Memory, Latches, & Registers

1) Structured Logic Arrays
2) Memory Arrays
3) Transparent Latches
4) How to save a few bucks at toll booths
5) Edge-triggered Registers
General Table Lookup Synthesis

<table>
<thead>
<tr>
<th>AB</th>
<th>Fn(A, B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0</td>
</tr>
<tr>
<td>01</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
</tr>
</tbody>
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**Generalizing:**
Remember from a few lectures ago that, in theory, we can build any 1-output combinational logic block with multiplexers.

For an N-input function we need a _____ input multiplexer.

**BIG Multiplexers?** How about 10-input function? 20-input?
General Table Lookup Synthesis

Generalizing:
Remember from a few lectures ago that, in theory, we can build any 1-output combinational logic block with multiplexers.

For an N-input function we need a $2^N$ input multiplexer.

BIG Multiplexers? How about 10-input function? 20-input?
A Mux’s Guts

Hmm, by sharing the decoder part of the logic MUXs could be adapted to make lookup tables with any number of outputs.

Multiplexers can be partitioned into two sections.

A DECODER that identifies the desired input, and a SELECTOR that enables that input onto the output.

A decoder generates all possible product terms for a set of inputs.
A New Combinational Device

DECODER:

k SELECT inputs,
N = 2^k DATA OUTPUTs.

Selected D_j HIGH;
all others LOW.

NOW, we are well on our way to building a general purpose table-lookup device.

We can build a 2-dimensional ARRAY of decoders and selectors as follows ...
We can build a general purpose “table-lookup” device called a Read-Only Memory (ROM), from which we can implement any truth table and, thus, any combinational device.

Made from PREWIRED connections ●, and CONFIGURABLE connections that can be either connected ☐ or not connected ○.
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This ROM stores 16 bits in 8 words of 2 bits.

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Logic According to ROMs

ROMs ignore the structure of combinational functions ...

- Size, layout, and design are independent of function
- Any Truth table can be “programmed” by minor reconfiguration:
  - Metal layer (masked ROMs)
  - Fuses (Field-programmable PROMs)
  - Charge on floating gates (EPROMs)
  ... etc.

Model: LOOK UP value of function in truth table...
Inputs: “ADDRESS” of a T.T. entry
ROM SIZE = # TT entries...
... for an N-input boolean function, size = __________
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... for an N-input boolean function, size = $2^N \times \# \text{outputs}$
Analog Storage: Using Capacitors

We’ve chosen to encode information using voltages and we know from physics that we can “store” a voltage as “charge” on a capacitor:

- **Pros:**
  - compact!

- **Cons:**
  - it leaks! ⇒ refresh
  - complex interface
  - reading a bit, destroys it
    (you have to rewrite the value after each read)
  - it’s NOT a digital circuit

To write:
- Drive bit line, turn on access fet, force storage cap to new voltage

To read:
- precharge bit line, turn on access fet, detect (small) change in bit line voltage

This storage circuit is the basis for commodity DRAMs
DRAM Organization

Row Address Selection

Column Address Selection

Row decoder 11-to-2048

2048 × 2048 array

Column latches

Mux

Dout

Address[10–0]
DRAM Errors

• Typical RAM cell stores about 75 fC (femtocoulombs) of charge.
• That’s about ½ million electrons
• Or at 3 Volts about 1.5 MeV (megaelectron volts)
• Sounds like a lot!
• Until you consider other sources.
• Google reports that error rates are 100’s to 1000’s of times higher than thought. Over 3700 errors per DIMM per year.

Cosmic Ray Flux vs Particle Energy (link)
A “Digital” Storage Element

It’s also easy to build a settable DIGITAL storage element (called a latch) using a MUX and FEEDBACK:

![Diagram of a latch circuit]
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Q stable

Q follows D
Looking Under the Covers

Let’s take a quick look at the equivalent circuit for our MUX when the gate is LOW (the feedback path is active)

This storage circuit is the basis for commodity SRAMs

Advantages:
1) Maintains remembered state for as long as power is applied.
2) State is DIGITAL

Disadvantage:
1) Requires more transistors
Why Does Feedback = Storage?

BIG IDEA: use positive feedback to maintain storage indefinitely. Our logic gates are built to restore marginal signal levels, so noise shouldn’t be a problem!

Result: a bistable storage element
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Waveform for inverter pair
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![Diagram showing feedback constraint and bistable storage element](image)

Result: a bistable storage element
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BIG IDEA: use **positive feedback** to maintain storage indefinitely. Our logic gates are built to restore marginal signal levels, so noise shouldn’t be a problem!

![Waveform for inverter pair](image)

**Result:** a bistable storage element

Feedback constraint: \( V_{IN} = V_{OUT} \)

Waveform for inverter pair

Three solutions:
- two end-points are **stable**
- middle point is unstable

We’ll get back to this!

Not affected by noise
Static D Latch

"static" means latch will hold data (i.e., value of Q) while G is inactive, however long that may be.
A DYNAMIC Discipline

Design of sequential circuits MUST guarantee that inputs to sequential devices are valid and stable during periods when they may influence state changes. This is assured with additional timing specifications.
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\[ t_{\text{PULSE}} > t_{\text{PULSE}} \]

\[ G \]

\[ D \]

\( t_{\text{PULSE}} \): minimum pulse width
guarantee \( G \) is active for long enough for latch to capture data
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\[ t_{\text{PULSE}} > t_{\text{SETUP}} \]

- **t\text{PULSE}**: minimum pulse width
  - guarantee \( G \) is active for long enough for latch to capture data
- **t\text{SETUP}**: setup time
  - guarantee that \( D \) value has propagated through feedback path before latch closes
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\[ G > t_{\text{PULSE}} \]
\[ D > t_{\text{SETUP}} > t_{\text{HOLD}} \]

\( t_{\text{PULSE}} \): minimum pulse width
- guarantee \( G \) is active for long enough for latch to capture data

\( t_{\text{SETUP}} \): setup time
- guarantee that \( D \) value has propagated through feedback path before latch closes

\( t_{\text{HOLD}} \): hold time
- guarantee latch is closed and \( Q \) is stable before allowing \( D \) to change
Flakey Control Systems

Here's a strategy for saving 2 bucks the next time you find yourself at a toll booth!
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WARNING:
Professional Drivers Used!
DON’T try this At home!
Escapement Strategy

The Solution:
Add two gates and only open one at a time.
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Add two gates and only open one at a time.

KEY: At no time is there an open path through both gates...
**Edge-triggered Flip Flop**

logical "escapement"

![Diagram of edge-triggered flip flop](image)

**Observations:**
- only one latch “transparent” at any time:
  - master closed when slave is open (CLK is high)
  - slave closed when master is open (CLK is low)
  - no combinational path through flip flop

- $Q$ only changes shortly after $0 \rightarrow 1$ transition of CLK, so flip flop appears to be “triggered” by rising edge of CLK

Transitions mark instants, not intervals
Flip Flop Waveforms

master closed
slave open

slave closed
master open
Two Issues

• Must allow time for the input’s value to propagate to the Master’s output while CLK is LOW.
  • This is called “SET-UP” time

• Must keep the input stable, just after CLK transitions to HIGH. This is insurance in case the SLAVE’s gate opens just before the MASTER’s gate closes.
  • This is called “HOLD-TIME”
  • Can be zero (or even negative!)

• Assuring “set-up” and “hold” times is what limits a computer’s performance
Flip-Flop Timing Specs

D — D — Q
CLK —

Q
CLK
D
Flip-Flop Timing Specs

$t_{PD}$: maximum propagation delay, $CLK \rightarrow Q$
Flip-Flop Timing Specs

\[ D \rightarrow D \rightarrow Q \rightarrow Q \]

\[ \text{CLK} \rightarrow \]

\[ Q \]

\[ \text{CLK} \]

\[ D \]

\[ \text{t}_{\text{PD}}: \text{maximum propagation delay, CLK} \rightarrow Q \]
Flip-Flop Timing Specs

\[ D \rightarrow D \quad Q \rightarrow Q \]

\[ \text{CLK} \rightarrow \]

\[ \begin{align*}
Q & < t_{PD} \\
\text{CLK} & \\
D & > t_{SETUP}
\end{align*} \]

\( t_{PD} \): maximum propagation delay, \( \text{CLK} \rightarrow Q \)

\( t_{SETUP} \): setup time

*guarantee that \( D \) has propagated through feedback path before master closes*
Flip-Flop Timing Specs

$t_{PD}$: maximum propagation delay, $CLK \rightarrow Q$

$t_{SETUP}$: setup time

guarantee that $D$ has propagated through feedback path before master closes

$t_{HOLD}$: hold time

guarantee master is closed and data is stable before allowing $D$ to change
Summary

• Regular Arrays can be used to implement arbitrary logic functions
  • ROMs decode every input combination (fixed-AND array) and compute the output for it (customized-OR array)
  • PLAs decode an minimal set of input combinations (both AND and OR arrays customized)

• Memories
  • ROMs are HARDWIRED memories
  • RAMs include storage elements at each WORD-line and BIT-line intersection
    • dynamic memory: compact, only reliable short-term
    • static memory: controlled use of positive feedback

• Level-sensitive D-latches for static storage
• Dynamic discipline (setup and hold times)