Digital Circuits

**DIGITAL CIRCUITS: AN OVERVIEW**

**BOOLEAN LOGIC**

**DIGITAL CIRCUIT DESIGN**

**IMPLEMENTING DIGITAL CIRCUITS**
Digital Circuits: An Overview

- Given binary memory, need to build **digital circuits** that implement computational operations (cf. **analog circuits**).
- Digital circuit as $n$-input $\implies m$-output transformation:

![Combinational Logic Diagram]

- Focus here on **combinatorial circuits** that do not involve feedback (cf. feedback-based **sequential circuits**).
Digital Circuits: An Overview (Cont’d)

- Two types of circuits: **arithmetic** and **control**.
- Specify circuit in terms of input-output behavior, e.g.,

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ $B$ $C$</td>
<td>$OUT_1$ $OUT_2$</td>
</tr>
<tr>
<td>0 0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>0 0 1</td>
<td>1 0</td>
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<td>0 1 0</td>
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<td>1 1 0</td>
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<td>1 1 1</td>
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</tbody>
</table>

...But how do we design circuits from specifications? ...
Boolean Logic: An Overview

- Self-taught mathematician.
- 1854 book *The Laws of Thought* developed algebraic approach to logic (Boolean logic); part of algebraic formalization of other areas of mathematics, e.g., geometry, probability.
- Based on variables with values True or False and three operators: AND (·), OR (+), and NOT (\(\overline{A}\)).

George Boole
(1815-1864)
Specify behavior of operators as **truth tables**.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>( A \ AND \ B )</th>
<th>( A \ OR \ B )</th>
<th>( NOT \ A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>False</td>
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Boolean Logic: An Overview (Cont’d)

- Operators and variables can be combined to create expressions, e.g.,
  \[
  ((A \cdot B) + \overline{C})
  \]
  \[
  \text{NOT } ((A \text{ AND } B) \text{ OR } \text{NOT } C)
  \]

- Each expression in turn has an associated truth table, which is created by applying the operators in the expression to each possible combination of values for the variables in the expression, e.g.,
  
  \[
  [A = False, B = True, C = False] \implies False
  \]

- What about deriving an expression for a given truth table?
Boolean Logic: An Overview (Cont’d)

OR together the AND-expressions corresponding to variable values in the rows of the truth table that yield result True, e.g.,

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th>RESULT</th>
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</thead>
<tbody>
<tr>
<td>False</td>
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\[ \Rightarrow (\overline{A} \cdot \overline{B} \cdot C) + (\overline{A} \cdot B \cdot C) + (A \cdot \overline{B} \cdot C) \]

\#1 #2 #3
Boolean Logic: The Sum-of-Products Algorithm

Get truth table
Construct AND subexpressions for rows with result *True*
Use ORs to combine the constructed AND subexpressions to create truth table expression
Digital Circuit Design: Beginnings

Claude Shannon (1916-2001)

Electromechanical Telephone Switch (1930s)
Digital Circuit Design: Beginnings (Cont’d)

- Shannon MSc thesis (MIT, 1937): Boolean logic can be used to design telephone switching networks!
- Let 0 and 1 in circuits correspond to *False* and *True* and abstract logic gates to Boolean operators.
Digital Circuit Design: Beginnings (Cont’d)

Represent network circuits as logic gate diagrams, e.g.,

\[ \text{NOT } ((A \text{ AND } B) \text{ OR } (\text{NOT } C)) \]

Boolean expression $\iff$ logic gate diagram
Truth table $\iff$ logic gate behavior specification
Digital Circuit Design: The Sum-of-Products Algorithm

Get behaviour specification for circuit
for each output column in specification do
  Construct AND subexpressions for rows
  with output 1
  Use ORs to combine the constructed AND
  subexpressions to create OR expression
Create logic circuit diagram corresponding to
OR expression
Digital Circuit Design:  
The Sum-of-Products Algorithm (Cont’d)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
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\[
\text{RESULT} = (\overline{A} \cdot \overline{B} \cdot C) + (\overline{A} \cdot B \cdot C) + (A \cdot \overline{B} \cdot C)
\]  

\#1 \hspace{2cm} \#2 \hspace{2cm} \#3
DIGITAL CIRCUIT DESIGN:
THE SUM-OF-PRODUCTS ALGORITHM (CONT’D):
WHY BOTHER?

AS LONG AS YOU CAN IMPLEMENT THE THREE ABSTRACT LOGIC GATES WITH INSTANCES OF (ELECTRONIC) DEVICE X, YOU CAN USE THE SOP ALGORITHM TO DESIGN DIGITAL CIRCUITS BASED ON X.
Arithmetic Circuit Design:
1-Bit Adder

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C_IN</th>
<th>SUM</th>
<th>C_OUT</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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\[ SUM = (A \cdot \overline{B} \cdot C_{IN}) + (A \cdot B \cdot \overline{C_{IN}}) + (A \cdot \overline{B} \cdot \overline{C_{IN}}) + (A \cdot B \cdot C_{IN}) \]

\[ C_{OUT} = (\overline{A} \cdot B \cdot C_{IN}) + (A \cdot \overline{B} \cdot C_{IN}) + (A \cdot B \cdot \overline{C_{IN}}) + (A \cdot B \cdot C_{IN}) \]
Arithmetic Circuit Design: 1-Bit Adder (Cont’d)

Figure 4.26 Complete 1-ADD Circuit for 1-Bit Binary Addition
Arithmetic Circuit Design: 1-Bit Adder (Cont’d)

Can dramatically decrease the number of gates by applying rules of Boolean algebra and using advanced logic gates such as XOR (Exclusive OR), e.g.,
Arithmetic Circuit Design: \( n \)-Bit Adder

Figure 4.27 The Complete Full Adder ADD Circuit
Arithmetic Circuit Design: 1-Bit Compare-For-Equality

- This type of circuit returns 1 if the two given bits $A$ and $B$ have the same value.

<table>
<thead>
<tr>
<th>$A$</th>
<th>$B$</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
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</table>

$RESULT = (\overline{A} \cdot \overline{B}) + (A \cdot B)$

- Again, there are several implementations of this circuit.
Arithmetic Circuit Design:
1-Bit Compare-For-Equality (Cont’d)

Figure 4.22
One-Bit Compare for Equality Circuit
Arithmetic Circuit Design: 
\(n\)-Bit Compare-For-Equality

N-bit Compare for Equality Circuit
Control Circuits: Overview

- Control circuits determine the order in which operations are carried and select the correct data values to be processed they are sequencing and decision-making circuits.

- Two main types:
  1. **Multiplexor**: Use $N$ input selector lines to determine which of $2^N$ input value lines has its value copied to the single output line (see Textbook, Figure 4.33, p. 211).
  2. **Decoder**: Use $N$ input selector lines to determine which of $2^N$ output lines is set to 1 (with all others being set to 0) (see Textbook, Figure 4.35, p. 213).
Control Circuit Design: Multiplexor (Abstract)

$2^N$ Input Value Lines

Multiplexor

N Input Selector Lines

1 Output Line
Control Circuit Design: Two-input Multiplexor Circuit

Figure 4.28
A Two-Input Multiplexor Circuit
Control Circuit Design: Data-routing Multiplexor

Figure 4.31 Example of the Use of a Multiplexor Circuit
Control Circuit Design: Decoder (Abstract)

N Input Lines \( \rightarrow \) 2^N Output Lines

Decoder
Control Circuit Design:
2-to-4 Decoder Circuit

Figure 4.29
A 2-to-4 Decoder Circuit
Control Circuit Design: Op-code Decoder

Figure 4.30 Example of the Use of a Decoder Circuit
Implementing Digital Circuits

Vacuum Tube (1904)

• Invented by John Ambrose Fleming (1849–1945).
• Basic component of early / mid 20th century electronics, e.g., radio, TV, radar.
• Require a lot of power and produce a lot of heat; prone to burnout if used continuously.
Implementing Digital Circuits (Cont’d)

ENIAC (1945)

Used 18,000 vacuum tubes; did 5000 calculations / sec.
Implementing Digital Circuits (Cont’d)

Gordon Moore (1929–) and Robert Noyce (1927–1990)

Co-founders of Fairchild Semiconductor; in 1959, Noyce develops planar process for creating integrated circuits.
Implementing Digital Circuits (Cont’d)

- Silicon is a natural semiconductor whose electrical conductivity can be chemically modified by doping.
- In the planar process, electrical components based on silicon and deposited metals are “micro-printed” photographically in separate stacked layers on wafers of pure silicon.
Implementing Digital Circuits (Cont’d)

Integrated Circuit (IC) (1959)  IC Internals (“Chip”)

**MOORE’S LAW (1965):** 2X TRANSISTOR DENSITY EVERY 18 MONTHS
... And If You Liked This ...

- MUN Computer Science courses on this area:
  - COMP 1002: Introduction to Logic for Computer Scientists
  - COMP 2003: Computer Architecture
  - COMP 4723: Introduction to Microprocessors
- MUN Computer Science professors teaching courses / doing research in this area:
  - Vinicius Prado da Fonseca
  - Antonina Kolokolova