



UNIVERSITY OF MASSACHUSETTS
Dept. of Electrical & Computer Engineering

Digital Computer Arithmetic
ECE 666

Part 6a
High-Speed Multiplication - I

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Speeding Up Multiplication

- ◆ Multiplication involves **2** basic operations - generation of partial products + their accumulation
- ◆ **2** ways to speed up - reducing number of partial products and/or accelerating accumulation
- ◆ **3** types of high-speed multipliers:
 - ◆ **Sequential multiplier** - generates partial products sequentially and adds each newly generated product to previously accumulated partial product
 - ◆ **Parallel multiplier** - generates partial products in parallel, accumulates using a fast multi-operand adder
 - ◆ **Array multiplier** - array of identical cells generating new partial products; accumulating them simultaneously
 - * No separate circuits for generation and accumulation
 - * Reduced execution time but increased hardware complexity

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Reducing Number of Partial Products

- ◆ Examining 2 or more bits of multiplier at a time
- ◆ Requires generating A (multiplicand), $2A$, $3A$
- ◆ Reduces number of partial products to $n/2$ - each step more complex
- ◆ Several algorithm which do not increase complexity proposed - one is **Booth's algorithm**
- ◆ Fewer partial products generated for groups of consecutive 0's and 1's

Booth's Algorithm

- ◆ Group of consecutive 0's in multiplier - no new partial product - only shift partial product right one bit position for every 0
- ◆ Group of m consecutive 1's in multiplier - less than m partial products generated
- ◆ $\dots 01\dots 110\dots = \dots 10\dots 000\dots - \dots 00\dots 010\dots$
- ◆ Using **SD** (signed-digit) notation $= \dots 100\dots 0\bar{1}0\dots$
- ◆ **Example:**
- ◆ $\dots 011110\dots = \dots 100000\dots - \dots 000010\dots = \dots 1000\bar{1}0\dots$ (decimal notation: $15=16-1$)
- ◆ Instead of generating all m partial products - only 2 partial products generated
- ◆ First partial product added - second subtracted - number of single-bit shift-right operations still m

Booth's Algorithm - Rules

| x_i | x_{i-1} | Operation | Comments | y_i |
|-------|-----------|--------------------|-------------------------------|-----------|
| 0 | 0 | shift only | string of zeros | 0 |
| 1 | 1 | shift only | string of ones | 0 |
| 1 | 0 | subtract and shift | beginning of a string of ones | $\bar{1}$ |
| 0 | 1 | add and shift | end of a string of ones | 1 |

- ◆ **Recoding multiplier** $x_{n-1} x_{n-2} \dots x_1 x_0$ in **SD** code
- ◆ **Recoded multiplier** $y_{n-1} y_{n-2} \dots y_1 y_0$
- ◆ x_i, x_{i-1} of multiplier examined to generate y_i
- ◆ Previous bit - x_{i-1} - only reference bit
- ◆ $i=0$ - reference bit $x_{-1}=0$
- ◆ Simple recoding - $y_i = x_{i-1} - x_i$
- ◆ No special order - bits can be recoded in parallel
- ◆ **Example:** Multiplier **0011110011(0)** recoded as **0100010101** - 4 instead of 6 add/subtracts

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Sign Bit

| | x_{n-1} | x_{n-2} | y_{n-1} |
|-----|-----------|-----------|-----------|
| (1) | 1 | 0 | $\bar{1}$ |
| (2) | 1 | 1 | 0 |

- ◆ Two's complement - sign bit x_{n-1} must be used
- ◆ Deciding on add or subtract operation - no shift required - only prepares for next step
- ◆ Verify only for negative values of X ($x_{n-1}=1$)
- ◆ **2 cases** $A \cdot X = A \cdot \tilde{X} - A \cdot x_{n-1} \cdot 2^{n-1}$ where $\tilde{X} = \sum_{j=0}^{n-2} x_j 2^j$
- ◆ **Case 1** - A subtracted - necessary correction
- ◆ **Case 2** - without sign bit - scan over a string of **1**'s and perform an addition for position **$n-1$**
 - * When $x_{n-1}=1$ considered - required addition not done
 - * Equivalent to subtracting $A \cdot 2^{n-1}$ - correction term

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Example

| | | | | | | | |
|----------|----------|---|-----------|---|-----------|---|--------------------|
| A | | 1 | 0 | 1 | 1 | | -5 |
| X | \times | 1 | 1 | 0 | 1 | | -3 |
| Y | | 0 | $\bar{1}$ | 1 | $\bar{1}$ | | recoded multiplier |
| | | | | | | | |
| Add $-A$ | | 0 | 1 | 0 | 1 | | |
| Shift | | 0 | 0 | 1 | 0 | 1 | |
| Add A | $+$ | 1 | 0 | 1 | 1 | | |
| | | | | | | | |
| | | 1 | 1 | 0 | 1 | 1 | |
| Shift | | 1 | 1 | 1 | 0 | 1 | 1 |
| Add $-A$ | $+$ | 0 | 1 | 0 | 1 | | |
| | | | | | | | |
| | | 0 | 0 | 1 | 1 | 1 | 1 |
| Shift | | 0 | 0 | 0 | 1 | 1 | 1 |

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Booth's Algorithm - Properties

- ◆ Multiplication starts from least significant bit
- ◆ If started from most significant bit - longer adder/subtractor to allow for carry propagation
- ◆ No need to generate recoded **SD** multiplier (requiring **2** bits per digit)
 - * Bits of original multiplier scanned - control signals for adder/subtractor generated
- ◆ **Booth's algorithm** can handle two's complement multipliers
 - * If unsigned numbers multiplied - **0** added to left of multiplier ($X_n=0$) to ensure correctness

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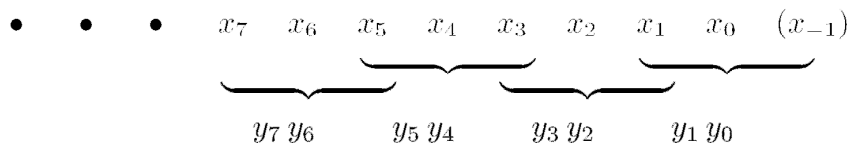
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Drawbacks to Booth's Algorithm

- ◆ Variable number of add/subtract operations and of shift operations between two consecutive add/subtract operations
 - * Inconvenient when designing a synchronous multiplier
- ◆ Algorithm inefficient with isolated 1's
- ◆ **Example:**
- ◆ 001010101(0) recoded as 01̄1̄1̄1̄1̄1̄1̄, requiring 8 instead of 4 operations
- ◆ Situation can be improved by examining 3 bits of X at a time rather than 2

Radix-4 Modified Booth Algorithm

- ◆ Bits x_i and x_{i-1} recoded into y_i and y_{i-1} - x_{i-2} serves as reference bit
- ◆ Separately - x_{i-2} and x_{i-3} recoded into y_{i-2} and y_{i-3} - x_{i-4} serves as reference bit
- ◆ Groups of 3 bits each overlap - rightmost being $x_1 x_0 (x_{-1})$, next $x_3 x_2 (x_1)$, and so on



Radix-4 Algorithm - Rules

| x_i | x_{i-1} | x_{i-2} | y_i | y_{i-1} | operation | comments |
|-------|-----------|-----------|-----------|-----------|-----------|------------------|
| 0 | 0 | 0 | 0 | 0 | +0 | string of zeros |
| 0 | 1 | 0 | 0 | 1 | +A | a single 1 |
| 1 | 0 | 0 | $\bar{1}$ | 0 | -2A | beginning of 1's |
| 1 | 1 | 0 | 0 | $\bar{1}$ | -A | beginning of 1's |
| 0 | 0 | 1 | 0 | 1 | +A | end of 1's |
| 0 | 1 | 1 | 1 | 0 | +2A | end of 1's |
| 1 | 0 | 1 | 0 | $\bar{1}$ | -A | a single 0 |
| 1 | 1 | 1 | 0 | 0 | +0 | string of 1's |

◆ $i=1,3,5,\dots$

◆ Isolated 0/1 handled efficiently

◆ If x_{i-1} is an isolated 1, $y_{i-1}=1$ - only a single operation needed

◆ Similarly - x_{i-1} an isolated 0 in a string of 1's - ...10(1)... recoded as ... $\bar{1}1$... or ... $0\bar{1}$... - single operation performed

◆ **Exercise:** To find required operation - calculate $x_{i-1}+x_{i-2}-2x_i$ for odd i 's and represent result as a 2-bit binary number $y_i y_{i-1}$ in **SD**

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Radix-4 vs. Radix-2 Algorithm

◆ 01|01|01|01|(0) yields 01|01|01|01| - number of operations remains 4 - the minimum

◆ 00|10|10|10|(0) yields 01|0 $\bar{1}$ |0 $\bar{1}$ |\bar{1}0|, requiring 4, instead of 3, operations

◆ Compared to **radix-2** Booth's algorithm - less patterns with more partial products; Smaller increase in number of operations

◆ Can design n -bit synchronous multiplier that generates exactly $n/2$ partial products

◆ Even n - two's complement multipliers handled correctly; Odd n - extension of sign bit needed

◆ Adding a 0 to left of multiplier needed if unsigned numbers are multiplied and n odd - 2 0's if n even

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Example

| | | | | | | |
|-------------|---|-------------|-----|-------------|----|------------------------------|
| A | | 01 | 00 | 01 | | 17 |
| X | × | 11 | 01 | 11 | | -9 |
| Y | | 0 $\bar{1}$ | 10 | 0 $\bar{1}$ | | recoded multiplier operation |
| | | -A | +2A | -A | | |
| <hr/> | | | | | | |
| Add -A | + | 10 | 11 | 11 | | |
| 2-bit Shift | | 1 | 11 | 10 | 11 | 11 |
| Add 2A | + | 0 | 10 | 00 | 10 | |
| <hr/> | | | | | | |
| | | 01 | 11 | 01 | 11 | |
| 2-bit Shift | | 00 | 01 | 11 | 01 | 11 |
| Add -A | + | 10 | 11 | 11 | | |
| <hr/> | | | | | | |
| | | 11 | 01 | 10 | 01 | 11 |
| | | | | | | - 153 |

- ◆ $n/2=3$ steps ; 2 multiplier bits in each step
- ◆ All shift operations are 2 bit position shifts
- ◆ Additional bit for storing correct sign required to properly handle addition of 2A

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Radix-8 Modified Booth's Algorithm

- ◆ Recoding extended to 3 bits at a time - overlapping groups of 4 bits each
- ◆ Only $n/3$ partial products generated - multiple 3A needed - more complex basic step
- ◆ **Example:** recoding 010(1) yields $y_i y_{i-1} y_{i-2}=011$
- ◆ Technique for simplifying generation and accumulation of $\pm 3A$ exists
- ◆ To find minimal number of add/subtract ops required for a given multiplier - find minimal SD representation of multiplier
- ◆ Representation with smallest number of nonzero digits -

$$\min \sum_{i=0}^{n-1} |y_i|$$

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Obtaining Minimal Representation of X

- ◆ $y_{n-1}y_{n-2}\dots y_0$ is a minimal representation of an SD number if $y_i \cdot y_{i-1} = 0$ for $1 \leq i \leq n-1$, given that most significant bits can satisfy $y_{n-1} \cdot y_{n-2} \neq 1$

◆ **Example:**

Representation of 7 with 3 bits
111 minimal representation
 although $y_i \cdot y_{i-1} \neq 0$

| x_{i+1} | x_i | c_i | y_i | c_{i+1} | Comments |
|-----------|-------|-------|-----------|-----------|------------------|
| 0 | 0 | 0 | 0 | 0 | string of 0's |
| 0 | 1 | 0 | 1 | 0 | a single 1 |
| 1 | 0 | 0 | 0 | 0 | string of 0's |
| 1 | 1 | 0 | $\bar{1}$ | 1 | beginning of 1's |
| 0 | 0 | 1 | 1 | 0 | end of 1's |
| 0 | 1 | 1 | 0 | 1 | string of 1's |
| 1 | 0 | 1 | $\bar{1}$ | 1 | a single 0 |
| 1 | 1 | 1 | 0 | 1 | string of 1's |

- ◆ For any X - add a 0 to its left to satisfy above condition

Canonical Recoding

- ◆ Multiplier bits examined one at a time from right; x_{i+1} - reference bit

| x_{i+1} | x_i | c_i | y_i | c_{i+1} | Comments |
|-----------|-------|-------|-----------|-----------|------------------|
| 0 | 0 | 0 | 0 | 0 | string of 0's |
| 0 | 1 | 0 | 1 | 0 | a single 1 |
| 1 | 0 | 0 | 0 | 0 | string of 0's |
| 1 | 1 | 0 | $\bar{1}$ | 1 | beginning of 1's |
| 0 | 0 | 1 | 1 | 0 | end of 1's |
| 0 | 1 | 1 | 0 | 1 | string of 1's |
| 1 | 0 | 1 | $\bar{1}$ | 1 | a single 0 |
| 1 | 1 | 1 | 0 | 1 | string of 1's |

- ◆ To correctly handle a single 0/1 in string of 1's/0's - need information on string to right
- ◆ "Carry" bit - 0 for 0's and 1 for 1's
- ◆ As before, recoded multiplier can be used without correction if represented in two's complement
- ◆ Extend sign bit x_{n-1} - $x_{n-1}x_{n-1}x_{n-2}\dots x_0$
- ◆ Can be expanded to two or more bits at a time
- ◆ Multiples needed for 2 bits - $\pm A$ and $\pm 2A$

Disadvantages of Canonical Recoding

- ◆ Bits of multiplier generated sequentially
- ◆ In **Booth's algorithm** - no "carry" propagation - partial products generated in parallel and a fast multi-operand adder used
- ◆ To take full advantage of minimum number of operations - number of add/subtracts and length of shifts must be variable - difficult to implement
- ◆ For uniform shifts - $n/2$ partial products - more than the minimum in canonical recoding

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Alternate 2-bit-at-a-time Algorithm

- ◆ Reducing number of partial products but still uniform shifts of 2 bits each

| x_{i+1} | x_i | x_{i-1} | Operation | Comments |
|-----------|-------|-----------|-----------|------------------|
| 0 | 0 | 0 | +0 | string of 0's |
| 0 | 0 | 1 | +2A | end of 1's |
| 0 | 1 | 0 | +2A | a single 1 |
| 0 | 1 | 1 | +4A | end of 1's |
| 1 | 0 | 0 | -4A | beginning of 1's |
| 1 | 0 | 1 | -2A | a single 0 |
| 1 | 1 | 0 | -2A | beginning of 1's |
| 1 | 1 | 1 | +0 | string of 1's |

- ◆ x_{i+1} reference bit for $x_i x_{i-1}$ - i odd
- ◆ $\pm 2A, \pm 4A$ can be generated using shifts
- ◆ $4A$ generated when $(x_{i+1})x_i(x_{i-1}) = (0)11$ - group of 1's - not for $(x_{i+3})(x_{i+2})x_{i+1} = 0$ in rightmost position
 - * Not recoding - cannot express 4 in 2 bits
 - * Number of partial products - always $n/2$
 - * Two's complement multipliers - extend sign bit
 - * Unsigned numbers - 1 or 2 0's added to left of multiplier

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Example

- ◆ Multiplier **01101110** - partial products:

$$\begin{array}{r}
 (0) \quad 01 \quad 10 \quad 11 \quad 10 \\
 \quad \quad +2A \quad -2A \quad +4A \quad -2A
 \end{array}$$

- ◆ Translates to the **SD** number **010 $\bar{1}$ 100 $\bar{1}$ 0** - not minimal - includes **2** adjacent nonzero digits
- ◆ Canonical recoding yields **0100 $\bar{1}$ 00 $\bar{1}$ 0** - minimal representation

Dealing with Least significant Bit

- ◆ For the rightmost pair x_1x_0 , if $x_0 = 1$ - considered continuation of string of 1's that never really started - no subtraction took place
- ◆ **Example:** multiplier **01110111** - partial products:

$$\begin{array}{r}
 \quad \quad 01 \quad 11 \quad 01 \quad 11 \\
 \quad \quad +2A \quad +0 \quad -2A \quad +0 \\
 \text{instead of} \quad +2A \quad +0 \quad -2A \quad -A
 \end{array}$$

- ◆ **Correction:** when $x_0=1$ - set initial partial product to **-A** instead of **0**
- ◆ **4 possible cases:**

| x_2 | x_1 | x_0 | Operation |
|-------|-------|-------|-----------------|
| 0 | 0 | 1 | $+2A - A = A$ |
| 0 | 1 | 1 | $+4A - A = 3A$ |
| 1 | 0 | 1 | $-2A - A = -3A$ |
| 1 | 1 | 1 | $0 - A = -A$ |

Example

| | | | | | | | |
|--------------|----------|-----|----|-------|----|----|-----------|
| A | | | 01 | 00 | 01 | | 17 |
| X | \times | (1) | 11 | 01 | 11 | | -9 |
| | | | 0 | $-2A$ | 0 | | Operation |
| Initial $-A$ | | | 10 | 11 | 11 | | |
| Add 0 | + | | 00 | 00 | 00 | | |
| 2-bit Shift | | 1 | 10 | 11 | 11 | | |
| Add $-2A$ | + | 1 | 01 | 11 | 10 | | |
| 2-bit Shift | | 1 | 01 | 10 | 01 | 11 | |
| Add 0 | + | | 11 | 01 | 10 | 01 | 11 |
| | | | 11 | 01 | 10 | 01 | 11 |
| | | | | | | | -153 |

◆ Previous example -

- ◆ Multiplier's sign bit extended in order to decide that no operation needed for first pair of multiplier bits
- ◆ As before - additional bit for holding correct sign is needed, because of multiples like $-2A$

Extending the Alternative Algorithm

- ◆ The above method can be extended to three bits or more at each step
- ◆ However, here too, multiples of A like $3A$ or even $6A$ are needed and
 - * Prepare in advance and store
 - * Perform two additions in a single step
- ◆ For example, for (0)101 we need $8-2=6$, and for (1)001, $-8+2=-6$

Implementing Large Multipliers Using Smaller Ones

- ◆ Implementing $n \times n$ bit multiplier as a single integrated circuit - several such circuits for implementing larger multipliers can be used
- ◆ $2n \times 2n$ bit multiplier can be constructed out of 4 $n \times n$ bit multipliers based on :

$$\begin{aligned}
 A \cdot X &= (A_H \cdot 2^n + A_L) \cdot (X_H \cdot 2^n + X_L) \\
 &= A_H \cdot X_H \cdot 2^{2n} + (A_H \cdot X_L + A_L \cdot X_H) \cdot 2^n + A_L \cdot X_L
 \end{aligned}$$

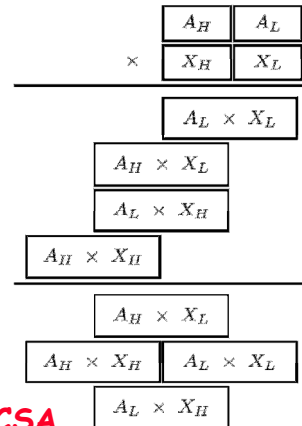
- ◆ A_H , A_L - most and least significant halves of A ;
 X_H , X_L - same for X

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Aligning Partial Products

- ◆ 4 partial products of $2n$ bits - correctly aligned before adding
- ◆ Last arrangement - minimum height of matrix - 1 level of carry-save addition and a CPA
- ◆ n least significant bits - already bits of final product - no further addition needed
- ◆ $2n$ center bits - added by $2n$ -bit CSA with outputs connected to a CPA
- ◆ n most significant bits connected to same CPA, since center bits may generate carry into most significant bits - $3n$ -bit CPA needed

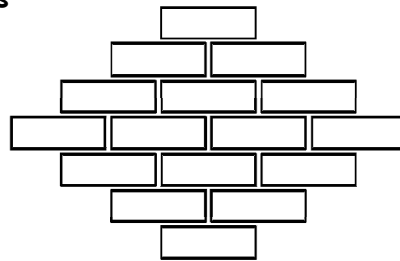


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Decomposing a Large Multiplier into Smaller Ones - Extension

- ◆ Basic multiplier - $n \times m$ bits - $n \neq m$
- ◆ Multipliers larger than $2n \times 2m$ can be implemented
- ◆ **Example:** $4n \times 4n$ bit multiplier - implemented using $n \times n$ bit multipliers
 - * $4n \times 4n$ bit multiplier requires 4 $2n \times 2n$ bit multipliers
 - * $2n \times 2n$ bit multiplier requires 4 $n \times n$ bit multipliers
 - * Total of 16 $n \times n$ bit multipliers
 - * 16 partial products - aligned before being added
- ◆ **Similarly** - for any $kn \times kn$ bit multiplier with integer k

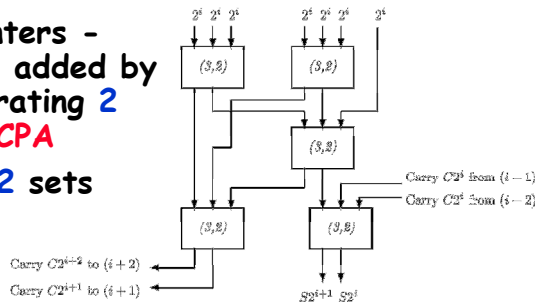
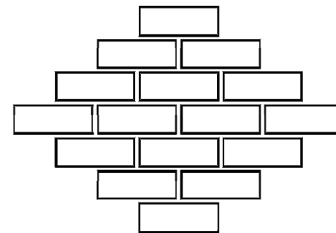


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Adding Partial Products

- ◆ After aligning 16 products - 7 bits in one column need to be added
- ◆ **Method 1:** (7,3) counters - generating 3 operands added by (3,2) counters - generating 2 operands added by a CPA
- ◆ **Method 2:** Combining 2 sets of counters into a set of (7;2) compressors
- ◆ Selecting more economical multi-operand adder - discussed next



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