Chapter 1 :: From Zero to One

Digital Logic Design

James E. Stine, Jr.

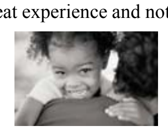
Portions of slides taken from Digital Design and Computer Architecture
D. M. Harris and S. L. Harris, Elsevier, 2007

Chapter 1 :: Topics

- **Course Logistics**
  - **What the Harry is this course about?**
  - **Why should I take this class?**
- **Background**
  - **The Art of Managing Complexity**
- **The Digital Abstraction**
- **Logic and Numbers**
- **Logic for the 21st Century**

ECEN 3233

- Digital Logic Design is the studying how to design digital logic in a nutshell!
- 99% of all devices today are digital.
- Probably your first class in Electrical and Computer Engineering
- My goal is to make it fun!!!
  - Believe it or not!
  - I want you to have a great experience and not just another course!



About the instructor….

- Instructor
  - James E. Stine, Jr.
  - Office: Engineering South (ES) 303D
  - E-mail: james.stine@okstate.edu
  - Phone: (405) 744-9244
  - AOL AIM: joia5
  - MSN Messenger: james.stine@okstate.edu
  - Office Hours: MWR 9:00 AM - 10:30 AM or anytime you see me (my door is almost always open!)
  - I encourage you to ask questions and give me feedback!
    - Tell me this course stinks or is great!!!
    - Will have an anonymous posting option to give me feedback without letting me know who you are.

Class

- Classroom : ES 201B
  - TR: 10:30 AM - 11:20 AM
- Lab (depending on section your registered for) : ES 101F
  - M: 1:30 PM - 3:20 PM
  - T: 3:30 PM - 5:20 PM
  - W: 5:30 PM - 7:20 PM
  - R: 3:30 PM - 5:20 PM
- Recitation (completely optional) : ES 412
  - F: 5:00 PM - 6:00 PM

A **recitation** is a discussion carried by a teaching assistant (TA) or instructor to supplement a lecture given by a senior faculty at an academic institution. During the recitation, the leader will review the lecture, expand on the concepts, and carry a discussion with the students. In classes involving mathematics and Engineering, the recitation is often used to perform derivations or solve problems similar to those assigned to the students. [Source: WikiPedia]

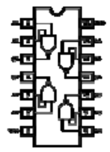
Teaching Assistants

- Jun Chen (jun.chen@okstate.edu)
- Harsha Choday (harsha.choday@okstate.edu)
- Both TAs are my graduate students, therefore, if you are unhappy with something they are doing, contact me immediately and I can take action on them.
- They will have office hours set later this week.
- Recitation (completely optional):
  - 5:00 PM - 6:00 PM : ES 412
  - TAs will go over a couple of examples every week and answer questions directly.
  - You can ask TAs anything at this time.
  - Each TA will alternate weeks, so you may have one the first week and the second the next week.
- Lee Clark: Lab Manager ES 101A (equipment/cables/parts)
- Kellen Butler: Lab Assistant ES 101A (parts) + web

Labs

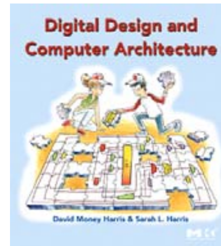
- Labs will involve using specific digital chips and wires called 7400 parts and a digital board.
  - http://en.wikipedia.org/wiki/List_of_7400_series_integrated_circuits
- Everyone is required to purchase the board and parts.
- You can use the board after the class in other classes, so think of it as an investment.
- We try to minimize the cost as much as possible and understand that cost is a little high, but we, as a department, feel that it will benefit your education greatly!

Sign handout with Name, CWID and Signature and cost will be applied to your bursar bill.



Text

- Fantastic new text!!!!!
- Bugs are listed in Errata on D2L.
  - Authors gives checks to those that catch errors in the book!



Grade Breakdown

- Weekly quizzes : 10%
  - Held on Tuesdays starting next week
    - Except November 25 due to Holidays!
  - Given at beginning of class, so do not be late!
  - You can drop lowest two grades
- Homework : 10%
- Two exams: 25% (12.5% each)
  - October 2, 2008
  - November 18, 2008
- Final exam: 20%
- Labs: 35%

Tests

- Tests are closed-book, closed notes.
- You can have a page of notes (only on front) that has handy facts.
- You must hand in this page of notes with your exam.
- I will give out a preliminary exam including solutions to help you study 1 week ahead of the exam.

Homework

- Homework is due 1 week after its initially given and is only accepted at beginning of class.
- Homework will not be accepted if a student is late without a legitimate excuse that can be corroborated.
- Do not try to complete before class.

Software

- There are a couple pieces of software that will be installed in computer labs, but can also be installed on your PC or laptop at home.
- The software is the same as used in industry by people who make a living designing digital logic.
- Tutorials:
  - On D2L at http://oc.okstate.edu
- Web Page
  - http://ecen3233.okstate.edu

Labs

- There will be several weekly labs (starting next week)
- Labs will deal with digital logic and your board, so make sure you bring them to lab.
  - Final lab will deal with my passion as a kid which was video game design.
  - Labs can be downloaded on http://ecen3233.okstate.edu
  - Your partner will be assigned to you.
  - Your first lab should be done individually, however, you may work together in your own teams of two.
- You are welcome to use the lab anytime its open, however, please be aware that other people are using the lab for other courses too.
- You can minimize your experience in lab if you do some pre-lab work.
- From experience, it is advisable to get a composition notebook to write down everything handy about your lab and/or course work.
  - If you need one and cannot find one in the bookstore, let me know!

Academic Integrity

- Please consult Academic Integrity website
  - http://academicintegrity.okstate.edu
- Academic misconduct will result in a failing class for this class.
  - Please ask for help and do not cheat!
  - I am here to help you and I will go above and beyond to help you.
  - I am also here to help if you just need to talk.
- You can also read books on taking classes effectively!
  - This helped me tremendously in school!
- Academic Affairs office also has self-help, advising, and tutoring available.
  - http://osu.okstate.edu/acadaffr/
- HKN (ECEN honor society) also has tutoring every week for free.
  - If you are having trouble find help from this organization, ask me and I can help - I am HKN's faculty adviser.

Lectures

- Lectures will be a combination of what I write down on paper and power point slides.
- Its good to print out the slides in note form and place your notes around the slides.
  - I will try to have notes handy 1 week in advance!
  - My experience is that students do not take notes when PowerPoint slides are used which is a bad habit!
    - Take notes!
  - I will scan my notes that I write down and put them on D2L and web site.
    - Let me know if this is helpful!
    - Provided scanner works!

Let's get started…

Eeeaaaaaaahhh!!!!

No offense Howard Dean - we just love your enthusiasm!

Background

- Microprocessors have revolutionized our world
  - Cell phones, Internet, rapid advances in medicine, etc.
- The semiconductor industry has grown from $21 billion in 1985 to $213 billion in 2004

The Game Plan

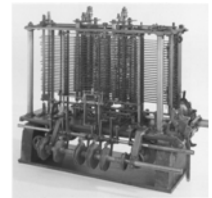
- The purpose of this course is that you:
  - Learn what's under the hood of a digital design.
  - Learn the principles of digital design
  - Design and build digital logic!
  - Have fun!!!

The Digital Abstraction

- Most physical variables are continuous, for example
  - Voltage on a wire
  - Frequency of an oscillation
  - Position of a mass
- Instead of considering all values, the digital abstraction considers only a discrete subset of values

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 it was finished

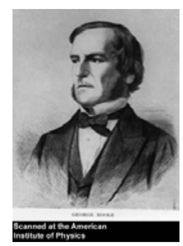


Digital Discipline: Binary

- Typically consider only two discrete values:
  - 1's and 0's
  - 1, TRUE, HIGH
  - 0, FALSE, LOW
- 1 and 0 can be represented by specific voltage levels, rotating gears, fluid levels, etc.
- Digital circuits usually depend on specific voltage levels to represent 1 and 0
- *Bit*: *B*inary dig*it*
  - Acronyms are abbreviations that are formed using the initial letters or word parts in a phrase or name [source: WikiPedia].

George Boole, 1815 - 1864

- Born to working class parents
- Taught himself mathematics and joined the faculty of Queen's College in Ireland.
- Wrote *An Investigation of the Laws of Thought* (1854)
- Introduced binary variables
- Introduced the three fundamental logic operations: AND, OR, and NOT.



Number Systems

- Decimal numbers

1000's column
100's column
10's column
1's column

$5374_{10} = 5 \times 10^3 + 3 \times 10^2 + 7 \times 10^1 + 4 \times 10^0$

five thousands, three hundreds, seven tens, four ones

- Binary numbers

8's column
4's column
2's column
1's column

$1101_2 = 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 13_{10}$

one eight, one four, no two, one one

Number Conversion

- Decimal to binary conversion:
  - Convert 10101_2 to decimal
- Decimal to binary conversion:
  - Convert 47_{10} to binary

Binary Values and Range

- Consider an N-digit decimal number
  - Represents 10^N possible values
  - Range is: $[0, 10^N - 1]$
  - For example, a 3-digit decimal number represents $10^3 =$ 1000 possible values, with a range of [0, 999]
- Consider an N-bit binary number
  - Represents 2^N possible values
  - Range is: $[0, 2^N - 1]$
  - For example, a 3-digit binary number represents $2^3 = 8$ possible values, with a range of [0, 7] (i.e., 000_2 to 111_2)

Hexadecimal Numbers

Hex Digit	Decimal Equivalent	Binary Equivalent
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Hexadecimal Numbers

- Base 16
- Shorthand for Binary

Hexadecimal to Binary Conversion

- Hexadecimal to binary conversion:
  - Convert $4AF_{16}$ (also written 0x4AF) to binary
- Hexadecimal to decimal conversion:
  - Convert 0x4AF to decimal

Hexadecimal to Binary Conversion

- **Hexadecimal to binary conversion:**
  - Convert $4AF_{16}$ (also written 0x4AF) to binary
  - **010010101111_2**
- **Hexadecimal to decimal conversion:**
  - Convert 0x4AF to decimal
  - $010010101111_2 = 1 + 2 + 4 + 8 + 32 + 128 + 1024$
    $= \mathbf{1199_{10}}$
  - 0x4AF $= (15 \times 16^0) + (10 \times 16^1) + (4 \times 16^2)$
    $= \mathbf{1199_{10}}$

Bits, Bytes, Nibbles…

- Bits

10010110
most significant bit
least significant bit

- Bytes & Nibbles

byte
10010110
nibble

- Bytes

CEBF9AD7
most significant byte
least significant byte

Powers of Two

- 2^{10} = 1 kilo ≈ 1000 (1024)
- 2^{20} = 1 mega ≈ 1 million (1,048,576)
- 2^{30} = 1 giga ≈ 1 billion (1,073,741,824)

Estimating Powers of Two

- What is the value of 2^{22}?
  - $2^2 \times 2^{20}$ = 4 Mega
- How many values can a 32-bit variable represent?
  - $2^2 \times 2^{30}$ = 4 Giga

Addition

- Decimal

```
  11  ← carries
  3734
+ 5168
  8902
```

- Binary

```
  11  ← carries
  1011
+ 0011
  1110
```


Binary Addition Examples

- Add the following 4-bit binary numbers

```
  1001
+ 0101
```

- Add the following 4-bit binary numbers

```
  1011
+ 0110
```


Overflow

- Digital systems operate on a fixed number of bits
- Addition overflows when the result is too big to fit in the available number of bits
- Example: add 13 and 5 using 4-bit numbers

```
  11 1
   1101
+  0101
  10010
```


Signed Binary Numbers

- Sign/Magnitude Numbers
- Two's Complement Numbers

Sign/Magnitude Numbers

- 1 sign bit, N-1 magnitude bits
- Sign bit is the most significant (left-most) bit
- Negative number: sign bit = 1
- Positive number: sign bit = 0
- Example, 4-bit representations of ± 5:
  - $-5 = 1101_2$
  - $+5 = 0101_2$
- Range of an *N*-bit sign/magnitude number: $[-(2^{N-1}-1), 2^{N-1}-1]$

Sign/Magnitude Numbers

- Problems:
  - Addition doesn't work, for example -5 + 5:

$$\begin{array}{r} 1101 \\ +\ 0101 \\ \hline 10010 \end{array}$$

  - Two representations of 0 (± 0):

    1000

    0000

Two's Complement Numbers

- Don't have same problems as sign/magnitude numbers:
  - Addition works
  - Single representation for 0

Two's Complement Numbers

- Same as unsigned binary, but the most significant bit (msb) has value of -2^{N-1}
- Most positive 4-bit number: 0111_2 (7_{10})
- Most negative 4-bit number: 1000_2 ($-2^3 = -8_{10}$)
- The most significant bit still indicates the sign (1 = negative, 0 = positive)
- Range of an *N*-bit two's complement number: $[-2^{N-1}, 2^{N-1}-1]$

"Taking the Two's Complement"

- Reversing the sign of a two's complement number
- Method:
  1. Invert the bits
  2. Add 1 or unit in the last position (ulp)
- Example: Reverse the sign of 0111_2
  1. 1000
  2. \+ 1

     1001

Two's Complement Examples

- Take the two's complement of 0110_2
  1. 1001
  2. \+ 1

     1010

- Take the two's complement of 1101_2
  1. 0010
  2. \+ 1

     0011

Two's Complement Addition

- Add 6 + (-6) using two's complement numbers

```
  111
   0110
+  1010
  10000
```

- Add -2 + 3 using two's complement numbers

```
  111
   1110
+  0011
  10001
```


Increasing Bit Width

- A value can be extended from *N* bits to *M* bits (where *M* > *N*) by using:
  - Sign-extension
  - Zero-extension

Sign-Extension

- Sign bit is copied into most significant bits.
- Number value remains the same.

- **Example 1:**
  - 4-bit representation of 3 = 0011
  - 8-bit sign-extended value: 00000011
- **Example 2:**
  - 4-bit representation of -5 = 1011
  - 8-bit sign-extended value: 11111011

Zero-Extension

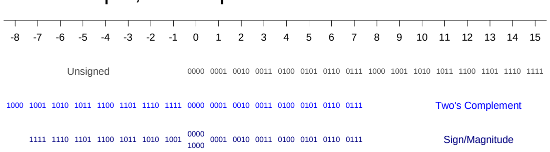
- Zeros are copied into most significant bits.
- Number value may change.

- **Example 1:**
  - 4-bit value = 0011
  - 8-bit zero-extended value: 00000011
- **Example 2:**
  - 4-bit value = 1011
  - 8-bit zero-extended value: 00001011

Number System Comparison

Number System	Range
Unsigned	$[0, 2^N-1]$
Sign/Magnitude	$[-(2^{N-1}-1), 2^{N-1}-1]$
Two's Complement	$[-2^{N-1}, 2^{N-1}-1]$

For example, 4-bit representation:

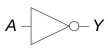


Logic Gates

- Perform logic functions: inversion (NOT), AND, OR, NAND, NOR, etc.
- Single-input:
  - NOT gate, buffer
- Two-input:
  - AND, OR, XOR, NAND, NOR, XNOR
- Multiple-input

Single-Input Logic Gates

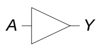
NOT



$Y = \overline{A}$

A	Y
0	1
1	0

BUF

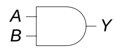


$Y = A$

A	Y
0	0
1	1

Two-Input Logic Gates

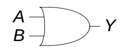
AND



$Y = AB$

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

OR

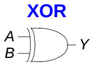


$Y = A + B$

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

More Two-Input Logic Gates

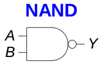
XOR



$Y = A \oplus B$

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

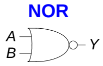
NAND



$Y = \overline{AB}$

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

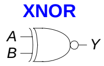
NOR



$Y = \overline{A + B}$

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

XNOR

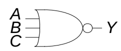


$Y = \overline{A \oplus B}$

A	B	Y
0	0	
0	1	
1	0	
1	1	

Multiple-Input Logic Gates

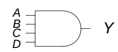
NOR3



$Y = \overline{A+B+C}$

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

AND4



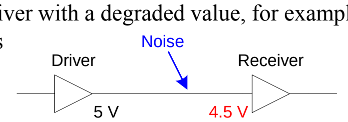
$Y = ABCD$

Logic Levels

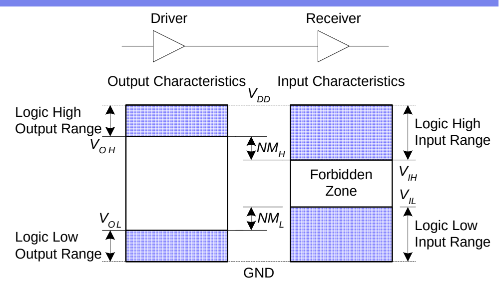
- Define discrete voltages to represent 1 and 0
- For example, we could define:
  - 0 to be *ground* or 0 volts
  - 1 to be V_{DD} or 5 volts
- But what if our gate produces, for example, 4.99 volts? Is that a 0 or a 1?
- What about 3.2 volts?

Logic Levels

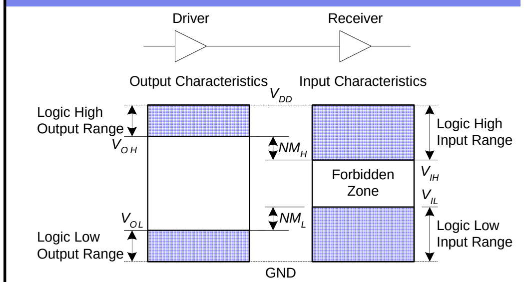
- Define a *range* of voltages to represent 1 and 0
- Define different ranges for outputs and inputs to allow for *noise* in the system
- Noise is anything that degrades the signal
- For example, a gate (driver) could output a 5 volt signal but, because of losses in the wire and other noise, the signal could arrive at the receiver with a degraded value, for example, 4.5 volts



Logic Levels



Noise Margins

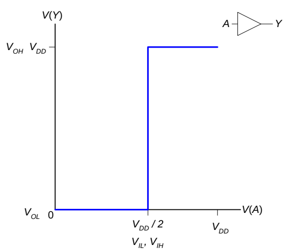


$NM_H = V_{OH} - V_{IH}$

$NM_L = V_{IL} - V_{OL}$

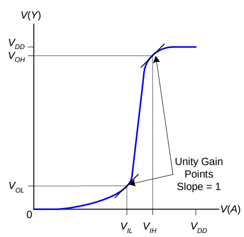
DC Transfer Characteristics

Ideal Buffer:



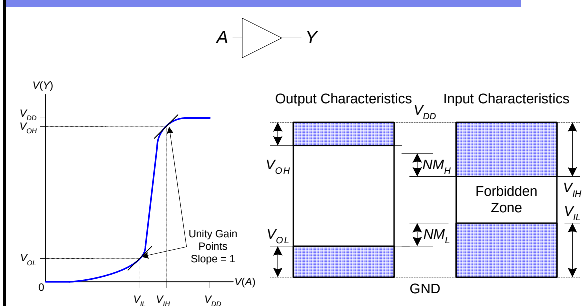
$NM_H = NM_L = V_{DD}/2$

Real Buffer:



$NM_H , NM_L < V_{DD}/2$

DC Transfer Characteristics



The Static Discipline

Logic Family	V_{DD}	V_{IL}	V_{IH}	V_{OL}	V_{OH}
TTL	5 (4.75 - 5.25)	0.8	2.0	0.4	2.4
CMOS	5 (4.5 - 6)	1.35	3.15	0.33	3.84
LVTTL	3.3 (3 - 3.6)	0.8	2.0	0.4	2.4
LVCMOS	3.3 (3 - 3.6)	0.9	1.8	0.36	2.7