The Digital Abstraction

- Analog Signaling & Noise
- Digital Signaling, Noise Margins
- Digital Devices & Static Discipline
- Overview of CMOS Technology
Representing information with voltage

Representation of each point \((x, y)\) on a B&W Picture:

- 0 volts: BLACK
- 1 volt: WHITE
- 0.37 volts: 37% Gray
- etc.

Representation of a picture:

Scan points in some prescribed raster order... generate continuous voltage waveform
Information Processing in the Analog Domain

First let’s introduce some processing blocks:

\[ v \rightarrow \text{Copy} \rightarrow v \]

\[ v \rightarrow \text{INV} \rightarrow 1 - v \]
Why have processing blocks?

• The goal of modular design:

  ABSTRACTION

• What does that mean anyway?
  - Rules simple enough for a 6-3 to follow...
  - Understanding BEHAVIOR without knowing IMPLEMENTATION
  - Predictable composition of functions
  - Tinker-toy assembly
  - Guaranteed behavior under REAL WORLD circumstances
Let's build a system!

input → Copy → INV → Copy → INV → Copy → INV → Copy → INV → (Reality) → output
Why did our system fail?

Why doesn’t reality match theory?

1. COPY Operator doesn’t work right
2. INVERSION Operator doesn’t work right
3. Theory is imperfect
4. Reality is imperfect
5. Our system architecture stinks

ANSWER: all of the above!

Noise and inaccuracy are inevitable; we can’t reliably engineer perfect components – we must design our system to tolerate some amount of error if it is to process information reliably.
The Key to System Design

A system is a structure that is guaranteed to exhibit a specified behavior, assuming all of its components obey their specified behaviors.

How is this achieved?

Contracts!

Every system component will have clear obligations and responsibilities. If these are maintained we have every right to expect the system to behave as planned. If contracts are violated all bets are off.
The Digital Panacea ... 

Why digital?
... because it keeps the contracts simple!

The price we pay for this robustness:

All the information that we transfer between modules is only 1 crummy bit!

But, we get a guarantee of reliable processing.
Keep in mind that the world is not digital, we would simply like to engineer it to behave that way. Furthermore, we must use real physical phenomena to implement digital designs!
A Digital Processing Element

- A combinational device is a circuit element that has
  - one or more digital inputs
  - one or more digital outputs
  - a functional specification that details the value of each output for every possible combination of valid input values
  - a timing specification consisting (at minimum) of an upper bound $t_{pd}$ on the required time for the device to compute the specified output values from an arbitrary set of stable, valid input values

\[\text{Output a "1" if at least 2 out of 3 of my inputs are a "1". Otherwise, output "0".}\]

\[\text{I will generate a valid output in no more than 2 minutes after seeing valid inputs}\]
A Combinational Digital System

• A set of interconnected elements is a combinational device if
  - each circuit element is a combinational device
  - every input is connected to exactly one output or a constant (e.g., some vast supply of 0's and 1's)
  - the circuit contains no directed cycles

• Why is this true?

  *Given an acyclic circuit meeting the above constraints, we can derive functional and timing specs for the input/output behavior from the specs of its components!*
We can encode information using voltages, currents, frequency, phase, etc. A common choice is to use a voltage encoding and a binary (0/1) signaling scheme.

Encoding Attempt #1:

But voltages very near VDD/2 can be hard to distinguish as 0 vs. 1.
Digital Signaling II

Encoding Attempt #2:

This avoids “close calls”, but now we have to consider noise (i.e. unavoidable perturbations to our signalling voltage)

So an output voltage just below \( V_L \) might become an illegal input voltage in the forbidden zone!
Big Idea: Noise Margins

Let’s leave room for bad things to happen! So we’ll design devices restore marginally valid input signals. They must accept marginal inputs and provide unquestionable outputs (i.e., to leave room for noise).

**OUTPUTS:**

- $0_{\text{OUT}}$:
  - $0$ to $V_{\text{OL}}$
  - $V_{\text{OL}}$ to $V_{\text{OH}}$
  - $V_{\text{OH}}$ to $V_{\text{DD}}$

- $1_{\text{OUT}}$:
  - $0$ to $V_{\text{OL}}$
  - $V_{\text{OL}}$ to $V_{\text{OH}}$
  - $V_{\text{OH}}$ to $V_{DD}$

**INPUTS:**

- $0_{\text{IN}}$:
  - $0$ to $V_{\text{OL}}$
  - $V_{\text{OL}}$ to $V_{\text{IL}}$
  - $V_{\text{IL}}$ to $V_{\text{IH}}$

- $1_{\text{IN}}$:
  - $0$ to $V_{\text{OL}}$
  - $V_{\text{OL}}$ to $V_{\text{IH}}$
  - $V_{\text{IH}}$ to $V_{\text{OH}}$

**Forbidden Zone**

**Noise Margins**
Using Voltages Digitally

Digital input: $V_{IN} < V_{IL}$ or $V_{IN} > V_{IH}$

Digital output: $V_{OUT} < V_{OL}$ or $V_{OUT} > V_{OH}$

Noise margins: $V_{OL} < V_{IL} < V_{IH} < V_{OH}$

Where $V_{OL}$, $V_{IL}$, $V_{IH}$ and $V_{OH}$ are part of the specification for a particular family of digital components.

The static discipline requires that a digital component produce a valid output given valid input within some specified period of time after the inputs become stable.
Example device: An Inverter

Static Discipline requires that we avoid the shaded regions aka “forbidden zones”), which correspond to valid inputs but invalid outputs. Net result: combinational devices must have \( \text{GAIN} > 1 \) and be NONLINEAR.

Voltage Transfer Characteristic:
Plot of \( V_{\text{OUT}} \) vs. \( V_{\text{IN}} \) where each measurement is taken after any transients have died out.

Note: VTC does not tell you anything about how fast a device is—it measures static behavior not dynamic behavior.
Combinational Device Wish List

- Design our system to tolerate some amount of error
  ⇒ Add positive noise margins
  ⇒ VTC: gain > 1 & nonlinearity
- Lots of gain ⇒ big noise margin
- Cheap, small
- Changing voltages will require us to dissipate power, but if no voltages are changing, we’d like zero power dissipation
- Want to build devices with useful functionality (what sort of operations do we want to perform?)
Wishes Granted: CMOS

\[ V_{\text{IN}} \leq V_{\text{IL}} \quad \Rightarrow \quad V_{\text{OUT}} \geq V_{\text{OH}} \]

\[ V_{\text{IN}} \geq V_{\text{IH}} \quad \Rightarrow \quad V_{\text{OUT}} \leq V_{\text{OL}} \]

\[ V_{\text{OUT}} \text{ eventually reaches } V_{\text{DD}} \]

\[ V_{\text{OUT}} \text{ eventually reaches GND} \]
MOSFETS: Gain & Non-linearity

MOSFETs (metal-oxide-semiconductor field-effect transistors) are four-terminal voltage-controlled switches. Current flows between the diffusion terminals if the voltage on the gate terminal is large enough to create a conducting “channel”, otherwise the mosfet is off and the diffusion terminals are not connected.

$L_{2006} = 65\text{nm}$  
#$\text{made}_{2006} \sim 10^{19}$  
Marginal cost: $\sim 25\text{n}\$
Digital Integrated Circuits

IBM photomicrograph (SiO$_2$ has been removed!)

Metal 2
M1/M2 via
Metal 1
Polysilicon
Diffusion

Mofet (under polysilicon gate)
CMOS Forever!?
Summary

• Use voltages to encode information

• “Digital” encoding
  - valid voltage levels for representing “0” and “1”
  - forbidden zone avoids mistaking “0” for “1” and vice versa

• Noise
  - Want to tolerate real-world conditions: NOISE.
  - Key: tougher standards for output than for input
  - devices must have gain and have a non-linear VTC

• Combinational devices
  - Each logic family has Tinkertoy-set simplicity, modularity
  - predictable composition: “parts work → whole thing works”
  - static discipline
    - digital inputs, outputs; restore marginal input voltages
    - complete functional spec
    - valid inputs lead to valid outputs in bounded time