

# **CS:APP Chapter 4**

## **Computer Architecture**

# **Logic Design**

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***Adapted from CMU course 15-213***

# Overview of Logic Design

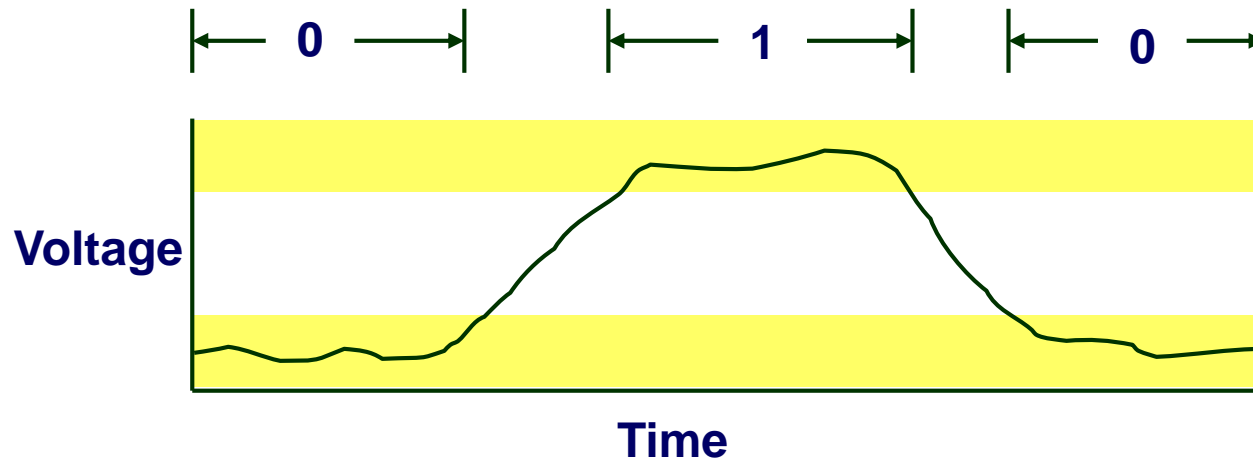
## Fundamental Hardware Requirements

- Communication
  - How to get values from one place to another
- Computation
- Storage

## Bits are Our Friends

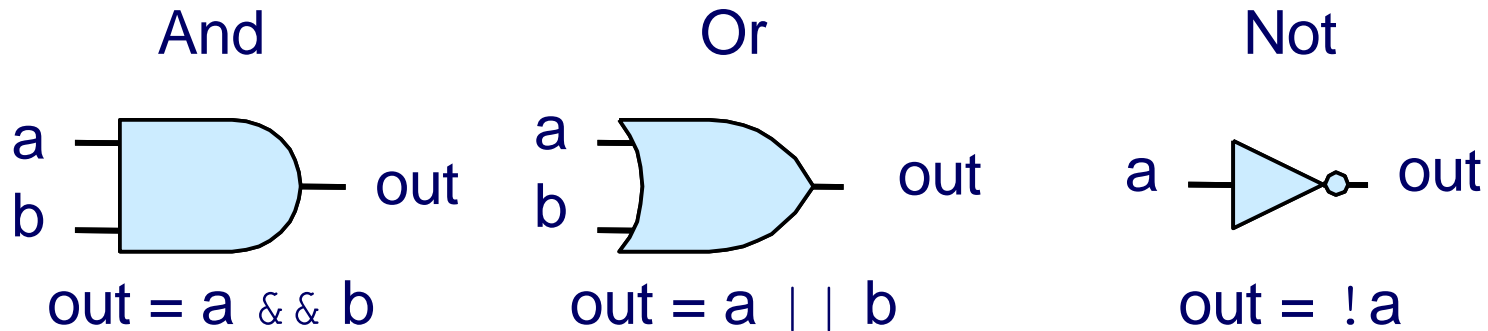
- Everything expressed in terms of values 0 and 1
- Communication
  - Low or high voltage on wire
- Computation
  - Compute Boolean functions
- Storage
  - Store bits of information

# Digital Signals

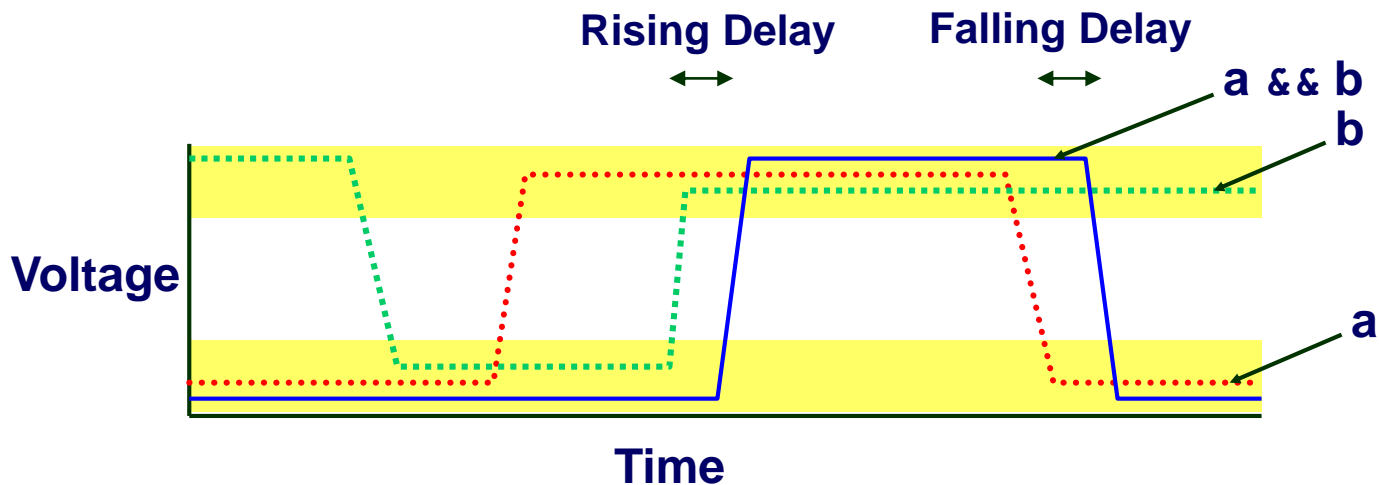


- Use voltage thresholds to extract discrete values from continuous signal
- Simplest version: 1-bit signal
  - Either high range (1) or low range (0)
  - With guard range between them
- Not strongly affected by noise or low quality circuit elements
  - Can make circuits simple, small, and fast

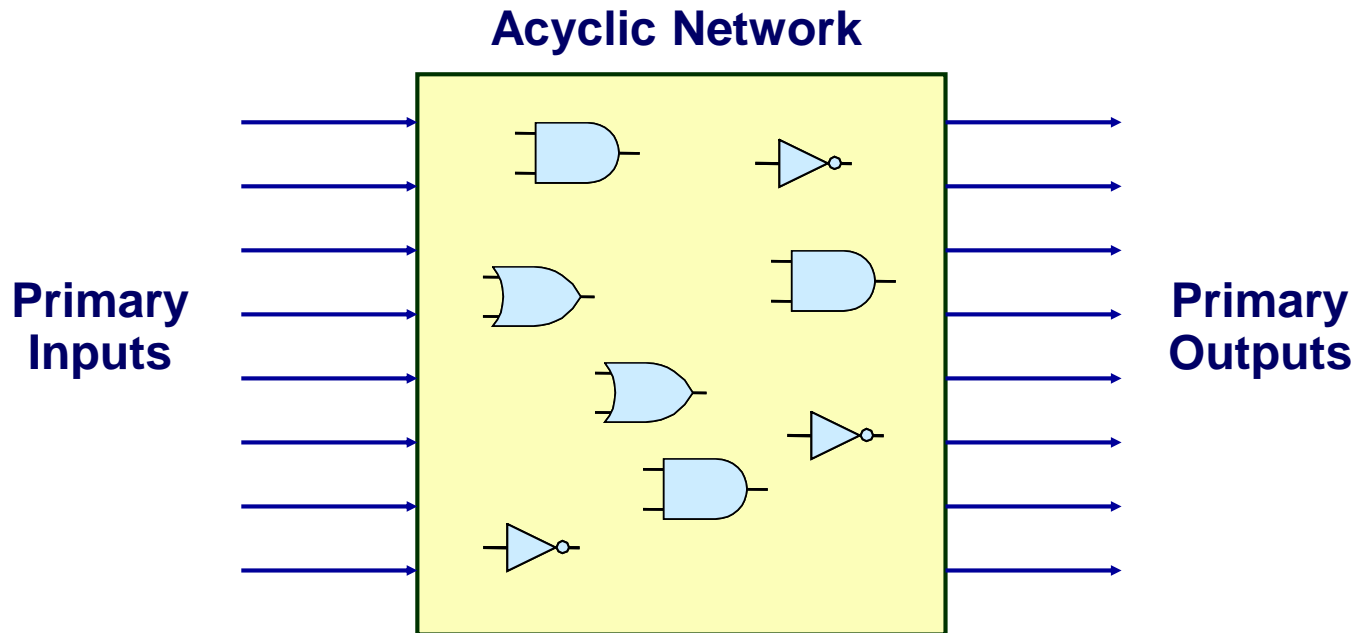
# Computing with Logic Gates



- Outputs are Boolean functions of inputs
- Respond continuously to changes in inputs
  - With some, small delay



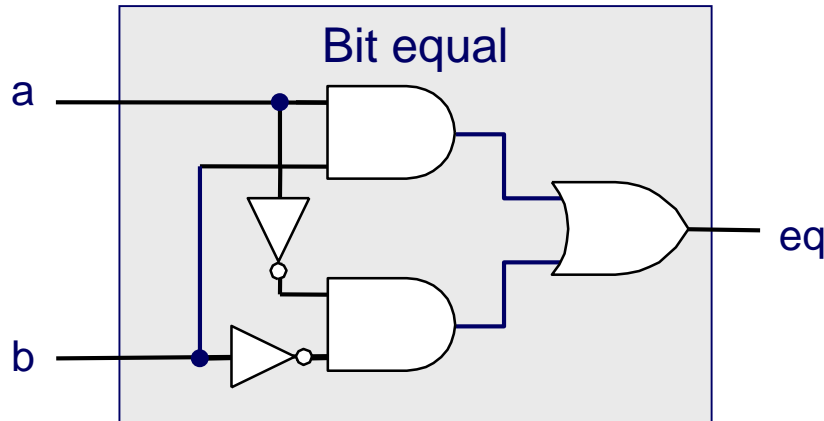
# Combinational Circuits



## Acyclic Network of Logic Gates

- Continuously responds to changes on primary inputs
- Primary outputs become (after some delay) Boolean functions of primary inputs

# Bit Equality



## HCL Expression

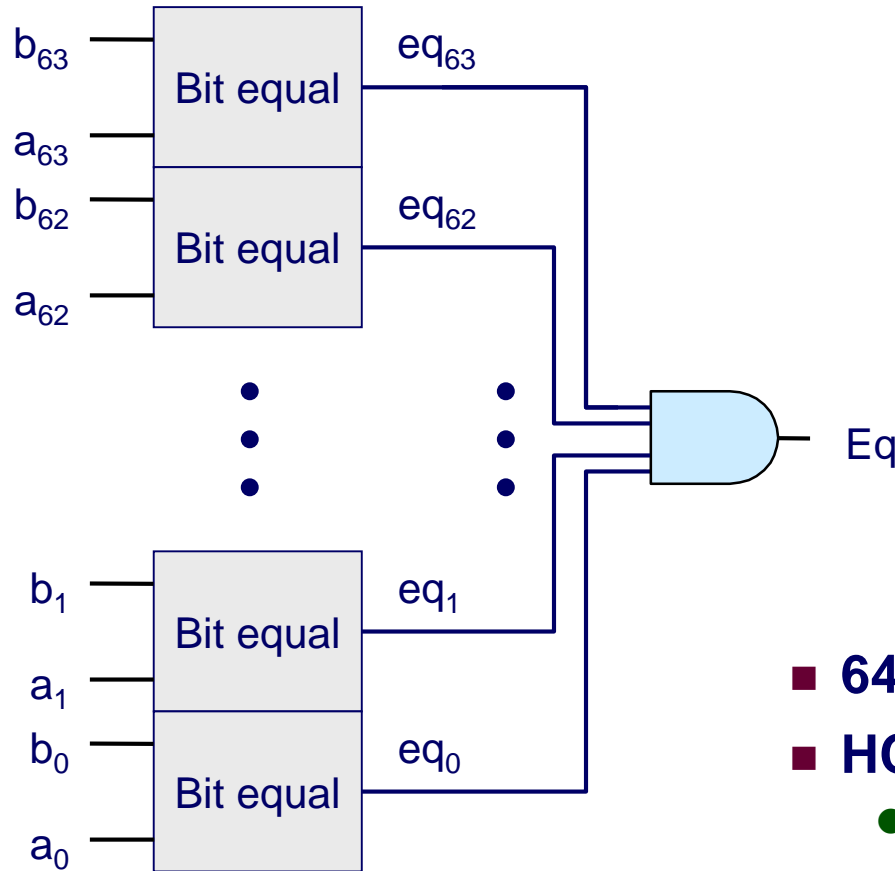
```
bool eq = (a&&b) || (!a&&!b)
```

- Generate 1 if a and b are equal

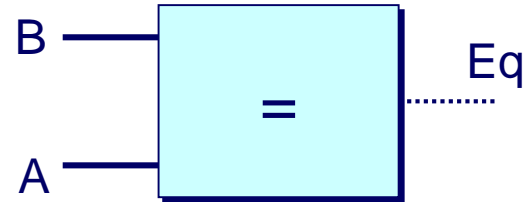
## Hardware Control Language (HCL)

- Very simple hardware description language
  - Boolean operations have syntax similar to C logical operations
- We'll use it to describe control logic for processors

# Word Equality



## Word-Level Representation

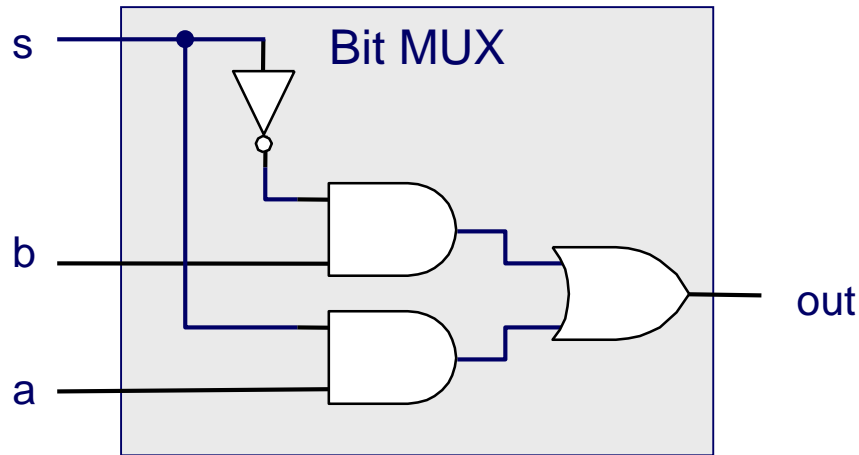


## HCL Representation

`bool Eq = (A == B)`

- 64-bit word size
- HCL representation
  - Equality operation
  - Generates Boolean value

# Bit-Level Multiplexor



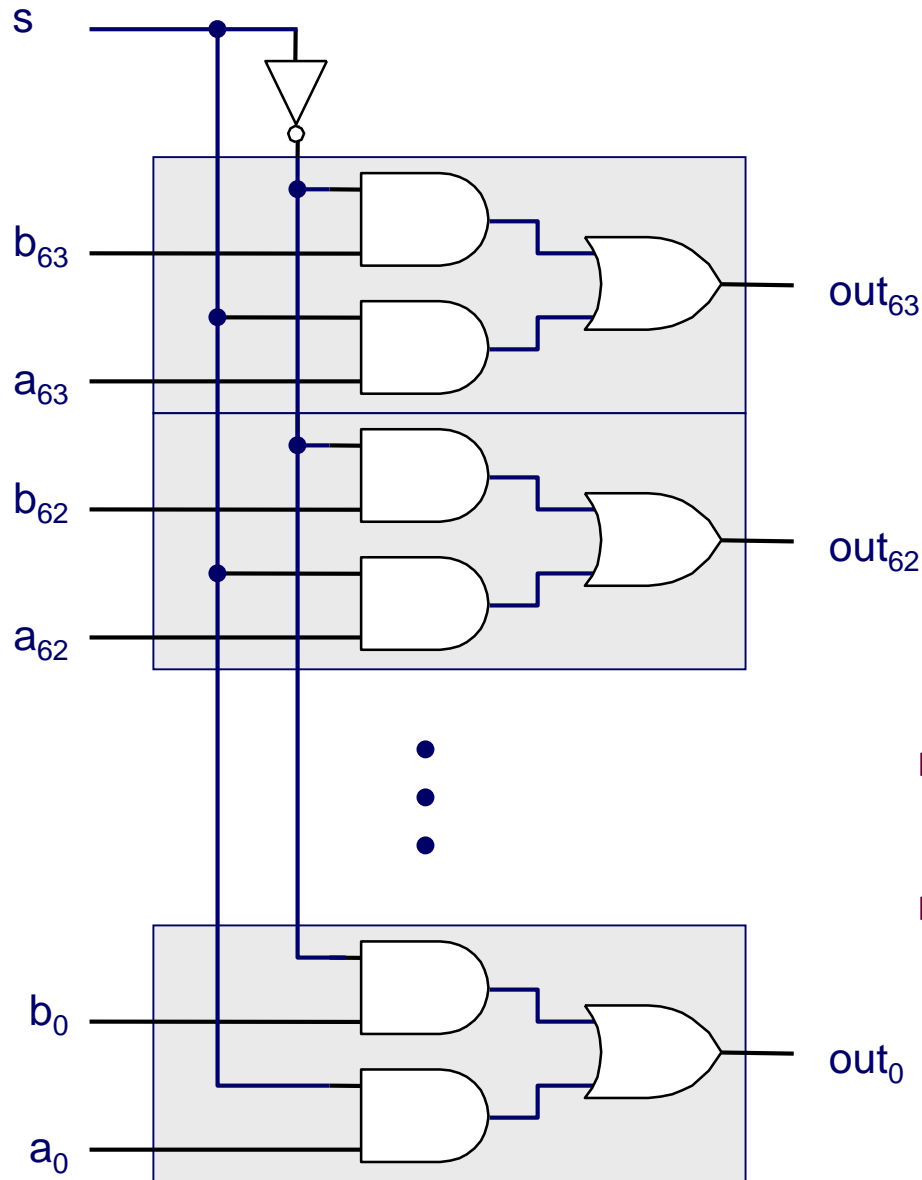
## HCL Expression

```
bool out = (s&&a) || (!s&&b)
```

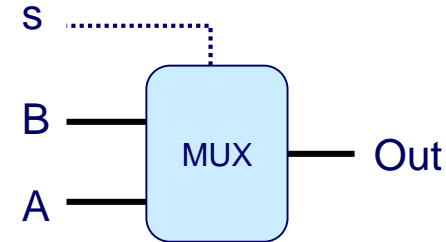
- Control signal  $s$
- Data signals  $a$  and  $b$
- Output  $a$  when  $s=1$ ,  $b$  when  $s=0$



# Word Multiplexor



## Word-Level Representation



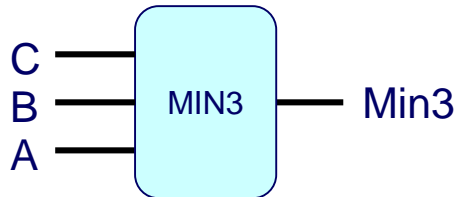
## HCL Representation

```
int Out = [  
    s : A;  
    1 : B;  
];
```

- Select input word A or B depending on control signal  $s$
- HCL representation
  - Case expression
  - Series of test : value pairs
  - Output value for first successful test

# HCL Word-Level Examples

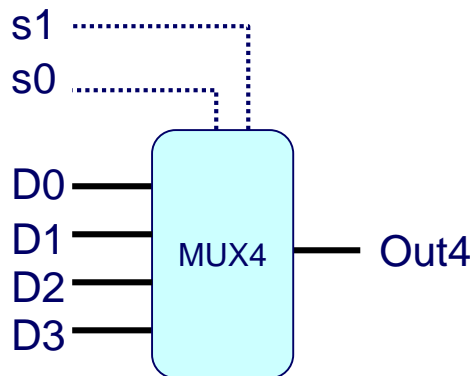
## Minimum of 3 Words



```
int Min3 = [  
    A < B && A < C : A;  
    B < A && B < C : B;  
    1                : C;  
];
```

- Find minimum of three input words
- HCL case expression
- Final case guarantees match

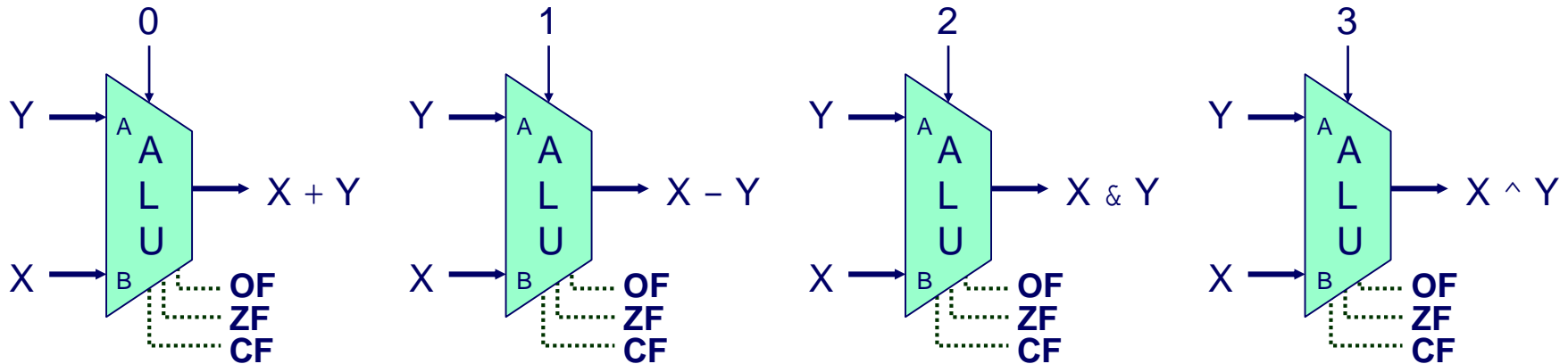
## 4-Way Multiplexor



```
int Out4 = [  
    !s1&&!s0: D0;  
    !s1      : D1;  
    !s0      : D2;  
    1        : D3;  
];
```

- Select one of 4 inputs based on two control bits
- HCL case expression
- Simplify tests by assuming sequential matching

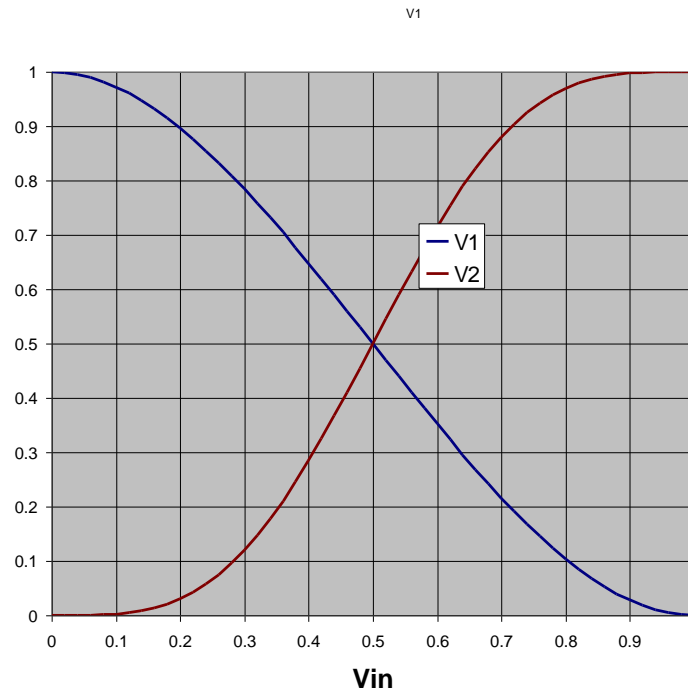
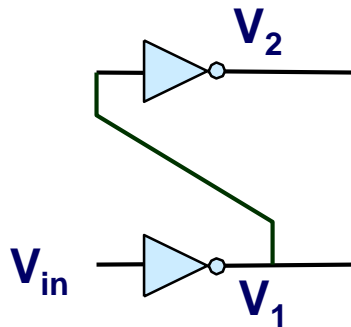
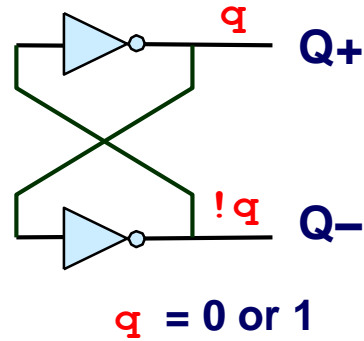
# Arithmetic Logic Unit



- **Combinational logic**
  - Continuously responding to inputs
- **Control signal selects function computed**
  - Corresponding to 4 arithmetic/logical operations in Y86-64
- **Also computes values for condition codes**

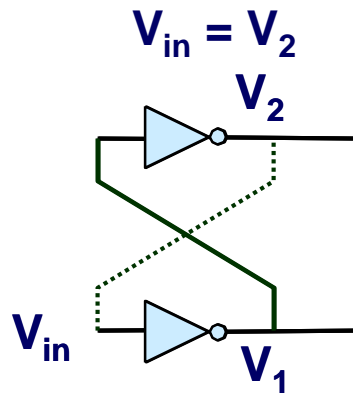
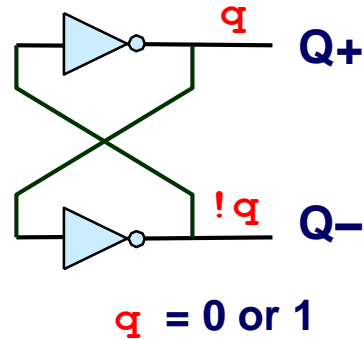
# Storing 1 Bit

## Bistable Element

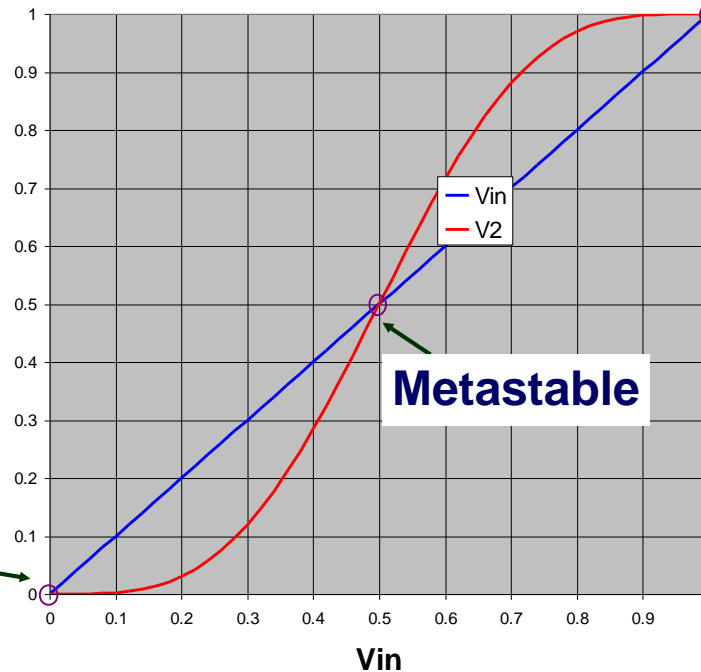


# Storing 1 Bit (cont.)

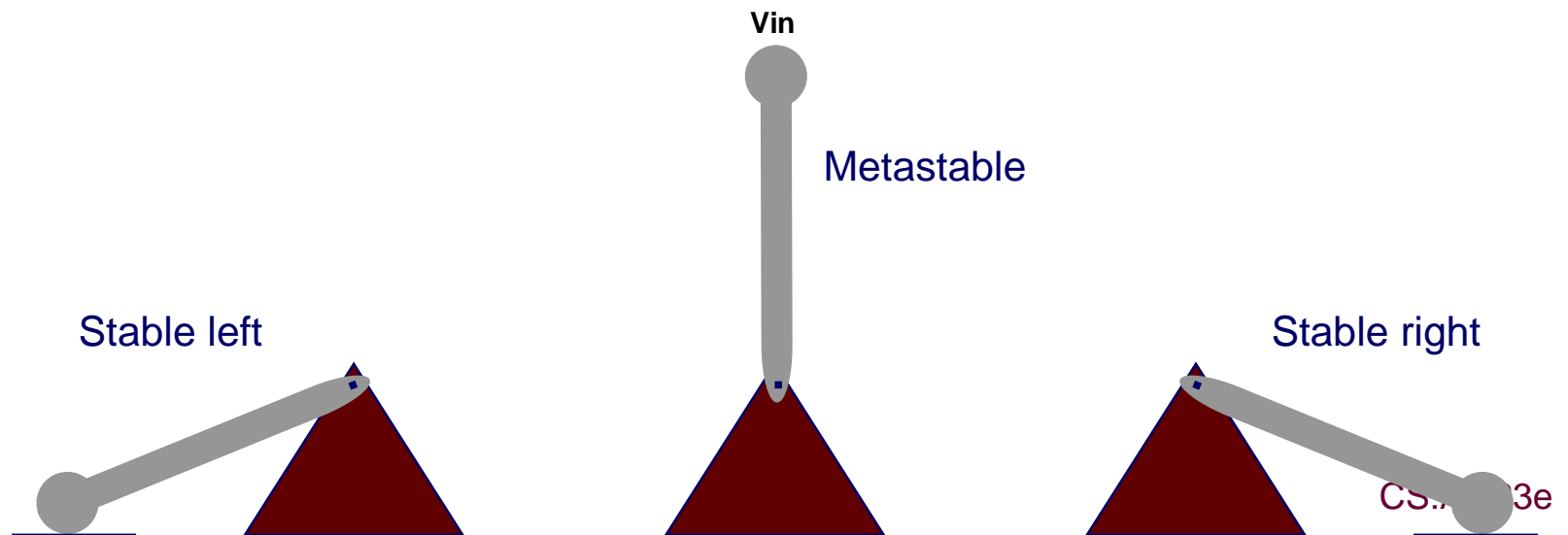
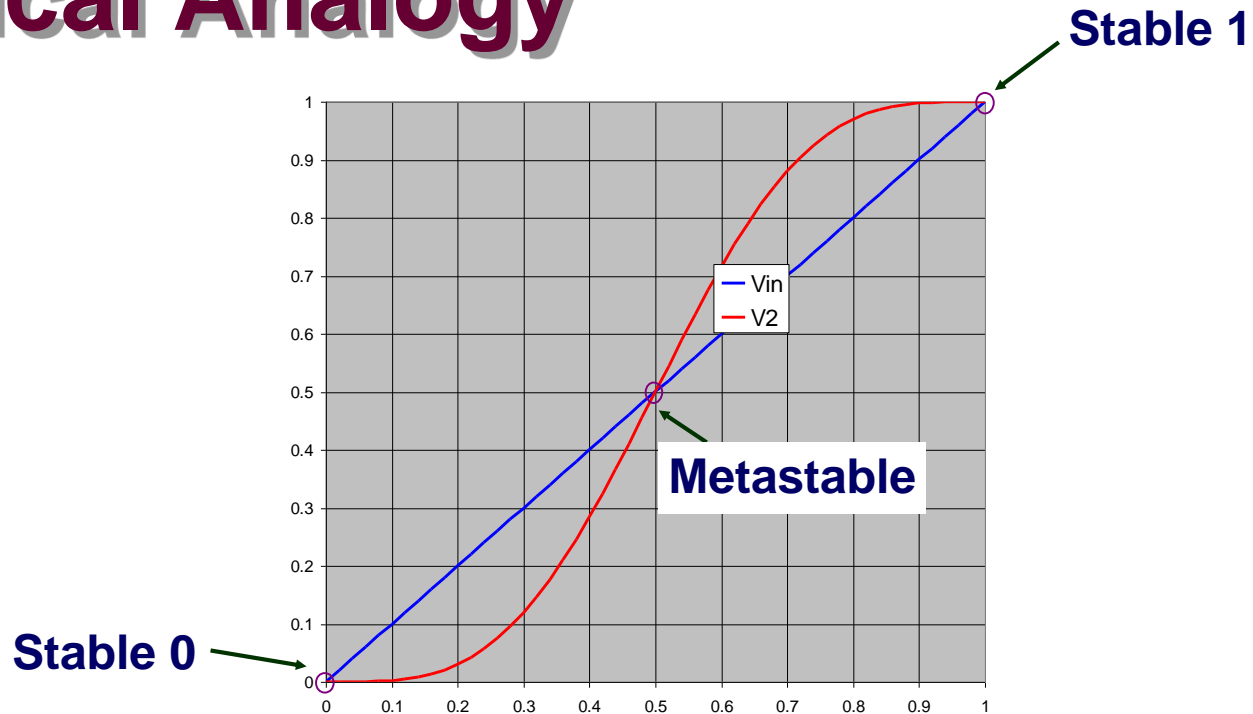
## Bistable Element



Stable 0

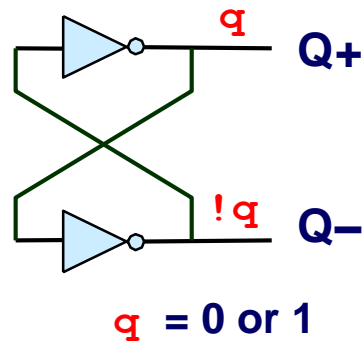


# Physical Analogy

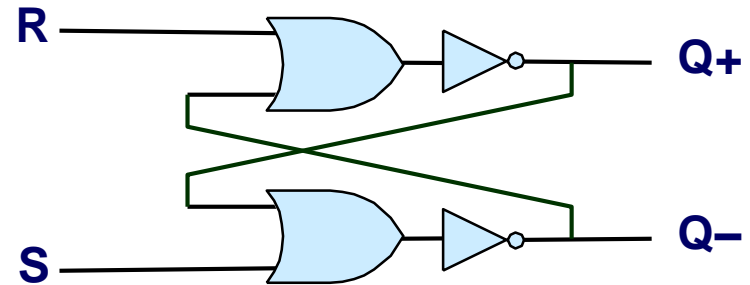


# Storing and Accessing 1 Bit

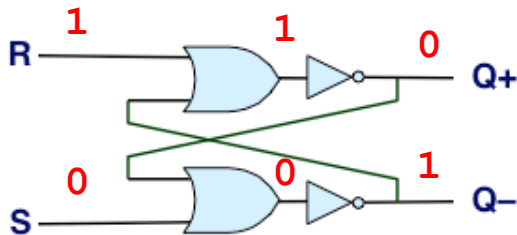
## Bistable Element



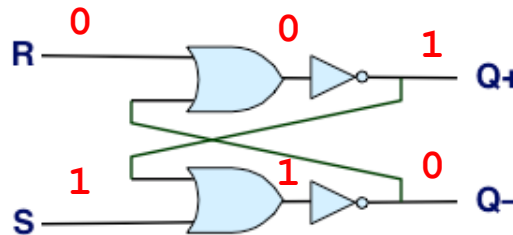
## R-S Latch



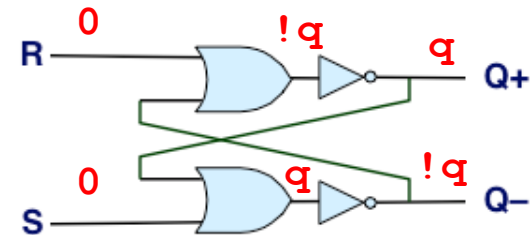
## Resetting



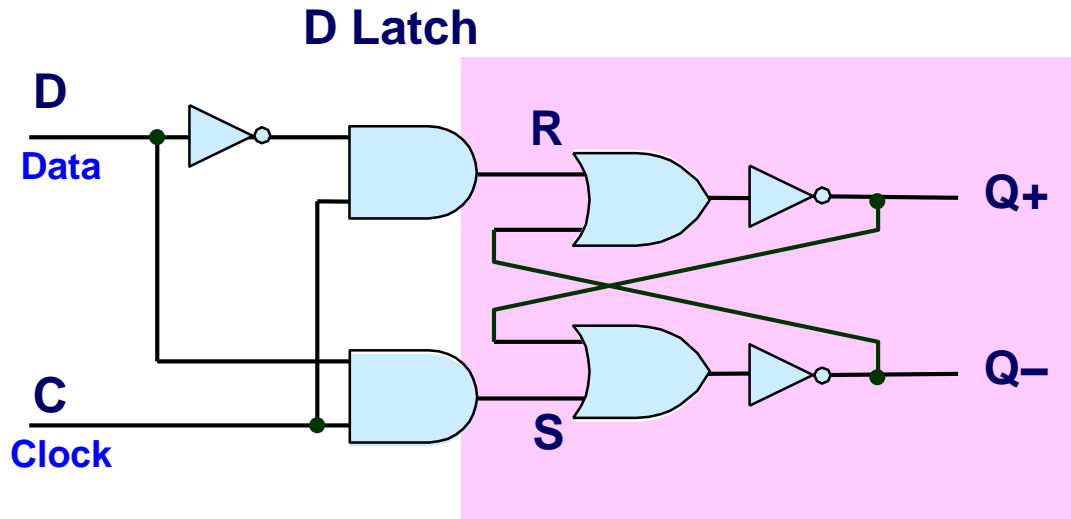
## Setting



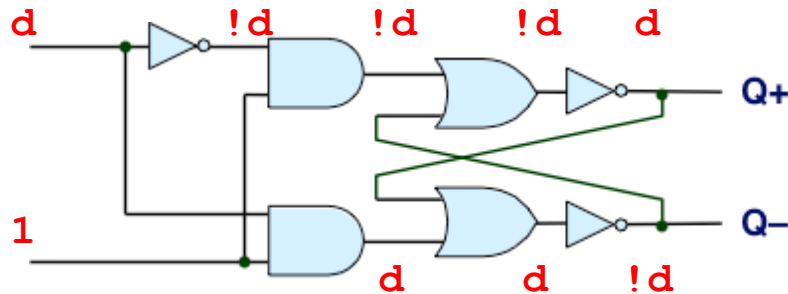
## Storing



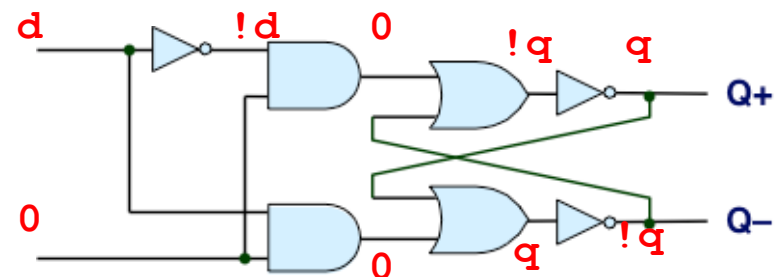
# 1-Bit Latch



## Latching



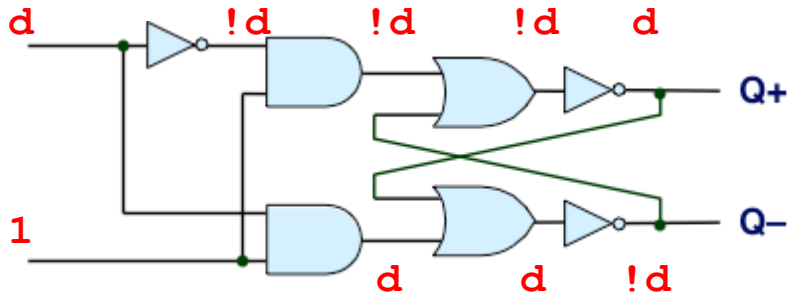
## Storing



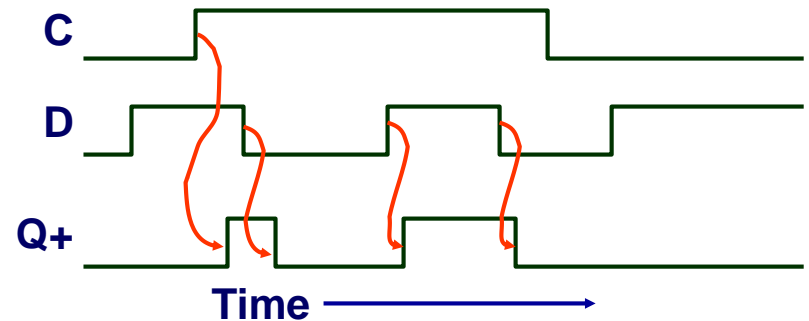


# Transparent 1-Bit Latch

## Latching

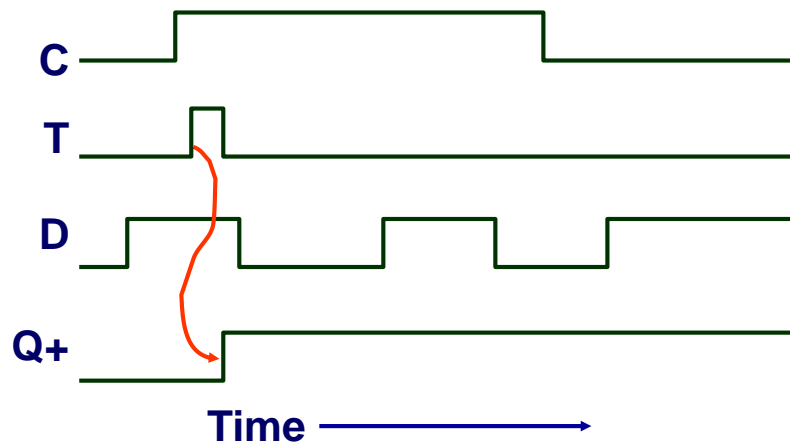
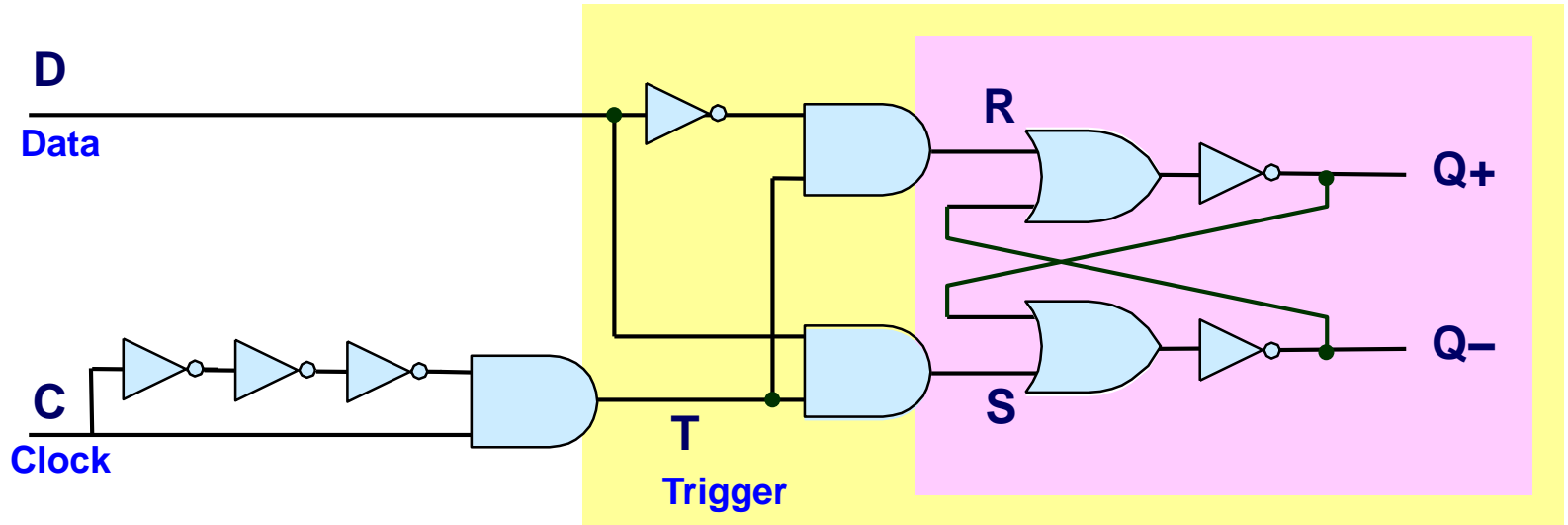


## Changing D



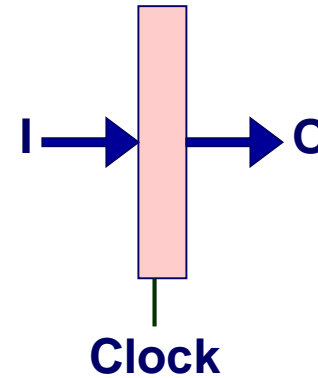
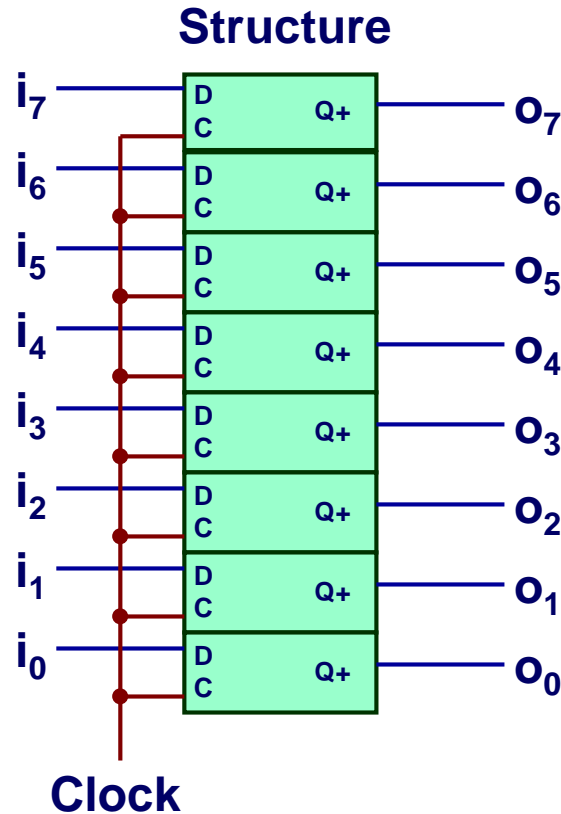
- When in latching mode, combinational propagation from  $D$  to  $Q+$  and  $Q-$
- Value latched depends on value of  $D$  as  $C$  falls

# Edge-Triggered Latch



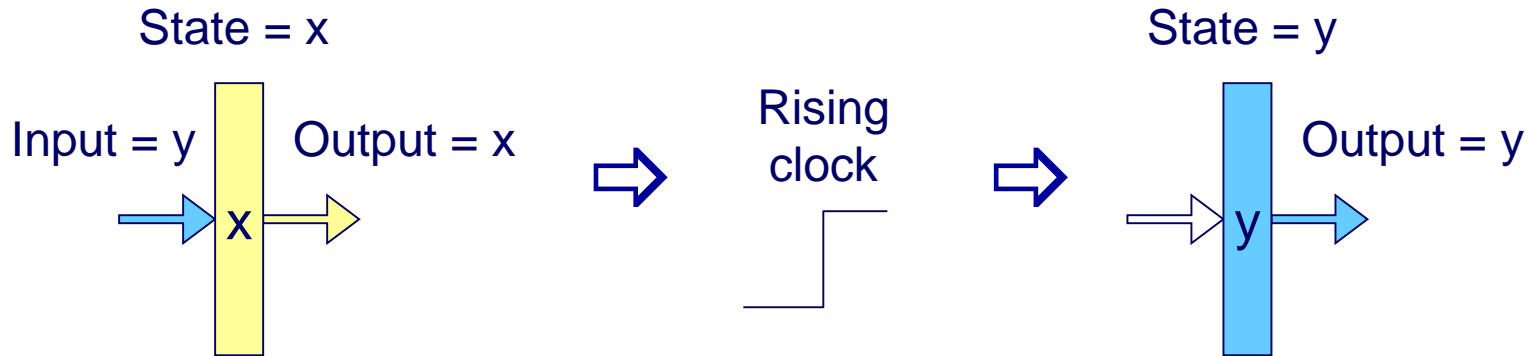
- Only in latching mode for brief period
  - Rising clock edge
- Value latched depends on data as clock rises
- Output remains stable at all other times

# Registers



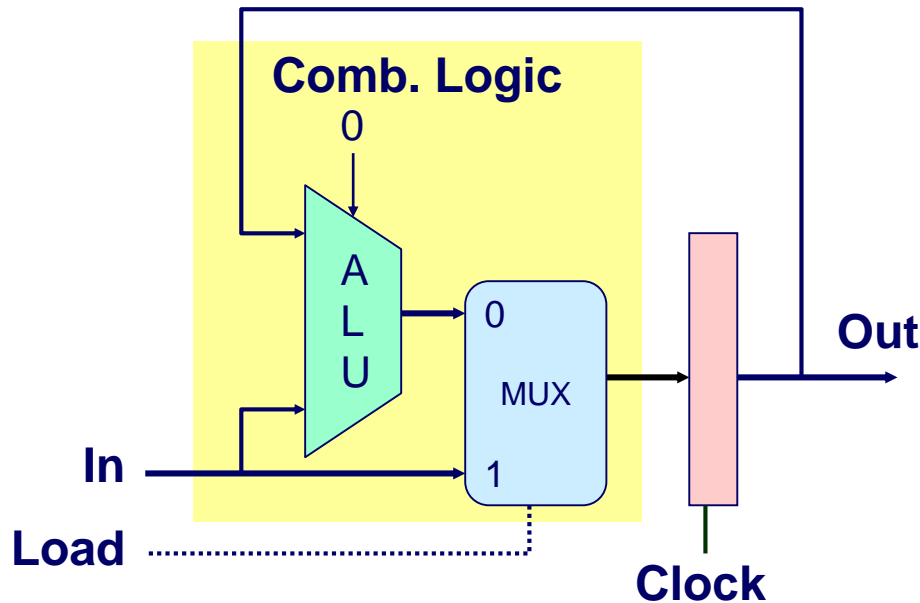
- Stores word of data
  - Different from *program registers* seen in assembly code
- Collection of edge-triggered latches
- Loads input on rising edge of clock

# Register Operation

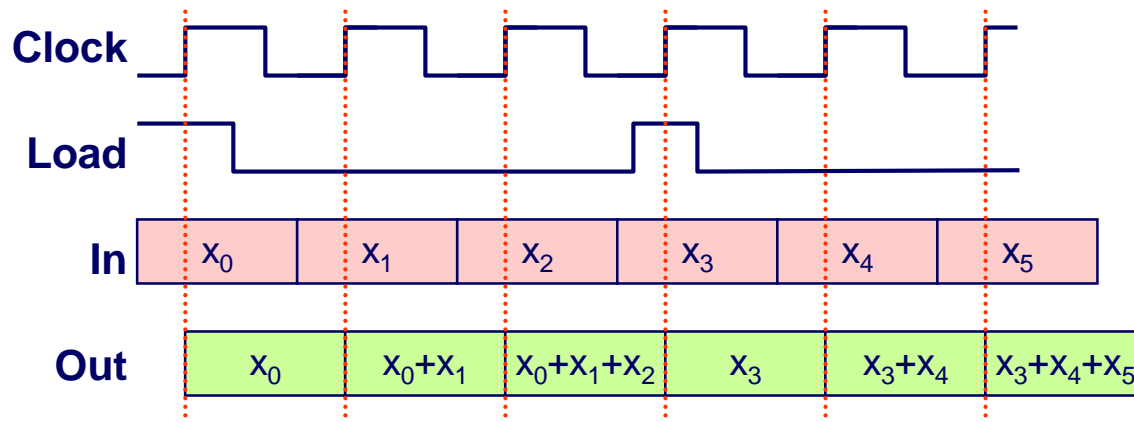


- Stores data bits
- For most of time acts as barrier between input and output
- As clock rises, loads input

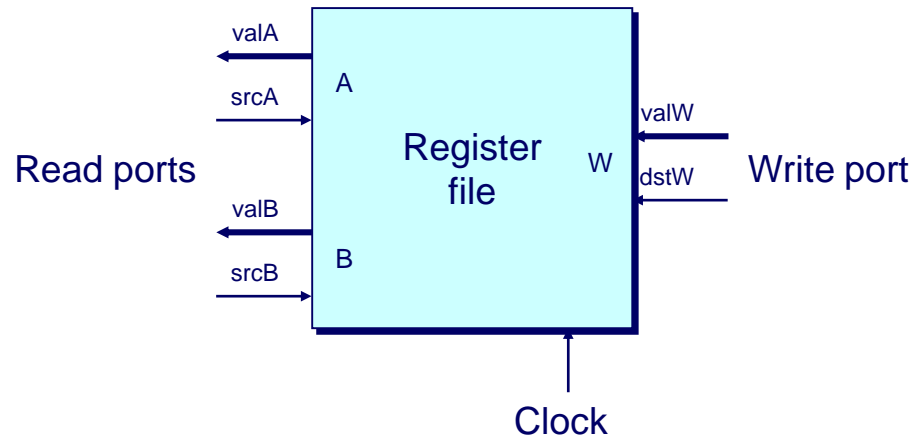
# State Machine Example



- Accumulator circuit
- Load or accumulate on each cycle

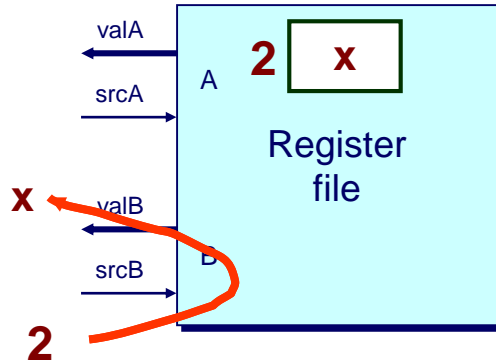


# Random-Access Memory



- **Stores multiple words of memory**
  - Address input specifies which word to read or write
- **Register file**
  - Holds values of program registers
  - `%rax`, `%rsp`, etc.
  - Register identifier serves as address
    - » ID 15 (0xF) implies no read or write performed
- **Multiple Ports**
  - Can read and/or write multiple words in one cycle
    - » Each has separate address and data input/output

# Register File Timing

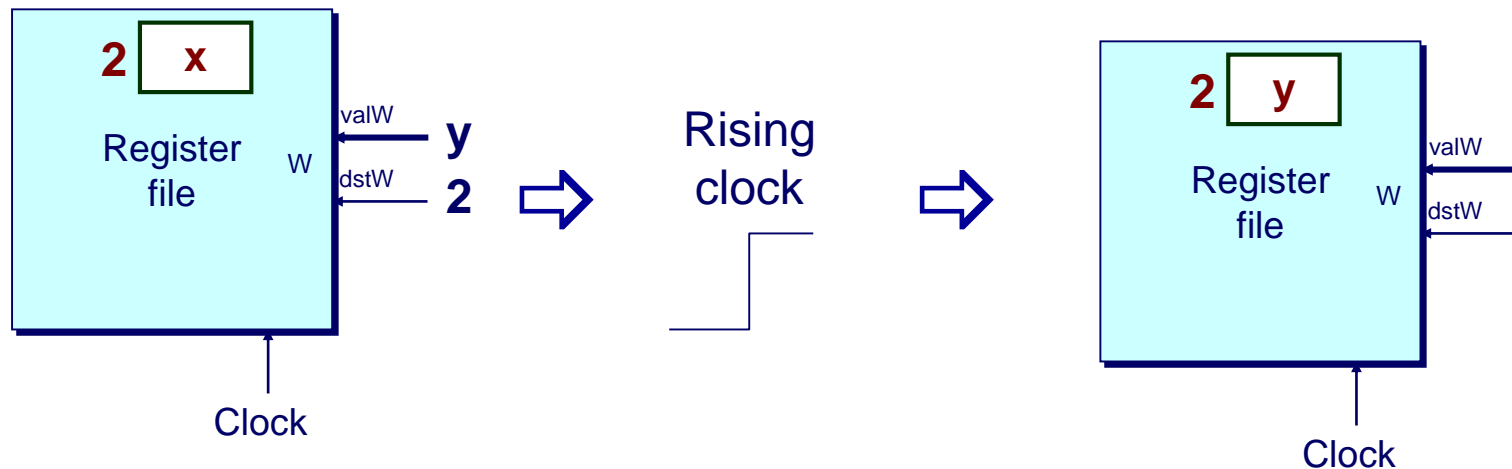


## Reading

- Like combinational logic
- Output data generated based on input address
  - After some delay

## Writing

- Like register
- Update only as clock rises



# Hardware Control Language

- Very simple hardware description language
- Can only express limited aspects of hardware operation
  - Parts we want to explore and modify

## Data Types

- `bool`: Boolean
  - `a, b, c, ...`
- `int`: words
  - `A, B, C, ...`
  - Does not specify word size---bytes, 64-bit words, ...

## Statements

- `bool a = bool-expr ;`
- `int A = int-expr ;`



# HCL Operations

- Classify by type of value returned

## Boolean Expressions

- Logic Operations
  - `a && b, a || b, !a`
- Word Comparisons
  - `A == B, A != B, A < B, A <= B, A >= B, A > B`
- Set Membership
  - `A in { B, C, D }`
    - » Same as `A == B || A == C || A == D`

## Word Expressions

- Case expressions
  - `[ a : A; b : B; c : C ]`
  - Evaluate test expressions `a, b, c, ...` in sequence
  - Return word expression `A, B, C, ...` for first successful test

# Summary

## Computation

- Performed by combinational logic
- Computes Boolean functions
- Continuously reacts to input changes

## Storage

- Registers
  - Hold single words
  - Loaded as clock rises
- Random-access memories
  - Hold multiple words
  - Possible multiple read or write ports
  - Read word when address input changes
  - Write word as clock rises