Contents

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0.1 Assessment

- Online Quizzes (10% = Best 10 $\times$ 1%)
  Due Mondays at 8am
- Mid-semester exam (10% or 20%)
  Saturday (centrally scheduled - sometime week 5 to 7)
  Multiple-choice, open-book
- Prac Exam (Pass/Fail)
  Held during Monday/Wednesday Learning Lab sessions in week 6
  You must pass in order to pass the course
- Project (20%)
  Develop a microcontroller program
- Final Exam (50% or 60%)
  Short answer, problem solving, open-book

Chapter 1

Lecture Notes

1.1 Bits, Bytes and Binary

1.1.1 Structured Computer Organization

Level 5: Problem-oriented language level
Level 4: Assembly language level
Level 3: Operating system machine level
Level 2: Instruction set architecture level
Level 1: Microarchitecture level
Level 0: Digital Logic level

1.1.2 Unsigned Number in Binary

Each bit position has a value $\rightarrow$ 2^n (starting at zero). Add all values of the positions together and that's unsigned value.

1.1.3 Converting Decimal to Binary

- Method 1

  rewrite n as sum of powers of 2 (by repeatedly subtracting largest power of 2 not greater than n)

  Assemble binary number from 1's in bit positions corresponding to those powers of 2, 0's elsewhere
- Method 2

  Divide n by 2

  Remainder of division (0 or 1) is next bit

  Repeat with n = quotient

Note 1: Example

Convert 53 to binary

$$\frac{53}{2} = 26 \text{ rem } 1 \Rightarrow 1$$
$$\frac{26}{2} = 13 \text{ rem } 0 \Rightarrow 0$$
$$\frac{13}{2} = 6 \text{ rem } 1 \Rightarrow 1$$
$$\frac{6}{2} = 3 \text{ rem } 0 \Rightarrow 0$$
$$\frac{3}{2} = 1 \text{ rem } 1 \Rightarrow 1$$
$$\frac{1}{2} = 1 \text{ rem } 1 \Rightarrow 1$$

$\therefore 53 \equiv 0b110101$

1.1.4 Least and Most Significant Bits

Most Significant Bit (MSB): Bit that's worth the most, the left-most bit

Least Significant Bit (LSB): Bit that's worth the least, the right-most bit

Note 2: Radices

- **Radix:** number system base
- A radix-k number system

  k different symbols to represent digits 0 to $k-1$

  Value of each digit is (from the right) $k^0, k^1, k^2, k^3, \ldots$
- Often convenient to deal with

  Octal (radix-8) - Symbols: 0, 1, 2, 3, 4, 5, 6, 7

  One octal digit corresponds to 3 bits

  Hexadecimal (radix-16) - Symbols: 0, 1, 2, 3, 4, 5, 6, 7, 7, 8, 9, A, B, C, D, E, F

  One hexadecimal digit corresponds to 4 bits (useful)

Note 3: Radix Identification

- Hexadecimal
  Leading 0x (C, Atmel AVR)
  Trailing h (Some assembly languages)
  Leading $ (Atmel AVR Assembly)
- Octal
  Leading 0 (C, Atmel AVR)
  Trailing q (Some assembly languages)
  Leading @ (Some assembly languages)
- Binary
  Leading 0b (Atmel AVR Assembly, Some C)
  Trailing b (Some assembly languages)
  Leading % (some assembly languages)

1.1.5 Conversions

Easiest to convert from most formats to binary then to the desired format.

Octal

From Binary: Group bits into series of 3 and then convert to decimal (0b010 = 02)

To Binary: Convert each octal number to binary and append

Hex

From Binary: Group bits into series of 4 and then convert to hex with overflow being apart of the alphabet (0b1100 = 0xC)

To Binary: Convert each hex number to binary and append

Decimal

From Binary: Add together the powers of two at each position n $(0b1010 = 2^3 + 2^1 = 10)$

To Binary: Starting with LSB, divide by 2 with the remainder being bit value at position. $(9 = 9/2 = 4rem1, 4/2 = 2rem0, 2/2 = 1rem0, 1/2 = 0rem1. \therefore 9 = 0b1001)$

1.1.6 Negative Numbers

Signed Magnitude

Leftmost bit is the sign bit, true is negative and false is positive

One's Complement

Leftmost bit = sign-bit (as per signed magnitude), true is negative and false is positive. If negative all bits are inverted

Two's Complement

MSB signifies if negative, true is negative and false is positive. To negate invert all bits and add decimal 1.

- Allows addition without requiring conversion

Excess 2^{m-1}

e.g. for 8 bits, excess-128. Add 128 to the original bit and convert to binary

1.2 Logic Gates

NOT Gate: Inverts the signal (i.e. input is true, output is false)

AND Gate: Output is true only if **all** inputs are true

NAND Gate: Opposite of AND, always true unless all inputs are true

OR Gate: Output is true when at **least one** input is true

XOR Gate: Output is true if only one input is true

Note 4: XOR Multiple Inputs

For more than 2 inputs, XOR is true if there is an odd number of inputs true. Also referred to as the "odd function"

1.2.1 Logic Functions

- Logic functions can be expressed as expressions involving:
  variables (literals), e.g. A B X
  functions, e.g. $+ . \oplus \overline{A}$
- Rules about how this works called **Boolean algebra**
- Variables and functions can only take on values **0** or **1**

Convenctions

Inversion: $\overline{A}$ (overline of A)
AND: dot(.) or implied by adjacency. $AB = A.B$
OR: plus sign. $OR(A,B,C) = A + B + C$
XOR: $OR(A,B) = A \oplus B = \overline{A}B + A\overline{B}$
NAND: $\overline{ABC}$
NOR: $\overline{A+B}$

Representations of Logic Functions

There are four representations of logic functions (assume function of n inputs)

- **Truth Table**
  Lists output for all 2^n combinations of inputs
- **Boolean Function** (or equation)
  Describes the conditions under which the function output is true
- **Logic Diagram**
  Combination of logic symbols joined by wires
- **Timing Diagram**

1.2.2 Logic Function Implementation

Any logic function can be implemented as the OR of AND combinations of the inputs. Called **sum of products**.

Table 1.1: Boolean Identities

Name	AND Form	OR Form
Identity Law	$1A = A$	$0 + A = A$
Null Law	$0A = 0$	$1 + A = 1$
Idempotent Law	$AA = A$	$A + A = A$
Commutative Law	$AB = BA$	$A + B = B + A$
Associative Law	$(AB)C = A(BC)$	$(A + B) + C = A + (B + C)$
Distributive Law	$A + BC = (A + B)(A + C)$	$A(B + C) = AB + AC$
Absorption Law	$A(A + B) = A$	$A + AB = AB$
De Morgan's Law	$\overline{AB} = \overline{A} + \overline{B}$	$\overline{A + B} = \overline{A}\,\overline{B}$

1.3 Binary Arithmetic

1.3.1 Equivalent Circuits

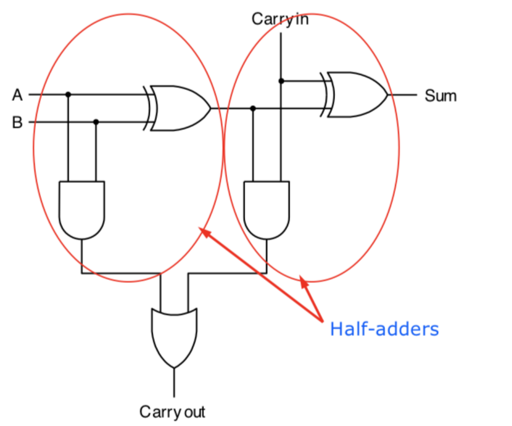
All circuits can be constructed from NAND and NOR gates

1.3.2 Overflow

Overflow with two's complement addition:

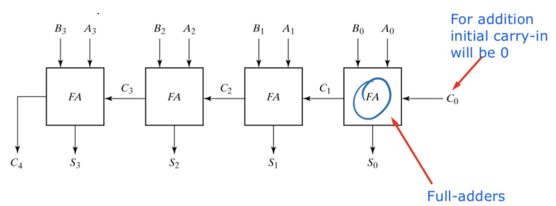
- Carry into sign-bit is different to the carry out of the sign-bit
- Equivalently, overflow occurs if
  Two negatives added together give a positive, or
  Two positives added together give a negative

1.3.3 Full Adder



1.3.4 Binary Adder

Can cascade full adders to make binary adder. This is a **ripple-carry adder**.



1.4 Combination Logic

1.4.1 Combinational Circuits

Each output can be expressed as a function of n input variables. Can write truth table also:

- n input columns
- m output columns
- 2^n rows (i.e. possible input combination)

Note 5: Multiplexer (or Mux)

- 2^n data inputs
- 1 output
- n control (or **select**) inputs - that **select** one of the inputs to be "sent" or "steered" to the output

Note 6: Decoder

Converts n-bit input to a logic-1 on exactly one of 2^n outputs

1.4.2 Timing Diagram

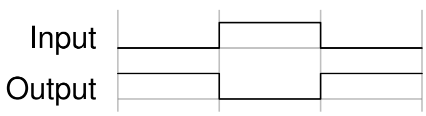


Figure 1.1: Timing Diagram of an inverter

There is a slight delay in logic timings in reality

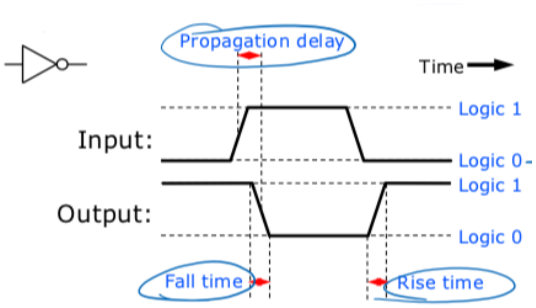


Figure 1.2: Reality of Timing

Propagation delay: time for change in input to affect output
Fall time: time taken for output to fall from 1 to 0
Rise time: time for output to rise from 0 to 1

1.5 Flip-flops

1.5.1 D Flip Flop

- **D** is input
- **Q** is output
- **CLK** (clock) is control input

Q copies the value of D (and remembers it) whenever CLK goes from 0 to 1 (**rising edge**).

Characteristic Table

Characteristic table defines operation of flip-flop in tabular form

Table 1.2: D Flip-Flop Characteristic Table

D	Q(t+1)
0	0
1	1

1.5.2 Flip-Flops Vs Latches

- The last few slides show **latches**
  These are **level-triggered** devices
- Remember we want to capture the input value at rising **edge** (a short instant)!
- Any devices based on edges are referred to as **flip-flops**
  These are **edge-triggered** devices

1.6 Shift Registers

1.6.1 Combinational vs Sequential Circuits

- **Combinational** Circuits
  - Logic gates only (no flip-flops)
  - Output is uniquely determined by the inputs
    i.e. you'll always get the same output for a given set of inputs
- **Sequential** Circuits
  - Include flip-flops
  - Output determined by current inputs and current **state** (values in the flip-flops)
  - Output can change when clock "ticks" (rising edge)

Sequential Circuits

- **State** is value stored in flip-flops

- Output depends on input and state
  or sometimes just the state
- Next state depends on inputs and state

Synchronous Sequential Circuit

- Storage elements (flip-flops) can only change at discrete instants of time

1.6.2 Registers

- A **register** is a group of flip-flops
  n-bit register consists of n flip-flops capable of storing n bits
- A register is a sequential circuit *without* any combinational logic

Shift Register

A shift register is a register which is capable of shifting its binary information in one or both directions

1.7 Counters

- A **counter** is a multi-bit register that goes through a determined sequence of states (values) upon the application of input pulses
- A counter which follows binary number sequence is a **binary counter**
  n-bit binary counter has n flip-flops and can count from 0 to $2^n - 1$

Note 7: State

- Values stored in the flip-flops can be considered the **current state** of the circuit
- D inputs to the flip-flops are the **next state**
- D inputs are some function of the current state and inputs

Key Points

- Next state is a function of previous state (and possibly inputs)
- Count sequence can be binary numbers but does not have to be
  If it is, counter is a **binary counter**
- Circuits are **synchronous**
  All flip-flops have the same clock

1.8 State Machines

- Sequential circuits can also be called
  state machines
  finite state machines (FSMs)
- State machine has
  - Finite number of possible states
  - Only one **current state**
  - Can **transition** to other states based on inputs and current state

Note 8: Types of State Machines

Mealy Machines: Outputs depend on current state and inputs

Moore Machines: Outputs depend only on current state (flip-flop values)
Outputs can only change when state changes

1.8.1 State diagram

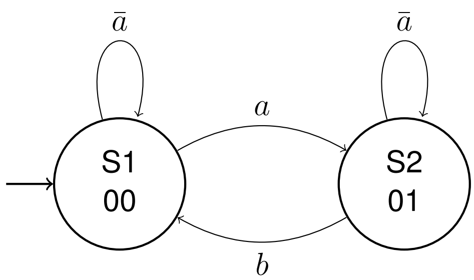


Figure 1.3: Example single input state diagram

Note: I couldn't figure out how to add the line that is meant to go between the state label and the state number

Completeness

Each possible combination of inputs should be addressed **exactly once** for each state. i.e. transition arrows from each state must encompass all possibilities (exactly once)

1.8.2 State tables

- State diagrams can also be represented in a state table

Table 1.3: Example State Table

Current State	Input U	Next State	Outputs Q_1	Q_2
S0	0	S3	0	0
S0	1	S1	0	0
S1	0	S0	0	1
S1	1	S2	0	1
S2	0	S1	1	0
S2	1	S3	1	0
S3	0	S2	1	1
S3	1	S1	1	1

Table 1.4: Two-dimensional state table

Current State	Next State $\bar{U}$	U	Outputs Q_1	Q_0
S0	S3	S1	0	0
S1	S0	S2	0	1
S2	S1	S3	1	0
S3	S2	S0	1	1

1.8.3 State encoding

- Must encode each state into flip-flop values
- Choose
  Number of flip-flops
  Bit patterns that represent each state
- Ideally, choose state encoding to make combinational logic simple, for both
  Output logic
  Next state logic

1.9 ALUs and Memory

1.9.1 Parts of a CPU

- **Control Unit**
  Fetches instructions from memory, makes the ALU and the registers perform the instruction
- **ALU**
  Performs arithmetic and logical operations
- **Registers**
  High speed memory – stores temporary results and control

1.9.2 Registers

Different types of registers

- **Program Counter Register**
  Stores the memory address of the next instruction to be fetched
- **Instruction Register**
  Contains the current instruction
- **General Purpose Registers**
  Contains data to be operated on (e.g. data read from memory), results of operations, ...
  Width is CPU word size
  Sometimes called the **register file**

1.9.3 Buses

Bus = Common pathway (collection of "wires") connecting parts of a computer
Characteristics:

- Can be **internal** to CPU (e.g. ALU to registers)
- Can be **external** to CPU (e.g. CPU to memory)
- Buses have a **width** – number of bits that can be transferred together over a bus
  May not always be the same as the word size of the computer

Note 9: Arithmetic Logic Unit (ALU)

Does more than adding... **Function** / **control** input dictates the operation that the ALU is to perform, e.g.

- Addition
- Increment (+1)
- Subtraction
- Bitwise AND
- Bitwise OR

Like adders, ALUs can be made up from 1-bit slices

1.9.4 Data Path

- Operands come from register file
- Result written to register file
- Implements routine instructions such as arithmetic, logical, shift
- Width of registers/buses is the CPU word size

1.10 CPU Control Unit

1.10.1 Control Unit

- Control signals come from the **control unit**

- Control unit must generate the control signals in the right order for a given instruction

  Instruction determined by contents of the **Instruction Register (IR)**

Data Influencing Control

- Need to know more than what's in the instruction register
- Control unit can't operate without knowing something about the data
- **Status Register**

  Determined by ALU operations

  Stores status of last ALU operation

Note 10: Status Register

Typically Includes:

Z: zero bit – was the last result 0?

V: overflow bit – did the last addition/subtraction operation overflow (assuming it was a two's complement operation)?

C: carry bit – was a carry out generated?

N: negative bit – was the result negative if considered as two's complement (i.e. what's the sign bit)?

1.11 AVR Introduction

1.11.1 Instructions

Opcode (Operation code): defines the operation

Operands : what's being operated on (e.g. particular registers or memory address)

1.12 Instruction Set Architecture

1.12.1 Instruction Set Architecture (ISA)

ISA defines the interface between hardware and software

- ISA is a specification
- **Microarchitecture** is how the control unit is built

For hardware (microarchitecture) designers

- Don't need to know about the high level software
- Just build a microarchitecture that implements the ISA

For software writers (machine language programmers and compiler writers)

- Don't need to know (much) about microarchitecture
- Just write or generate instructions that match the ISA

What makes an ISA?

- Memory modules
  - Issues
    - Addressable cell size
    - Alignment
    - Address spaces
    - Endianness
- Registers
- Instructions
- Data types

Note 11: Addressable Cell Size

- Memory has cells, each of which has a unique address (or cell number)
- Most common cell size is 8 bits (but not always!)

  AVR Instruction memory has 16 bit cells
- Bus is used to transport the content of cell, but sometimes the data bus may be wider

Bus Sizes

For every doubling of data bus width, remove least significant bit of address bus. e.g. data bus of 32 bits, address bus of n-2 bits, four cells transferred at a time

Note 12: Alignment

Many architectures require **natural alignment**

Note 13: Address Spaces

Many microprocessors have a single linear memory address space (**von Neumann** architecture). However, **Harvard architecture** is separate address spaces for instructions and data

Note 14: Endianness

- Different machines may support different byte orderings
- **Little endian** - little end (least significant byte) stored first (at lowest address)
- **Big endian** - big end stored first

Registers

Two types of registers:

- General purpose (used for temporary results)
- Special purpose
  - Program Counter (PC)
  - Stack Pointer (SP)
  - Input/Output Registers
  - Status Register (Tanenbaum calls this Program Status Word)

Some other registers are part of the microarchitecture NOT the ISA (e.g. Instruction Register (IR))

Note 15: AVR I/O Registers

AVR ATmega324A has 224 I/O register addresses to control peripherals and get data to/from them, e.g.

- Timers and counters
- Analog to Digital Converters
- Serial input/output
- General purpose input/output ports
- Three registers associated with each

  DDRx - Data direction register
  PORTx - Values to output
  PINx - Values on the pins

Instructions

Instruction types include:

Input/Output - communicate with I/O devices
Load/Store - move data from/to memory
Move - copy data between registers
Arithmetic - addition, subtraction, ...
Logical - Boolean operations
Branching - for deciding which instruction to perform next