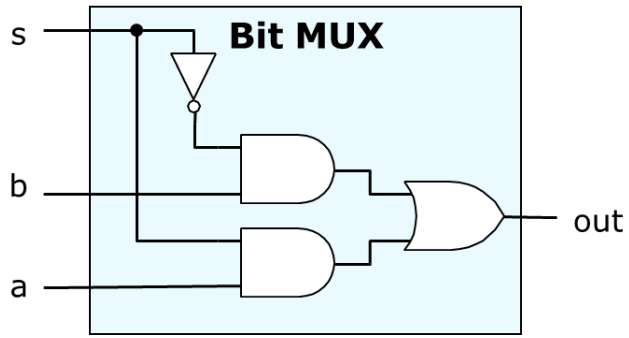
Processor Architecture

Logic Design



HCL Expression

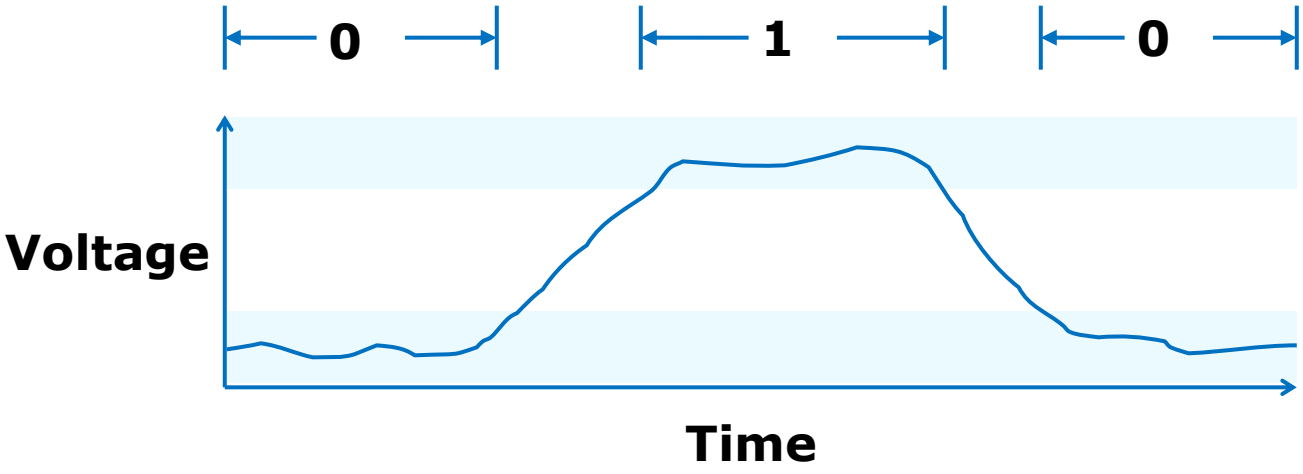
```
bool out = (s&&a)||(!s&&b)
```

Overview of Logic Design

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

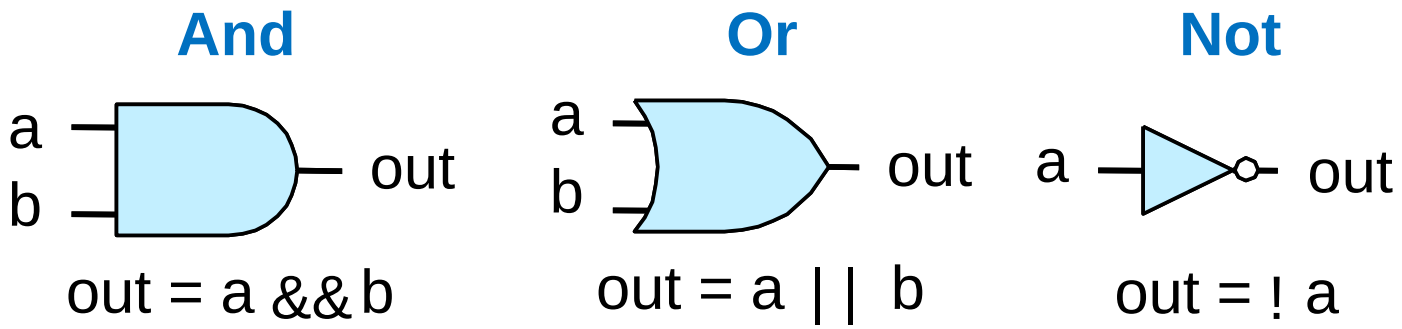
- Bits are Our Friends
  - Everything expressed in terms of values 0 and 1
  - Computation
    - Compute Boolean functions
  - Storage
    - Store bits of information
  - Communication
    - Low or high voltage on wire

Digital Signals

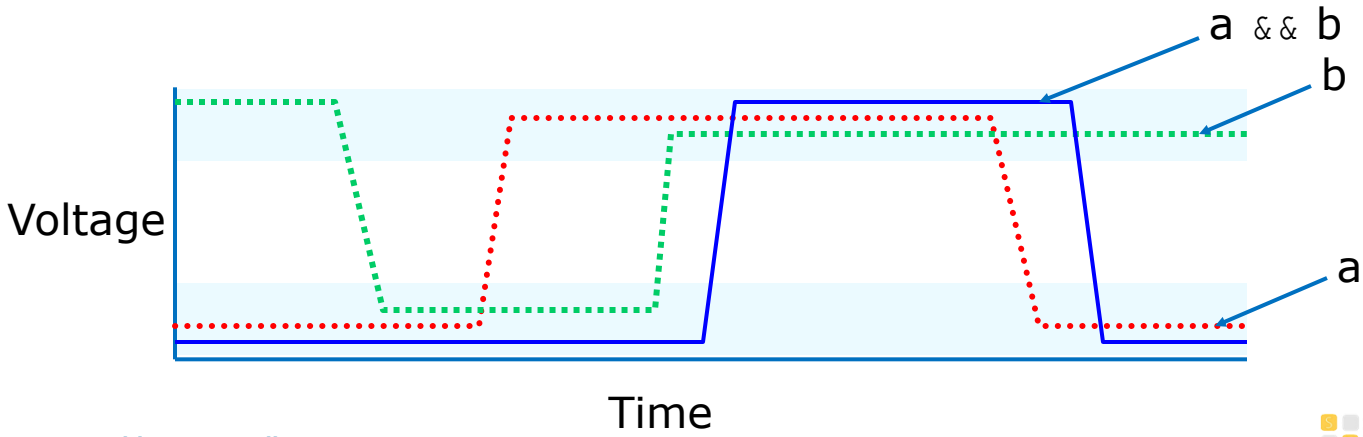


- Use voltage thresholds to extract discrete values from continuous signal
- Simplest version: 1-bit signal
  - Either high range (1) or low range (0)
  - With guard range between them
- Not strongly affected by noise or low quality circuit elements
  - Can make circuits simple, small, and fast

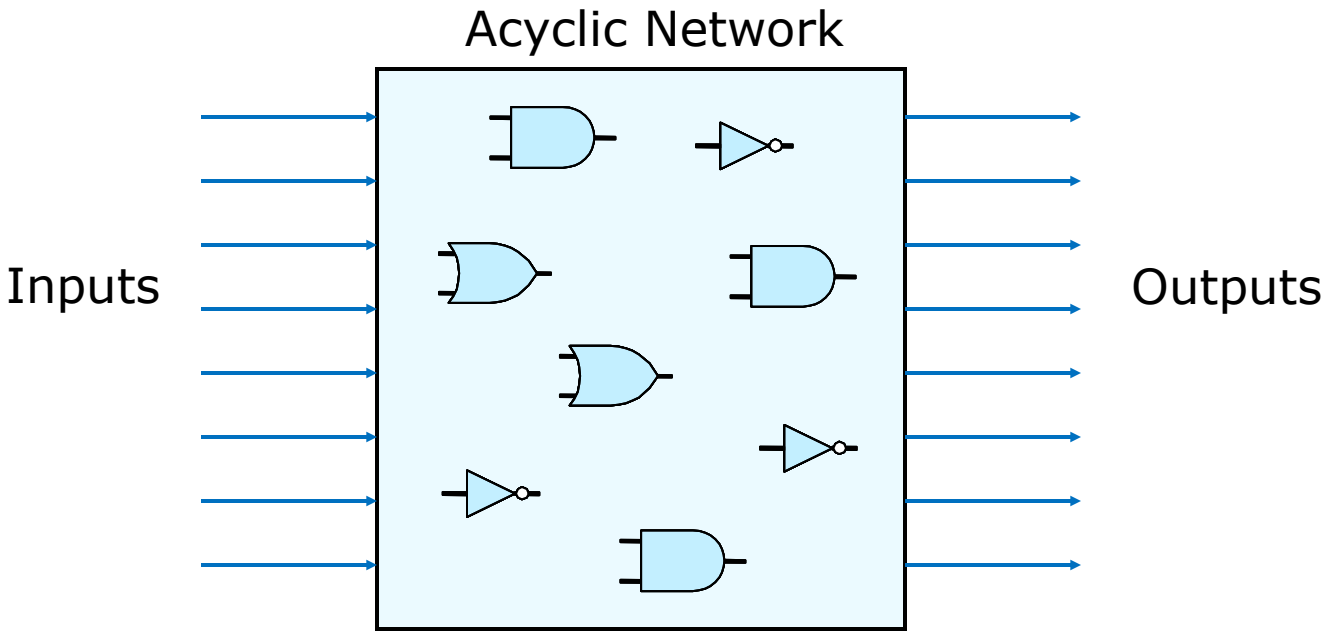
Computing with Logic Gates



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

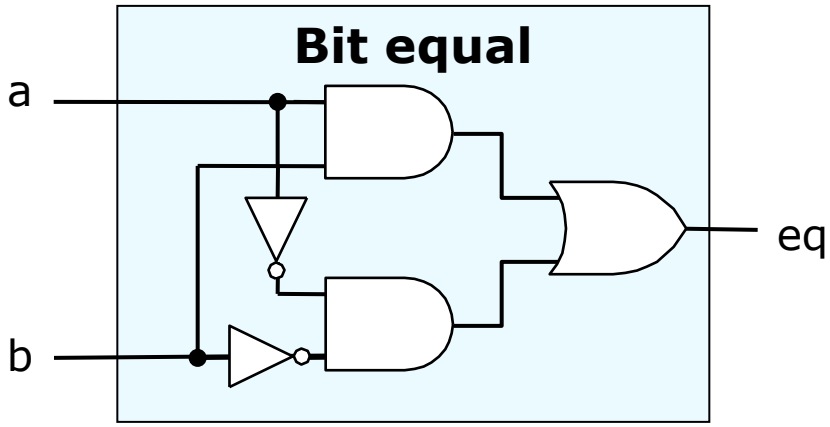


Combinational Circuits



- Acyclic Network of Logic Gates
  - Continuously responds to changes on inputs
  - Outputs become (after some delay) Boolean functions of inputs

Bit Equality



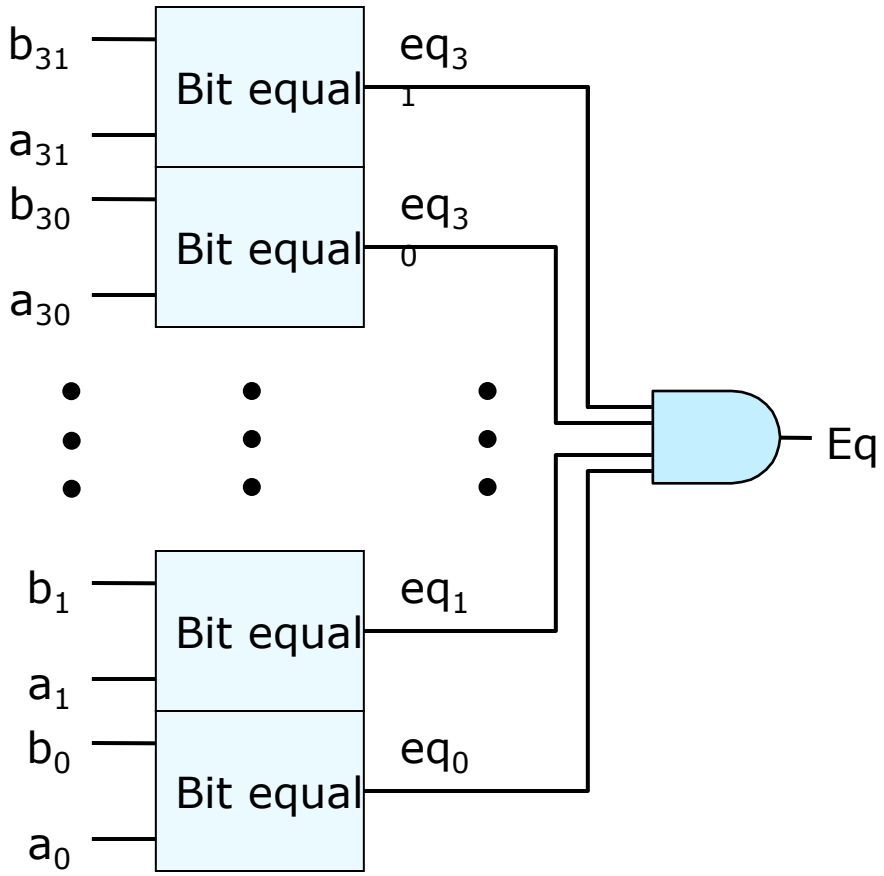
HCL Expression

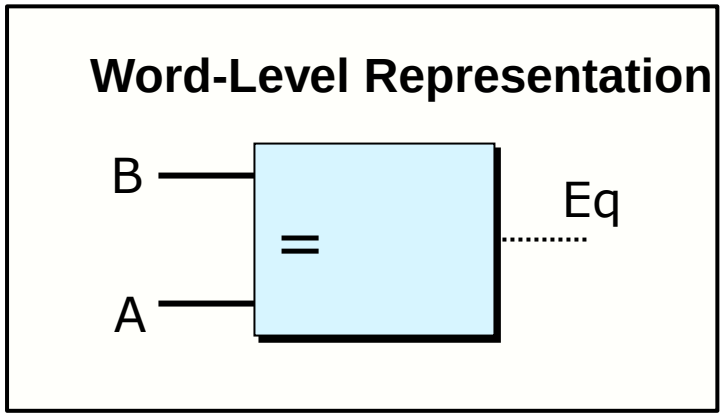
```
bool eq = (a&&b)||(!a&&!b)
```

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



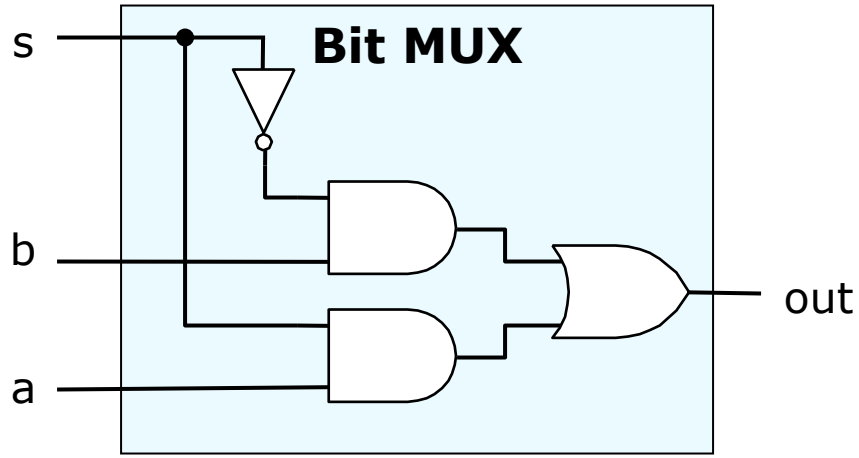


HCL Representation

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

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

Bit-Level Multiplexor

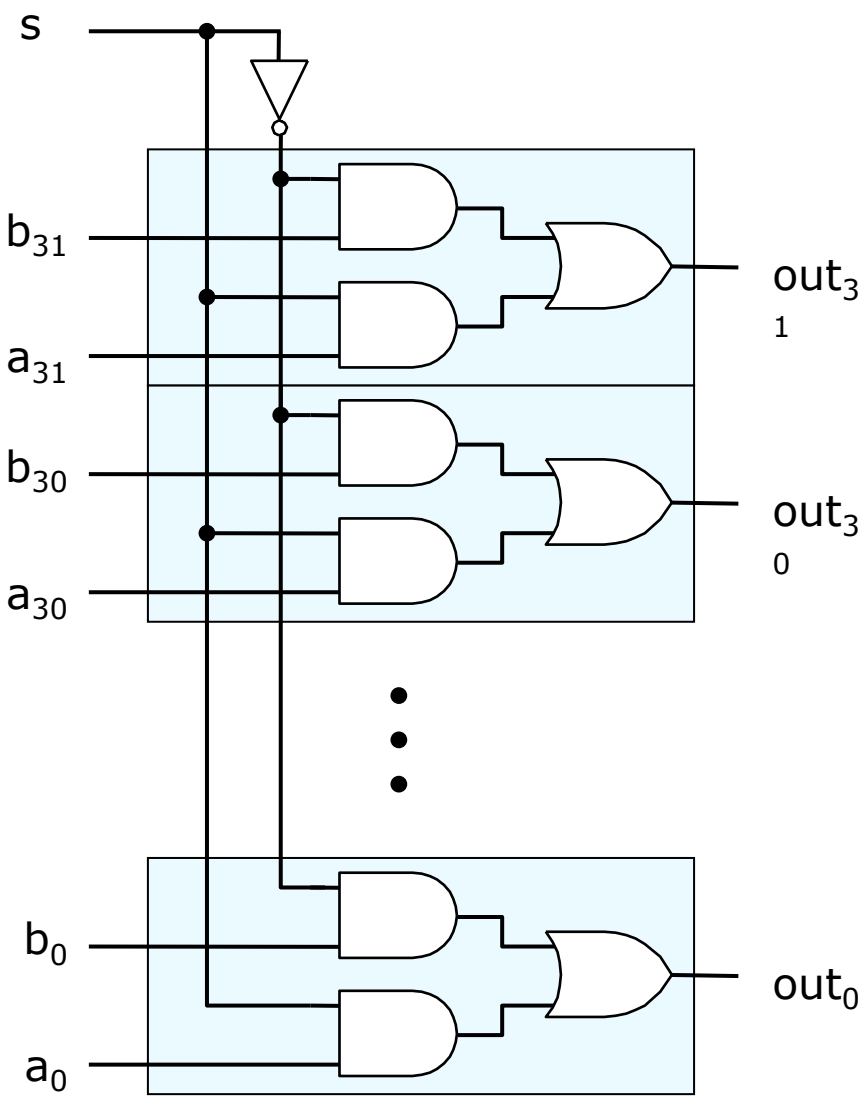


HCL Expression

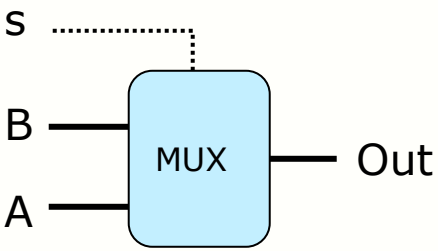
```
bool out = (s&&a)||(!s&&b)
```

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

Word Multiplexor



Word-Level Representation

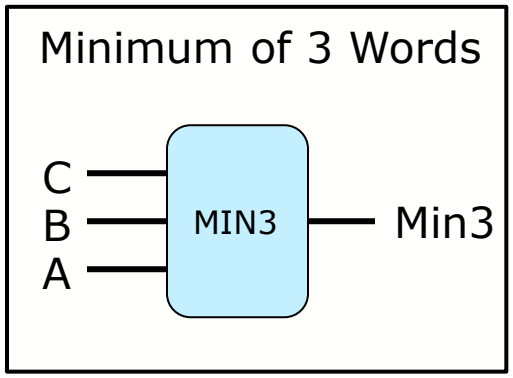


HCL Representation

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

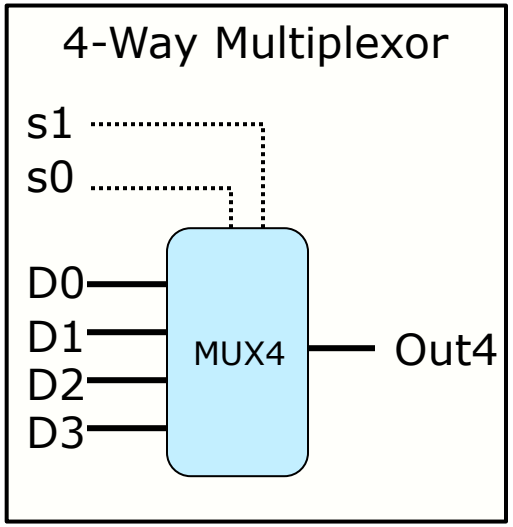
- Select input word A or B depending on control signal s
- HCL representation
  - Case expression
  - Series of test : value pairs
  - Output value for first successful test

HCL Word-Level Examples




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

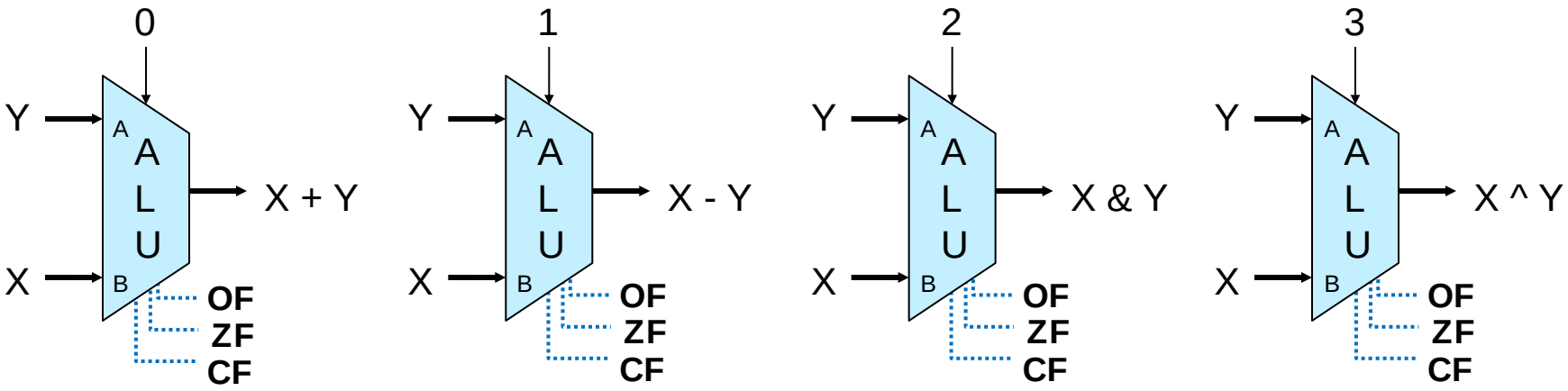
- Find minimum of three input words
- HCL case expression
- Final case guarantees match




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

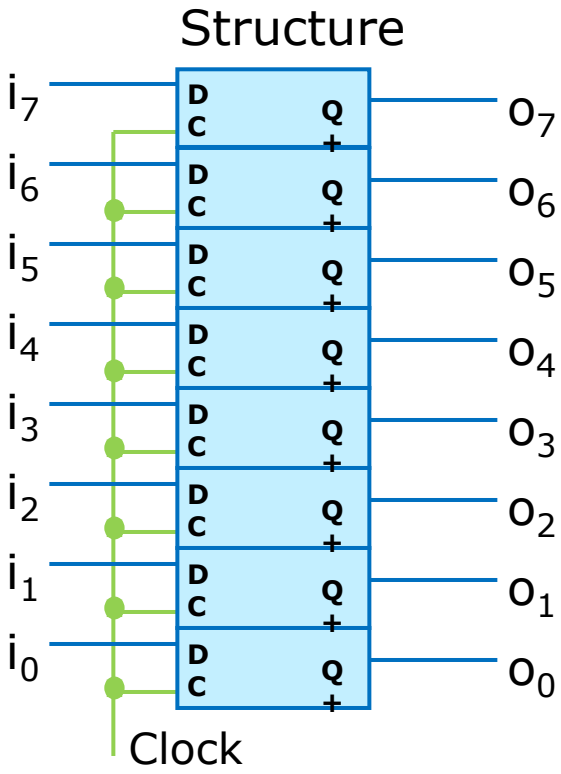
- Select one of 4 inputs based on two control bits
- HCL case expression
- Simplify tests by assuming sequential matching

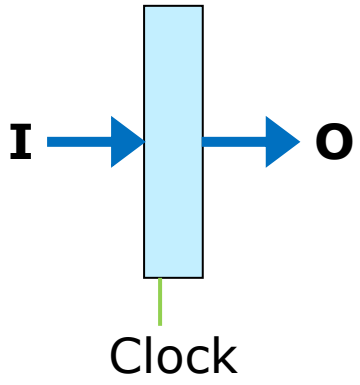
Arithmetic Logic Unit



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

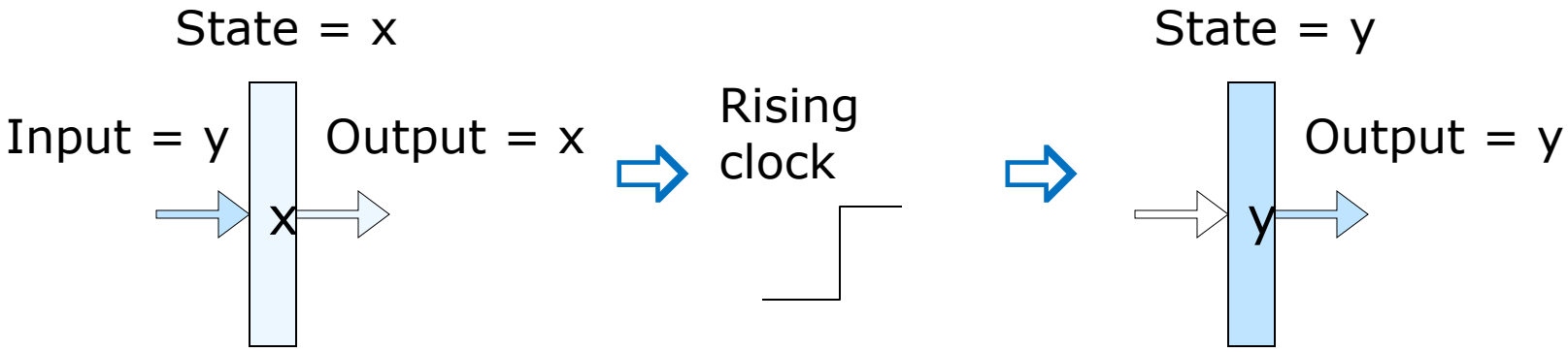
Sequential Circuit: Registers





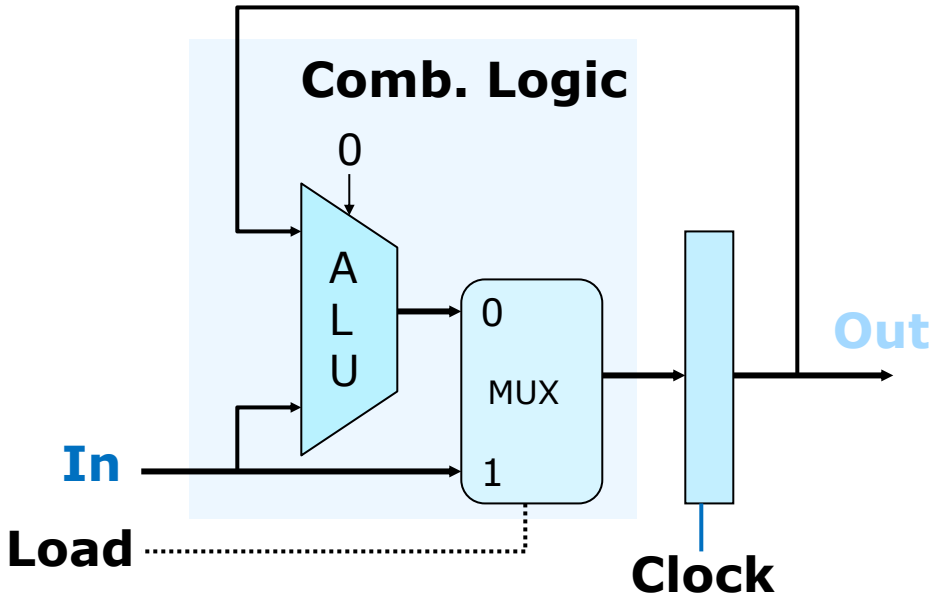
- Stores word of data
  - Different from *program registers* seen in assembly code
- Collection of edge-triggered latches
- Loads input on rising edge of clock

Register Operation

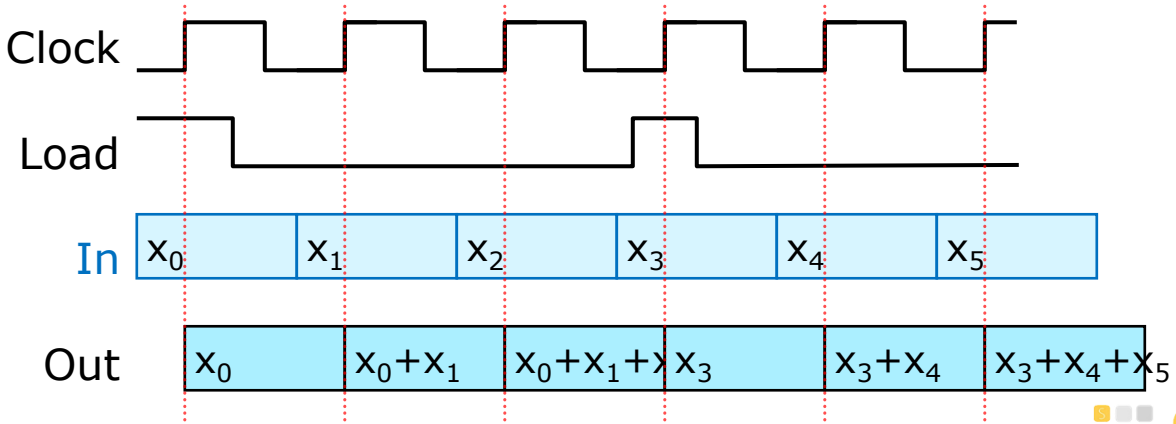


- Stores data bits
- For most of time acts as barrier between input and output
- As clock rises, loads input

State Machine Example

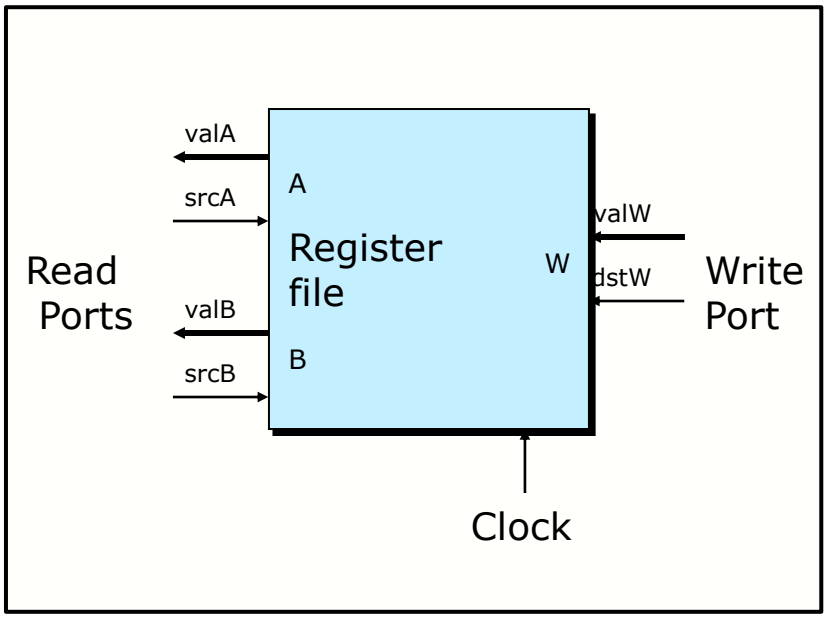


- Accumulator circuit
- Load or accumulate on each cycle

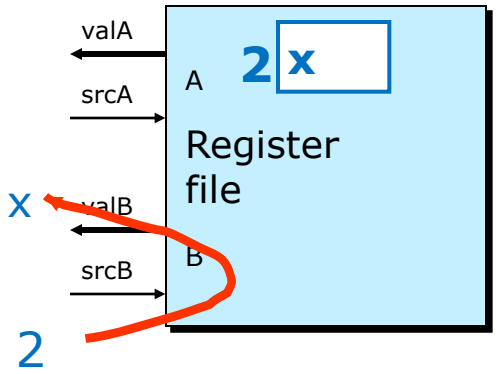


Random-Access Memory

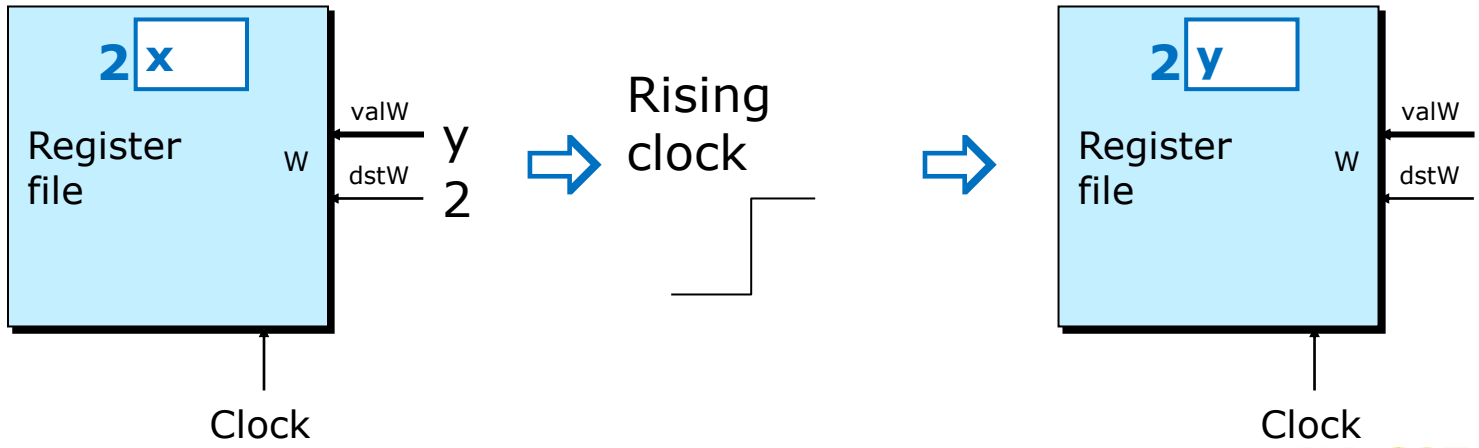
- Stores multiple words of memory
  - Address input specifies which word to read or write
- Register file
  - Holds values of program registers
  - `%eax`, `%esp`, etc.
  - Register identifier serves as address
    - ID 15 (0xF) implies no read or write performed
- Multiple Ports
  - Can read and/or 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, 32-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

- Combinational circuit: Computation
  - Performed by combinational logic
  - Computes Boolean functions
  - Continuously reacts to input changes

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