(Yet Another) Introduction

Lecture 1
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Outline: Introduction

Textbook: [K&B2e] 1.1, 1.3, 1.4

- **Logic Design**
- Computation
  - Switches
  - Transistors
- Combinational vs. Sequential Digital Circuits
- Examples
  - Combinational digital circuit
  - Sequential digital circuit

Logic design: Why we study?

- **It is the implementation basis for all modern computing devices**
  - Building large things from small components
  - provide a model of how a computer works

- **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

Logic design: What we learn in the class?

- **The basics of logic design**
  - Boolean algebra, logic minimization, state, timing, CAD tools

- **The concept of state in digital systems**
  - Analogous to variables in software systems

Logic design: What we learn in the class?

- **How to specify/simulate/compile/realize our designs**
  - hardware description languages (HDLs)
  - tools to simulate the workings of our designs
  - logic compilers to synthesize the hardware blocks of our designs
  - mapping onto programmable hardware

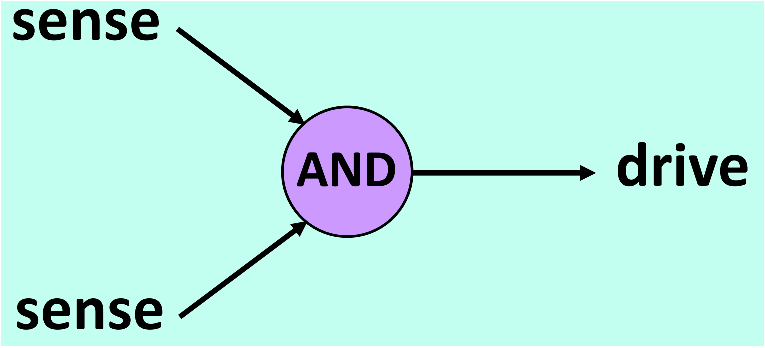
- **Contrast with software design**
  - sequential and parallel implementations
  - specify algorithm as well as computing/storage resources it will use

Logic design: What is it?

- **What is design?**
  - Given problem spec, solve it with available components
  - While meeting quantitative (size, cost, power) and qualitative (beauty, elegance)
- **What is logic design?**
  - Choose digital logic components to perform specified control, data ma nipulation, or communication function and their interconnection
  - Which logic components to choose?
    Many implementation technologies (fixed-function components, prog rammable devices, individual transistors on a chip, etc.)
  - Design optimized/transformed to meet design constraints

Logic design: What is digital hardware?

- **Collection of devices that sense and/or control wires, which carry a digital value (i.e., a physical quantity that can be interpreted as a “0” or “1”)**
  - example: digital logic where voltage <0.8V is a “0” and >2.0V is 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



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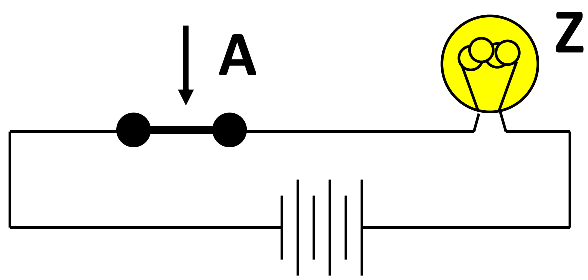
Computation: abstract vs. implementation

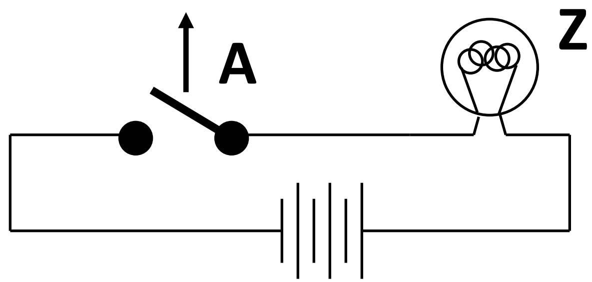
- **Computation has been a mental exercise (paper, programs)**
- **This class is about physically *implementing* computation using voltages to represent logical values**
- **Basic units of computation are:**
  - representation: "0", "1" on a wire
    set of wires (e.g., binary integer)
  - assignment: 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



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)

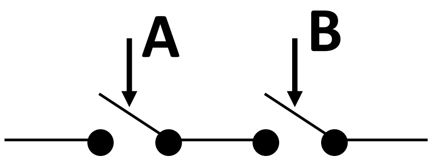
$$Z \equiv A$$

Z and A are equivalent boolean variables

Switches: Basic element of physical implementations

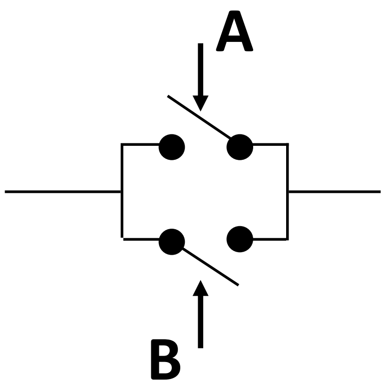
- Compose switches into more complex ones (Boolean functions):

AND



Z ≡ A <u>and</u> B

OR



Z ≡ A <u>or</u> B

Switches: 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.

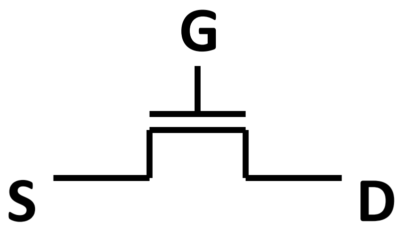
Transistors

- **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: nMOS and pMOS
- **MOS transistors act as voltage-controlled switches**

*** CMOS: complementary metal-oxide semiconductor**

Transistors: MOS transistors

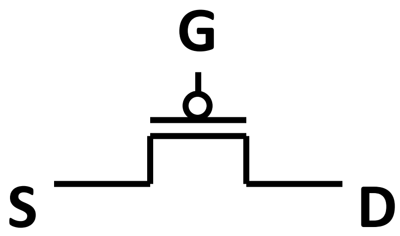
- **MOS transistors have three terminals: drain, gate, and source**
  - they act as switches in the following way:
    if the voltage on the gate terminal is (some amount) higher/lower than the source terminal, then a conducting path will be established between the drain and source terminals



n-channel

open when voltage at G is low

closed when voltage at G is high

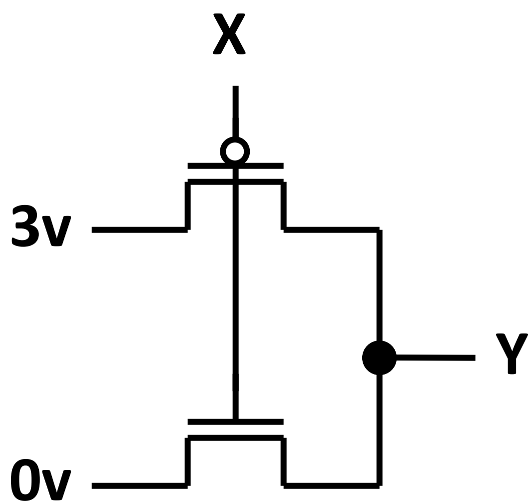


p-channel

closed when voltage at G is low

open when voltage at G is high

Transistors: MOS networks

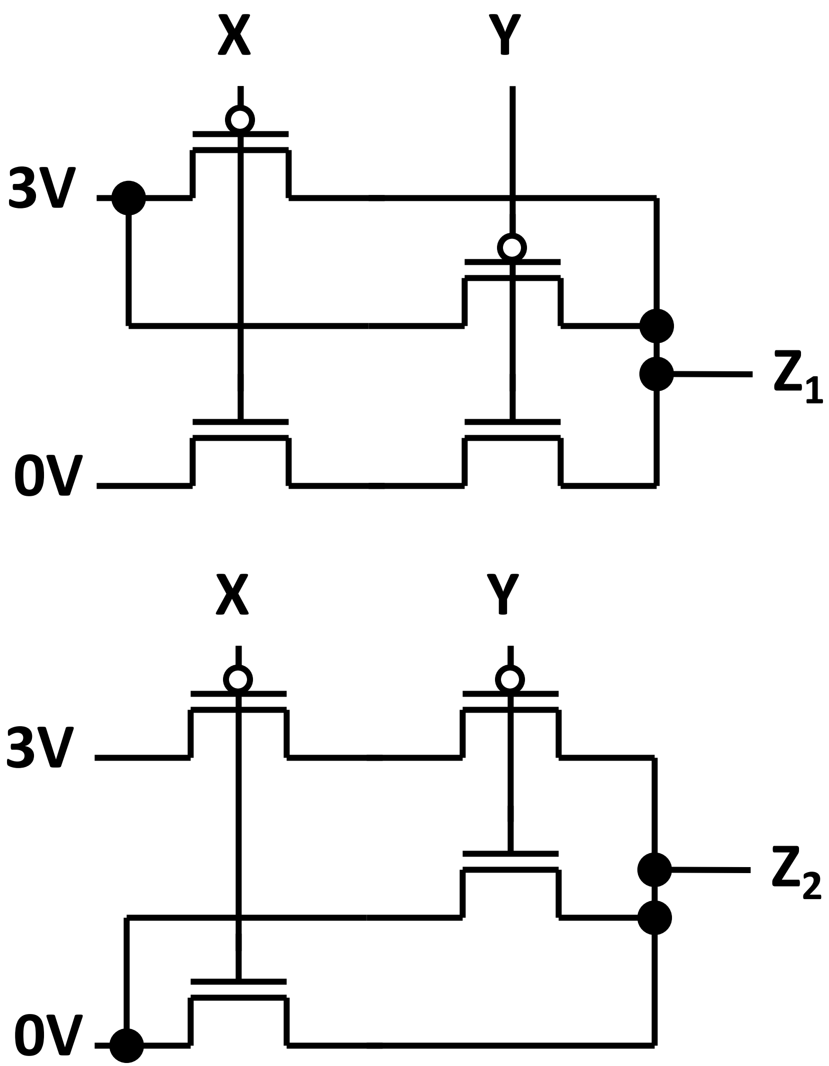


what is the relationship between x and y?

x	y
0 volts	
3 volts	

- **A simple component is made up of two transistors**
  - X: input
  - Y: output
  - What is this function?
- **In CMOS circuits, pMOS and nMOS are used in pair**

Transistors: Two input networks

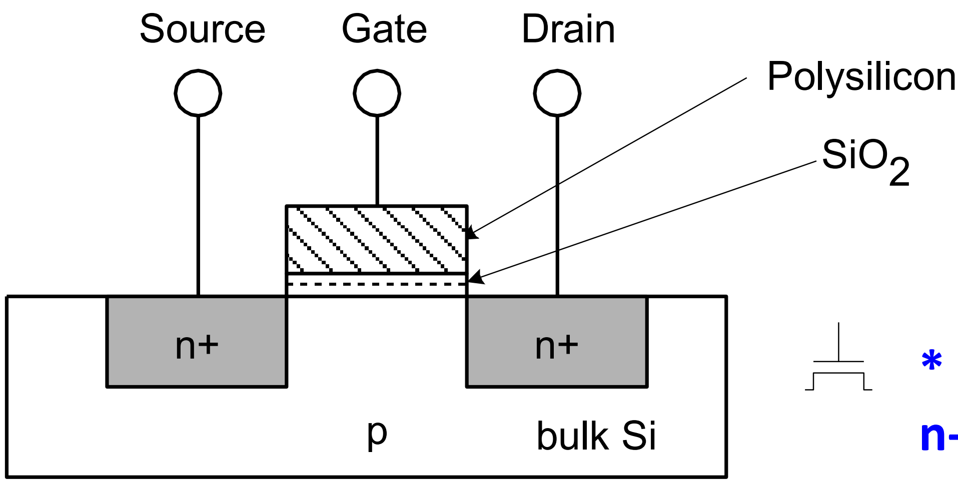


What is the relationship between x, y and z1/z2?

x	y	z1	z2
0 volts	0 volts		
0 volts	3 volts		
3 volts	0 volts		
3 volts	3 volts		

Transistors: n-channel (or n-type) MOS (nMOS)

- **Three terminals: source-gate-drain (or S-G-D for short)**
- **Three layers: polysilicon (used to be metal) – SiO2 – substrate**

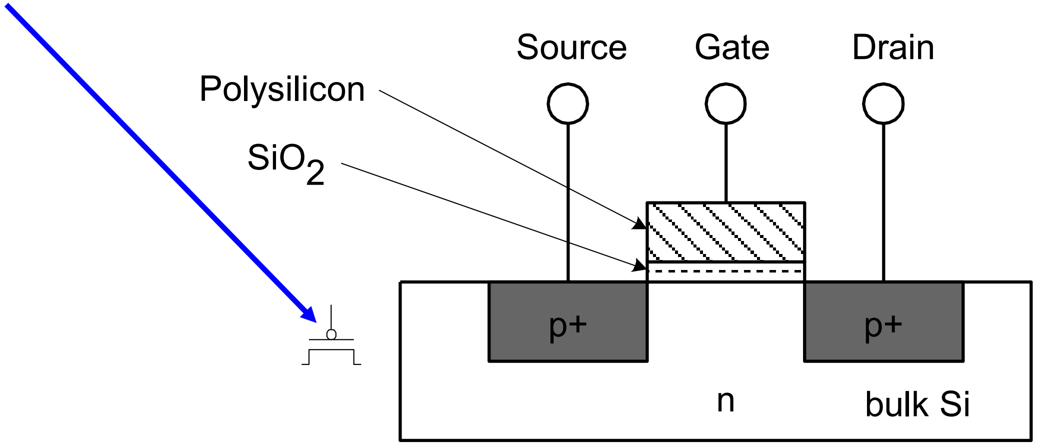


*** n+: heavily doped n-type semiconductor**

- **If G is at positive voltage, electrons in the substrate will move toward G terminal, which sets up a channel between S and D**
  - And D is at high voltage, current will flow from drain to source
- **Metal is replaced by polysilicon which is more adhesive**

Transistors: p-channel (or p-type) MOS (pMOS)

- **Three terminals: source-gate-drain (or S-G-D for short)**
- **Same principle, but reverse doping and voltage**
  - Source (Vss) is positive with regard to drain (Vdd)
- **Bubble indicates the inverted behavior**



- **If G is at positive voltage, the current does not flow**
- **If G is at ground level, the current flows**

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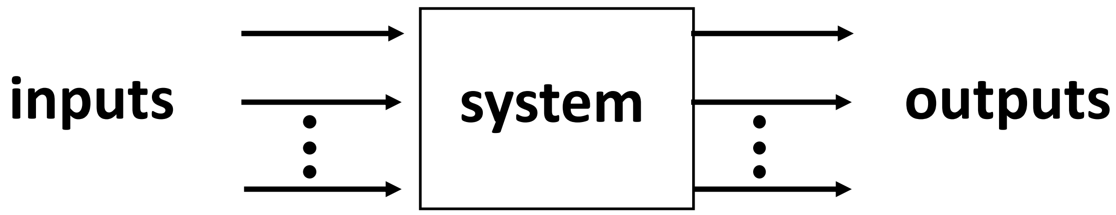
- **Combinational vs. Sequential digital circuits**
- Examples
  - Combinational digital circuit
  - Sequential digital circuit

Review: Digital vs. Analog

- **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
  - Quantization error (loss of information), though
- **Why does it work?**
  - does not propagate small errors in values
  - always resets to 0 or 1

Combinational vs. sequential digital circuits

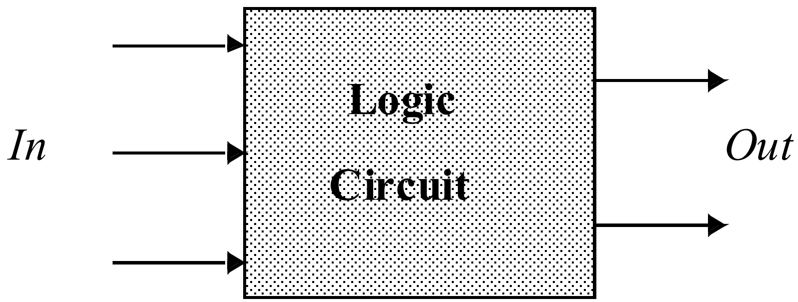
- **A simple model of a digital system is a unit with inputs and outputs:**



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

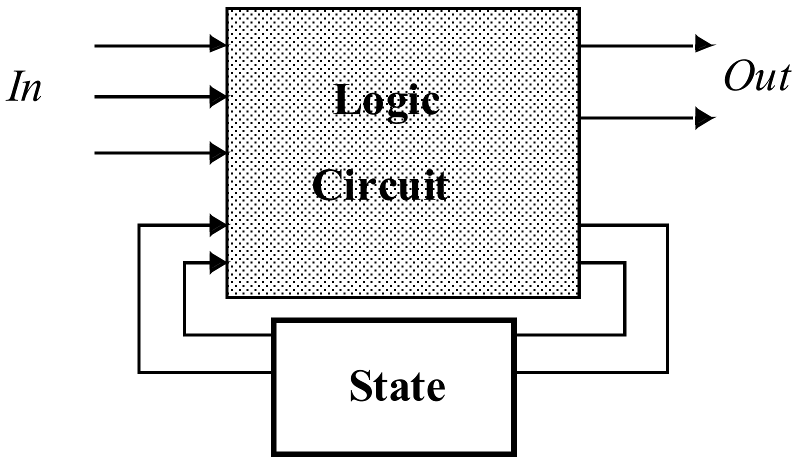
- **Sequential systems**
  - exhibit behaviors (output values) that depend not only on the current input values, but also on previous input values

Combinational vs. sequential digital circuits



(a) Combinational

Output = $f(In)$



(b) Sequential

Output = $f(In, \textit{Previous In})$

Combinational logic symbols

- **Common combinational logic systems have standard symbols called logic gates**
  - Buffer, NOT

  - AND, NAND

  - OR, NOR

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

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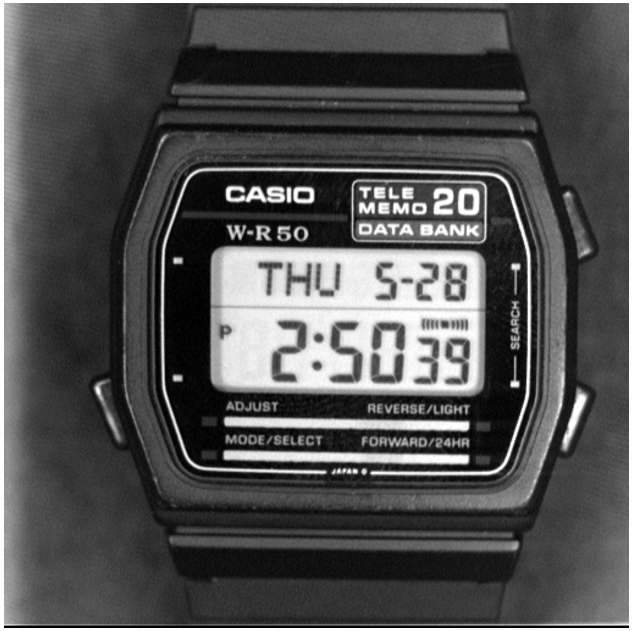
Example #1: Combinational digital circuit

- **Calendar subsystem: number of days in a month (to control watch display)**
  - Combinational logic
  - used in controlling the display of a wrist-watch LCD screen

  - inputs: month, leap year flag
  - outputs: number of days



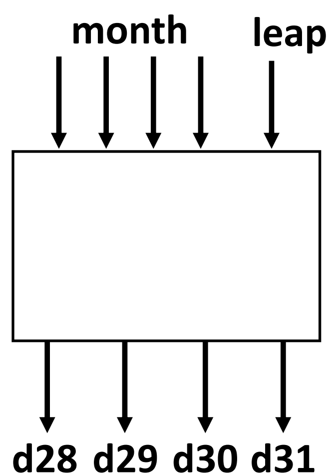
Example #1: Combinational digital circuit

- Reference implementation in software

```
integer number_of_days (month, leap_year_flag)
{
   switch (month) {
      case 1: return (31);
      case 2: if (leap_year_flag == 1) then return (29)
                                       else return (28);
      case 3: return (31);
      ...
      case 12: return (31);
      default: return (0);
   }
}
```

Example #1: Combinational digital circuit

- **Implementation as a combinational digital system**
  - Encoding:
    - how many bits for each input/output?
    - binary number for month
    - four wires for 28, 29, 30, and 31
  - Behavior:
    - combinational
    - truth table specification



Don't care

month	leap	d28	d29	d30	d31
0000	–	–	–	–	–
0001	–	0	0	0	1
0010	0	1	0	0	0
0010	1	0	1	0	0
0011	–	0	0	0	1
0100	–	0	0	1	0
0101	–	0	0	0	1
0110	–	0	0	1	0
0111	–	0	0	0	1
1000	–	0	0	0	1
1001	–	0	0	1	0
1010	–	0	0	0	1
1011	–	0	0	1	0
1100	–	0	0	0	1
1101	–	–	–	–	–
111–	–	–	–	–	–

Example #1: Combinational digital circuit

- **Truth-table to logic to switches to gates**
  - d28 = 1 when month=0010 and leap=0
  - d28 = m8'•m4'•m2•m1'•leap'
  - d31 = 1 when month=0001 or month=0011 or ... month=1100
  - d31 = (m8'•m4'•m2'•m1) + (m8'•m4'•m2•m1) + ... (m8•m4•m2'•m1')
  - d31 = can we simplify more?

symbol for not

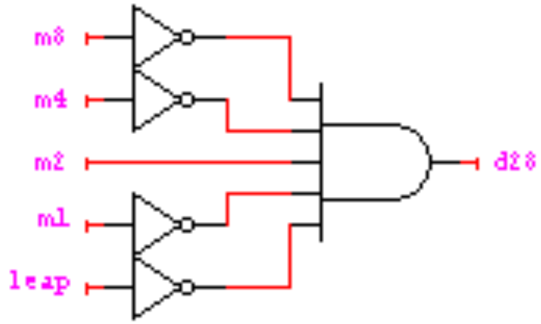
symbol for and

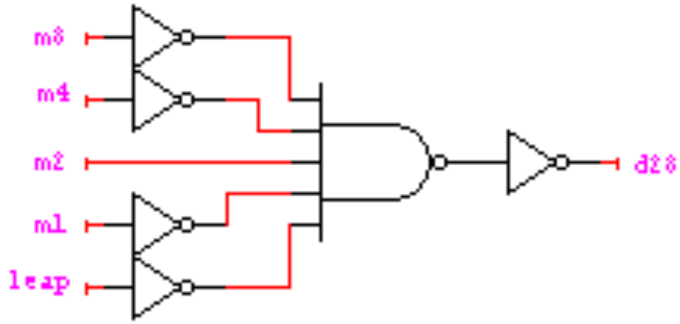
symbol for or

month	leap	d28	d29	d30	d31
0001	–	0	0	0	1
0010	0	1	0	0	0
0010	1	0	1	0	0
0011	–	0	0	0	1
0100	–	0	0	1	0
...					
1100	–	0	0	0	1
1101	–	–	–	–	–
111–	–	–	–	–	–
0000	–	–	–	–	–

Example #1: Combinational digital circuit

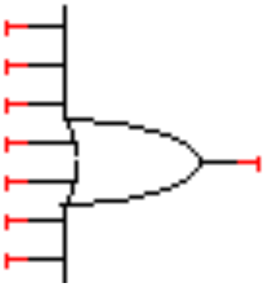
- d28 = m8'•m4'•m2•m1'•leap’
- d29 = m8'•m4'•m2•m1'•leap
- d30 = (m8'•m4•m2'•m1') + (m8'•m4•m2•m1') +
  (m8•m4'•m2'•m1) + (m8•m4'•m2•m1)
  = (m8'•m4•m1') + (m8•m4'•m1)
- d31 = (m8'•m4'•m2'•m1) + (m8'•m4'•m2•m1) +
  (m8'•m4•m2'•m1) + (m8'•m4•m2•m1) +
  (m8•m4'•m2'•m1') + (m8•m4'•m2•m1') +
  (m8•m4•m2'•m1')

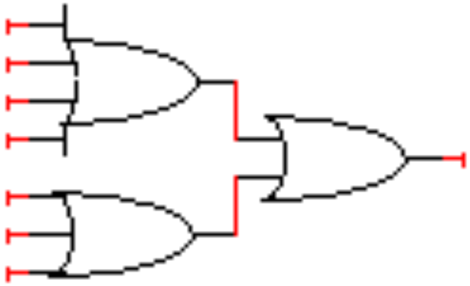




Example #1: Combinational digital circuit

- d28 = m8'•m4'•m2•m1'•leap’
- d29 = m8'•m4'•m2•m1'•leap
- d30 = (m8'•m4•m2'•m1') + (m8'•m4•m2•m1') +
  (m8•m4'•m2'•m1) + (m8•m4'•m2•m1)
- d31 = (m8'•m4'•m2'•m1) + (m8'•m4'•m2•m1) +
  (m8'•m4•m2'•m1) + (m8'•m4•m2•m1) +
  (m8•m4'•m2'•m1') + (m8•m4'•m2•m1') +
  (m8•m4•m2'•m1')





Example #1: Combinational digital circuit

- **Summary of Combinational Circuit Design**
  - **Step 1: Block Diagram (Specify Inputs and Outputs)**
  - **Step 2: Truth Table**
  - **Step 3: Implementation**

Example #2: Sequential digital circuit

- **Door combination lock**
  - punch in 3 values in sequence and the door opens; if there is an error the lock must be reset; once the door opens the lock must be reset
  - sequential logic
  - inputs: sequence of input values, reset
    - Numeric number: 4 wires
  - outputs: door open/close
  - memory: must remember combination or always have it available as an input

Example #2: Sequential digital circuit

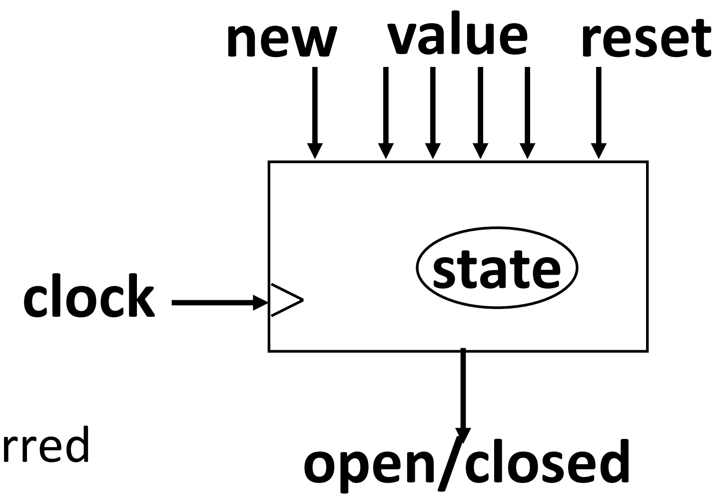
- Reference implementation in software

```
integer combination_lock ( ) {
    integer v1, v2, v3;
    integer error = 0;
    static integer c[3] = 3, 4, 2;

    while (!new_value( ));
    v1 = read_value( );
    if (v1 != c[1]) then error = 1;

    while (!new_value( ));
    v2 = read_value( );
    if (v2 != c[2]) then error = 1;

    while (!new_value( ));
    v3 = read_value( );
    if (v2 != c[3]) then error = 1;

    if (error == 1) then return(0); else return (1);
}
```

Array index starts from 1

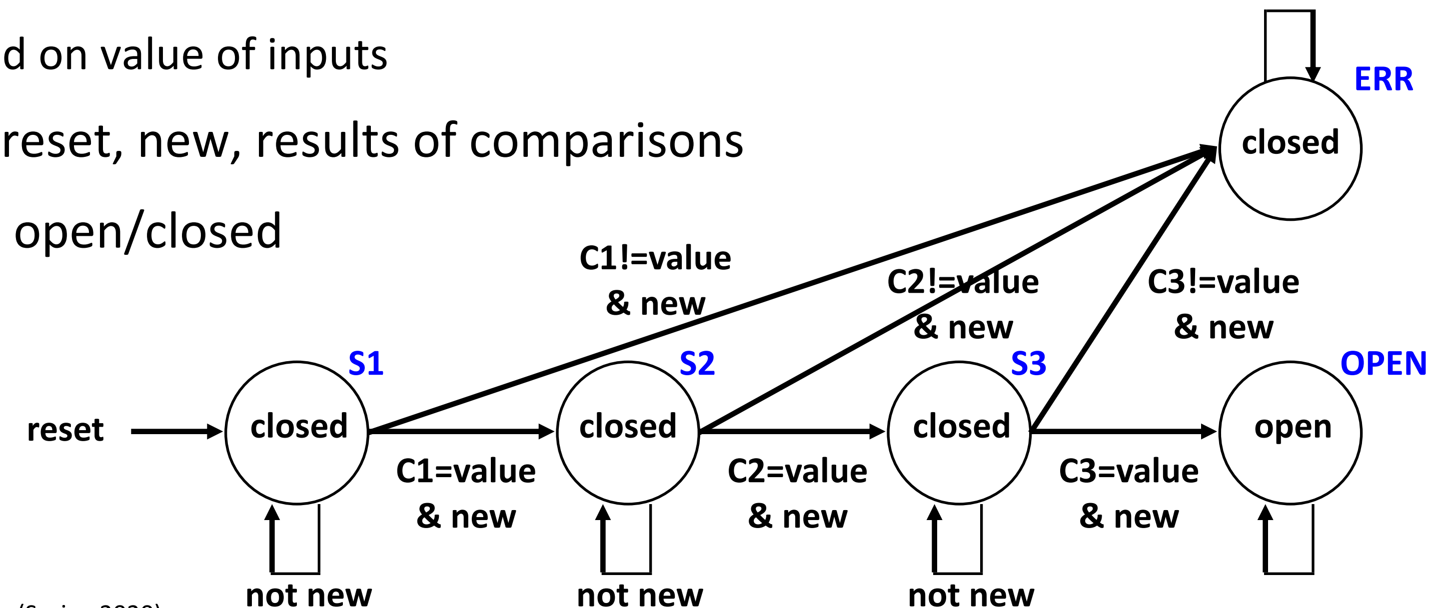
Example #2: Sequential digital circuit

- **Implementation as a sequential digital system**
  - Encoding:
    - how many bits per input value?
    - how many values in sequence?
    - how do we know a new input value is entered?
    - how do we represent the states of the system?
  - Behavior:
    - clock wire tells us when it's ok
      to look at inputs
      (i.e., they have settled after change)
    - sequential: sequence of values
      must be entered
    - sequential: remember if an error occurred
    - finite-state specification



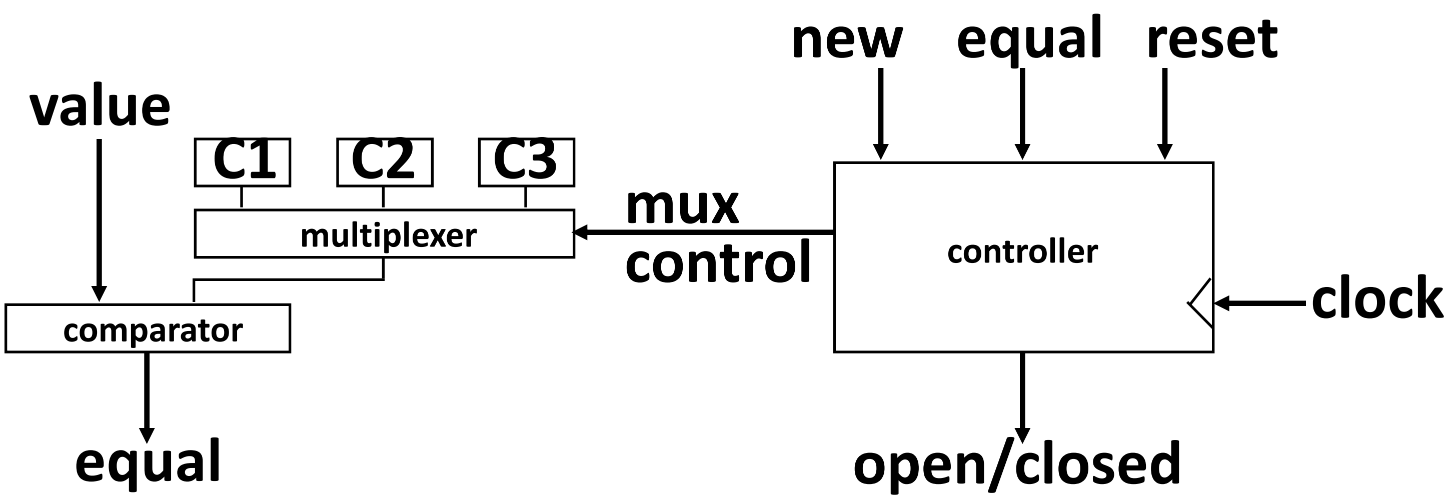
Example #2: Sequential digital circuit

- **Abstract control: Finite-state diagram**
  - states: 5 states
    - represent point in execution of machine
    - each state has inputs and outputs
  - transitions: 6 from state to state, 5 self transitions, 1 global
    - changes of state occur when clock says it's ok
    - based on value of inputs
  - inputs: reset, new, results of comparisons
  - output: open/closed



Example #2: Sequential digital circuit

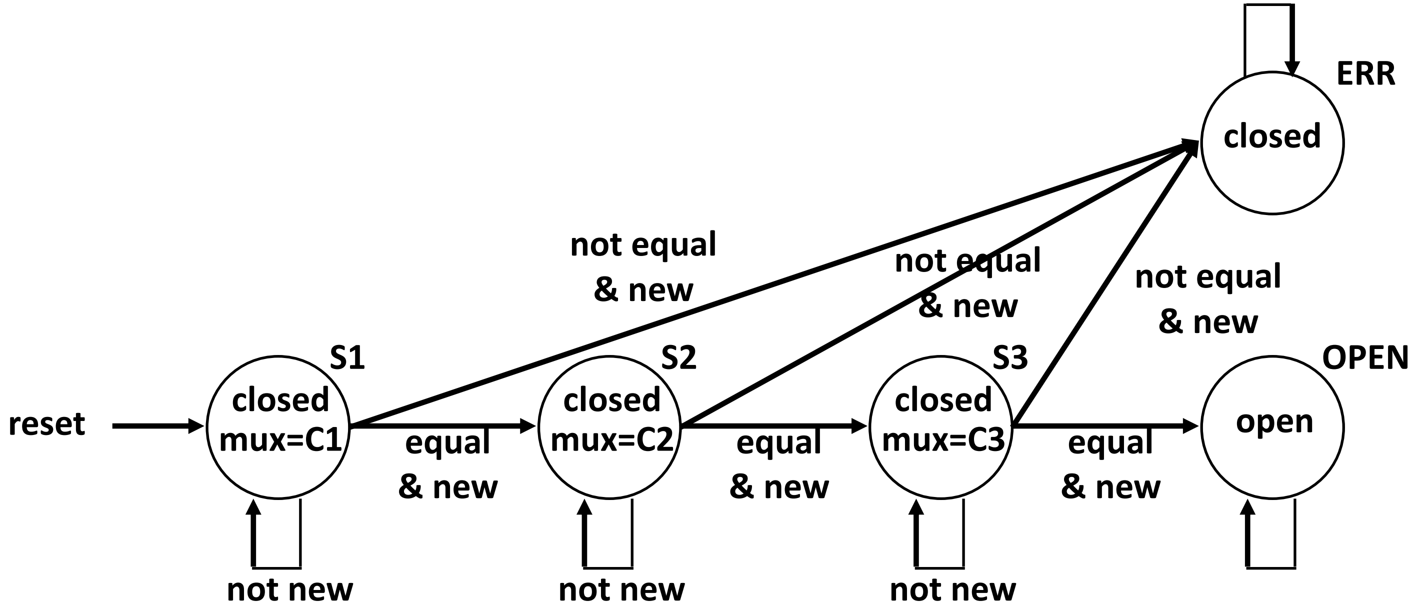
- **Internal structure: Data-path vs. control**
  - data-path
    - storage for combination
    - comparators
  - control
    - finite-state machine controller
    - control for data-path
    - state changes controlled by clock



*** Multiplexer (MUX)**

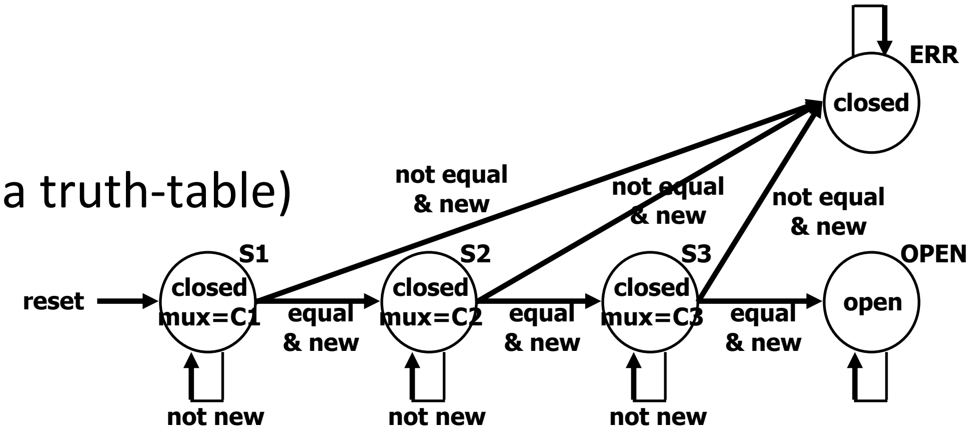
Example #2: Sequential digital circuit

- **Finite-state machine (FSM)**
  - refine state diagram to include internal structure



Example #2: Sequential digital circuit

- Finite-state machine (cont'd)
  - generate state table (much like a truth-table)



reset	new	equal	state	next state	mux	open/closed
1	–	–	–	S1	C1	closed
0	0	–	S1	S1	C1	closed
0	1	0	S1	ERR	–	closed
0	1	1	S1	S2	C2	closed
0	0	–	S2	S2	C2	closed
0	1	0	S2	ERR	–	closed
0	1	1	S2	S3	C3	closed
0	0	–	S3	S3	C3	closed
0	1	0	S3	ERR	–	closed
0	1	1	S3	OPEN	–	open
0	–	–	OPEN	OPEN	–	open
0	–	–	ERR	ERR	–	closed

* state is not input, but internal variable

Example #2: Sequential digital circuit

- **Encoding: Encode state table**
  - state can be: S1, S2, S3, OPEN, or ERR
    - needs at least 3 bits to encode: 000, 001, 010, 011, 100
    - and as many as 5: 00001, 00010, 00100, 01000, 10000
    - choose 4 bits: 0001, 0010, 0100, 1000, 0000
  - output mux can be: C1, C2, or C3
    - needs 2 to 3 bits to encode
    - choose 3 bits: 001, 010, 100
  - output open/closed can be: open or closed
    - needs 1 or 2 bits to encode
    - choose 1 bits: 1, 0

Example #2: Sequential digital circuit

- **Encoding: Encode state table (cont'd)**
  - state can be: S1, S2, S3, OPEN, or ERR
    - choose 4 bits: 0001, 0010, 0100, 1000, 0000
  - output mux can be: C1, C2, or C3
    - choose 3 bits: 001, 010, 100
  - output open/closed can be: open or closed
    - choose 1 bits: 1, 0

Internal input

Internal output

system's or external output

external input

reset	new	equal	state	next state	mux	open/closed
1	–	–	–	0001	001	0
0	0	–	0001	0001	001	0
0	1	0	0001	0000	–	0
0	1	1	0001	0010	010	0
0	0	–	0010	0010	010	0
0	1	0	0010	0000	–	0
0	1	1	0010	0100	100	0
0	0	–	0100	0100	100	0
0	1	0	0100	0000	–	0
0	1	1	0100	1000	–	1
0	–	–	1000	1000	–	1
0	–	–	0000	0000	–	0

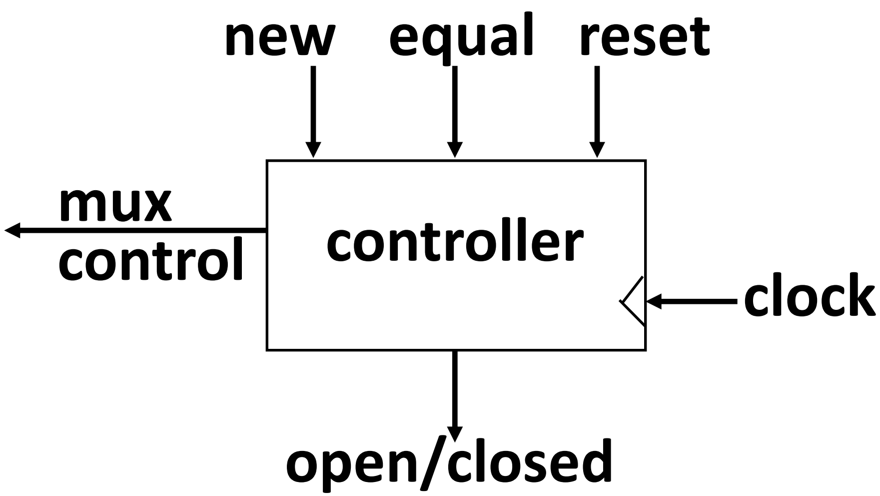
good choice of encoding!

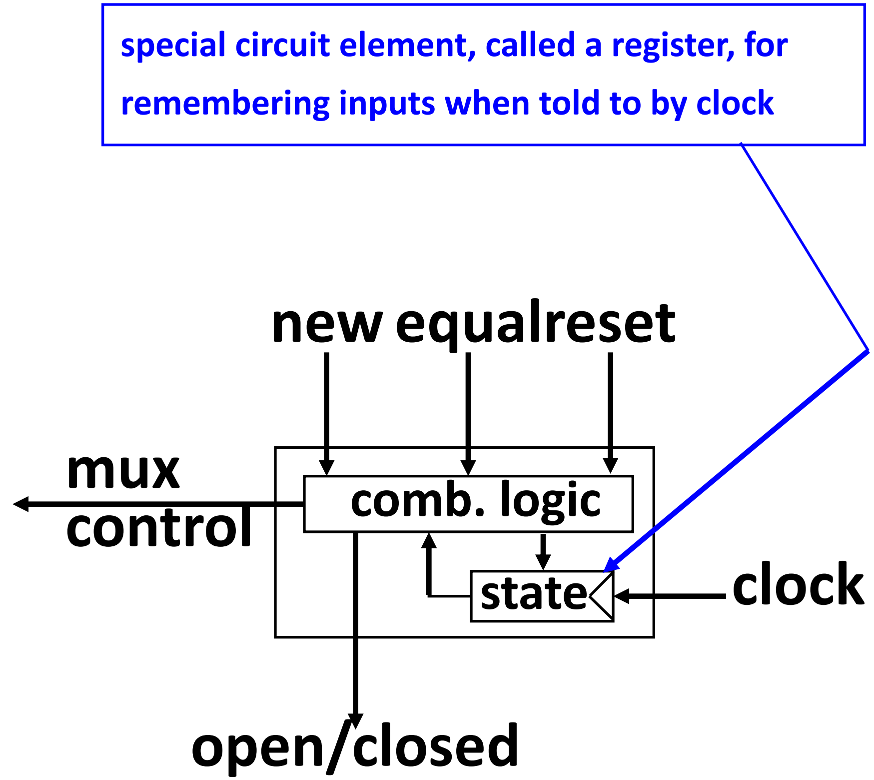
mux is identical to last 3 bits of next state

open/closed is identical to first bit of next state

Example #2: Sequential digital circuit

- Implementation of the controller





Example #2: Sequential digital circuit

- **Summary of Sequential Circuit Design**
  - **Step 1: Block diagram (Specify Inputs and Outputs)**
  - **Step 2: State diagram**
  - **Step 3: Decomposition into data part and control part**
  - **Step 4: FSM for control part**
  - **Step 5: Implementation**

Summary

- **That was what the entire course is about**
  - converting solutions for problems into combinational and sequential networks effectively organizing the design hierarchically
  - doing so with a modern set of design tools that lets us handle large designs effectively
  - taking advantage of optimization opportunities
- **Now let's do it again**
  - this time we'll take the rest of the semester!