Lecture 7
Multiplication

School of Computer Science and Engineering
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3. Arithmetic for Computers

3.1 Introduction

3.2 Addition and Subtraction

3.3 Multiplication

3.4 Division

3.5 Floating Point

3.6 Parallelism and Computer Arithmetic: Subword Parallelism

3.7 Real Stuff: x86 Streaming SIMD Extensions and Advanced Vector Extensions

3.8 Going Faster: Subword Parallelism and Matrix Multiply

3.9 Fallacies and Pitfalls

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3.11 Historical Perspective and Further Reading

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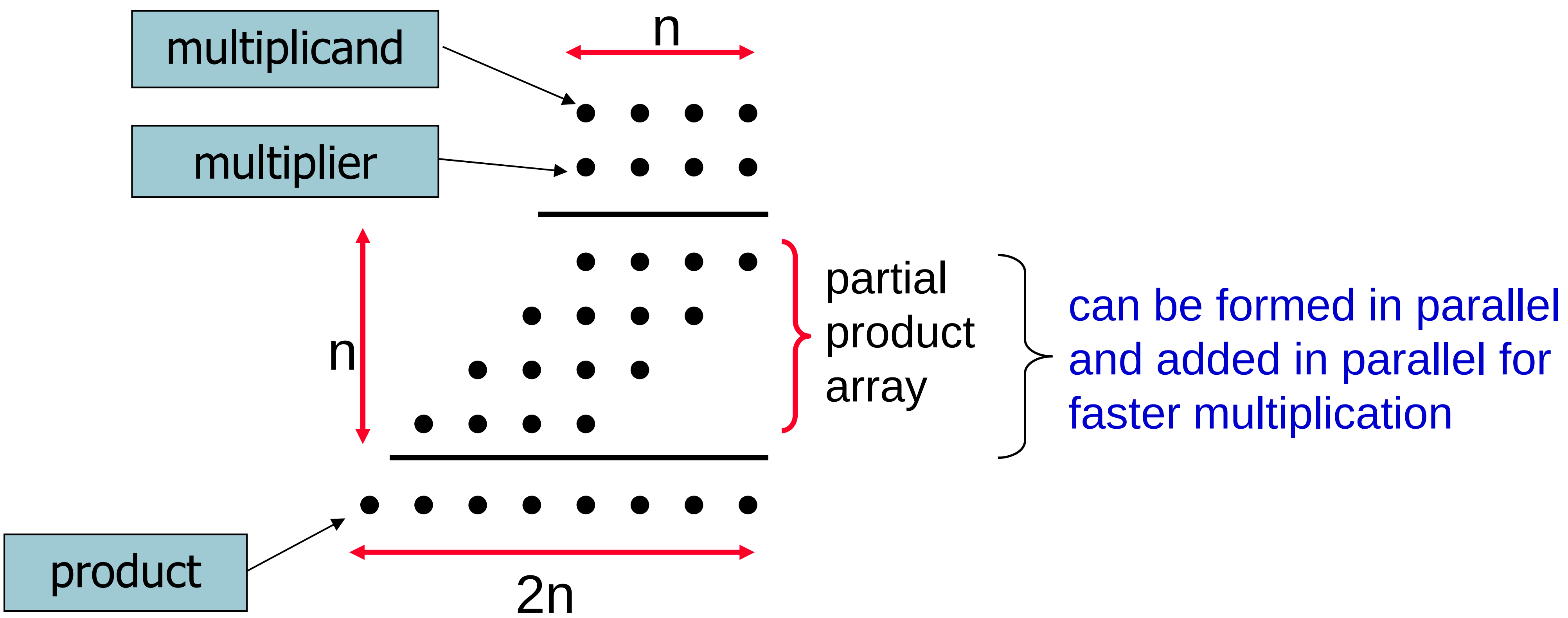
3.3 Multiplication

- Binary multiplication is just a bunch of left shifts and adds

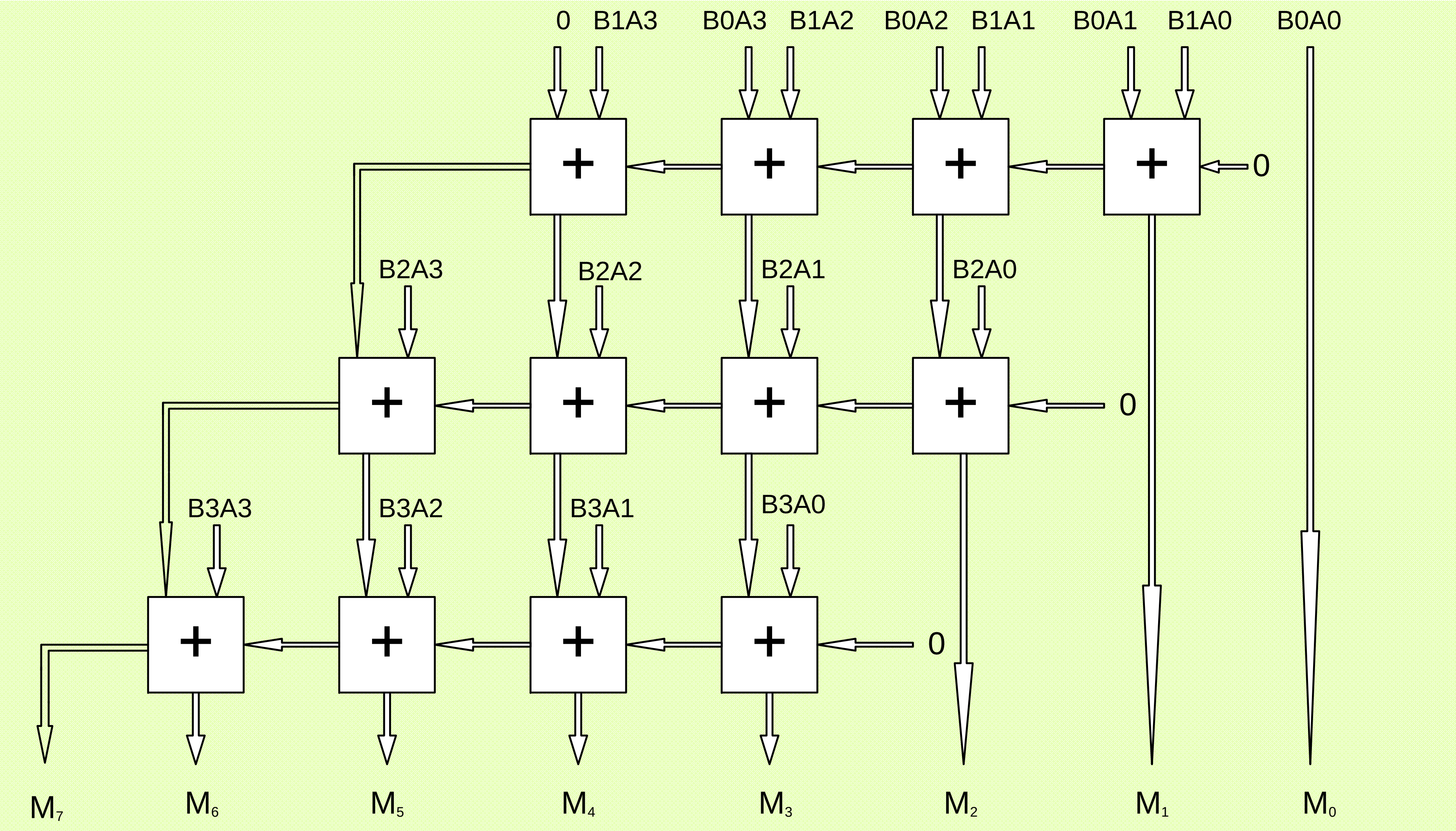


Length of product is the sum of operand lengths

Pencil and Paper Algorithm

```
                                    A3      A2      A1      A0
                                 *  B3      B2      B1      B0
                                   -----------------------------
                                  B0•A3   B0•A2   B0•A1   B0•A0
                          B1•A3   B1•A2   B1•A1   B1•A0
                  B2•A3   B2•A2   B2•A1   B2•A0
          B3•A3   B3•A2   B3•A1   B3•A0
 ---------------------------------------------------------------
  M7      M6      M5      M4      M3      M2      M1      M0
```

Array Multiplier



Binary Multiplication

- **An example: 8 x 9 = 72**

```
Multiplicand:                    1   0   0   0
Multiplier:                *     1   0   0   1
                             -----------------
                                 1   0   0   0
                             0   0   0   0
                         0   0   0   0
                     1   0   0   0
                     --------------------------
Product:             1   0   0   1   0   0   0
```

- **Ignoring the sign bits,**
  - n-bit multiplicand and m-bit multiplier
  - Then $(n+m)$-bit product
- **Each step of the multiplication**
  - If multiplier bit = 1, copy the multiplicand.
  - If multiplier bit = 0, place all 0's.

Sequential Version of the Multiplication Algorithm and Hardware

- **First version of the multiplication hardware**

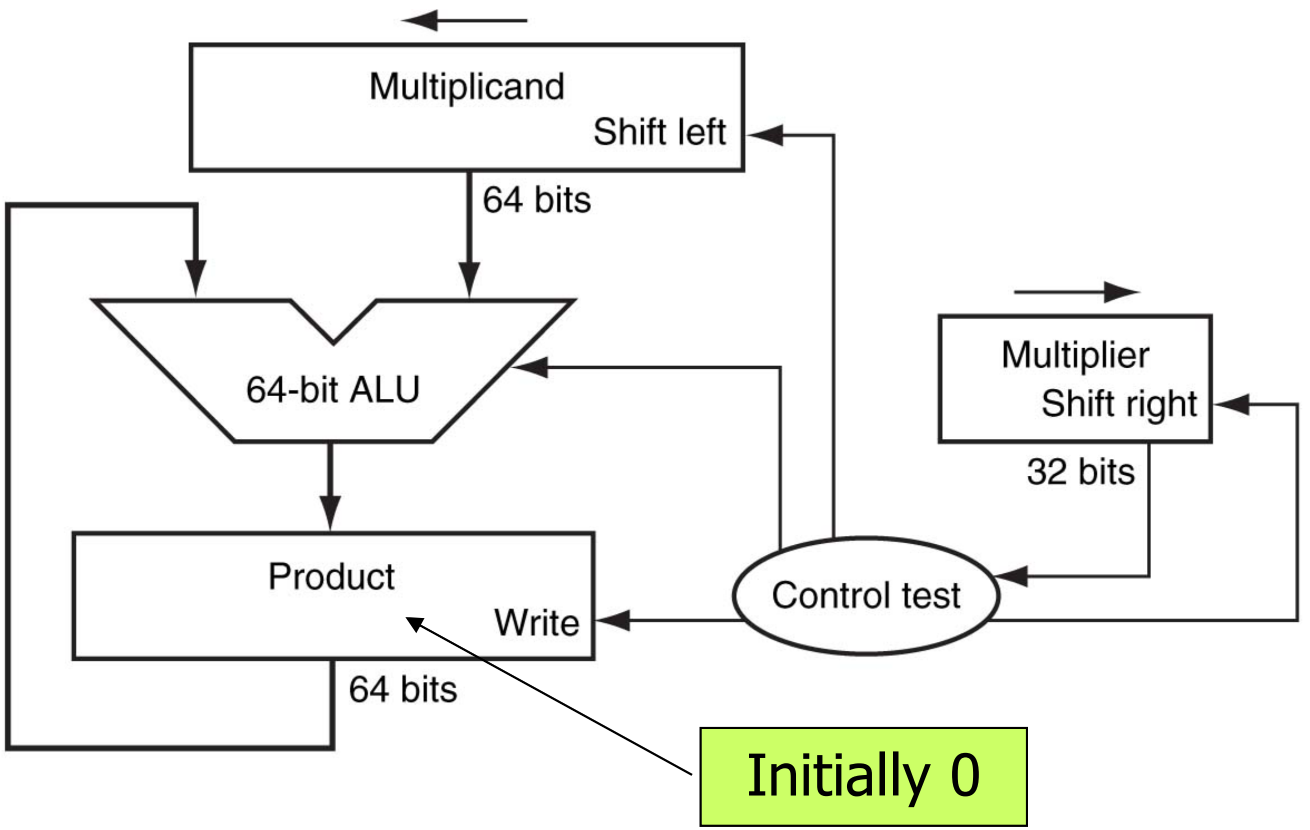


Figure 3.3

First Version - Algorithm

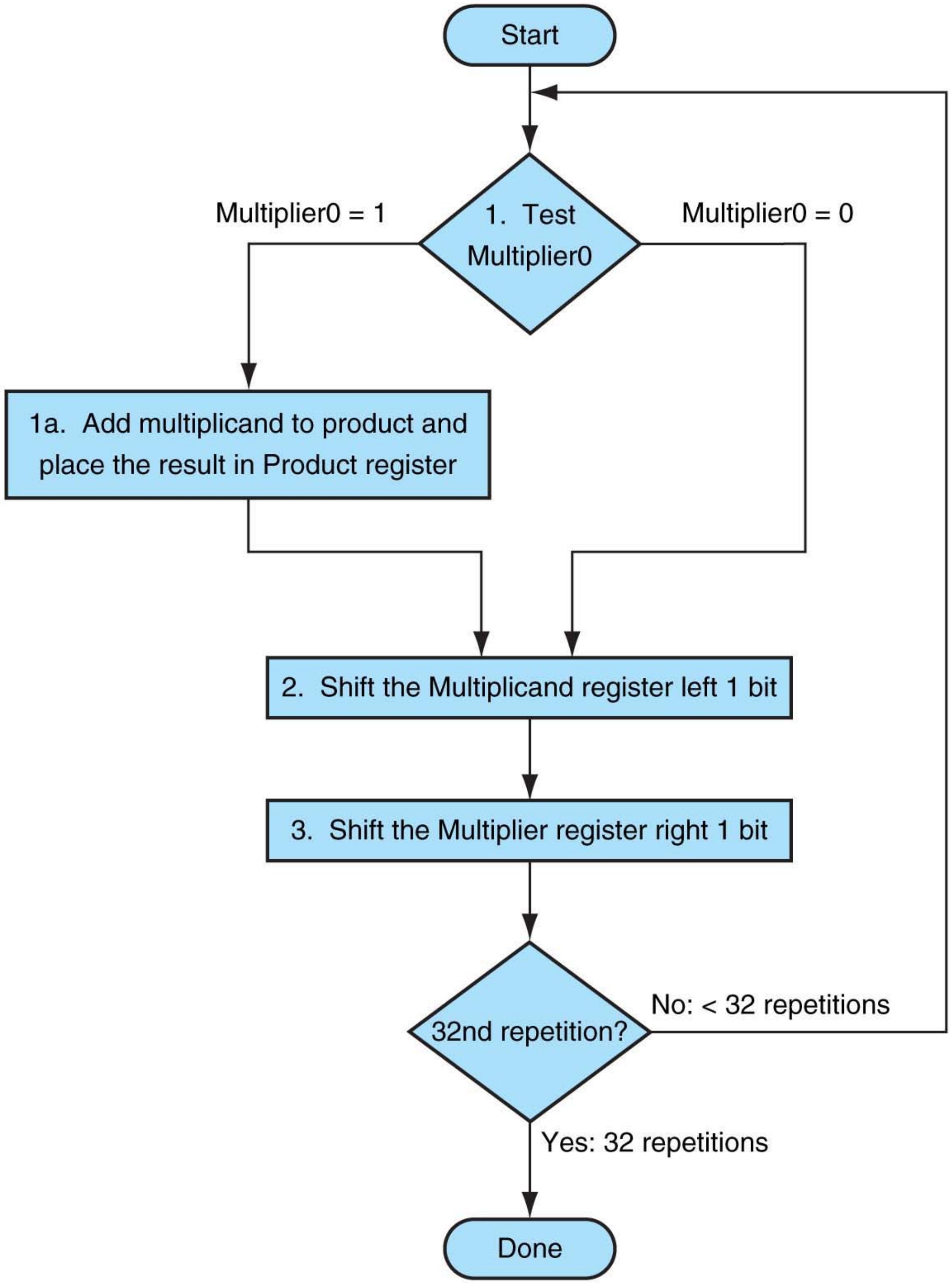


Figure 3.4

Example: First Version

- **Multiply 0010_{two} X 0011_{two}.**
  [Answer] Multiplication time … almost 100 clock cycles

Iteration	Step	Multiplier	Multiplicand	Product
0	Initial values	0011	0000 0010	0000 0000
1	1a: 1 ⇒ Product += Multiplicand	0011		0000 0010
	2: Shift Multiplicand left		0000 0100	
	3: Shift Multiplier right	0001		
2	1a: 1 ⇒ Product += Multiplicand	0001		0000 0110
	2: Shift Multiplicand left		0000 1000	
	3: Shift Multiplier right	0000		
3	1: 0 ⇒ no operation	0000		0000 0110
	2: Shift Multiplicand left		0001 0000	
	3: Shift Multiplier right	0000		
4	1: 0 ⇒ no operation	0000		0000 0110
	2: Shift Multiplicand left		0010 0000	
	3: Shift Multiplier right	0000		0000 0110

Second Version - Hardware

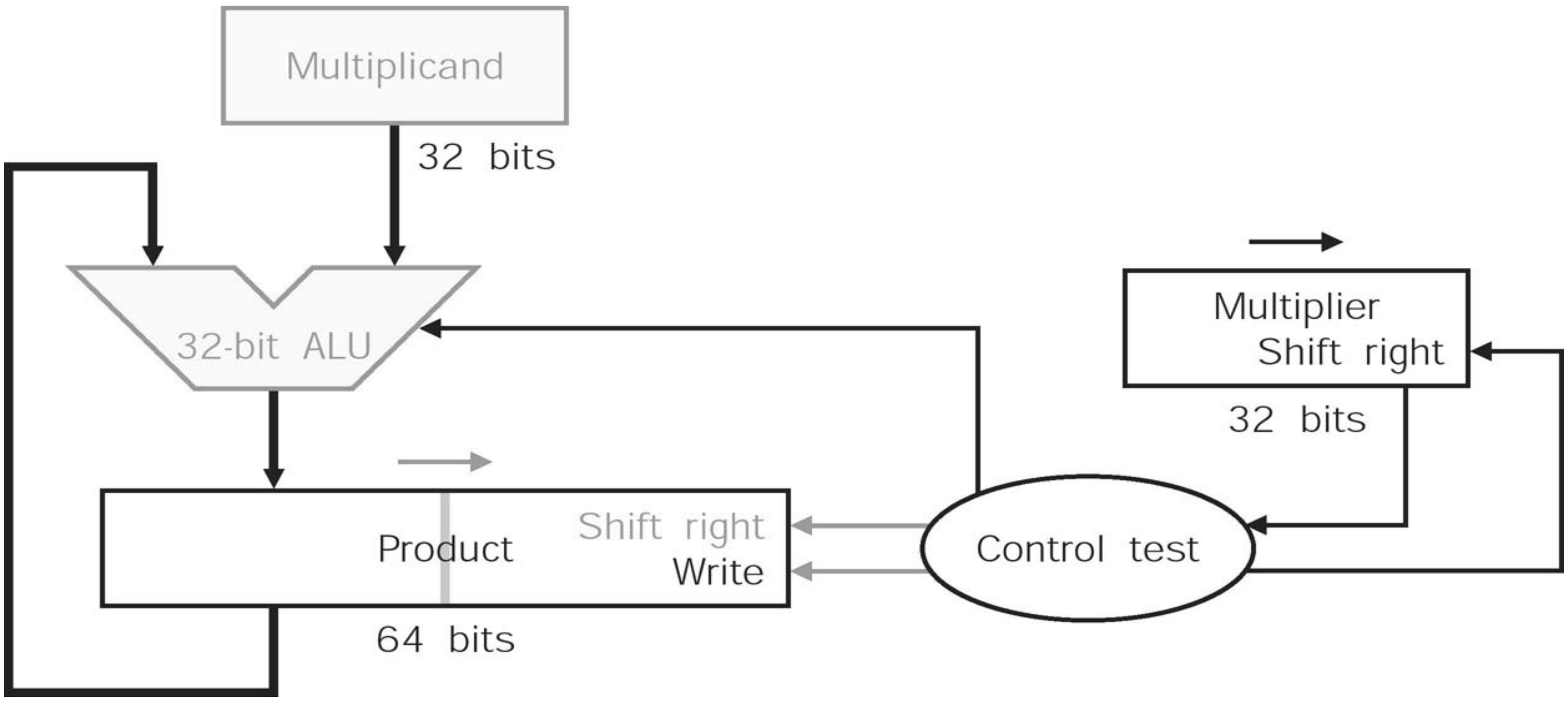


Figure 4.28 of 2ed.

Example: Second Version

- **Multiply 0010_{two} X 0011_{two}.**
  [Answer]

Figure 4.30 of 2ed.

Iteration	Step	Multiplier	Multiplicand	Product
0	Initial values	0011	0010	0000 0000
1	1a: 1 ⇒ Product += Multiplicand	0011		0010 0000
	2: Shift Product right			0001 0000
	3: Shift Multiplier right	0001		
2	1a: 1 ⇒ Product += Multiplicand	0001		0011 0000
	2: Shift Product right			0001 1000
	3: Shift Multiplier right	0000		
3	1: 0 ⇒ no operation	0000		0001 1000
	2: Shift Product right			0000 1100
	3: Shift Multiplier right	0000		
4	1: 0 ⇒ no operation	0000		0000 1100
	2: Shift Product right			0000 0110
	3: Shift Multiplier right	0000		0000 0110

Refined Version - Hardware

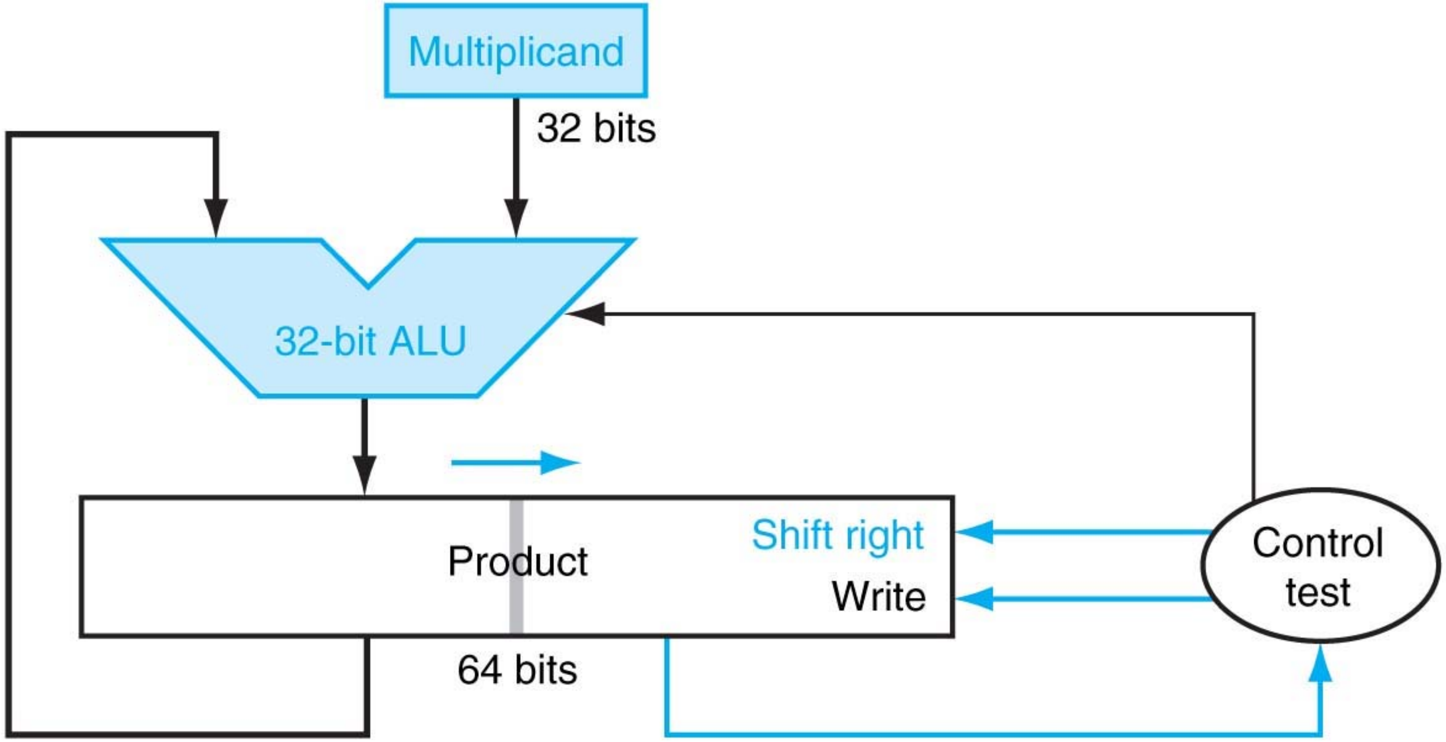


Figure 3.5

Refined Version - Algorithm

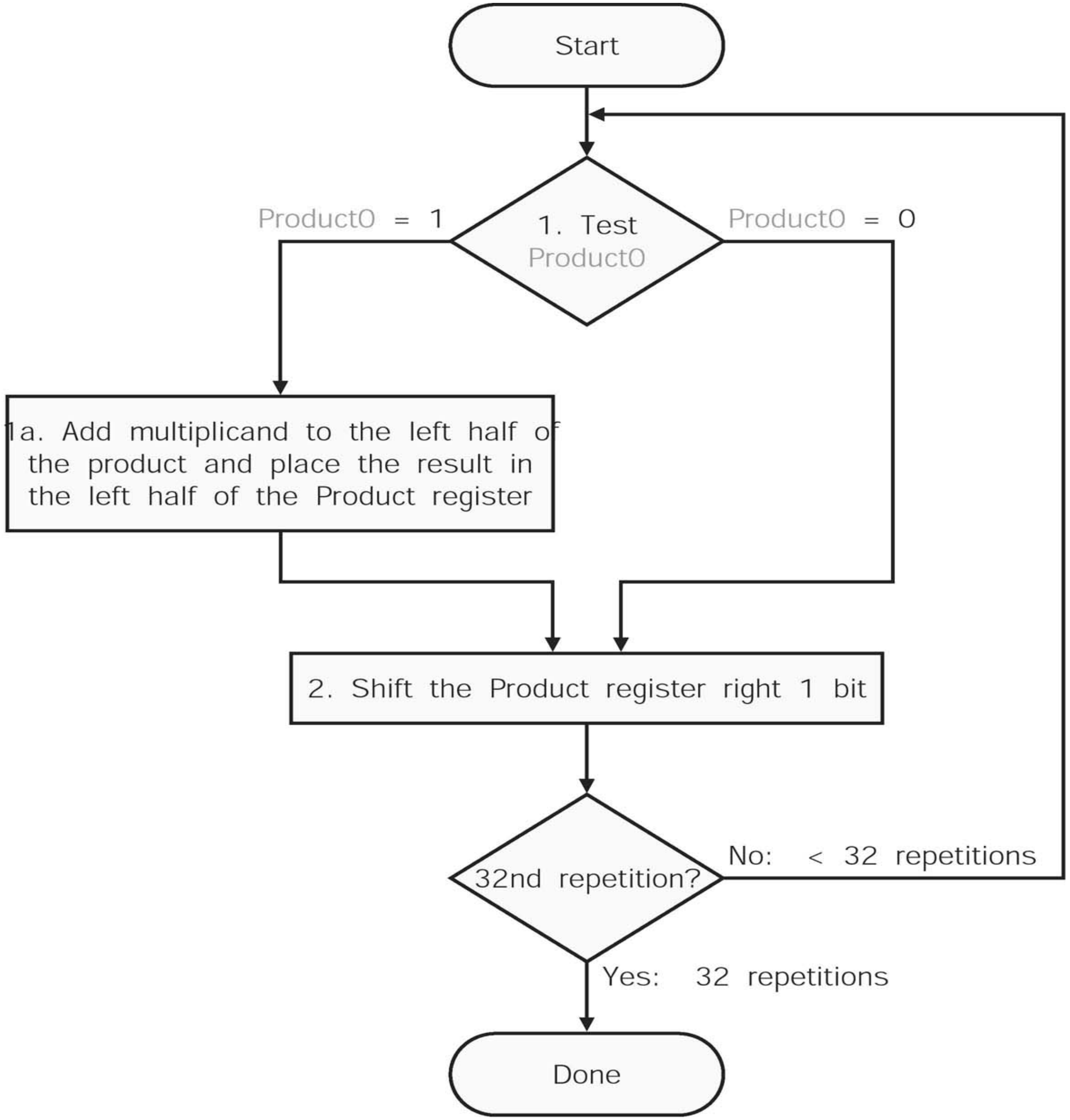


Figure 4.32 in 2ed.

Example 1: Refined Version

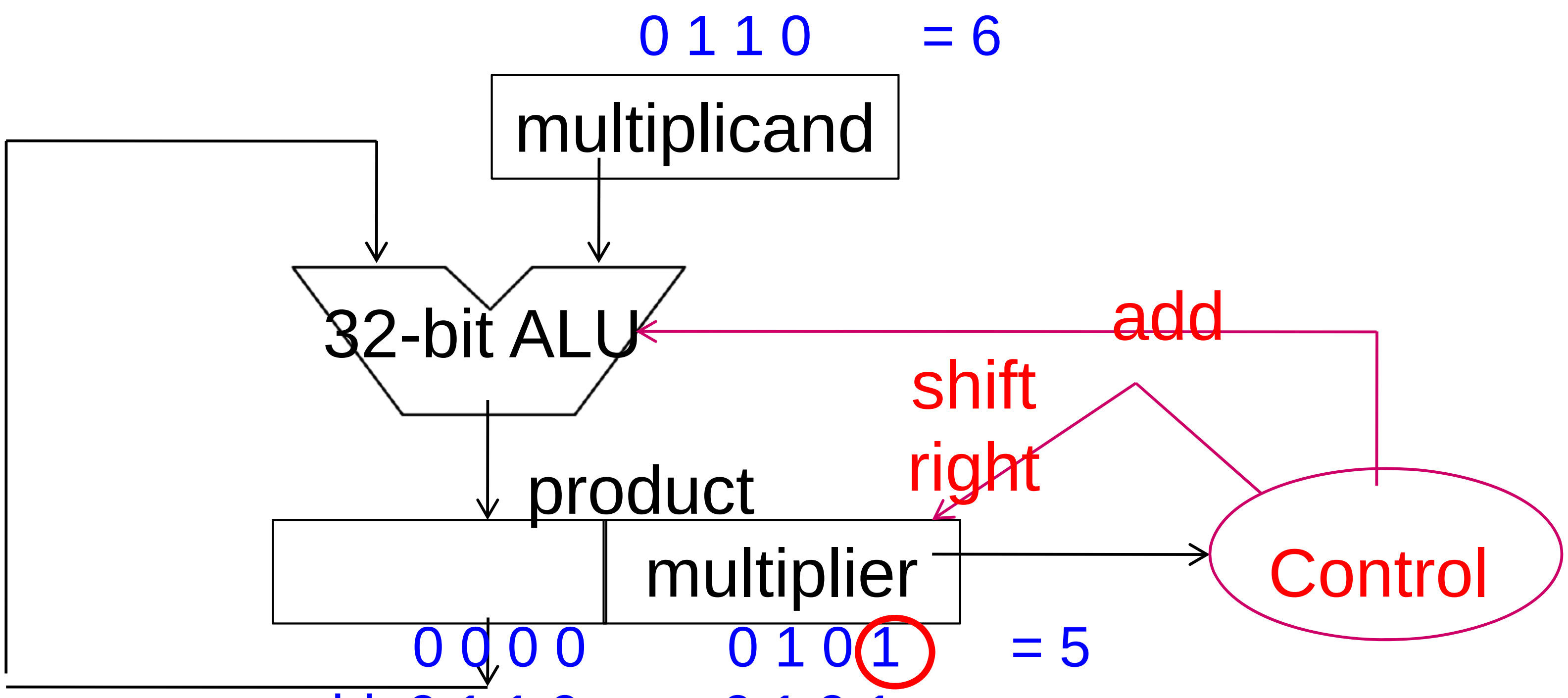
- **Multiply 0010_{two} X 0011_{two}.**

  [Answer]

Iteration	Step	Multiplicand	Product
0	Initial values	0010	0000 0011
1	1a: 1 ⇒ Product += Multiplicand		0010 0011
	2: Shift Product right		0001 0001
2	1a: 1 ⇒ Product += Multiplicand		0011 0001
	2: Shift Product right		0001 1000
3	1: 0 ⇒ no operation		0001 1000
	2: Shift Product right		0000 1100
4	1: 0 ⇒ no operation		0000 1100
	2: Shift Product right		0000 0110

Figure 4.33 of 2ed.

Example 2: Refined Version



add	0 1 1 0	0 1 0 1	
	0 0 1 1 →	0 0 1 0	
no add	0 0 1 1	0 0 1 0	
	0 0 0 1 →	1 0 0 1	
add	0 1 1 1	1 0 0 1	
	0 0 1 1 →	1 1 0 0	
no add	0 0 1 1	1 1 0 0	
	0 0 0 1 →	1 1 1 0	= 30

Signed Multiplication

- **Booth's Algorithm**
  - Multiplication algorithm for signed 2's complement numbers
- **Key idea**
  - $30_{ten} = 16_{ten} + 8_{ten} + 4_{ten} + 2_{ten}$
    $= 32_{ten} - 2_{ten}$
  - 011110_{two}
    $= 010000_{two} + 001000_{two} + 000100_{two} + 000010_{two}$
    $= 100000_{two} - 000010_{two}$

Multiplication by Booth's Algorithm

1. Depending on the current and previous bits

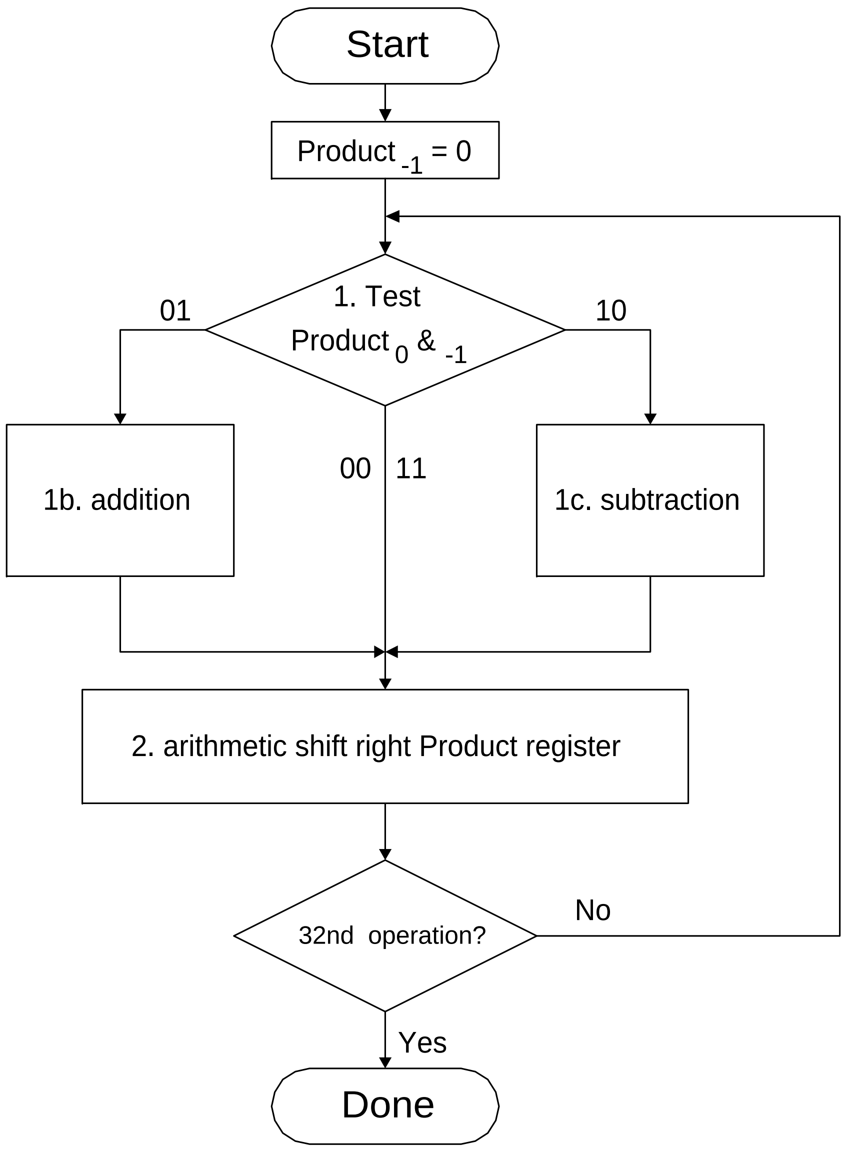
00, 11: No arithmetic

01: Addition (end of a string of 1s)

10: Subtraction (beginning of a string of 1s)

2. Arithmetic shift right the product register.

Booth's Algorithm - Flowchart



Example: Booth's Algorithm

- **Multiply 0010_{two} X 1101_{two}**
  [Answer]

Iteration	Step	Multiplicand	Product
0	Initial values	0010	0000 1101 0
1	1c: 10 ⇒ Prod = Prod - Mcand	0010	1110 1101 0
	2 : Shift Product right	0010	1111 0110 1
2	1b: 01 ⇒ Prod = Prod + Mcand	0010	0001 0110 1
	2 : Shift Product right	0010	0000 1011 0
3	1c: 10 ⇒ Prod = Prod - Mcand	0010	1110 1011 0
	2 : Shift Product right	0010	1111 0101 1
4	1d: 11 ⇒ no operation	0010	1111 0101 1
	2 : Shift Product right	0010	1111 1010 1

Comparison

Iteration	Multiplicand	Original algorithm		Booth's algorithm	
		Step	Product	Step	Product
0	0010	Initial values	0000 0110	Initial values	0000 0110 0
1	0010	1: 0 => no operation	0000 0110	1a: 00 => no operation	0000 0110 0
	0010	2: Shift right Product	0000 0011	2: Shift right Product	0000 0011 0
2	0010	1a: 1 => Prod=Prod+Mcand	0010 0011	1c: 10 => Prod=Prod-Mcand	1110 0011 0
	0010	2: Shift right Product	0001 0001	2: Shift right Product	1111 0001 1
3	0010	1a: 1 => Prod=Prod+Mcand	0011 0001	1d: 11 => no operation	1111 0001 1
	0010	2: Shift right Product	0001 1000	2: Shift right Product	1111 1000 1
4	0010	1: 0 => no operation	0001 1000	1b: 01 => Prod=Prod+Mcand	0001 1000 1
	0010	2: Shift right Product	0000 1100	2: Shift right Product	0000 1100 0

Figure 4.34 in 2ed.

Theoretical Background of Booth's Algorithm

- **Booth's algorithm with signed 2's complement numbers**
  - If $((a_{i-1} - a_{i}) == 0)$ do nothing;
    else if $((a_{i-1} - a_i) == (+1))$ add B;
    else if $((a_{i-1} - a_i) == (-1))$ subtract B;
  - Product $= (a_{-1} - a_0) \times B$

$$
\begin{aligned}
&+ (a_0 - a_1) \times B \times 2^1 \\
&+ (a_1 - a_2) \times B \times 2^2 \\
&\quad \cdots \\
&+ (a_{29} - a_{30}) \times B \times 2^{30} \\
&+ (a_{30} - a_{31}) \times B \times 2^{31}
\end{aligned}
$$

Theoretical Background of Booth's Algorithm

- Product $= B\times((a_{-1} + (a_0 \times 2^0) + (a_1 \times 2^1) + \ldots$

  $+ (a_{30} \times 2^{30}) + (a_{31} \times -2^{31}))$

  $= B\times((a_0 \times 2^0) + (a_1 \times 2^1) + \ldots$

  $+ (a_{30} \times 2^{30}) + (a_{31} \times -2^{31}))$

  $= B\times(-a_{31} \times 2^{31} + \Sigma\, a_i \times 2^i)$

  $\Rightarrow$ B×(value of *A* in two's complement representation)

(cf) Value of $X = x_{n-1}x_{n-2}\cdots x_1 x_0$ in signed 2'complement

$$V(X) = -x_{n-1}\cdot 2^{n-1} + \sum_{k=0}^{n-2} x_k \cdot 2^k$$

Supplement

MIPS Multiply Instruction

- Multiply (**`mult`** and **`multu`**) produces a double precision product

```
mult   $s0, $s1  # hi||lo = $s0 * $s1
```

0	16	17	0	0	0x18

  - Low-order word of the product is left in processor register **`lo`** and the high-order word is left in register **`hi`**
  - Instructions **`mfhi rd`** and **`mflo rd`** are provided to move the product to (user accessible) registers in the register file

- Multiplies are usually done by fast, dedicated hardware and are much more complex (and slower) than adders

Multiply in MIPS

- **A separate pair of 32-bit registers**
  - *Hi* and *Lo* registers
  - 64-bit product store
- **Instructions**
  - **`mult  $s2,$s3 # Hi,Lo = $s2 x $s3 (signed)`**
  - **`multu $s2,$s3 # Hi,Lo = $s2 x $s3 (unsigned)`**
  - **`mul $t0,$s2,$s3 # $t0 = lower 32 bits of $s2 x $s3`**
  - **`mflo  $s1       # $s1 = Lo (move from lo)`**
  - **`mfhi  $s1       # $s1 = Hi (move from hi)`**
- **Pseudoinstructions**
  - **`(mul $t0,$s2,$s3`** &) **`mulu $t0,$s2,$s3`** (no overflow check)
  - **`mulo $t0,$s2,$s3`** & **`mulou $t0,$s2,$s3`** (overflow check)

Overflow Check

- **Example C program**

```
integer x, y, z;
x = y * z;
```

  - `Y * z` in `Hi-Lo` register
- **For signed multiply**
  - When (Lo_{31} == 0), if (Hi $\neq$ 0000…0) then overflow
  - When (Lo_{31} == 1), if (Hi $\neq$ 1111…1) then overflow
- **For unsigned multiply**
  - If (Hi $\neq$ 0000…0) then overflow