Computer Systems Architecture

Fundamentals Of Digital Logic

Our Goal

- Understand
  - Fundamentals and basics
  - Concepts
  - How computers work at the lowest level
- Avoid whenever possible
- Complexity
- Implementation details
- Engineering design rules

Electrical Terminology

- Voltage
  - Quantifiable property of electricity
  - Measure of potential force
  - Unit of measure: *volt*
- Current
- Quantifiable property of electricity
- Measure of electron flow along a path
- Unit of measure: *ampere (amp)*

Analog For Electricity

- Voltage is analogous to water pressure
- Current is analogous to flow of water
- Can have
  - High pressure with little flow
  - Large flow with little pressure

Voltage

- Device used to measure called voltmeter
- Can only be measured as difference between two points
- To measure voltage
  - Assume one point represents zero volts (known as *ground*)
  - Express voltage of second point wrt ground

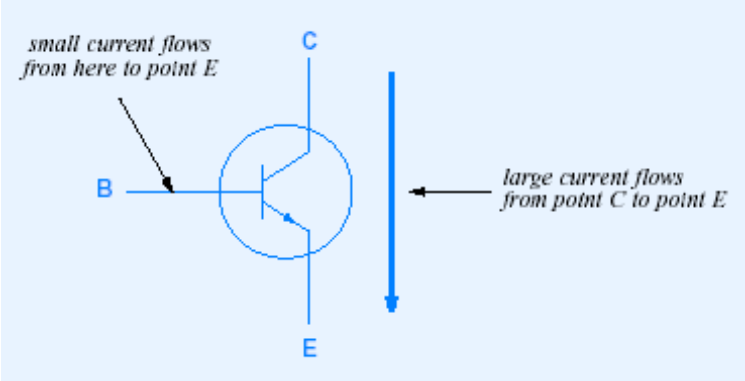
In Practice

- Typical digital circuit operates on five volts
- Two wires connect each chip to power supply
  - Ground (zero volts)
  - Power (five volts)
- Digital logic diagrams do not usually show power and ground connections

Transistor

- Basic building block of digital circuits
- Operates on electrical current
- Acts like a miniature switch — small input current controls flow of large current
- Three external connections
  - Emitter
  - Base (control)
  - Collector
- Current between base and emitter controls current between collector and emitter

Illustration Of A Transistor



Boolean Logic

- Mathematical basis for digital circuits
- Three basic functions: and, or, and not

A	B	A and B
0	0	0
0	1	0
1	0	0
1	1	1

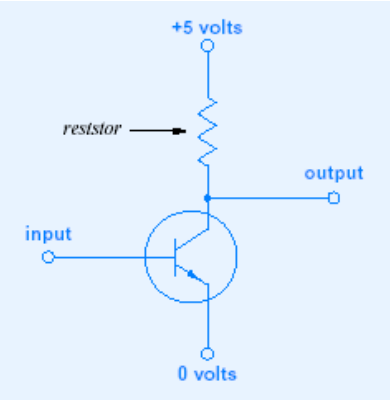
A	B	A or B
0	0	0
0	1	1
1	0	1
1	1	1

A	not A
0	1
1	0

Digital Logic

- Can implement Boolean functions with transistors
- Five volts represents Boolean 1
- Zero volts represents Boolean 0

Transistor Implementing Boolean Not



- When input is zero volts, output is five volts
- When input is five volts, output is zero volts

Logic Gate

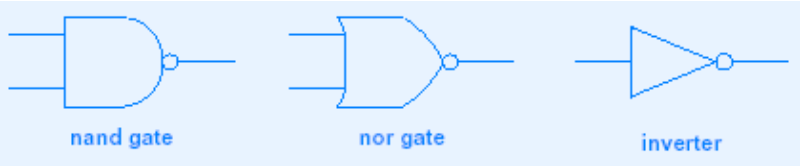
- Hardware component
- Consists of integrated circuit
- Implements an individual Boolean function
- To reduce complexity, provide inverse of Boolean functions
- Nand gate implements not and
- Nor gate implements not or
- Inverter implements not

Truth Tables For Nand and Nor Gates

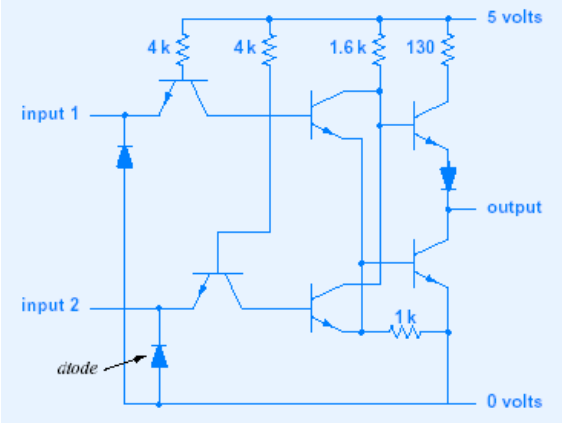
A	B	A nand B
0	0	1
0	1	1
1	0	1
1	1	0

A	B	A nor B
0	0	1
0	1	0
1	0	0
1	1	0

Symbols Used In Schematic Diagrams



Example Of Internal Gate Structure (Nor Gate)



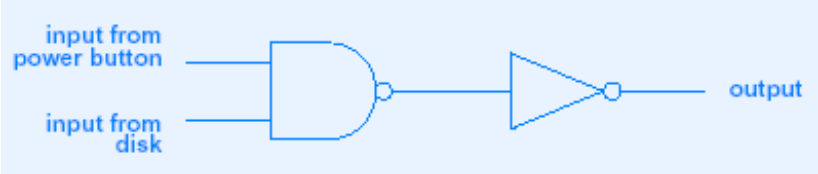
Solid dot indicates electrical connection

Technology For Logic gates

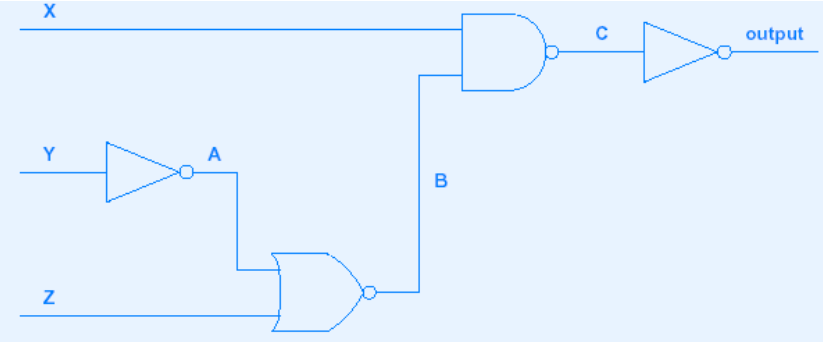
- Most popular technology known as Transistor-Transistor Logic (TTL)
- Allows direct interconnection (a wire can connect output from one gate to input of another)
- Single output can connect to multiple inputs
  - Called fanout
  - Limited to a small number

Example Interconnection Of TTL Gates

- Two logic gates needed to form logical and
  - Output from nand gate connected to input of inverter

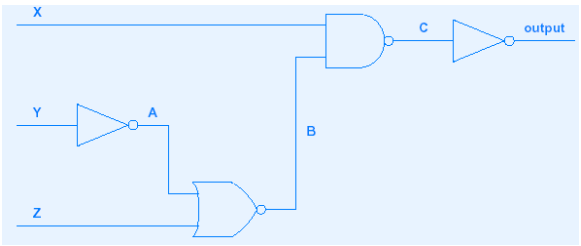


Consider The Following Circuit



- What does the circuit implement?

Describing a circuit with Boolean algebra



- Value at point *A* is *not Y*
- Value at *B* is: *Z nor (not Y)*
- Output is: *X and (Z nor (not Y))*
- Alternatively, Output is: *X and not (Z or (not Y))*

Describing A Circuit With A Truth Table

X	Y	Z	A	B	C	output
0	0	0	1	0	1	0
0	0	1	1	0	1	0
0	1	0	0	1	1	0
0	1	1	0	0	1	0
1	0	0	1	0	1	0
1	0	1	1	0	1	0
1	1	0	0	1	0	1
1	1	1	0	0	1	0

- Table lists all possible inputs and output for each
- Can also state values for intermediate points

Avoiding Nand / Nor Operations

- Circuits use nand and nor gates
- Sometimes easier for humans to use *and* and *or* operations
- Example circuit or truth table output can be described by Boolean expression:

X and Y and (not Z))

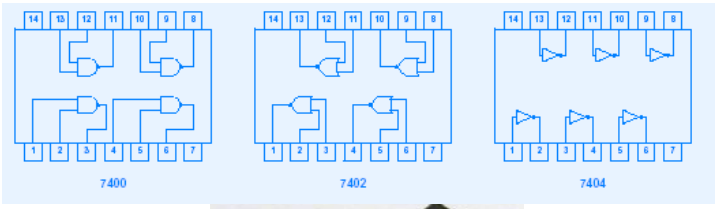
In Practice

- Only a few connections needed per gate
- Chip has many pins for external connections
- Result: can package multiple gates placed on each chip

Example Of Logic Gates

- 7400 family of chips
- Package is about one-half inch long
- Implement TTL logic
- Powered by five volts
- Contain multiple gates per chip

Examples Of Gates On 7400-Series Chips



Pins 7 and 14 connect to ground and power

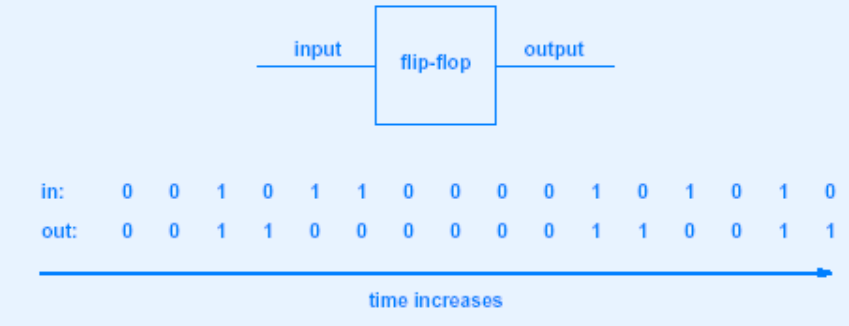
Circuits That Maintain State

- More sophisticated than *combinatorial circuits*
- Output depends on history of previous input as well as values on input lines

Example Of Circuit That Maintains State

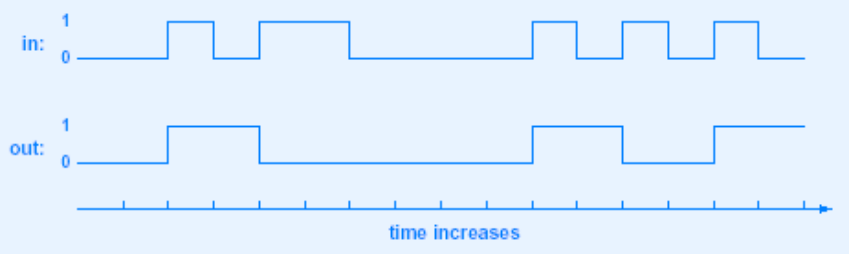
- Basic *flip-flop*
- Analogous to push-button power switch
- Each new 1 received as input causes output to reverse
  - First input pulse to causes flip-flop to turn on
  - Second pulse causes flip-flop to turn off

Output of a Flip-Flop



- Note: output only changes when input makes a transition from zero to one

Flip-Flop Action Plotted As Transition Diagram

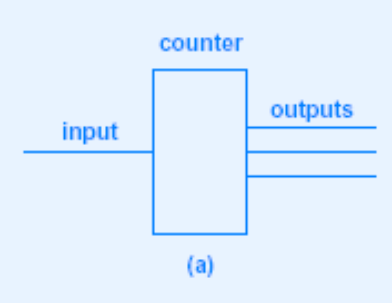


- Output changes on *leading edge* of input
- Also called *rising edge*

Binary Counter

- Counts input pulses
- Output is binary value
- Includes reset line to start count at zero
- Example: 4-bit counter available as single integrated circuit

Illustration Of Counter



input	outputs	decimal
0	0 0 0	0
0	0 0 0	0
1	0 0 1	1
0	0 0 1	1
1	0 1 0	2
1	0 1 0	2
0	0 1 0	2
1	0 1 1	3
0	0 1 1	3
1	1 0 0	4
0	1 0 0	4
1	1 0 1	5
	⋮	

time increases

(b)

- Counts

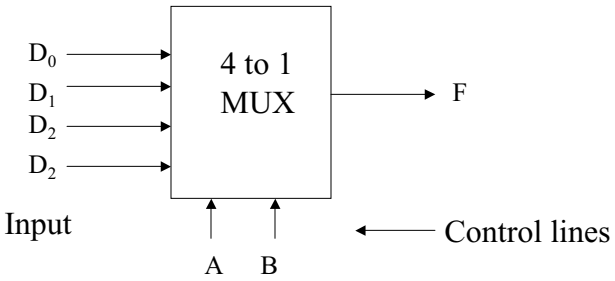
Clock

- Electronic circuit that pulses regularly
- Measured in cycles per second (Hz)
- Digital output of clock is sequence of 0 1 0 1 ...
- Permits active circuits

Multiplexers

Multiplexers: -

- Connects multiple inputs to a single output
- At any one time, one of the inputs is selected to be passed to the output



Multiplexers

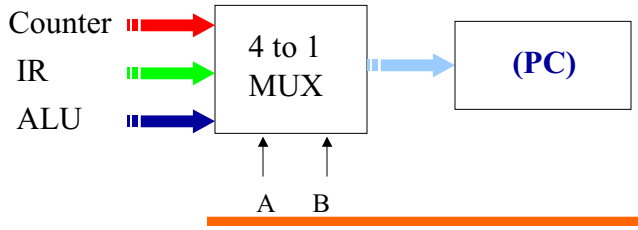
Multiplexers: - Truth Table and Implementation

Multiplexers

Multiplexers: - Applications (will reappear later on in the course)

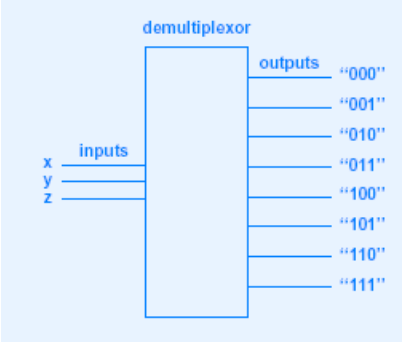
J Control signal and data routing

J e.g. loading Program Counter (PC)



Demultiplexor

- Takes binary value as input
- Uses input to select one output



Decoder

Decoders: - takes n inputs, and select exactly one of the 2^n outputs

Example: 3 - 8 decoder

Address Decoder

Decoders: - Address Decoder (will be revisited)

Adder

Adders: - an essential part of the CPU

J Half Adder

Truth Table **Circuit**

A	B	Sum	Carry-Out

Adder

Adders: - an essential part of the CPU

J Full Adder

Truth Table

A	B	Carry-In	Sum	Carry-Out

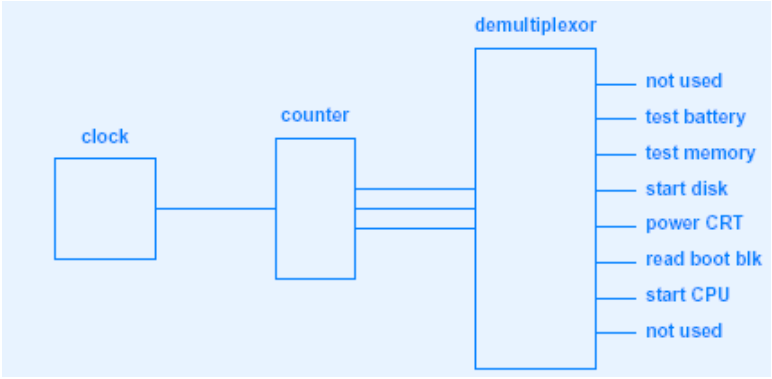
Adder

Adders: - n-bit adder

Example Circuit That Executes A Sequence Of Steps

- Desired sequence
  - – Test the battery
  - – Power on and test the memory
  - – Start the disk spinning
  - – Power up CRT
  - – Read boot sector from disk into memory
  - – Start CPU

Circuit To Execute Sequence

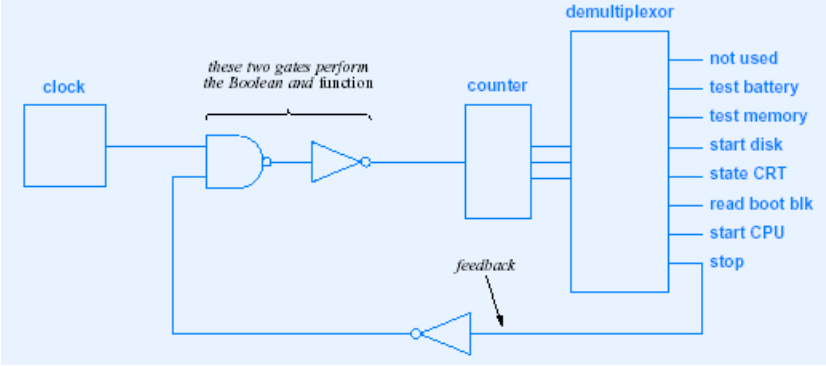


Feedback

- Output of circuit used as an input
- Allows more control
- Example: stop sequence when output *F* becomes active
- Boolean algebra

CLOCK *and* (*not* F)

Illustration Of Feedback For Termination



- Note additional input needed to restart sequence

Practical Engineering Concerns

- Power consumption (wiring must carry sufficient power)
- Heat dissipation (chips must be kept cool)
- Timing (gates take time to settle after input changes)
- Clock synchronization (clock signal must reach all chips simultaneously)

Summary

- Computer systems are constructed of digital logic circuits
- Fundamental building block is *gate*
- Digital circuit can be described by
  - – Boolean algebra (most useful when designing)
  - – Truth table (most useful when debugging)
- Clock allows active circuit to perform sequence of operations
- Feedback allows output to control processing
- Practical engineering concerns include
  - – Power consumption and heat dissipation
  - – Clock skew and synchronization