CSEP567: **Design and Implementation of Digital Systems**

- Course staff:
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- Course web:
  - http://www.cs.washington.edu/education/courses/csep567/04sp/
  - My office: CSE 464 Allen Center, 206 543-6274

- Today
  - Class administration, overview of course web, and logistics
  - What is logic design?
  - What is digital hardware?
  - What will we be doing in this class?

Highlights:

- -- we'll be reading hand-outs and papers from various sources.
- -- The course work will be built around an embedded-core processor in an FPGA.
- -- Tools are Active-HDL from Aldec, Synplify, and Xilinx ISE.
  -- Languages are verilog and C.

- -- Applications in the FPGA will include some audio.
- -- Lecture-discussion for an hour or so, then into the lab for the rest of the evening.
  -- No hardware experience required.

Labs:

- Lab 1- Atmel AVR Microprocessor PWM experiment
- Lab 2 Tutorials:
  1. Introduction to Active-HAL
  2. Using Verilog with Active-HDL
- Lab 3- AFX_XC1000 Blink program in Verilog
- Lab 4- MicroBlaze Blink Program
- Lab 5- MicroBlaze PWM Program
- Lab 6- Verilog String Synthesis Example
- Lab 7- MicroBlaze String Controller

Why are we here?

- Obvious reasons
  - this course is part of the PMP requirements
  - 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

What will we learn in CSEP567?

- The language of logic design
  - Boolean algebra, logic minimization, state, timing, CAD tools
- The concept of state in digital systems
  - analogous to variables and program counters in software systems
- How to specify/simulate/compile/realize our designs
  - hardware description languages
  - tools to simulate the workings of our designs
  - logic compilers to synthesize the hardware blocks of our designs
  - Use of IP (software microprocessor core)
- Contrast with software design
  - sequential and parallel implementations
  - specify algorithm as well as computing/storage resources it will use

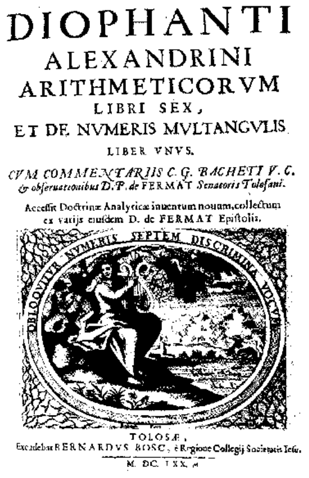
Applications of logic design

- Conventional computer design
  - CPUs, busses, peripherals
- Networking and communications
  - phones, modems, routers
- Embedded products
  - in cars, toys, appliances, entertainment devices
- Scientific equipment
  - testing, sensing, reporting
- The world of computing is much much bigger than just PCs!

The Digital Age

- Computing is in its infancy
  - Processing power
    - Doubles every 18 months
    - Factor of 100 / decade
  - Disk capacity
    - Doubles every 12 months
    - Factor of 1000 / decade
  - Optical fiber transmission capacity
    - Doubles every 9 months
    - Factor of 10,000 / decade
- The bases are mathematics and switches
  - How did we get here?

Diophantus of Alexandria b. ~200 BCE


DIOPHANTI
ALEXANDRINI
ARITHMETICORVM
LIBRI SEX,
ET DE NVMERIS MVLTANGVLIS
LIBER VNVS.
CVM COMMENTARIIS C. G. BACHETI V. C.
& obſeruationibus D. P. de FERMAT Senatoris Toloſani.
Acceſſit Doctrinæ Analyticæ inuentum nouum, collectum
ex varijs eiuſdem D. de FERMAT Epiſtolis.
OBLOQVITVR NVMERIS SEPTEM DISCRIMINA VOCVM
TOLOSÆ,
Excudebat BERNARDVS BOSC, è Regione Collegij Societatis Ieſu.
M. DC. LXX.

Known as the "father of algebra"

***Arithmetica* is a collection of 130 problems that gives numerical solutions of determinate equations, which have a unique solution, and indeterminate equations.**

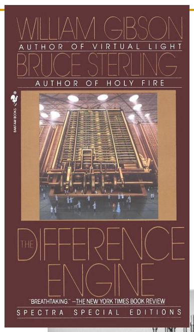
The Later Alexandrian Age was a time when mathematicians were discovering many ideas that lead to our concept of mathematics today.

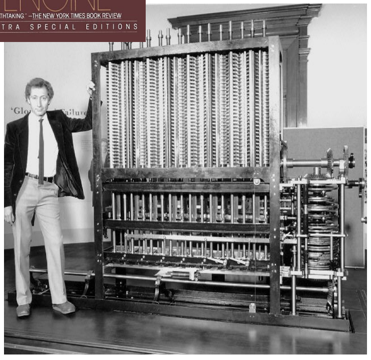
850 AD

- Abu Ja'far Muhammad ibn Musa **al-Khwarizmi**
- Lived in Baghdad, 780 to 850 AD. One of the first to write on algebra (using words, not letters) and also Hindu-Arabic numbers (1, 2, 3, ...).
- From his name and writings came the words "algebra" and "algorithm".
- Book:*Hisab **al-jabr** w'al-muqabala*

1822

- Charles Babbage
  - Father of computing
- 1822 Difference Engine
  - A calculator
- 1834 Analytical Engine
  - A computer
  - Programmable





Analytical Engine

1854

- George Boole
  - Boolean algebra
- Number system with 2 values
  - 0/1 ⇔ false/true
  - Do math on logic statements
  - 3 operations (NOT, AND, OR)

All computers use Boolean algebra

NOT

A	Out
0	1
1	0

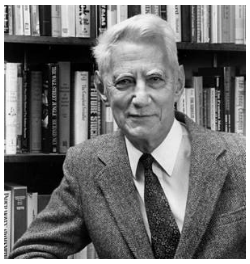
AND

A	B	Out
0	0	0
0	1	0
1	0	0
1	1	1

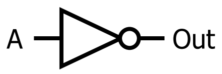
OR

A	B	Out
0	0	0
0	1	1
1	0	1
1	1	1

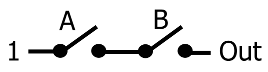
1938



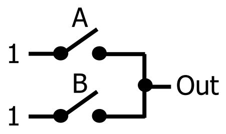
- Claude Shannon
  - Implemented Boolean algebra using switches
  - Described information using binary digits (bits)



NOT



AND



OR

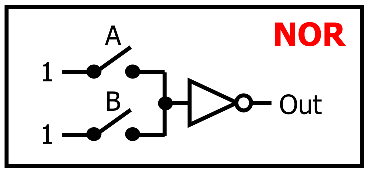
A	Out
0	1
1	0

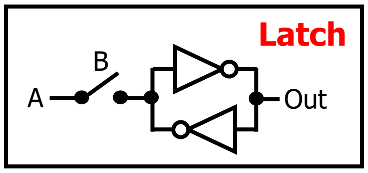
A	B	Out
0	0	0
0	1	0
1	0	0
1	1	1

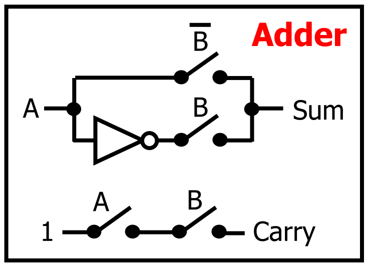
A	B	Out
0	0	0
0	1	1
1	0	1
1	1	1

Computer Hardware

- Components
  - Logic
  - Memory





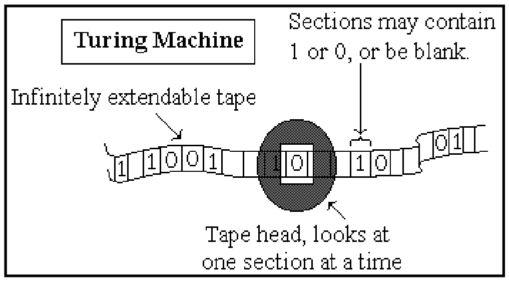


Adder

A	B	Sum	Carry
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

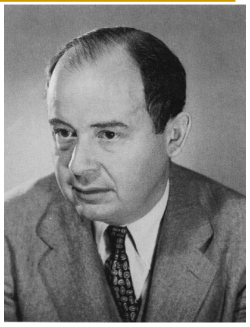
1937

- Alan Turing
  - Turing Machines
- Simple computer model
  - Can something be computed?


Turing Machine
Sections may contain 1 or 0, or be blank.
Infinitely extendable tape
Tape head, looks at one section at a time

Also pioneered artificial intelligence

1945



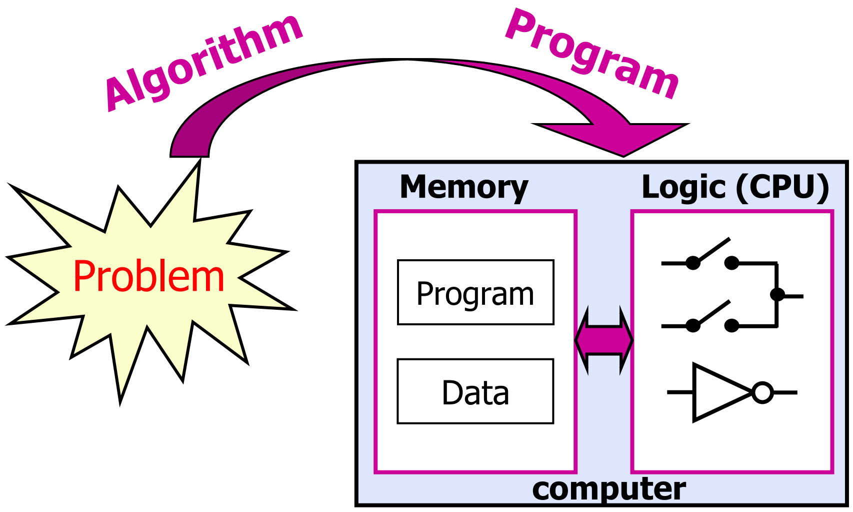
- John von Neumann
  - First stored computer program
- A sequence of operations
  - Read from memory
  - Operate using logic gates
  - Store result into memory

Other contributions:
Quantum Mechanics
Cellular Automata
Game Theory

Stored Programs = Software

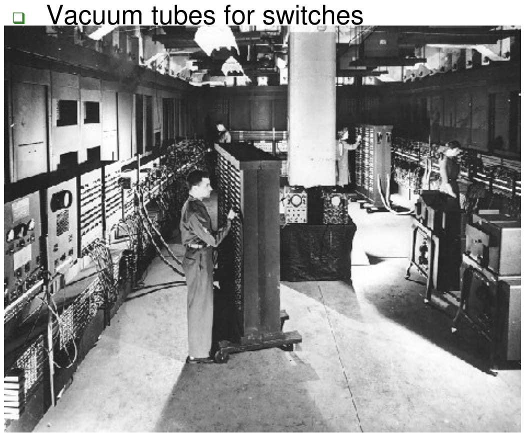
Bill Gates and Paul Allen, Lakeside, 1968

Hardware + Software



1946

- ENIAC…the first computer
  - Vacuum tubes for switches



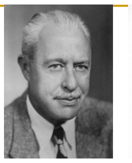
1000x faster than anything before...

19,000 tubes

200 kilowatts

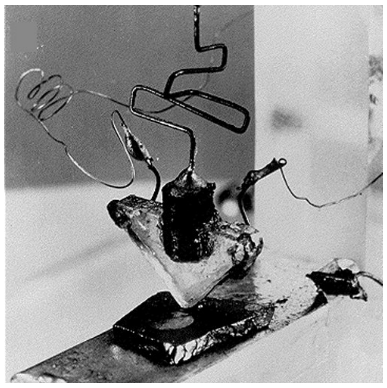
357 multiplies per second

1947



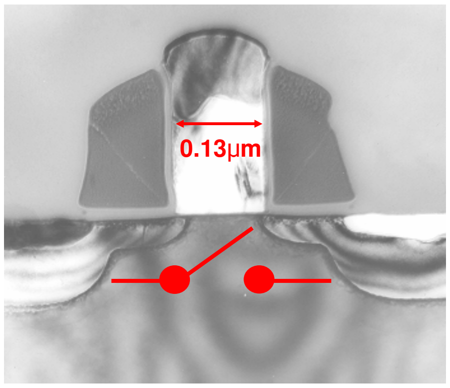
- Bardeen, Brattain, Shockley invent the transistor

1947



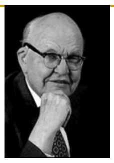
Nobel Prize, 1956

2000

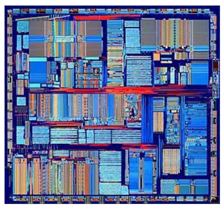


Courtesy Mark Bohr, Intel

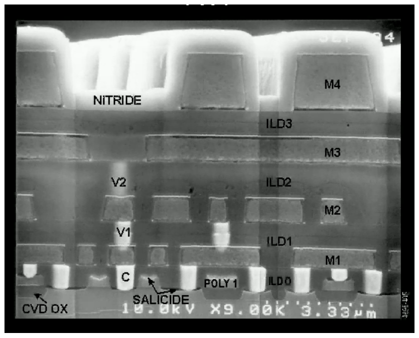
1958



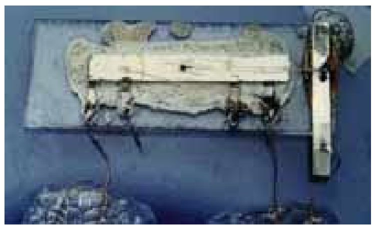
- Kilby and Noyce invent the integrated circuit



2000



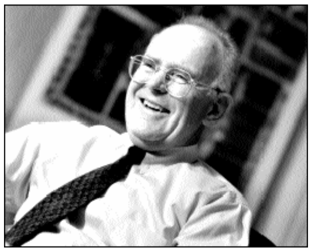
1958



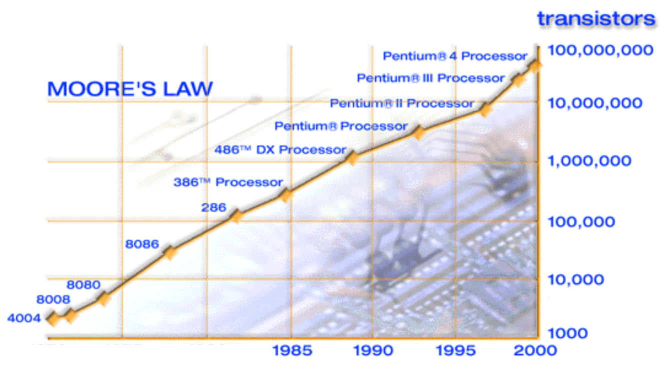
Nobel Prize, 2000

Courtesy Yan Borodovsky, Intel

1965



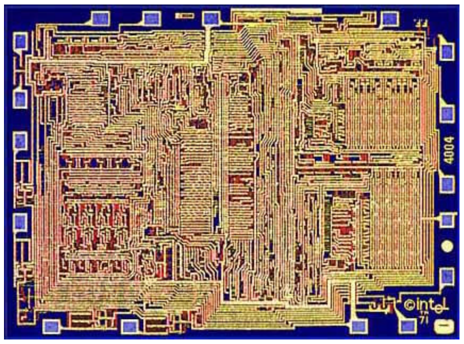
- Gordon Moore
  - Moore's Law: The transistor density of silicon chips doubles every 18 months



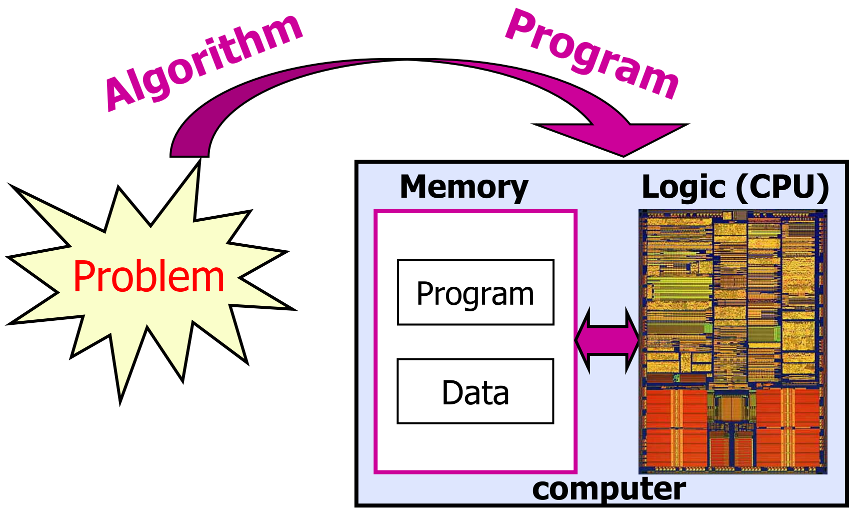
1971

- Ted Hoff invents the microprocessor

  - Intel 4004
    - 2,300 transistors
    - 3 mm by 4 mm
    - As powerful as the ENIAC



Hardware + Software + Technology



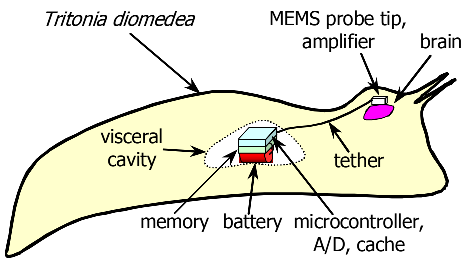
1977 and 1981

- Apple II and IBM PC
  - The first microcomputers

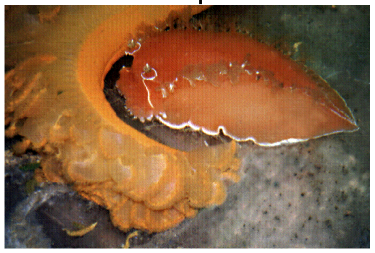
[13]

A modern example

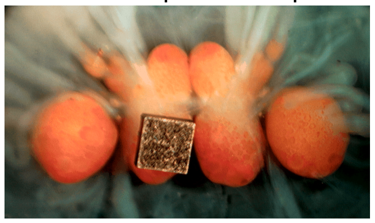
- Goal: Interface a computer to an animal brain
  - Measure brain signals in intact animals



Tritonia and seapen



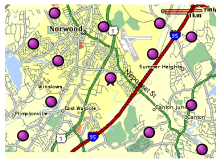
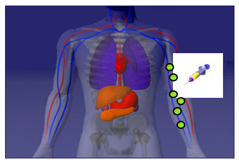
Brain with implanted chip



Courtesy Jim Beck and Russell Wyeth

More modern examples

- Computing everywhere
  - Wireless/wired networking
  - Wearable devices
  - Smart sensors

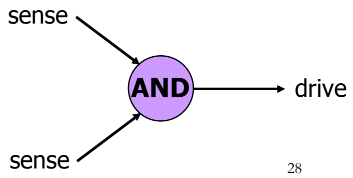



What is logic design?

- What is design?
  - 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, cost, power, beauty, elegance, etc.
- 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

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 < 0.8v is a “0” and > 2.0v 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
  - cheaper and cheaper products
- 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

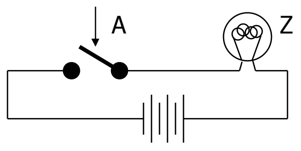
- Up to now, computation has been a mental exercise (paper, programs)
- This class is about physically implementing computation using physical devices that use voltages to represent logical values
- Basic units of computation are:

representation:	"0", "1" on a wire set of wires (e.g., for binary ints)
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;

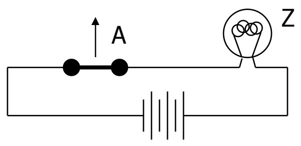
- We will study how each of these are implemented in hardware and composed into computational structures

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)



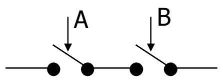
open switch (if A is "0" or unasserted) and turn off light bulb (Z)

Z ≡ A

Switches (cont'd)

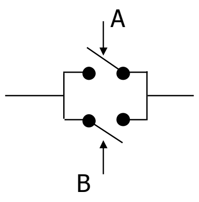
- Compose switches into more complex ones (Boolean functions):

AND



Z ≡ A <u>and</u> B

OR



Z ≡ A <u>or</u> B

Switching networks

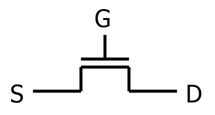
- Switch settings
  - determine whether or not a conducting path exists to light the light bulb
- To build larger computations
  - use a light bulb (output of the network) to set other switches (inputs to another network).
- Connect together switching networks
  - to construct larger switching networks,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

Transistor networks

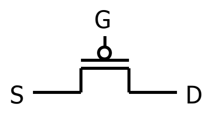
- Modern digital systems are designed in CMOS technology
  - MOS stands for Metal-Oxide on Semiconductor
  - C is for complementary because there are both normally-open and normally-closed switches
- MOS transistors act as voltage-controlled switches
  - similar, though easier to work with than relays.

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

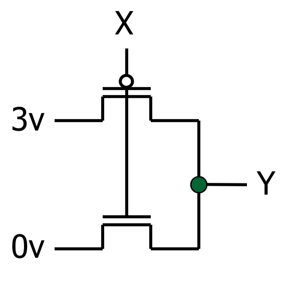


n-channel
open when voltage at G is low
closes when:
voltage(G) > voltage (S) + ε



p-channel
closed when voltage at G is low
opens when:
voltage(G) < voltage (S) – ε

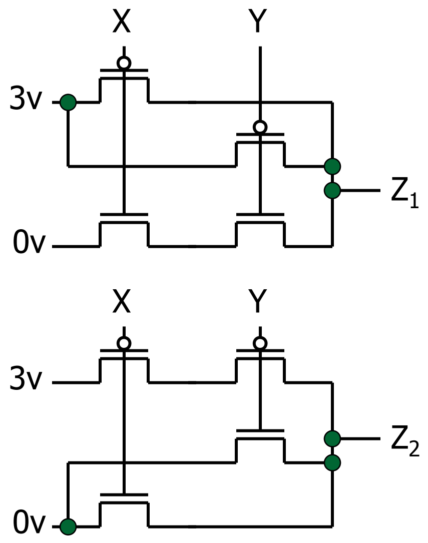
MOS networks



what is the relationship between x and y?

x	y
0 volts	
3 volts	

Two input networks



what is the relationship between x, y and z?

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

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

Representation of digital designs

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

scope of CSE P 567

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

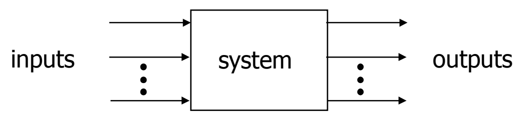
- Why do we make the digital abstraction anyway?
  - switches operate this way
  - easier to think about a small number of discrete values
- Why does it work?
  - does not propagate small errors in values
  - always resets to 0 or 1

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 vs. sequential digital circuits

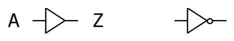
- A simple model of a digital system is a unit with inputs and outputs:



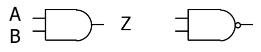
- Combinational means "memory-less"
  - a digital circuit is combinational if its output values only depend on its input values

Combinational logic symbols

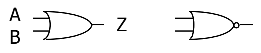
- Common combinational logic systems have standard symbols called logic gates
  - Buffer, NOT



  - AND, NAND



  - OR, NOR



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

Sequential logic

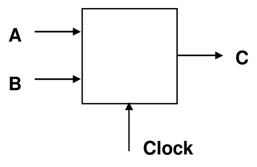
- Sequential systems
  - exhibit behaviors (output values) that depend not only on the current input values, but also on previous input values
- In reality, all real circuits are sequential
  - because the outputs do not change instantaneously after an input change
  - why not, and why is it then sequential?
- A fundamental abstraction of digital design is to reason (mostly) about steady-state behaviors
  - look at the outputs only after sufficient time has elapsed for the system to make its required changes and settle down

Synchronous sequential digital systems

- Outputs of a combinational circuit depend only on current inputs
  - after sufficient time has elapsed
- Sequential circuits have memory
  - even after waiting for the transient activity to finish
- The steady-state abstraction is so useful that most designers use a form of it when constructing sequential circuits:
  - the memory of a system is represented as its state
  - changes in system state are only allowed to occur at specific times controlled by an external periodic clock
  - the clock period is the time that elapses between state changes it must be sufficiently long so that the system reaches a steady-state before the next state change at the end of the period

Example of combinational and sequential logic

- Combinational:
  - input A, B
  - wait for clock edge
  - observe C
  - wait for another clock edge
  - observe C again: will stay the same
- Sequential:
  - input A, B
  - wait for clock edge
  - observe C
  - wait for another clock edge
  - observe C again: may be different



Abstractions

- Some we've seen already
  - digital interpretation of analog values
  - transistors as switches
  - switches as logic gates
  - use of a clock to realize a synchronous sequential circuit
- Some others we will see
  - truth tables and Boolean algebra to represent combinational logic
  - encoding of signals with more than two logical values into binary form
  - state diagrams to represent sequential logic
  - hardware description languages to represent digital logic
  - waveforms to represent temporal behavior

An example

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

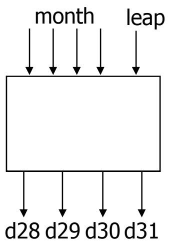
  - inputs: month, leap year flag
  - outputs: number of days

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);
  }
}
```

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



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–	–	–	–	–	–

Combinational example (cont'd)

- 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 <u>not</u>

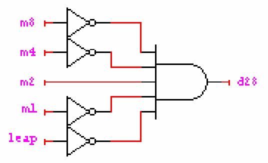
symbol for <u>and</u>

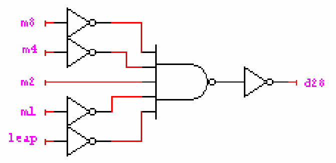
symbol for <u>or</u>

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	–	–	–	–	–

Combinational example (cont'd)

- 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')



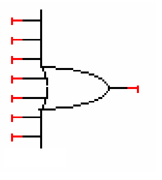


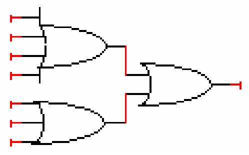
Activity

- How much can we simplify d31?
- What if we started the months with 0 instead of 1? (i.e., January is 0000 and December is 1011)

Combinational example (cont'd)

- 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'•m4') + (m8•m4'•m2•m1') +
  (m8•m4•m2'•m1')





Another example

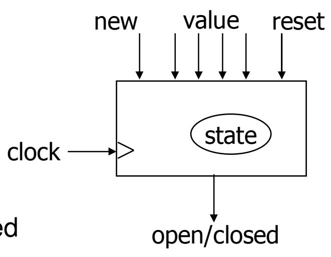
- Door combination lock:
  - punch in 3 values in sequence and the door opens; if there is an error the lock must be reset; once the door opens the lock must be reset
  - inputs: sequence of input values, reset
  - outputs: door open/close
  - memory: must remember combination
    or always have it available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

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);
}
```

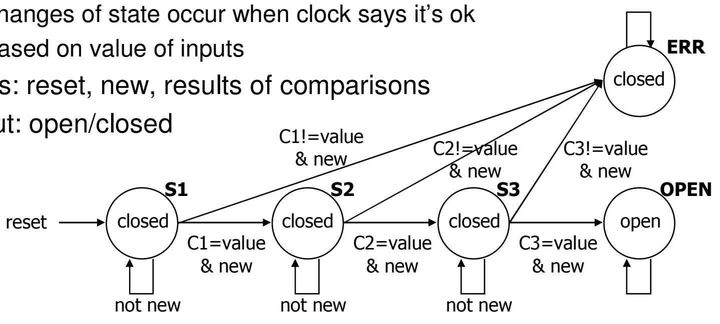
Implementation as a sequential digital system

- 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



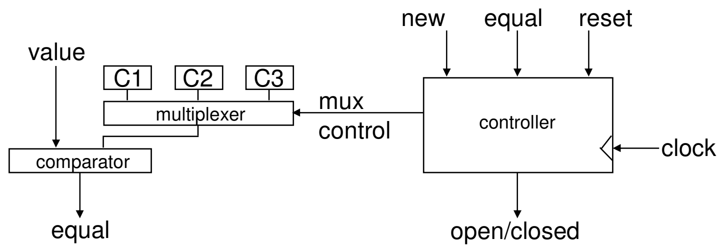
Sequential example (cont'd): abstract control

- Finite-state diagram
  - states: 5 states
    - represent point in execution of machine
    - each state has 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



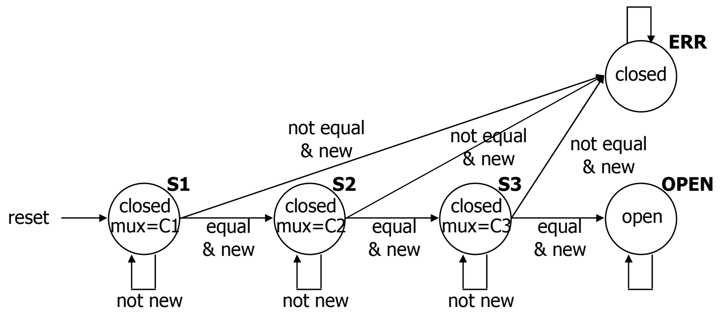
Sequential example (cont'd): data-path vs. control

- Internal structure
  - data-path
    - storage for combination
    - comparators
  - control
    - finite-state machine controller
    - control for data-path
    - state changes controlled by clock



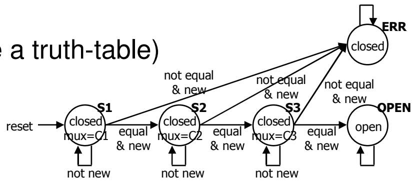
Sequential example (cont'd): finite-state machine

- Finite-state machine
  - refine state diagram to include internal structure



Sequential example (cont'd): finite-state machine

- Finite-state machine
  - 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

Sequential example (cont'd): 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

Sequential example (cont'd): encoding

- Encode state table
  - 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

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 state

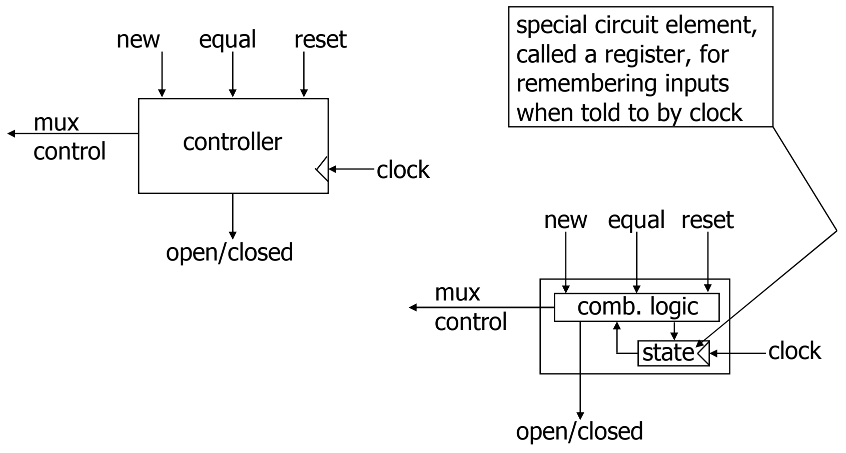
open/closed is identical to first bit of state

Activity

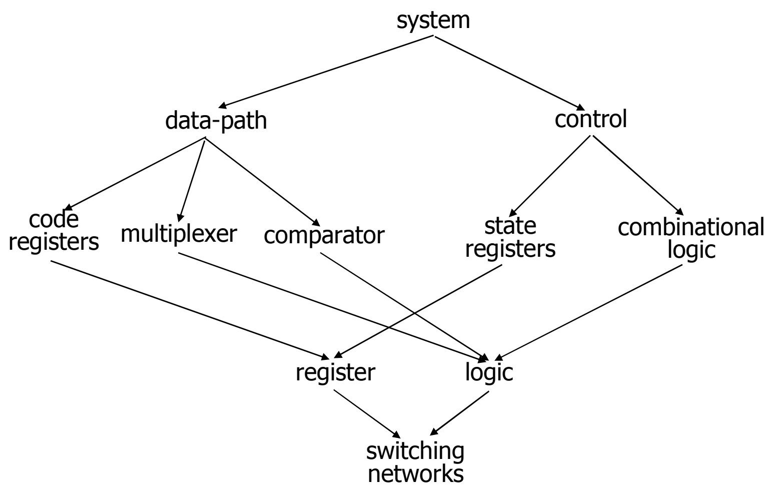
- Have lock always wait for 3 key presses exactly before making a decision

Sequential example (cont'd): controller implementation

- Implementation of the controller



Design hierarchy



Summary

- That was what the entire course is about (mostly)
  - converting solutions to 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
  - Exploring pre-packaged IP (cores)
- Now lets do it again
  - this time we'll take nine weeks instead of one