

Design of Digital Circuits and Systems

ASM with Datapath III

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Relevant Course Information

- ❖ Homework 3 due tomorrow
- ❖ Homework 4 released today and due 5/5
 - ASMDs and algorithm implementation debugging
- ❖ Quiz 2 (ROM, RAM, Reg files) @ 11:50 am
- ❖ Lab 3 reports due next Friday (5/2)
 - Ideally finish by early next week so you can start Lab 4
- ❖ Lab 4 released today and due 5/9
 - Implementing bit counting and binary search algorithms

ASMD Chart Review Questions

❖ Circle all that apply:

- Where can **control signals** be found?

State boxes

Decision boxes

Conditional output boxes

- Where can **status signals** be found?

State boxes

Decision boxes

Conditional output boxes

- Where can **external input signals** be found?

State boxes

Decision boxes

Conditional output boxes

- What is the *first* thing a path should encounter in an **ASM block**?

State boxes

Decision boxes

Conditional output boxes

- What can be found outside of **ASM blocks**?

State boxes

Decision boxes

Conditional output boxes

- What can **RTL operations** be attached to?

Control signals

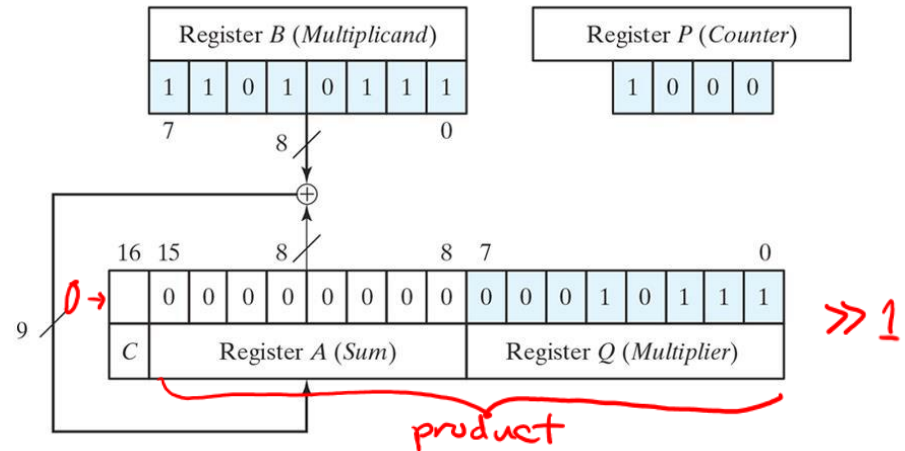
Status signals

External output signals

Sequential Binary Multiplier Operation

❖ A few steps of:

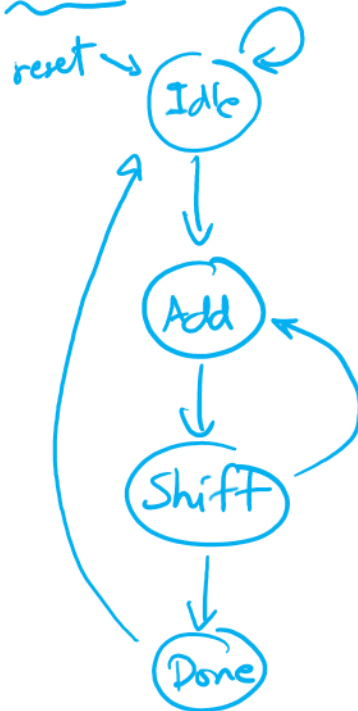
$$\begin{array}{r} 11010111 \\ \times 00010111 \\ \hline \end{array}$$



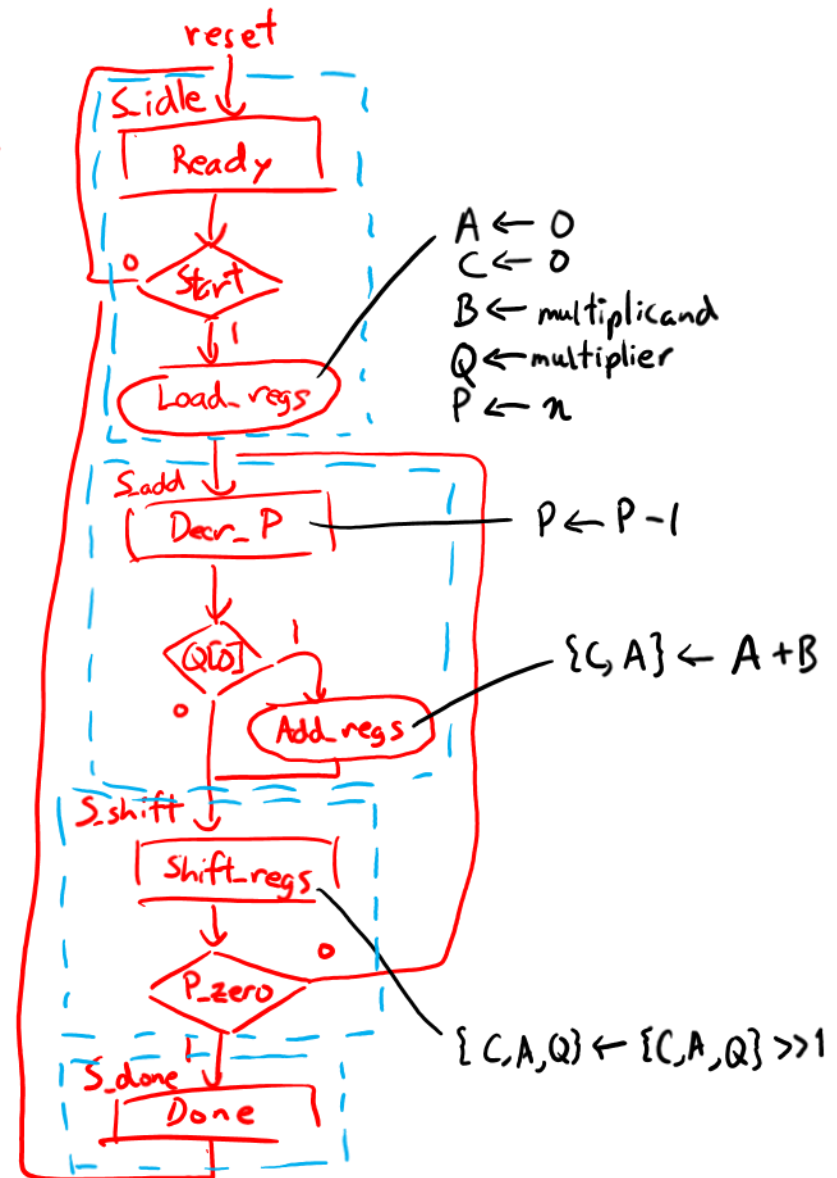
Operation (completed)	C	A	Q	P
Initialize computation	0	00000000	00010111	1000
Add (Q[8] = 1)	0	11010111	00010111	0111
Shift	0	01101011	10001011	0111
Add (Q[7] = 1)	1	01000010	10001011	0110
Shift	0	10100001	01000101	0110
Add (Q[6] = 1)	1	01111000	01000101	0101
Shift	0	10111100	00100010	0101

Binary Multiplier (ASMD Chart)

States:



ASMD:



ASMD Process Review

- 1) Identify datapath components, control signals, and status signals from description or pseudocode.
- 2) *[optional]* Create control-datapath circuit diagram.
- 3) *[optional]* Create state outline to plan out states and transitions between them.
- 4) Draw out ASM state boxes, decision boxes, and paths between them.
- 5) Augment state boxes with Moore-type outputs and add conditional output boxes with Mealy-type outputs.
- 6) Add ASM blocks to organize states.
- 7) Add RTL operations to control signals.
- 8) Double-check decision box edge cases and timing of operations (*i.e.*, debug).

Short Tech Break

Division Circuit

- ❖ Design a circuit that implements the long-division algorithm:

$$\begin{array}{r} 15 \\ 9 \overline{) 140} \\ \underline{9} \\ 50 \\ \underline{45} \\ 5 \end{array}$$

(a) An example using decimal numbers

$$\begin{array}{r} \text{divisor} \rightarrow 1001 \quad \begin{array}{r} 00001111 \leftarrow \text{quotient} \\ 10001100 \leftarrow \text{dividend} \\ \underline{1001} \\ 10001 \\ \underline{1001} \\ 10000 \\ \underline{1001} \\ 1110 \\ \underline{1001} \\ 101 \leftarrow \text{remainder} \end{array} \end{array}$$

(b) Using binary numbers

- ❖ Considerations:
 - Main operations?
 - Stop condition?

Division Circuit

- ❖ Design a circuit that implements the long-division algorithm:
 - 1) Double the **dividend** width by appending 0's in front and align the **divisor** to the leftmost bit of the *extended dividend*.
 - 2) If the corresponding **dividend** bits are \geq the **divisor**, subtract the **divisor** from the **dividend** bits and make the corresponding **quotient** bit 1. Otherwise, keep the original **dividend** bits and make the **quotient** bit 0.
 - 3) Append one additional **dividend** bit to the previous result and shift the divisor to the right one position.
 - 4) Repeat steps 2 and 3 until all dividend bits are used.

Division Circuit

$$\begin{array}{r}
 \text{divisor} \\
 0010 \overline{) 00001101} \\
 \underline{0000} \\
 0001 \\
 \underline{0000} \\
 0011 \\
 \underline{0010} \\
 0010 \\
 \underline{0010} \\
 0001 \text{ — remainder}
 \end{array}
 \begin{array}{l}
 00110 \text{ — quotient} \\
 00001101 \text{ — dividend}
 \end{array}$$

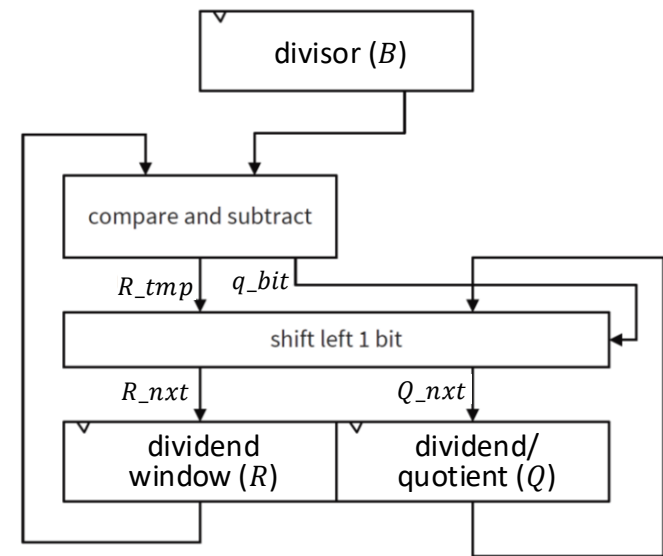
❖ Implementation Notes:

- If current **dividend window** is smaller than the **divisor**, skip subtraction
- Instead of shifting **divisor** to the right, we will shift the **dividend** (and the **quotient**) *to the left*
- We will re-use the lower half of the **dividend** register to store the **quotient**

Division Circuit Operation

❖ A few steps of:

$$0010 \overline{) 1111}$$



Op (done)	B	R	Q	q_bit	R_tmp	R_nxt	Q_nxt	P
Initialize	0010	0000	1111	0	0000	0001	1110	100

Division Circuit Specification

❖ Datapath

- $2n$ -bit *register* with bits split into n -bit R and n -bit Q
- Divisor stored in register B , dividend stored in Q , R holds 0
- A “compare and subtract” module outputs $\{R, 0\}$ if $R < B$ and $\{R - B, 1\}$ otherwise ($\{R_{tmp}, q_{bit}\}$)
- A *shifter* left shifts q_{bit} into $\{R_{tmp}, Q\}$ and outputs to the inputs of R and Q
- A $\lceil \log_2(n + 1) \rceil$ -bit *counter* P

❖ Control

- Inputs *Start* and *Reset*, outputs *Ready* and *Done*
- Status signals:
- Control signals:

Division Circuit (ASMD Chart)

Division Circuit Implementation

❖ Controller Logic

Load_regs =

Enable_RQ =

Finish_RQ =

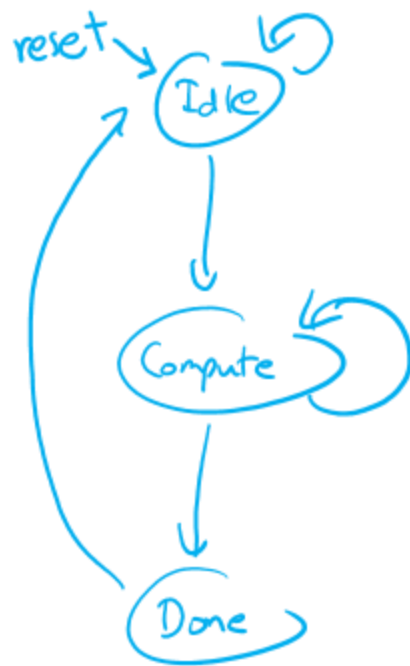
Decr_P =

Ready =

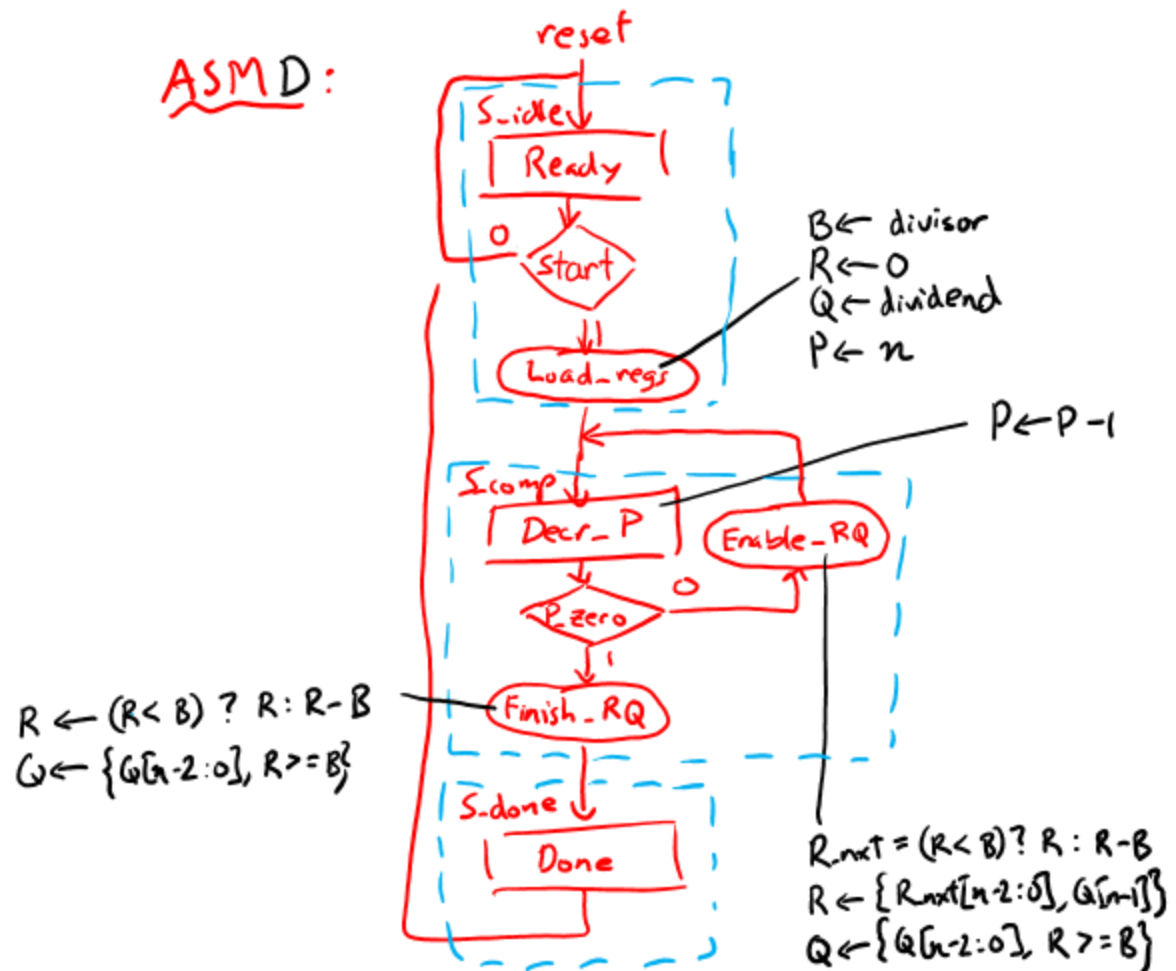
Done =

Division Circuit (ASMD Chart)

States:



ASMD:



Division Circuit Implementation

❖ Controller Logic

$$Load_regs = S_idle \cdot Start$$

$$Enable_RQ = S_comp \cdot \overline{P_zero}$$

$$Finish_RQ = S_comp \cdot P_zero$$

$$Decr_P = S_comp$$

$$Ready = S_idle$$

$$Done = S_done$$

Division Circuit (SV, Datapath)

```
module datapath #(parameter WIDTH=4)
    (Q, P, divisor, dividend, clk,
     Load_regs, Enable_RQ, Enable_R, Decr_P);

    // port definitions
    output logic [2*WIDTH-1:0] product;
    output logic [WIDTH-1:0] Q, P; // note: unnecessary bits for P
    input  logic [WIDTH-1:0] multiplicand, multiplier;
    input  logic clk, Load_regs, Shift_regs, Add_regs, Decr_P;

    // internal logic
    logic [WIDTH-1:0] B, R, R_tmp, R_nxt;
    logic q_bit;

endmodule
```

Division Circuit (SV, Datapath)

```
module datapath #(parameter WIDTH=4)
    (Q, P, divisor, dividend, clk,
     Load_regs, Enable_RQ, Enable_R, Decr_P);

    // port definitions & internal logic
    ...

    // assignments
    assign q_bit = (R >= B);
    assign R_tmp = (R < B) ? R : R-B;
    assign R_nxt = {R_tmp[WIDTH-2:0], Q[WIDTH-1]};
    assign Q_nxt = {Q[WIDTH-2:0], q_bit};

    // datapath logic
    always_ff @(posedge clk) begin
        if (Load_regs) begin
            R <= 0;      Q <= dividend;
            P <= WIDTH;  B <= divisor;
        end
        if (Decr_P)      P <= P - 1;
        if (Comp_regs)   {R, Q} <= {R_nxt, Q_nxt};
        if (Done_regs)   {R, Q} <= {R_tmp, Q_nxt};
    end // always_ff

endmodule
```

Lab 4 Preview: Bit Counter

- ❖ Design a circuit that counts the number of bits in a register *A* that have the value 1
- ❖ Algorithm:

```
B = 0;    // counter
while A != 0 do
    if A[0] = 1 then
        B = B + 1
    endif
    A = A >> 1
endwhile
```