Logic Design: A Review

Lecture 2.1
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Today

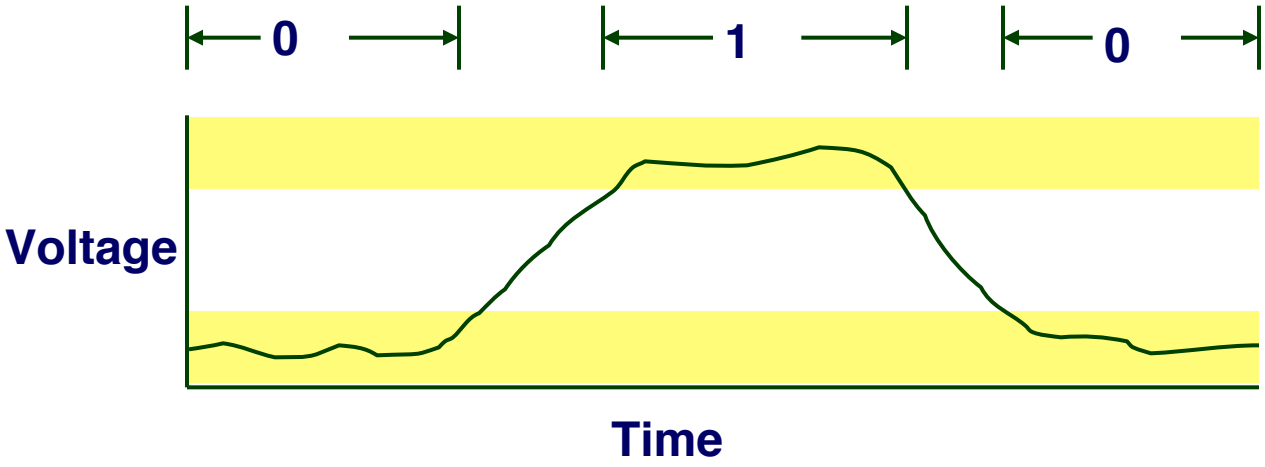
Reference: [CS:APP3e] 4.2

- **Overview**
- **Computation (Combinational Logic)**
- **Storage (Sequential Logic)**

Overview: Logic Design

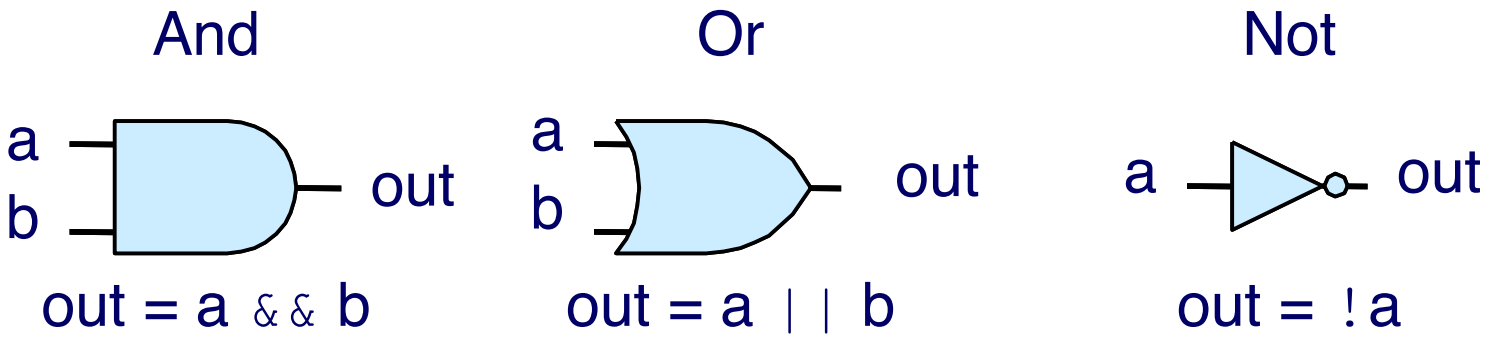
- **Fundamental hardware requirements**
  - Communication
    - How to get values from one place to another
  - Computation
  - Storage
- **Bits are our friends**
  - Everything expressed in terms of values 0 and 1
  - Communication
    - Low or high voltage on wire
  - Computation
    - Compute Boolean functions
  - Storage
    - Store bits of information

Overview: Digital Signals

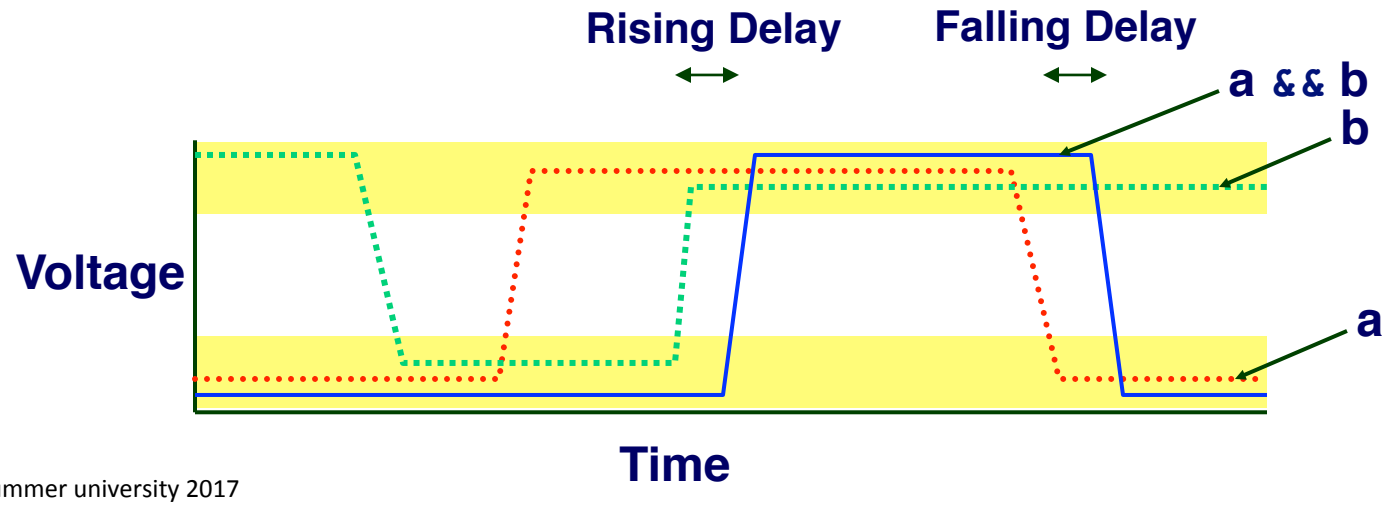


- Use **voltage thresholds** to extract discrete values from continuous signal
- Simplest version: 1-bit signal
  - Either high range (1) or low range (0)
  - With guard range between them
- Not strongly affected by noise or low quality circuit elements
  - Can make circuits simple, small, and fast

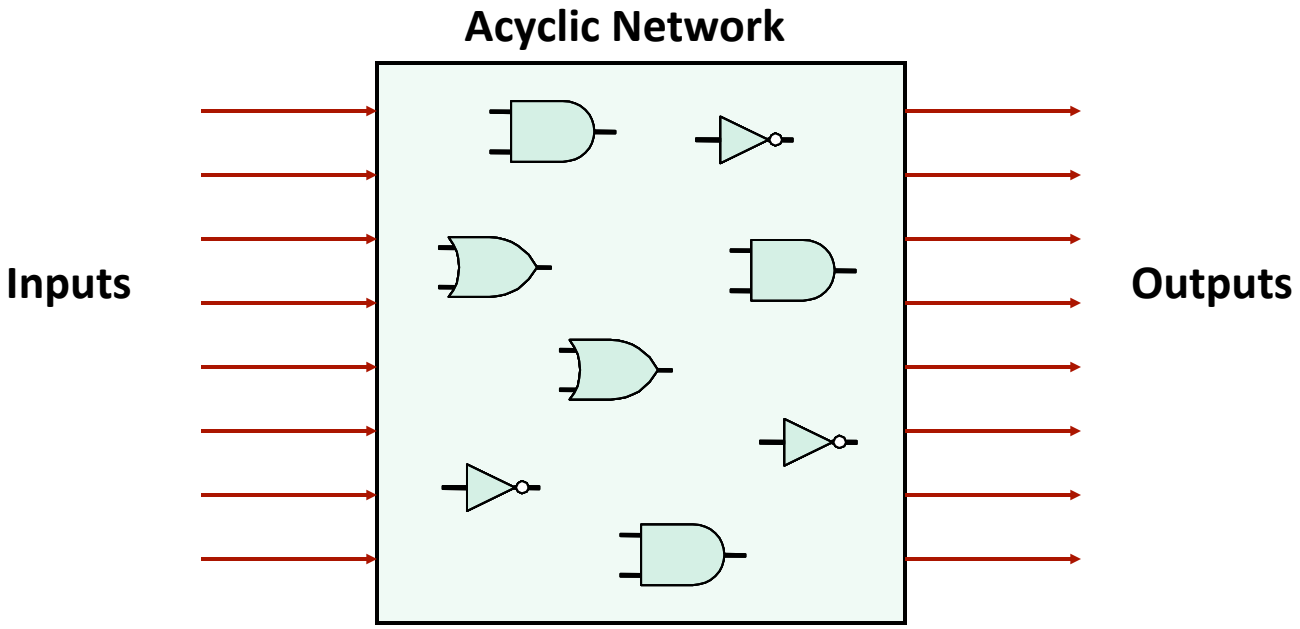
Computing with Logic Gates



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

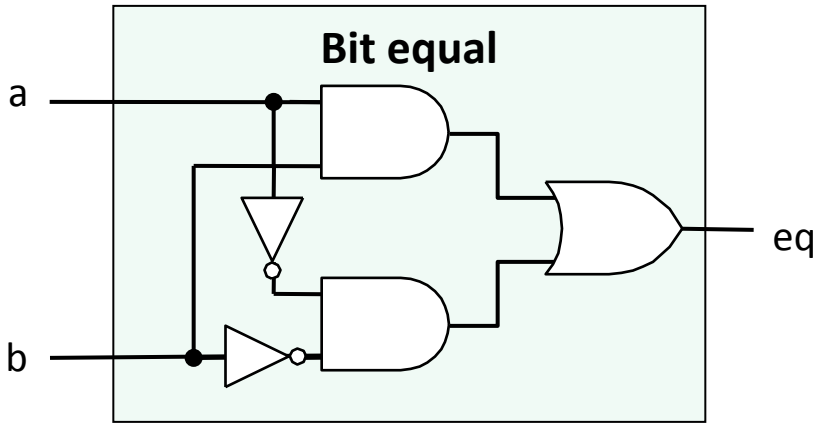


Computation: Combinational Circuits



- **Acyclic network of logic gates**
  - Continuously responds to changes on primary inputs
  - Outputs become (after some delay) Boolean functions of inputs

Computation: Bit Equality

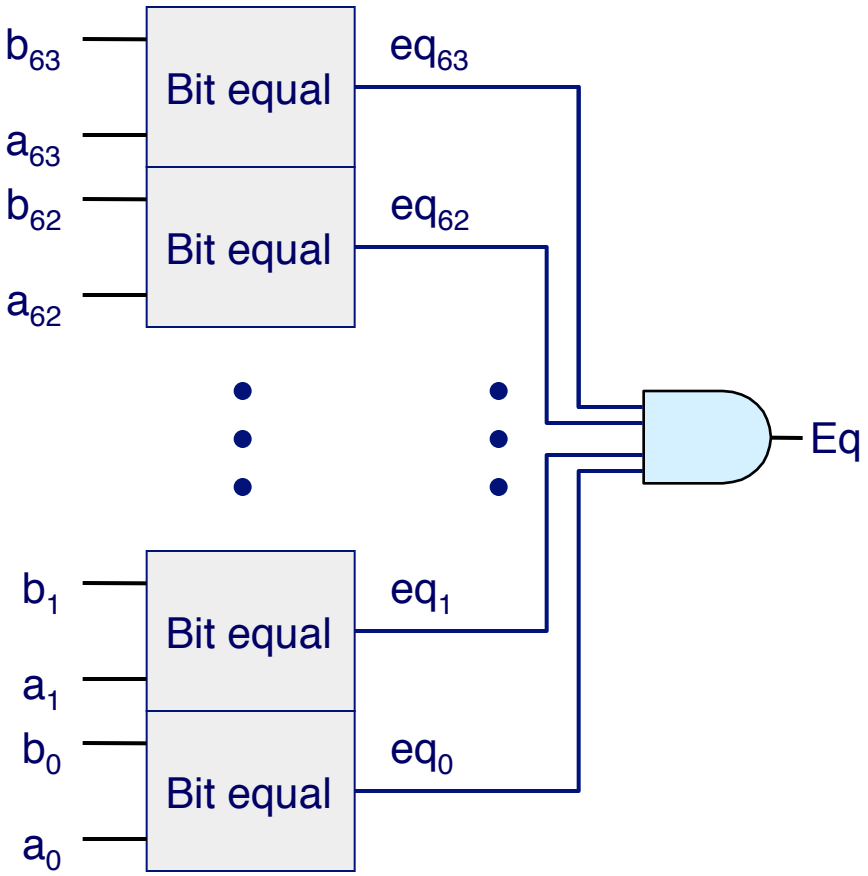


C Expression

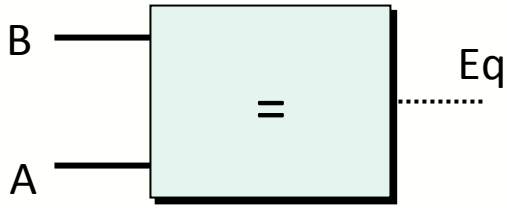
```
eq = (a&&b)||(!a&&!b)
```

- Generate 1 if a and b are equal

Computation: Word Equality



Word-Level Representation

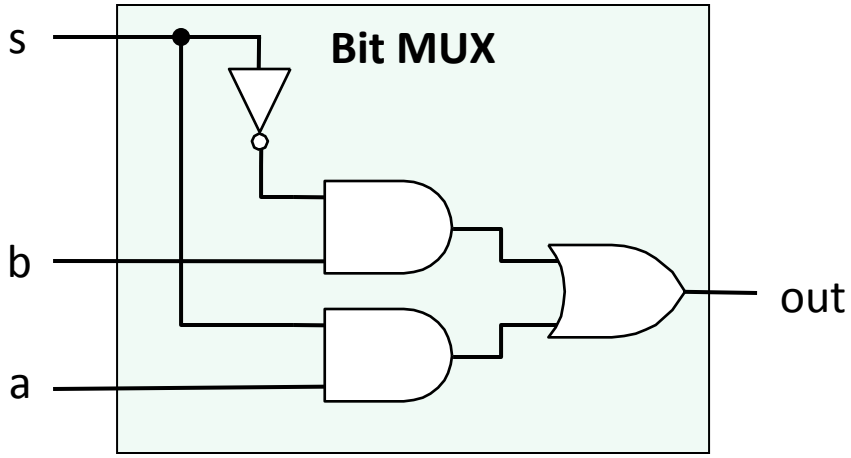


C Representation

```
Eq = (A == B)
```

- **64-bit word size**
- **C representation**
  - Equality operation
  - Generates Boolean value

Computation: Bit-Level Multiplexor

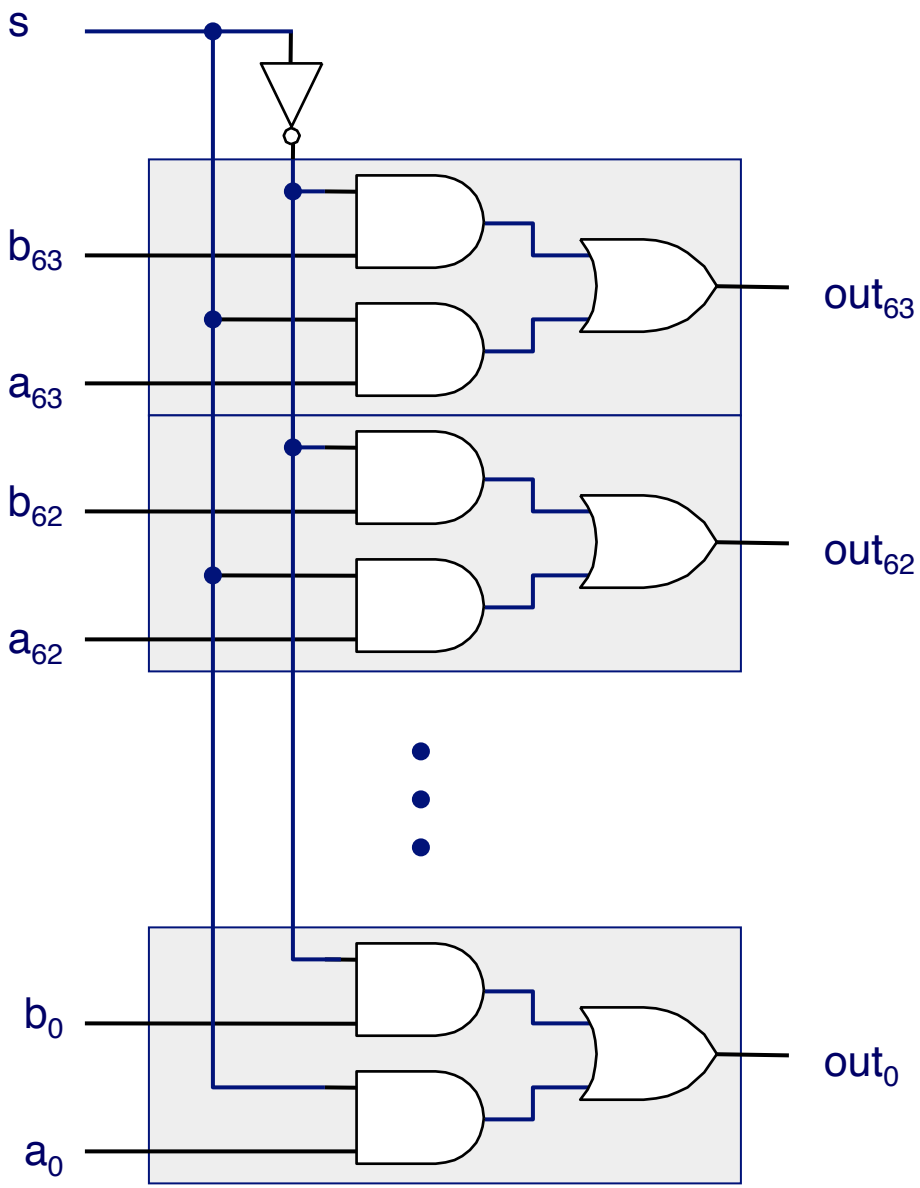


C Expression

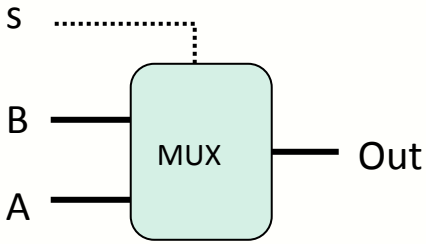
```
out = (s&&a)||(!s&&b)
```

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

Computation: Word Multiplexor



Word-Level Representation

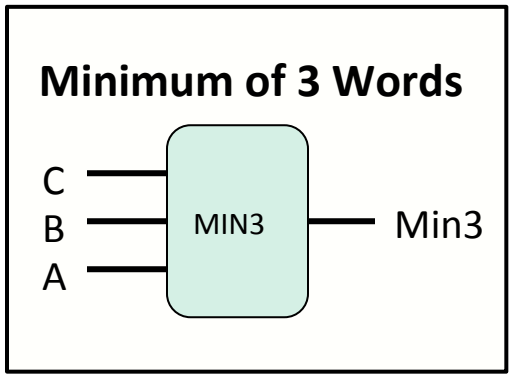


C Representation

```
Out = (s==1) ?
  A : B;
```

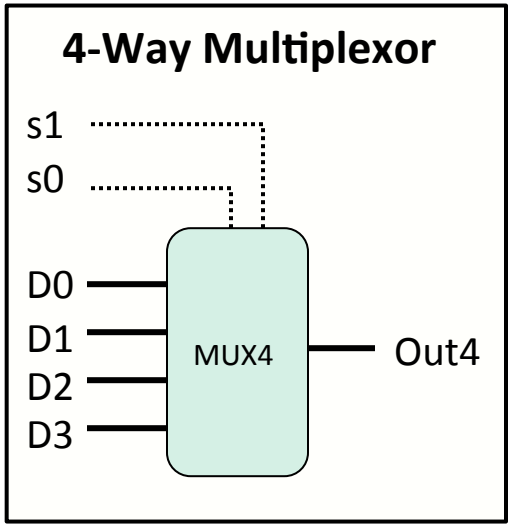
- **Select input word A or B depending on control signal s**

Computation: Word-Level Examples




```
(int) Min3 =
 (A < B && A < C) ? A :
 ( (B < A && B < C) ?
    B : C
 );
```

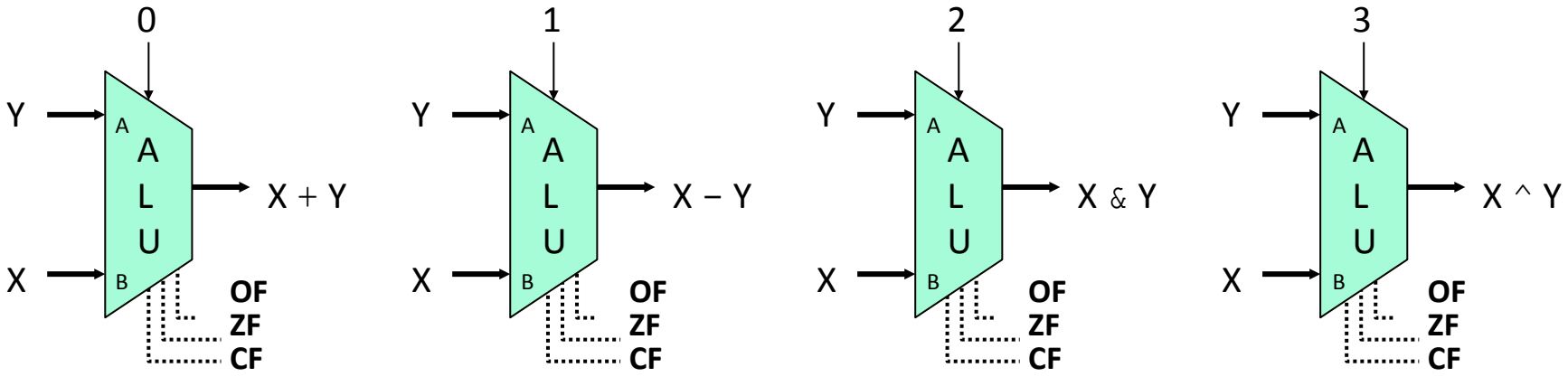
- Find minimum of three input words




```
(int) Out4 =
  (!s1&&!s0) ? D0 :
  ( (!s1) ? D1 :
    ( (!s0) ?
      D2 : D3
    )
  );
```

- Select one of 4 inputs based on two control bits

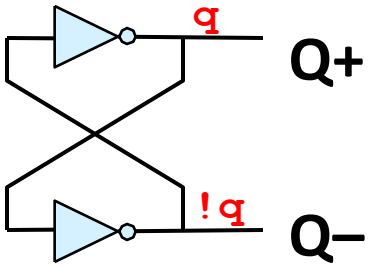
Computation: Arithmetic Logic Unit



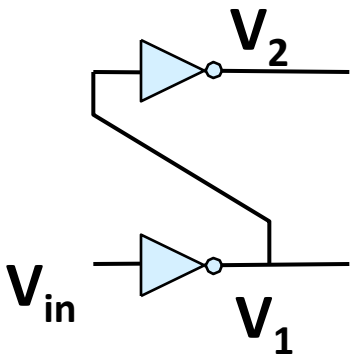
- Combinational logic
  - Continuously responding to inputs
- Control signal selects function computed
  - Corresponding to 4 arithmetic/logical operations
- Also computes values for condition codes

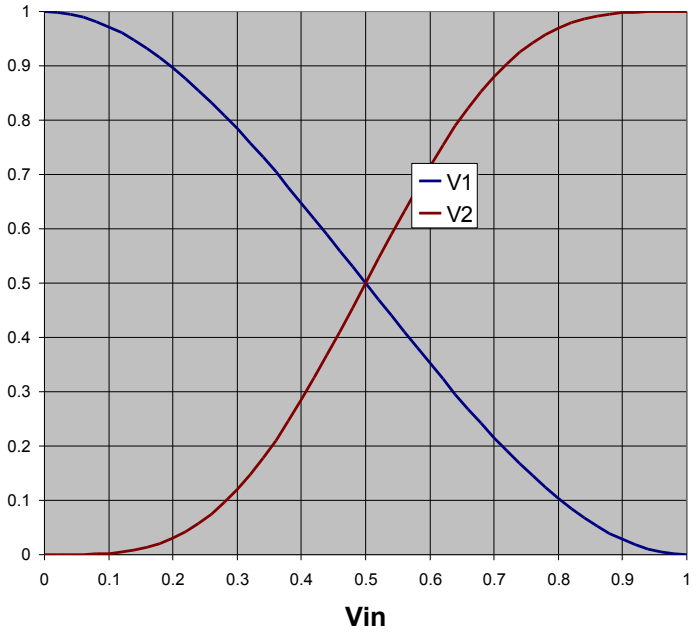
Storage: Storing 1 Bit

Bistable Element



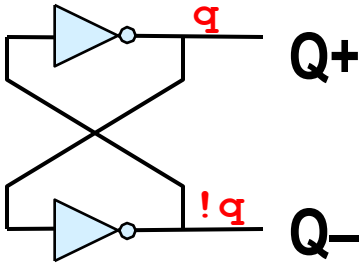
q = 0 or 1



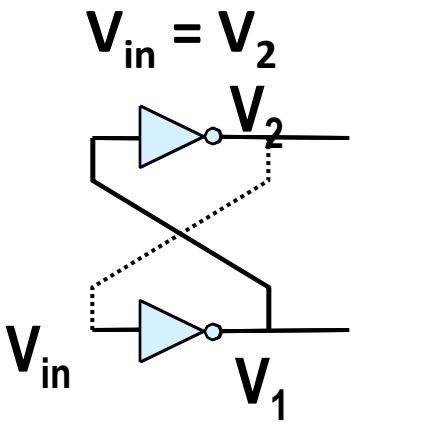


Storage: Storing 1 Bit (cont.)

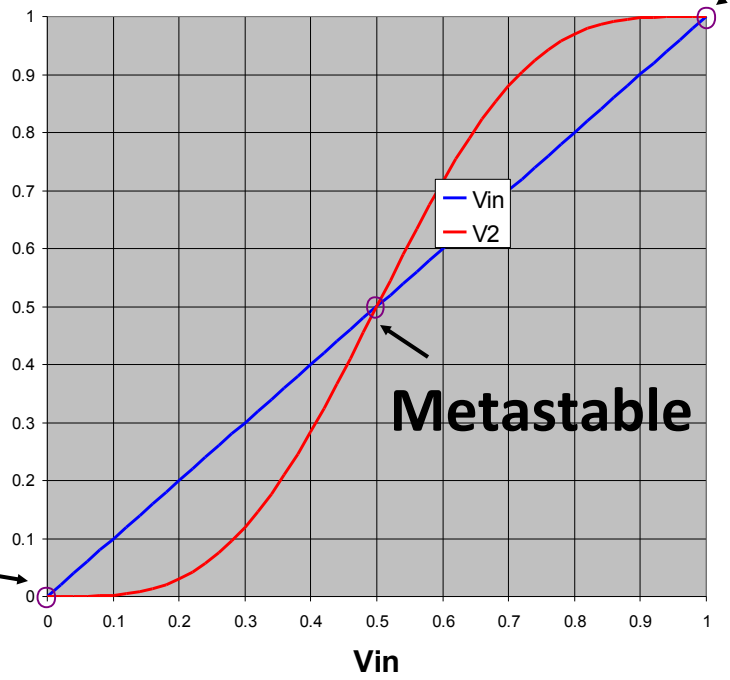
Bistable Element



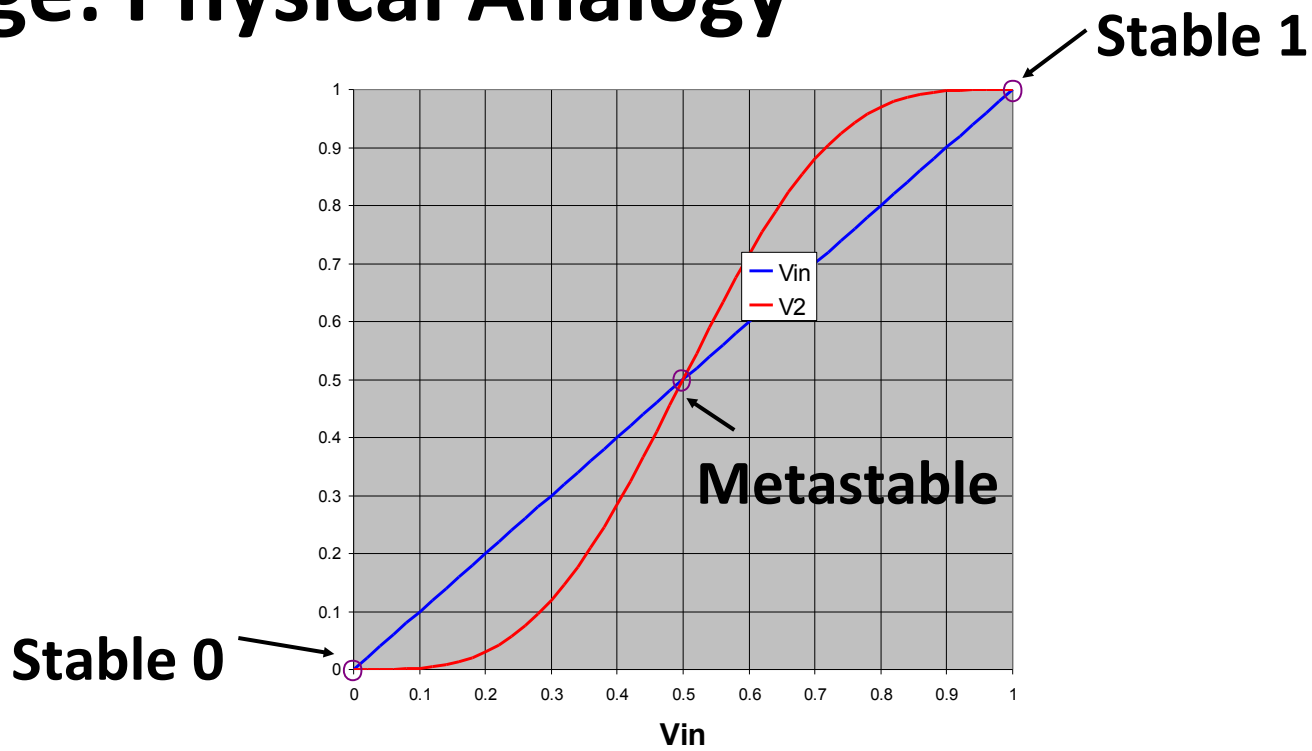
q = 0 or 1

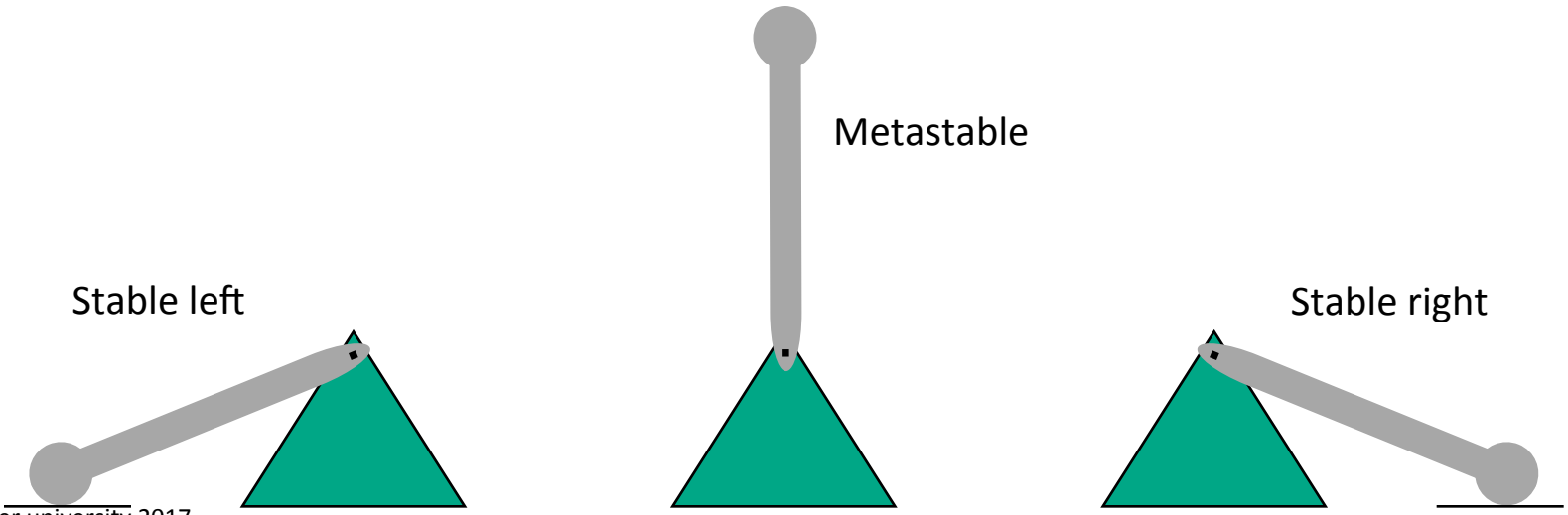


Stable 0

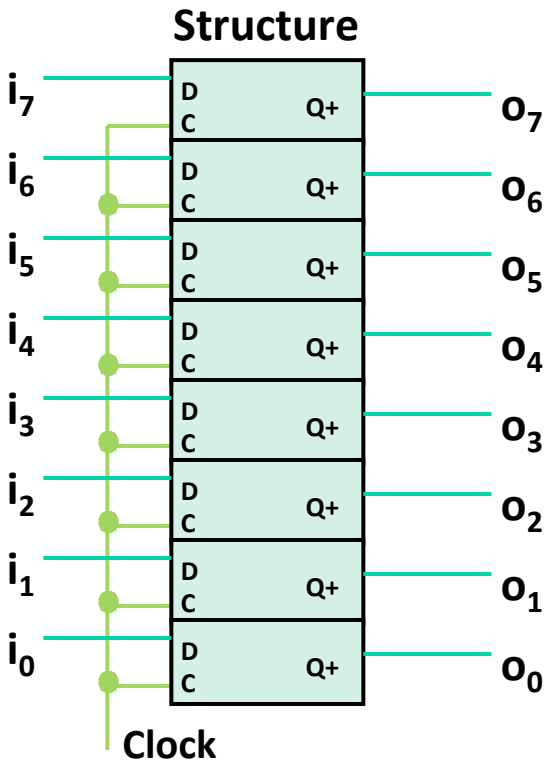


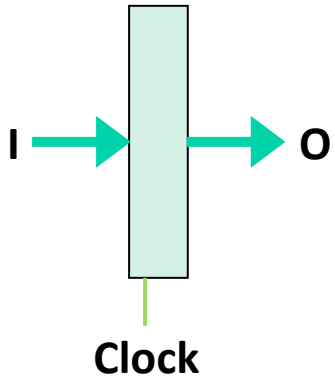
Storage: Physical Analogy





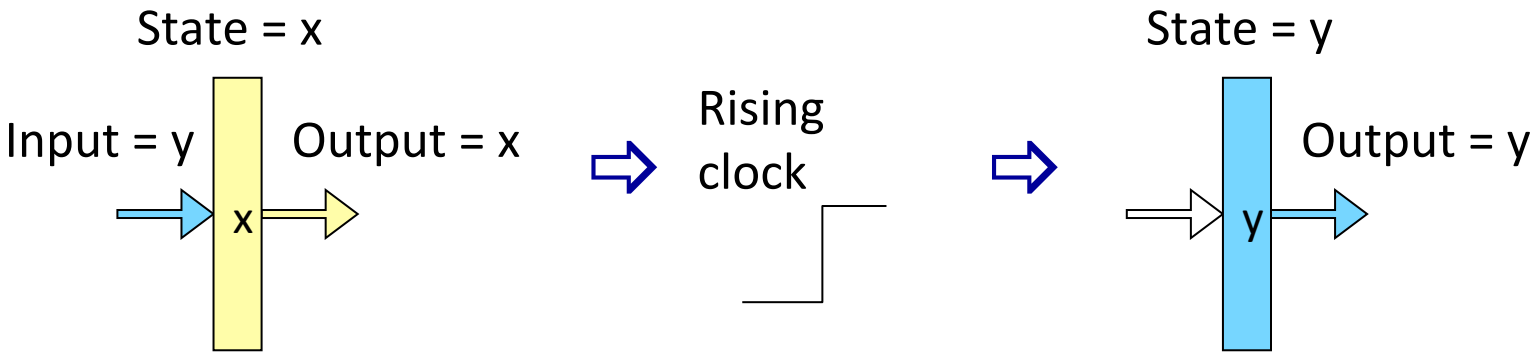
Storage: Sequential Circuit - Registers





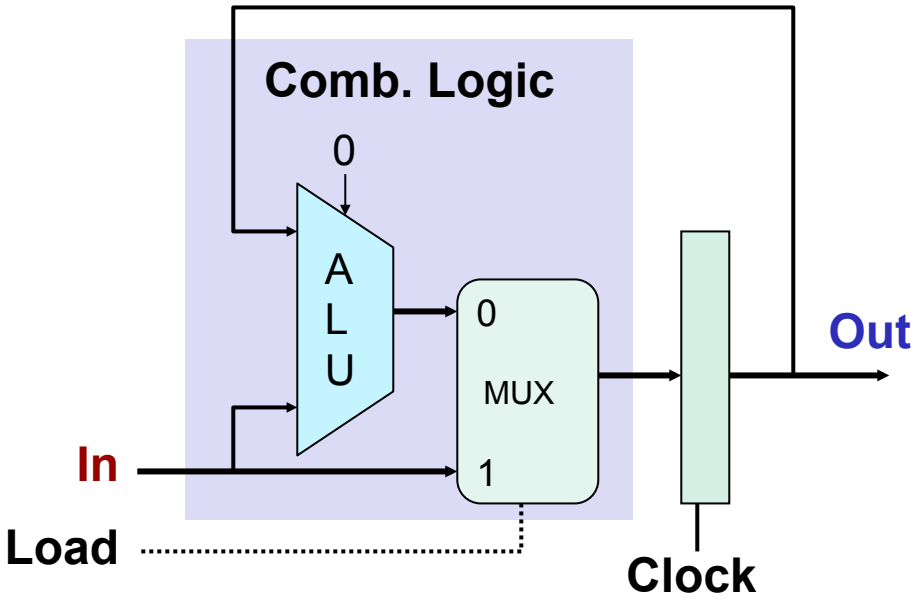
- Stores word of data
  - Different from *program registers* seen in assembly code
- Collection of edge-triggered flip-flops
- Loads input on rising edge of clock

Storage: Register Operation

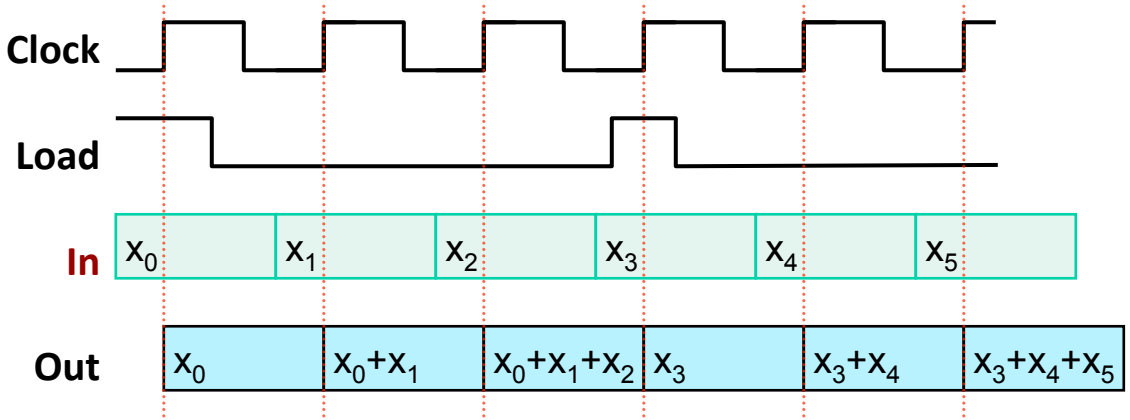


- Stores data bits
- For most of time acts as barrier between input and output
- As clock rises, loads input

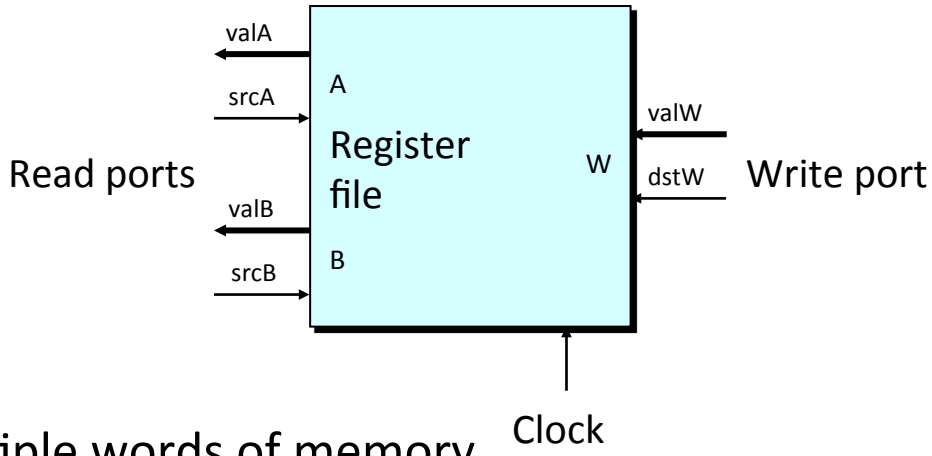
Storage+Computation: State Machine Example



- Accumulator circuit
- Load or accumulate on each cycle

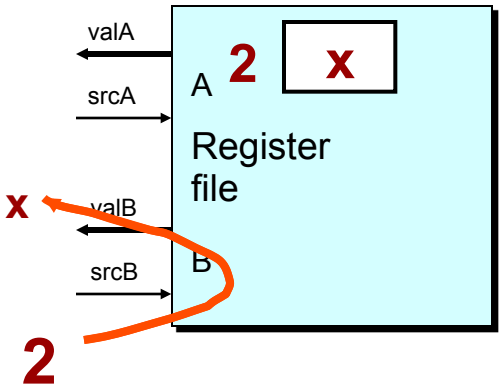


Storage: Register File

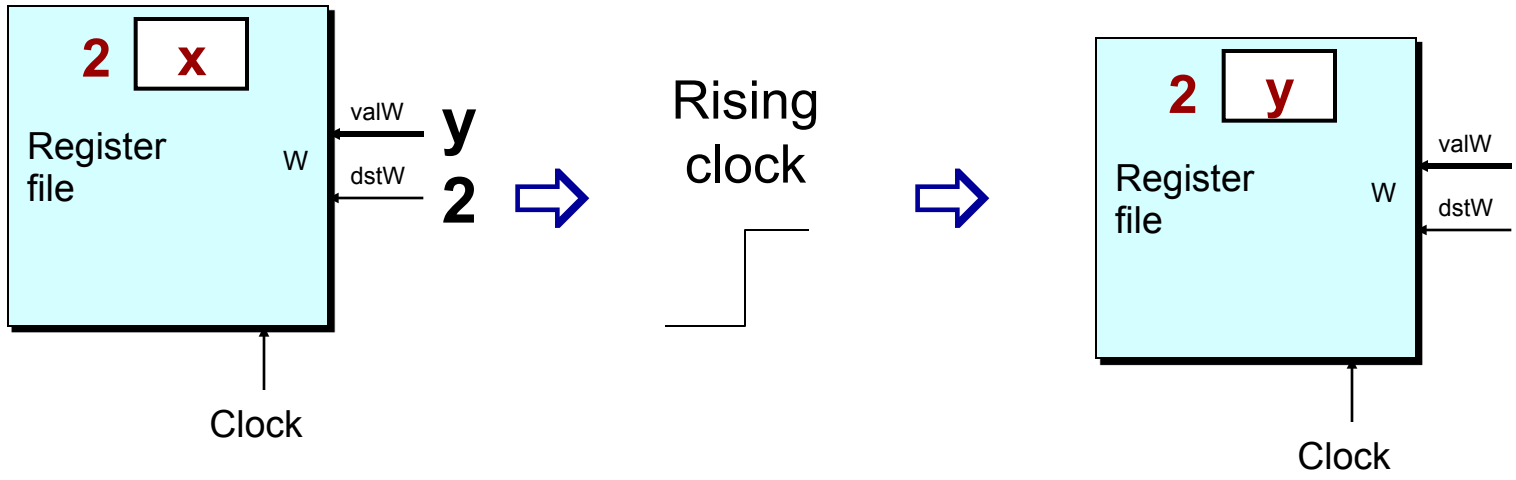


- Stores multiple words of memory
  - Address input specifies which word to read or write
- Register file
  - Holds values of program registers
  - `%t0`, `%t1`, etc.
  - Register identifier serves as address
    - Register 0 is hardwired to zero in MIPS ISA
- **Multiple Ports**
  - Can read and/or write multiple words in one cycle
    - Each has separate address and data input/output

Storage: 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



Summary

- **Computation**
  - Performed by combinational logic
  - Computes Boolean functions
  - Continuously reacts to input changes
- **Storage**
  - Registers
    - Hold single words
    - Loaded as clock rises
  - Register file (random-access memories)
    - Hold multiple words
    - Possible multiple read or write ports
    - Read word when address input changes
    - Write word as clock rises

Extra Slides

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