# Digital Logic Design

4190.201.001

2014 Spring Semester

## 1. Introduction

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## About the lecturer

- Instructor: Professor Naehyuck Chang
  - 30 year hardware design experience
  - ACM SIGDA (Design Automation) Chair
  - IEEE Fellow
  - ACM Distinguished Scientist
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## About the teaching assistants

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## Course information

- Two 75 min classes a week
  - Monday and Wednesday
  - 03:30 PM to 4:45 PM (extended to 5:00 PM)
  - Language: English
- Laboratory class
  - Monday and Wednesday, Tuesday and Thursday (It can be changed)
  - 7:00 PM to 10:00 PM
  - 302-310-2
- No class
  - 3/5, 3/24, 3/26, 4/21, 6/2
  - Can be compensated with 15 minute additional lectures
- Midterm
  - 4/23
- Final
  - 6/3

## What is design?

- **A plan or drawing produced to show the look and function**
  - Given a specification of a problem, come up with a way of solving it choosing appropriately from a collection of available components
  - While meeting some criteria for size, performance, cost, power, beauty, elegance, etc.
- Design a complicated system
  - Divide and conquer
- How to divide a big problem?
  - Functional dividing
  - Spatial dividing
- Other ways toward efficient design
  - Design reuse
  - Design methodology
    - To manage a process effectively and efficiently
- Design tools
  - Formal description and modeling
  - Systematic optimization
  - Mathematics

## Logic design

- Digital circuits
  - Interconnected collections of switches to perform a desired function
- Major resources
  - Switches
  - Interconnects
    - Interconnections are more important in recent designs
- Digital abstraction
  - 0 or 1
  - Noise immunity
  - A group of signals represent analog quantity after quantization
- Choose a right components to solve the problem
  - Constraints: speed, power, area, etc.
- Types of circuits
  - Combinational circuits
  - Sequential circuits
- Logic design is a set of abstractions and methodologies
  - Devise, understand, and manipulate large collections of digital circuits

## Logic design

- What is logic design?
  - Determining the collection of digital logic components to perform a specified control and/or data manipulation and/or communication function and the interconnections between them
  - Which logic components to choose?
    - There are many implementation technologies (e.g., off-the-shelf fixed-function components, programmable devices, transistors on a chip, etc.)
  - The design may need to be optimized and/or transformed to meet design constraints

## Why study logic design?

- Obvious reasons
  - Fundamentals of computer system hardware and software design
  - We live in the Electric Age (neither Stone Age, nor Bio Age)
    - Implementation basis for all modern computing devices (digital semiconductor devices)
  - Theory: target independent
    - Provide a model of how a computer works
  - Practice: target dependent
    - Building large things from small components
- More important reasons
  - The inherent parallelism in hardware is often our first exposure to parallel computation
  - It offers an interesting counterpoint to software design and is therefore useful in furthering our understanding of computation, in general
  - **Neither hardware, nor software cannot be a system alone**
    - **To have a leading position, you must know both**
    - **We have plenty of software course and interest though**

# What will we learn in this class?

- Languages of logic design
  - Boolean algebra, logic minimization, state, timing, CAD tools, and so on
  - Discrepancy between programming languages and hardware description
- The concept of state in digital systems
  - Analogous to variables and program counters in software systems
- How to specify/simulate/realize our designs
  - Schematic design
    - No hardware description languages are used except for Boolean equations
  - Tools to simulate the workings of our designs
  - Contemporary logic design and implementation methods
  - Prototype implementation and debugging concepts/techniques
- Contrast with software design
  - Sequential and parallel implementations
  - Specify algorithm as well as computing/storage resources it will use
  - Understanding the differences between theory and practice
    - Target devices are not ideal
    - More sensitive to the optimal design, i.e., cost

# Coverage of this course

- Mandatory knowledge and experience to understand logic design and implementation
  - Intermediate goal: optimal design of combinational circuits
  - Final goal: synchronous state machines
- CAD based front-end design
  - The same CAD tool as used in Computer System Design: Xilinx ISE
  - Schematic and Boolean equation entry
  - Logic simulation
- No logic synthesis
  - Until a concrete concept of logic design is established
  - Computer System Design will cover logic synthesis using Verilog HDL
- **Legacy component based design**
  - TTL 74 family or equivalent
  - Boolean equations with PAL
- **Implementation and debugging techniques**
  - Lab course

## Applications of logic design

- Conventional computer design
  - CPUs, busses, peripherals, storages and so forth
- Networking and communications
  - Phones, modems, routers, sensors and so forth
- **Embedded products**
  - In cars, toys, appliances, factories, aircrafts, spaceships, entertainment devices, robots, and so forth
- Scientific equipment
  - Testing, sensing, reporting, and so forth
- The world of computing is much much bigger than just PCs!
  - Computer engineering is not only programming with a PC or a server environment
  - **All the modern devices, systems, equipments fall in computer engineering**
  - Logic design course is the first step toward computers and their applications

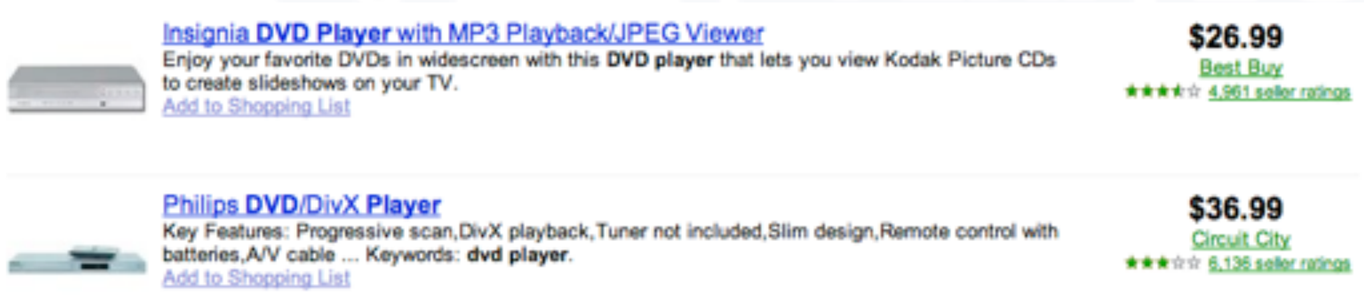
## A quick history lesson

- 1850: George Boole invents Boolean algebra
  - Maps logical propositions to symbols
  - Permits manipulation of logic statements using mathematics
- 1938: Claude Shannon links Boolean algebra to switches
  - His Masters’ thesis
- 1945: John von Neumann develops the first stored program computer
  - Its switching elements are vacuum tubes (a big advance from relays)
- 1946: ENIAC... The world’s first completely electronic computer
  - 18,000 vacuum tubes
  - Several hundred multiplications per minute
- 1947: Shockley, Brittain, and Bardeen invent the transistor
  - Replaces vacuum tubes
  - Enable integration of multiple devices into one package
  - Gateway to modern electronics

# Contemporary logic design

- Our systems become more complex
  - Integrate more functions

- Very narrow market windows and short design times
  - Cell phone market window
- Digital hardware becomes so cheap



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## Digital and analog signal

- Convenient to think of digital systems as having only discrete, digital, input/output values
- In reality, real electronic components exhibit continuous, analog, behavior

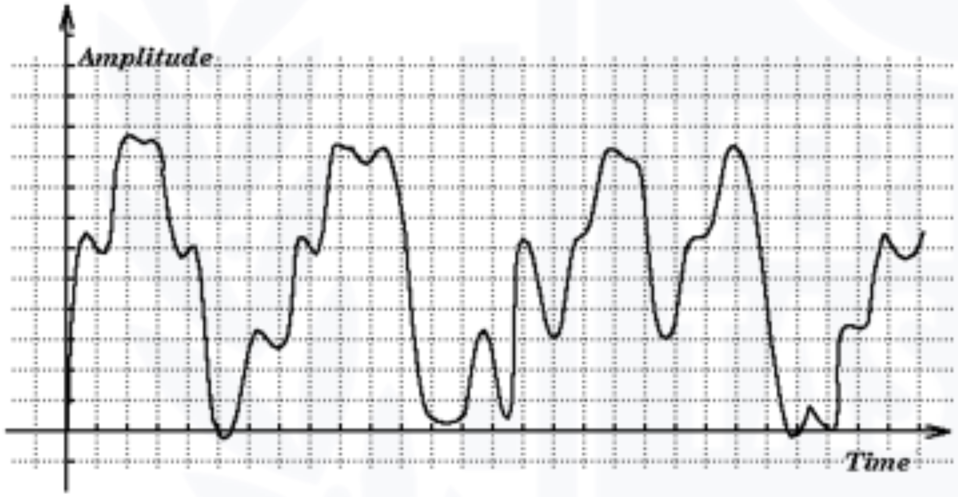
- Why do we make the digital abstraction anyway?
  - switches operate this way
  - easier to think about a small number of discrete values
- Why does it work?
  - does not propagate small errors in values
  - always resets to 0 or 1

# Digital and analog signal

- Continuous time and discrete time signals
  - Y=f(t): t is a continuous variable
  - Y=F($t_i$): $t_i$ is an index
  - Sampling converts continuous time signal to discrete time signal
- Digital signal
  - Logic 0 and logic 1
  - A group of digital signals can represent analog quantity by quantization
- Analog signals are converted to digital signals via sampling and quantization

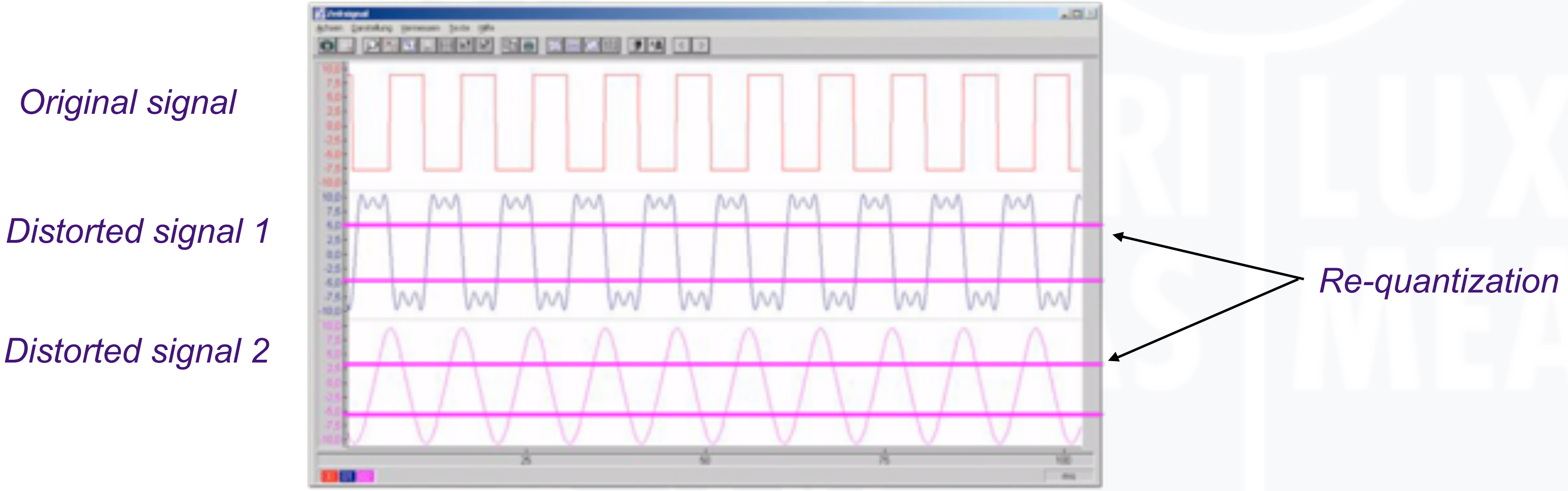
# Digital and analog signal

- Analog signals
  - Continuous time signals
  - Continuous values
  - Natural signals
  - Noise prone
    - Additive noise permanently changes the original signal



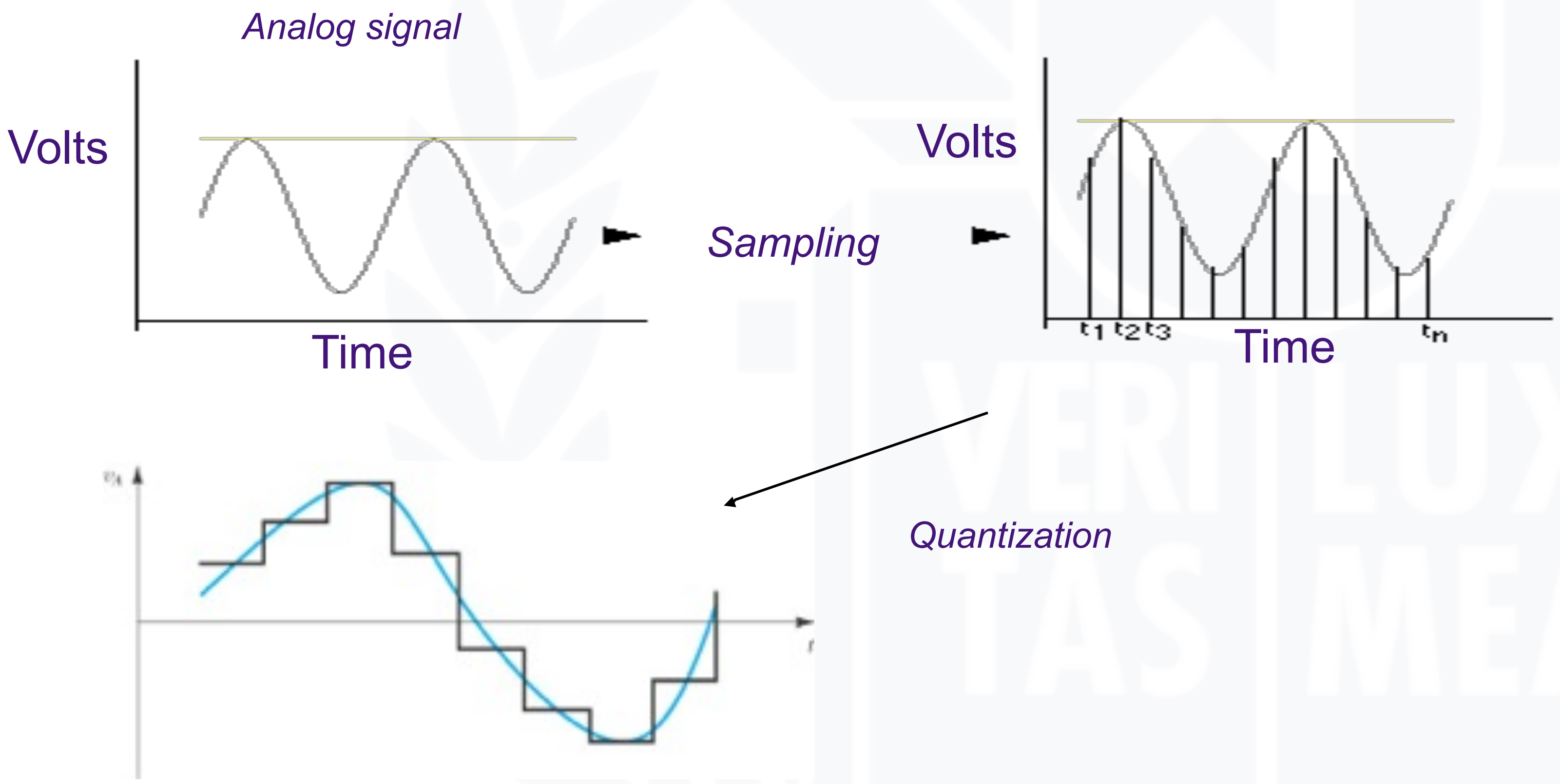
## Digital and analog signal

- Digital signals
  - Discrete time signals
  - Discrete values
  - Not an original signal
    - Sampling and quantization error Noise immunity within noise margin
    - Additive noise can be canceled



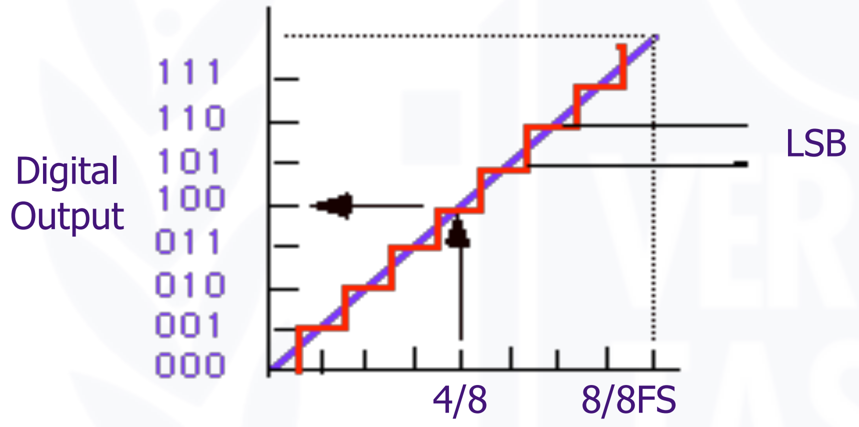
## Digital and analog signal

- Signal translations



## Digital and analog signal

- Resolution: The number of bits the ADC uses to represent the digital data determines the resolution
  - Example: A 3-bit ADC. For a full-scale voltage of 10 volts, the resolution will be 10/(23)=1.25 V.
  - However, if we increase the number of bits to 12, then resolution becomes 10/(212)=2.44 mV.

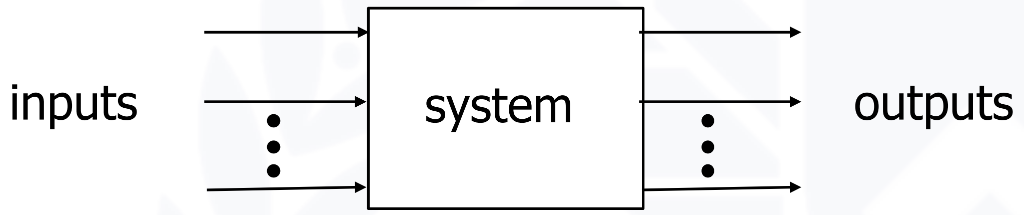


## Mapping from physical world to binary world

| Technology | State 0 | State 1 |
|---|---|---|
| Relay logic | Circuit Open | Circuit Closed |
| CMOS logic | 0.0-1.0 volts | 2.0-3.0 volts |
| Transistor transistor logic (TTL) | 0.0-0.8 volts | 2.0-5.0 volts |
| Fiber Optics | Light off | Light on |
| Dynamic RAM | Discharged capacitor | Charged capacitor |
| Nonvolatile memory (erasable) | Trapped electrons | No trapped electrons |
| Programmable ROM | Fuse blown | Fuse intact |
| Bubble memory | No magnetic bubble | Bubble present |
| Magnetic disk | No flux reversal | Flux reversal |
| Compact disc | No pit | Pit |

## Combinational circuit

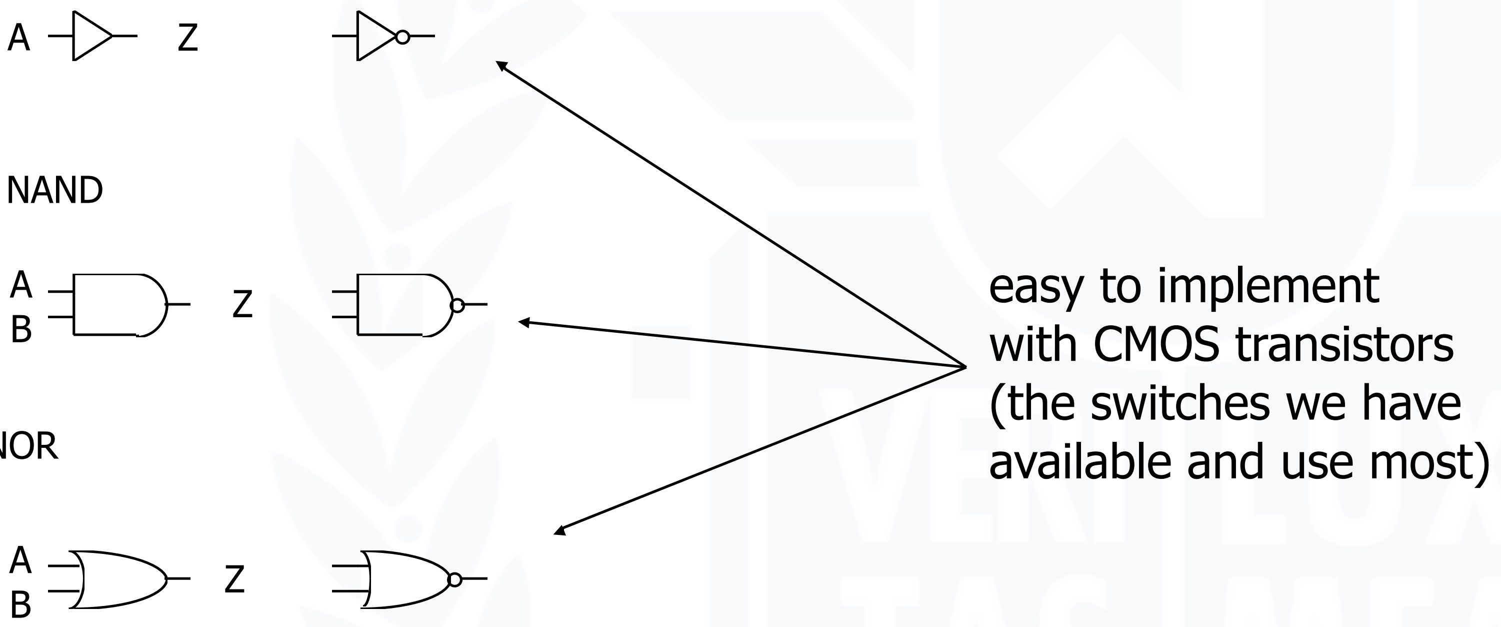
- A simple model of a digital system is a unit with inputs and outputs:



- Combinational means "memory-less"
  - a digital circuit is combinational if its output values only depend on its input values

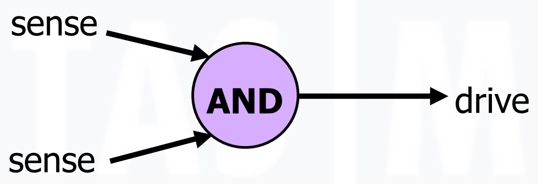
## Combinational logic symbols

- Common combinational logic systems have standard symbols called logic gates
  - Buffer, NOT
  - AND, NAND
  - OR, NOR


A
Z
A
B
Z
A
B
Z
easy to implement with CMOS transistors (the switches we have available and use most)

## What is digital hardware?

- Collection of devices that sense and/or control wires that carry a digital value (i.e., a physical quantity that can be interpreted as a "0" or "1")
  - Example: digital logic where voltage < 0.8 V is a "0" and > 2.0 V is a "1"
  - Example: pair of transmission wires where a "0" or "1" is distinguished by which wire has a higher voltage (differential)
  - Example: orientation of magnetization signifies a "0" or a "1"
- Primitive digital hardware devices
  - Logic computation devices (sense and drive)
    - Are two wires both "1" - make another be "1" (AND)
    - Is at least one of two wires "1" - make another be "1" (OR)
    - Is a wire "1" - then make another be "0" (NOT)
  - Memory devices (store)
    - Store a value
    - Recall a previously stored value



## What is happening now in digital design?

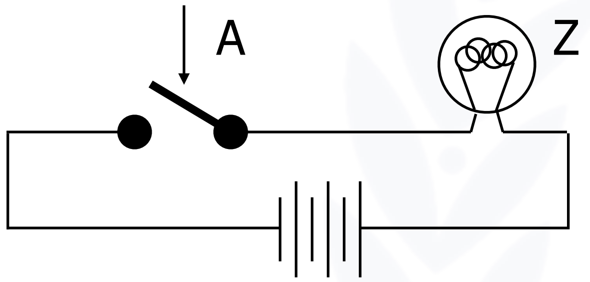
- Important trends in how industry does hardware design
  - Larger and larger designs
  - Shorter and shorter time to market and market window
  - Cheaper and cheaper products
- To optimize
  - Scale
    - Pervasive use of computer-aided design tools over hand methods
    - Multiple levels of design representation
  - Time
    - Emphasis on abstract design representations
    - Programmable rather than fixed function components
    - Automatic synthesis techniques
    - Importance of sound design methodologies
  - Cost
    - Higher levels of integration
    - Use of simulation to debug designs
    - Simulate and verify before you build

## Computation: abstract vs. implementation

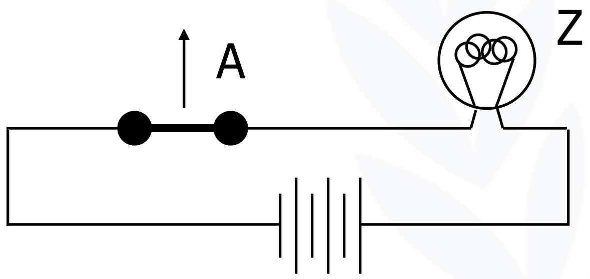
- Up to now, computation has been a mental exercise (paper, programs)
- This class is about physically implementing computation using physical devices that use voltages to represent logical values
- Basic units of computation are:
  - representation: "0", "1" on a wire
    set of wires (e.g., for binary int)
  - assignment: x = y
  - data operations: x + y – 5
  - control:
    sequential statements: A; B; C
    conditionals: if x == 1 then y
    loops: for ( i = 1 ; i == 10, i++)
    procedures: A; proc(...); B;
- We will study how each of these are implemented in hardware and composed into computational structures

## Switches

- Basic element of physical implementations
- Implementing a simple circuit (arrow shows action if wire changes to "1"):



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

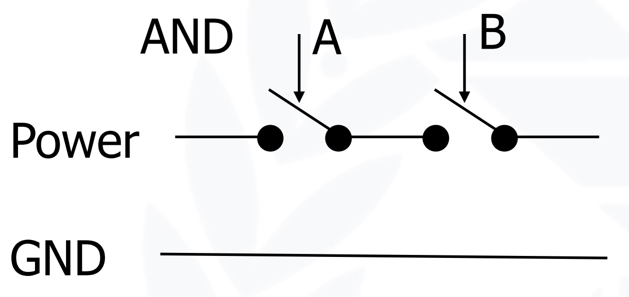


open switch (if A is "0" or unasserted)
and turn off light bulb (Z)

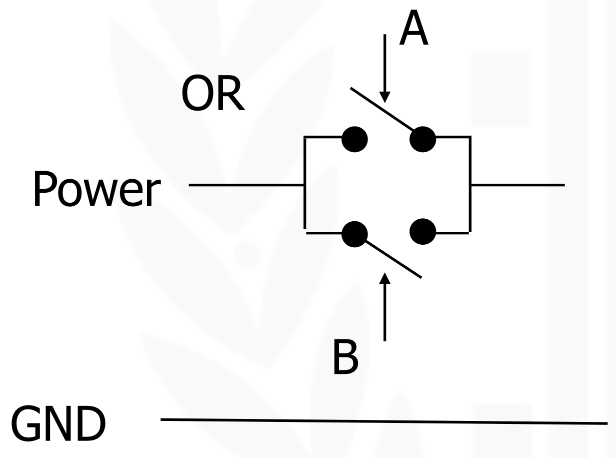
$Z \equiv A$

## Switches (continue)

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



Z ≡ A <u>and</u> B



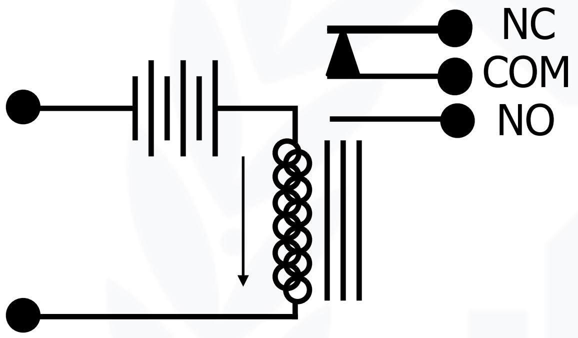
Z ≡ A <u>or</u> B

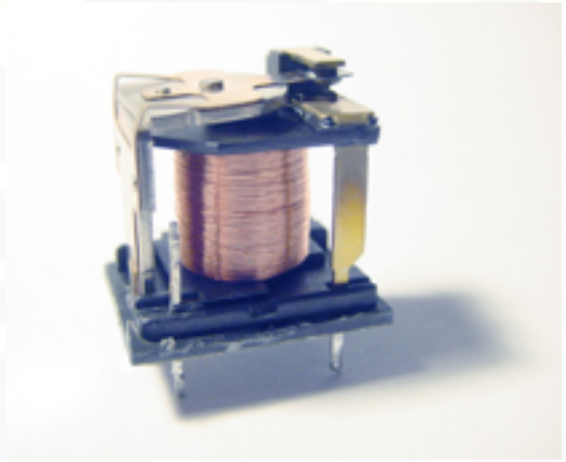
## Switching networks

- Switch settings
  - determine whether or not a conducting path exists to light the light bulb
- To build larger computations
  - use a light bulb (output of the network) to set other switches (inputs to another network).
- Connect together switching networks
  - to construct larger  switching networks, i.e., there is a way to connect outputs of one network to the inputs of the next.

# Relay networks

- A simple way to convert between conducting paths and switch settings is to use (electro-mechanical) relays.
- What is a relay?





conducting path composed of switches closes circuit

current flowing through coil magnetizes core and causes normally closed (nc) contact to be pulled open

when no current flows, the spring of the contact returns it to its normal position

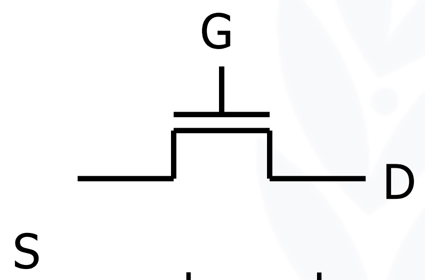
- What determines the switching speed of a relay network?

# Transistor networks

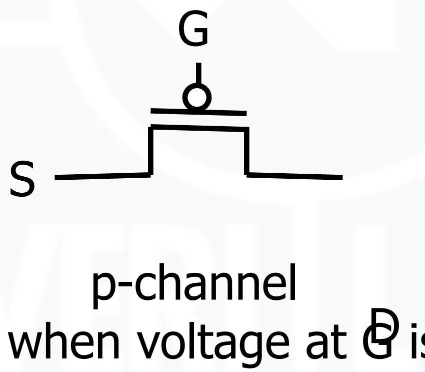
- Relays are seldom used much anymore
  - Some traffic light controllers are still electro-mechanical
  - Programmable logic controller (PLC)
    - Ladder network
- Modern digital systems are designed in CMOS technology
  - MOS stands for Metal-Oxide on Semiconductor
  - C is for complementary because there are both normally-open and normally-closed switches
- MOS transistors act as voltage-controlled switches
  - Similar, though easier to work with than relays
  - Small, low-power and fast

# MOS transistors

- MOS transistors have three terminals: drain, gate, and source
  - they act as switches in the following way:
    if the voltage on the gate terminal is (some amount) higher/lower than the source terminal then a conducting path will be established between the drain and source terminals



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

## Speed of MOS networks

- What influences the speed of CMOS networks?
  - Charging and discharging of voltages on wires and gates of transistors
- Capacitors hold charge
  - Capacitance is at gates of transistors and wire material
- Resistors slow movement of electrons
  - Resistance mostly due to transistors
- Threshold voltage determines the switching speed and power consumption
  - High threshold is low power and low speed
  - Low threshold is high power and high speed

# Representation of digital designs

- Physical devices (transistors,  relays)
- Switches
- Truth tables
- Boolean algebra
- Gates
- Waveforms
- Finite state behavior
- Register-transfer behavior
- Concurrent abstract specifications
- Prototype implementation
- Design practice

scope of 4190.201

scope of the lab