CS61C

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Great Ideas
in
Computer Architecture
(a.k.a. Machine Structures)

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# Introduction to Synchronous Digital Systems (SDS): Switches, Transistors, Signals, & Waveforms

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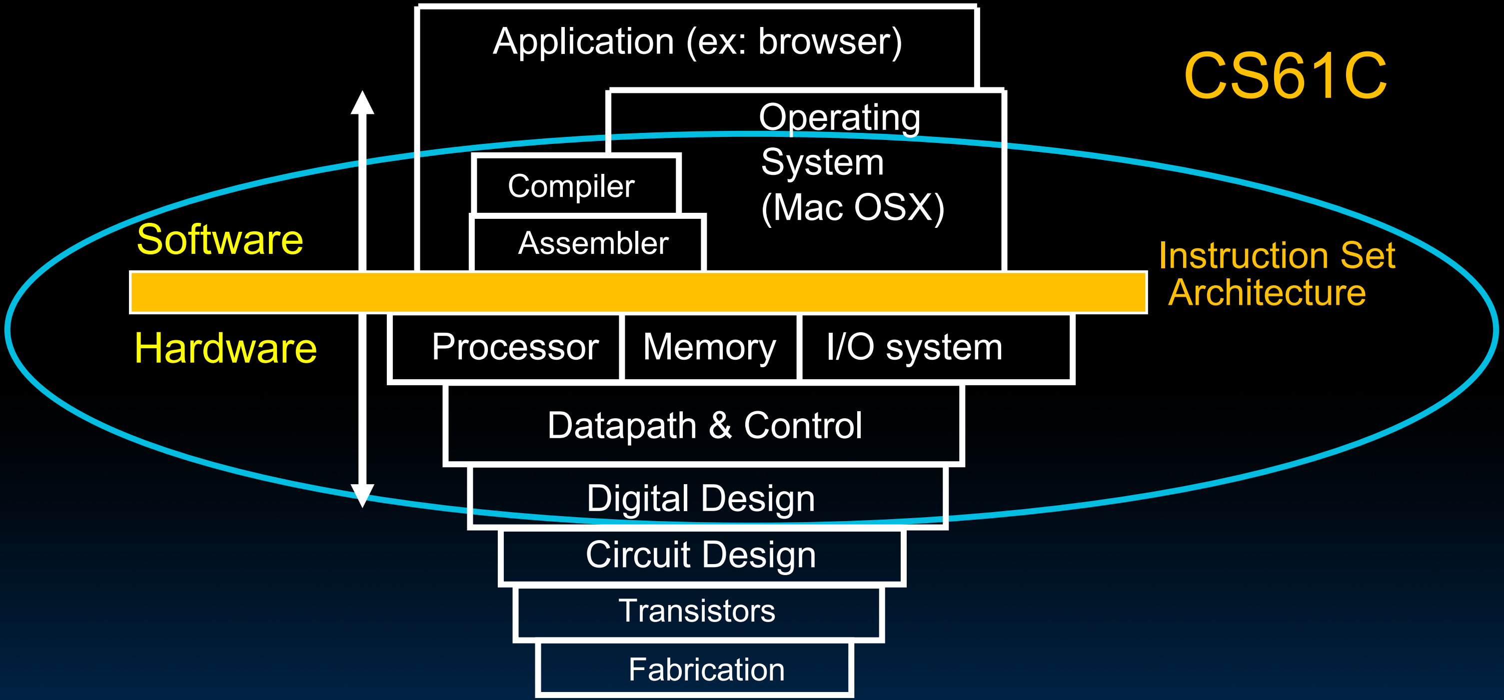
# Switches

# Machine Structures



# New-School Machine Structures

Software

Harness Parallelism & Achieve High Performance

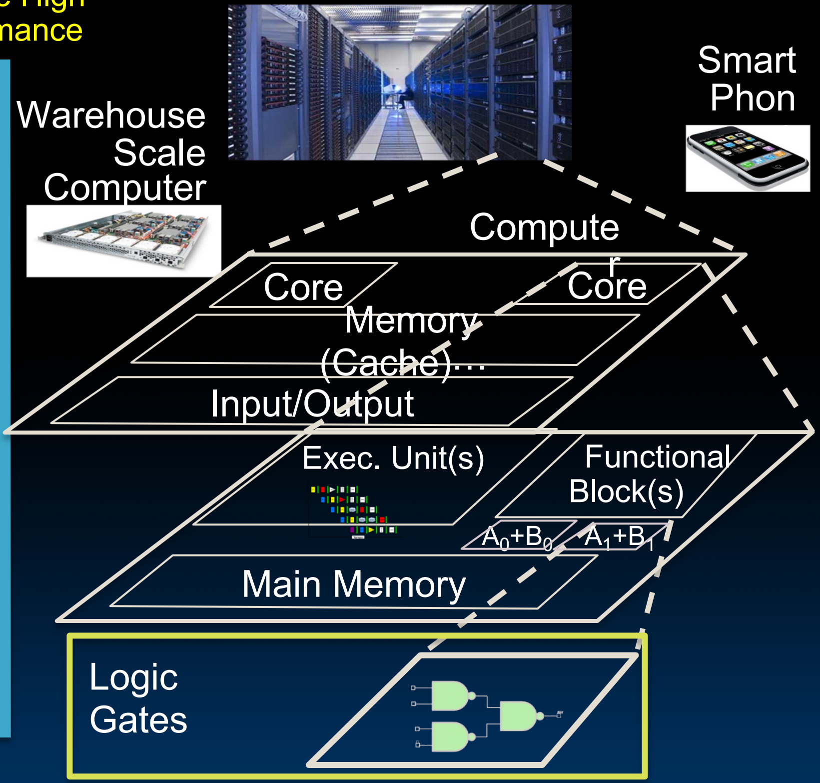
## Parallel Requests
Assigned to computer
e.g., Search "Cats"

## Parallel Threads
Assigned to core e.g., Lookup, Ads

## Parallel Instructions
>1 instruction @ one time
e.g., 5 pipelined instructions

## Parallel Data
>1 data item @ one time
e.g., Add of 4 pairs of words

## Hardware descriptions
All gates work in parallel at same time




**Synchronous Digital Systems** (4)



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# Great Idea #1: Abstraction (Levels of Representation/Interpretation)

High Level Language Program (e.g., C)

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Compiler

Assembly Language Program (e.g., RISC-V)

```
lw    x3, 0(x10)
lw    x4, 4(x10)
sw    x4, 0(x10)
sw    x3, 4(x10)
```

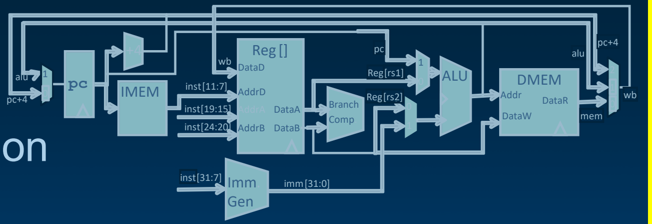
Assembler

Machine Language Program (RISC-V)

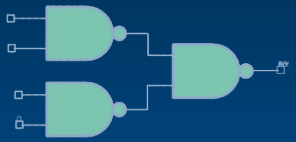
```
1000 1101 1110 0010 0000 0000 0000 0000
1000 1110 0001 0000 0000 0000 0000 0100
1010 1110 0001 0010 0000 0000 0000 0000
1010 1101 1110 0010 0000 0000 0000 0100
```

Hardware Architecture Description (e.g., block diagrams)

Architecture Implementation




Logic Circuit Description (Circuit Schematic Diagrams)



# Synchronous Digital Systems

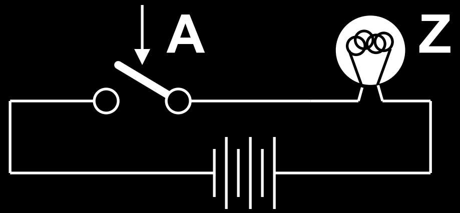
- Hardware of a processor, e.g., RISC-V, is a Synchronous Digital System
- Synchronous:
  - All operations coordinated by a central clock
  - "Heartbeat" of the system!
- Digital:
  - All values represented by discrete values
  - Electrical signals are treated as 1s and 0s; grouped together to form words

# Logic Design

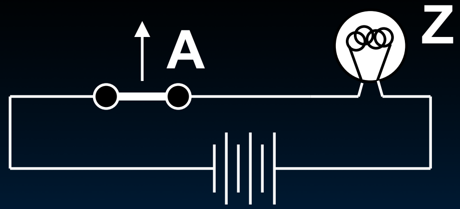
- Next several weeks: we'll study how a modern processor is built; starting with basic elements as building blocks
- Why study hardware design?
  - Understand capabilities and limitations of HW in general and processors in particular
  - What processors can do fast and what they can't do fast (avoid slow things if you want your code to run fast!)
  - Background for more in depth HW courses (150, 152)
  - There is just so much you can do with standard processors: you may need to design own custom HW for extra performance

# Switches: Basic Element of Physical Circuit

- Implementing a simple circuit
  - Close switch when **A** is 1, open when **A** is 0




Close switch (if **A** is "1" or asserted) and turn on light bulb (**Z**)




Open switch (if **A** is "0" or unasserted) and turn off light bulb (**Z**)

$$Z \equiv A$$

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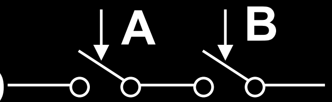
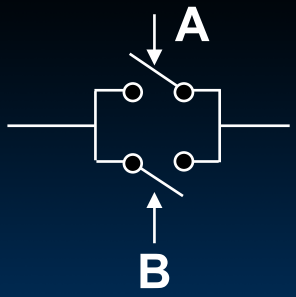
# Switches (continued)

- Compose switches into more complex ones (Boolean functions):

AND


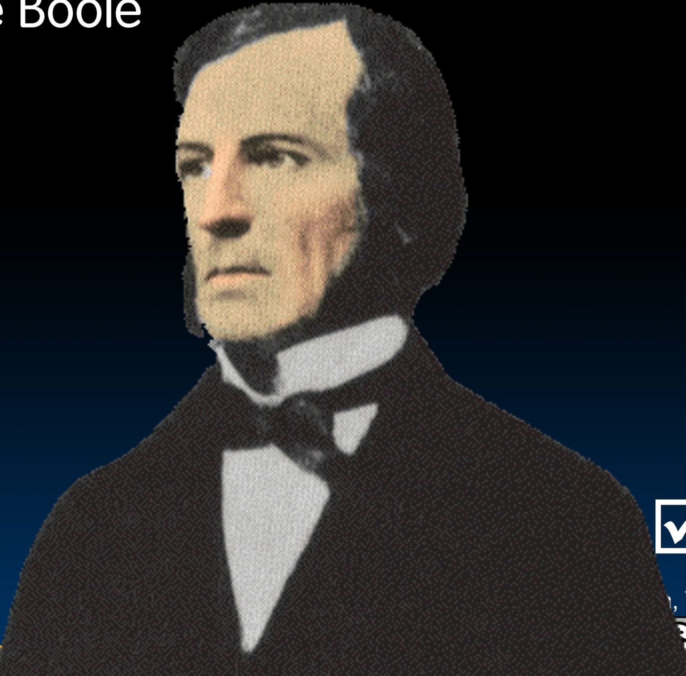

Z ≡ A **and** B

OR



Z ≡ A **or** B

# Historical Note

- Early computer designers built ad hoc circuits from switches
- Began to notice common patterns in their work: ANDs, ORs, …
- Master's thesis (by Claude Shannon) made link between transistors and 19th Century Mathematician George Boole
  - Called it "Boolean" in his honor
- Could apply math to give theory to hardware design, minimization, …



# Transistors

# The Transistor ("born" 1947-12-23)

en.wikipedia.org/wiki/History_of_the_transistor
www.pbs.org/transistor
youtu.be/-td7YT-Pums
youtu.be/OwS9aTE2Go4

- Semiconductor device to amplify or switch signals
  - Key component in ALL modern electronics
- Who?
  - John Bardeen, William Shockley, Walter Brattain
- Before that?
  - Vacuum Tubes
- After that?
  - Integrated circuit, microprocessor


"The Transistor was probably THE most important invention of the 20th Century"
- Ira Flatow, Transistorized! (PBS Special)

# Transistor Networks

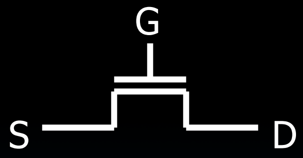
- Modern digital systems designed in CMOS
  - MOS: Metal-Oxide on Semiconductor
  - C for complementary: normally-open and normally-closed switches

- MOS transistors act as voltage-controlled switches

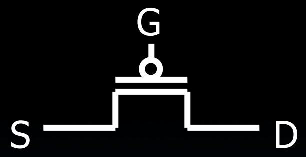
# MOS Transistors

- Three terminals: Drain, Gate, Source
  - Switch action: Dan Garcia Says
    if voltage on gate terminal is (some amount) higher/lower than source terminal then conducting path established between drain and source terminals

To remember:
n ("normal")
p (has a circle, like the top part of P itself)




n-channel
open when voltage at G is low
closes when:
voltage(G) > voltage (S) + ε



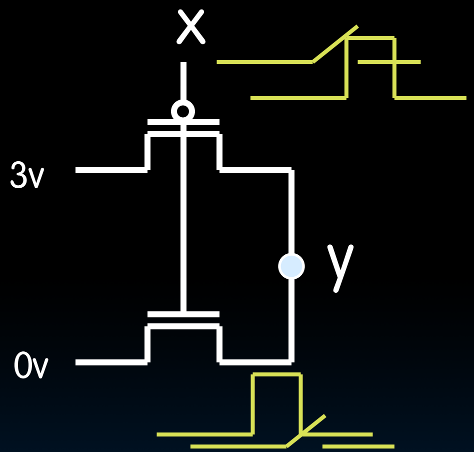

p-channel
closed when voltage at G is low
opens when:
voltage(G) > voltage (S) + ε

**G LOW**
**G HIGH**

# MOS Networks

"1"
(voltage
source)

"0"
(ground)

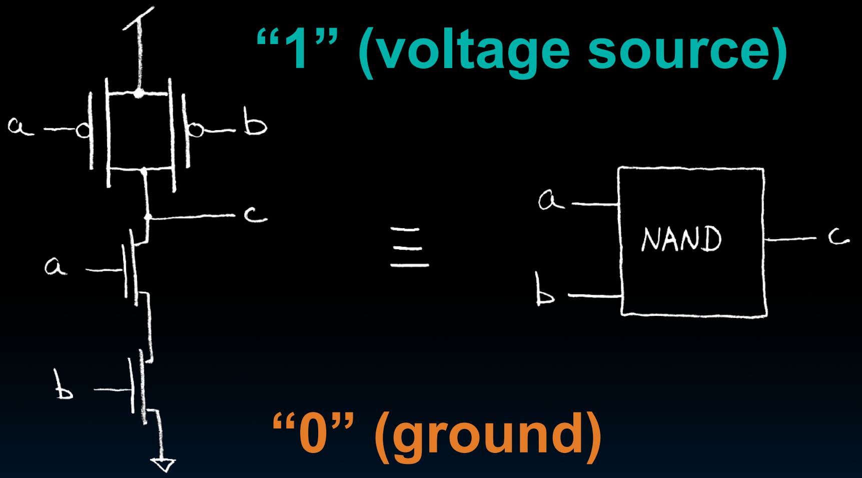



What is the relationship between x and y ?

| x | y |
|---|---|
| 0 volts | 3 volts |
| 3 volts | 0 volts |

# Transistor Circuit Rep. vs. Block diagram

- Chips are composed of nothing but transistors and wires.
- Small groups of transistors form useful building blocks.

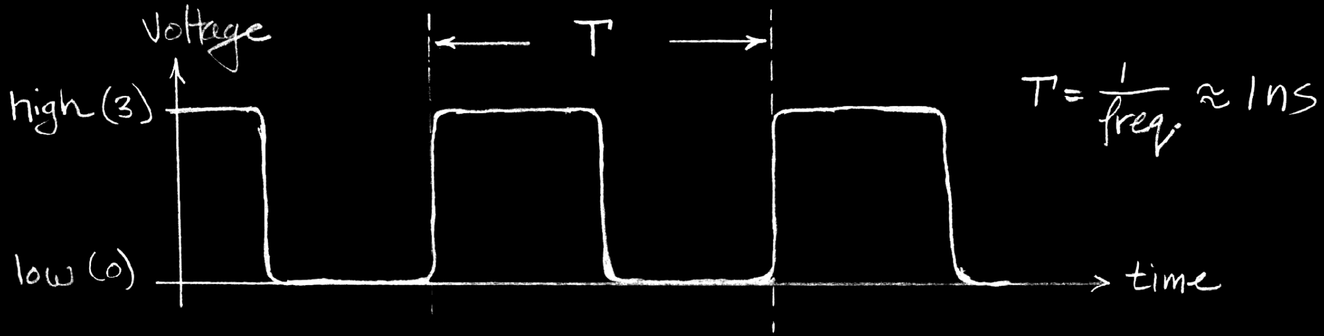



| a | b | c |
|---|---|---|
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

- Block are organized in a hierarchy to build higher-level blocks: ex: adders.
- You can build AND, OR, NOT out of NAND!

# Signals and Waveforms

# Signals and Waveforms: Clocks




- Signals
  - When digital is only treated as 1 or 0
  - Is transmitted over wires continuously
  - Transmission is effectively instant
  - Implies that a wire contains 1 value at a time



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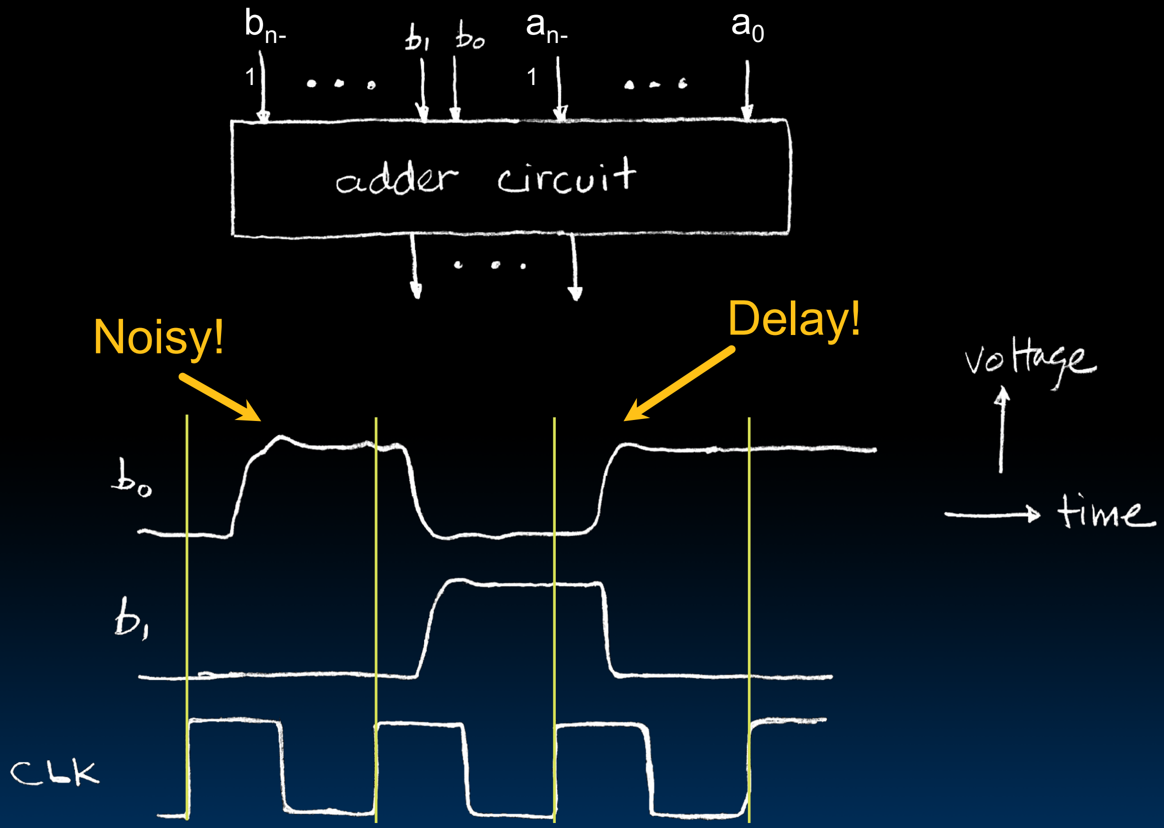
# Signals and Waveforms







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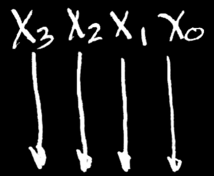
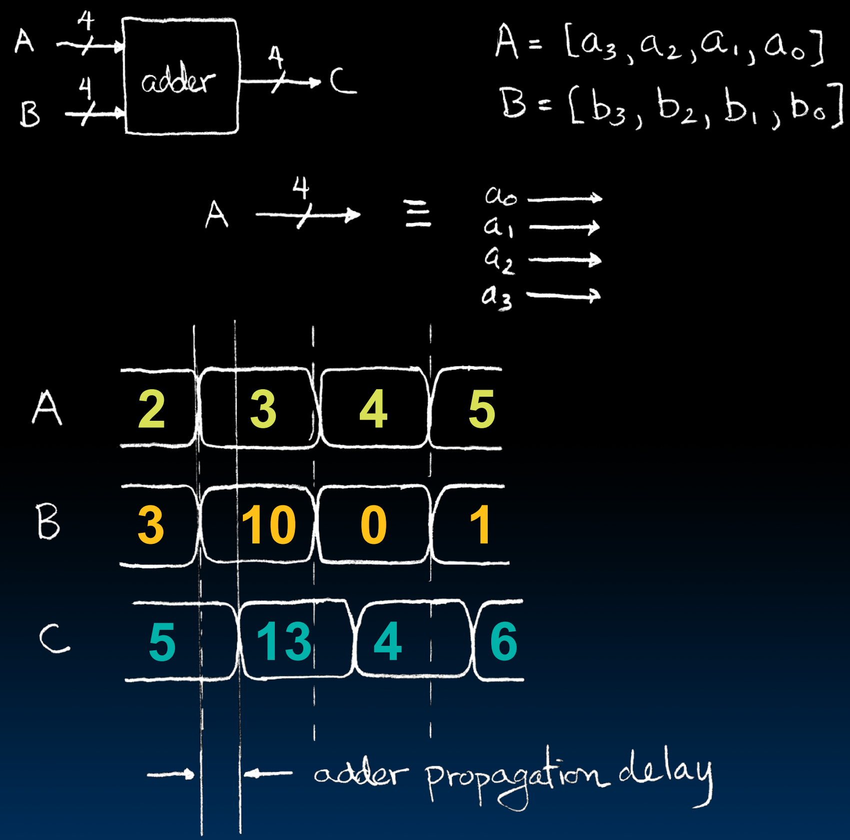
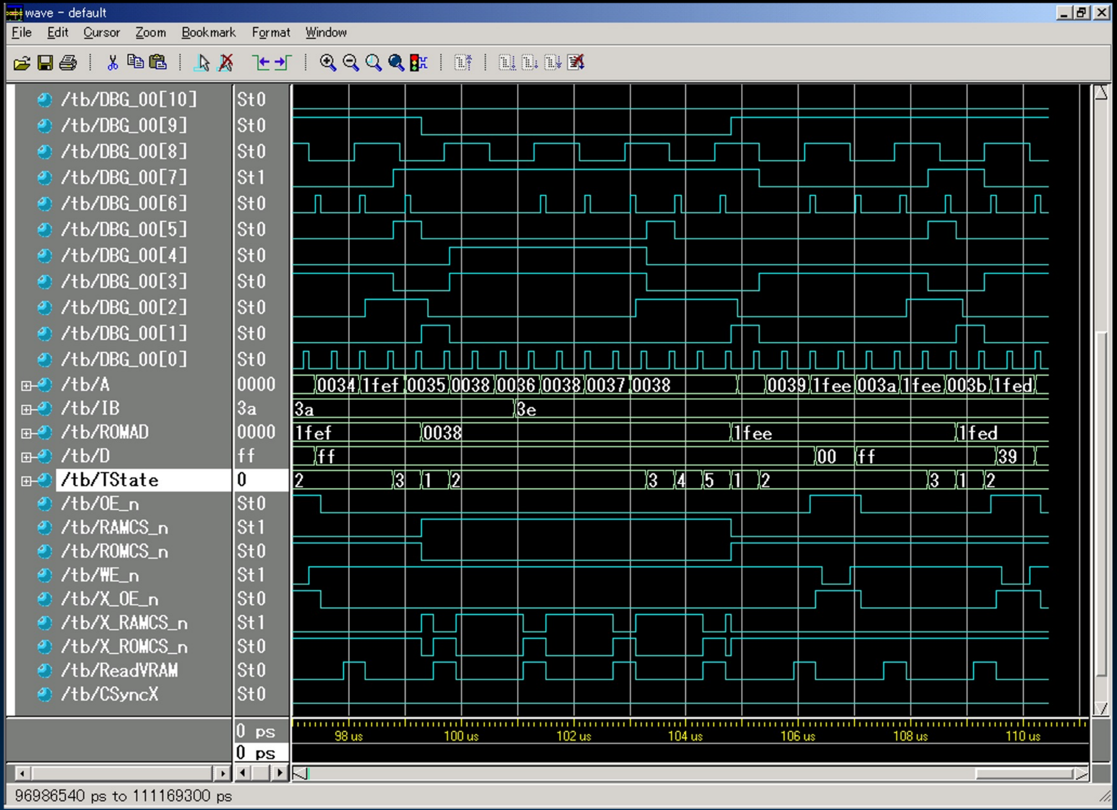
# Signals and Waveforms: Grouping




# Signals and Waveforms: Circuit Delay



# Sample Debugging Waveform

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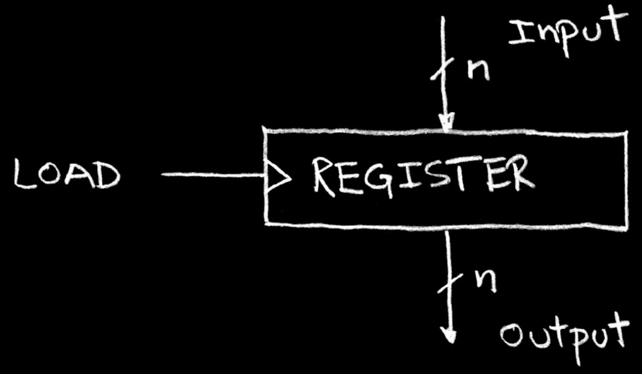
# Type of Circuits

- Synchronous Digital Systems are made up of two basic types of circuits:
- Combinational Logic (CL) circuits
  - Our previous adder circuit is an example.
  - Output is a function of the inputs only.
  - Similar to a pure function in mathematics, $y = f(x)$. (No way to store information from one invocation to the next, no side effects)
- State Elements
  - circuits that store information.

# Circuits with STATE (e.g., register)



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# L14 SW can peek at HW (past ISA abstraction boundary) for optimizations | SW can depend on particular HW implementation of ISA | Timing diagrams serve as a critical debugging tool in the EE toolkit

FFF
FFT
FTF
FTT
TFF
TFT
TTF
TTT

# And in conclusion…

- Clocks control pulse of our circuits
- Voltages are analog, quantized to 0/1
- Circuit delays are fact of life
- Two types of circuits:
    - Stateless Combinational Logic (&, |, ~)
    - State circuits (e.g., registers)