overline{S} = 1$ & assume $\overline{Q} = 0 \rightarrow Q = 1$.
- $\overline{S} = 1$ & assume $\overline{Q} = 1 \rightarrow Q = 0$.
- $\overline{R} = 0$ & assume $Q = 0 \rightarrow \overline{Q} = 1$.
- $\overline{R} = 0$ & assume $Q = 1 \rightarrow \overline{Q} = 1$.

consistent $\rightarrow \overline{R} = 0 \& \overline{S} = 1 \rightarrow Q = 0 \& \overline{Q} = 1$
How does a flip-flop work?

Basic flip-flop: the SR latch

\[ \overline{\bar{Q}} = \overline{\bar{S}} = 0: \]
\[ \rightarrow \text{The opposite of } \overline{\bar{R}} = 0 & \overline{\bar{S}} = 1 \text{ by symmetry.} \]

Logic table

<table>
<thead>
<tr>
<th>$\overline{S}$</th>
<th>$\overline{R}$</th>
<th>$Q$</th>
<th>$\overline{Q}$</th>
</tr>
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<tbody>
<tr>
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$Q_0 =$ value before S&R changes
How does a flip-flop work?

Basic flip-flop: the SR latch

- **R = 1 & S = 1:**
  - \( \overline{S} = 1 \) & assume \( \overline{Q} = 0 \) → \( Q = 1 \).
  - \( \overline{S} = 1 \) & assume \( \overline{Q} = 1 \) → \( Q = 0 \).
  - \( \overline{R} = 1 \) & assume \( Q = 0 \) → \( \overline{Q} = 1 \).
  - \( \overline{R} = 1 \) & assume \( Q = 1 \) → \( \overline{Q} = 0 \).

**Logic table**

<table>
<thead>
<tr>
<th>( S )</th>
<th>( \overline{R} )</th>
<th>( Q )</th>
<th>( \overline{Q} )</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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Q₀ = value before S&R changes
How does a flip-flop work?

**Basic flip-flop: the SR latch**

- **Logic table**

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</table>

- \( Q_0 = \) value before S&R changes

**SR latch**

- \( \bar{R} = 1 \) & \( \bar{S} = 1 \):  
  - \( \bar{S} = 1 \) & assume \( \bar{Q} = 0 \) \( \Rightarrow Q = 1 \), consistent \( \bar{R}=1 & \bar{S}=1 \rightarrow Q=1 & \bar{Q}=0 \)
  - \( \bar{S} = 1 \) & assume \( Q = 1 \) \( \Rightarrow \bar{Q} = 0 \), consistent \( \bar{R}=1 & \bar{S}=1 \rightarrow Q=0 & \bar{Q}=1 \)
  - \( \bar{R} = 1 \) & assume \( Q = 0 \) \( \Rightarrow \bar{Q} = 1 \), consistent \( \bar{R}=1 & \bar{S}=1 \rightarrow Q=1 & \bar{Q}=0 \)
  - \( \bar{R} = 1 \) & assume \( \bar{Q} = 1 \) \( \Rightarrow Q = 0 \), consistent \( \bar{R}=1 & \bar{S}=1 \rightarrow Q=0 & \bar{Q}=1 \)
How does a flip-flop work?

Basic flip-flop: the SR latch

![SR latch diagram]

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<tr>
<td>0</td>
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</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Q₀ = value before S&R changes

**Two settings are possible**

- $\overline{R} = 1$ & $\overline{S} = 1$: $\overline{S} = 1$ & assume $\overline{Q} = 0 \rightarrow Q = 1$. consistent $\overline{R}=1 & \overline{S}=1 \rightarrow Q=1 & \overline{Q}=0$
- $\overline{R} = 1$ & assume $\overline{Q} = 1 \rightarrow Q = 0$. consistent $\overline{R}=1 & \overline{S}=1 \rightarrow Q=0 & \overline{Q}=1$
- $\overline{R} = 1$ & assume $Q = 0 \rightarrow \overline{Q} = 1$.
- $\overline{R} = 1$ & assume $Q = 1 \rightarrow \overline{Q} = 0$.

$\rightarrow$ i.e. flip-flop keeps its state.
SR latch flip-flops are not used much for memory, but they are used for debouncing switches.

**Switch Bounce:**

When a switch is toggled it will not go smoothly from HIGH to LOW, or vice versa.
Clock Circuit Analysis:

- **C = 1 & D = 1** → \(\overline{S} = 0 \& \overline{R} = 1\).
- **C = 1 & D = 0** → \(\overline{S} = 1 \& \overline{R} = 0\).

- **C = 0 & D = 1** → \(\overline{S} = 1 \& \overline{R} = 1\).
- **C = 0 & D = 0** → \(\overline{S} = 1 \& \overline{R} = 1\).

---

**Logic table**

<table>
<thead>
<tr>
<th></th>
<th>(D)</th>
<th>(C)</th>
<th>(Q)</th>
<th>(\overline{Q})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X)</td>
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<td>(\overline{Q_0})</td>
<td>(Q_0)</td>
<td></td>
</tr>
<tr>
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<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Clock Circuit Analysis:

- **Clock HIGH:** D sets the flip-flop state
  - $C = 1 \& D = 1 \Rightarrow \bar{S} = 0 \& \bar{R} = 1.$
  - $C = 1 \& D = 0 \Rightarrow \bar{S} = 1 \& \bar{R} = 0.$

- **Clock LOW:** flip-flop state is locked
  - $C = 0 \& D = 1 \Rightarrow \bar{S} = 1 \& \bar{R} = 1.$
  - $C = 0 \& D = 0 \Rightarrow \bar{S} = 1 \& \bar{R} = 1.$

### Logic table

<table>
<thead>
<tr>
<th>$D$</th>
<th>$C$</th>
<th>$Q$</th>
<th>$\bar{Q}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
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<td>$\bar{Q}_0$</td>
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<td>0</td>
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**Clock Circuit Analysis:**

- **Clock HIGH:** D sets the flip-flop state
  - $C = 1 \& D = 1 \Rightarrow \overline{S} = 0 \& \overline{R} = 1.$
  - $C = 1 \& D = 0 \Rightarrow \overline{S} = 1 \& \overline{R} = 0.$

- **Clock LOW:** flip-flop state is locked
  - $C = 0 \& D = 1 \Rightarrow \overline{S} = 1 \& \overline{R} = 1.$
  - $C = 0 \& D = 0 \Rightarrow \overline{S} = 1 \& \overline{R} = 1.$
Note: The flip-flop triggers on a the falling edge of the clock.
74LS74 D-type edge-triggered flip-flop

Note: The flip-flop triggers on a the rising edge of the clock.

Both \( \overline{PRE} \) and \( \overline{CLR} \) behave like \( \overline{S} \) and \( \overline{R} \) inputs, respectively, on the SR latch.

**IMPORTANT:** Both \( \overline{PRE} \) and \( \overline{CLR} \) must be high for normal D-type operation.

[FUNCTION TABLE]

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \overline{PRE} )</td>
<td>( \overline{CLR} )</td>
</tr>
<tr>
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<td>H</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
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<td>H</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

[Texas Instruments 74LS74 flip-flop datasheet]
JK-type flip-flops are used in counters.
Flip-flops in FPGAs

Architecture of a single Logic Element

- **LUT**
- **CLOCK triggers**
- **Memory** (a few bits)

Inputs:
- Inputs
- Clock signals

Outputs:
- Global
- Local

Feedback:

Frequently a D-type Flip-Flop

FPGAs are already set-up for synchronous circuit designs
Flip-flops in FPGAs

Architecture of a single Logic Element

- LUT
- CLOCK triggers
- Memory (a few bits)

Frequently a D-type Flip-Flop

FPGAs are already set-up for synchronous circuit designs
module adder_always(clock, input1, input2, result);

input [3:0] input1; // 4-bit input, first number
input [3:0] input2; // 4-bit input, second number

input clock; // 1-bit clock input

output reg [4:0] result; // 5-bit output register

always@(posedge clock) // performs this section on the positive clock edge
begin
    result = input1 + input2; // Standard 4-bit addition
end

endmodule
module adder_always(clock, input1, input2, result);

  input [3:0] input1;       // 4-bit input, first number
  input [3:0] input2;       // 4-bit input, second number

  input clock;              // 1-bit clock input

  output reg [4:0] result;  // 5-bit output register

  always@ (posedge clock)   // performs this section on the positive clock edge
    begin
      result = input1 + input2;  // Standard 4-bit addition
    end

endmodule
Synchronous programming in Verilog (I)

Read as “always at the positive clock edge do the following ... ”

“always” is the core command for synchronous programming, it should be used as frequently as possible.

“assign” should be used as little as possible. It is only useful for DC-type signals (signals that don’t change).
Synchronous programming in Verilog (II)

Quartus II circuit simulation
Synchronous programming in Verilog (II)

Quartus II circuit simulation

Clock

Line

No more glitches
How did the FPGA implement the circuit?

Tools > Netlists > Technology Map Viewer
How did the FPGA implement the circuit?

Tools > Netlists > Technology Map Viewer

D-type edge-triggered flip-flops
Always use “always”

– A. Stummer, U. of Toronto.
Parallel programming in Verilog

- The “always” structure is used for exploiting the parallel processing features of the FPGA.
- Parallel processing must almost always be synchronous if several processes exchange data.

**Parallel and Sequential processing examples:**

**Sequential**

```verilog
always@ (negedge clock)
begin
a = b;
c = a;
end
```

**Parallel**

```verilog
always@ (negedge clock)
begin
a <= b;
c <= a;
end
```
The “always” structure is used for exploiting the parallel processing features of the FPGA.

Parallel processing must almost always be synchronous if several processes exchange data.

**Parallel and Sequential processing examples:**

**Sequential**

```verilog
always@ (negedge clock)
begin
    a = b;
    c = a;
end
```

**Parallel**

```verilog
always@ (negedge clock)
begin
    a <= b;
    c <= a;
end
```

executed simultaneously

```
 a = b
 c = a (previous value)
```