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>
</table>

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

Hmmm, by sharing the decoder part of the logic MUXs could be adapted to make lookup tables with any number of outputs.
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 ...
There’s an extra level of inversion that isn’t necessary in the logic. However, it reduces the capacitive load on the module driving this one.

This ROM stores 16 bits in 8 words of 2 bits.

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 ○.
ROM Implementation Details

Tiny PFETs with gates tied to ground = resistor pullup that makes wire “1” unless one of the NFET pulldowns is on.

Advantages:
- Very regular design
  (can be entirely automated)

Problems:
- Active Pull-ups
  (Static Power)
- Long metal runs
  (Large Caps)
- Slow

JARGON:
- Inputs to a ROM are called ADDRESSES.
- The decoder’s outputs are called WORD LINES, and the outputs lines of the selector are called BIT LINES.
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 (Flash 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 = \(2^N \times \# \text{outputs}\)
Example: 7-sided Die

What nature can’t provide… electronics can
(and with the same number of LEDs!).

We want to construct a die with the following sides:

![Dice Diagram]

An array of LEDs, labeled as follows, can be used to display the outcome of the die:

![LED Array Diagram]
ROM-Based Design

Once we’ve written out the truth table we’ve basically finished the design.

Possible optimizations:
- Eliminate redundant outputs
- Addressing tricks

Truth Table for a 7-sided Die

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>T</th>
<th>U</th>
<th>V</th>
<th>W</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
A Simple ROM implementation

That was Easy!

ROMs are even more flexible than MUXes, because you can design the H/W first, and figure out the logic later!

This is the essence of programability: “LATE-BINDING” logic specification.
“Programmable” Look-up Tables

Remember, EVERY combinational circuit can be expressed as a lookup table. As a result a ROM is a universal logic device. Unfortunately, the ROMs we’ve built thus far are “HARDWIRED”. That is, the function that they compute is encoded by the pull-down transistors that are built into the OR-plane of the ROM. What we’d really like is a combinational gate that could be reconfigured dynamically. For this we’ll need some form of storage.
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:

![Capacitor Diagram]

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
Dynamic Memory

- TiN top electrode ($V_{REF}$)
- Ta$_2$O$_5$ dielectric
- Poly word line
- Access FET

Image of TiN/Ta$_2$O$_5$/W Capacitor with labeled word line.
A “Digital” Storage Element

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

Here’s a feedback path, so it’s no longer a combinational circuit.

“state” signal appears as both input and output

<table>
<thead>
<tr>
<th>G</th>
<th>D</th>
<th>Q_{IN}</th>
<th>Q_{OUT}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>--</td>
<td>1</td>
</tr>
</tbody>
</table>

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

Feedback constraint: $V_{IN} = V_{OUT}$

VTC for inverter pair

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

Not affected by noise

We’ll get back to this!
"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.**

\[ \text{ Pulse: } t_{\text{PULSE}} \]

\[ \text{ Setup: } t_{\text{SETUP}} \]

\[ \text{ Hold: } t_{\text{HOLD}} \]

- **\( t_{\text{PULSE}} \):** 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
Does this work?

“start” button → ROM
“O” button → unlock
“1” button → Next state

Current state → Q D

Hmm. Hard to get pulse width exactly right!
Flakey Control Systems

Here’s a strategy for saving 2 bucks the next time you find yourself at a toll booth!
**Edge-triggered Flip Flop**

logical “escapement”

---

**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 → 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

$t_{PD}$: 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)