ECE 2050 Digital Logic and Systems

Chapter 1 : Introductory Concepts

Instructor: Yue ZHENG, Ph.D.

香港中文大學（深圳）
The Chinese University of Hong Kong, Shenzhen

Teaching Team

- Instructor:
  - Name: Prof. Tinghuan Chen (陈廷欢), Ph.D.
  - Email: chentinghuan@cuhk.edu.cn
  - Office: TC413B
  - Office Hour: Thur. 15:00-16:00 (TC413B)

L1 Session	Location
Mon. 9:00-10:30	Teaching Complex C203
Wed. 9:00-10:30	

- Instructor:
  - Name: Prof. Yue Zheng (郑月), Ph.D.
  - Email: zhengyue@cuhk.edu.cn
  - Office: CD414
  - Office Hour: Just drop by or send email for appointment

L2 Session	Location
Mon. 10:30-12:00	Teaching Complex C203
Wed. 10:30-12:00	

Teaching Assistants

• **Name**: Junguang Yao Lead TA • **Office**: TD205 • **Email**: junguangyao@link.cuhk.edu.cn • **Office Hour**: Tue 14:00-15:00	• **Name:** Xin Wang • **Office:** TD205 • **Email:** xinwang3@link.cuhk.edu.cn • **Office Hour:** Wed 10： 00-11： 00
• **Name**: Kexin Chen • **Office**: ZX307 • **Email**: kexinchen2@link.cuhk.edu.cn • **Office Hour**: Tue 15:00-16:00	• **Name**: Yiyang Li • **Office**: ZX107 • **Email**: 222010039@link.cuhk.edu.cn • **Office Hour**: Tue 11： 00-12： 00
• **Name**: Wangqian Chen • **Office**: ZR305 • **Email**: 221019052@link.cuhk.edu.cn • **Office Hour**: TBD	• **Name**: Hanxu Zhang • **Office**: ZX201 • **Email**: 120030021@link.cuhk.edu.cn • **Office Hour**: Thu 20:00-21:00
• **Name**: Huaiyu Li • **Office**: ZX301B • **Email**: 223010059@link.cuhk.edu.cn • **Office Hour**: Thu 14:00-15:00	• **Name**: Zhipeng Xu • **Office**: TBD • **Email**: 222010049@link.cuhk.edu.cn • **Office Hour**: TBD

Tutorials

<table>
<tr><td>Monday</td><td>18:00-19:00</td><td>Xin Wang</td><td>224010106</td><td rowspan="4">TD114</td></tr>
<tr><td>Monday</td><td>19:00-20:00</td><td>Junguang Yao</td><td>224010136</td></tr>
<tr><td>Tuesday</td><td>18:00-19:00</td><td>Kexin Chen</td><td>221019028</td></tr>
<tr><td>Tuesday</td><td>19:00-20:00</td><td>Yiyang Li</td><td>222010039</td></tr>
<tr><td>Wednesday</td><td>18:00-19:00</td><td>Wangqian Chen</td><td>221019052</td><td rowspan="4">TC108</td></tr>
<tr><td>Wednesday</td><td>19:00-20:00</td><td>Hanxu Zhang</td><td>120030021</td></tr>
<tr><td>Thursday</td><td>18:00-19:00</td><td>Huaiyu Li</td><td>223010059</td></tr>
<tr><td>Thursday</td><td>19:00-20:00</td><td>Zhipeng Xu</td><td>222010049</td></tr>
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Activity Highlights

Company Visit in 2020

Company Visit in 2023

Invited seminars

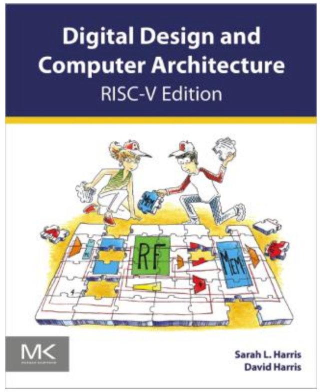
Course Outline

- This course gives science and engineering students exposure to the basic concepts and techniques in digital logic and system design. Topics include digital system concepts, numbering systems and codes, Boolean algebra, logic gates and logic circuit elements, logic functions and simplification, logic circuits design, latches and flip-flops, counters, registers, memory and storage systems, FPGA, and introduction to CAD tools.

Assessment	**% weight**
Assignments	25%
Project	15%
Mid-term Test	25%
Final Exam	35%

Textbook & References

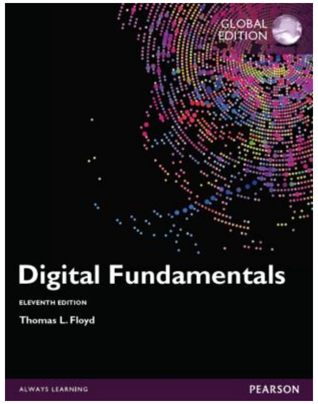
- Digital Design and Computer Architecture RISC-V Edition (main)
  - by Sarah L. Harris and David Harris



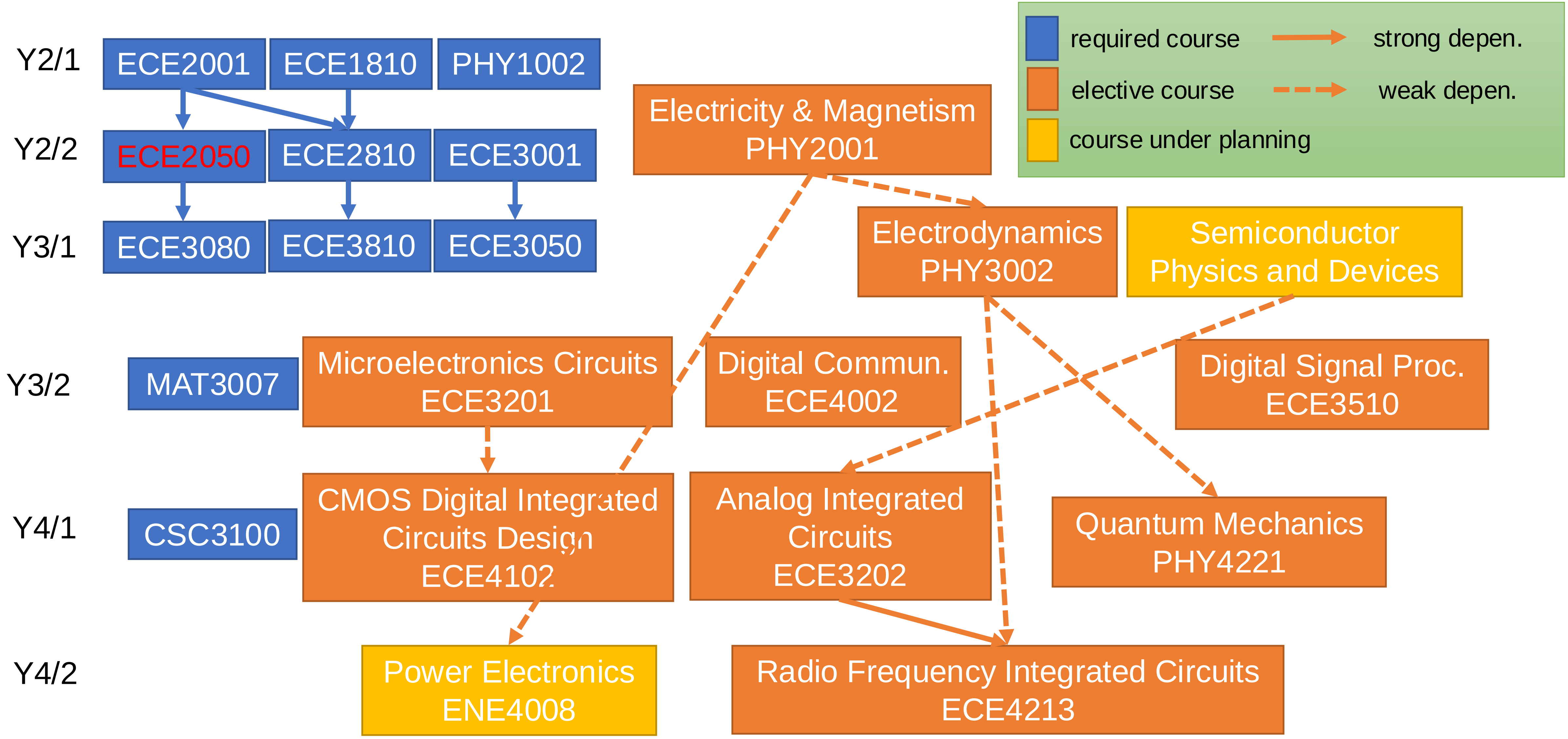
Companion Resources - All (zip)
Lecture slides (zip)
Labs (zip)
Figures (zip)
Chapter 9: Embedded I/O Systems (pdf)
Appendix A: Digital System Implementation (pdf)
Appendix B: RISC-V ISA Summary (pdf)
Appendix C: C Programming (pdf)
HDL (zip)
Errata (pdf)
Solutions: Odd-numbered Exercises (pdf)
Videos
Verilog Resources

https://pages.hmc.edu/harris/ddca/ddcarv.html

- Digital Fundamentals (11th Edition)
  - By Thomas Floyd



Course Map: Circuits



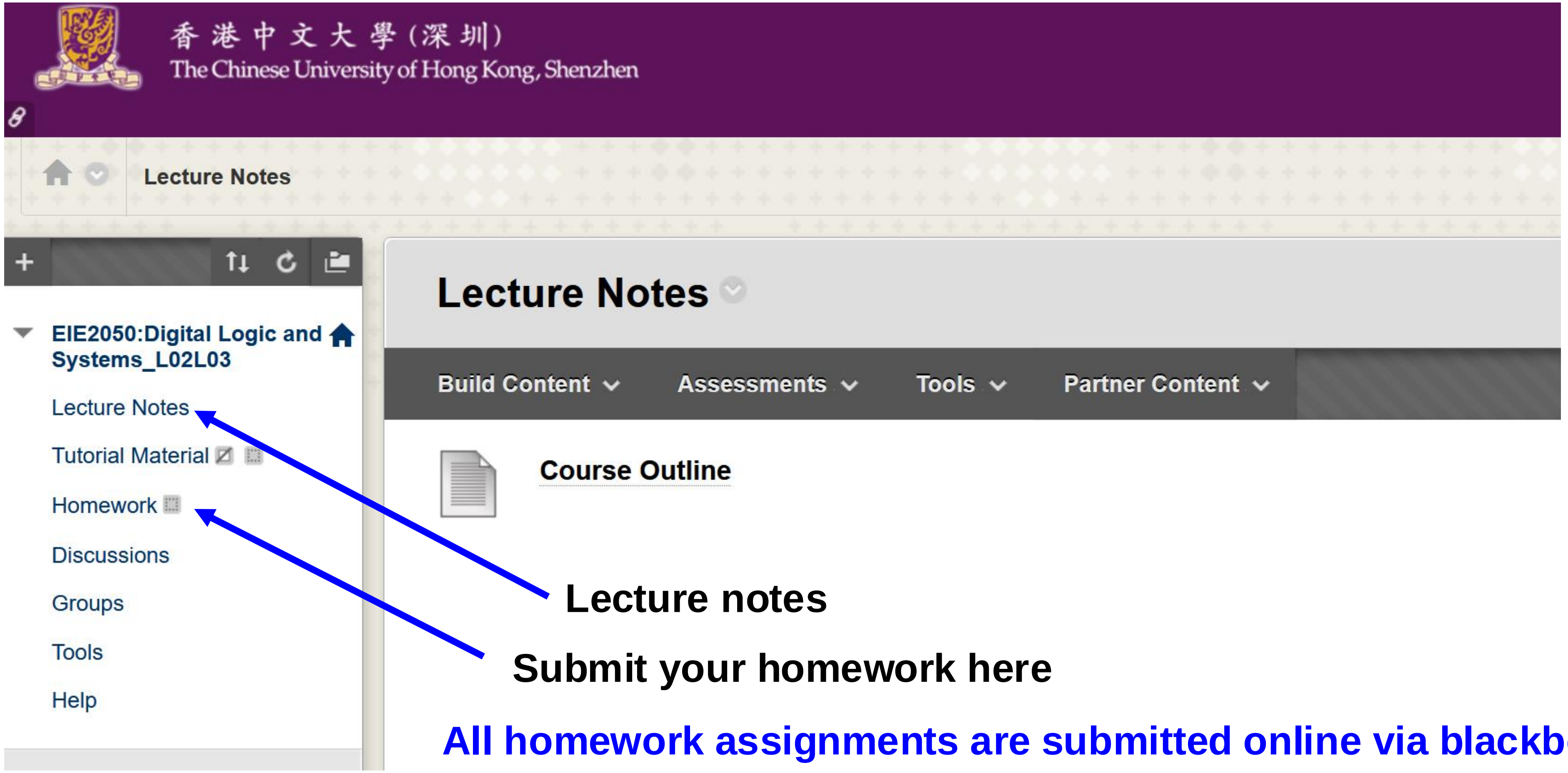
Teaching Plan

Week		Content/ topic/ activity
1	1/6 - 1/12	**Ch1. Introductory concepts** Digital and analog quantities, Binary digits, Basic logic operations, System concept, Fixed-function integrated circuits
2	1/13 - 1/19	**Ch2. Number systems** Number systems and conversions, Binary arithmetic and operations, Signed numbers and operations, Binary coded decimal, Digital codes, Error detection codes
	1/20 -2/9	Lunar New Year Holiday
3	2/10 - 2/16	**Ch3. Logic gates** The inverter, Logic gates (AND, OR, NAND, NOR, XOR, XNOR), logic levels
4	2/17 - 2/23	**Ch4. Boolean algebra and logic simplification** Boolean operations, Boolean algebra, De Morgan's theorem, Boolean analysis of logic circuits, Simplification using Boolean algebra, Standard forms, Truth tables, Karnaugh map and minimization
5	2/24 - 3/2	**Ch4. Boolean algebra and logic simplification & Ch5. Combinational logic design** Basic combinational logic circuits and implementation, the universal property, Combinational logic with NAND and NOR gates
6	3/3 - 3/9	**Ch5. Combinational logic design & Ch6. Combinational building blocks** Basic adders, Parallel adders, Comparators, Decoders, Encoders, Code converter

Teaching Plan (Cont'd)

Week		Content/ topic/ activity
7	3/10 - 3/16	**Ch6. Combinational Building Blocks** Adders, Comparators, Encoder & Decoder, Multiplexer
8	3/17 - 3/23	Midterm & **Ch7. Sequential Logic Design** bistable circuits, SR Latch, D Latch, D Flip Flop, JK Flip Flop,
9	3/24 - 3/30	**Ch8. Shift registers** Serial/Parallel in Serial/Parallel out, bidirectional shift registers, applications
10	3/31 - 4/6	**Ch9. Finite State Machine** (Qingming Festival) Moore/Mealy FSM, timing, set up time, hold time
11	4/7 - 4/13	**Ch10. Counters** Asynchronous counters, Synchronous counters, Design, Applications
12	4/14 - 4/20	**Ch10. Counters** Asynchronous counters, Synchronous counters, Design, Applications
13	4/21 - 4/27	**Ch11. Memory & Logic Arrays** Memory basics, RAM, ROM, Flash memory, PLAs & FPGAs

Blackboard



Lecture notes

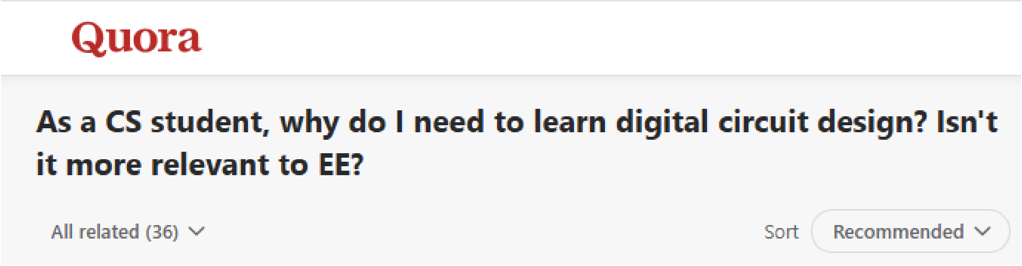
Submit your homework here

All homework assignments are submitted online via blackboard

Why do we need to learn digital logic & systems?

Some Reasons

- Major Required
- An insight into the specialty
- Circuit design
- Computer architecture
- Built upon Boolean algebra, theoretical CS
- High-performance software design requires you to understand the hardware layer
- Microprocessors, datasheet, schematic diagram

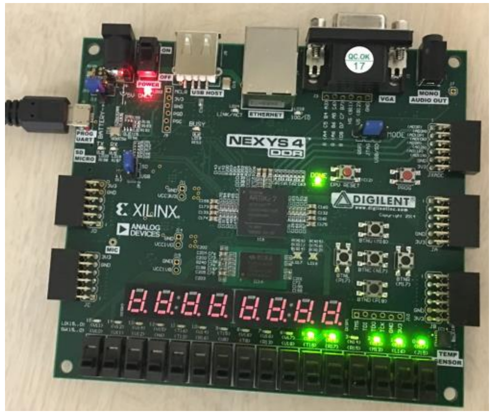


Microprocessors

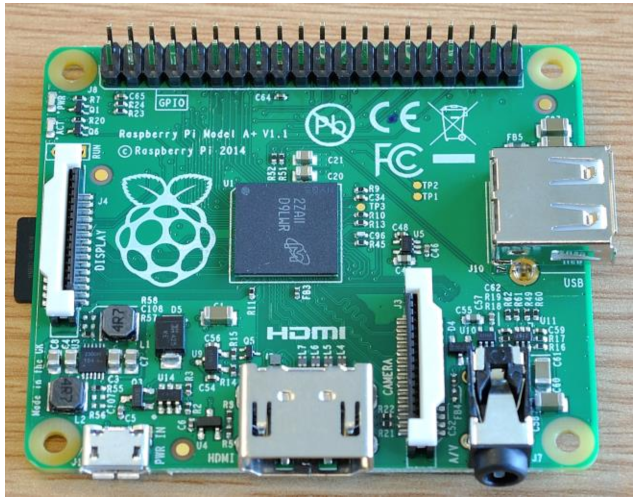
- CPU
- GPU
- DSP
- MCU
- SoC
- ASIC
- FPGA
- …

CPU

GPU



FPGA



MCU
(microcontroller)

How to design a Microprocessor?

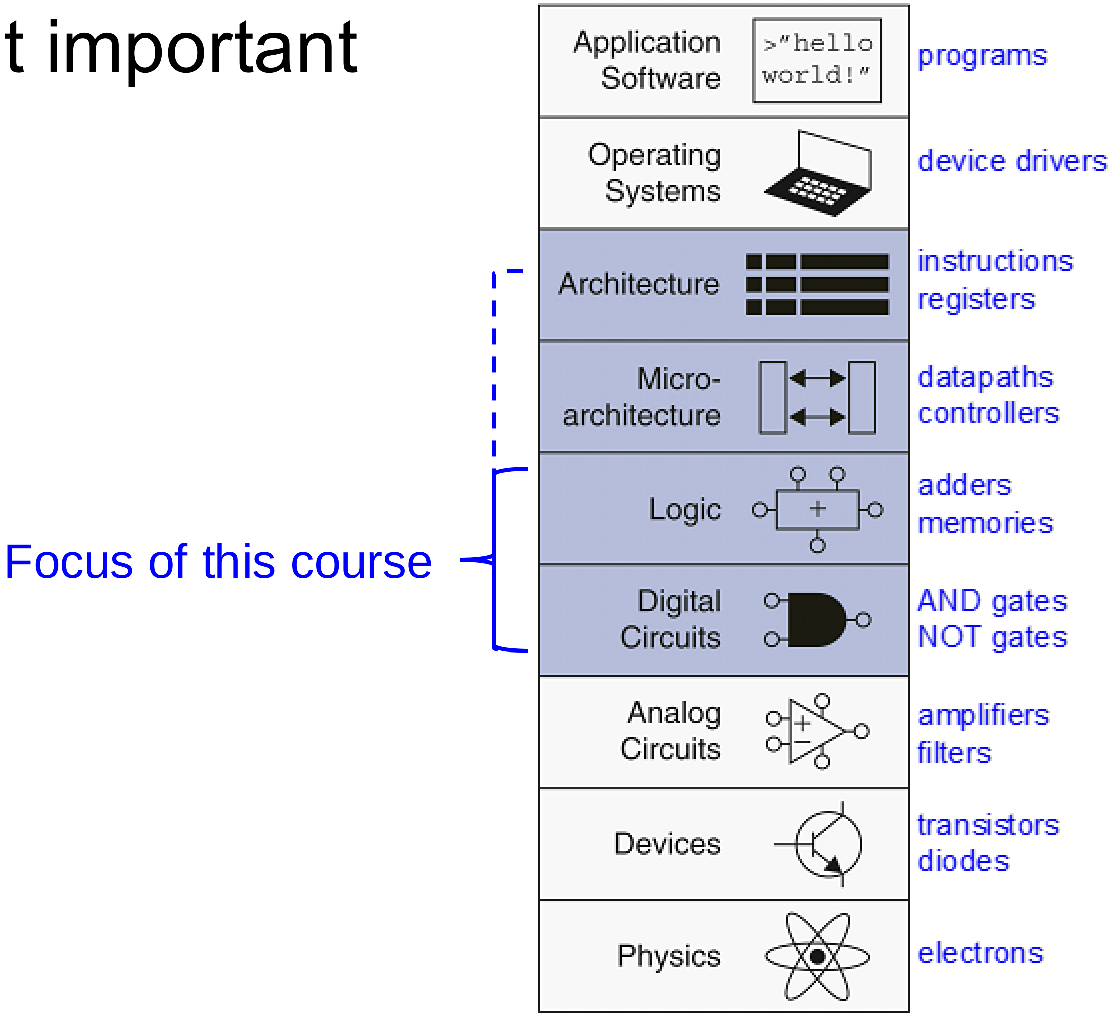
Managing Complexity

- Modern digital systems:
  - Millions or billions of transistors

- How do we design things that are too big to fit in one person's head at once?
  - Abstraction
  - Discipline
  - The 3-Y's
    - Hierarchy
    - Modularity
    - Regularity

Abstraction

- Hiding details when they aren't important



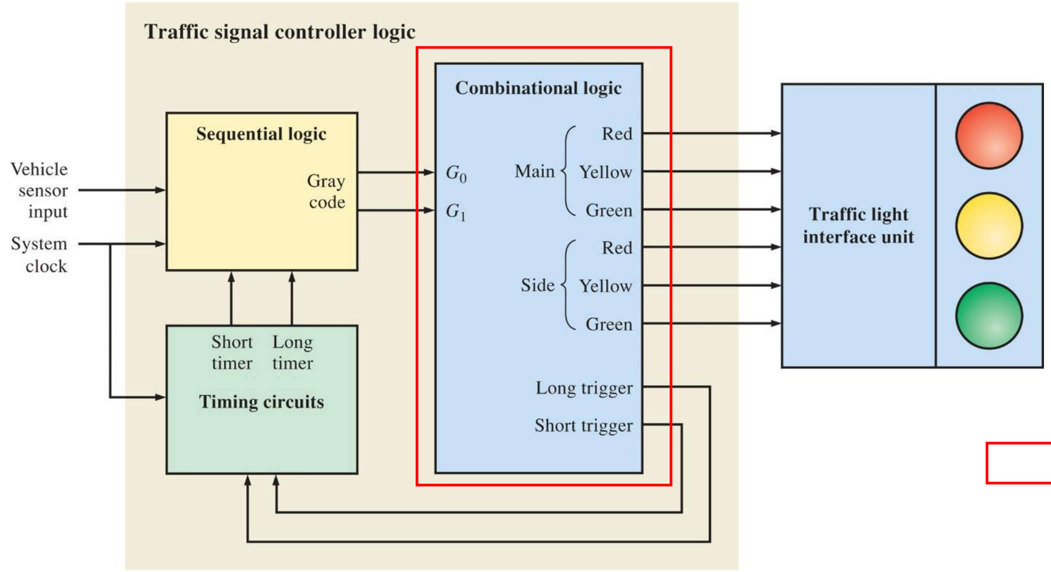
Discipline

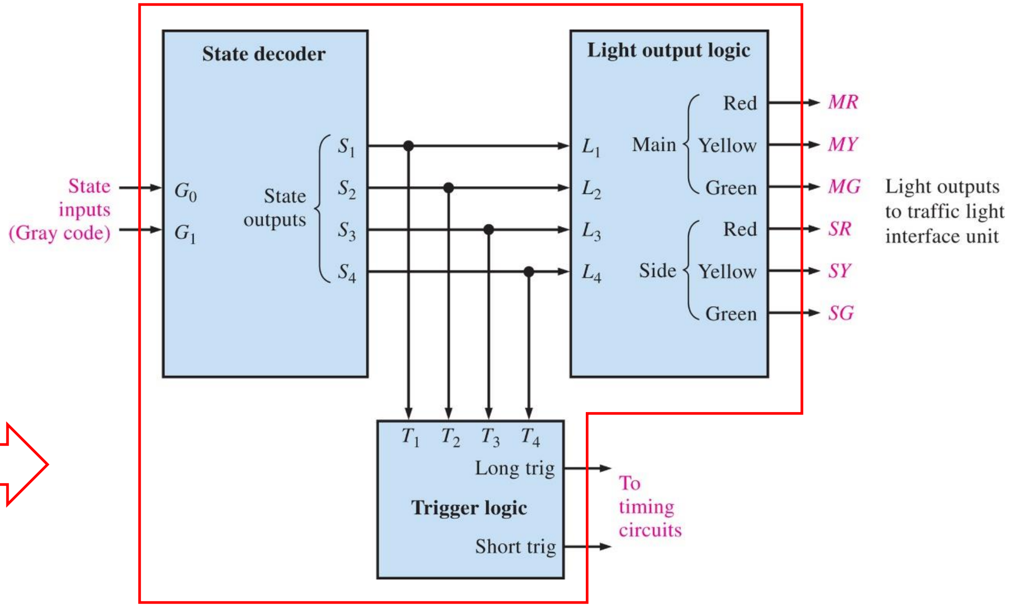
- Intentionally restrict design choices
- Example: Digital discipline
  - Discrete voltages instead of continuous
  - Simpler to design than analog circuits – can build more sophisticated systems
  - Digital systems replacing analog predecessors:

    i.e., digital cameras, digital television, cell phones, CDs

The 3-y's

- Hierarchy
  - A system divided into modules and submodules
- Modularity
  - Having well-defined functions and interfaces
- Regularity
  - Encouraging uniformity, so modules can be easily reused





Example: Model T Ford

- Famous early (1908) example of interchangeable parts.
  - Most previous cars were hand-crafted by skilled tradesmen.
  - Mass production on moving assembly lines greatly reduced cost.

en.wikipedia.org/wiki/Ford_Model_T#/media/File:1925_Ford_Model_T_touring.jpg

- Henry Ford:

  I will build a motor car for the great multitude. It will be large enough for the family, but small enough for the individual to run and care for. It will be constructed of the best materials, by the best men to be hired, after the simplest designs that modern engineering can devise. But it will be so low in price that no man making a good salary will be unable to own one – and enjoy with his family the blessing of hours of pleasure in God's great open spaces.

Example: Model T Ford

- Hierarchy
  - Car has chassis, wheels, seats, engine.
  - Engine has cylinders, spark plugs, exhaust, carburetor.
  - Carburator has air intake, inlet needle, feed pipe, coupling nut.

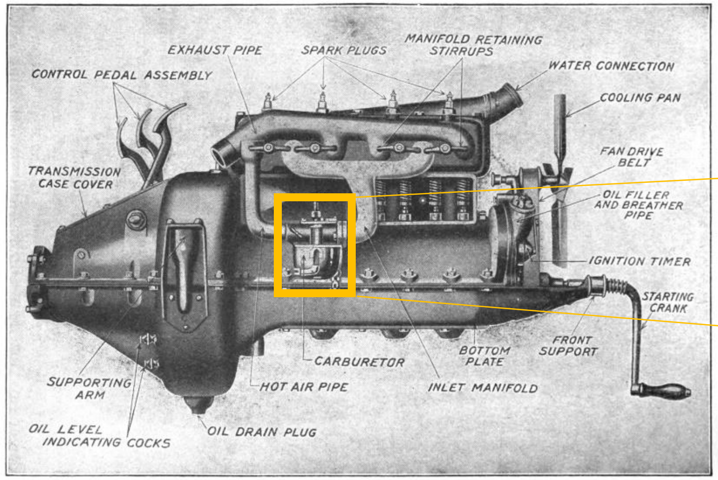


Fig. 8.—Valve Side of the Ford Model T Unit Power Plant Showing Manifolds, Carburetor and Interior of One of the Valve Spring Chambers.

https://en.wikipedia.org/wiki/Ford_Model_T_engine#/media/File:Pagé_1917_Model_T_Ford_Car_Figure_08.png

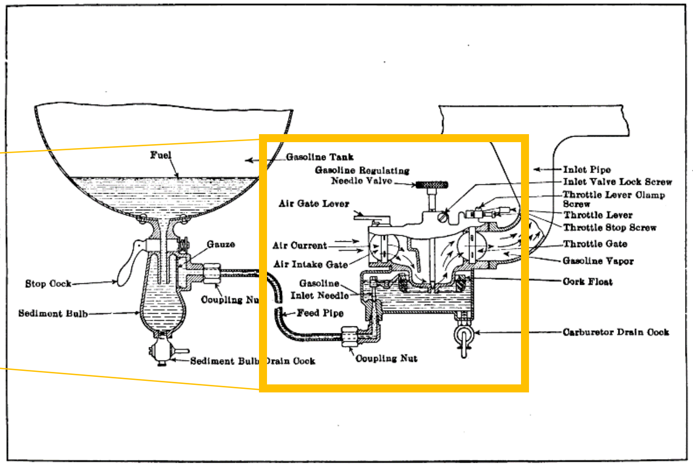


Fig. 14.—The Ford Model T Fuel Supply and Gas Making System.

https://en.wikipedia.org/wiki/Ford_Model_T_engine#/media/File:Pagé_1917_Model_T_Ford_Car_Figure_14.png

Example: Model T Ford

- Modularity
  - Function of coupling nut:
    - Hold fuel line to intake elbow
    - Prevent leaks
    - Easily removable
  - Interface of coupling nut:
    - Standardized diameter, thread pitch, torque
- Regularity
  - Interchangeable parts
    - Standard nut could be purchased from many suppliers
  - “Any customer can have a car painted any color that he wants so long as it is black.” - Henry Ford

The Digital Abstraction

- Most physical variables are **continuous**
  - Voltage on a wire
  - Frequency of an oscillation
  - Position of a mass

Analog quantity :
continuous values

Vinyl records
12 inches (~30cm), 3.5 hours

- Digital abstraction considers **discrete subset** of values

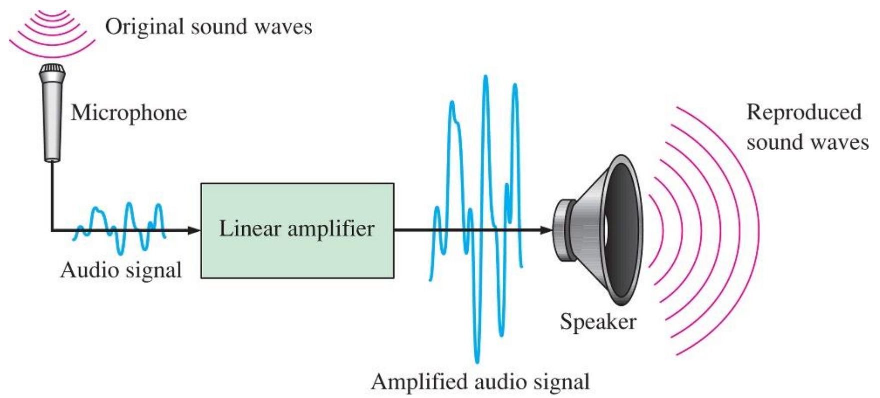
Digital quantity :
a discrete set of values

Compact Disk (CD)
12cm, 74 minutes

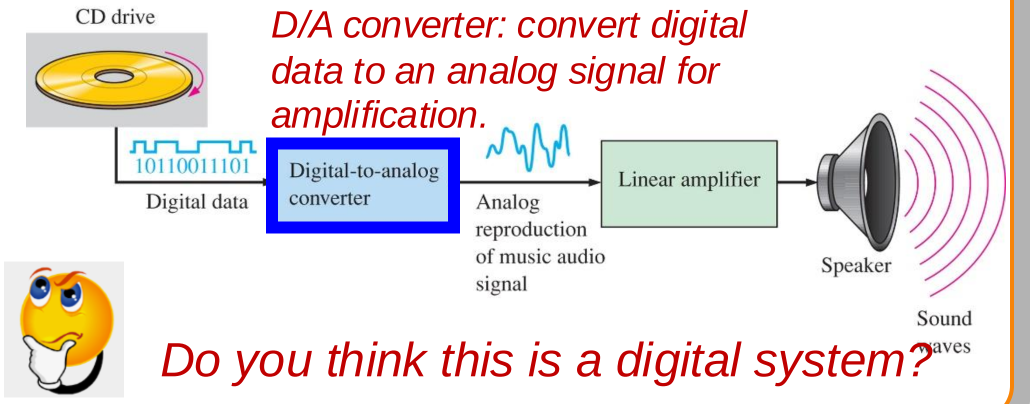
The Digital Advantages

- Digital data can be stored, processed and transmitted more efficiently and reliably
- Digital data is more noise resilient

A typical analog system



An audio system with a CD player



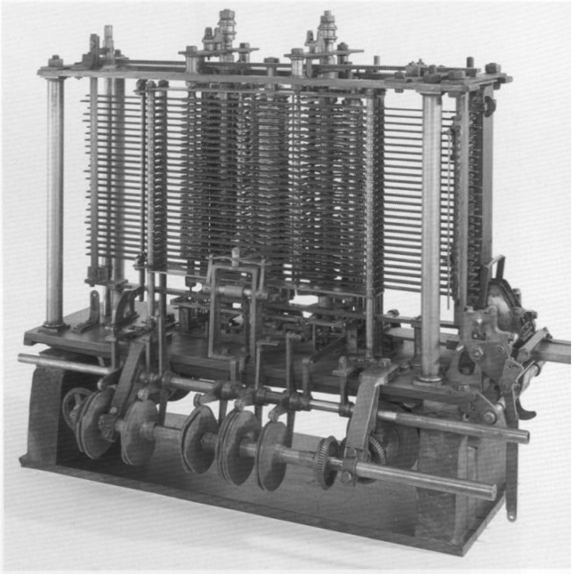
D/A converter: convert digital data to an analog signal for amplification.

Do you think this is a digital system?

- Can you think of any disadvantages of digital systems?

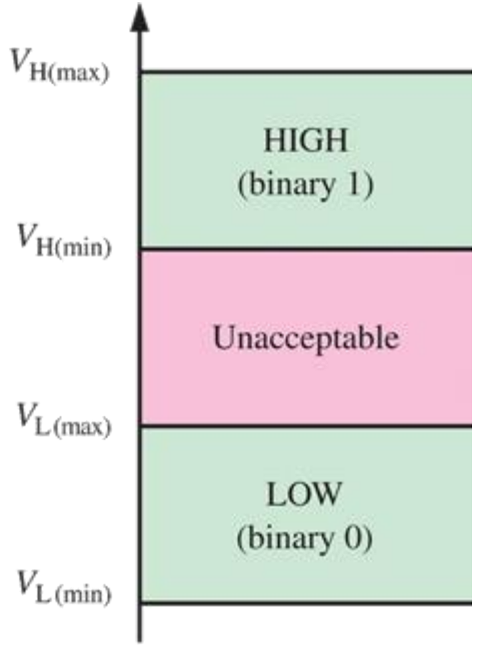
The Analytical Engine

- Designed by Charles Babbage from 1834 – 1871
- Considered to be the first digital computer
- Built from mechanical gears, where each gear represented a discrete value (0-9)
- Babbage died before finishing it



Digital Discipline: Binary Values

- **Two discrete values**:
  - 1’s and 0’s
  - 1, TRUE, HIGH
  - 0, FALSE, LOW
- **1 and 0**: voltage levels, rotating gears, fluid levels, etc.
- Digital circuits use voltage levels
  - 0: low voltage (GND)
  - 1: high voltage (VDD)
- **Bit**: Binary digit



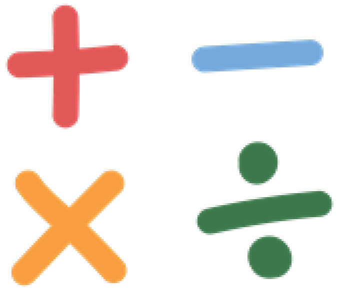
Bit

- Binary digit: a single number is either 0 or 1
- Positive Logic:
  - 1 is represented by the higher voltage level → **HIGH**,
  - 0 is represented by the lower voltage level → **LOW**
- Negative logic : 1 → Low, 0 → High

Number Systems

Decimal	Binary	Octal	Hex
0	0000	00	0
1	0001	01	1
2	0010	02	2
3	0011	03	3
4	0100	04	4
5	0101	05	5
6	0110	06	6
7	0111	07	7
8	1000	10	8
9	1001	11	9

Decimal	Binary	Octal	Hex
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	17	F



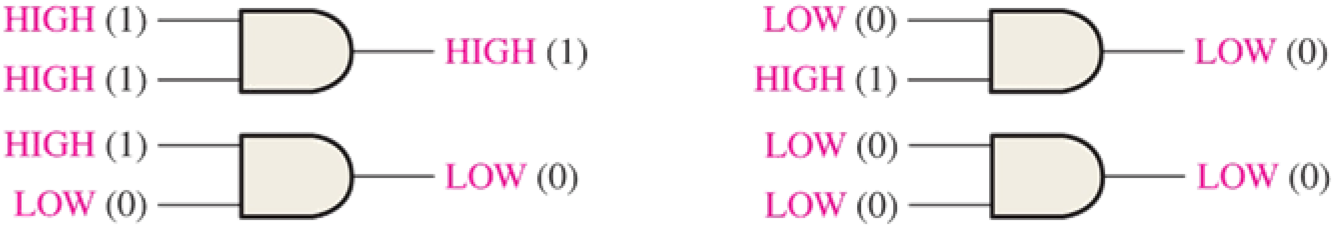
Logic Gates

- Logic **gate :** A **circuit** that performs a specified logic **function**

NOT

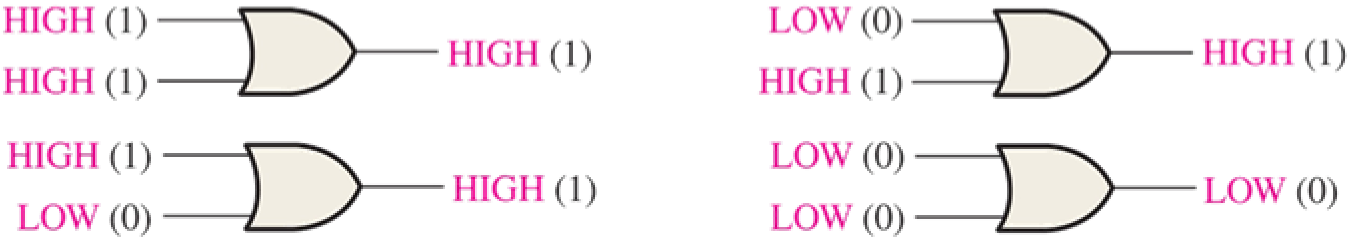
Opposite

AND



True only if all inputs are true (can have more than two inputs)

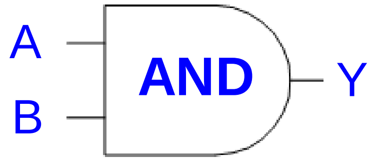
OR



True if one of the inputs is true (can have more than two inputs)

Combinational Circuits & Sequential Circuits

- **Combinational Logic**
  - Memory*less*
  - Outputs determined by current values of inputs
- **Sequential Logic**
  - Has memory
  - Outputs determined by previous and current values of inputs



Truth Table

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Boolean Equation

$Y = AB$

Boolean Algebra and Logic Simplification

- Boolean Algebra

Laws

- Commutative laws
- Associative laws
- Distributive law

Rules

1. $A + 0 = A$
2. $A + 1 = 1$
3. $A \cdot 0 = 0$
4. $A \cdot 1 = A$
5. $A + A = A$
6. $A + \bar{A} = 1$
7. $A \cdot A = A$
8. $A \cdot \bar{A} = 0$
9. $\bar{\bar{A}} = A$
10. $A + AB = A$
11. $A + \bar{A}B = A + B$
12. $(A + B)(A + C) = A + BC$

Demorgan's Theorems

$$\overline{A \cdot B} = \bar{A} + \bar{B}$$

$$\overline{A + B} = \bar{A} \cdot \bar{B}$$

- $$\begin{aligned} Y &= \bar{A}B\bar{C} + \bar{A}BC + ABC \\ &= \bar{A}B\bar{C} + \bar{A}BC + \bar{A}BC + ABC \\ &= \bar{A}B(\bar{C} + C) + (\bar{A} + A)BC \\ &= \bar{A}B + BC \end{aligned}$$

Karnaugh Map

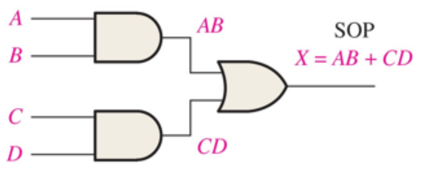
Y

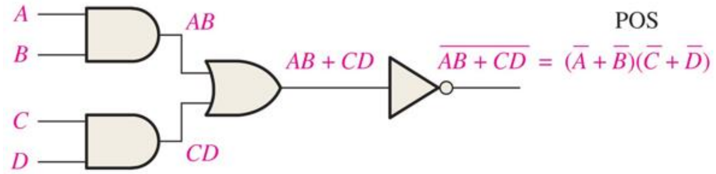
C \ AB	00	01	11	10
0	0	1	0	0
1	0	1	1	0

$Y = \bar{A}B + BC$

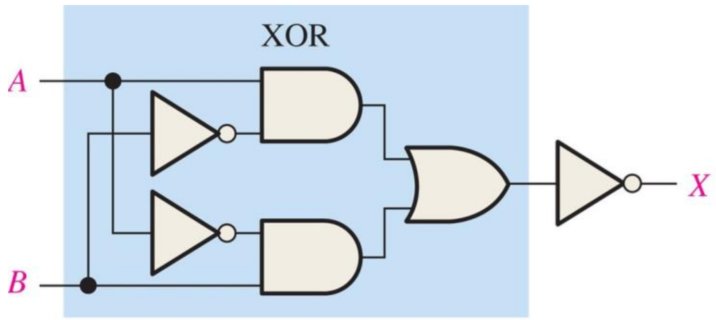
Combinational Logic

- Basic combinational logic circuits
  - AND-OR Logic
  - AND-OR-Invert Logic
  - Exclusive-OR Logic
  - Exclusive-NOR Logic





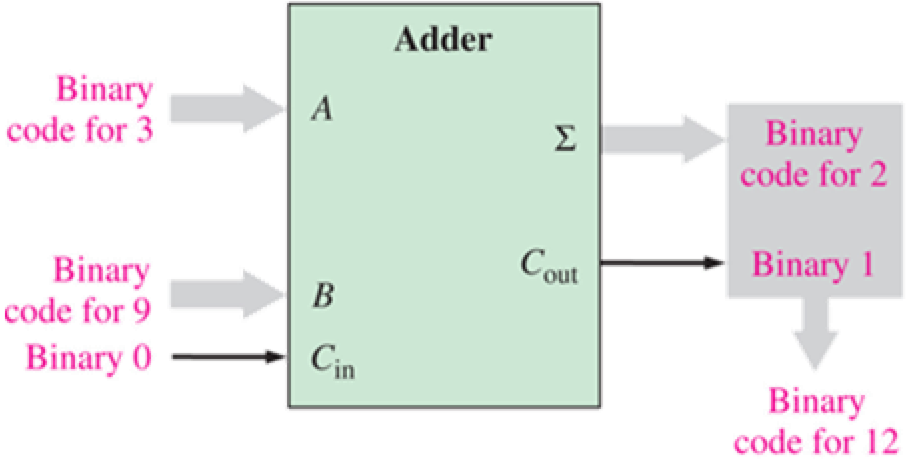
- Implementing combinational logic
  - From Boolean equation to logic circuit
  - From truth table to logic circuit



Combinational Building Blocks

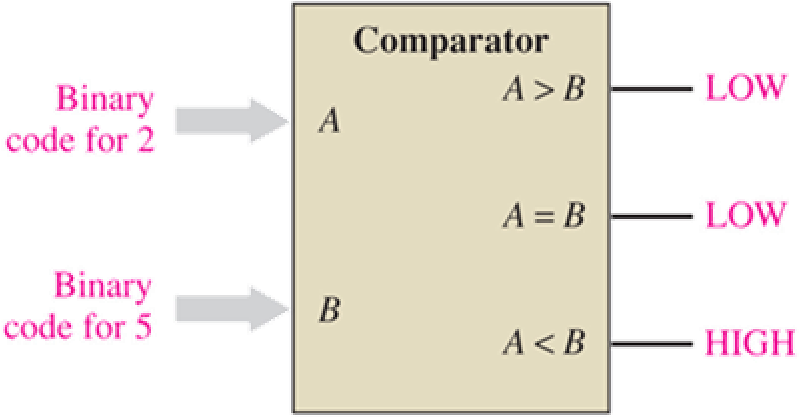
- Adders

E.g. A plus B (3+9 = 12)



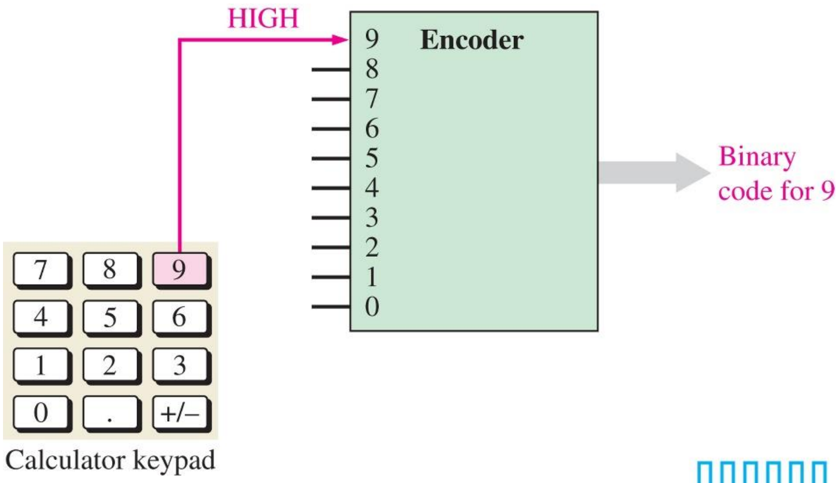
- Comparator

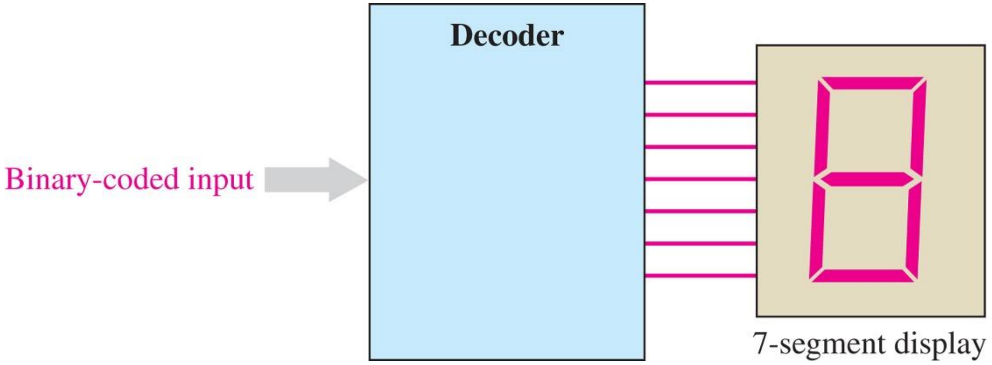
E.g. A is less than B (2<5) as indicated by the High output (A<B)



Combinational Building Blocks

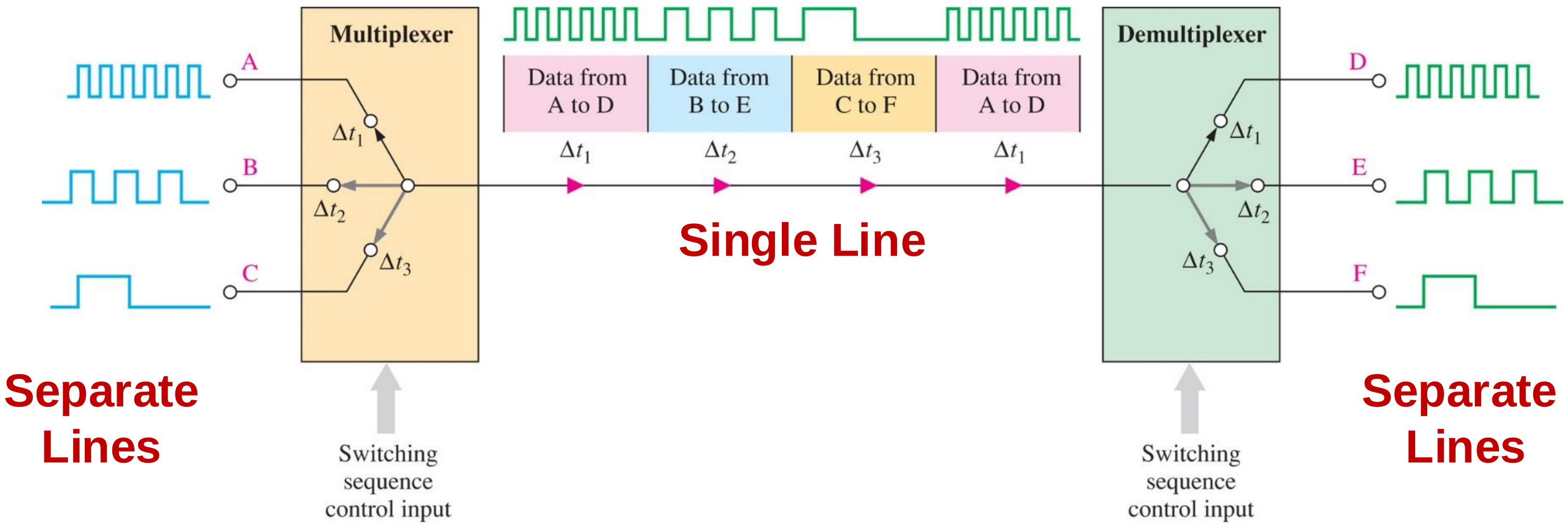
- Encoders & Decoders





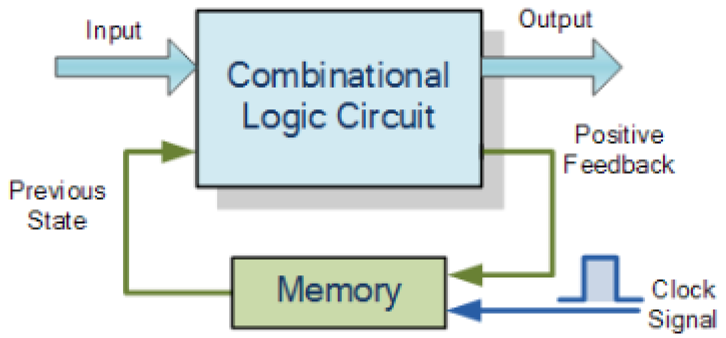
- Multiplexer

& Demultiplexer



Sequential Logic Design

- Outputs of sequential logic depend on current *and* prior input values – it has ***memory***.



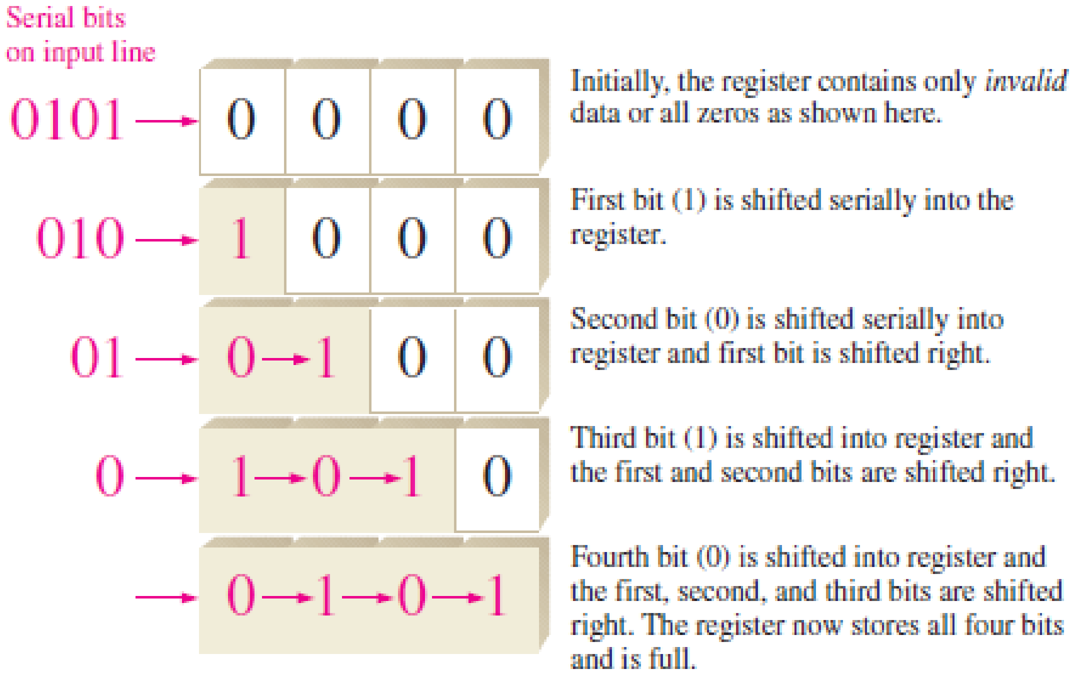
- State: all the information about a circuit necessary to explain its future behavior

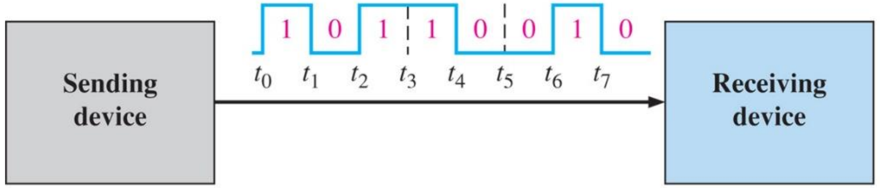
- Latches and Flip-flops:

  - Bistable circuit: 2 stable states
  - store only one bit at a time, either a 0 or a 1
  - SR Latch, D Latch
  - D Flip-flops, JK Flip-flops

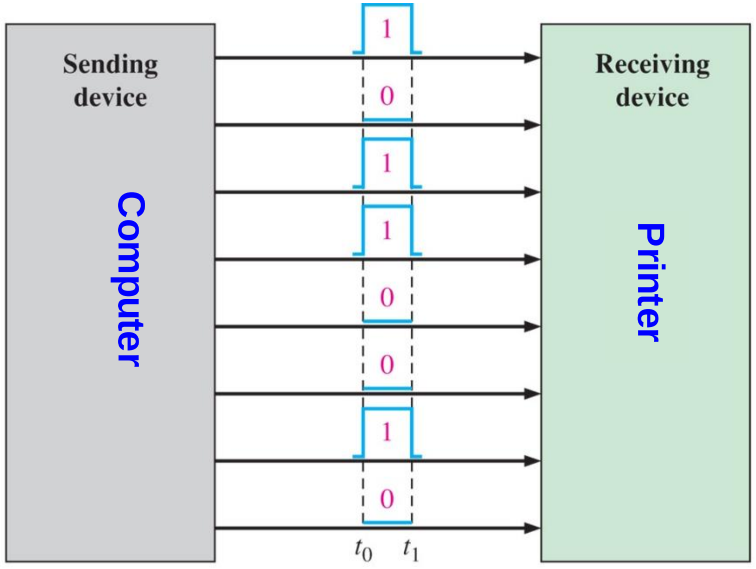
Shift Registers

- Shift register: Several Flip-Flops
  - Data Storage
  - Data Movement





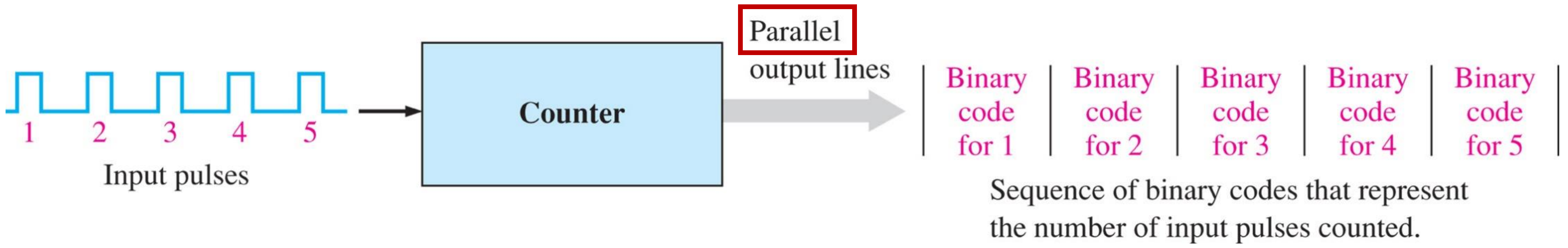
Serial: One bit at a time over a single line
Example: 8 time intervals for 8 bits



Parallel : multiple bits at the same time over separate lines
Example: 1 time interval for 8 bits

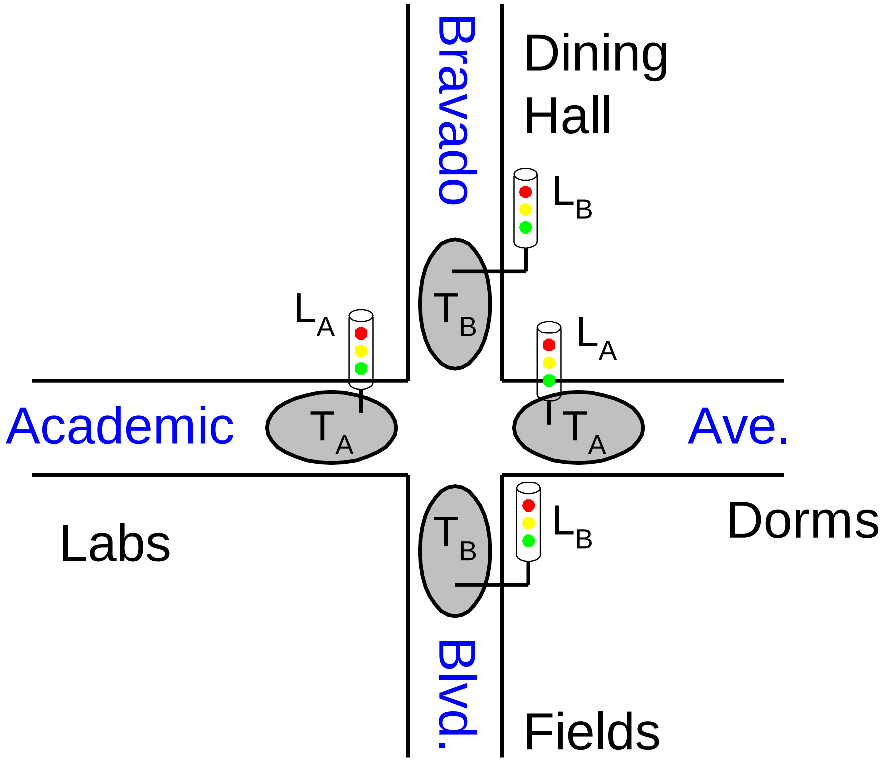
Counters

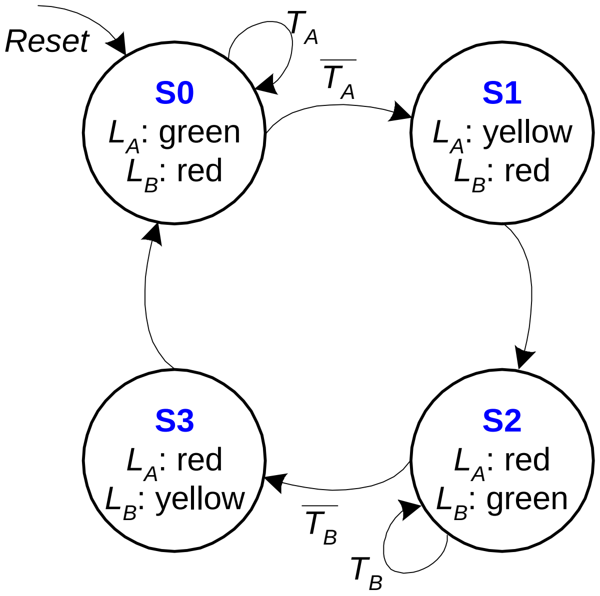
- To count, the counter must "**remember**" the present number so that it can go to the next proper number **in sequence**.
- **Storage** capability is an important characteristic of all counters, and **flip-flops** are generally used to implement them.



Finite State Machine

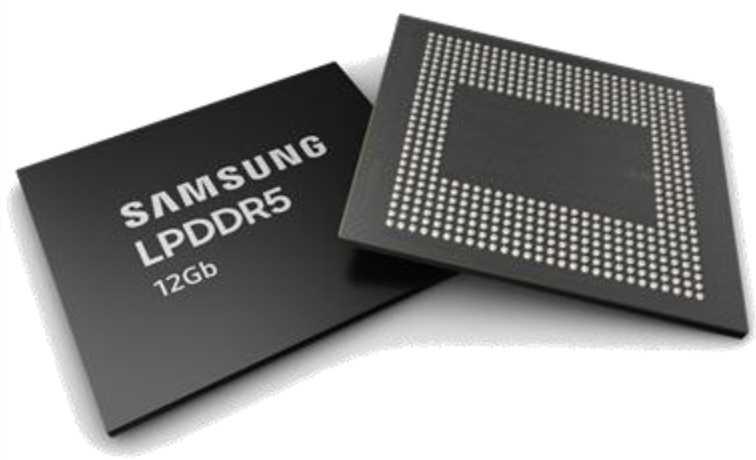
- State Register + Combinational Logic
- States and transitions
- Example: Traffic light controller system

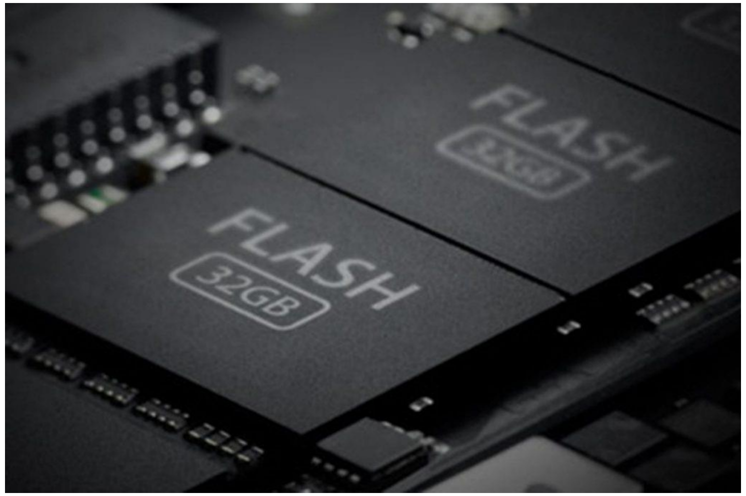




Memory

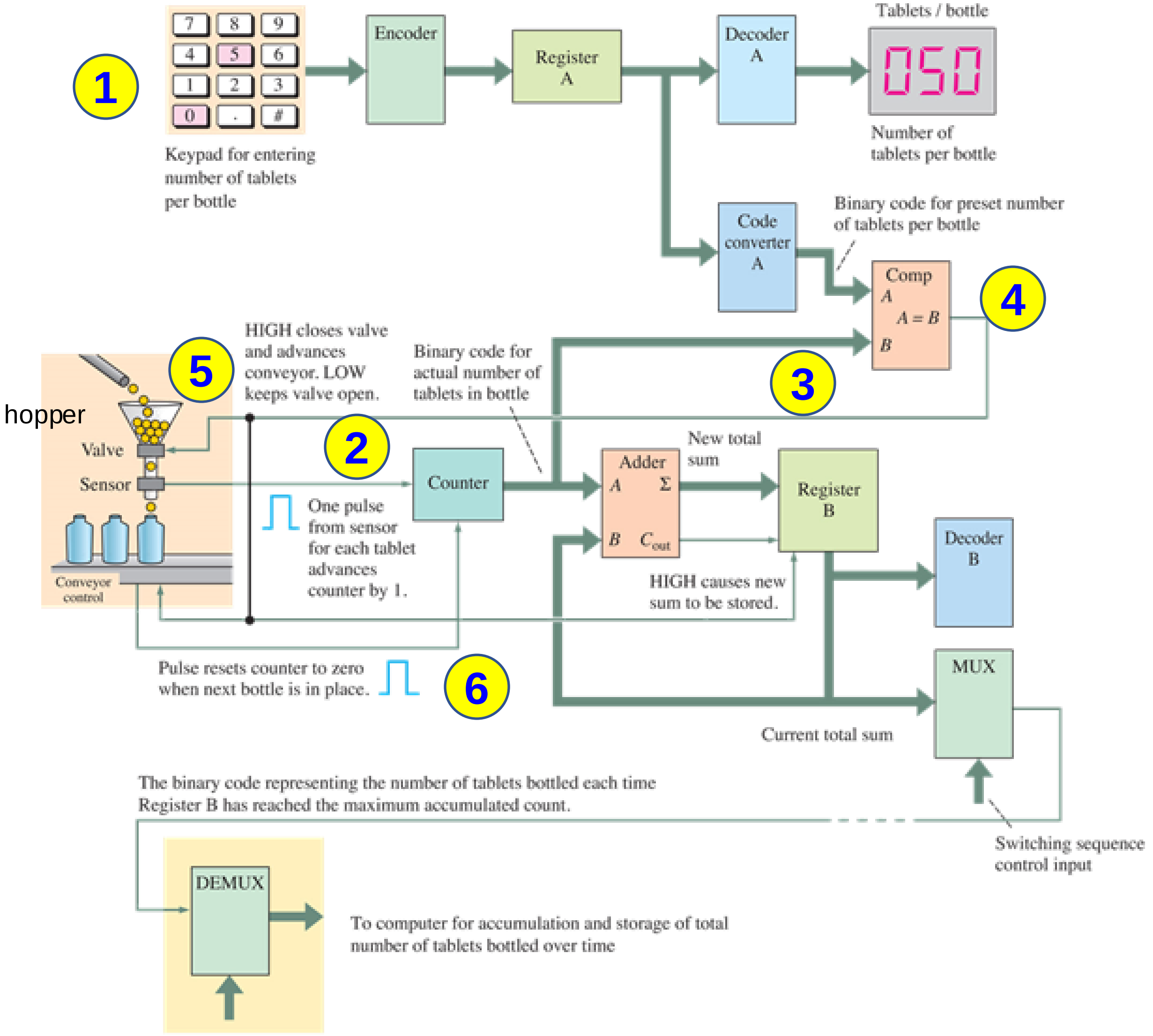
- SRAM, DRAM
- ROM
- Flash





Example: A Process Control System

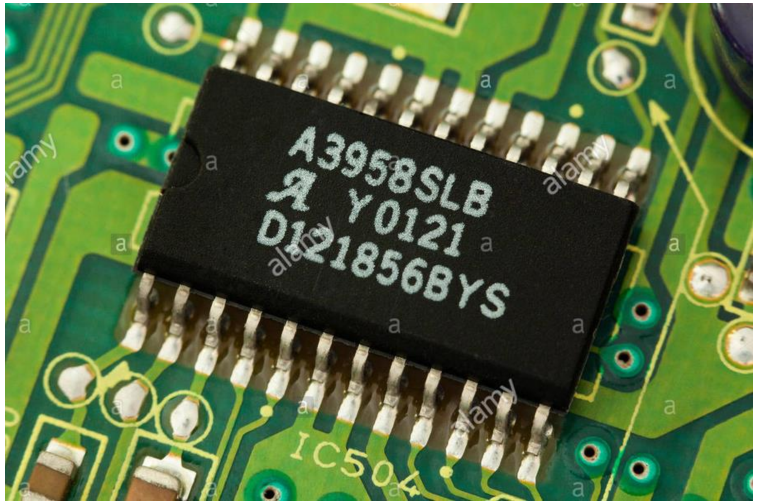
1. The maximum # of tablets per bottle is entered from the keypad;
2. An optical sensor detects each passing tablet & produces a pulse going to the **Counter** → Counter advanced by one;
3. The binary count is transferred from the counter to the B input of the **comparator**;
4. If A=B, **comparator** output goes HIGH, implying the bottle is full;
5. The HIGH comparator output closes the hopper valve & stop the flow of tablets while activating the conveyor to move the next empty bottle into place
6. When the bottle is in place, a pulse is issued to reset the counter to zero → the comparator output goes back LOW & the hopper valve restarts the flow of tablets.



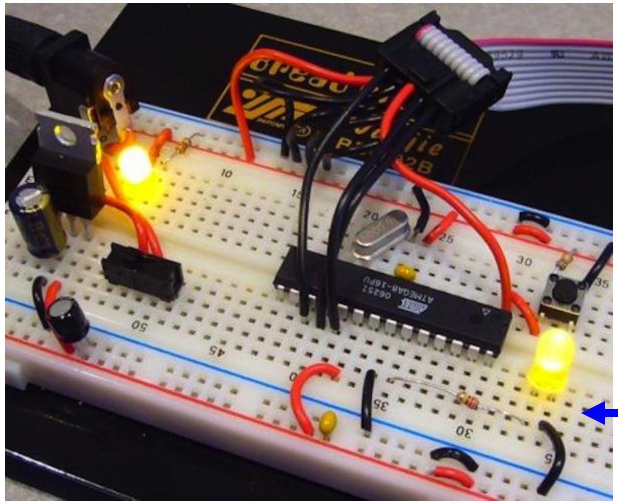
Integrated Circuits (IC)

- An electronic circuit entirely constructed on a single small chip of silicon
- Programmable and Fixed-function Logic
- IC packages :

Surface-mounted



Through-hole mounted

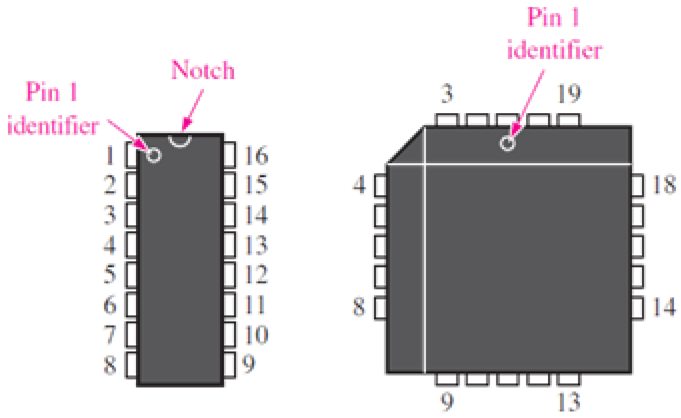


面包板
or
免焊万用电路板
Solderless
breadboard

Complexity of Fixed-Function ICs

	# of gate circuits on a single chip	Typical Examples
Small-scale integration (SSI)	<10	Basic gates and flip-flop
Medium-scale integration (MSI)	10 to 100	Encoders, Decoders, Counters, Registers, Multiplexers, Arithmetic circuits, Small memories
Very large-scale integration (VLSI)	10,000 to 100,000	Memories
Ultra large-scale integration (ULSI)	>100,000	Very large memories, Larger micro-processors, Larger single-chip computers

Pin Numbering

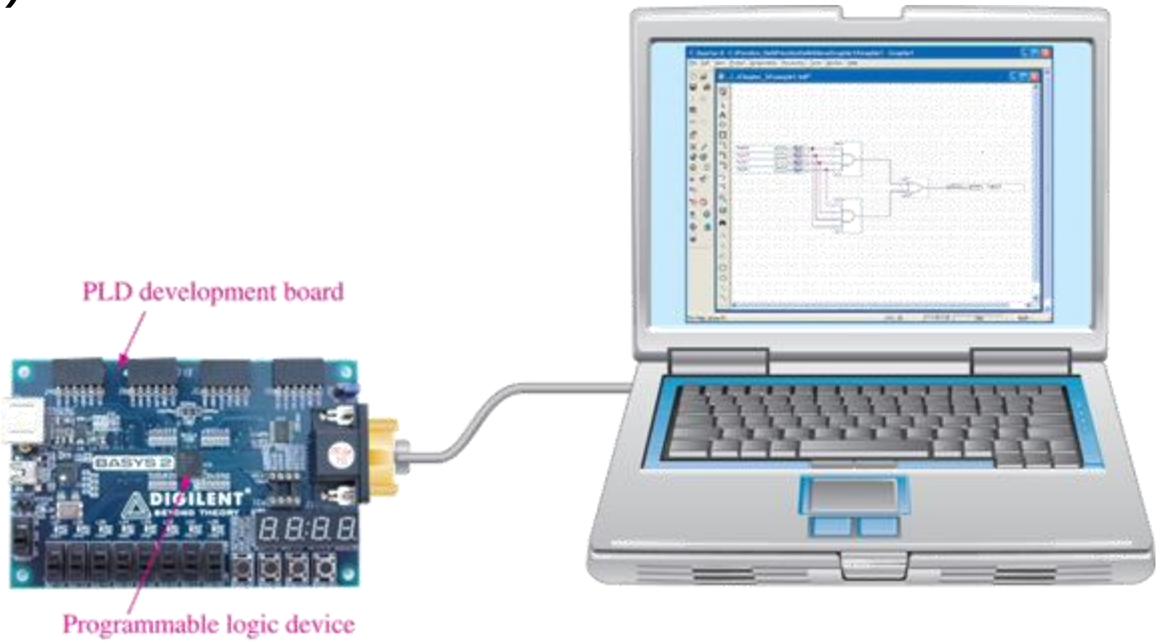


Programmable Logic

- Programmable Logic Devices (PLDs)
  - SPLDs (simple PLDs)
  - CPLDs (complex PLDs)

- Field-Programmable Gate Array (FPGA)

- Programing Process
  - Software development package installed on a computer
    - Graphic entry of a logic circuit
    - Text entry such as VHDL
  - A development board
  - A cable



Chapter Review

- Analog versus Digital
- Bits (Binary digits), Logic Levels and Digital Waveforms
- Basic logic functions: NOT, AND and OR
- Combinational & sequential logic functions:

  comparator, adder, encoder/decoder, (de)multiplexer,

  flip-flops, registers, counter
- Integrated circuit (IC): Programmable versus Fixed-function
  - Package: Surface-mounted and Through-hole
  - Programmable: PLD (SPLD and CPLD) and FPGA
  - Fixed-function : SSI/MSI/VLSI/ULSI

True/False Quiz

- ✓ An analog quantity is one having continuous values.
- ✗ A digital quantity has no discrete values.
- ✓ There are two digits in the binary system.
- ✓ The term bit is short for binary digit.
- ✗ In positive logic, a LOW level represents a binary 1.
- ✗ An AND function is implemented by a logic circuit known as an inverter.
- ✗ A flip-flop is a bistable logic circuit that can store only two bits at a time.
- ✓ Two broad types of digital integrated circuits are fixed-function and programmable.