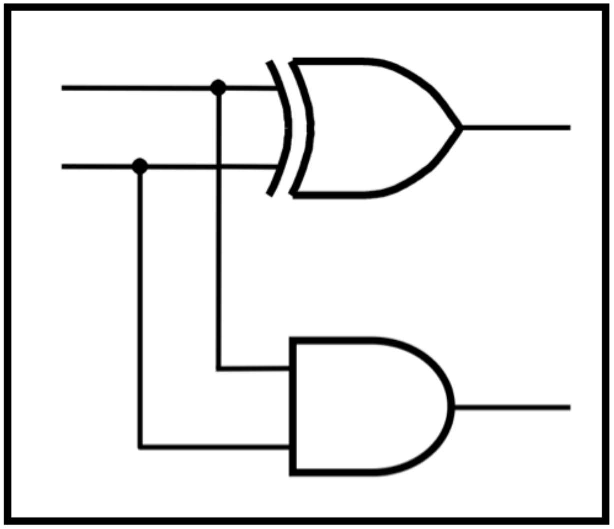


CprE 281: Digital Logic

Instructor: Alexander Stoytchev

http://www.ece.iastate.edu/~alexs/classes/

Simple Processor

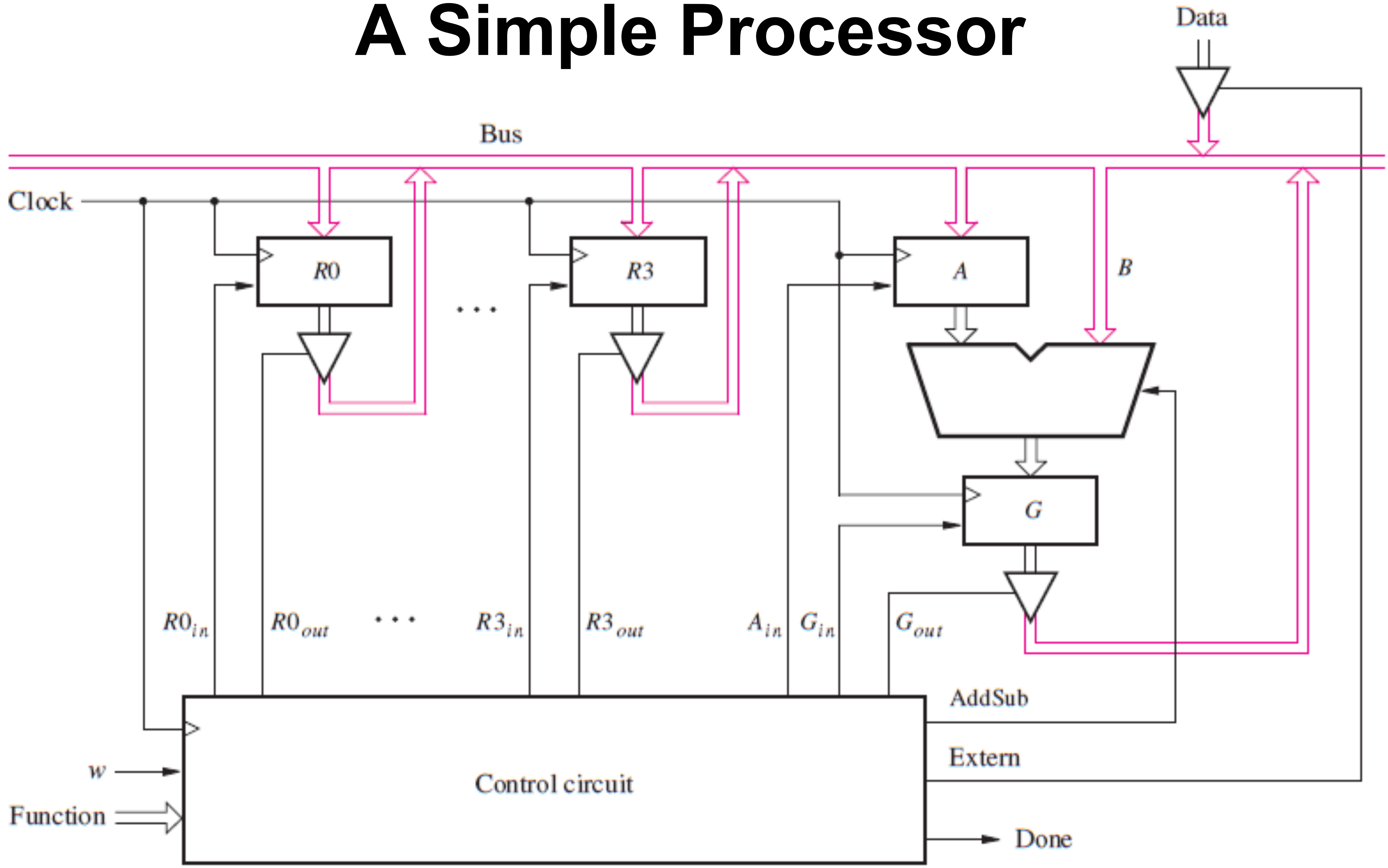
CprE 281: Digital Logic
Iowa State University, Ames, IA

Digital System

- **Datapath circuit**
  - To store data
  - To manipulate data
  - To transfer data from one part of the system to another
  - Comprise building blocks such as registers, shift registers, counters, multipliers, decoders, encoders, adders, etc.

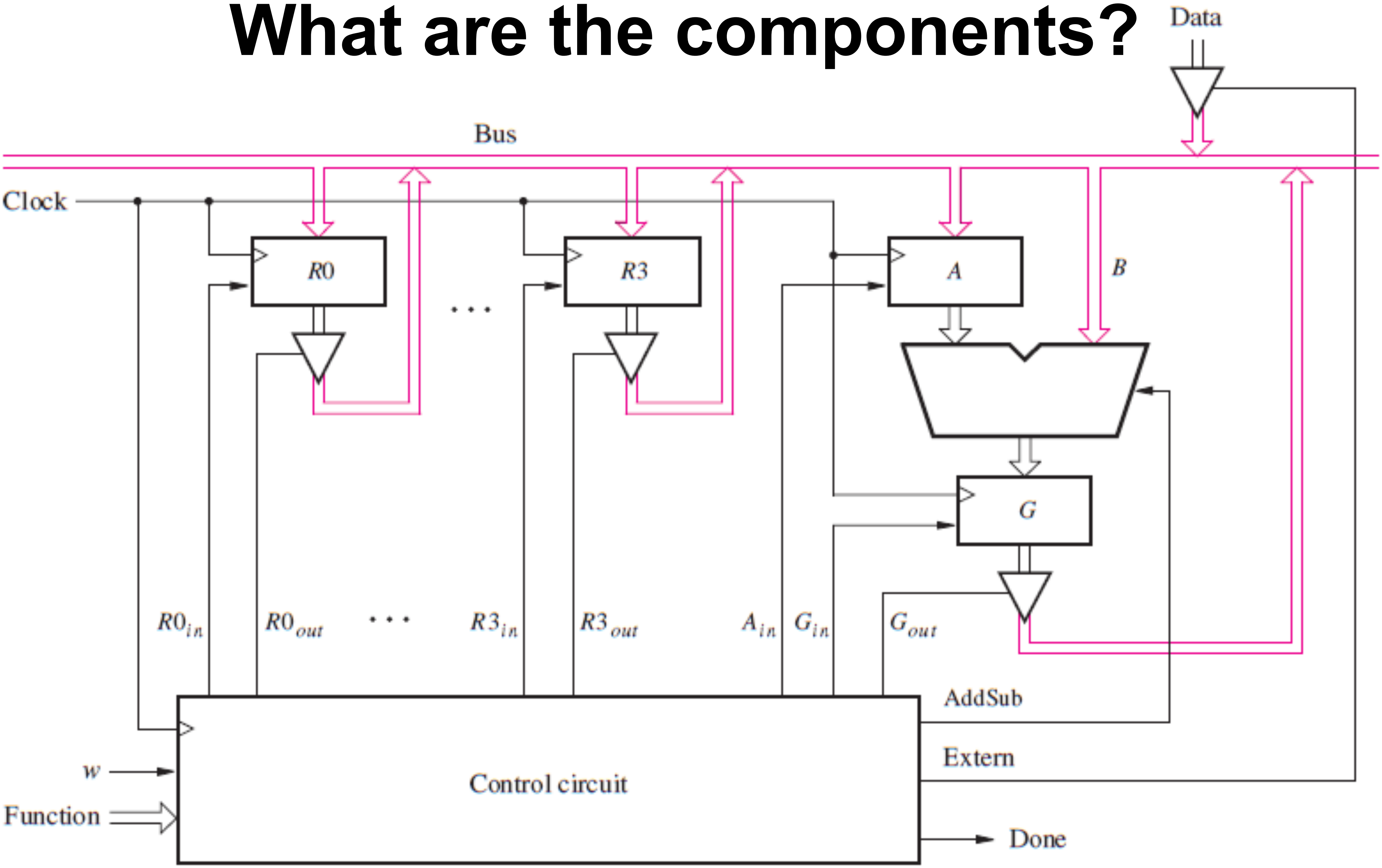
- **Control circuit**
  - Controls the operation of the datapath circuit
  - Designed as a FSM

A Simple Processor



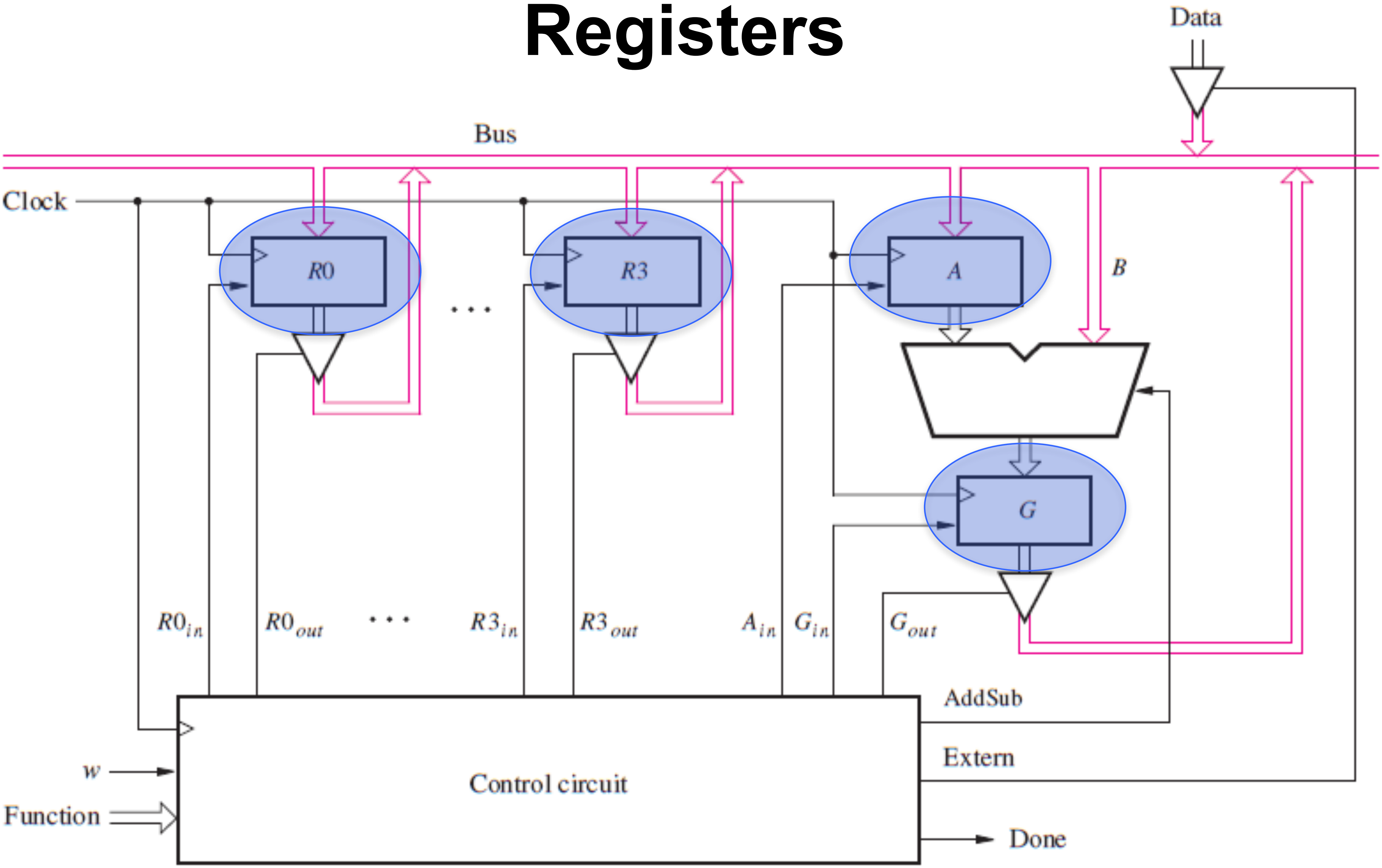
[Figure 7.9 from the textbook]

What are the components?



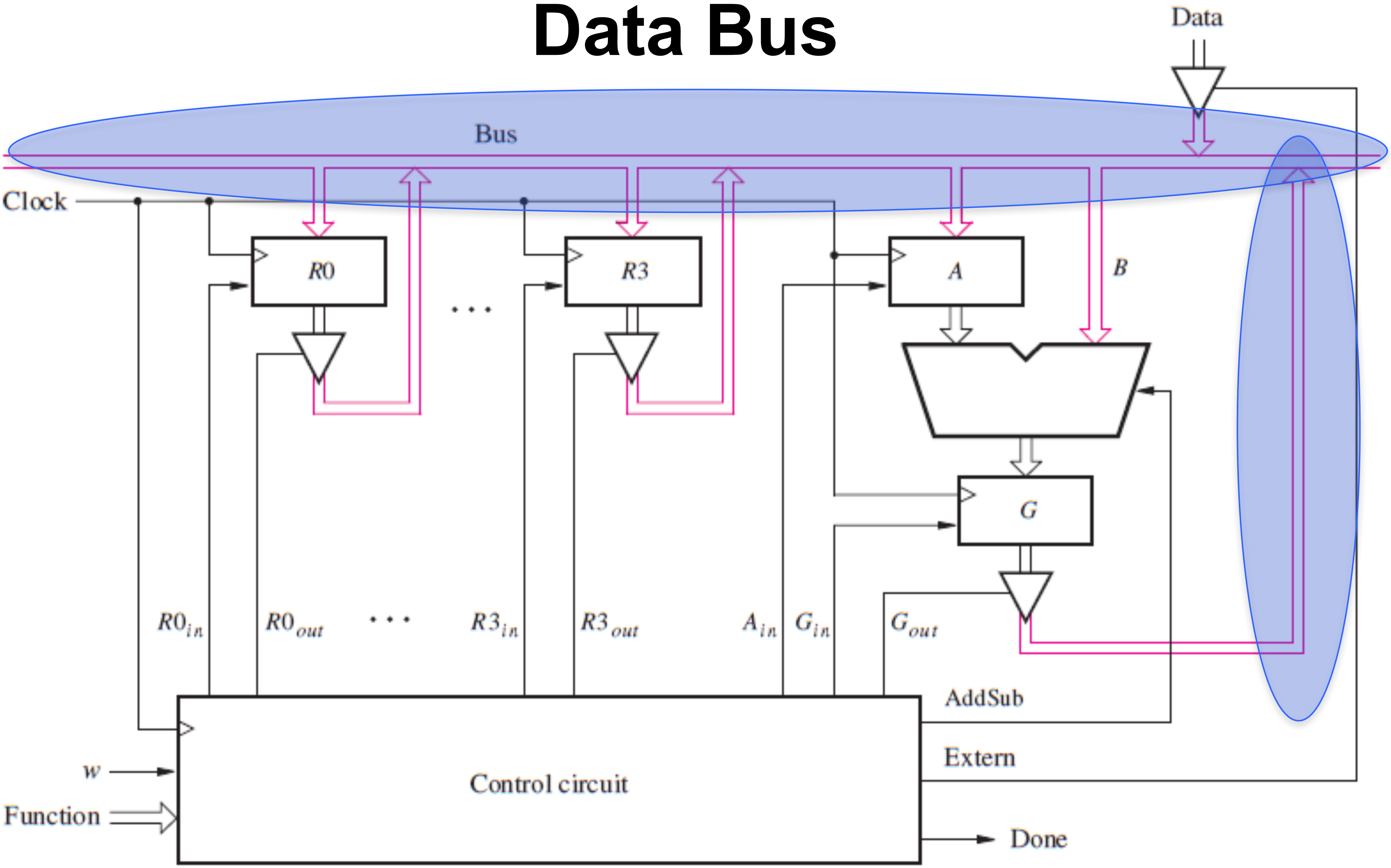
[Figure 7.9 from the textbook]

Registers



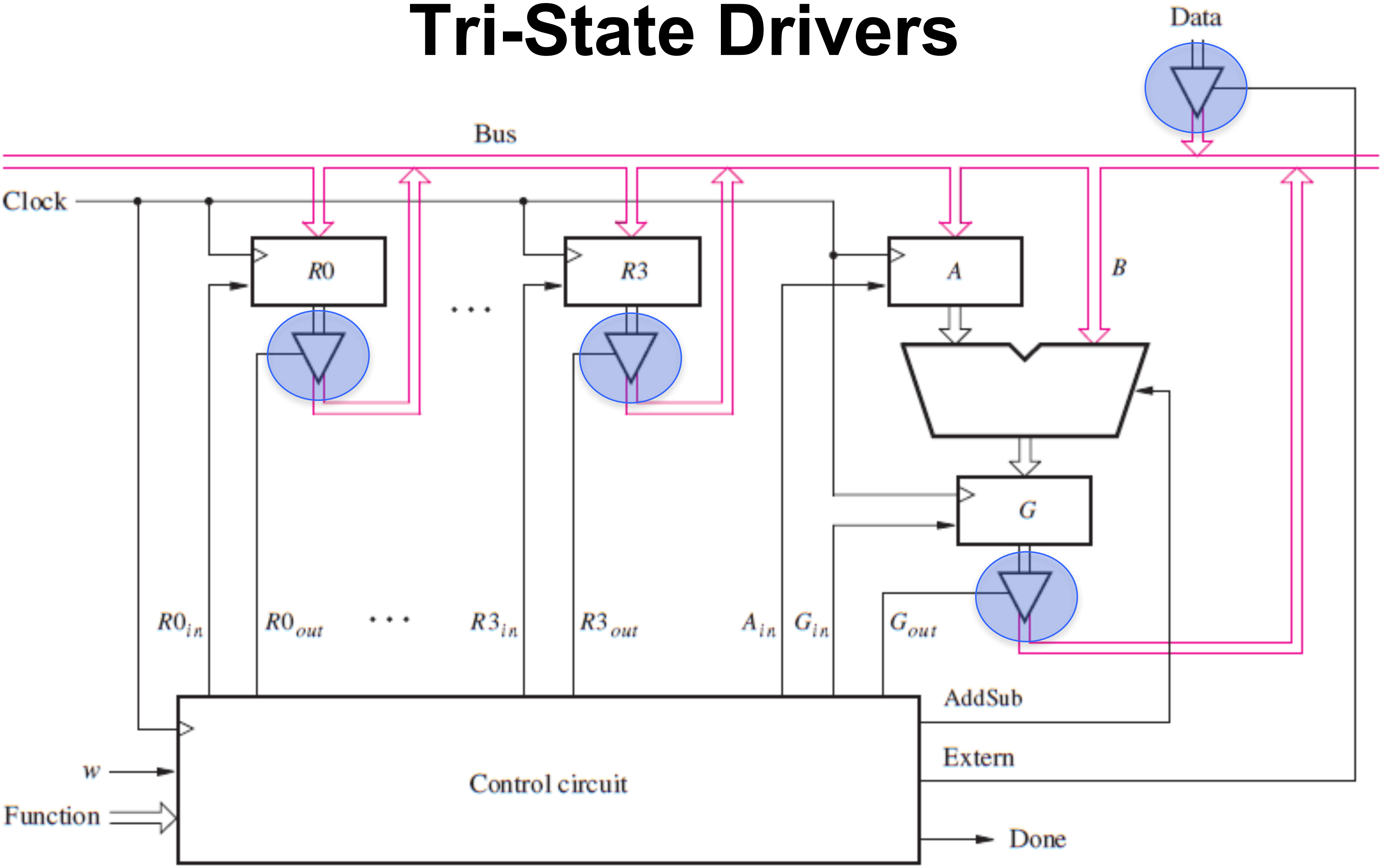
[Figure 7.9 from the textbook]

Data Bus



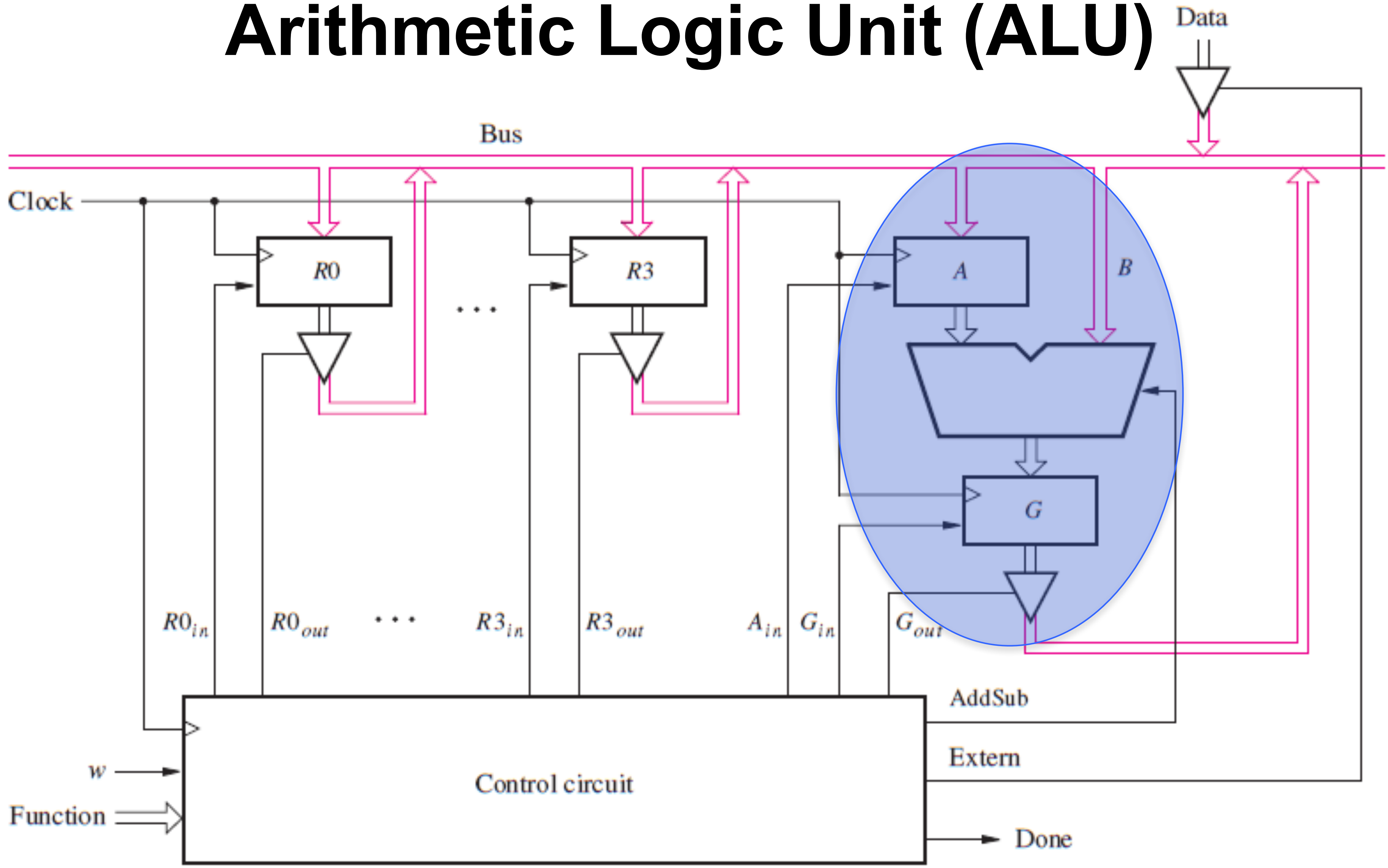
[Figure 7.9 from the textbook]

Tri-State Drivers



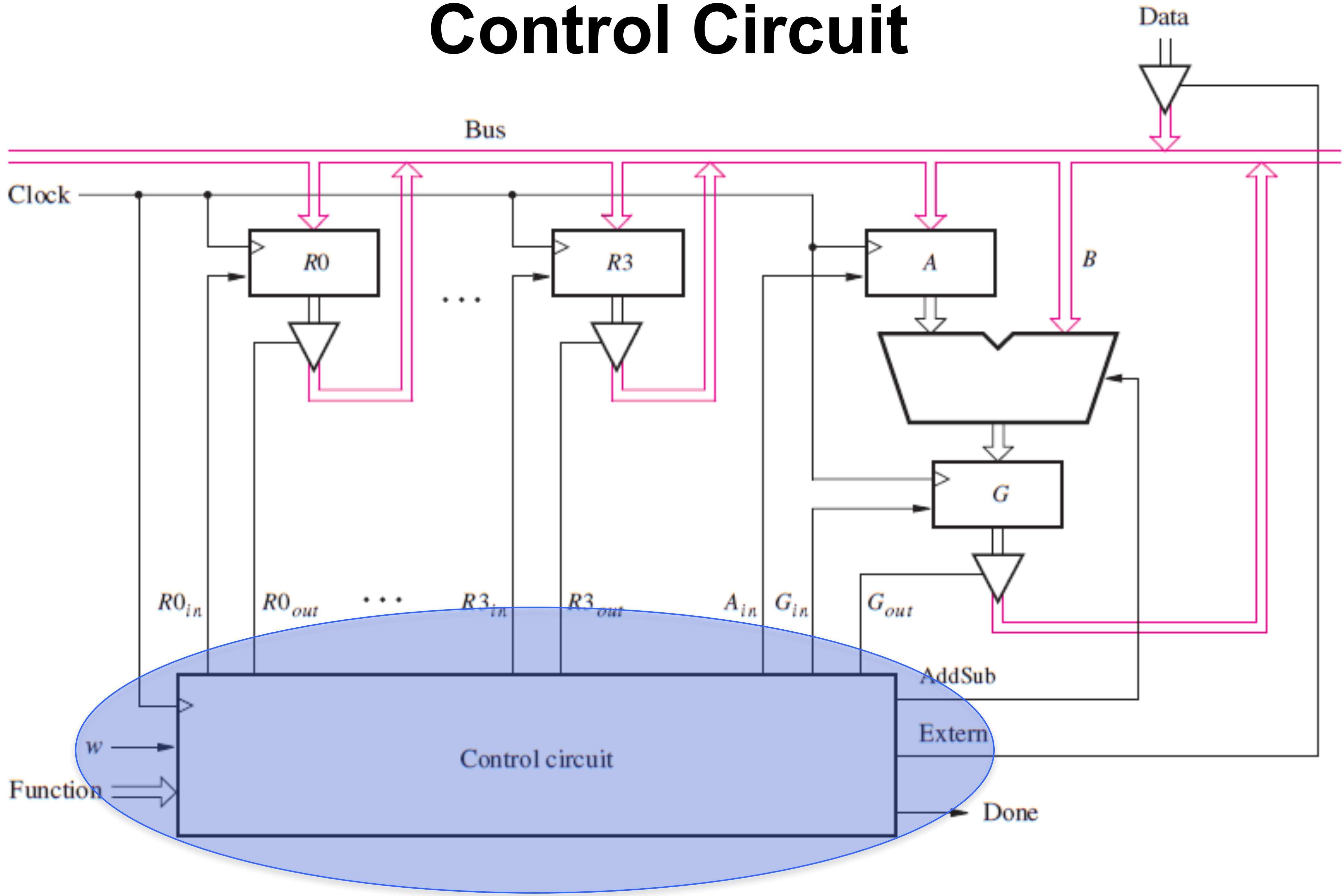
[Figure 7.9 from the textbook]

Arithmetic Logic Unit (ALU)



[Figure 7.9 from the textbook]

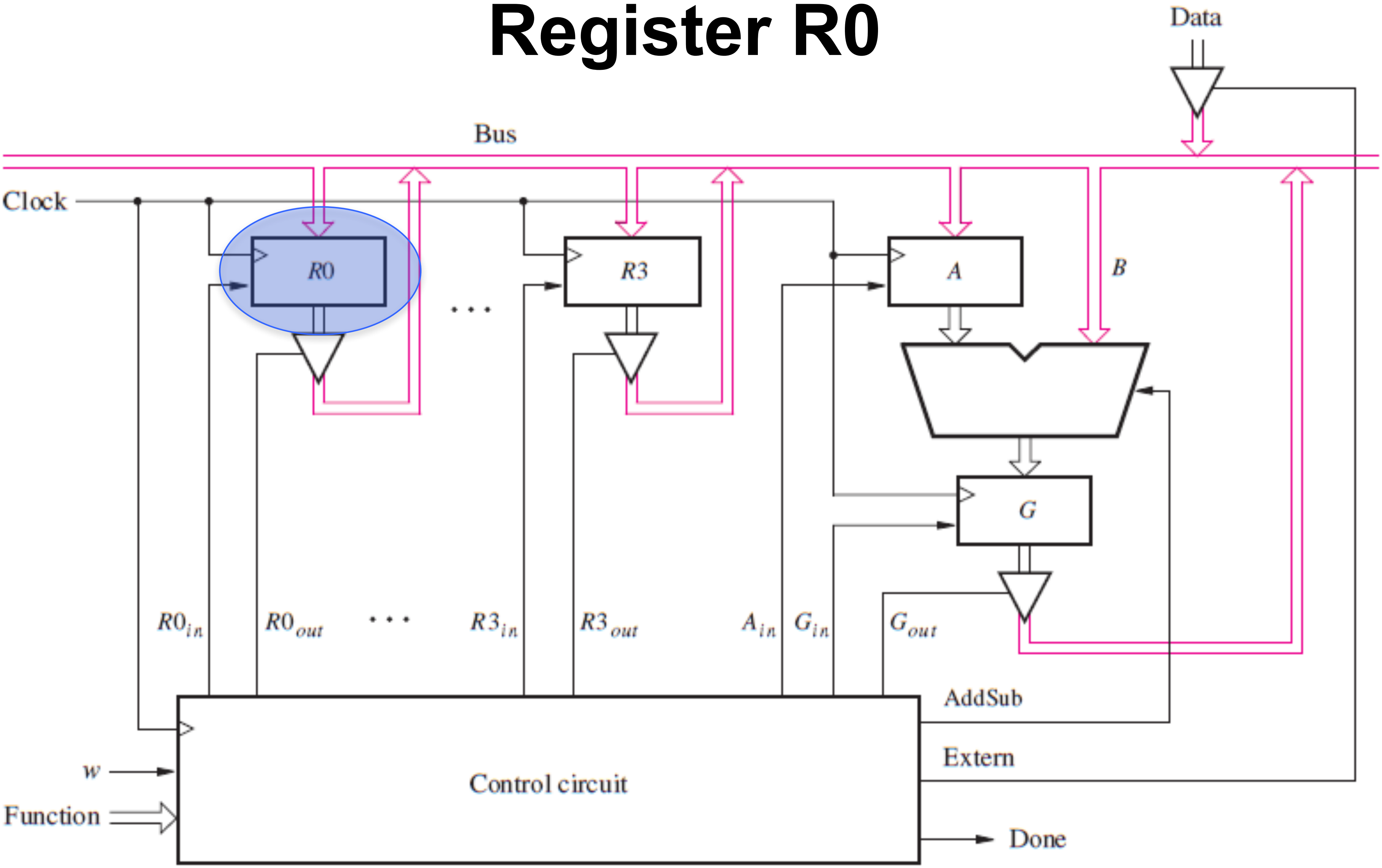
Control Circuit



[Figure 7.9 from the textbook]

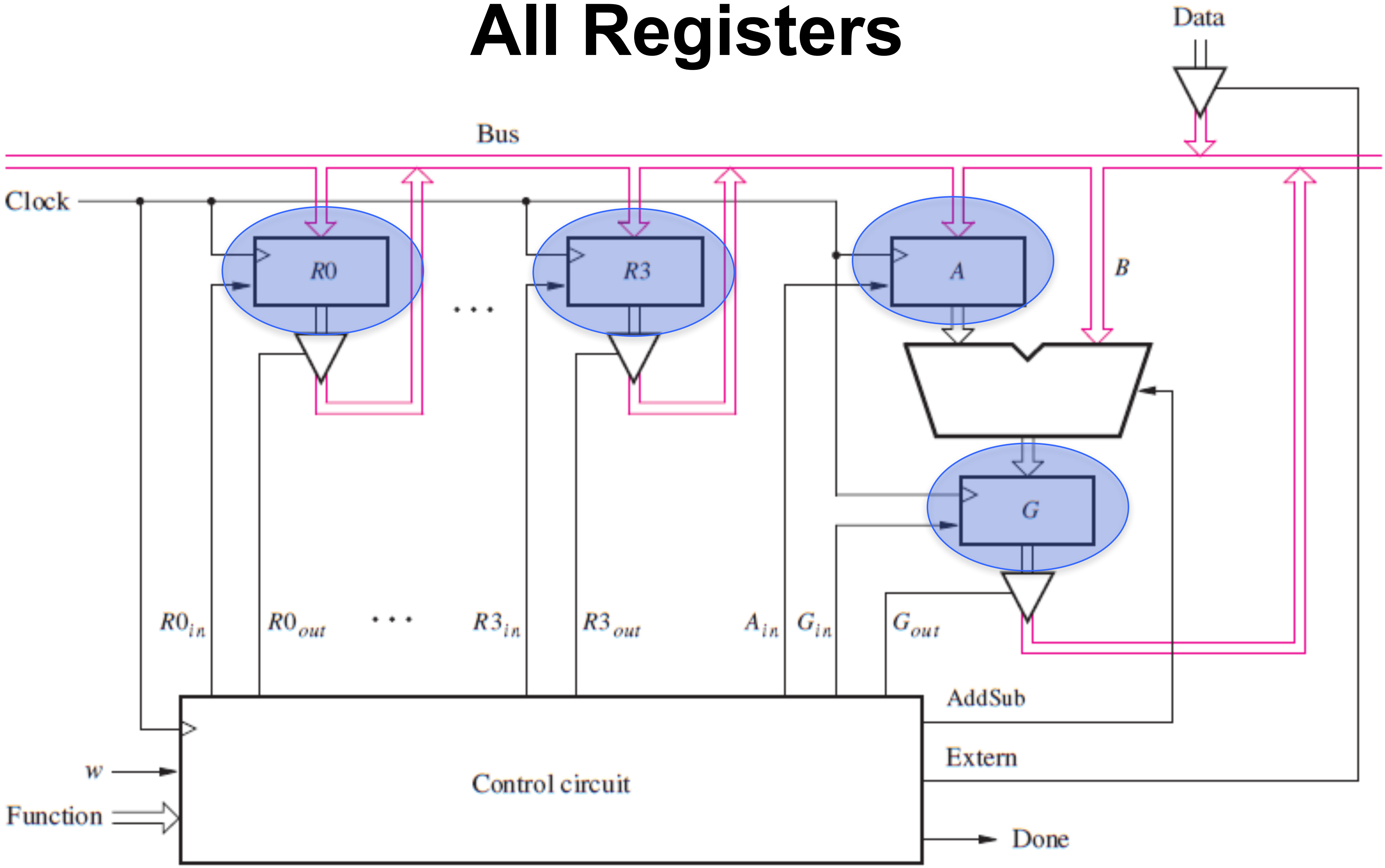
A Closer Look at the Registers

Register R0



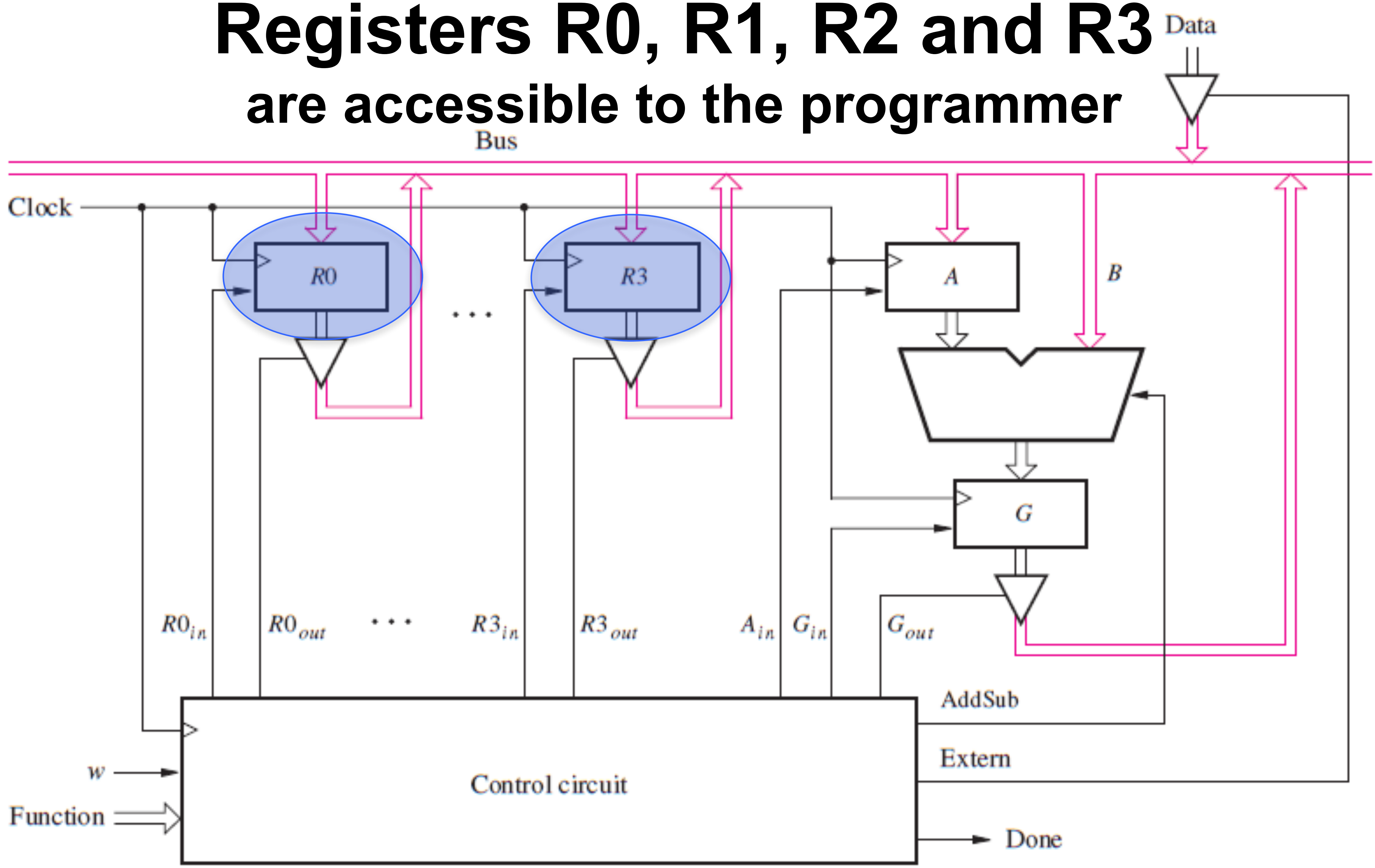
[Figure 7.9 from the textbook]

All Registers



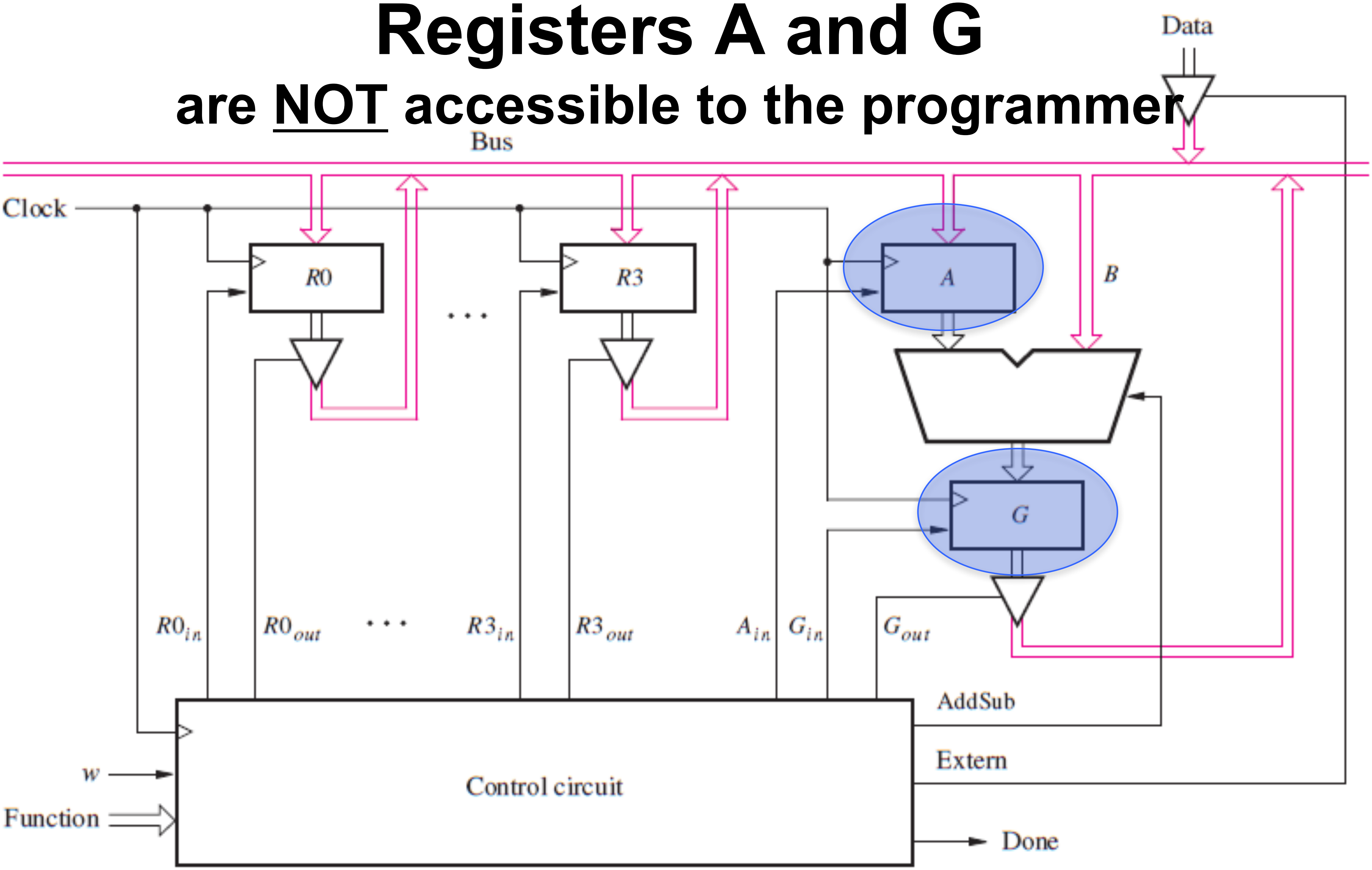
[Figure 7.9 from the textbook]

Registers R0, R1, R2 and R3
are accessible to the programmer



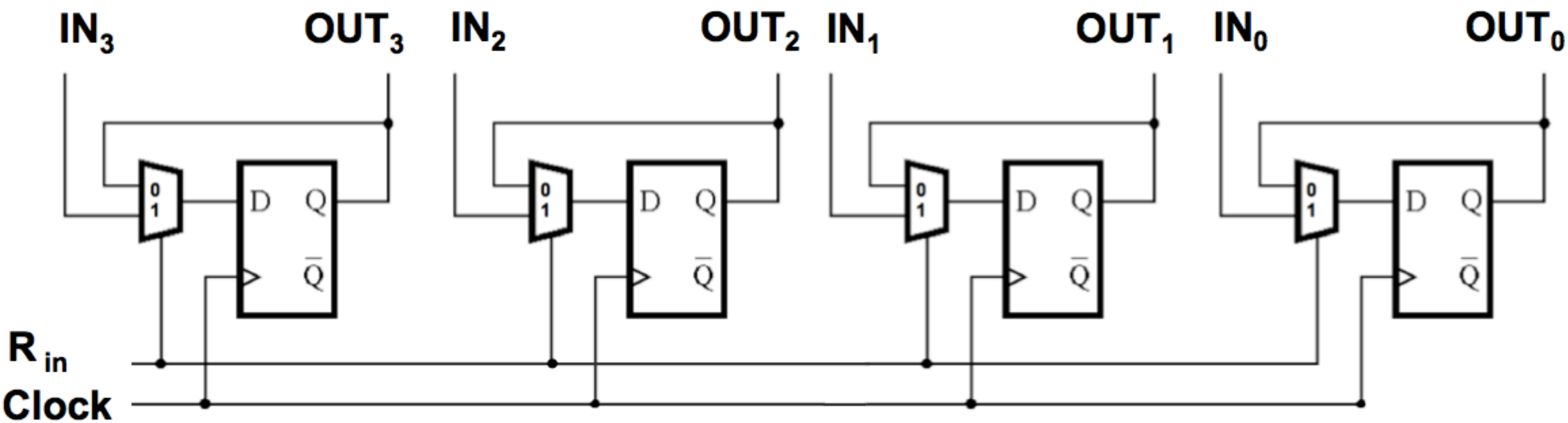
[Figure 7.9 from the textbook]

Registers A and G
are <u>NOT</u> accessible to the programmer

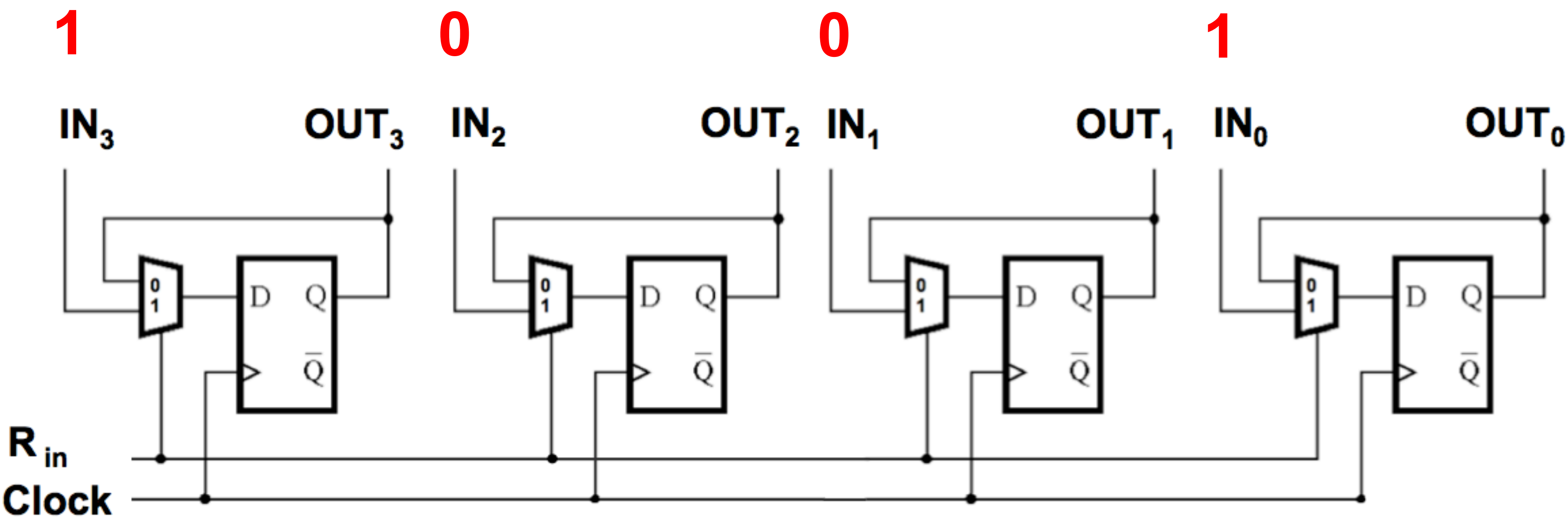


[Figure 7.9 from the textbook]

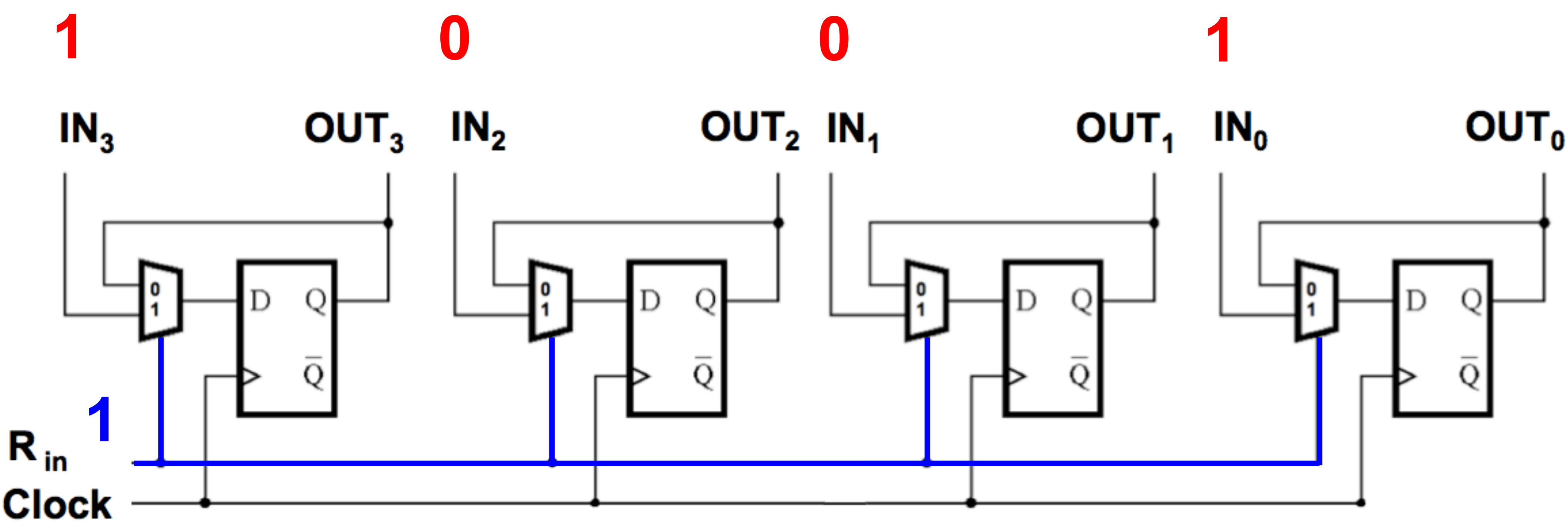
4-Bit Register



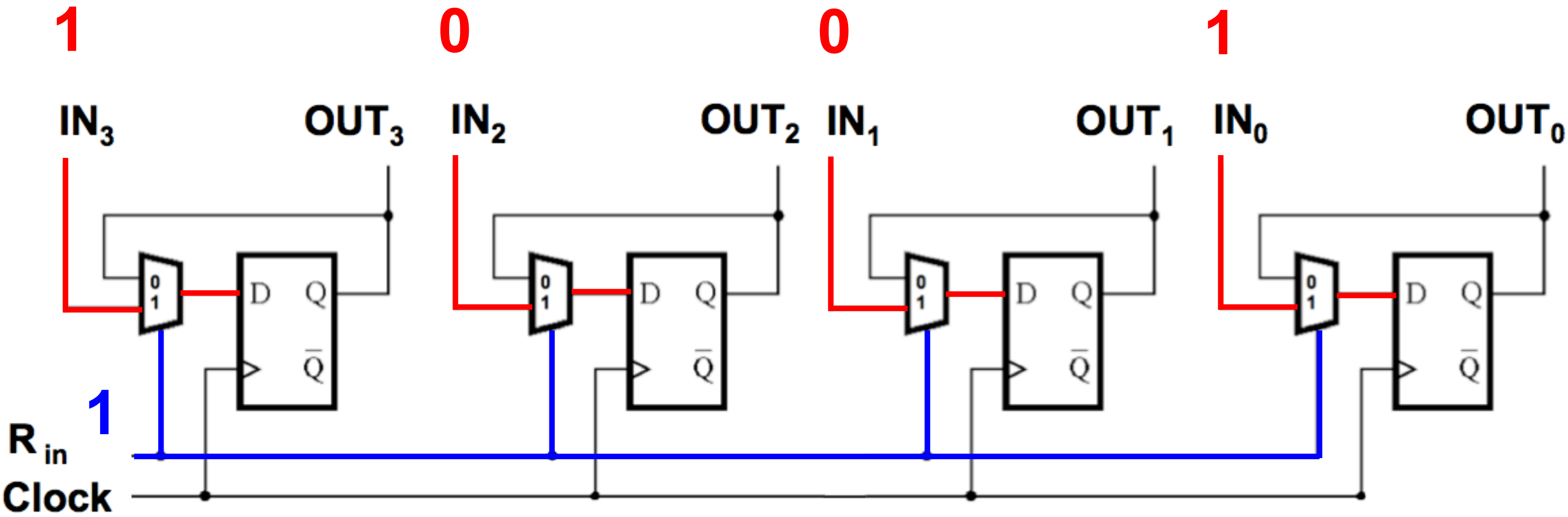
Loading Data into the Register



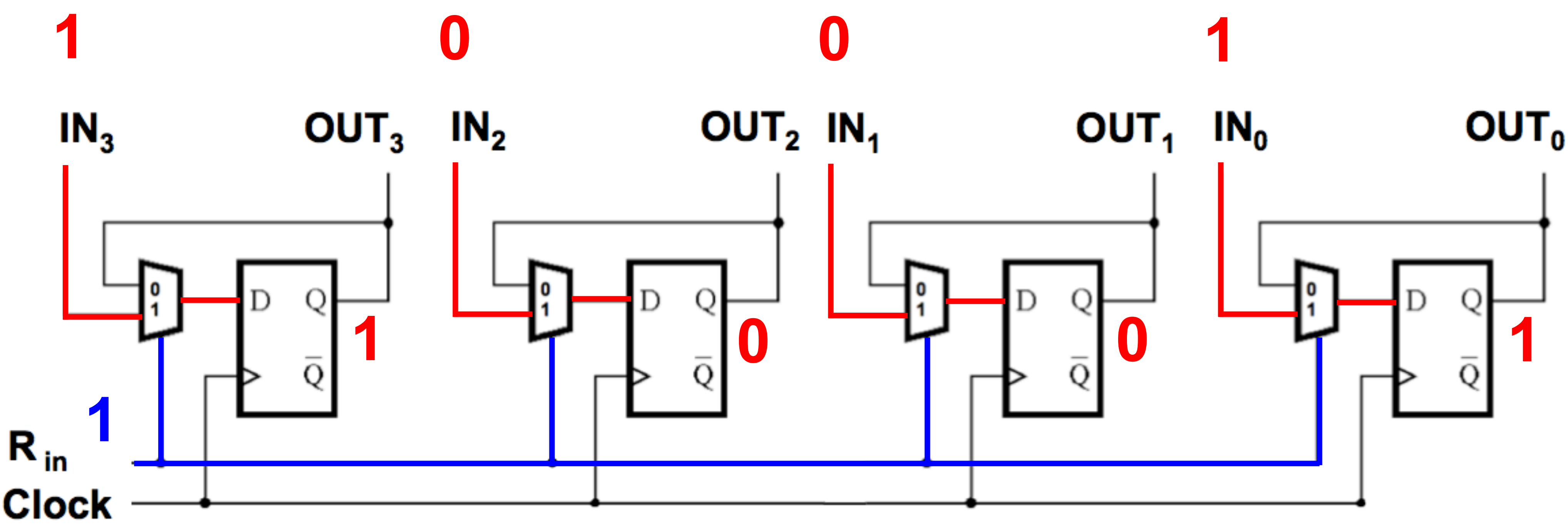
Loading Data into the Register



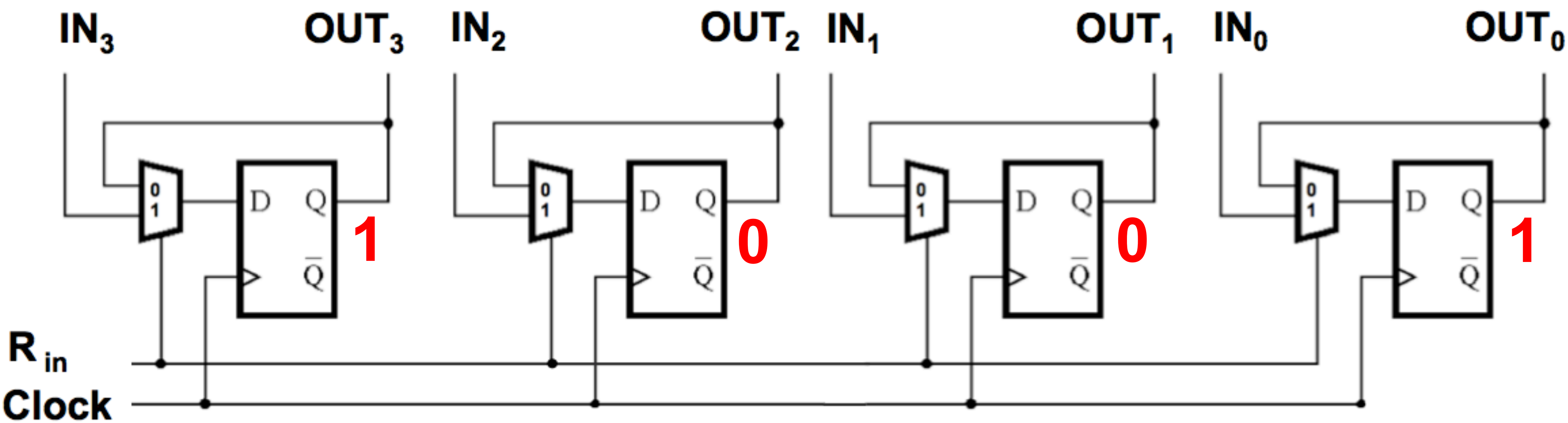
Loading Data into the Register



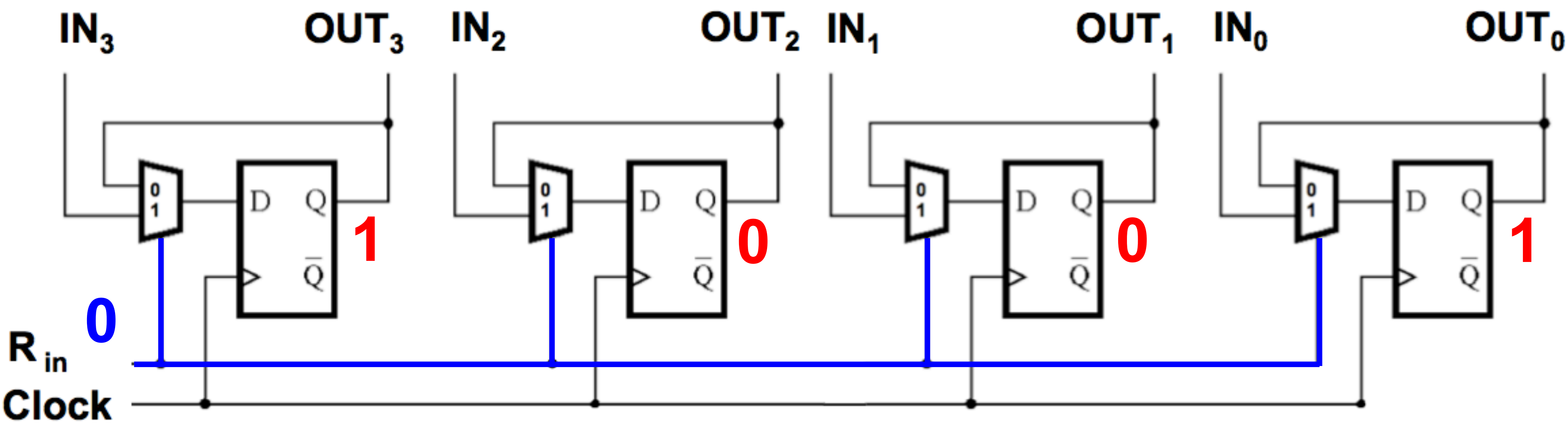
Loading Data into the Register



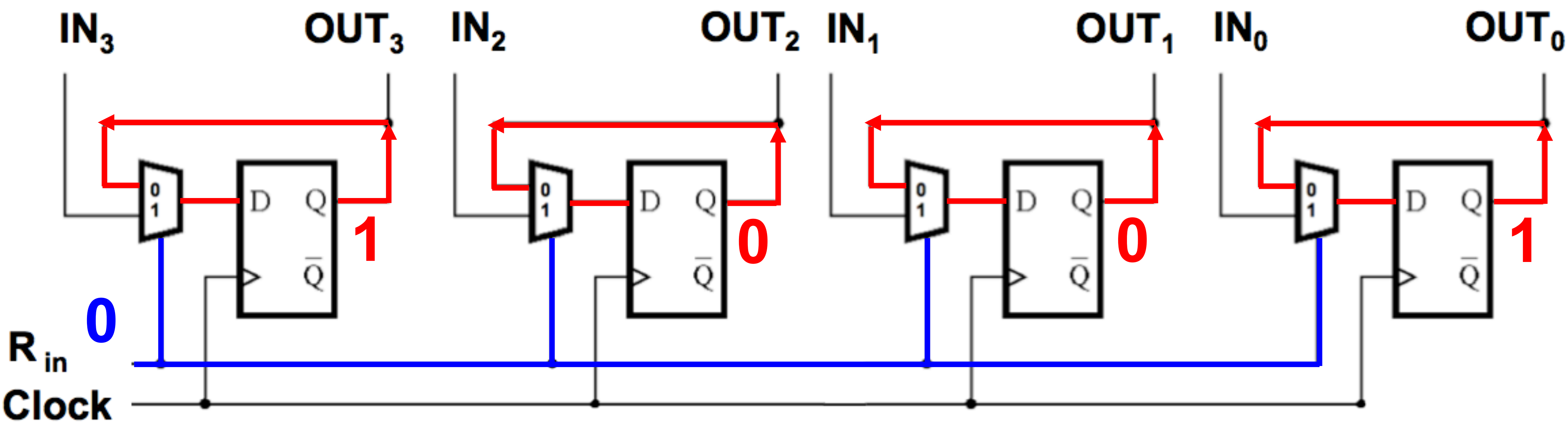
Keeping Data into the Register



Keeping Data into the Register

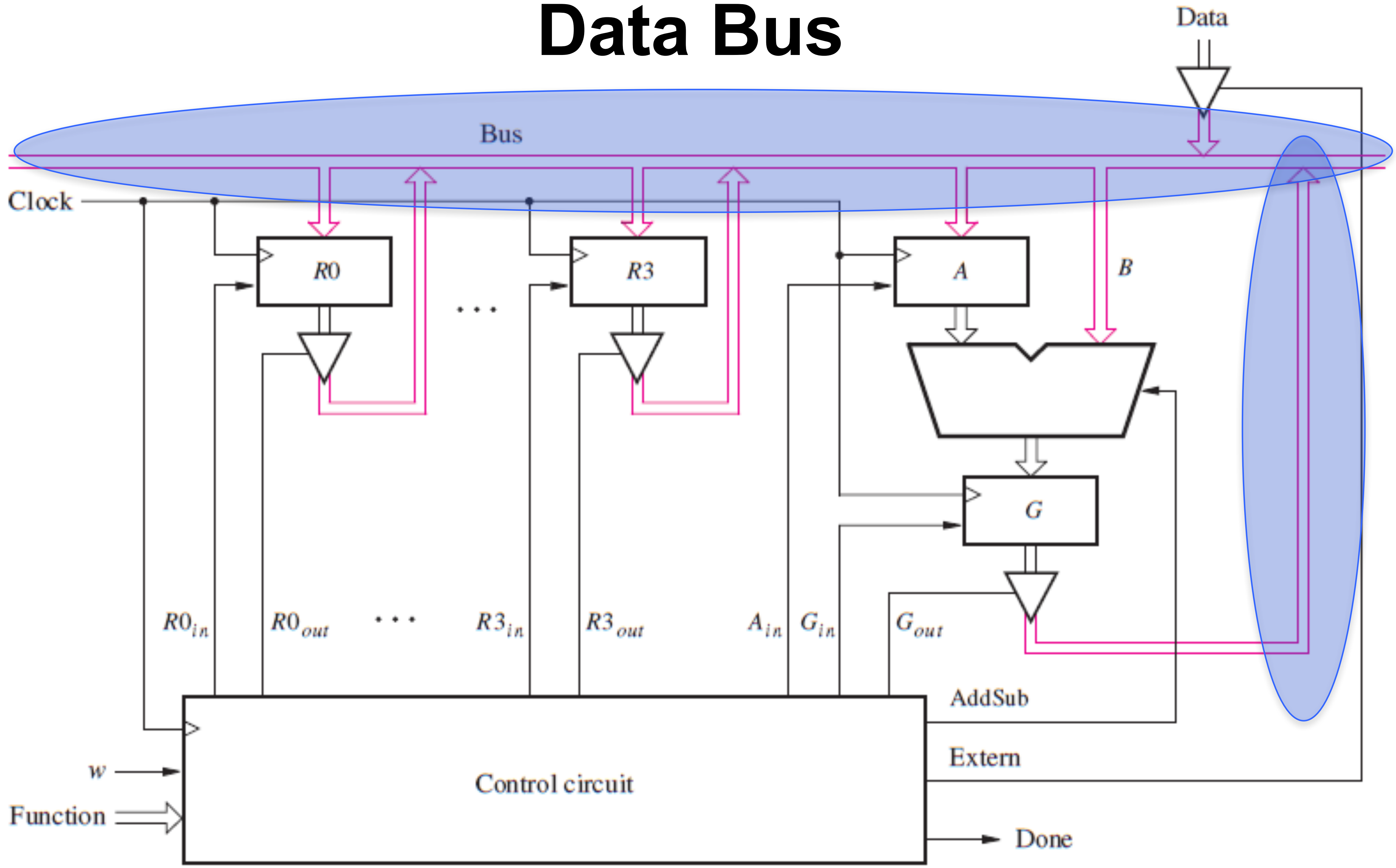


Keeping Data into the Register



A Closer Look at the Data Bus

Data Bus

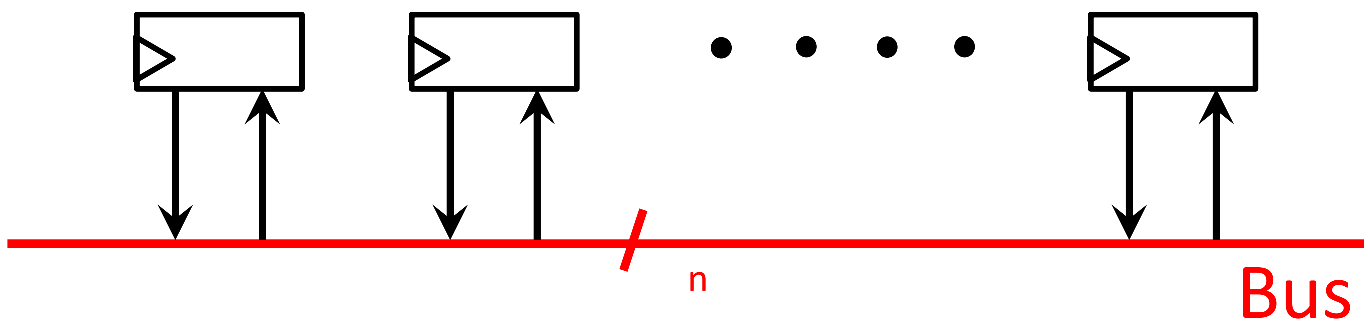


[Figure 7.9 from the textbook]

Bus Structure

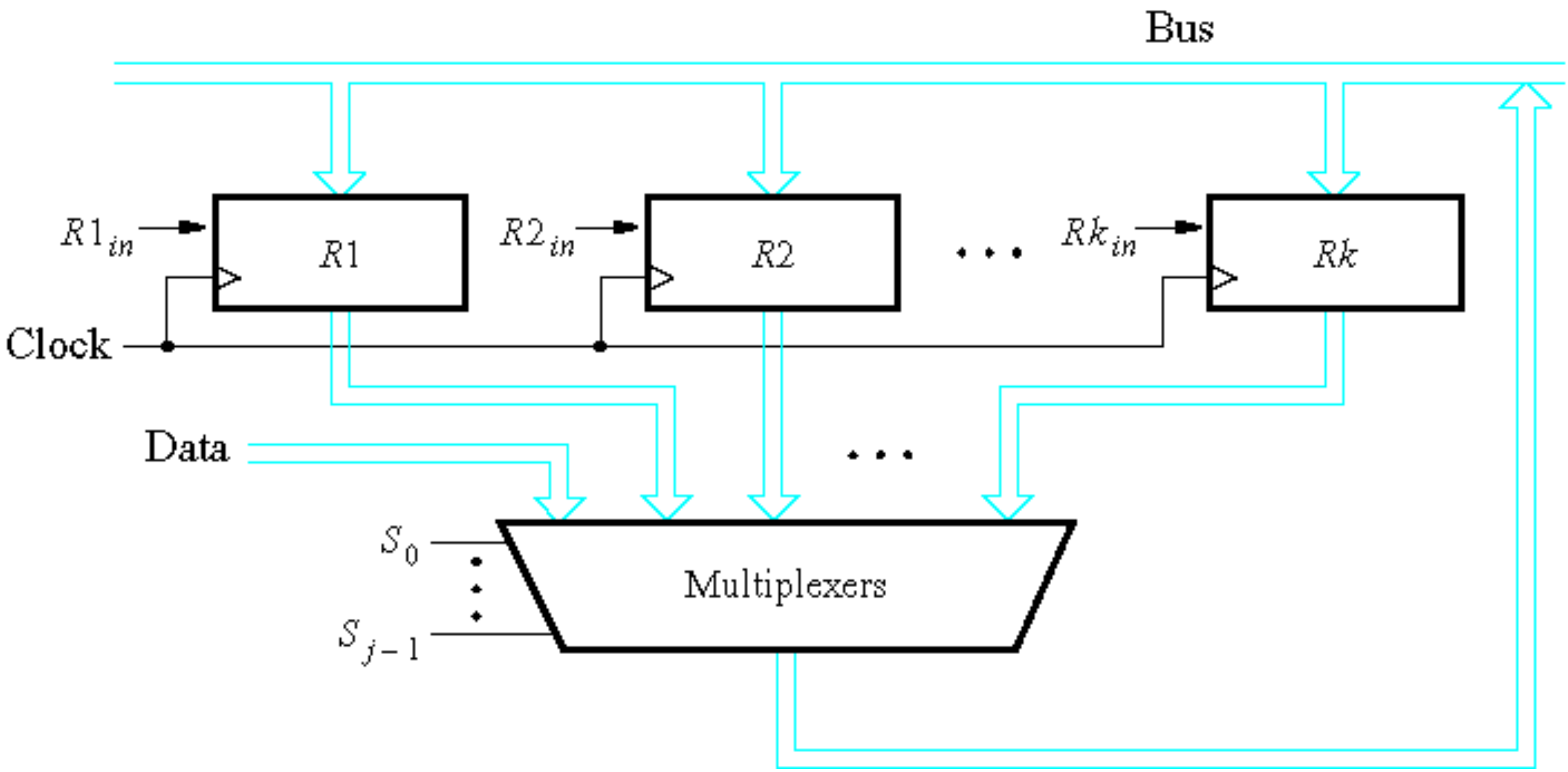
- We need a way to transfer data from any register (device) to any other register (device)

- A bus is simply a set of n wires to transfer n-bit data



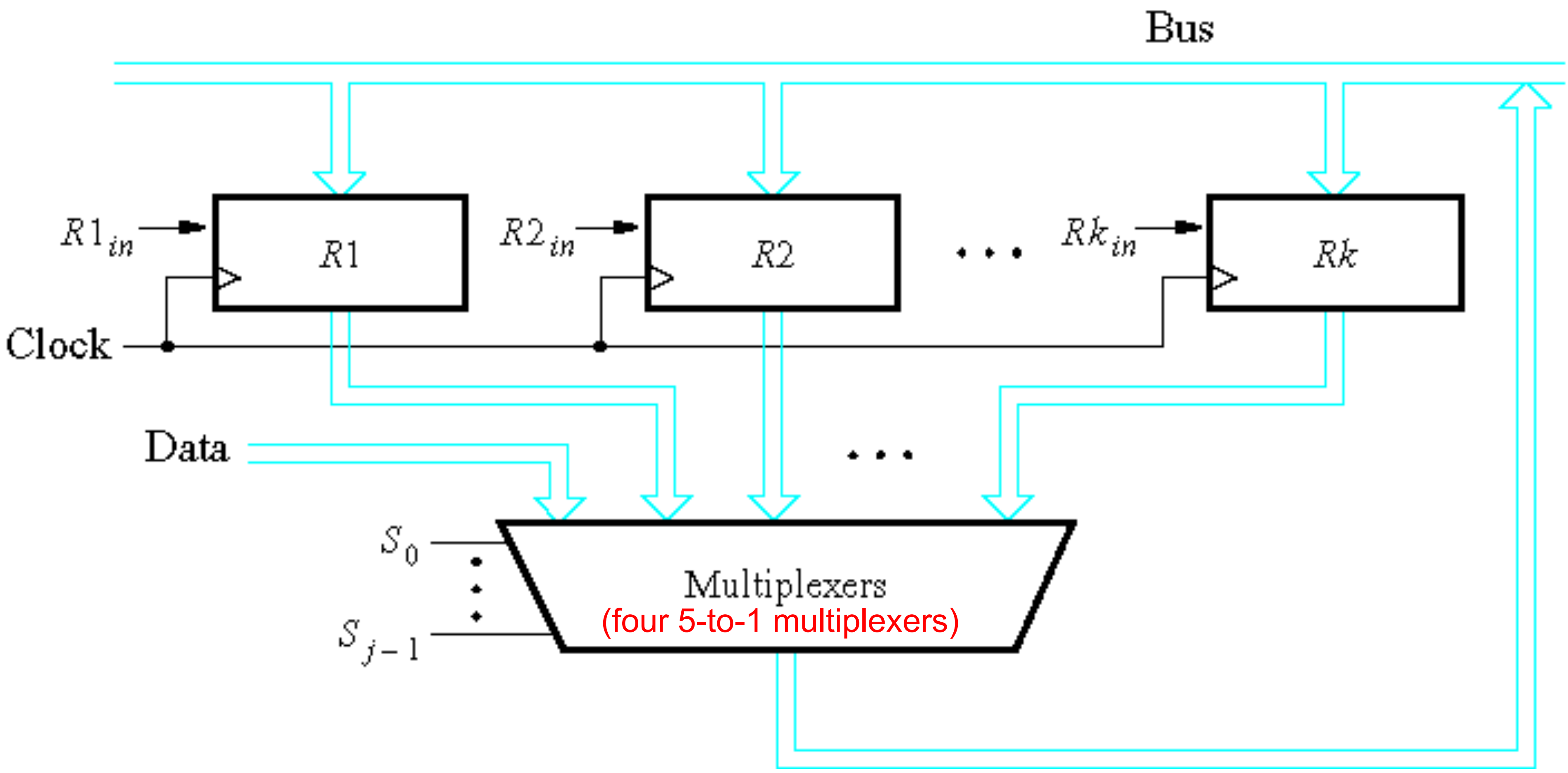
- What if two registers write to the bus at the same time?

One way to implement a data bus is to use multiplexers



[Figure 7.4 from the textbook]

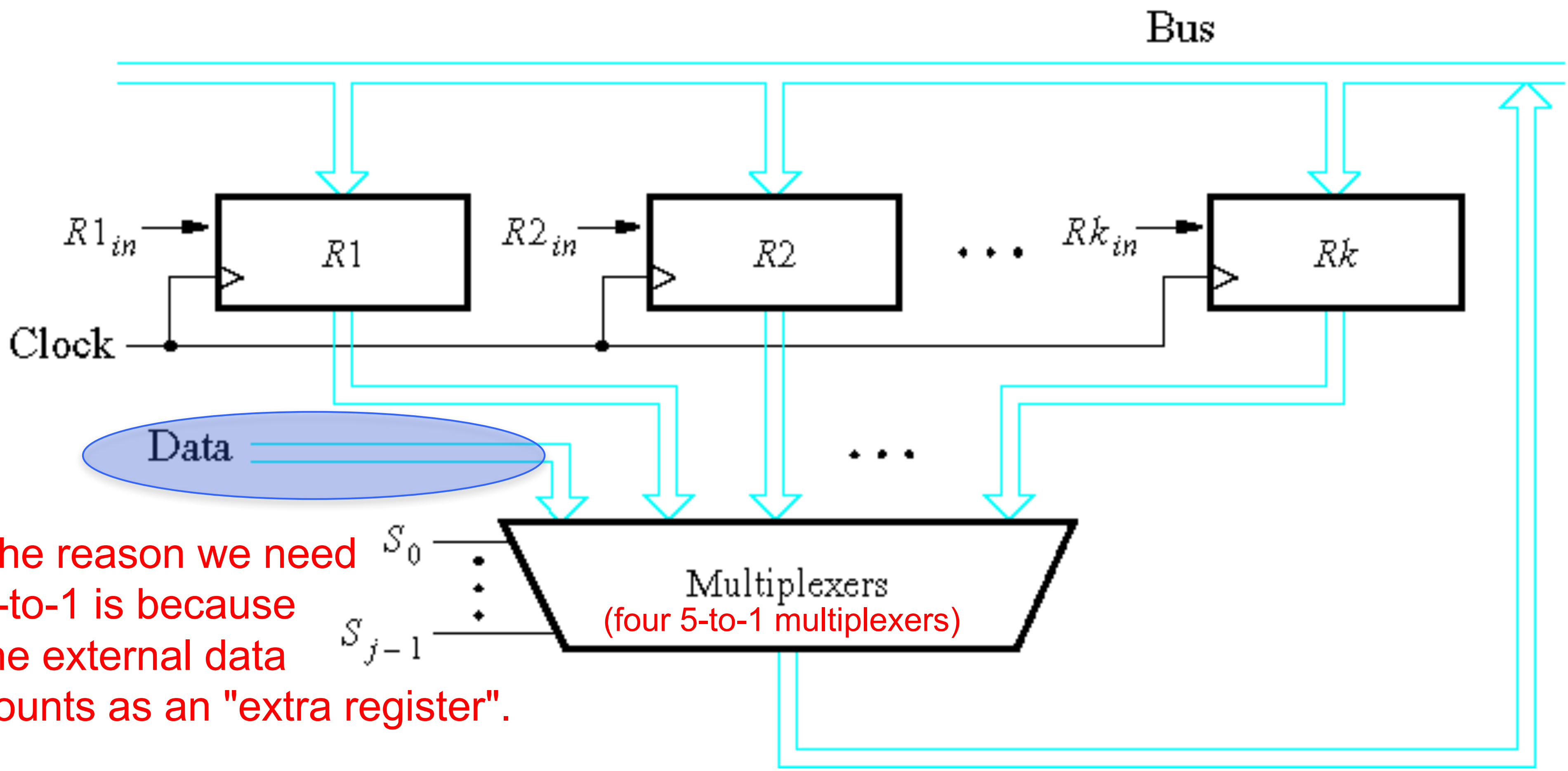
One way to implement a data bus is to use multiplexers



This requires one multiplexer per bit.
Assuming there are four 4-bit registers, we need four 5-to-1 multiplexers.

[Figure 7.4 from the textbook]

One way to implement a data bus is to use multiplexers

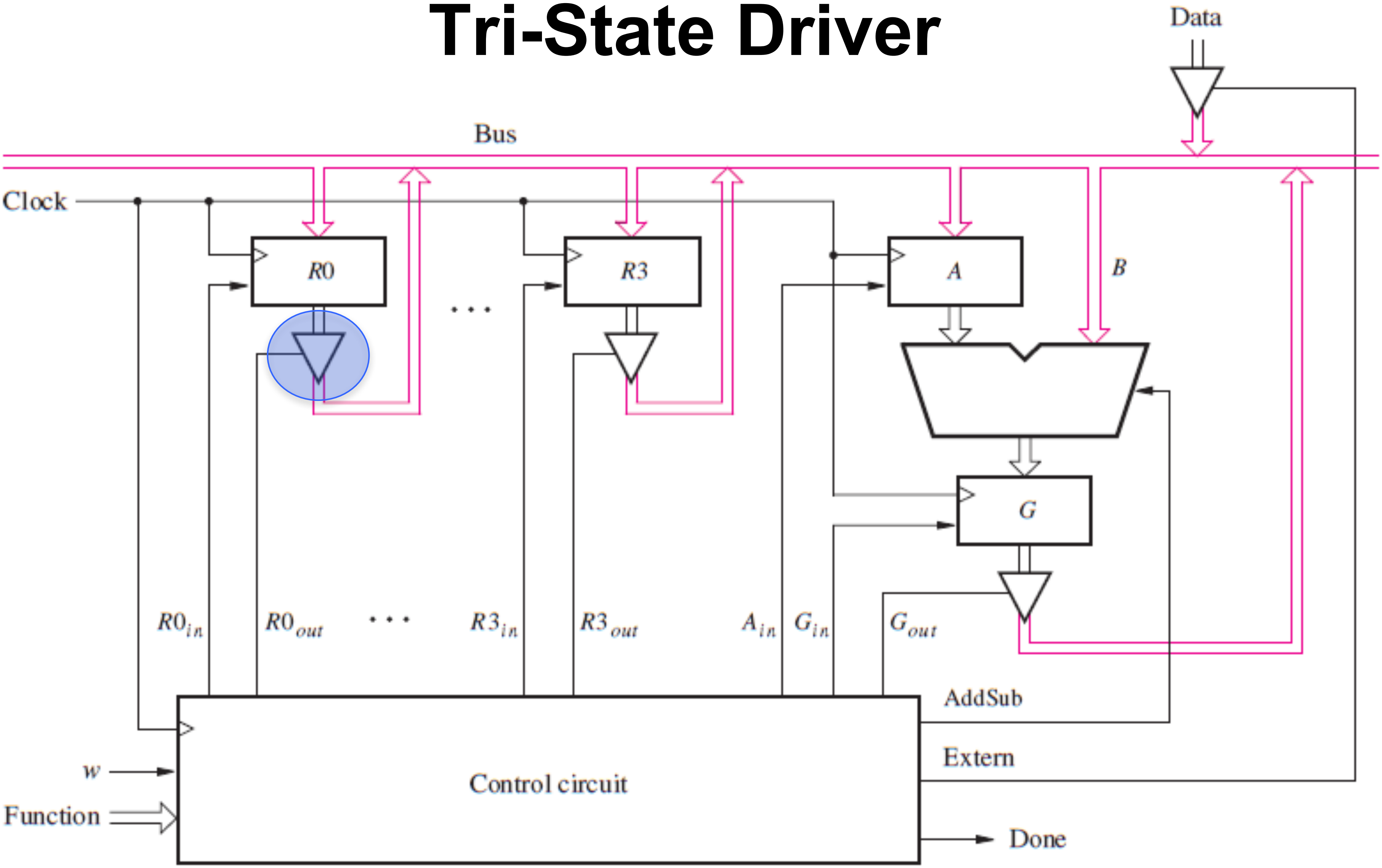


The reason we need 5-to-1 is because the external data counts as an "extra register".

[Figure 7.4 from the textbook]

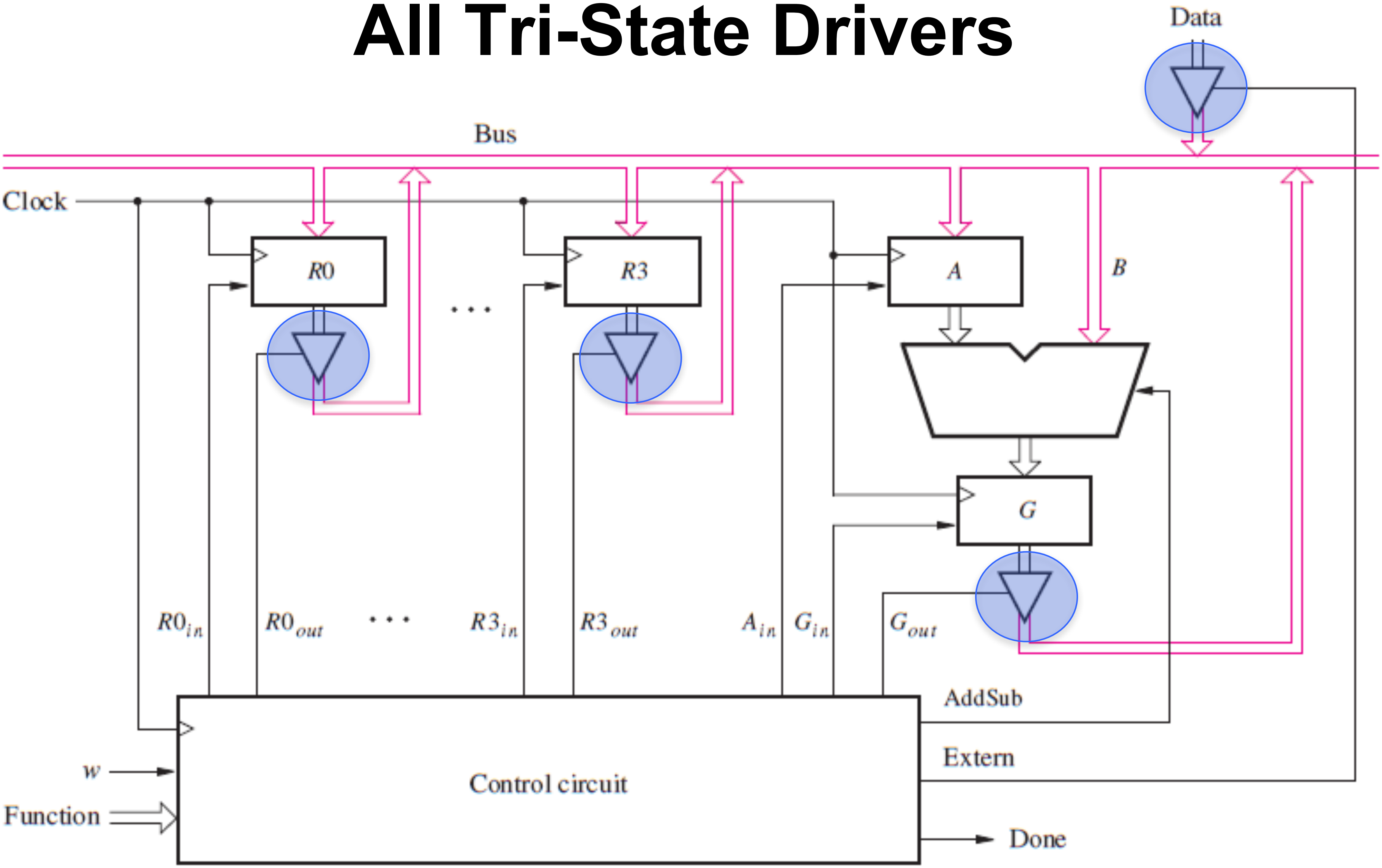
A Closer Look at the Tri-State Driver

Tri-State Driver



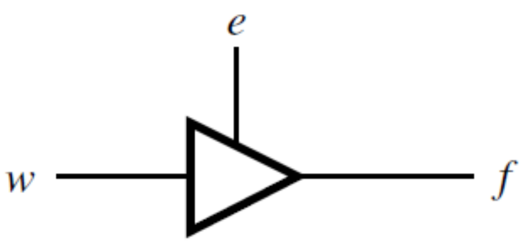
[Figure 7.9 from the textbook]

All Tri-State Drivers

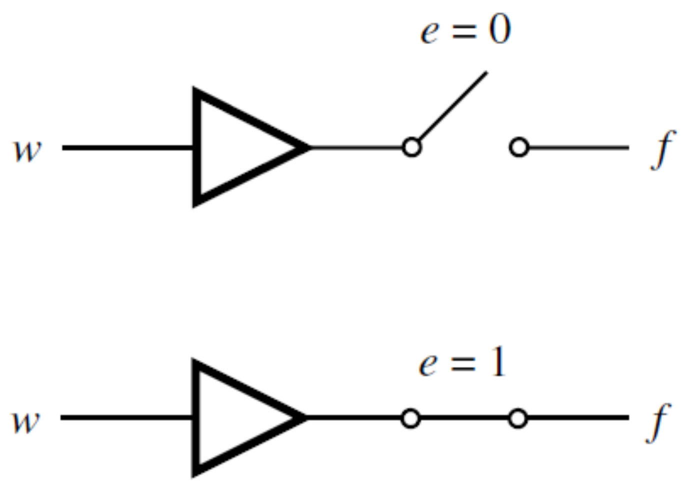


[Figure 7.9 from the textbook]

Tri-state driver
(see Appendix B for more details)



(a) Symbol



(b) Equivalent circuit

Z: High impedance state

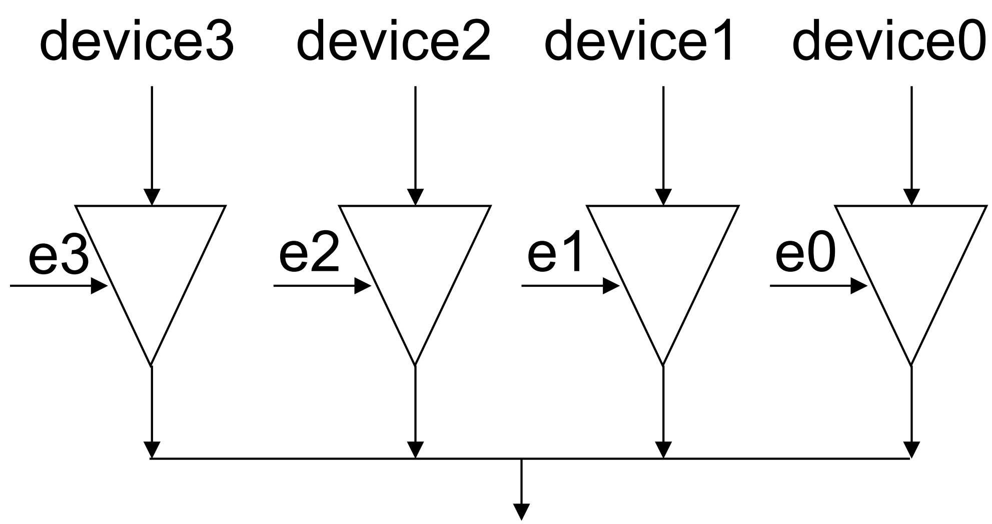
e	w	f
0	0	Z
0	1	Z
1	0	0
1	1	1

(c) Truth table

[Figure 7.1 from the textbook]

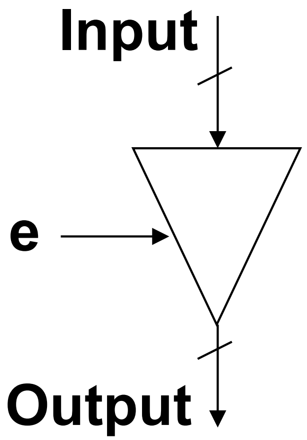
Tri-state driver
(see Appendix B for more details)

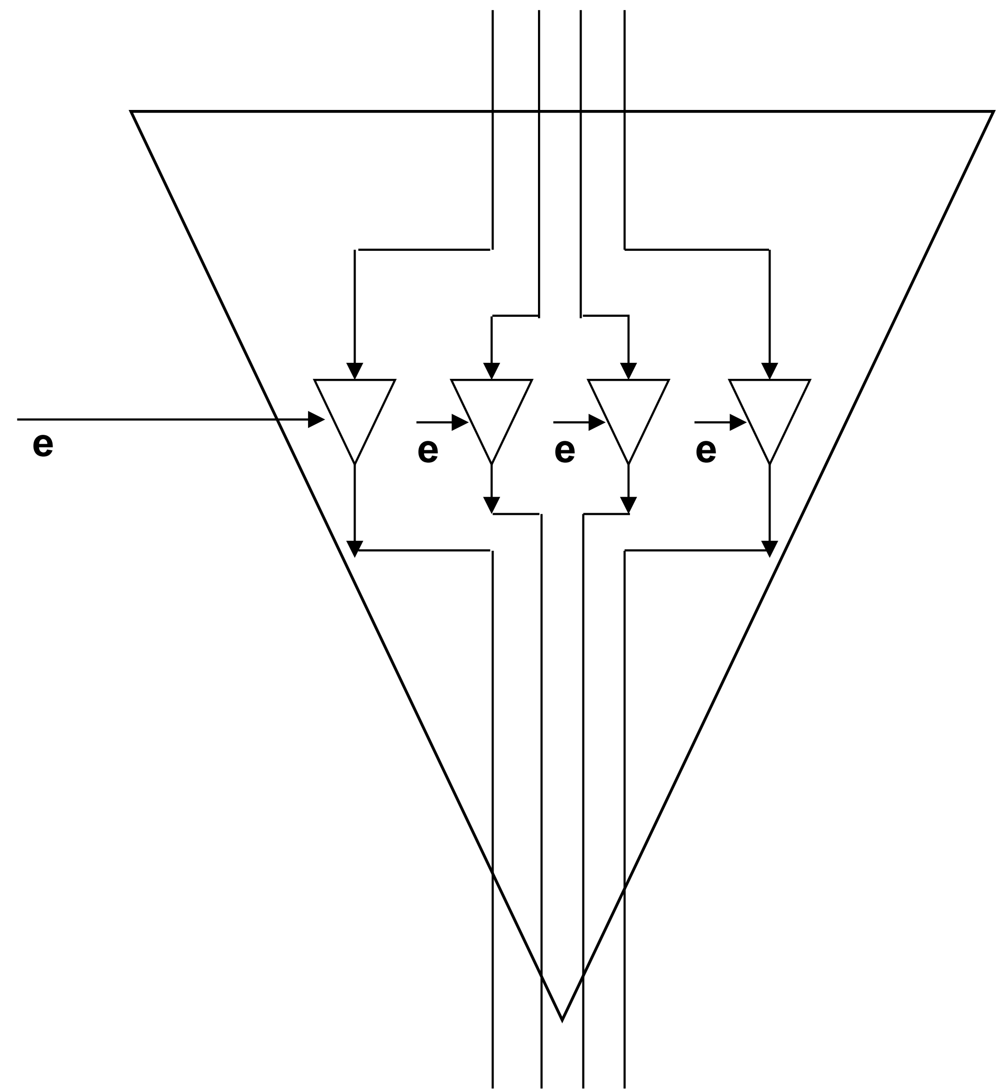
- **Alternative way to implement a data bus**
- **Allows several devices to be connected to a single wire (this is not possible with regular logic gates because their outputs are always active; an OR gate is needed)**
- **Note that at any time, at most one of e0, e1, e2, and e3 can be set to 1**



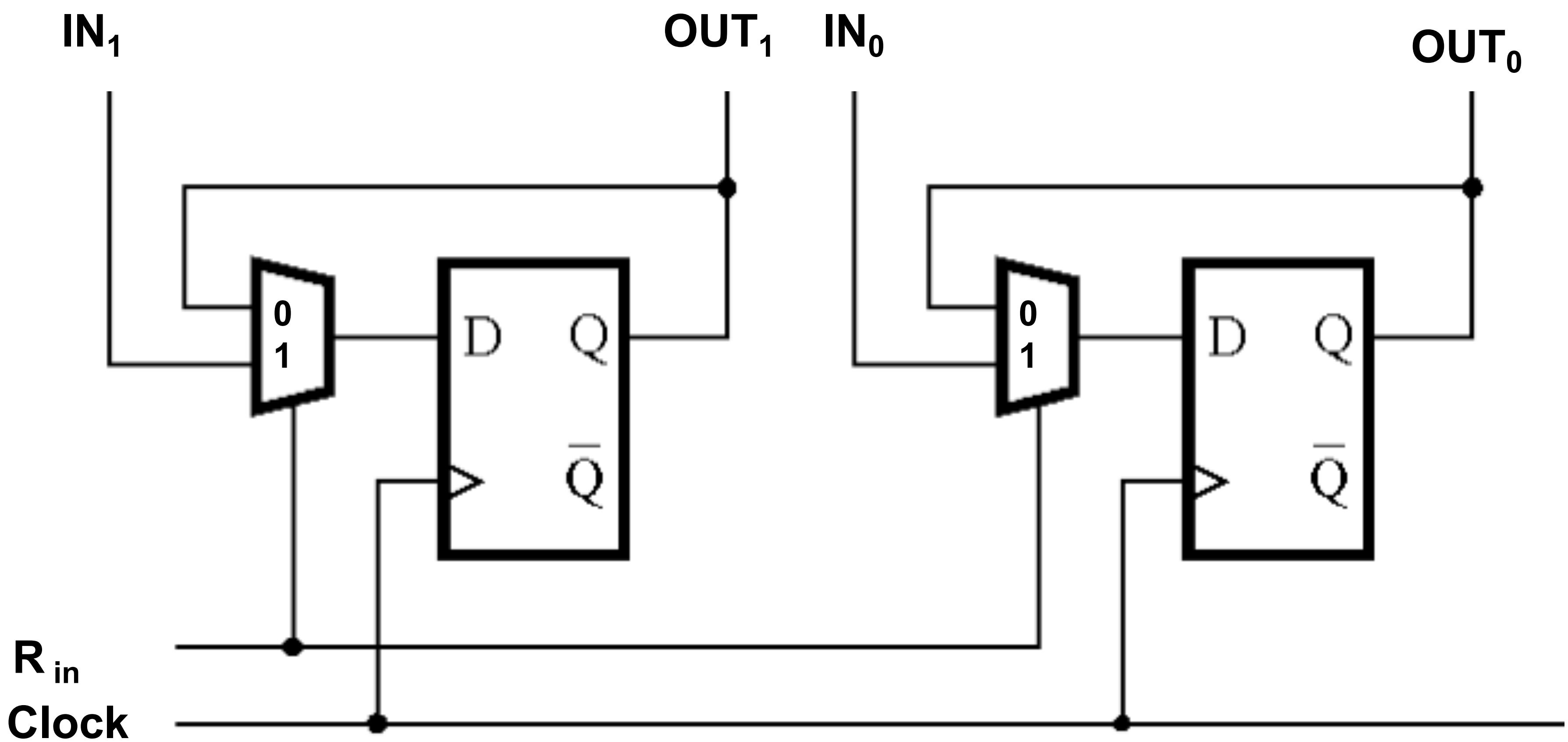
An n-bit Tri-State Driver

can be constructed using n 1-bit tri-state buffers

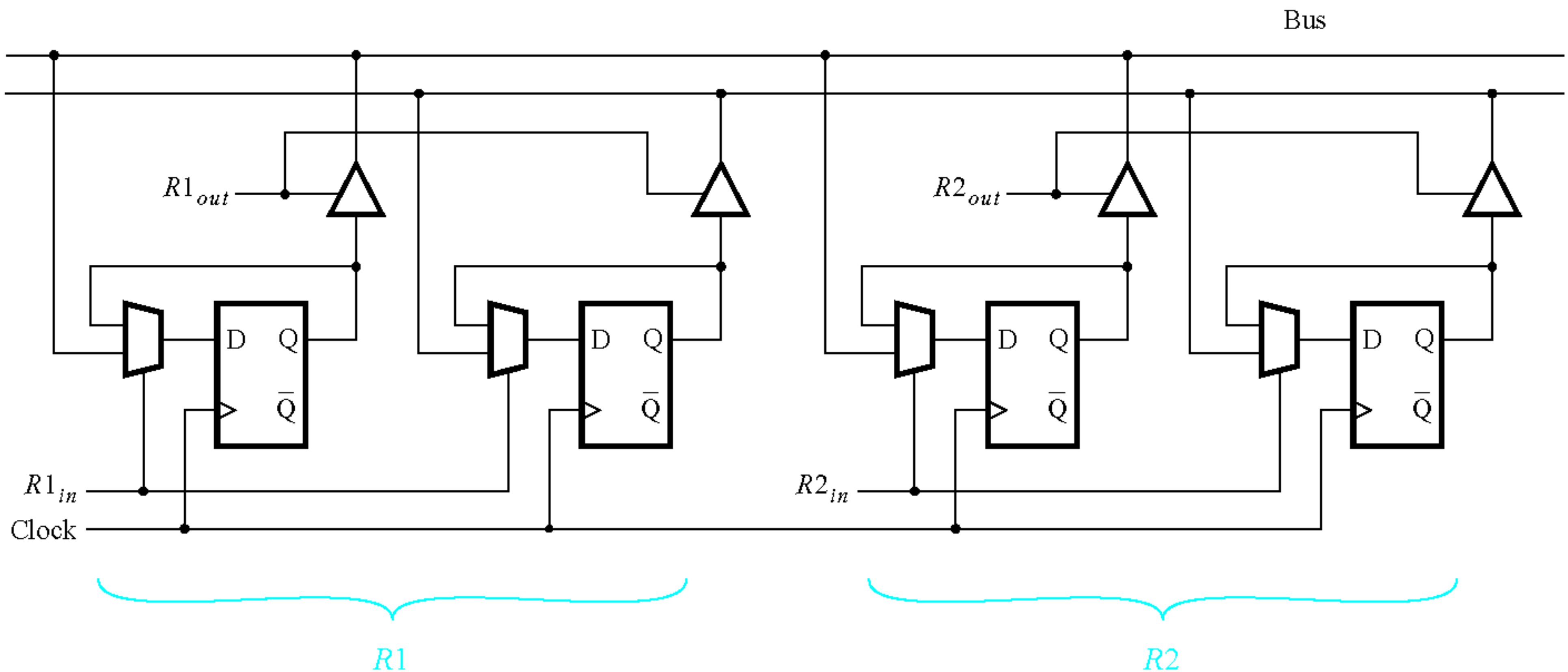




2-Bit Register



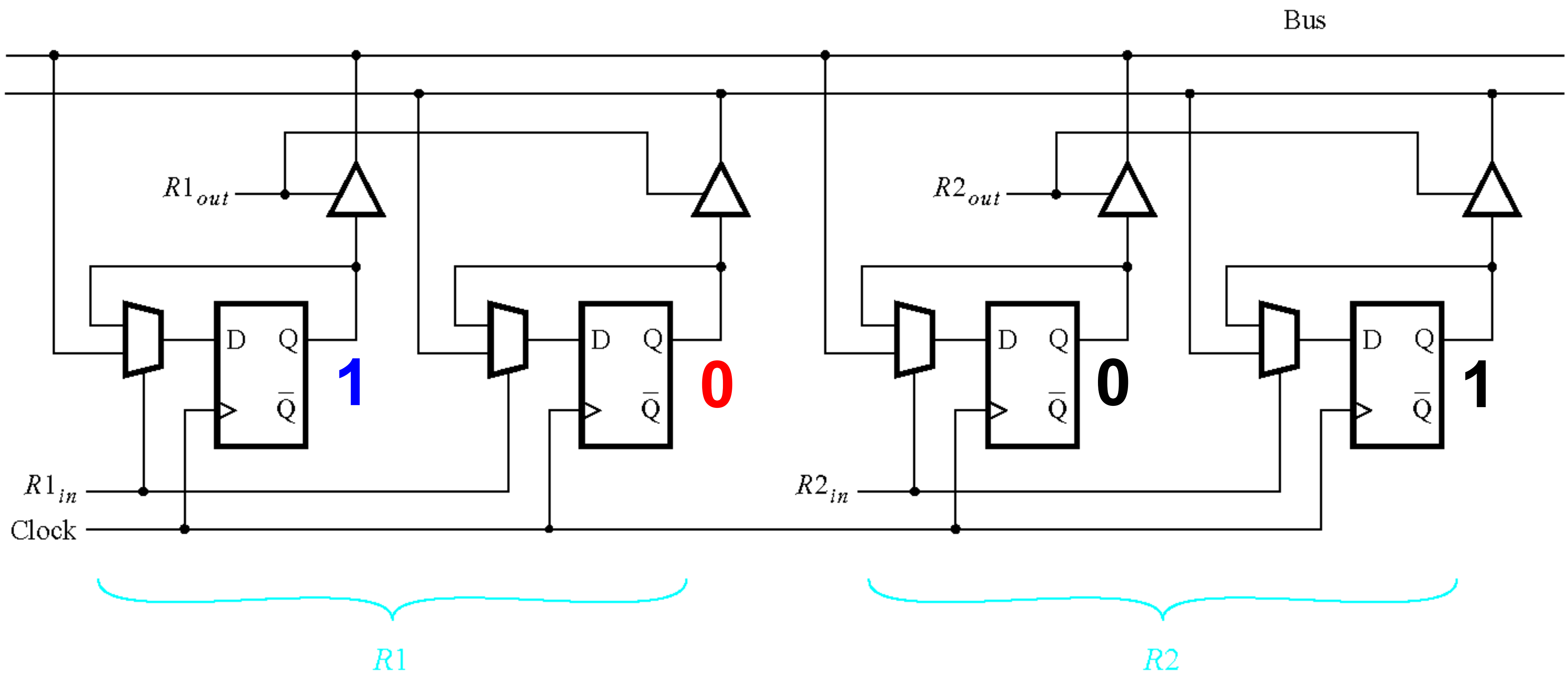
How to connect two 2-bit registers to a bus (using tri-state drivers)



This shows only two 2-bit registers, but this design scales to more and larger registers.

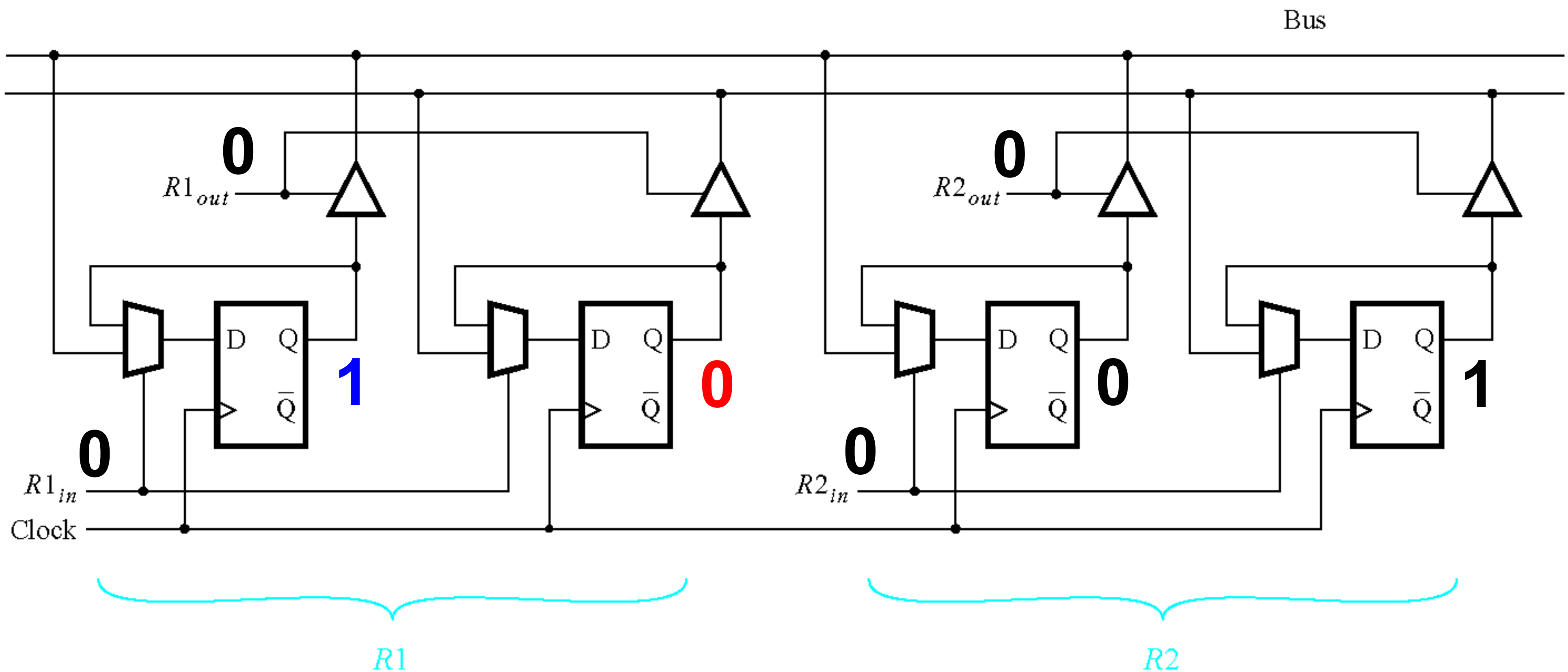
[Figure 7.3 from the textbook]

Moving the Contents of R1 to R2



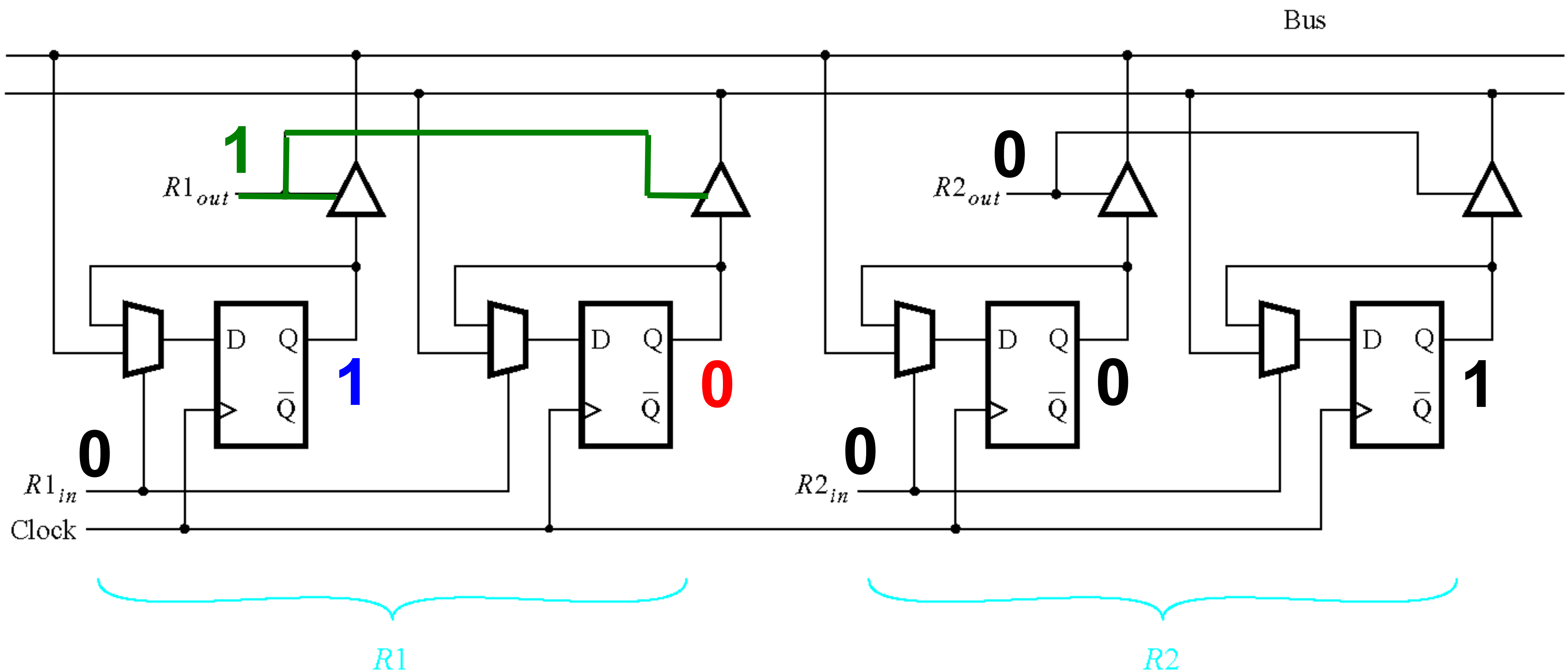
Register 1 stores the number 2_{10} = 10_2 Register 2 stores the number 1_{10} = 01_2

Moving the Contents of R1 to R2



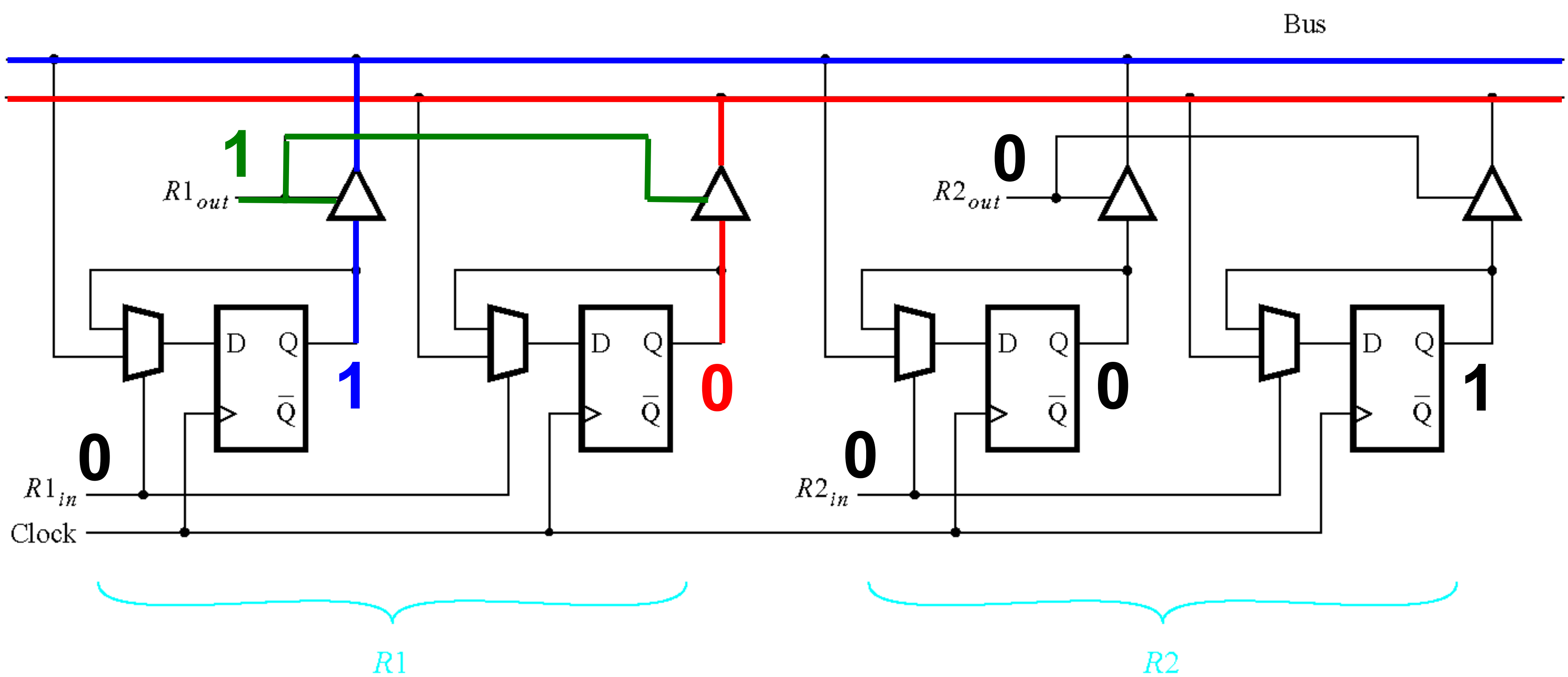
Initially all control inputs are set to 0 (no reading or writing allowed).

Moving the Contents of R1 to R2



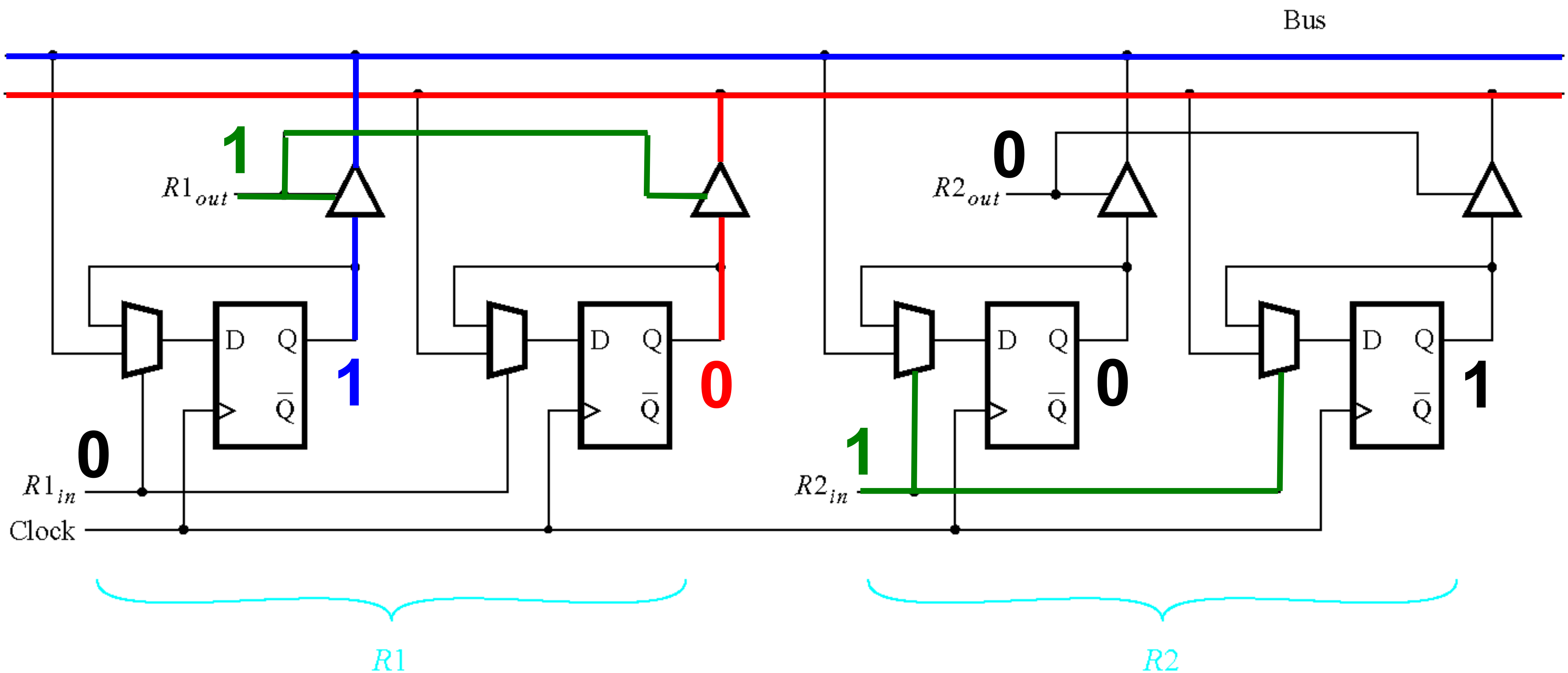
$R1_{out}$ is set to 1 (this enables reading from register 1).

Moving the Contents of R1 to R2



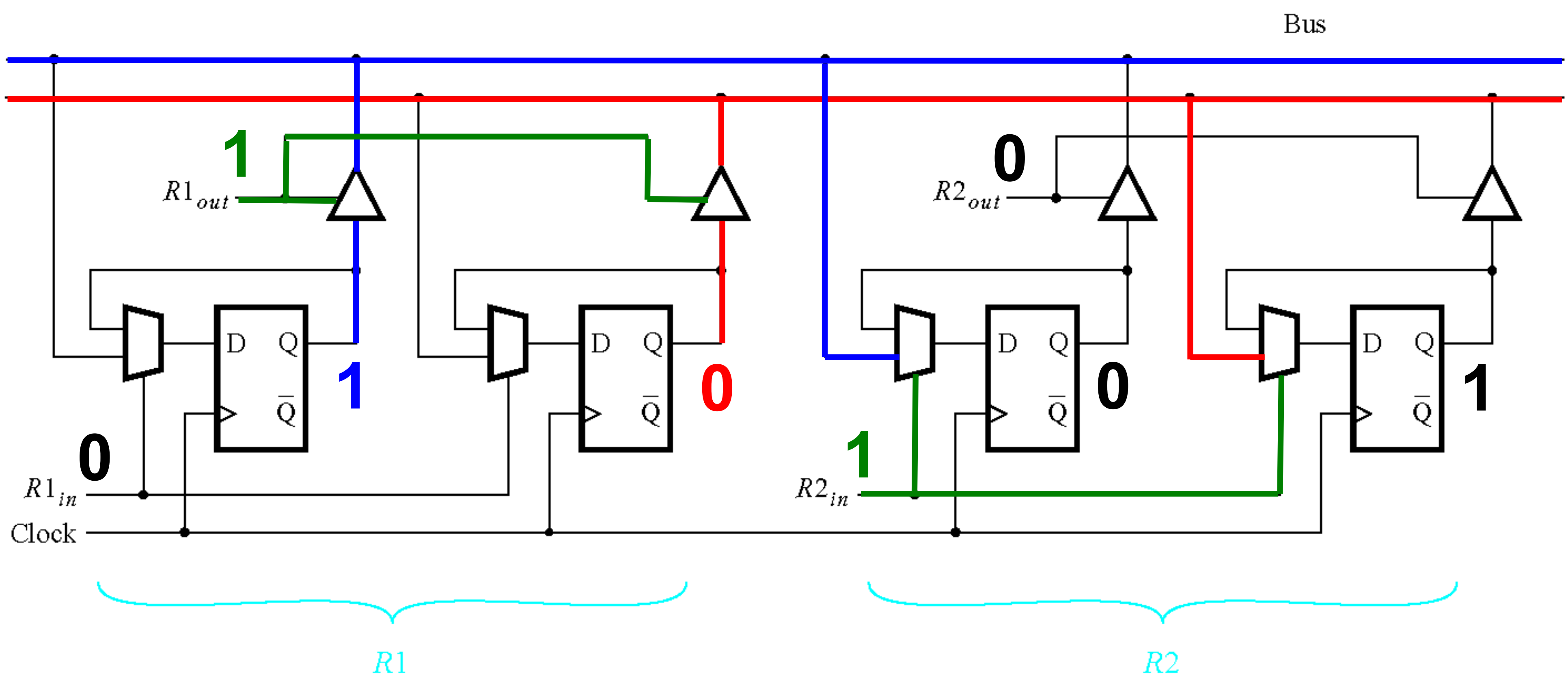
The bits of R1 are now on the data bus (2-bit data bus in this case).

Moving the Contents of R1 to R2



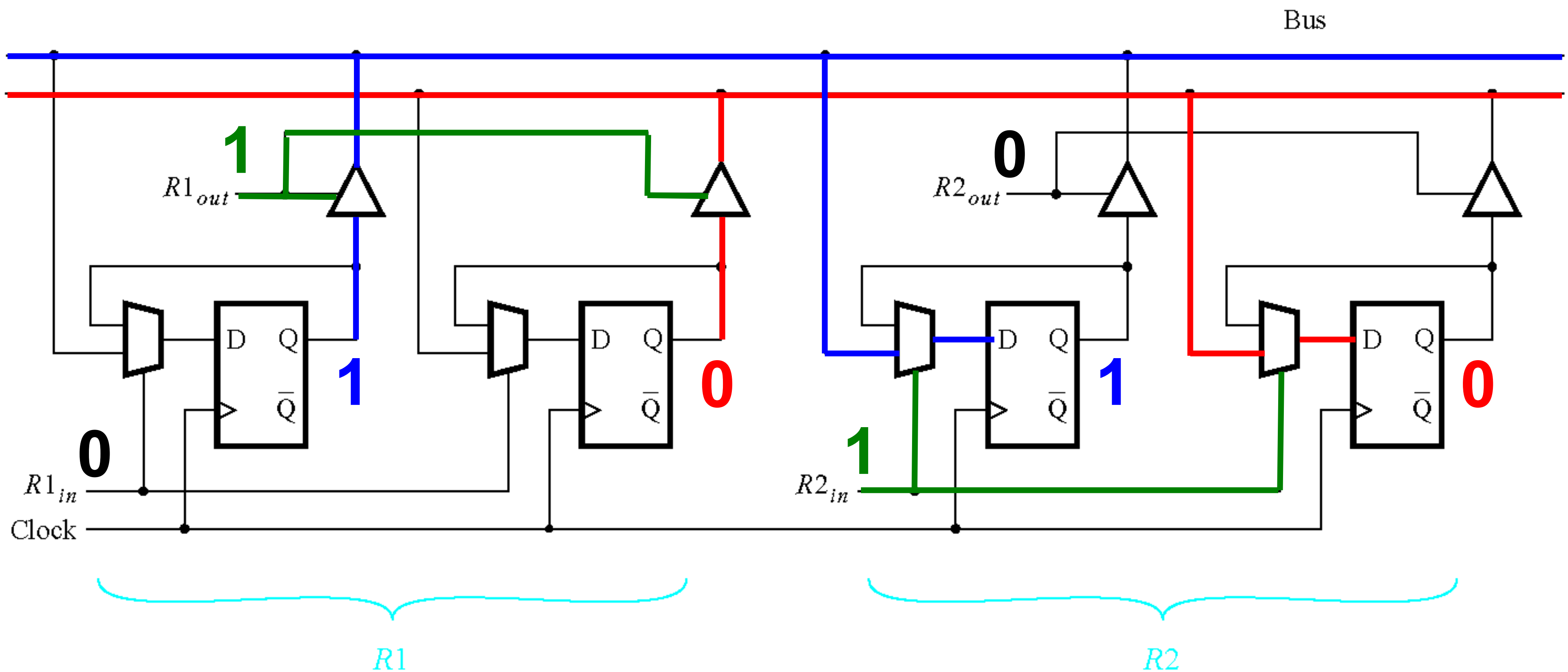
$R2_{in}$ is set to 1 (this enables writing to register 2).

Moving the Contents of R1 to R2



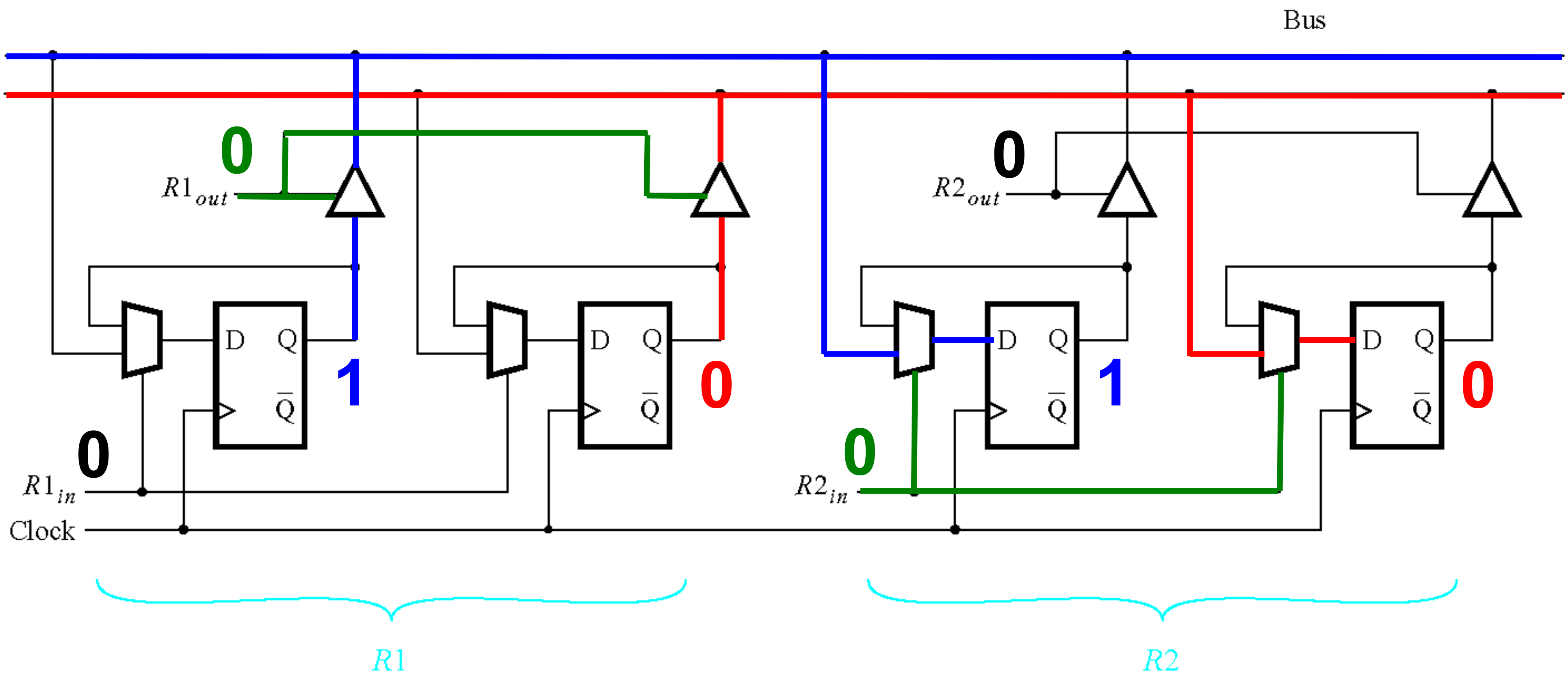
The bits of R1 are still on the bus and they propagate to the multiplexers...

Moving the Contents of R1 to R2



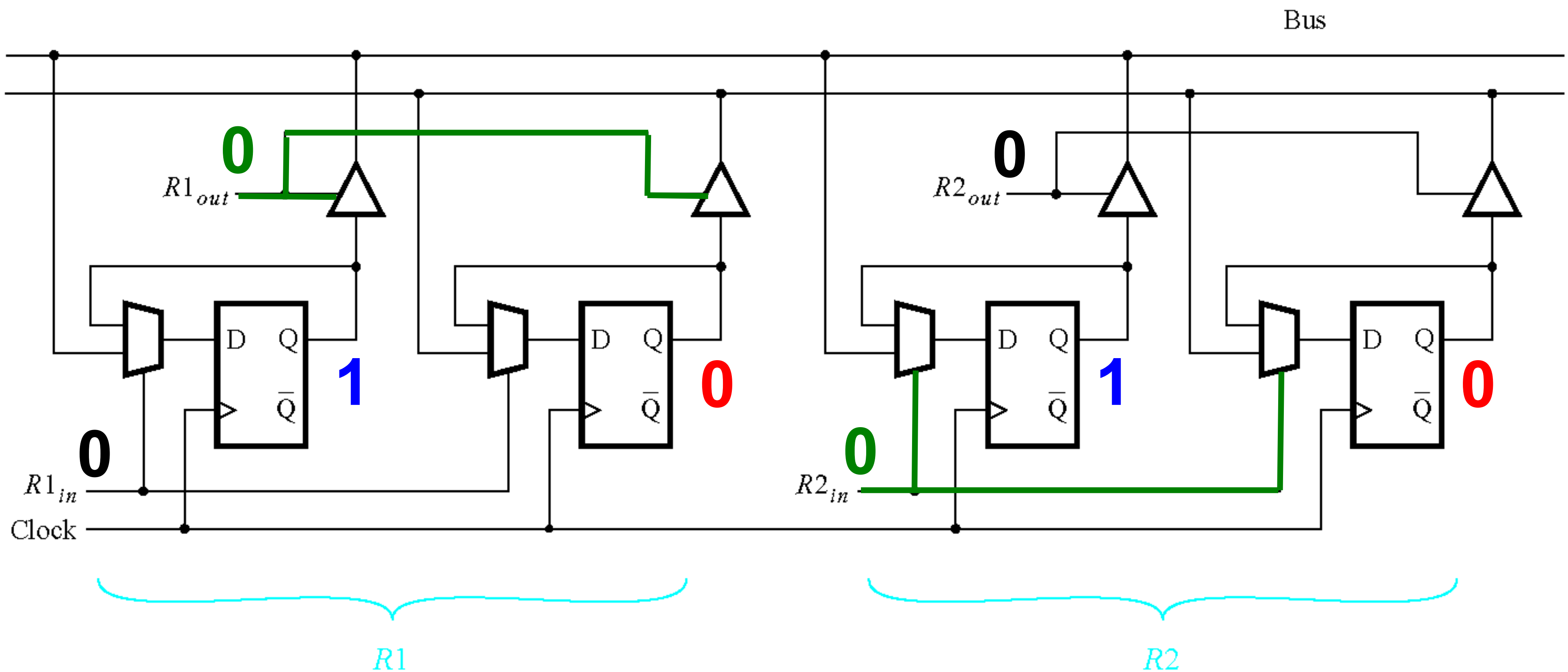
... and on the next positive clock edge to the outputs of the flip-flops of R2.

Moving the Contents of R1 to R2



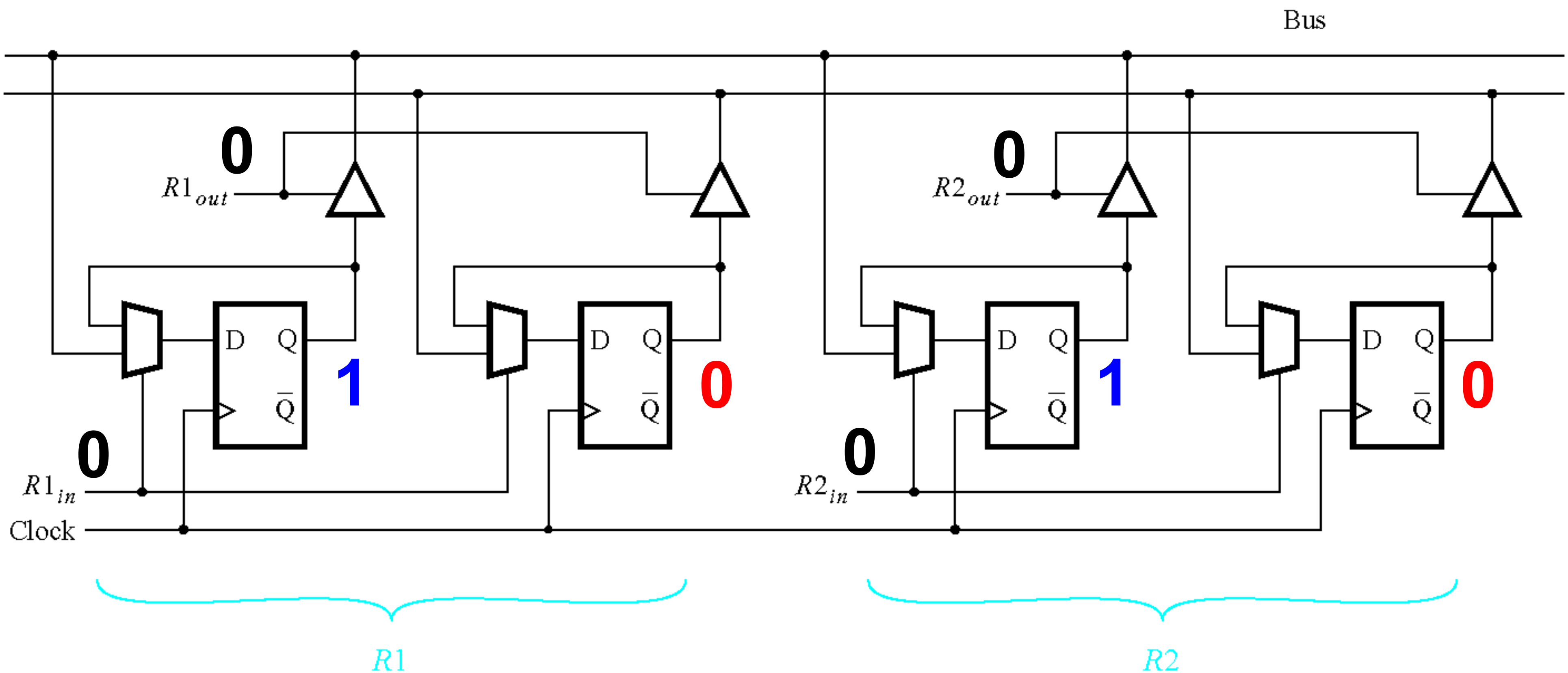
After the copy is complete $R1_{out}$ and $R2_{in}$ are set to 0.

Moving the Contents of R1 to R2



All control inputs are now disabled (no reading or writing is allowed).

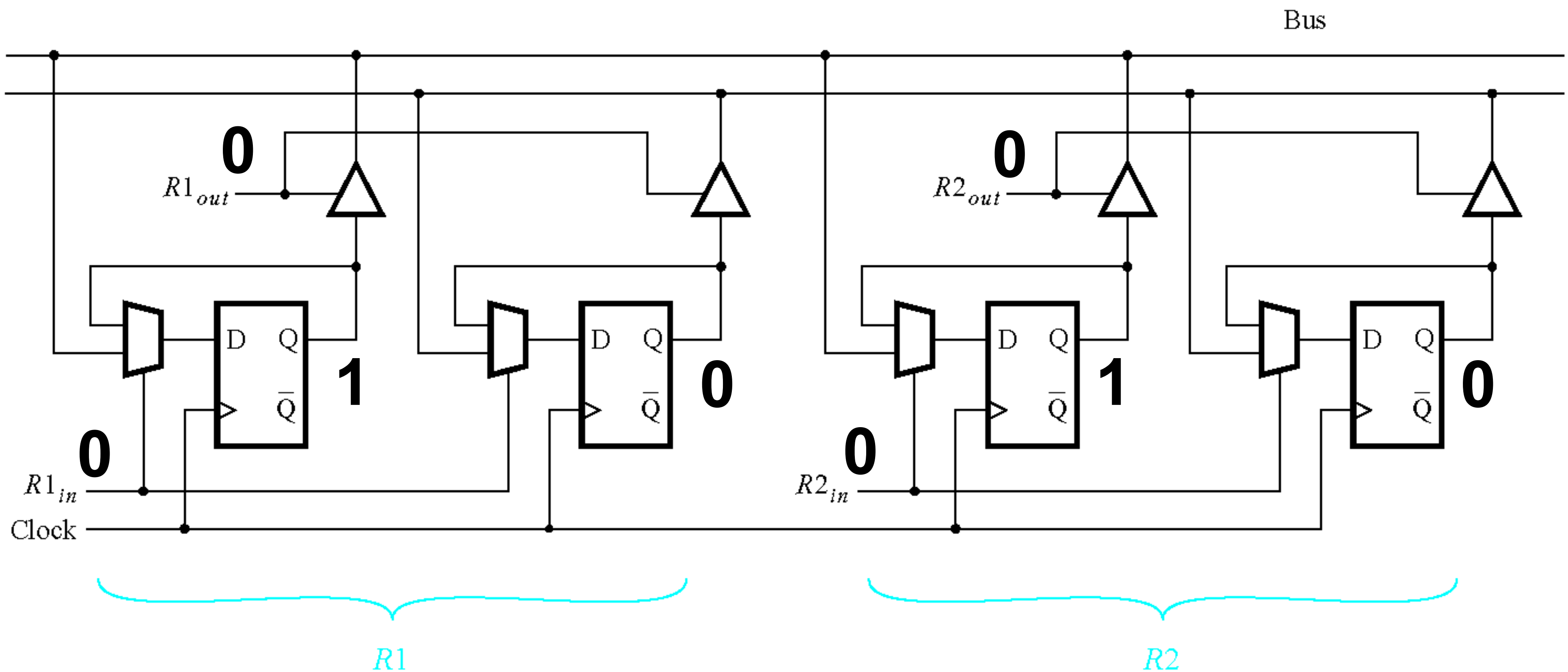
Moving the Contents of R1 to R2



Register 2 now holds the same value as register 1.

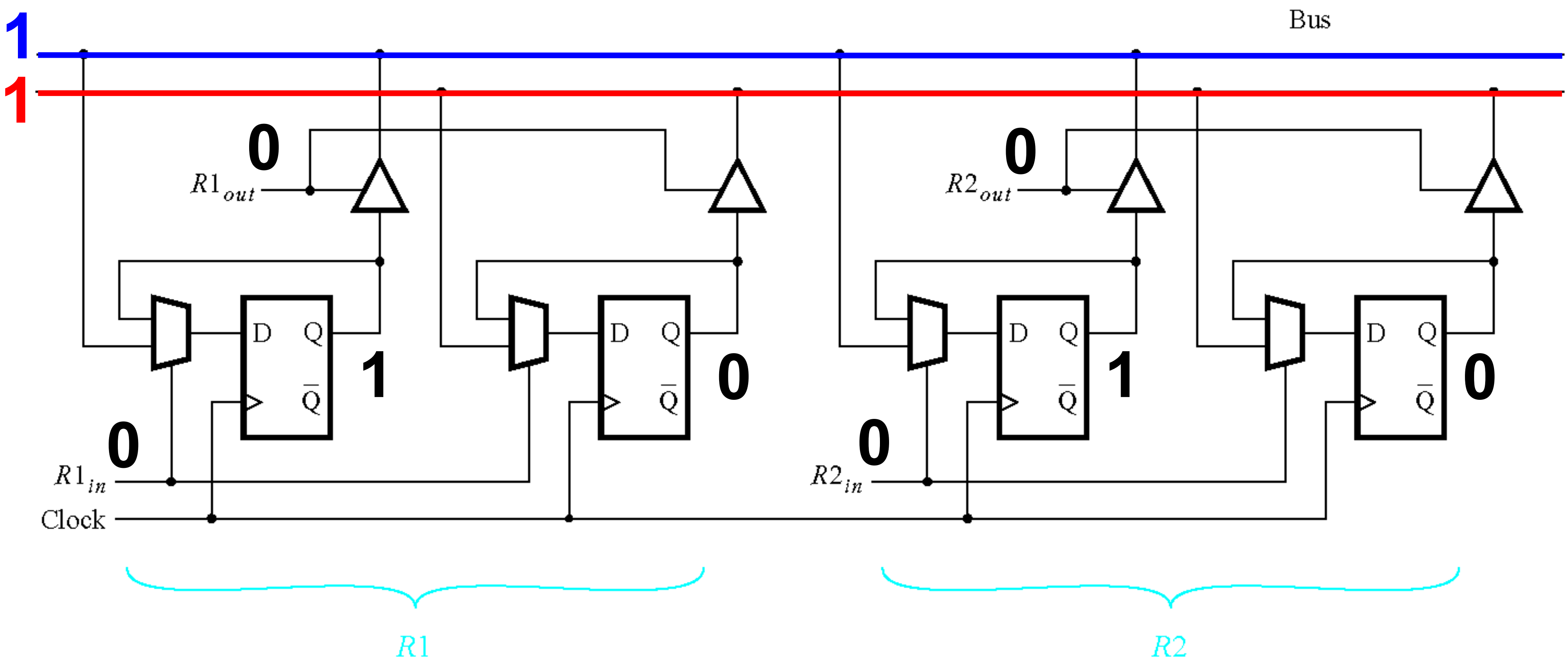
Another Example

Loading Data From The Bus Into R2



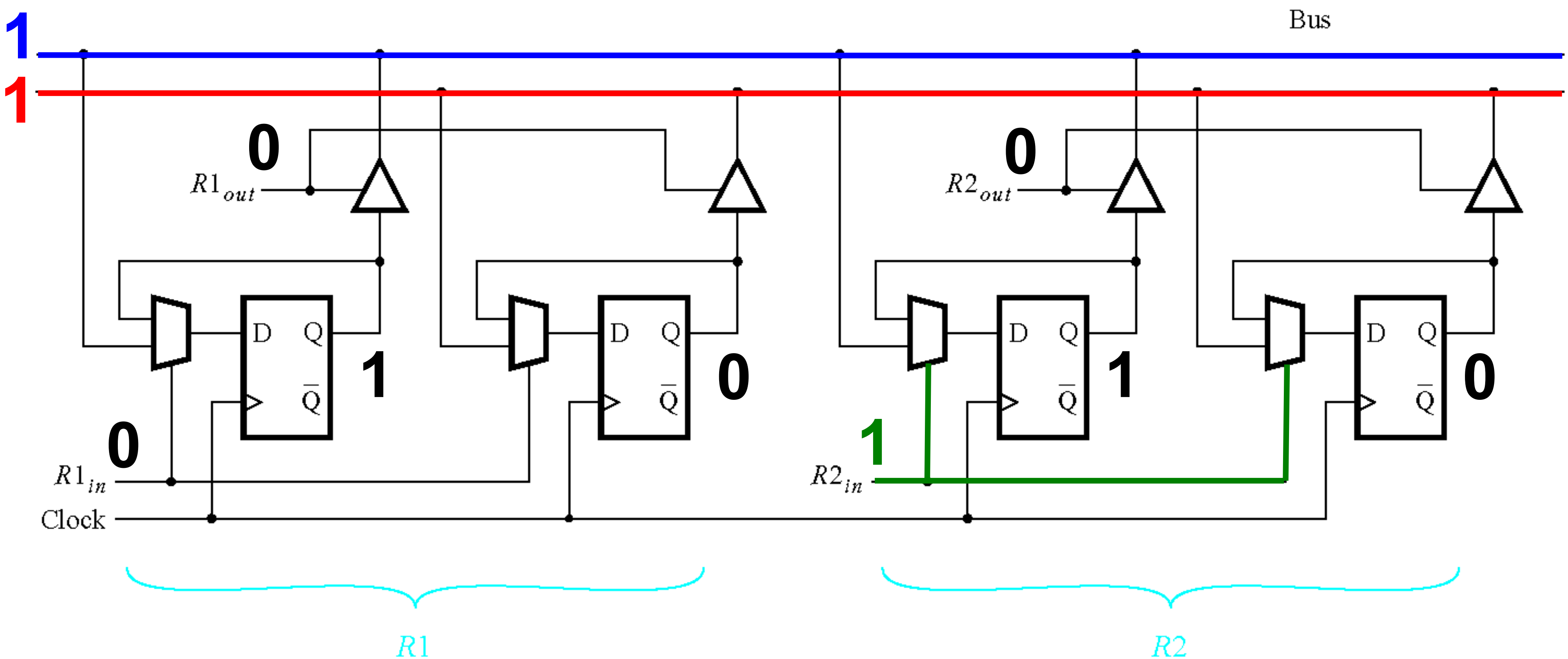
Initially all control inputs are set to 0 (no reading or writing allowed).

Loading Data From The Bus Into R2



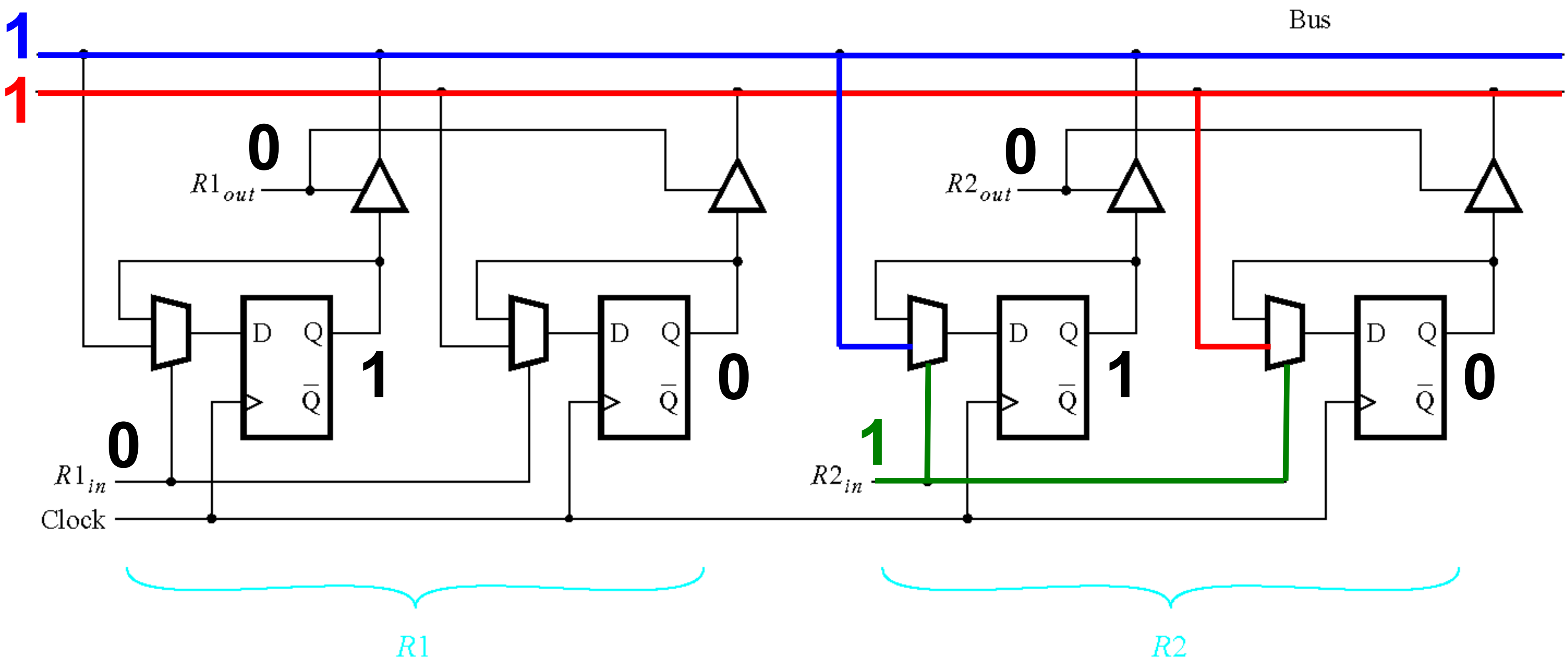
The number 3_{10}=11_2 is placed on the 2-bit data bus.

Loading Data From The Bus Into R2



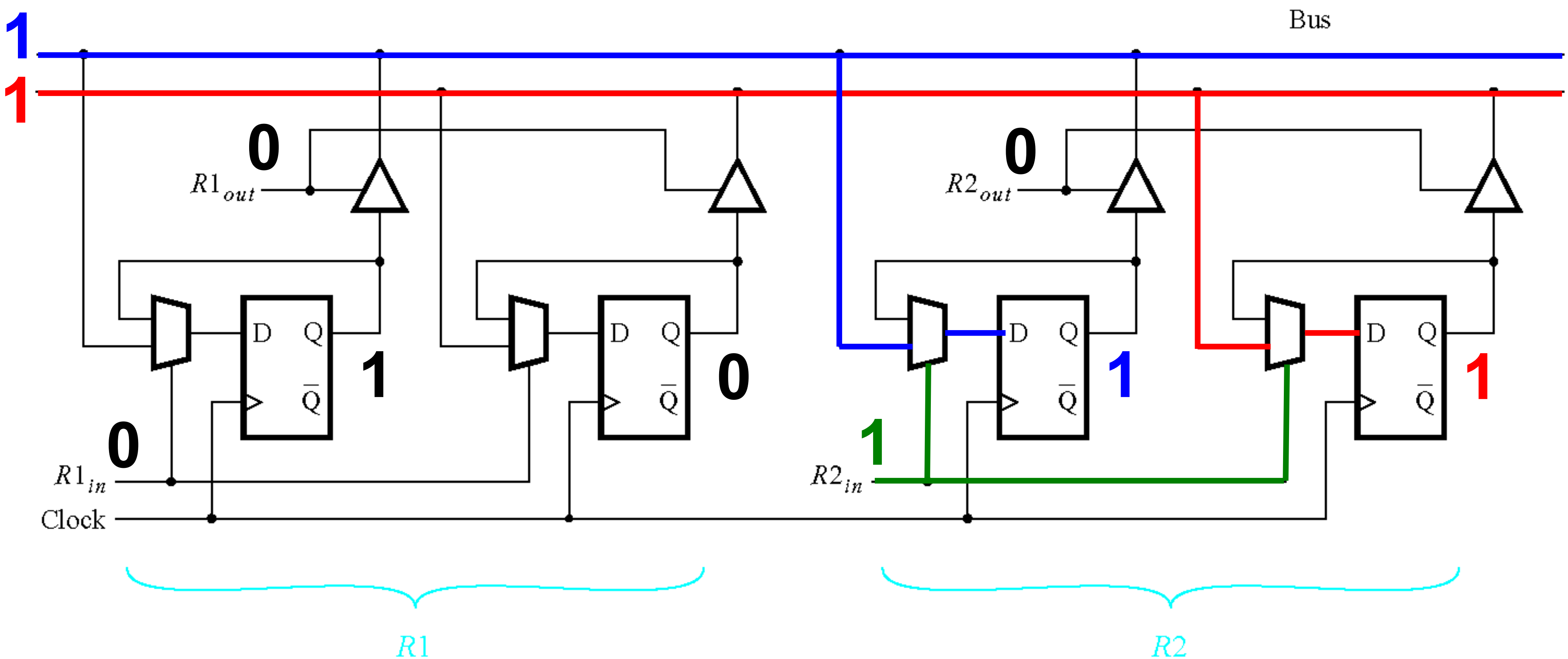
$R2_{in}$ is set to 1 (this enables writing to register 2).

Loading Data From The Bus Into R2



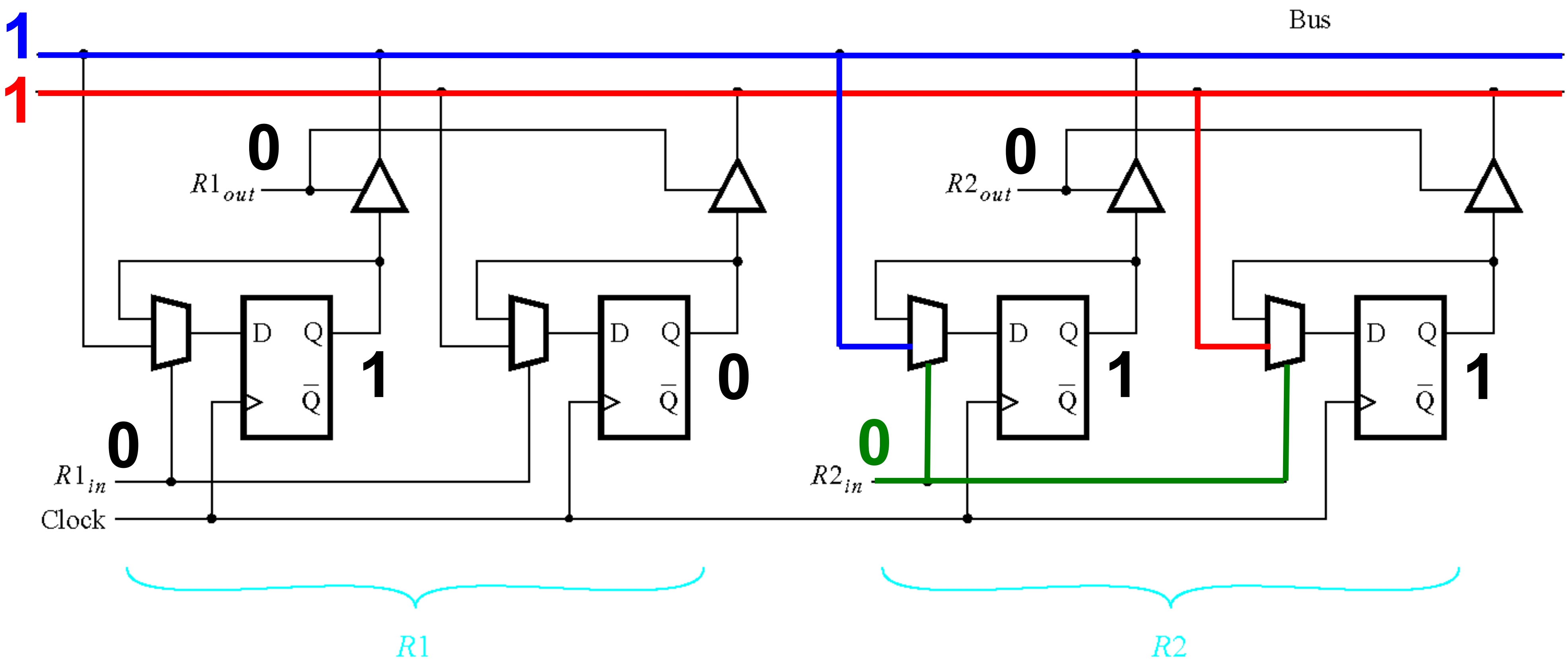
The bits of the data propagate the the multiplexers...

Loading Data From The Bus Into R2



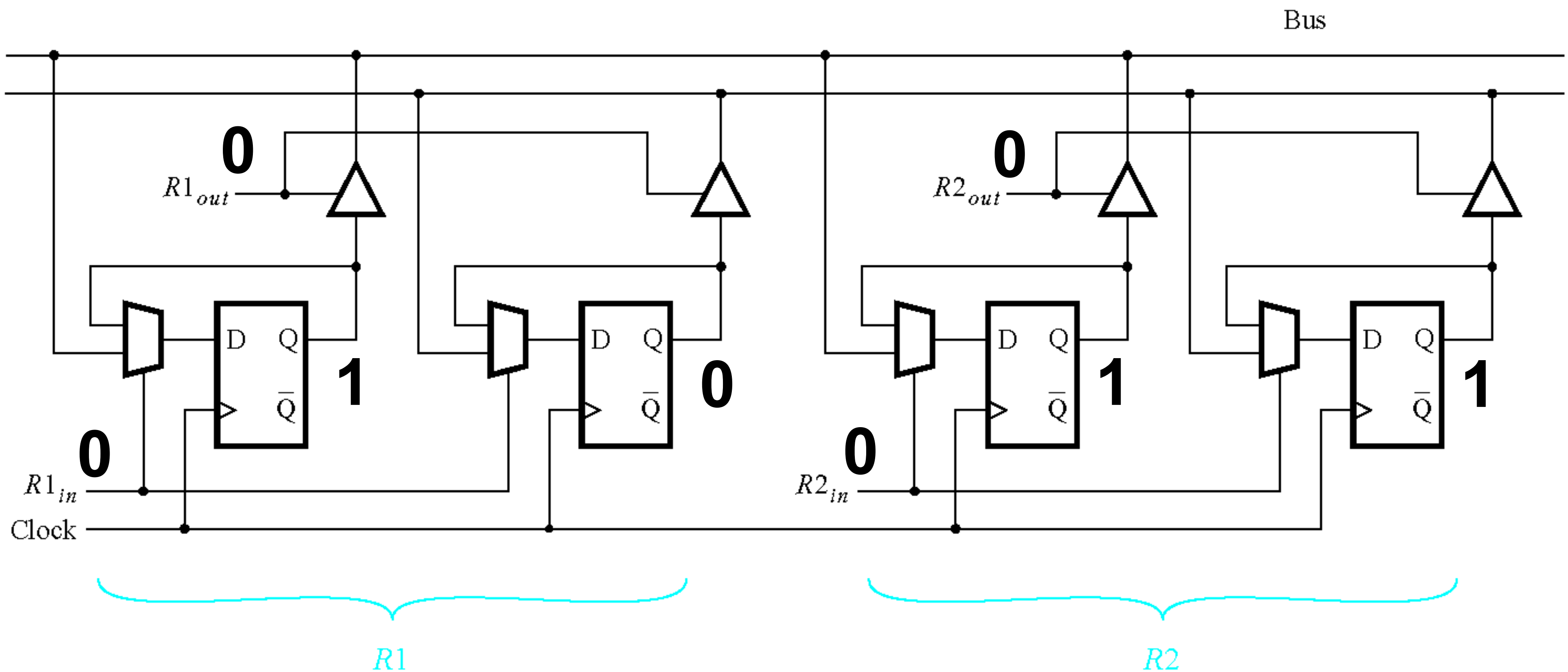
... and on the next positive clock edge to the outputs of the flip-flops of R2.

Loading Data From The Bus Into R2



After the loading is complete $R2_{in}$ is set to 0.

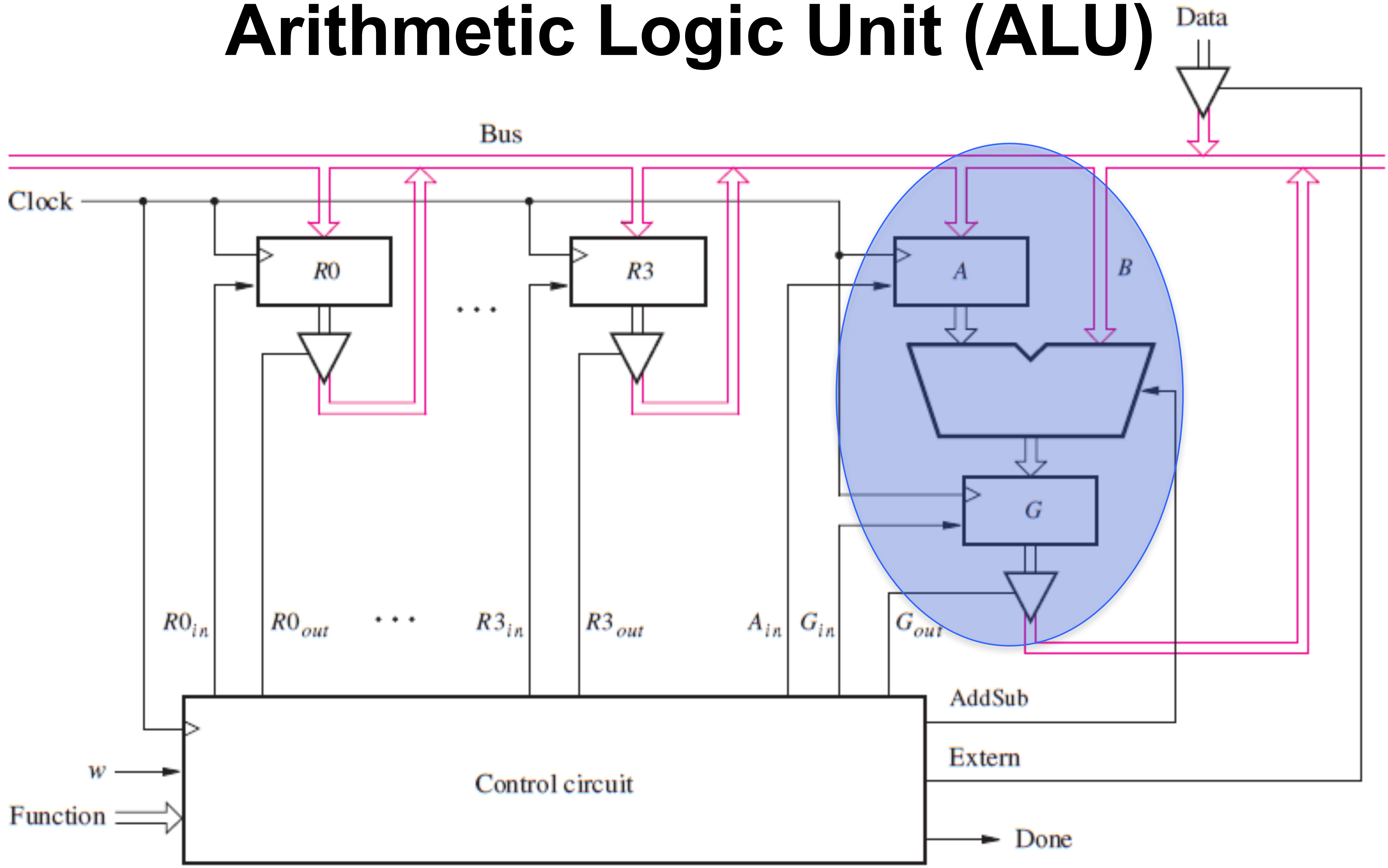
Loading Data From The Bus Into R2



Register 2 now stores the number $3_{10}=11_2$.

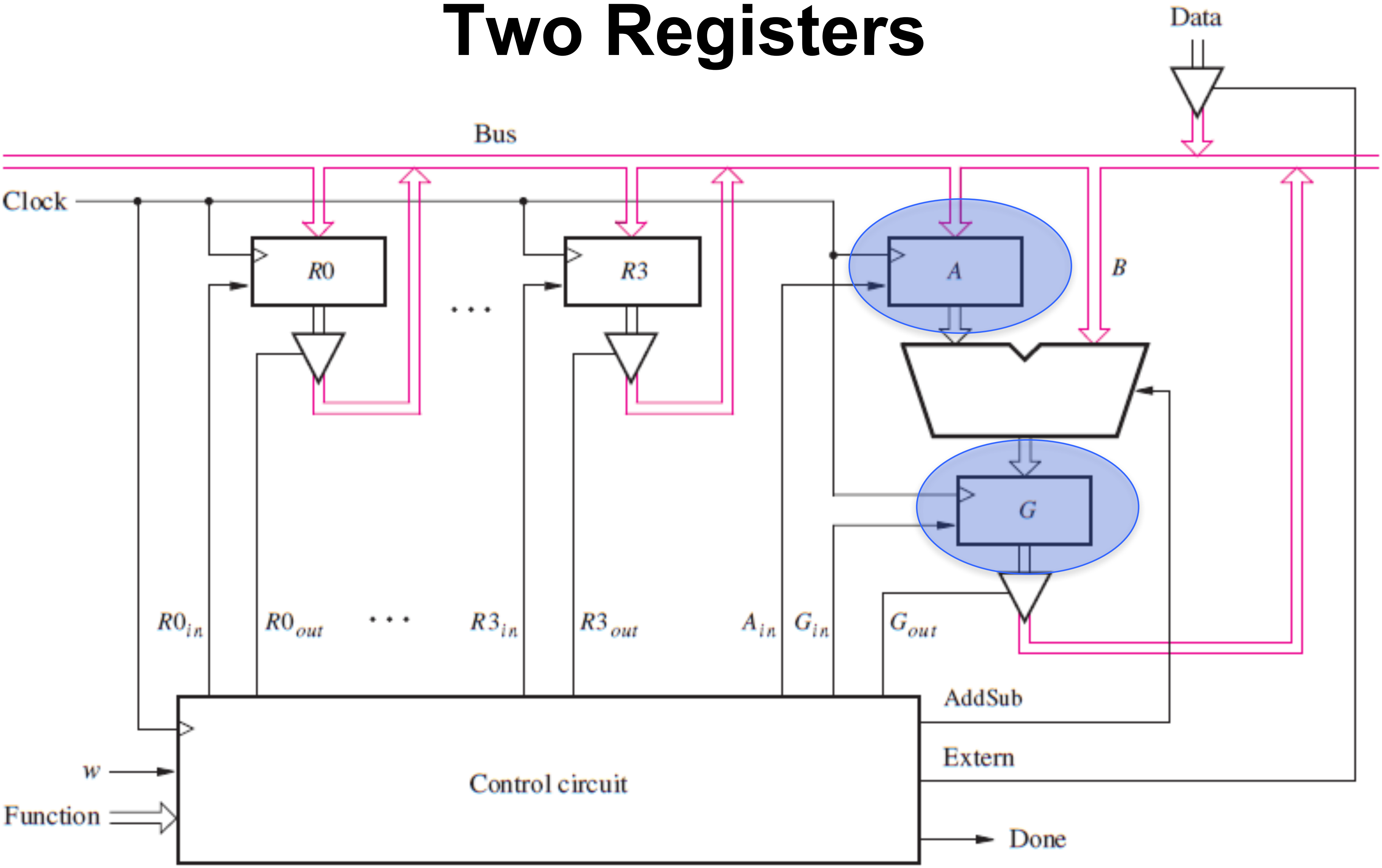
A Closer Look at the Arithmetic Logic Unit (ALU)

Arithmetic Logic Unit (ALU)



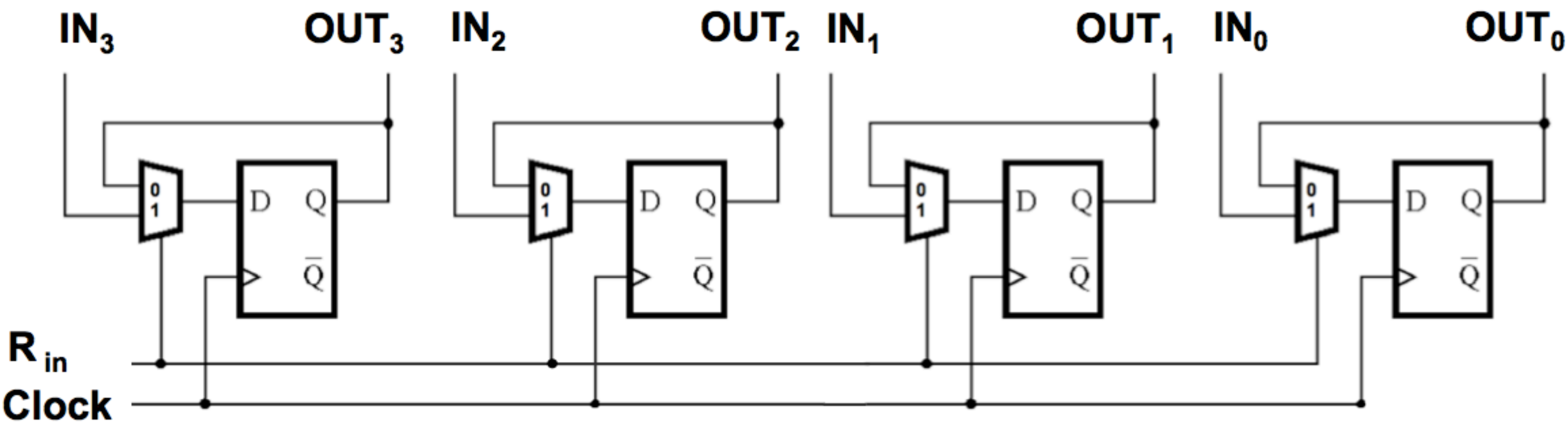
[Figure 7.9 from the textbook]

Two Registers

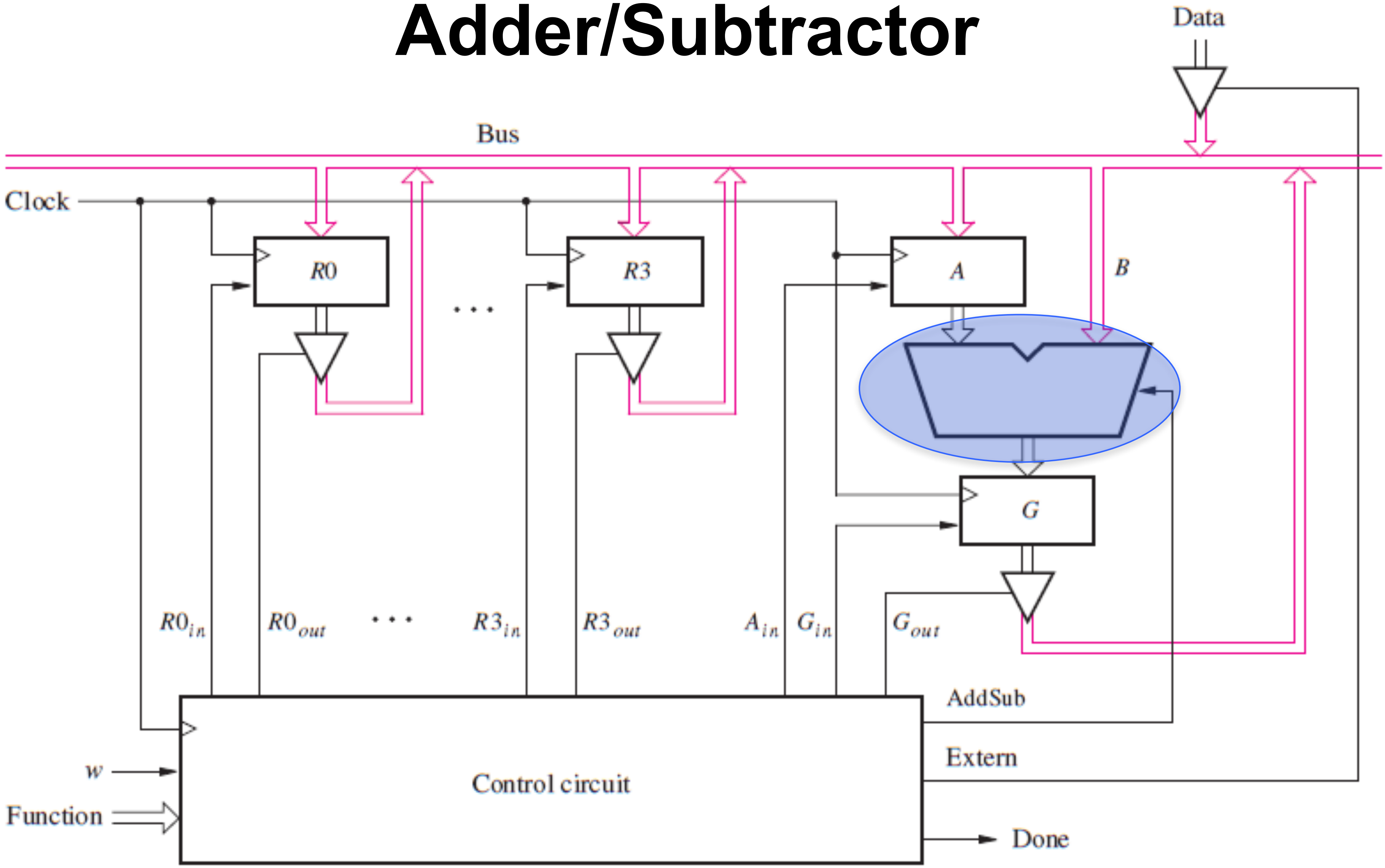


[Figure 7.9 from the textbook]

4-Bit Register

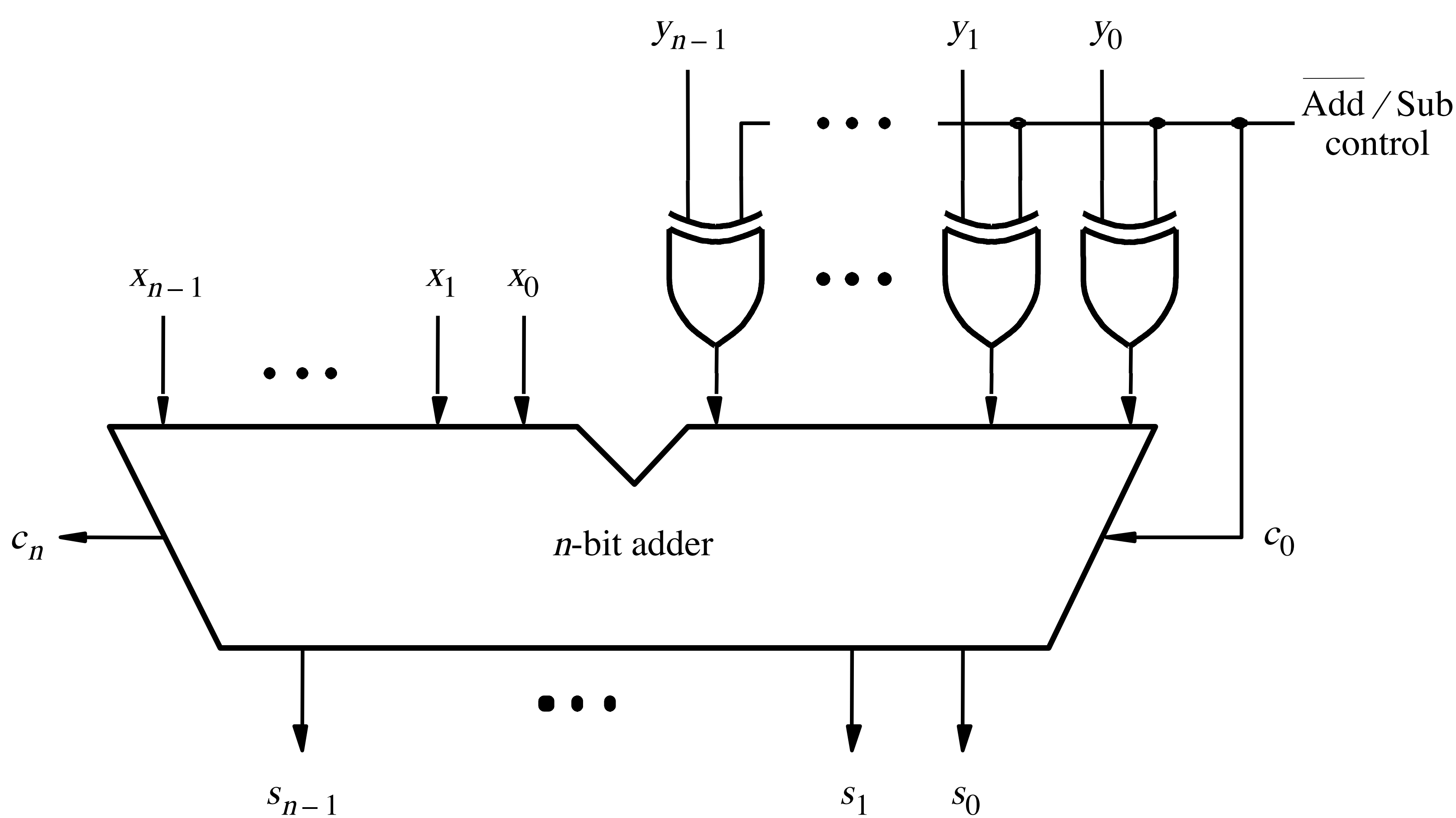


Adder/Subtractor



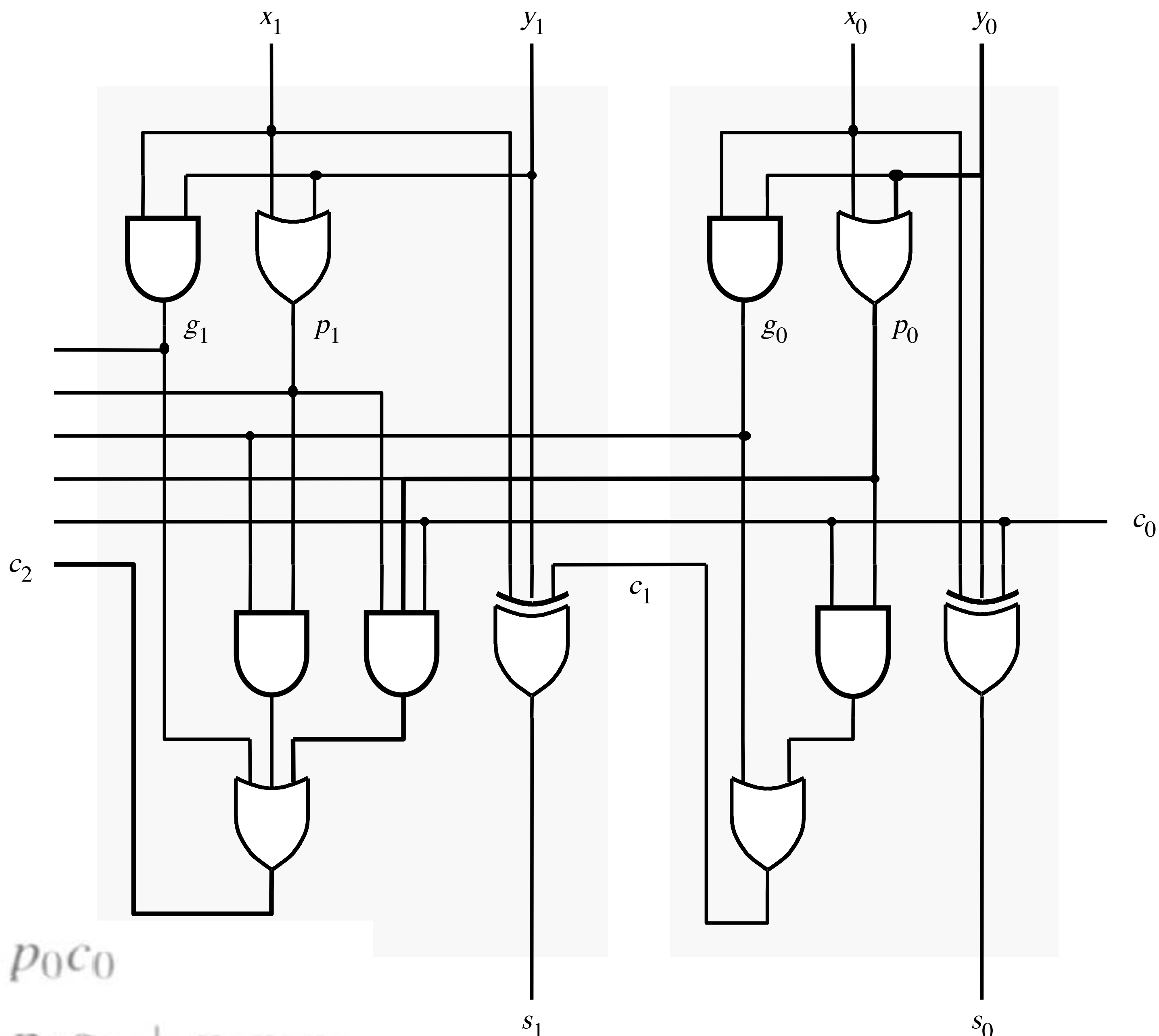
[Figure 7.9 from the textbook]

Adder/Subtractor unit



[Figure 3.12 from the textbook]

The first two stages of a carry-lookahead adder

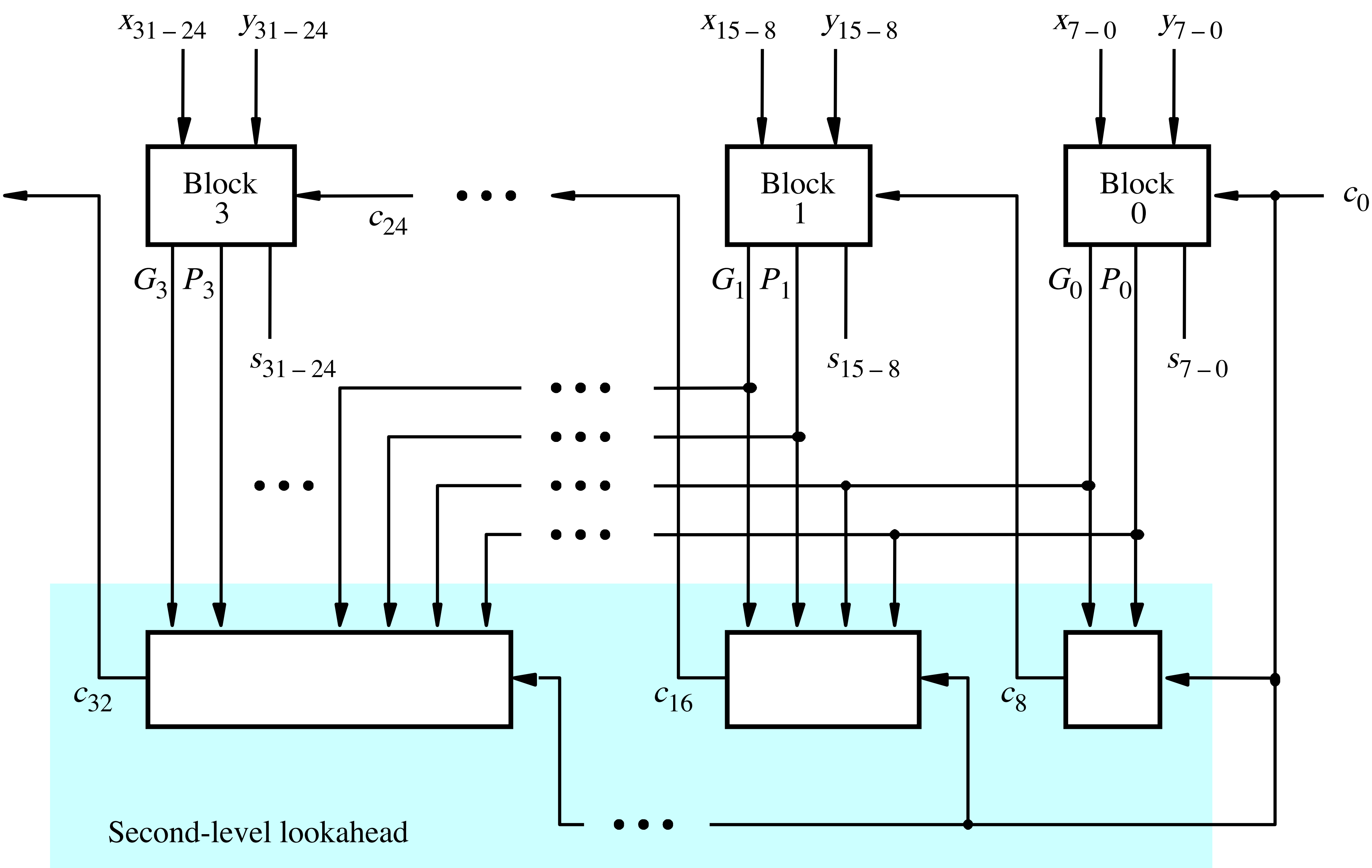


$$c_1 = g_0 + p_0 c_0$$

$$c_2 = g_1 + p_1 g_0 + p_1 p_0 c_0$$

[Figure 3.15 from the textbook]

A hierarchical carry-lookahead adder



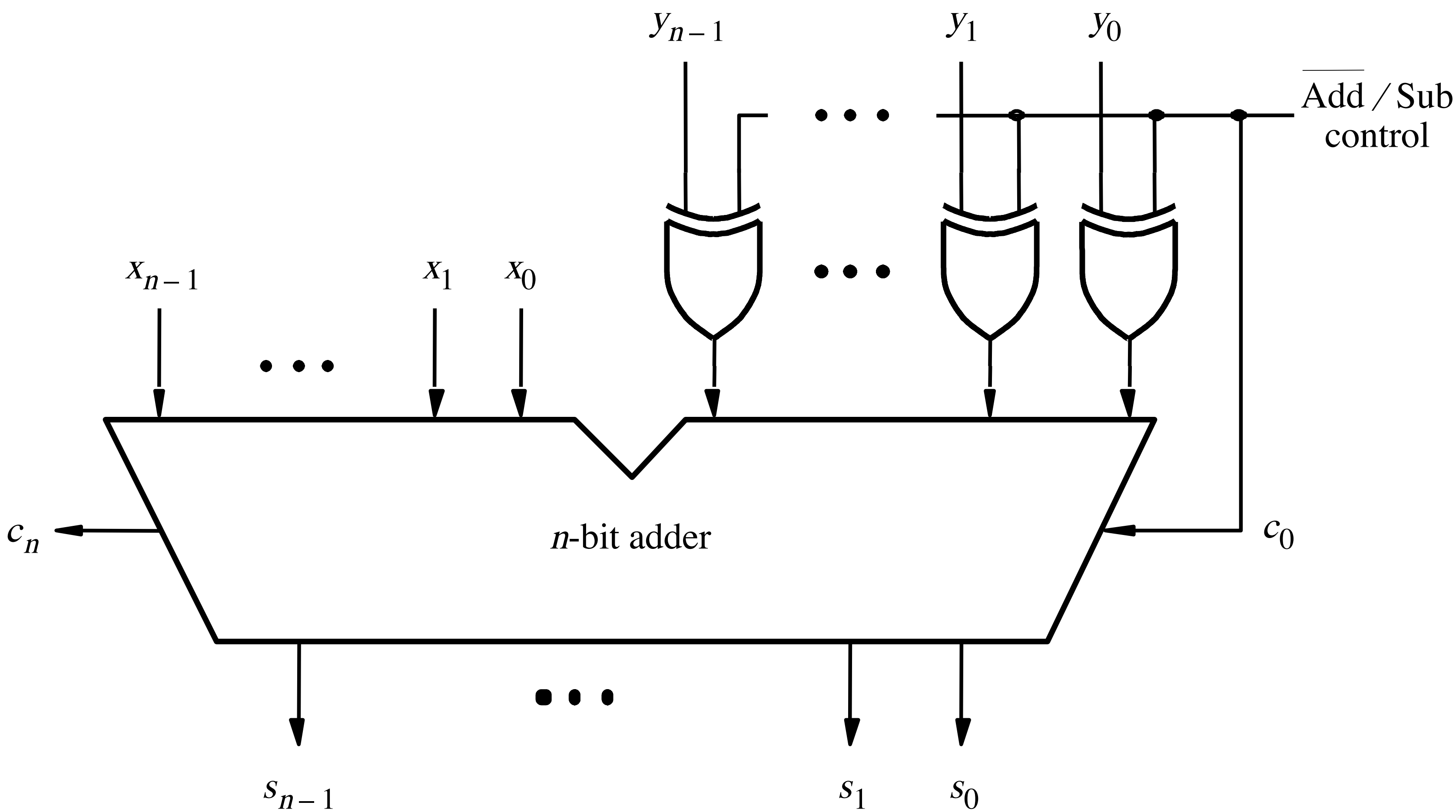
[Figure 3.17 from the textbook]

Adder/subtractor unit

- Subtraction can be performed by simply adding the 2's complement of the second number, regardless of the signs of the two numbers.

- Thus, the same adder circuit can be used to perform both addition and subtraction !!!

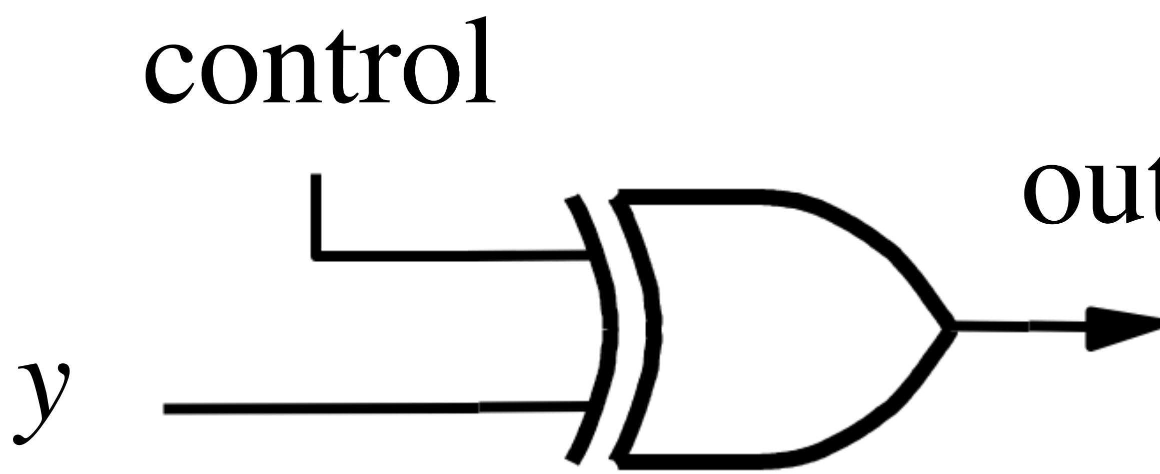
Adder/subtractor unit



[Figure 3.12 from the textbook]

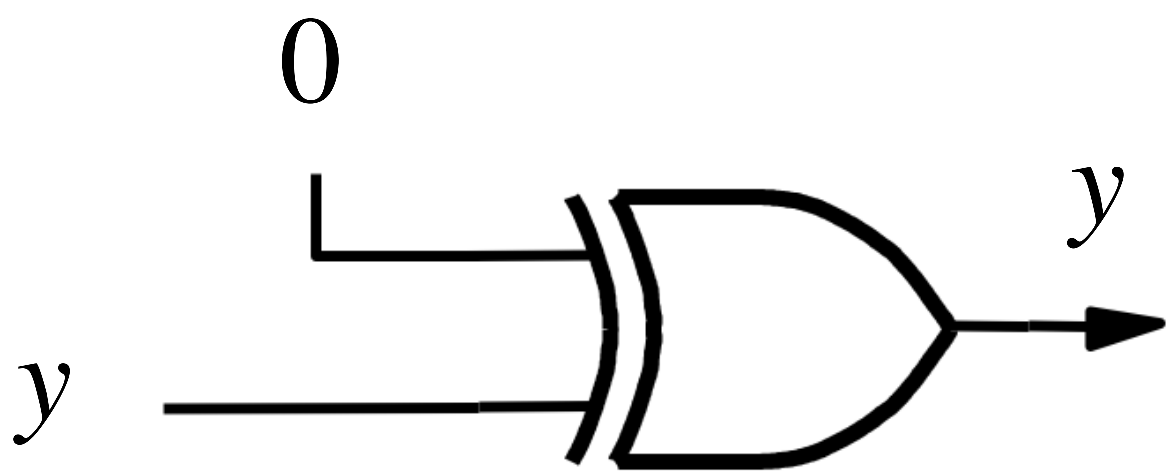
XOR Tricks

control	y	out
0	0	0
0	1	1
1	0	1
1	1	0



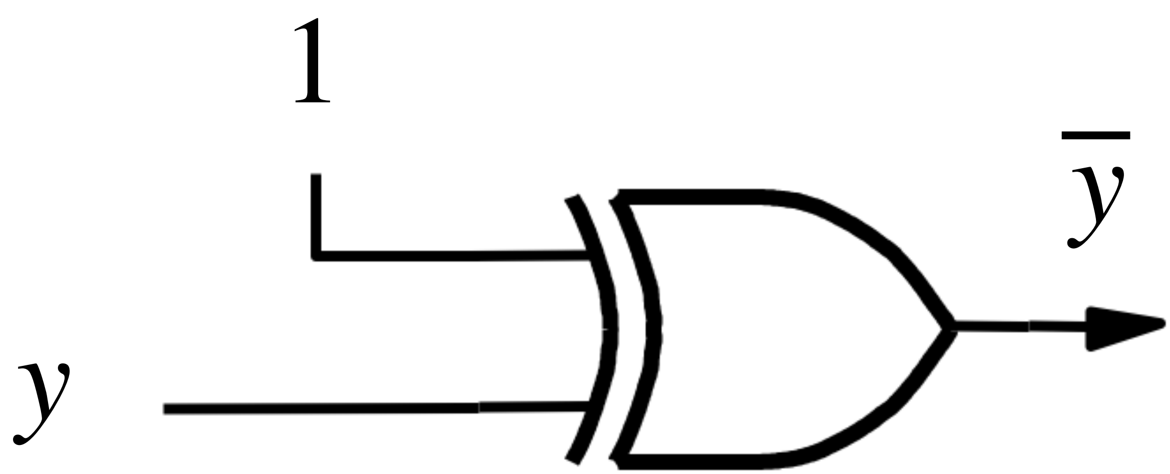
XOR as a repeater

control	y	out
0	0	0
0	1	1
1	0	1
1	1	0

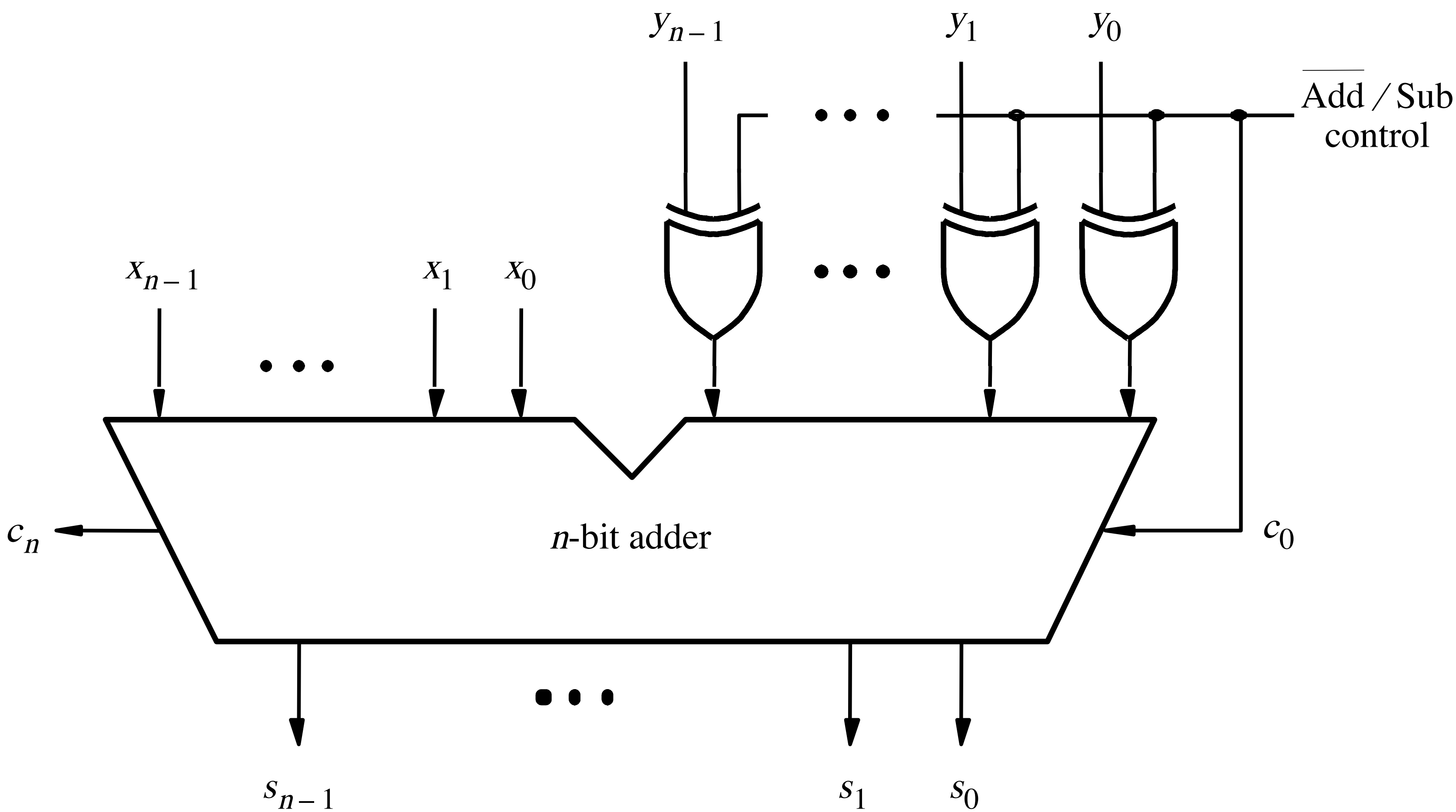


XOR as an inverter

control	y	out
0	0	0
0	1	1
1	0	1
1	1	0

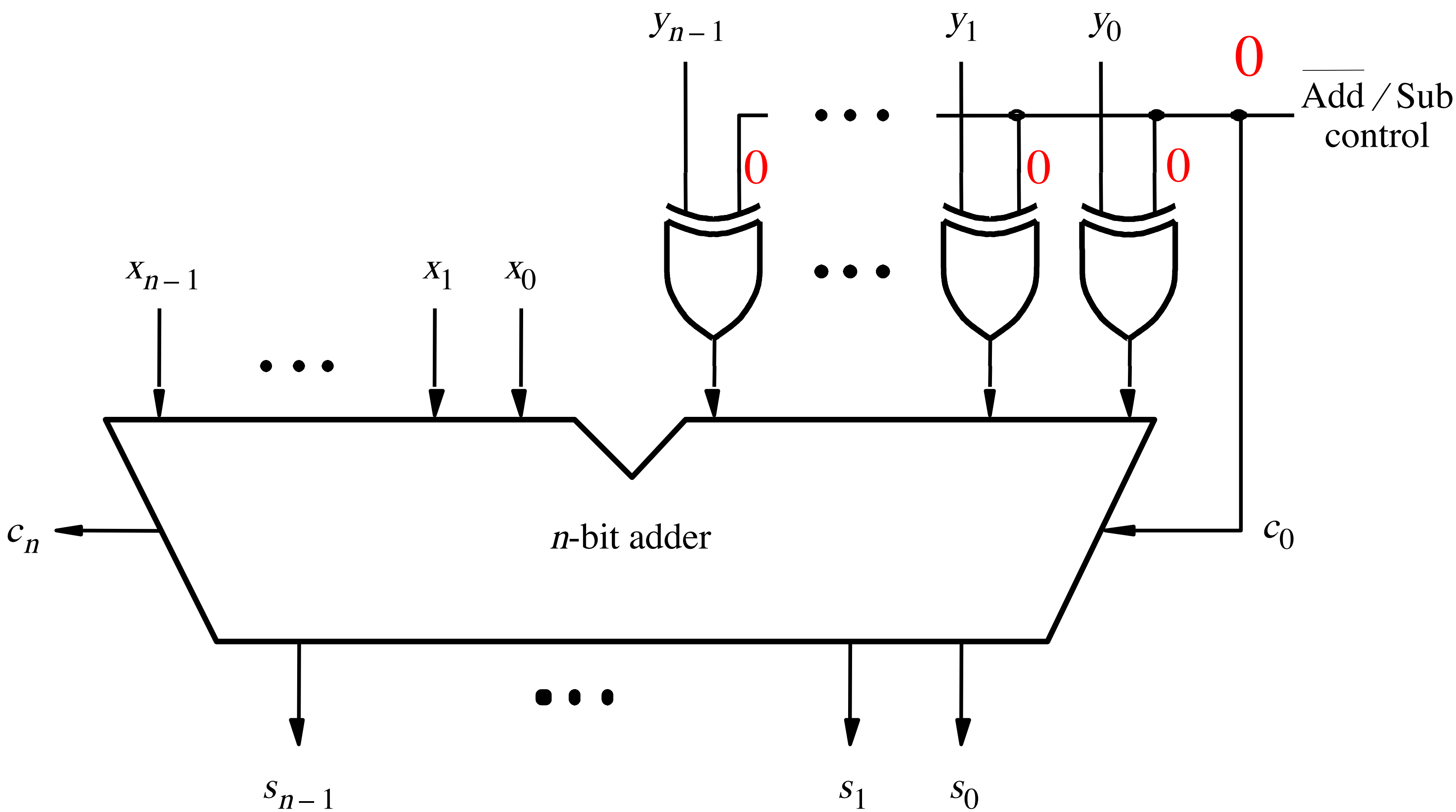


Addition: when control = 0



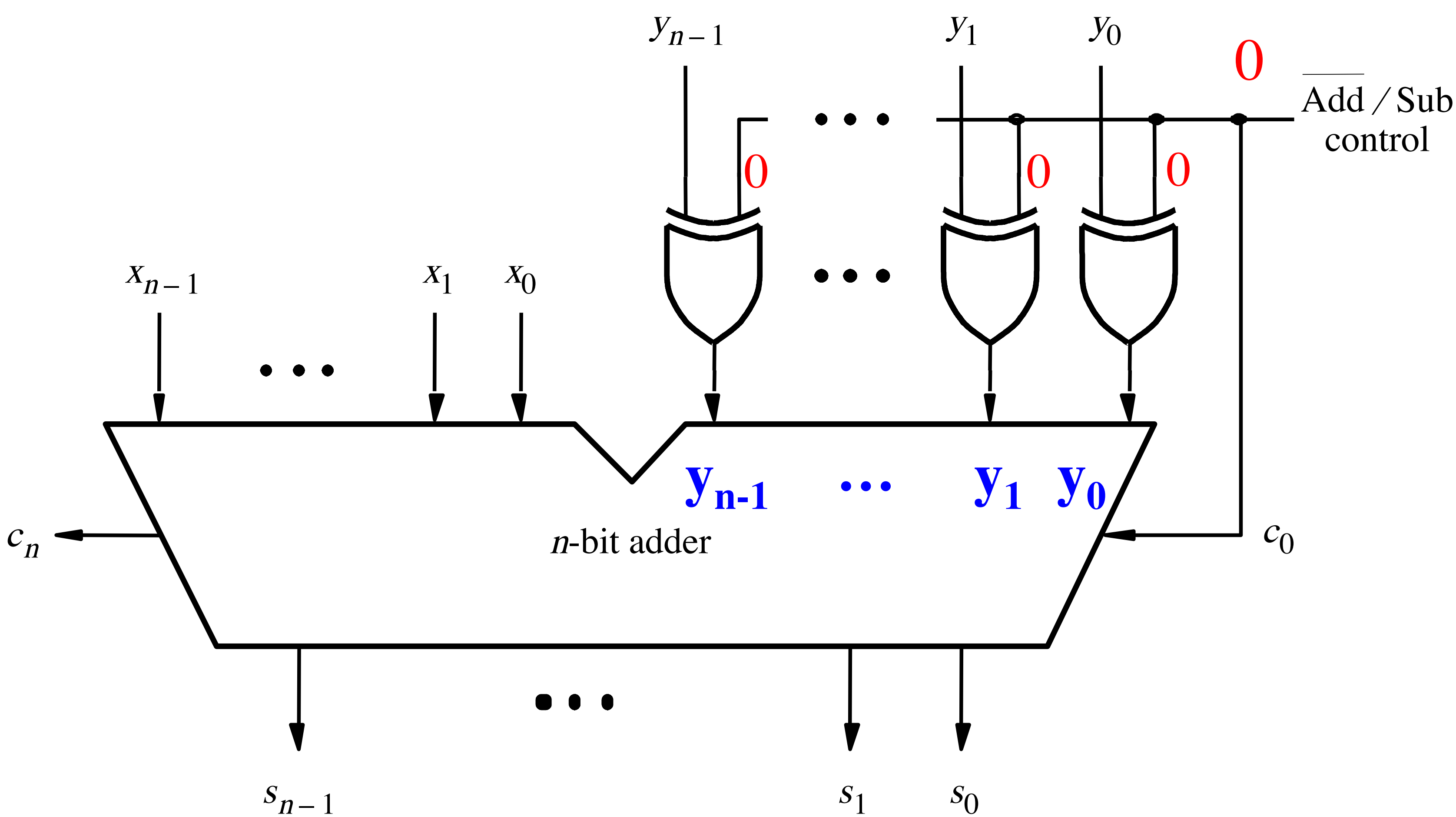
[Figure 3.12 from the textbook]

Addition: when control = 0



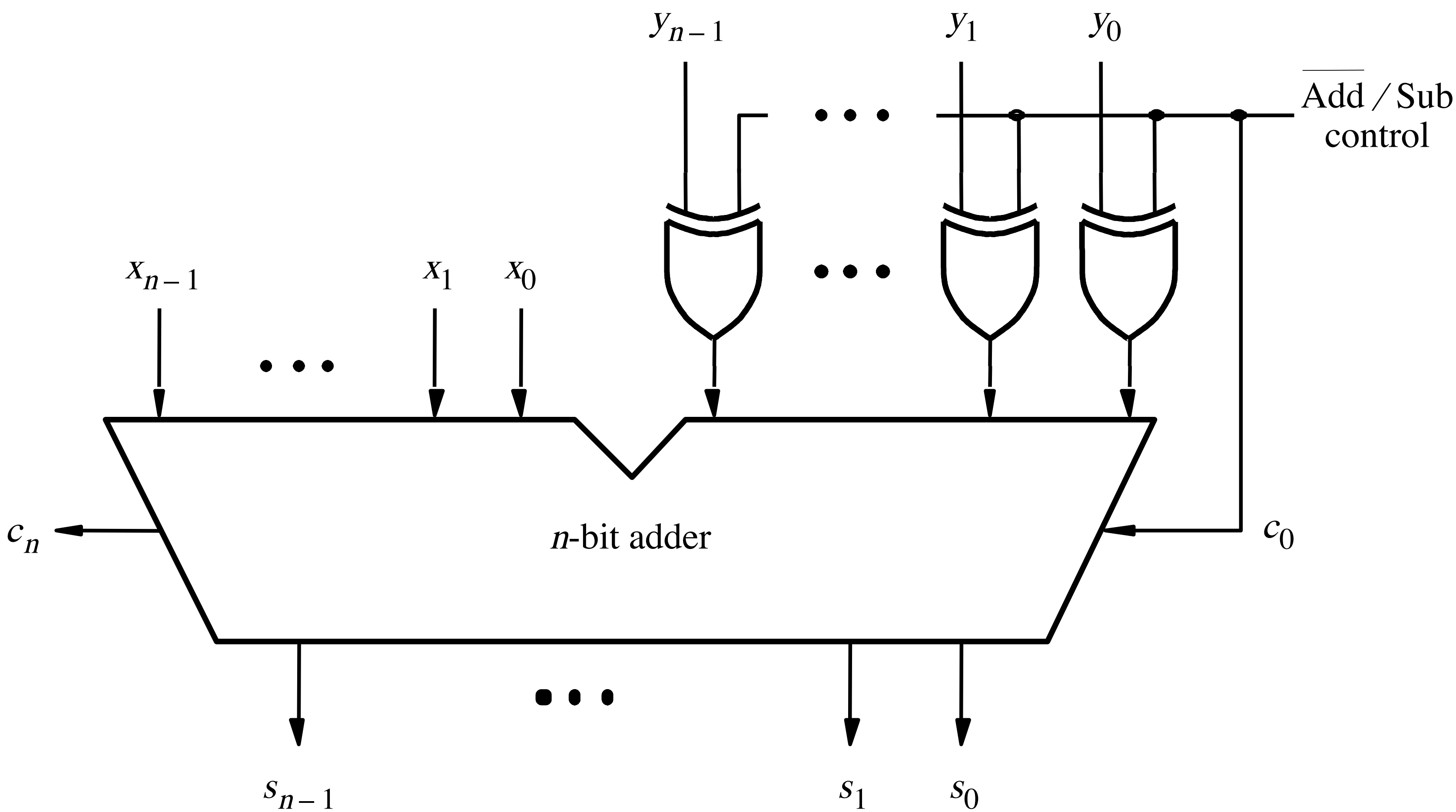
[Figure 3.12 from the textbook]

Addition: when control = 0



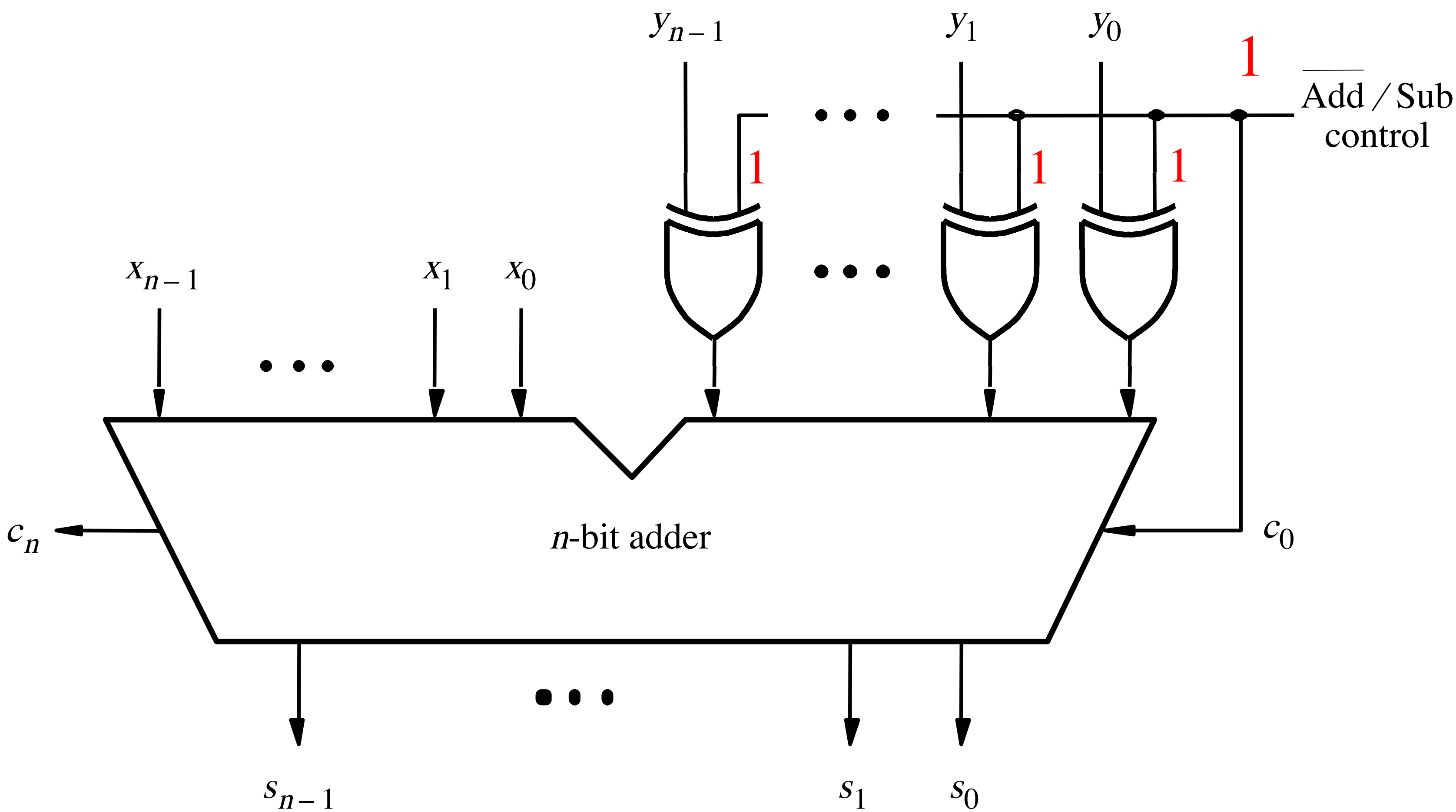
[Figure 3.12 from the textbook]

Subtraction: when control = 1



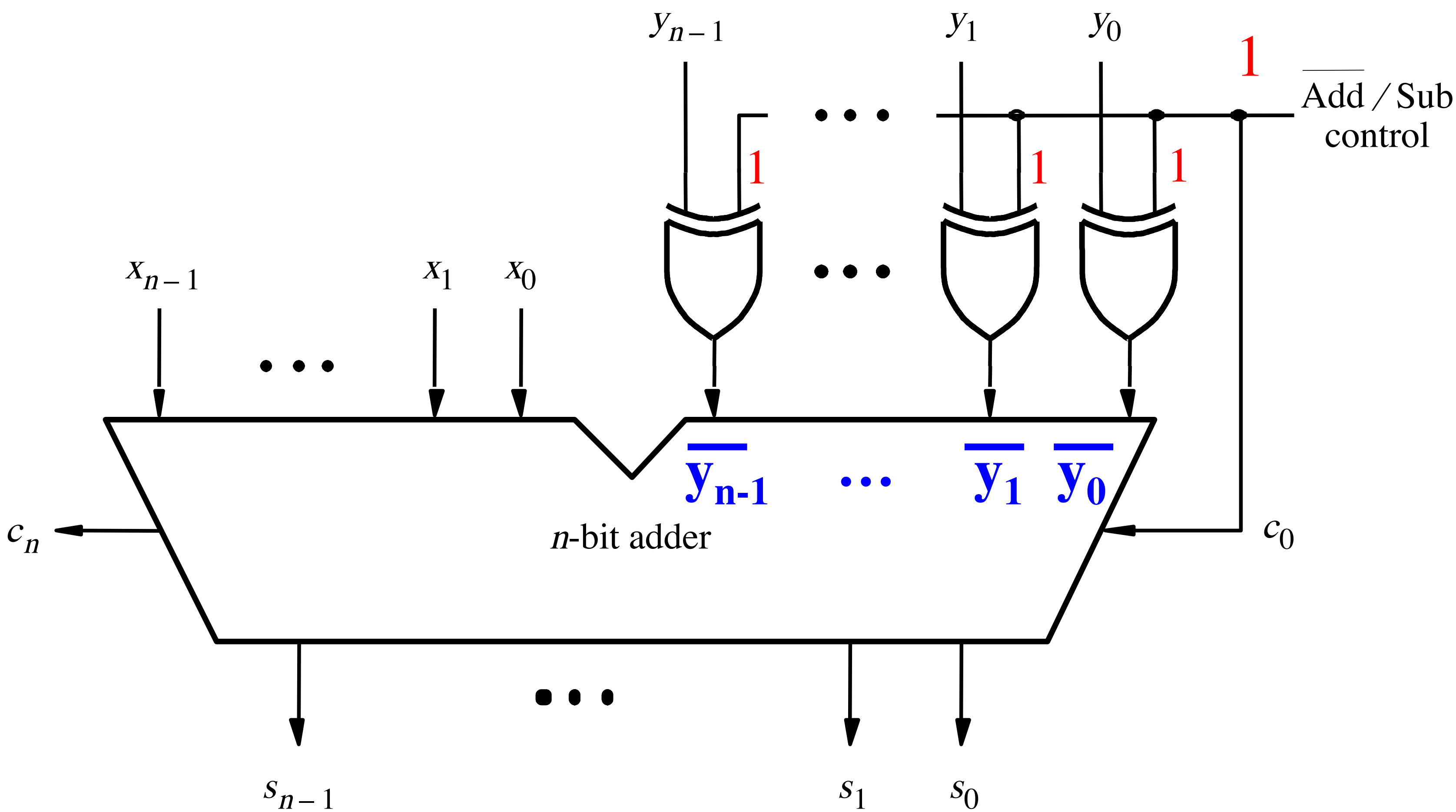
[Figure 3.12 from the textbook]

Subtraction: when control = 1



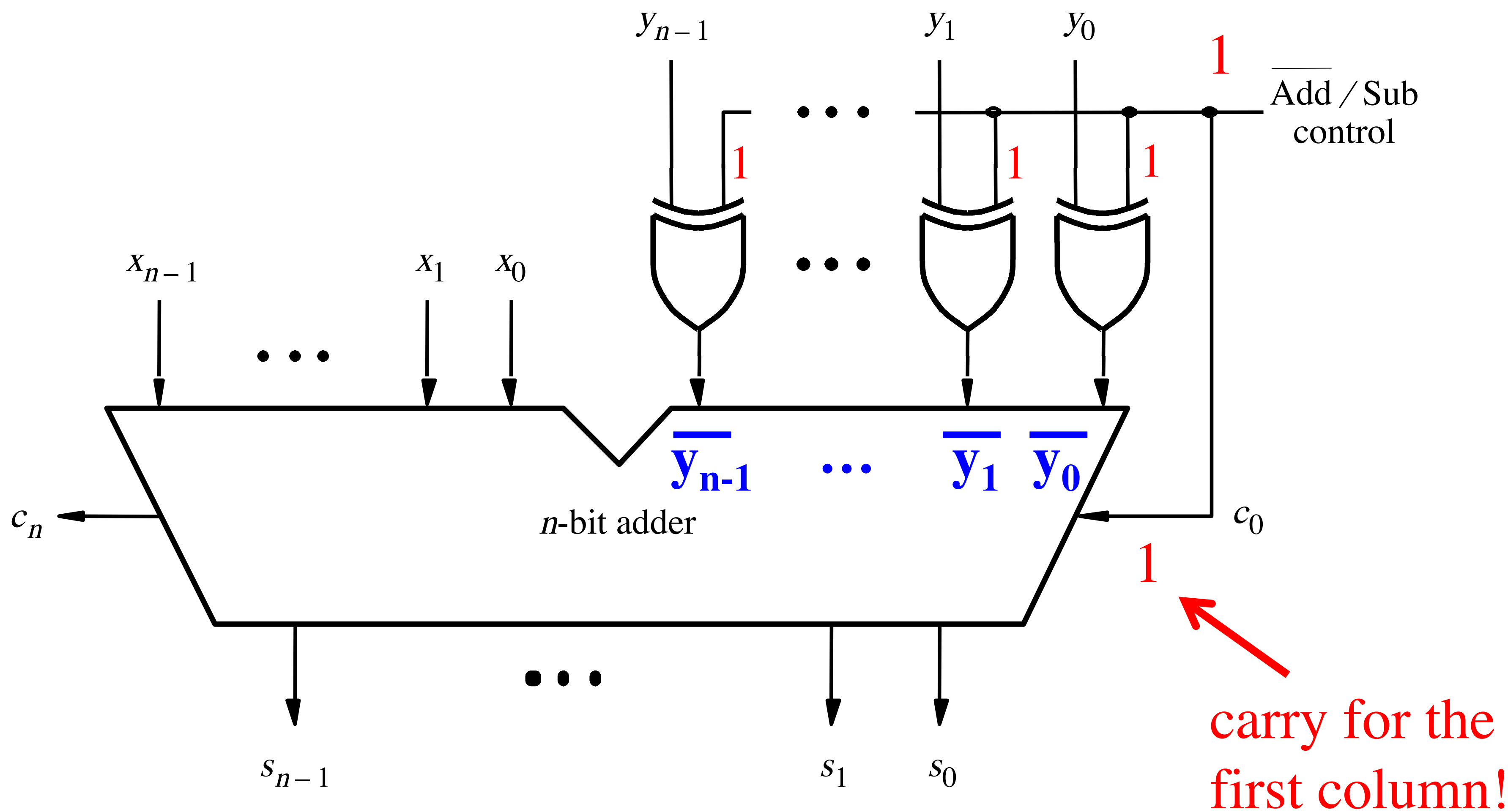
[Figure 3.12 from the textbook]

Subtraction: when control = 1



[Figure 3.12 from the textbook]

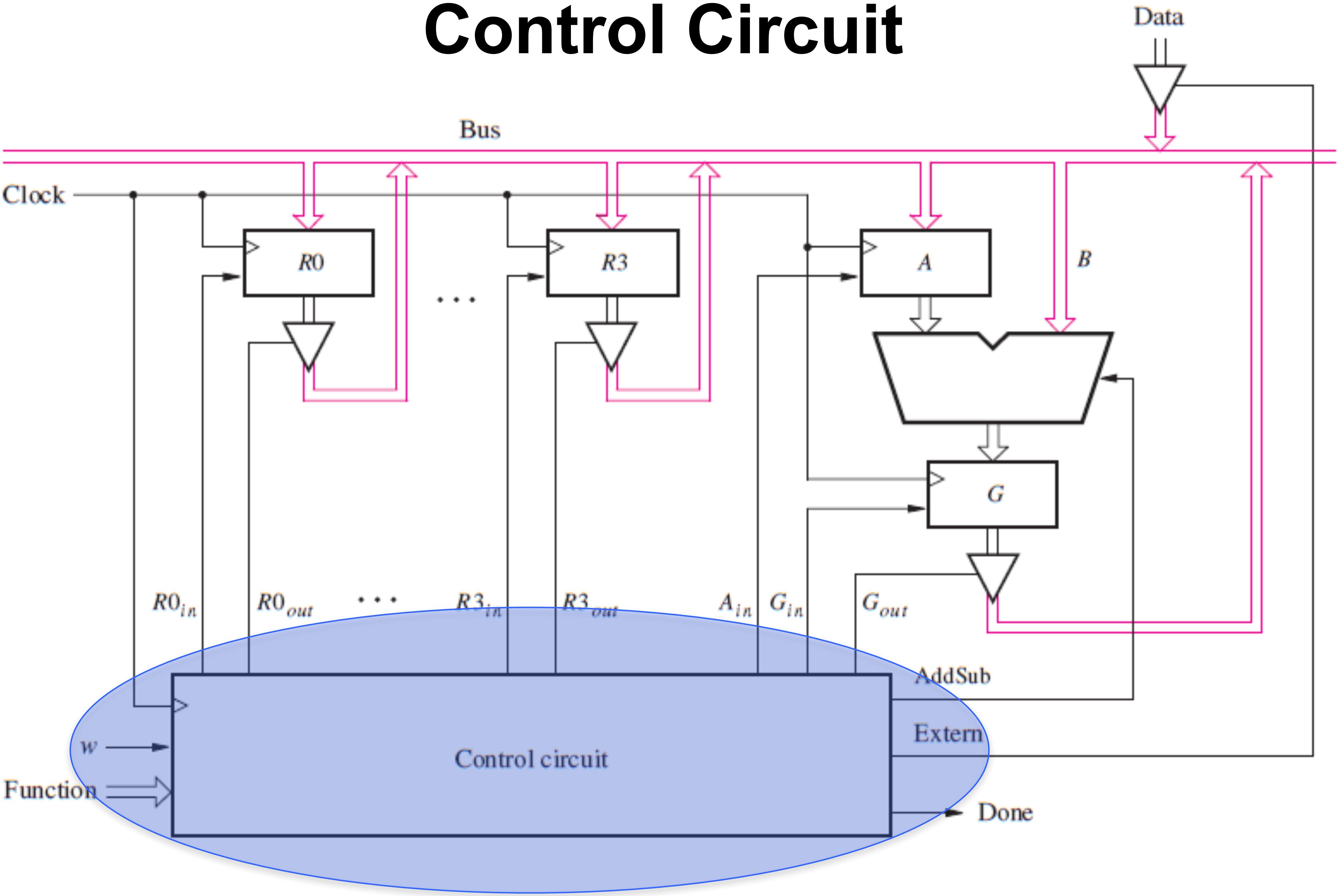
Subtraction: when control = 1



[Figure 3.12 from the textbook]

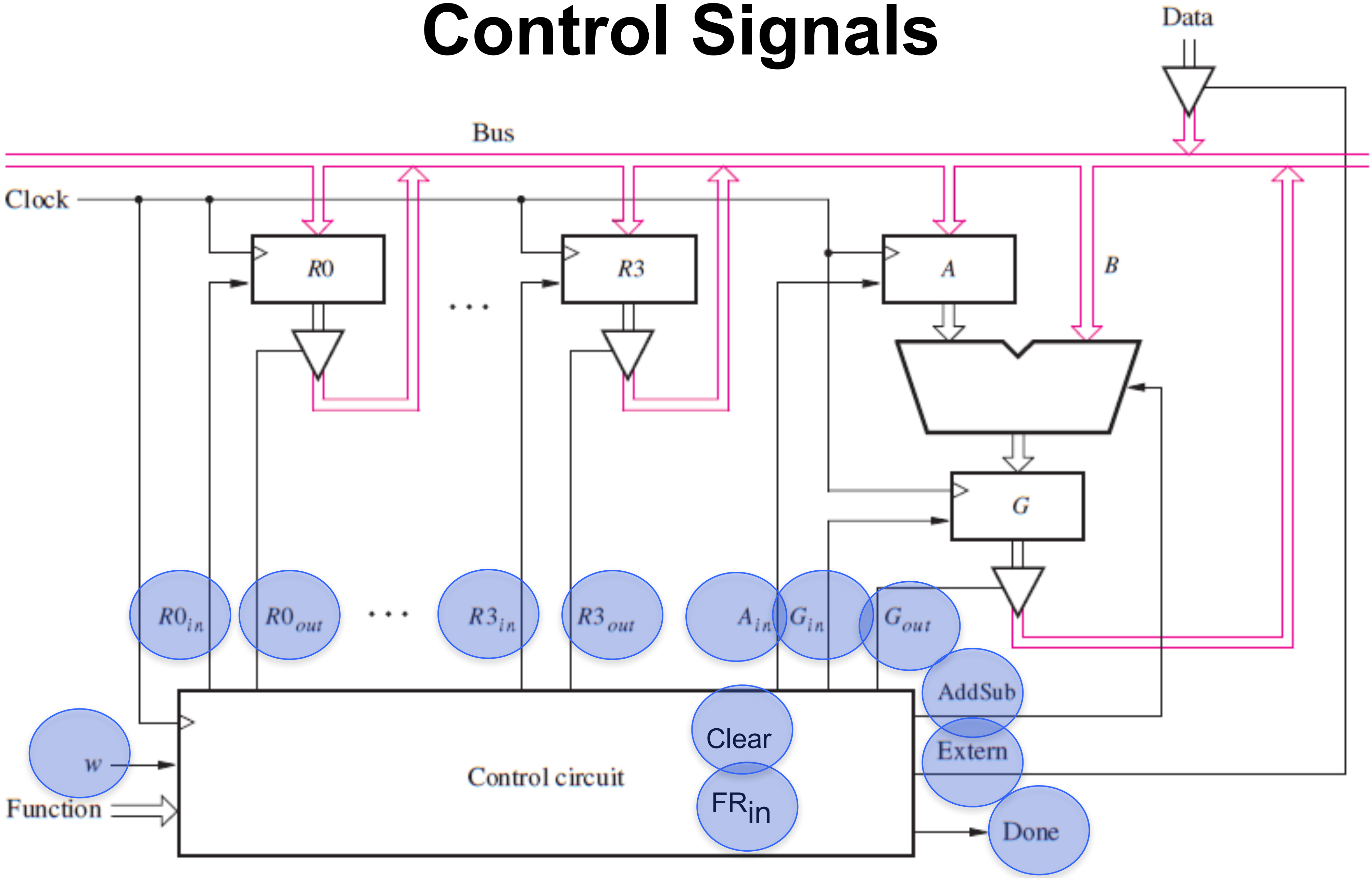
A Closer Look at the Control Circuit

Control Circuit



[Figure 7.9 from the textbook]

Control Signals



[Figure 7.9 from the textbook]

Design a FSM with input w and outputs

- $R0_{in}$
- $R0_{out}$
- $R1_{in}$
- $R1_{out}$
- $R2_{in}$
- $R2_{out}$
- $R3_{in}$
- $R3_{out}$
- A_{in}
- Gin
- G_{out}
- Clear
- FR_{in}
- AddSub
- Extern
- Done

Design a FSM with input w and outputs

- $R0_{in}$
- $R0_{out}$
- $R1_{in}$
- $R1_{out}$
- $R2_{in}$
- $R2_{out}$
- $R3_{in}$
- $R3_{out}$

- A_{in}
- Gin
- G_{out}
- Clear
- FR_{in}

- AddSub
- Extern
- Done

- T_0
- T_1
- T_2
- T_3

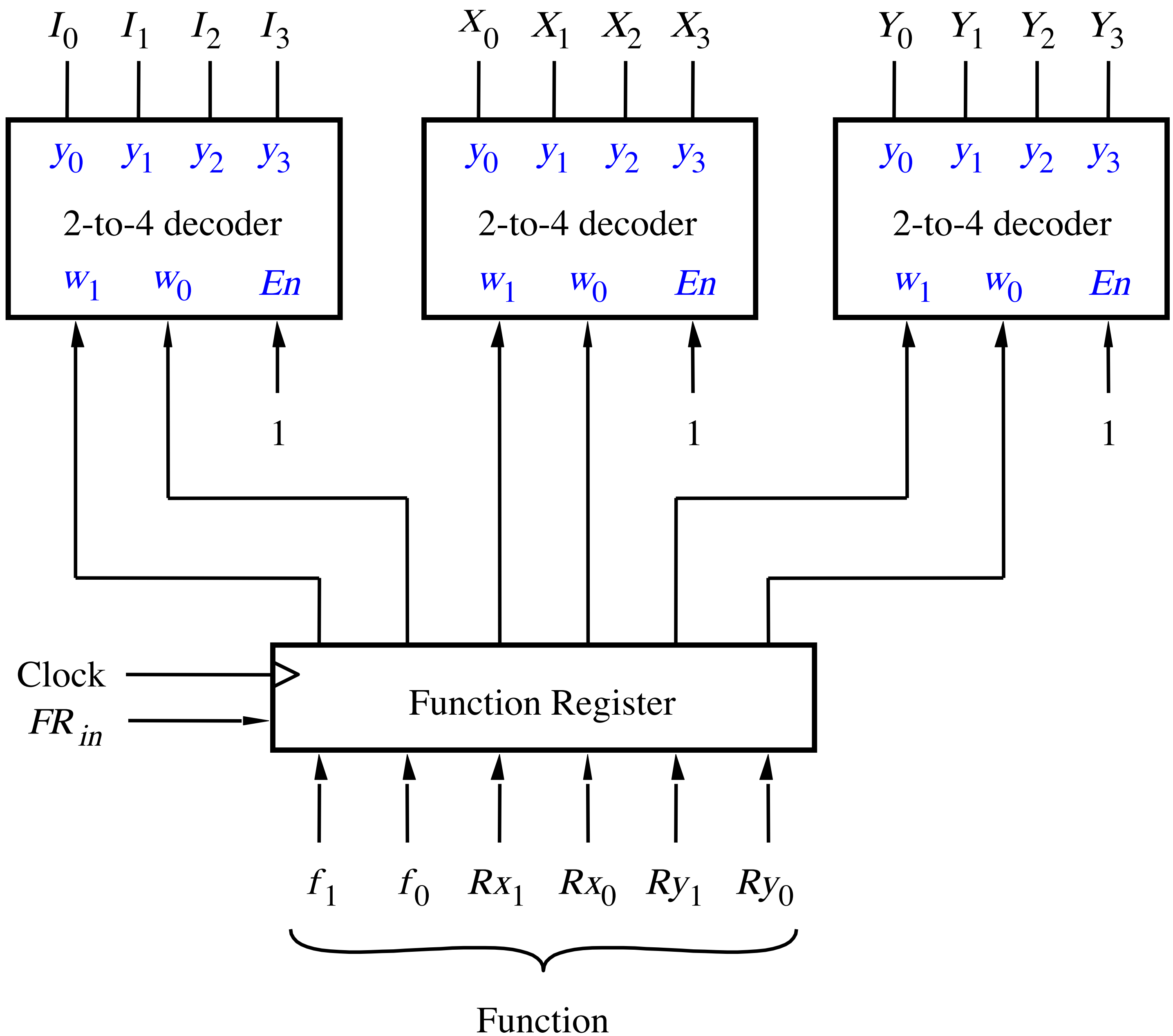
- I_0
- I_1
- I_2
- I_3

- X_0
- X_1
- X_2
- X_3

- Y_0
- Y_1
- Y_2
- Y_3

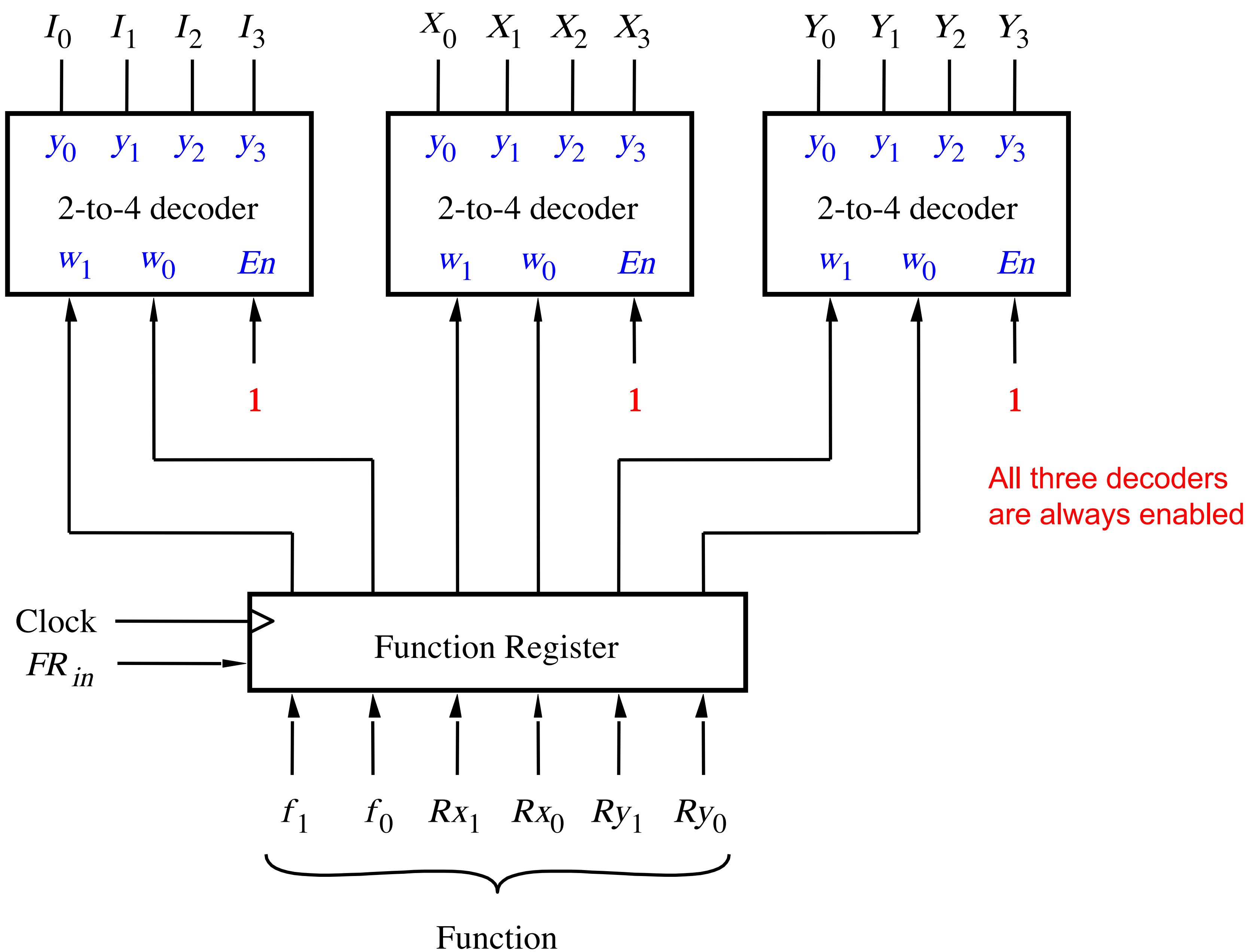
These are helper outputs that are one-hot encoded. They are used to simplify the expressions for the other outputs.

The function register and decoders



[Figure 7.11 from the textbook]

The function register and decoders



[Figure 7.11 from the textbook]

Operations performed by this processor

Operation	Function Performed
Load Rx, Data	Rx ← Data
Move Rx, Ry	Rx ← [Ry]
Add Rx, Ry	Rx ← [Rx] + [Ry]
Sub Rx, Ry	Rx ← [Rx] – [Ry]

[Table 7.1 from the textbook]

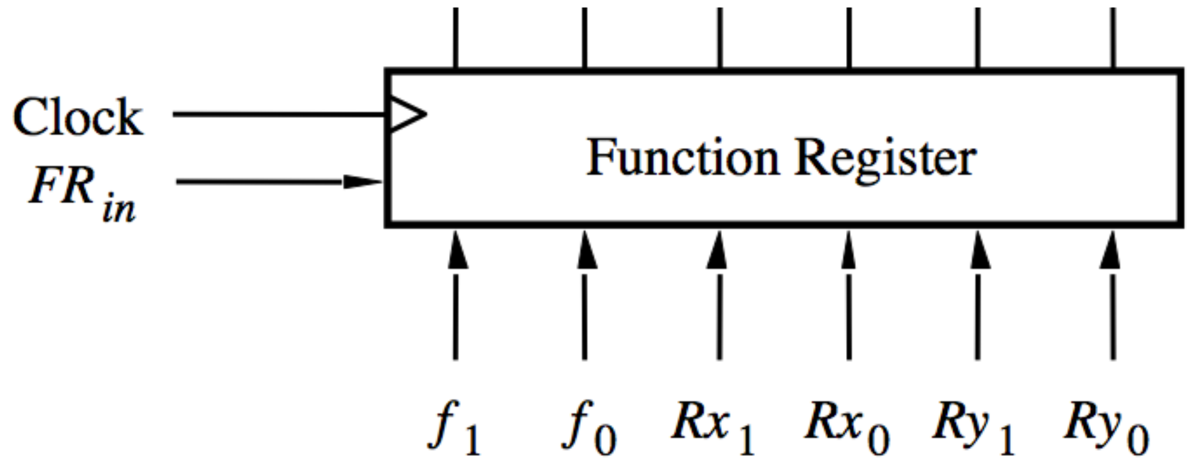
Operations performed by this processor

Operation	Function Performed
Load Rx, Data	Rx ← Data
Move Rx, Ry	Rx ← [Ry]
Add Rx, Ry	Rx ← [Rx] + [Ry]
Sub Rx, Ry	Rx ← [Rx] – [Ry]

Where Rx and Ry can be one of four possible options: R0, R1, R2, and R3

[Table 7.1 from the textbook]

Operations performed by this processor

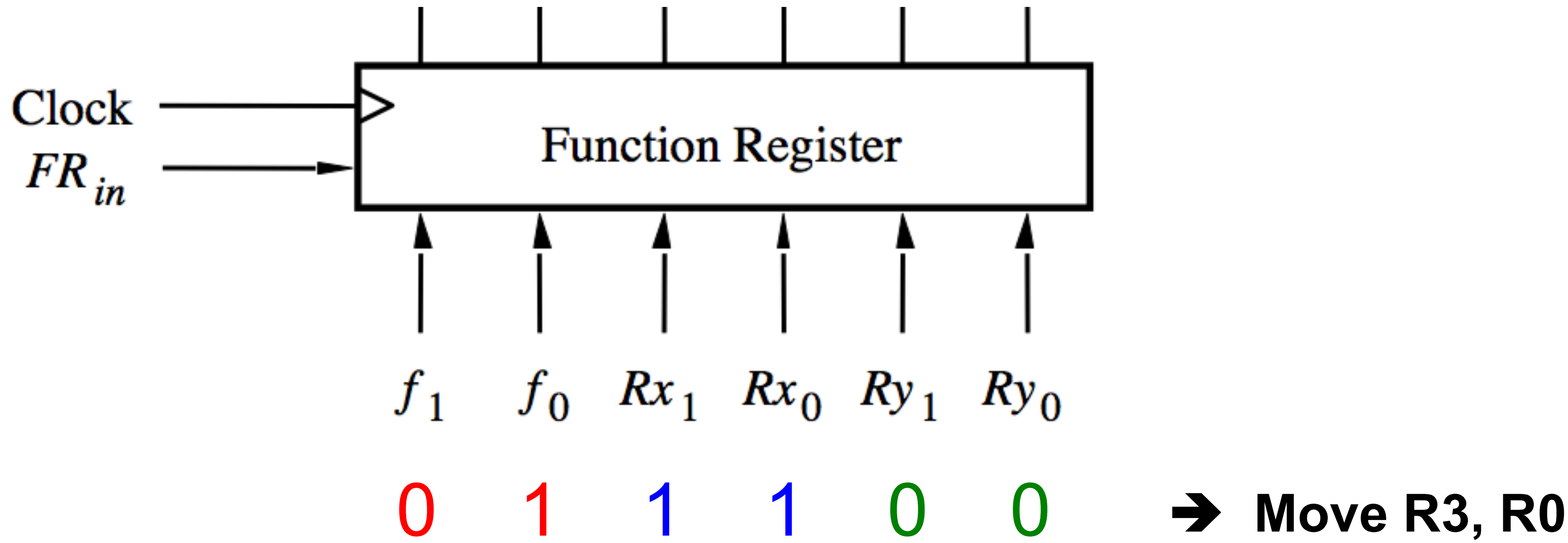


f_1	f_0	Function
0	0	Load
0	1	Move
1	0	Add
1	1	Sub

Rx_1	Rx_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Ry_1	Ry_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Operations performed by this processor

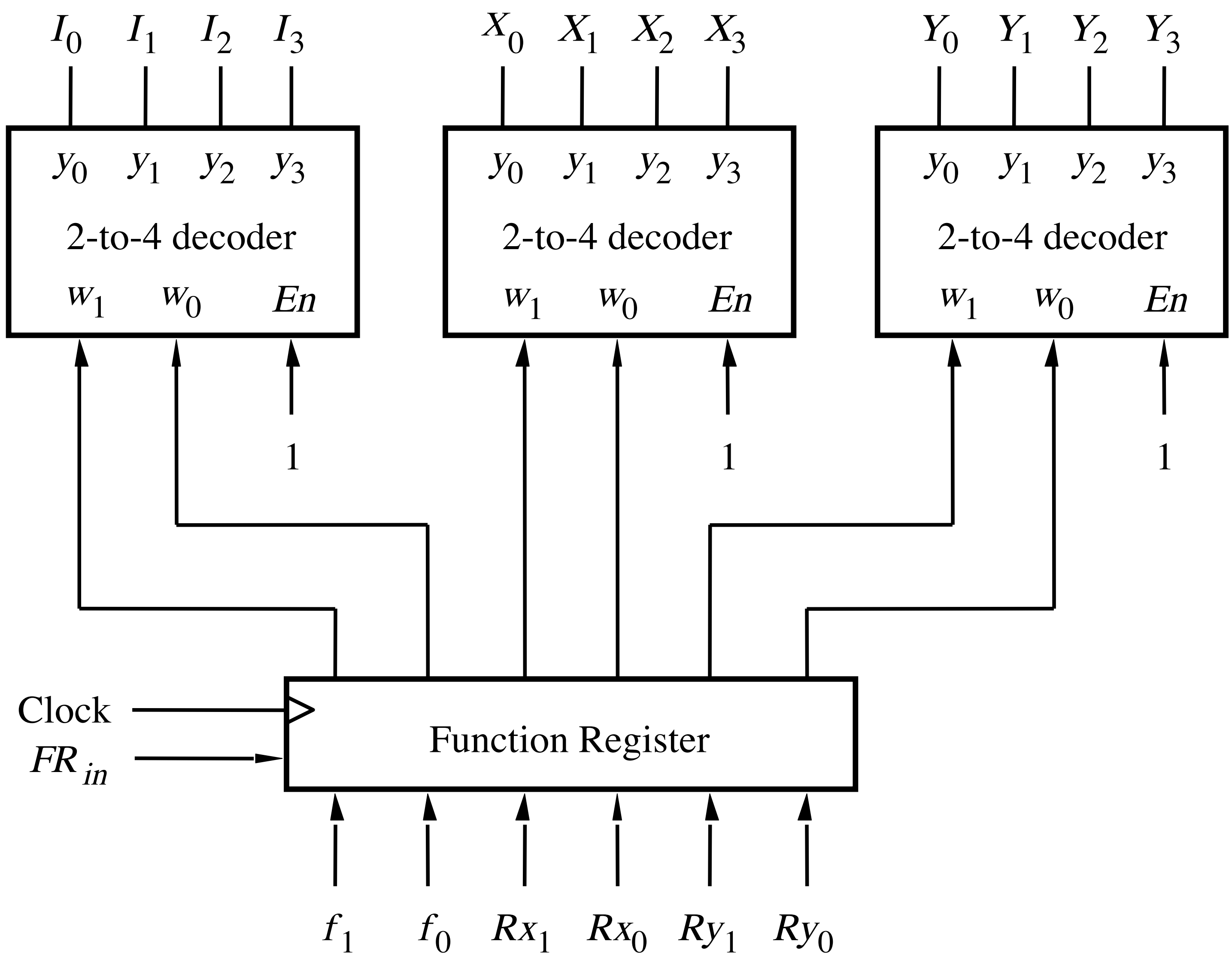


f_1	f_0	Function
0	0	Load
0	1	Move
1	0	Add
1	1	Sub

Rx_1	Rx_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

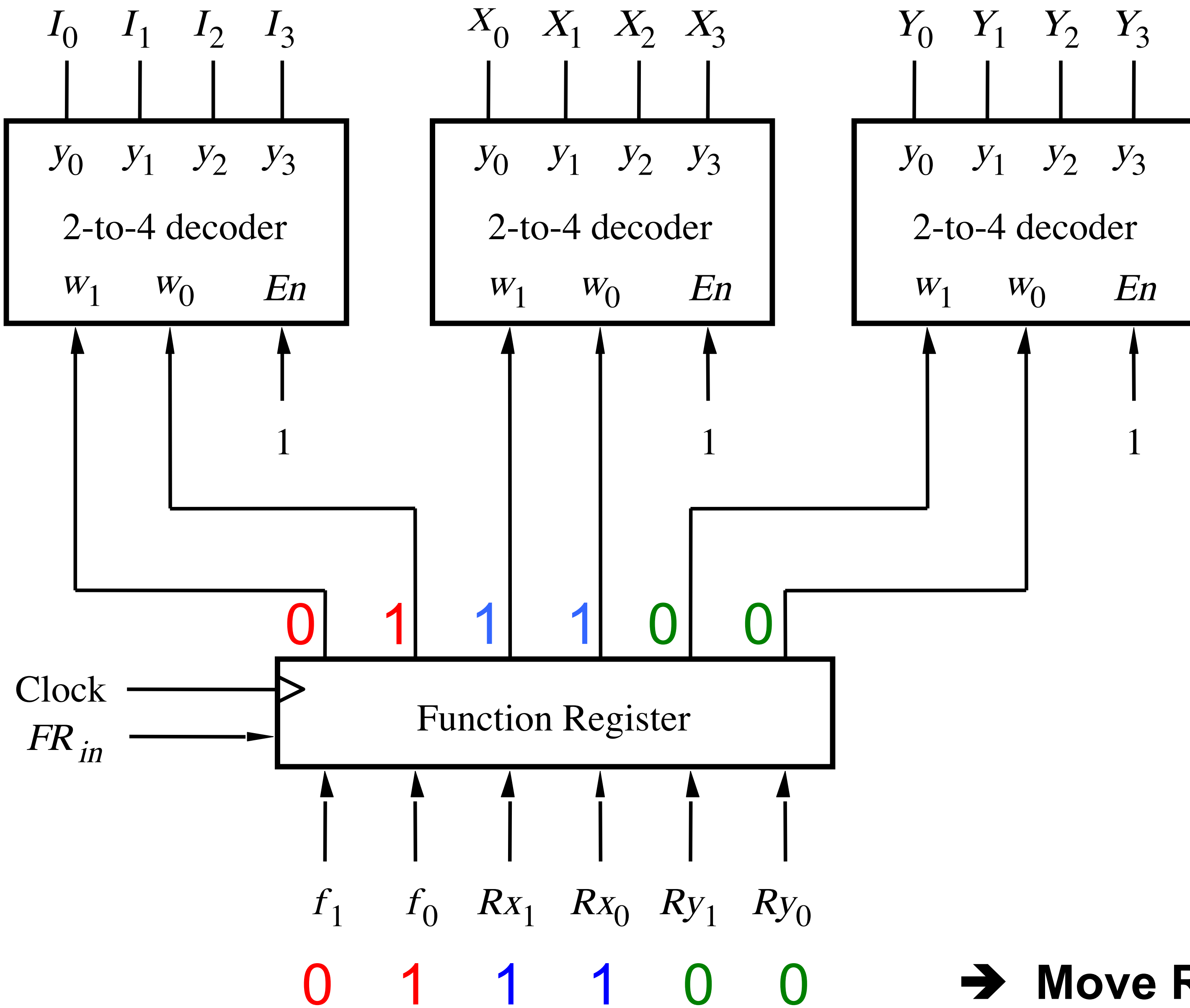
Ry_1	Ry_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

The function register and decoders



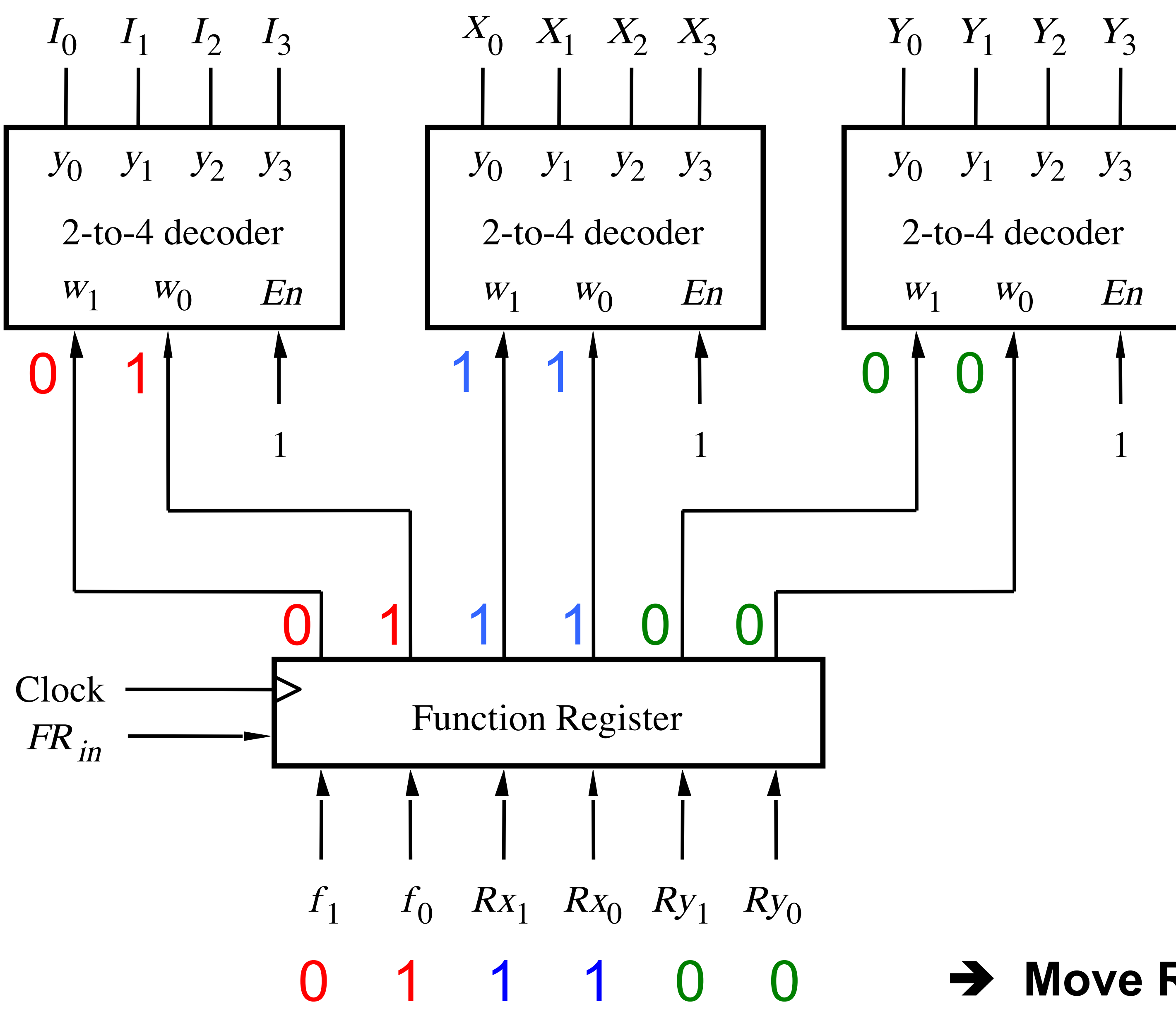
0 1 1 1 0 0 → **Move R3, R0**

The function register and decoders



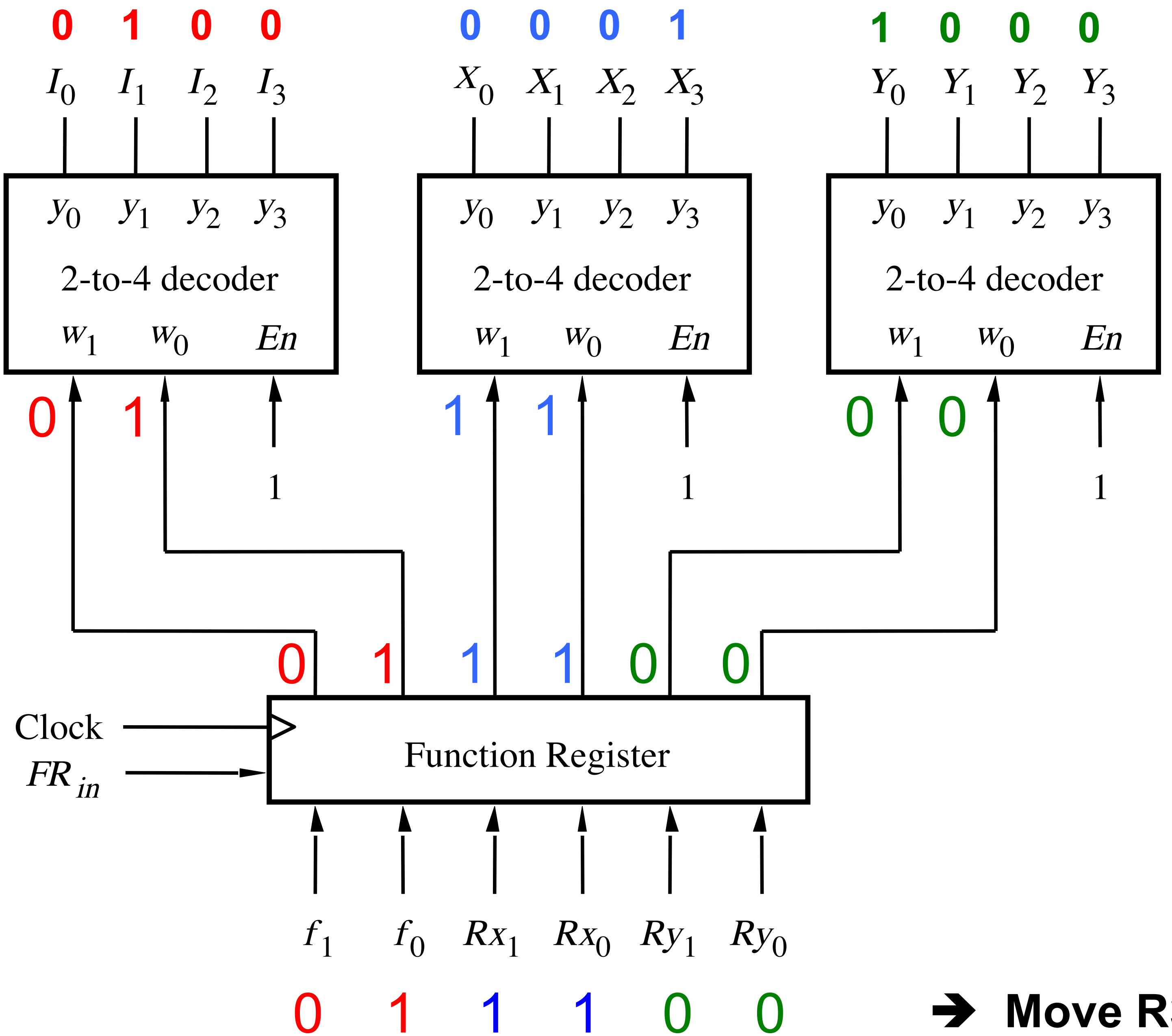
➔ **Move R3, R0**

The function register and decoders



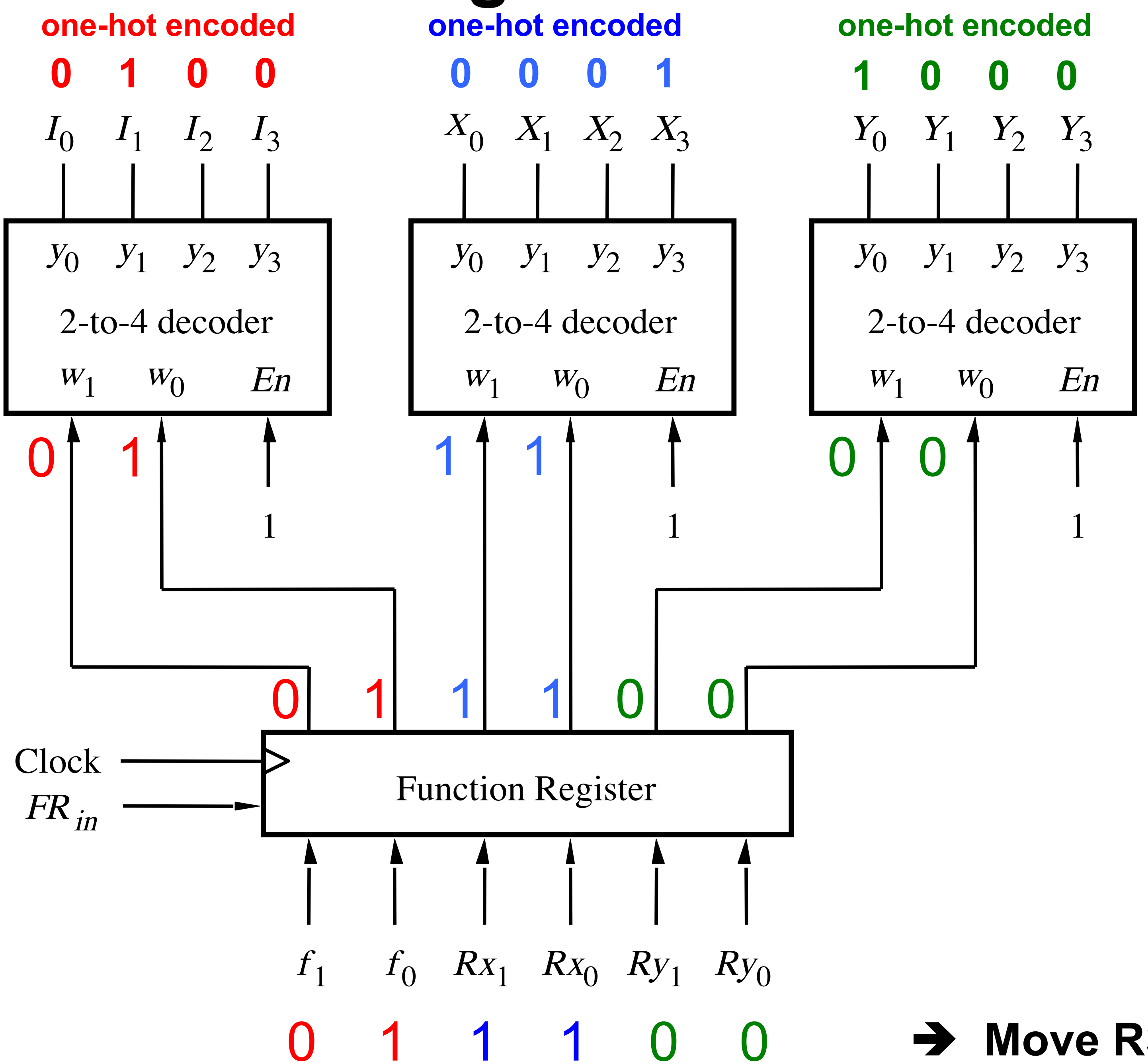
➔ **Move R3, R0**

The function register and decoders



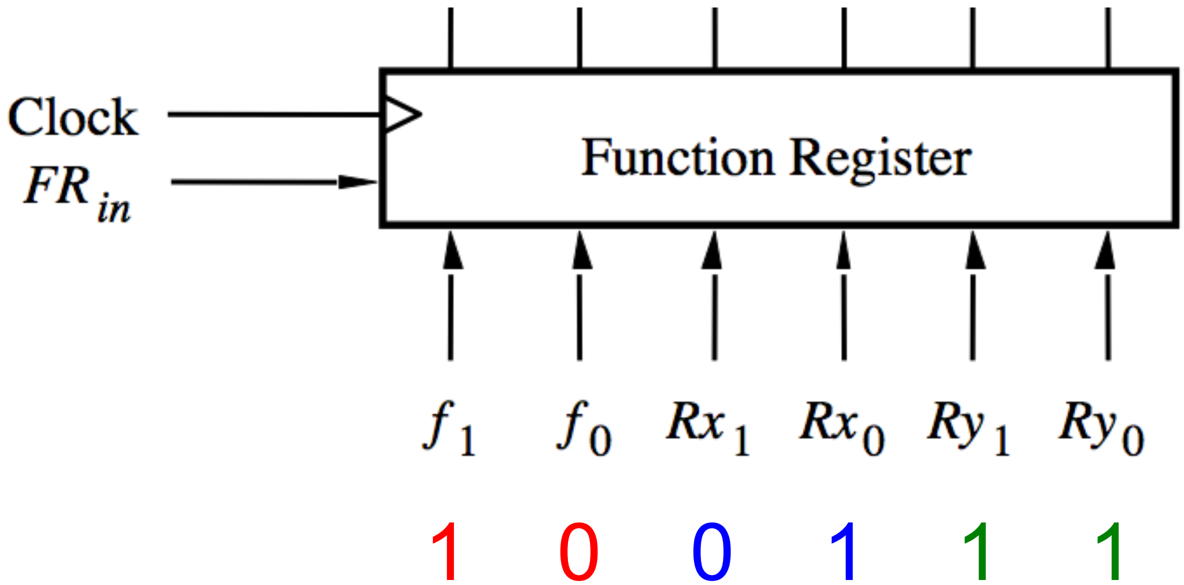
➔ **Move R3, R0**

The function register and decoders



➔ **Move R3, R0**

Operations performed by this processor



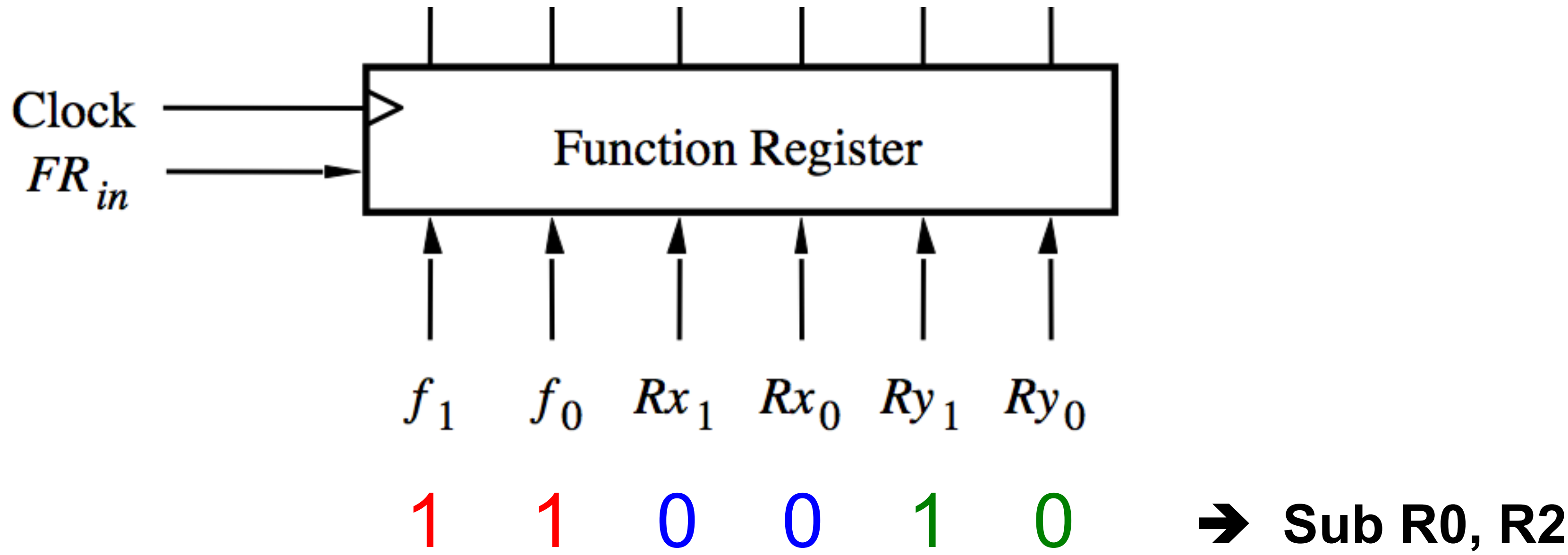
→ **Add R1, R3**

f_1	f_0	Function
0	0	Load
0	1	Move
1	0	Add
1	1	Sub

Rx_1	Rx_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Ry_1	Ry_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Operations performed by this processor

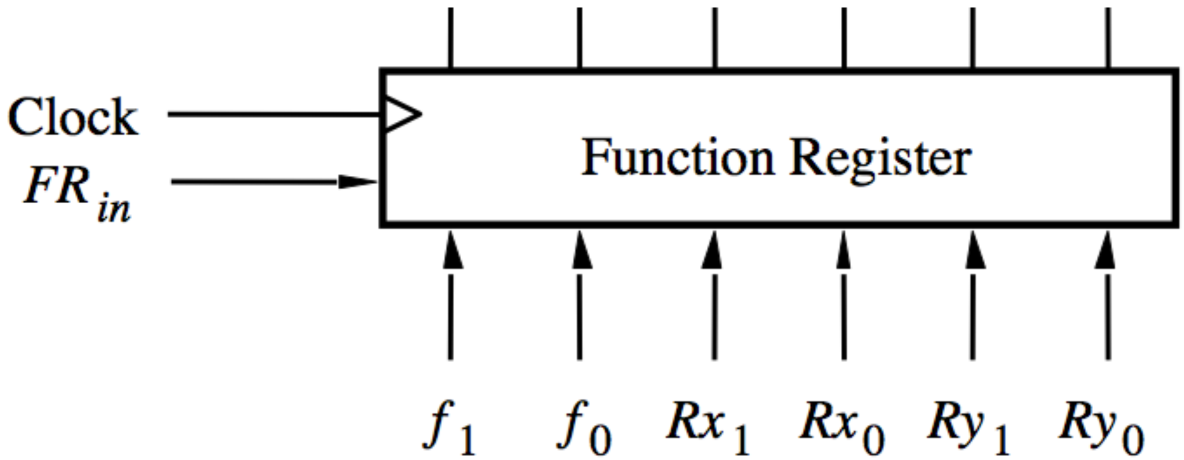


f_1	f_0	Function
0	0	Load
0	1	Move
1	0	Add
1	1	Sub

Rx_1	Rx_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Ry_1	Ry_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Operations performed by this processor



0 0 1 0 x x → **Load R2, Data**

f_1	f_0	Function
0	0	Load
0	1	Move
1	0	Add
1	1	Sub

Rx_1	Rx_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Ry_1	Ry_0	Register
0	0	R0
0	1	R1
1	0	R2
1	1	R3

Similar Encoding is Used by Modern Chips

MIPS32 Add Immediate Instruction

001000	00001	00010	0000000101011110
OP Code	Addr 1	Addr 2	Immediate value

Equivalent mnemonic: addi $r1 , $r2 , 350

[http://en.wikipedia.org/wiki/Instruction_set]

Sample Assembly Language Program For This Processor

```
Move  R3, R0
Add   R1, R3
Sub   R0, R2
Load  R2, Data
```

Machine Language vs Assembly Language

Machine Language	Assembly Language	Meaning / Interpretation
011100	Move R3, R0	R3 ← [R0]
100111	Add R1, R3	R1 ← [R1] + [R3]
110010	Sub R0, R2	R0 ← [R0] – [R2]
001000	Load R2, Data	R2 ← Data

Machine Language vs Assembly Language

Machine Language	Assembly Language	Meaning / Interpretation
011100	Move R3, R0	R3 ← [R0]
100111	Add R1, R3	R1 ← [R1] + [R3]
110010	Sub R0, R2	R0 ← [R0] – [R2]
001000	Load R2, Data	R2 ← Data

Machine Language vs Assembly Language

Machine Language	Assembly Language	Meaning / Interpretation
011100	Move R3, R0	R3 ← [R0]
100111	Add R1, R3	R1 ← [R1] + [R3]
110010	Sub R0, R2	R0 ← [R0] – [R2]
001000	Load R2, Data	R2 ← Data

For short, each line can be expressed as a hexadecimal number

Machine Language vs Assembly Language

Machine Language	Assembly Language	Meaning / Interpretation
1C	Move R3, R0	R3 ← [R0]
27	Add R1, R3	R1 ← [R1] + [R3]
32	Sub R0, R2	R0 ← [R0] – [R2]
08	Load R2, Data	R2 ← Data

Intel 8086

```
; _memcpy(dst, src, len)
; Copy a block of memory from one location to another.
;
; Entry stack parameters
;       [BP+6] = len, Number of bytes to copy
;       [BP+4] = src, Address of source data block
;       [BP+2] = dst, Address of target data block
;
; Return registers
;       AX = Zero

0000:1000                      org     1000h        ; Start at 0000:1000h

0000:1000           _memcpy    proc
0000:1000 55                   push    bp           ; Set up the call frame
0000:1001 89 E5                mov     bp,sp
0000:1003 06                   push    es           ; Save ES
0000:1004 8B 4E 06             mov     cx,[bp+6]    ; Set CX = len
0000:1007 E3 11                jcxz    done         ; If len=0, return
0000:1009 8B 76 04             mov     si,[bp+4]    ; Set SI = src
0000:100C 8B 7E 02             mov     di,[bp+2]    ; Set DI = dst
0000:100F 1E                   push    ds           ; Set ES = DS
0000:1010 07                   pop     es

0000:1011 8A 04     loop       mov     al,[si]      ; Load AL from [src]
0000:1013 88 05                mov     [di],al      ; Store AL to [dst]
0000:1015 46                   inc     si           ; Increment src
0000:1016 47                   inc     di           ; Increment dst
0000:1017 49                   dec     cx           ; Decrement len
0000:1018 75 F7                jnz     loop         ; Repeat the loop

0000:101A 07        done       pop     es           ; Restore ES
0000:101B 5D                   pop     bp           ; Restore previous call frame
0000:101C 29 C0                sub     ax,ax        ; Set AX = 0
0000:101E C3                   ret                  ; Return
0000:101F                      end proc
```

[http://en.wikipedia.org/wiki/Intel_8086]

Intel 8086

Memory Address

```
                                        ; _memcpy(dst, src, len)
                                        ; Copy a block of memory from one location to another.
                                        ;
                                        ; Entry stack parameters
                                        ;       [BP+6] = len, Number of bytes to copy
                                        ;       [BP+4] = src, Address of source data block
                                        ;       [BP+2] = dst, Address of target data block
                                        ;
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                                        ;       AX = Zero

0000:1000                                           org     1000h       ; Start at 0000:1000h

0000:1000                           _memcpy         proc
0000:1000  55                                       push    bp          ; Set up the call frame
0000:1001  89 E5                                    mov     bp,sp
0000:1003  06                                       push    es          ; Save ES
0000:1004  8B 4E 06                                 mov     cx,[bp+6]   ; Set CX = len
0000:1007  E3 11                                    jcxz    done        ; If len=0, return
0000:1009  8B 76 04                                 mov     si,[bp+4]   ; Set SI = src
0000:100C  8B 7E 02                                 mov     di,[bp+2]   ; Set DI = dst
0000:100F  1E                                       push    ds          ; Set ES = DS
0000:1010  07                                       pop     es

0000:1011  8A 04                    loop            mov     al,[si]     ; Load AL from [src]
0000:1013  88 05                                    mov     [di],al     ; Store AL to [dst]
0000:1015  46                                       inc     si          ; Increment src
0000:1016  47                                       inc     di          ; Increment dst
0000:1017  49                                       dec     cx          ; Decrement len
0000:1018  75 F7                                    jnz     loop        ; Repeat the loop

0000:101A  07                       done            pop     es          ; Restore ES
0000:101B  5D                                       pop     bp          ; Restore previous call frame
0000:101C  29 C0                                    sub     ax,ax       ; Set AX = 0
0000:101E  C3                                       ret                 ; Return
0000:101F                                           end proc
```

[http://en.wikipedia.org/wiki/Intel_8086]

Intel 8086

Machine Language

```
                          ; _memcpy(dst, src, len)
                          ; Copy a block of memory from one location to another.
                          ;
                          ; Entry stack parameters
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                          ;
                          ; Return registers
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0000:1000                 _memcpy   proc
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0000:1009  8B 76 04                 mov     si,[bp+4]     ; Set SI = src
0000:100C  8B 7E 02                 mov     di,[bp+2]     ; Set DI = dst
0000:100F  1E                       push    ds            ; Set ES = DS
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0000:1011  8A 04          loop      mov     al,[si]       ; Load AL from [src]
0000:1013  88 05                    mov     [di],al       ; Store AL to [dst]
0000:1015  46                       inc     si            ; Increment src
0000:1016  47                       inc     di            ; Increment dst
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0000:101A  07             done      pop     es            ; Restore ES
0000:101B  5D                       pop     bp            ; Restore previous call frame
0000:101C  29 C0                    sub     ax,ax         ; Set AX = 0
0000:101E  C3                       ret                   ; Return
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; Return registers
;       AX = Zero
```

Assembly Language

```
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0000:1000 55                       push    bp          ; Set up the call frame
0000:1001 89 E5                    mov     bp,sp
0000:1003 06                       push    es          ; Save ES
0000:1004 8B 4E 06                 mov     cx,[bp+6]   ; Set CX = len
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0000:1009 8B 76 04                 mov     si,[bp+4]   ; Set SI = src
0000:100C 8B 7E 02                 mov     di,[bp+2]   ; Set DI = dst
0000:100F 1E                       push    ds          ; Set ES = DS
0000:1010 07                       pop     es

0000:1011 8A 04      loop          mov     al,[si]     ; Load AL from [src]
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0000:1018 75 F7                    jnz     loop        ; Repeat the loop

0000:101A 07         done          pop     es          ; Restore ES
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0000:101E C3                       ret                 ; Return
0000:101F                          end proc
```

[http://en.wikipedia.org/wiki/Intel_8086]

Intel 8086

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0000:1009 8B 76 04           mov     si,[bp+4]    ; Set SI = src
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0000:100F 1E                 push    ds           ; Set ES = DS
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0000:1018 75 F7              jnz     loop         ; Repeat the loop

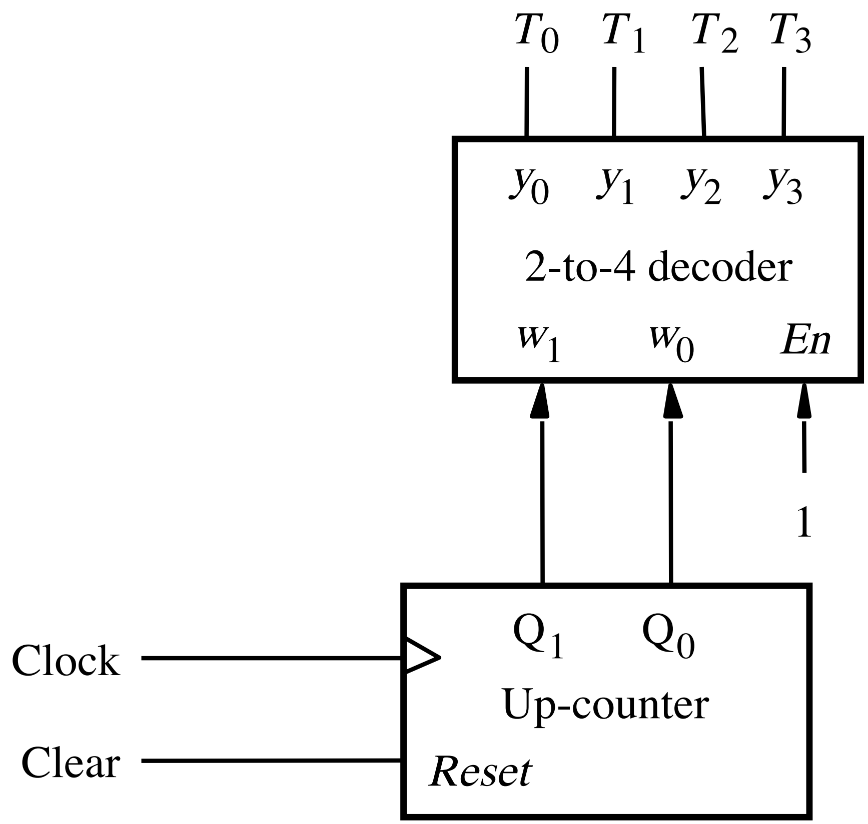
0000:101A 07        done     pop     es           ; Restore ES
0000:101B 5D                 pop     bp           ; Restore previous call frame
0000:101C 29 C0              sub     ax,ax        ; Set AX = 0
0000:101E C3                 ret                  ; Return
0000:101F                    end proc
```

Comments

[http://en.wikipedia.org/wiki/Intel_8086]

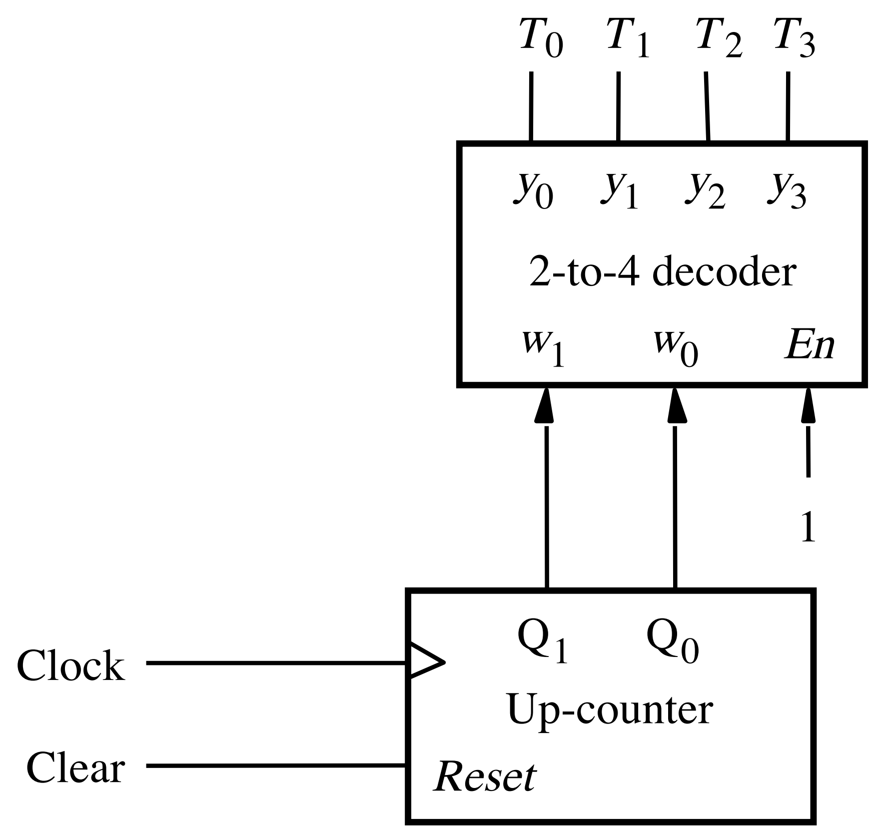
Another Part of The Control Circuit

A part of the control circuit for the processor



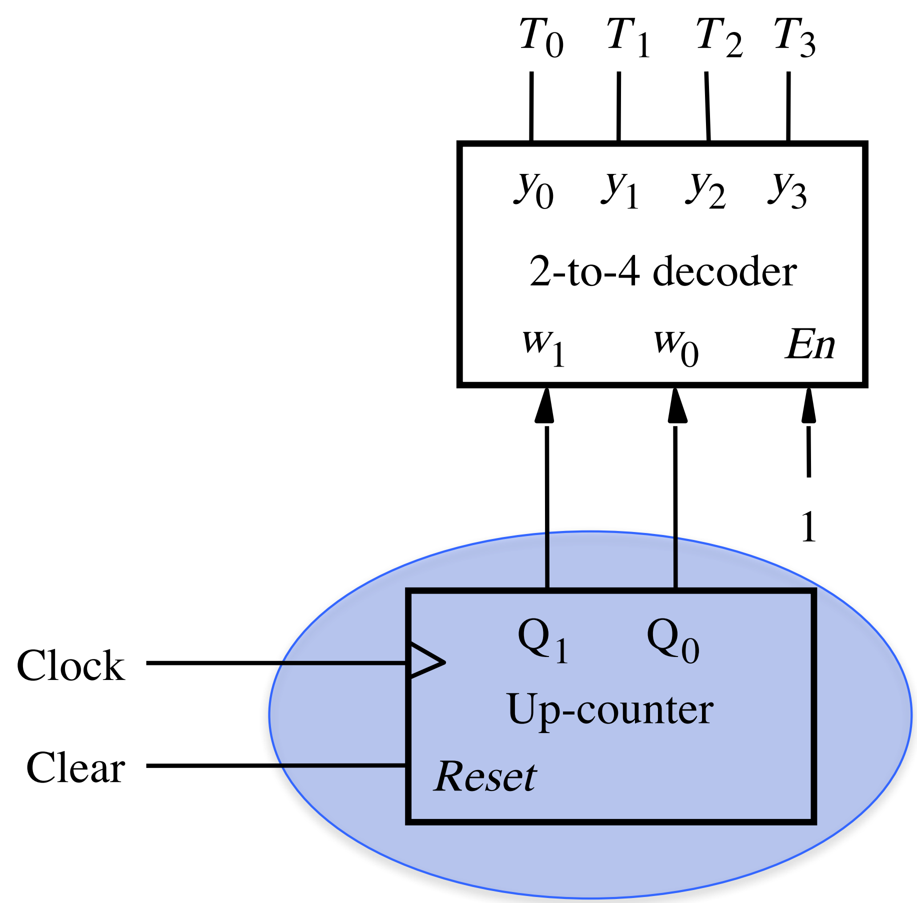
[Figure 7.10 from the textbook]

What are the components?



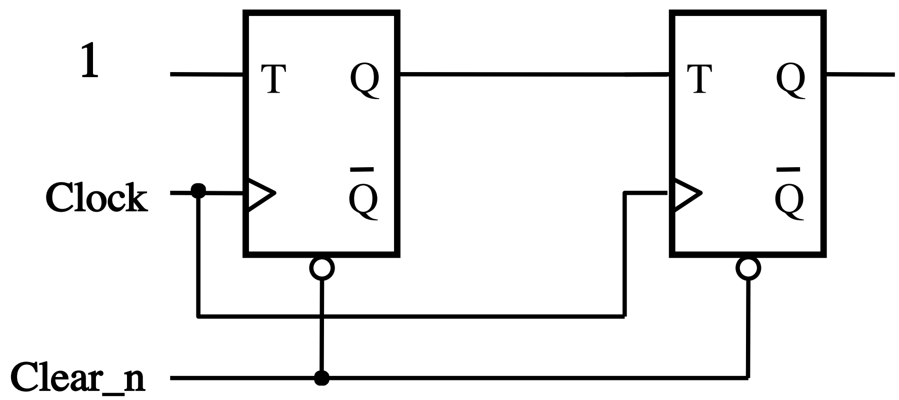
[Figure 7.10 from the textbook]

2-Bit Up-Counter

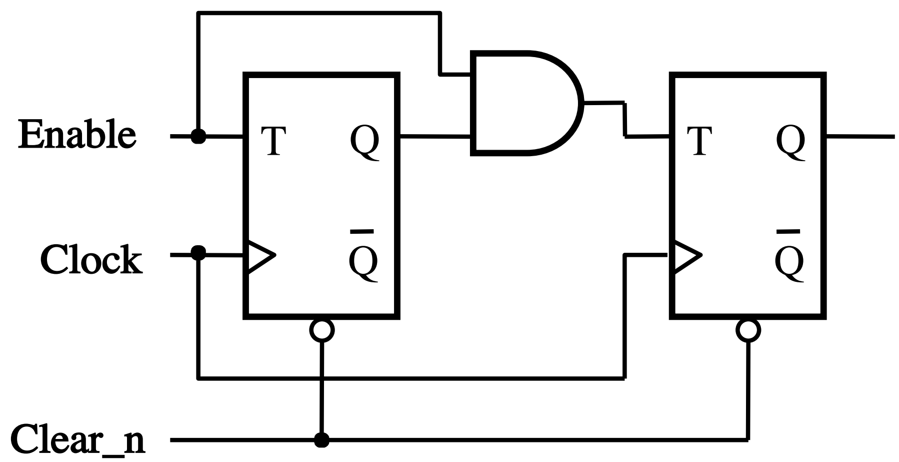


[Figure 7.10 from the textbook]

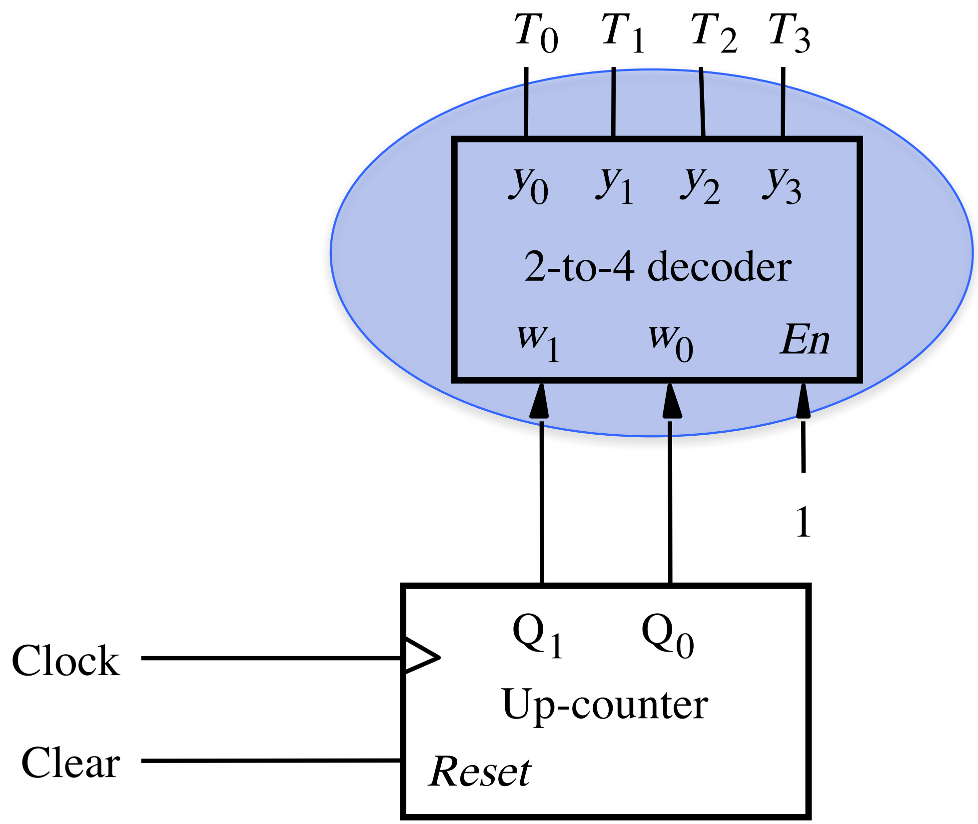
2-bit Synchronous Up-Counter



2-bit Synchronous Up-Counter with Enable

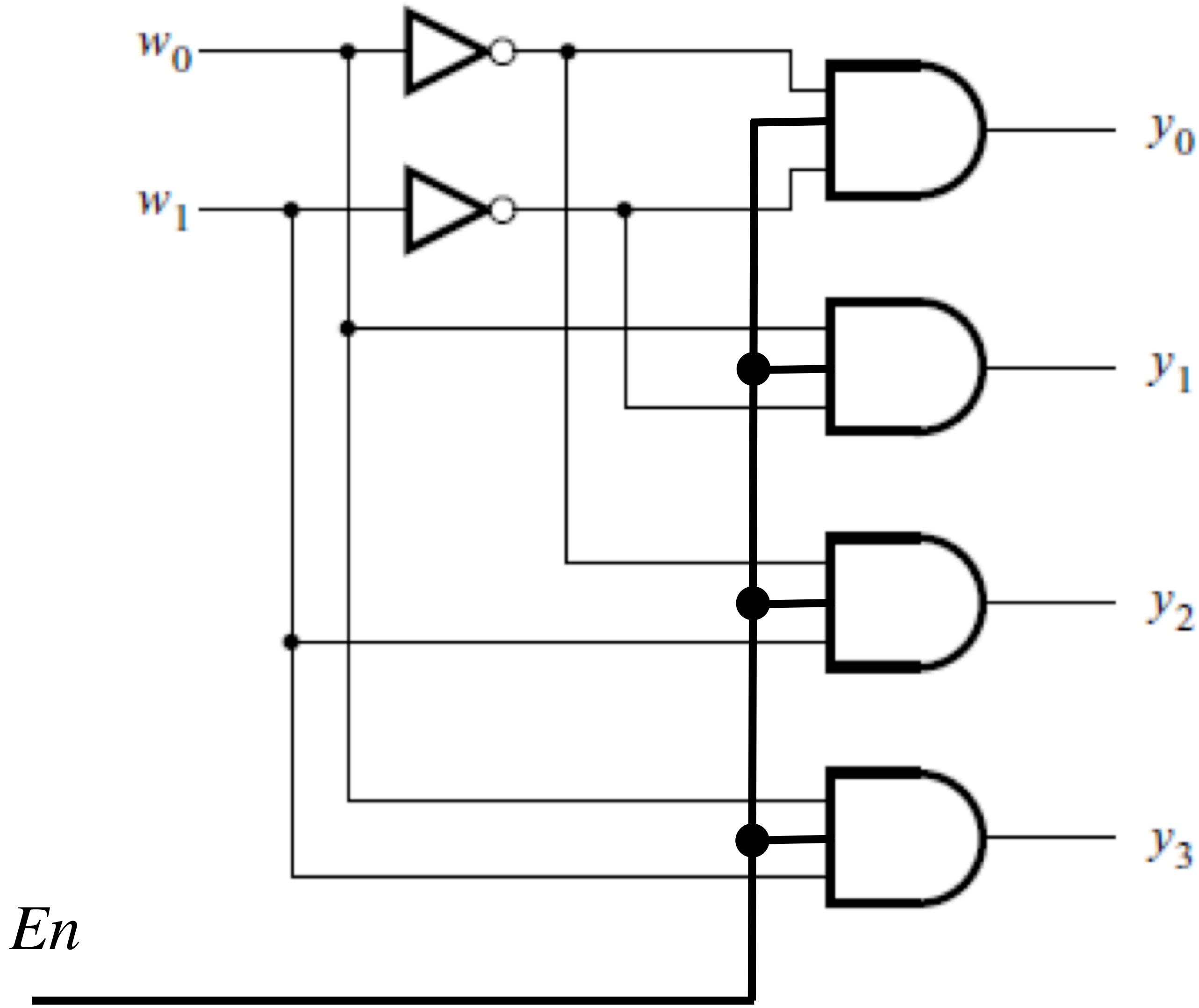


2-to-4 Decoder with Enable Input



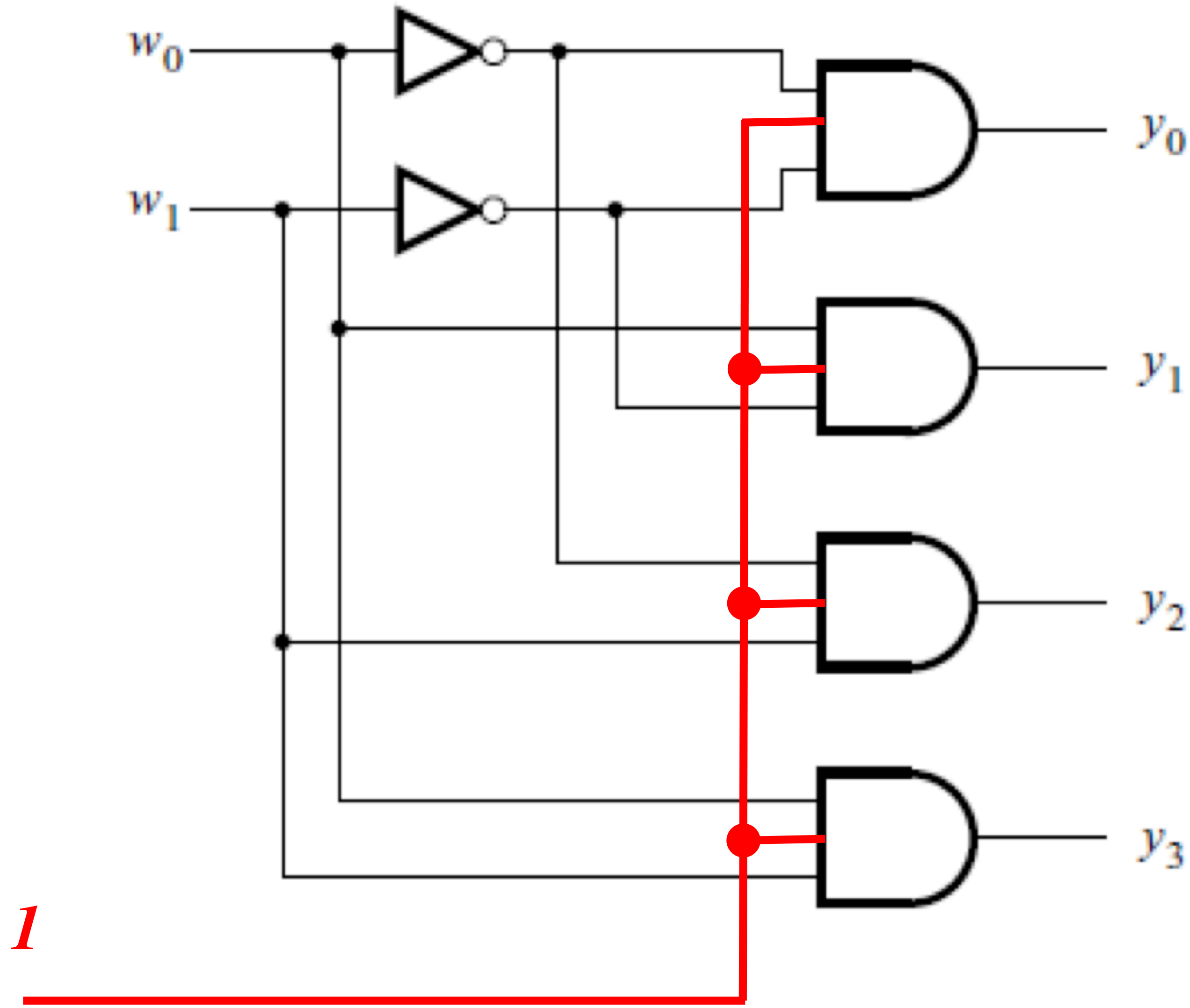
[Figure 7.10 from the textbook]

2-to-4 Decoder with an Enable Input



[Figure 4.13c from the textbook]

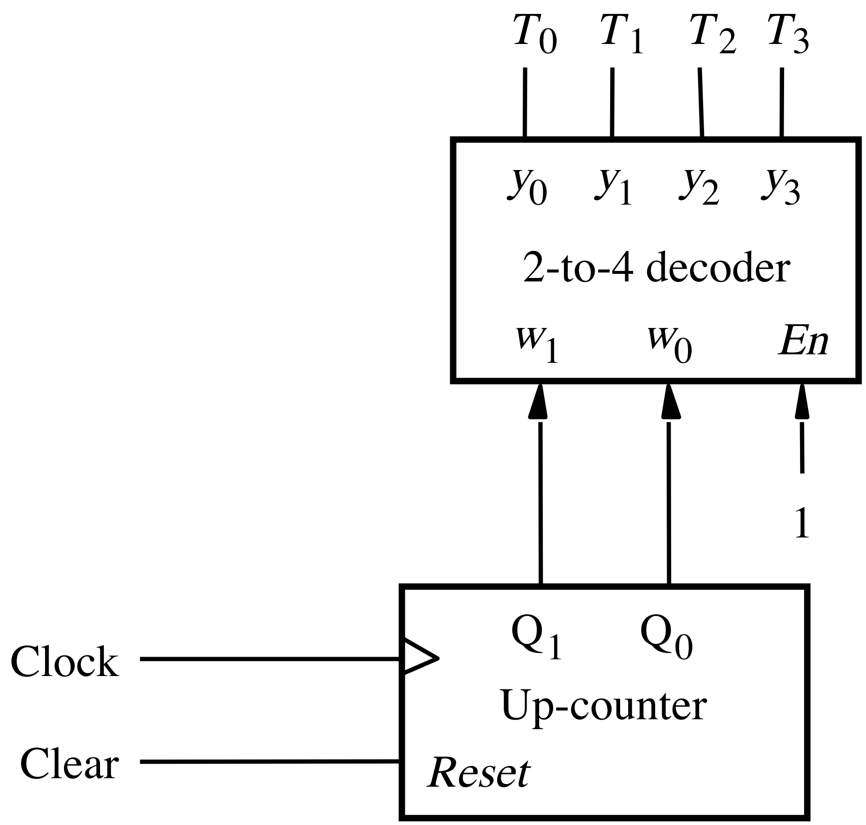
2-to-4 Decoder with an Enable Input



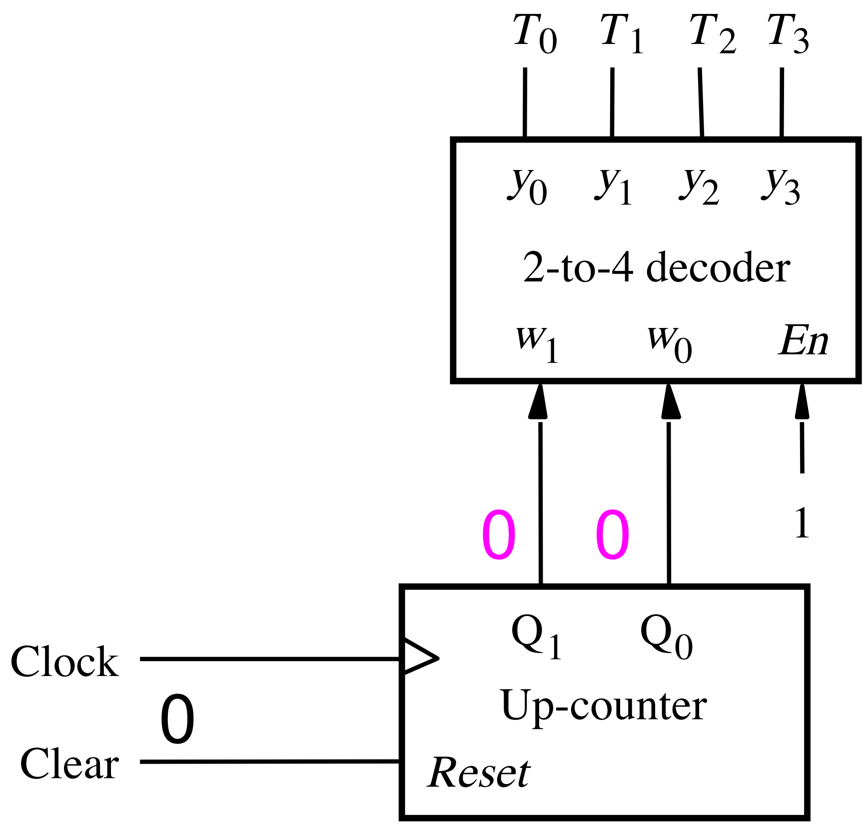
(always enabled in this example)

[Figure 4.13c from the textbook]

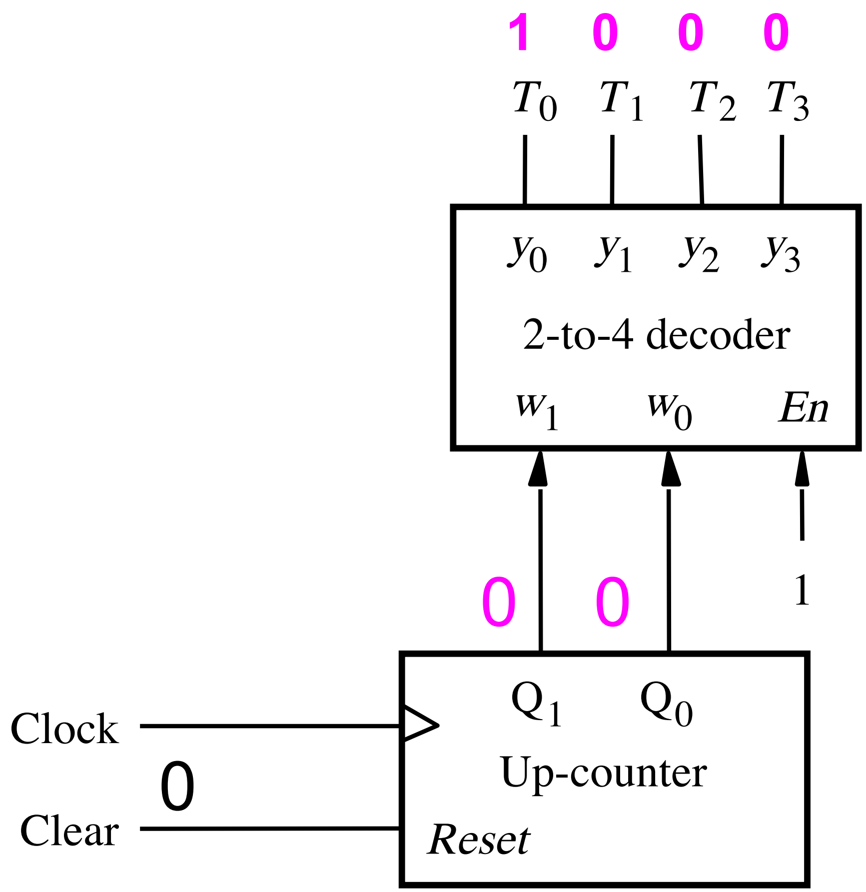
So How Does This Work?



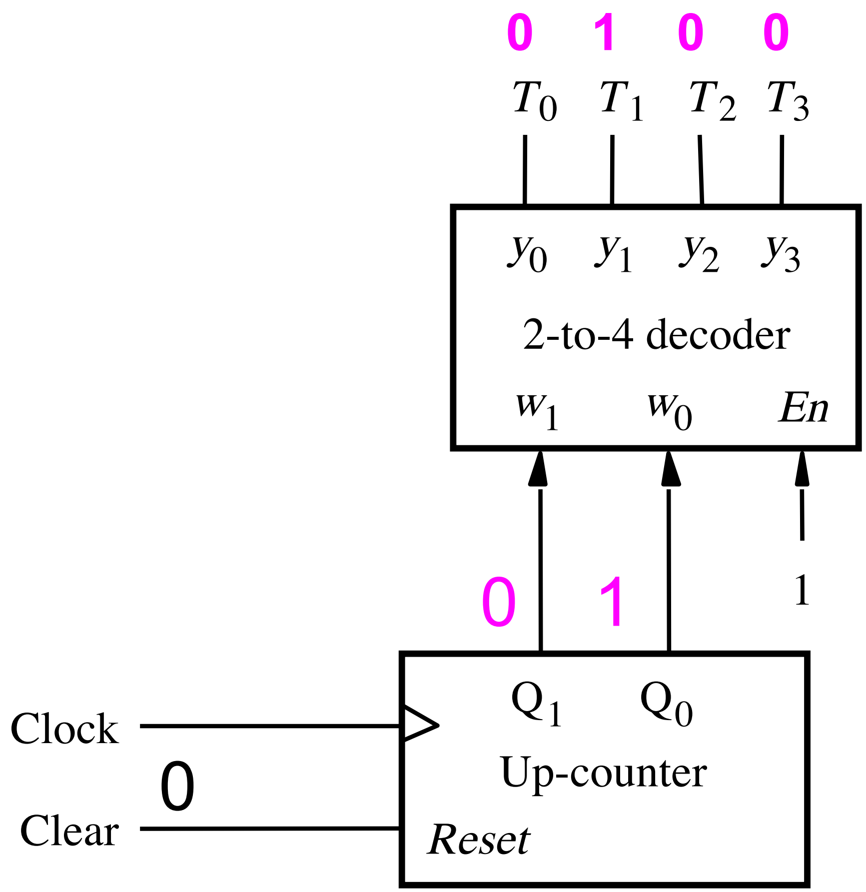
So How Does This Work?



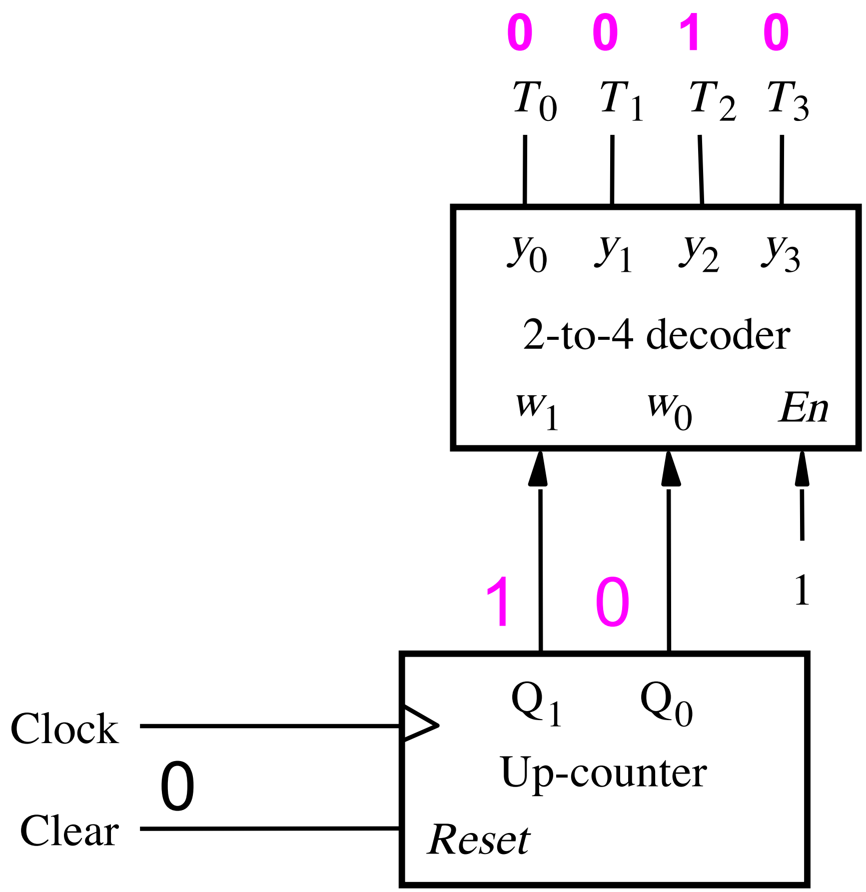
So How Does This Work?



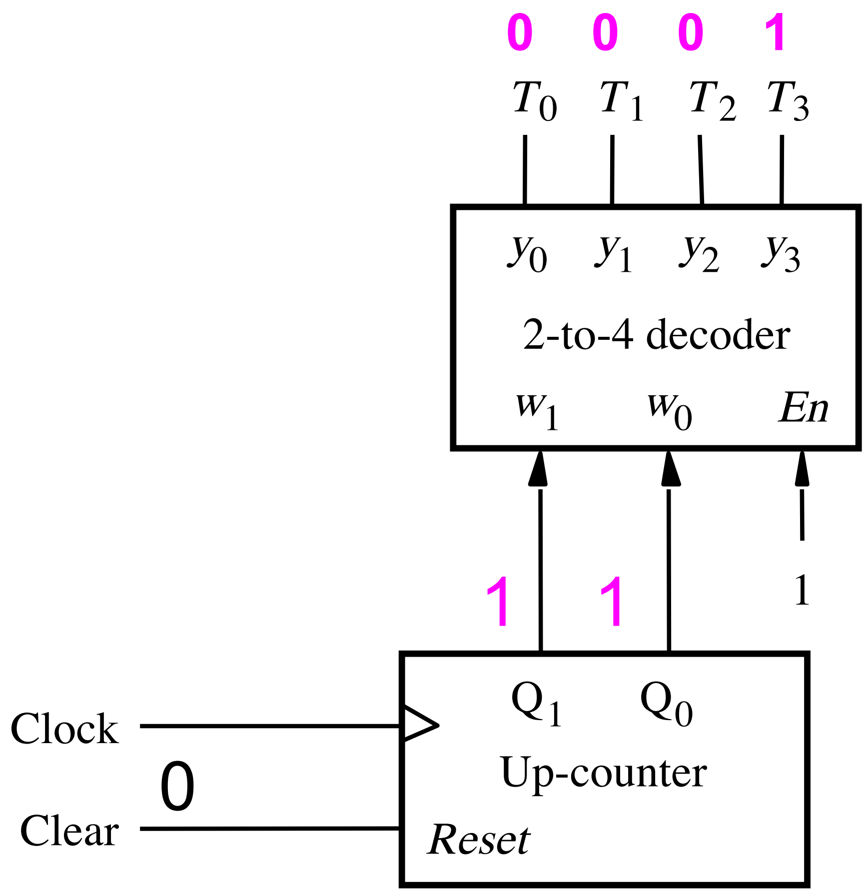
So How Does This Work?



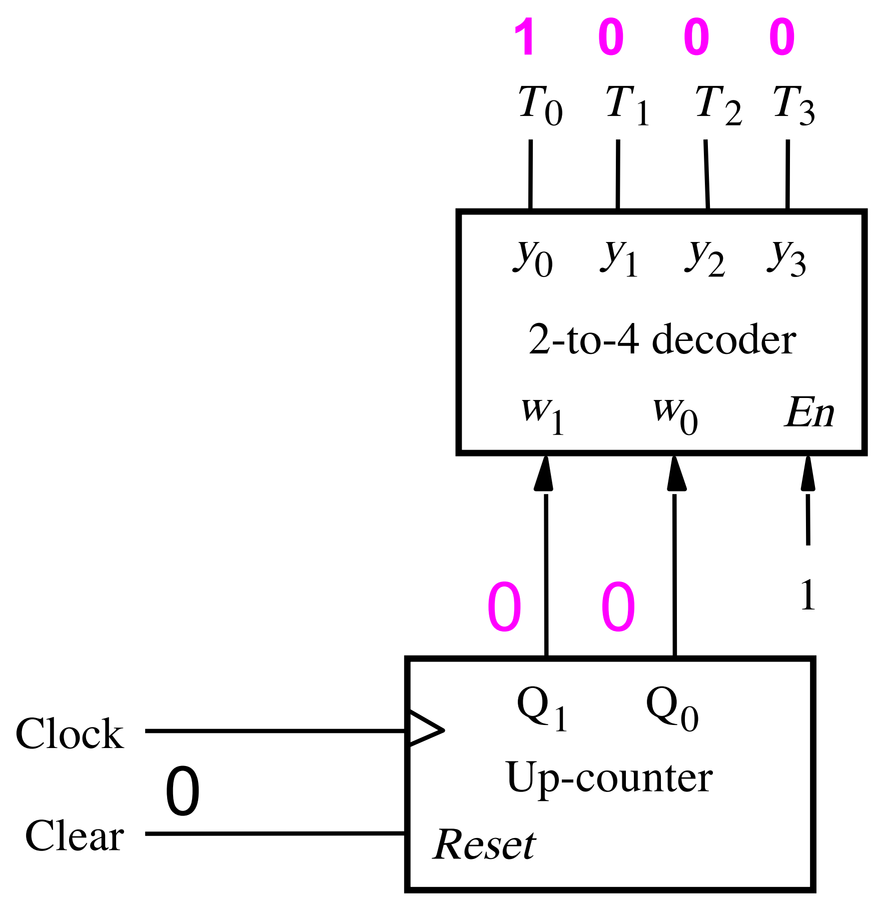
So How Does This Work?



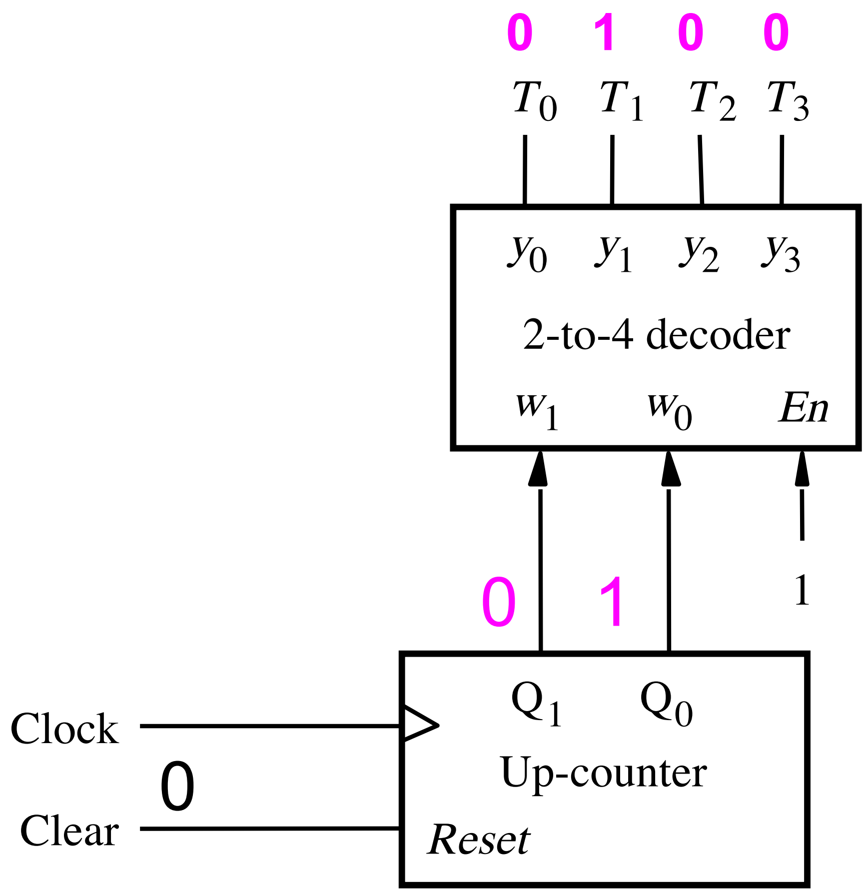
So How Does This Work?



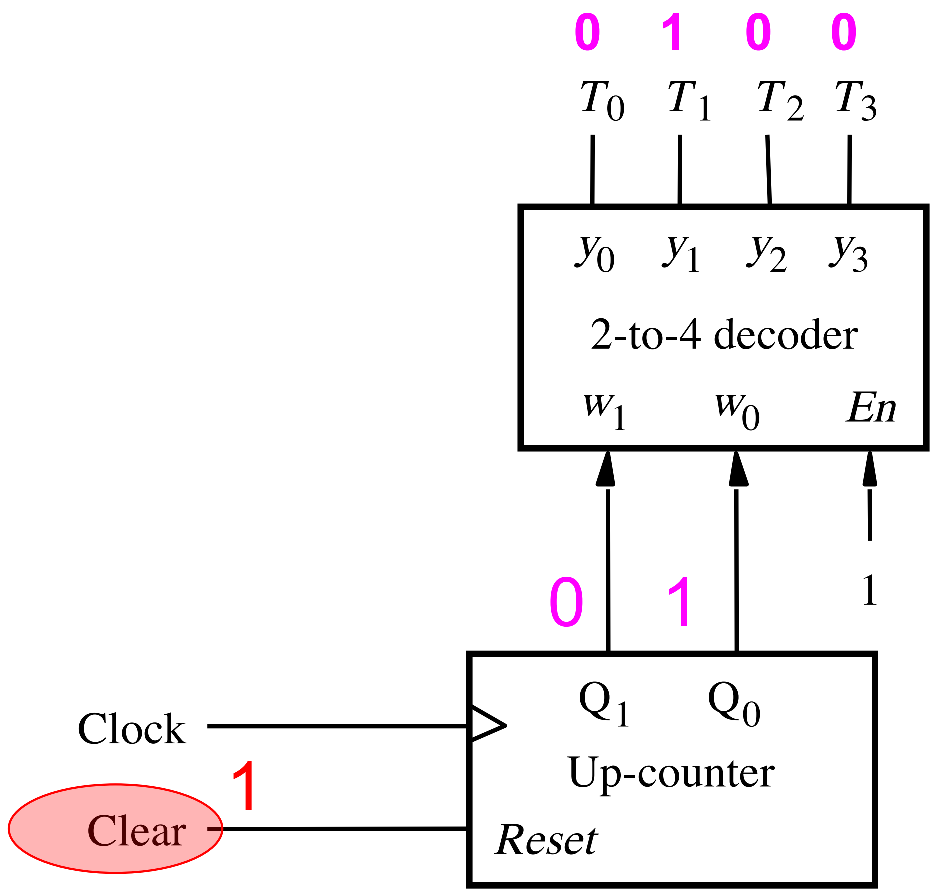
So How Does This Work?



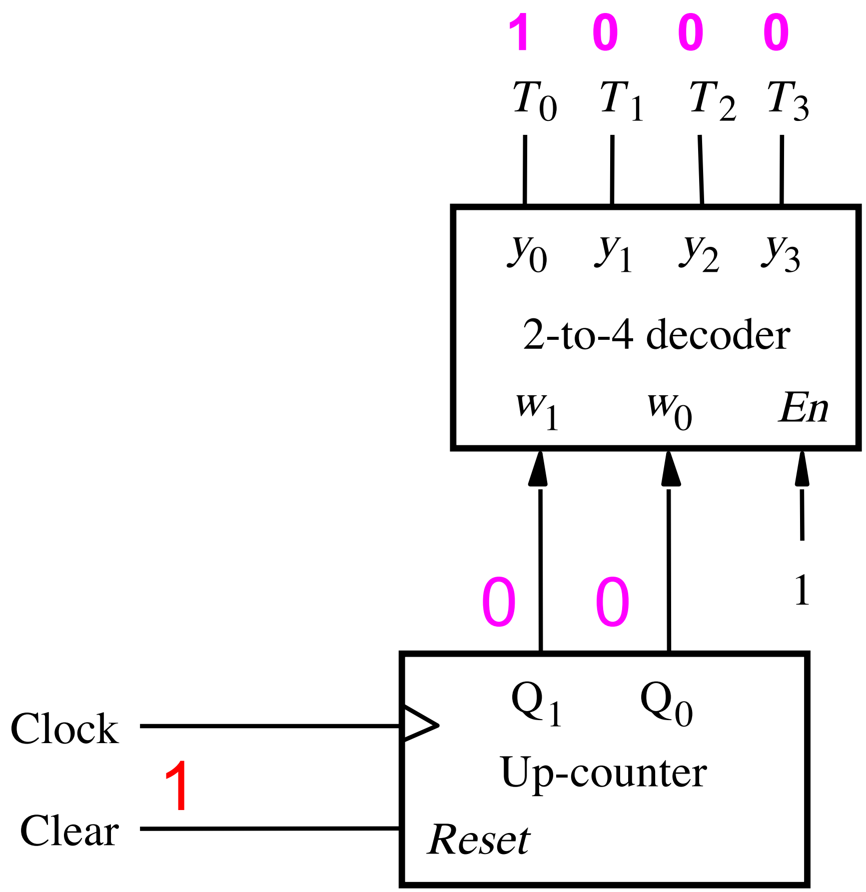
So How Does This Work?



So How Does This Work?



So How Does This Work?



Meaning/Explanation

- This is like a FSM that cycles through its four states one after another.
- But it also can be reset to go to state 0 at any time.
- The implementation uses a counter followed by a decoder. The outputs of the decoder are one-hot-encoded.
- This is like choosing a state assignment for an FSM in which there is one Flip-Flop per state, i.e., one-hot encoding (see Section 6.2.1 in the textbook)

Deriving the Control Signals

Design a FSM with input w and outputs

- $R0_{in}$
- $R0_{out}$
- $R1_{in}$
- $R1_{out}$
- $R2_{in}$
- $R2_{out}$
- $R3_{in}$
- $R3_{out}$

- A_{in}
- Gin
- G_{out}
- Clear
- FR_{in}

- AddSub
- Extern
- Done

- T_0
- T_1
- T_2
- T_3

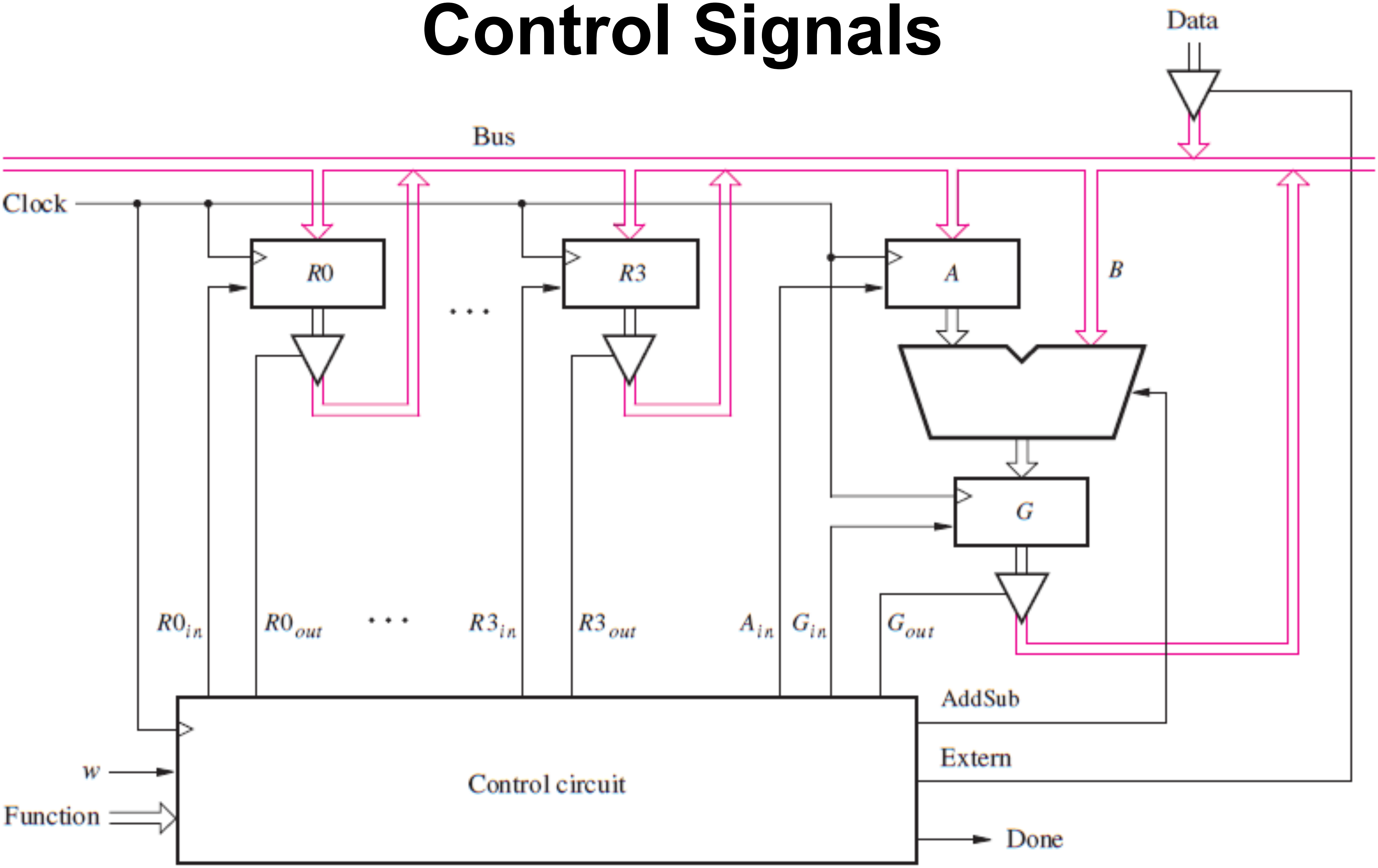
- I_0
- I_1
- I_2
- I_3

- X_0
- X_1
- X_2
- X_3

- Y_0
- Y_1
- Y_2
- Y_3

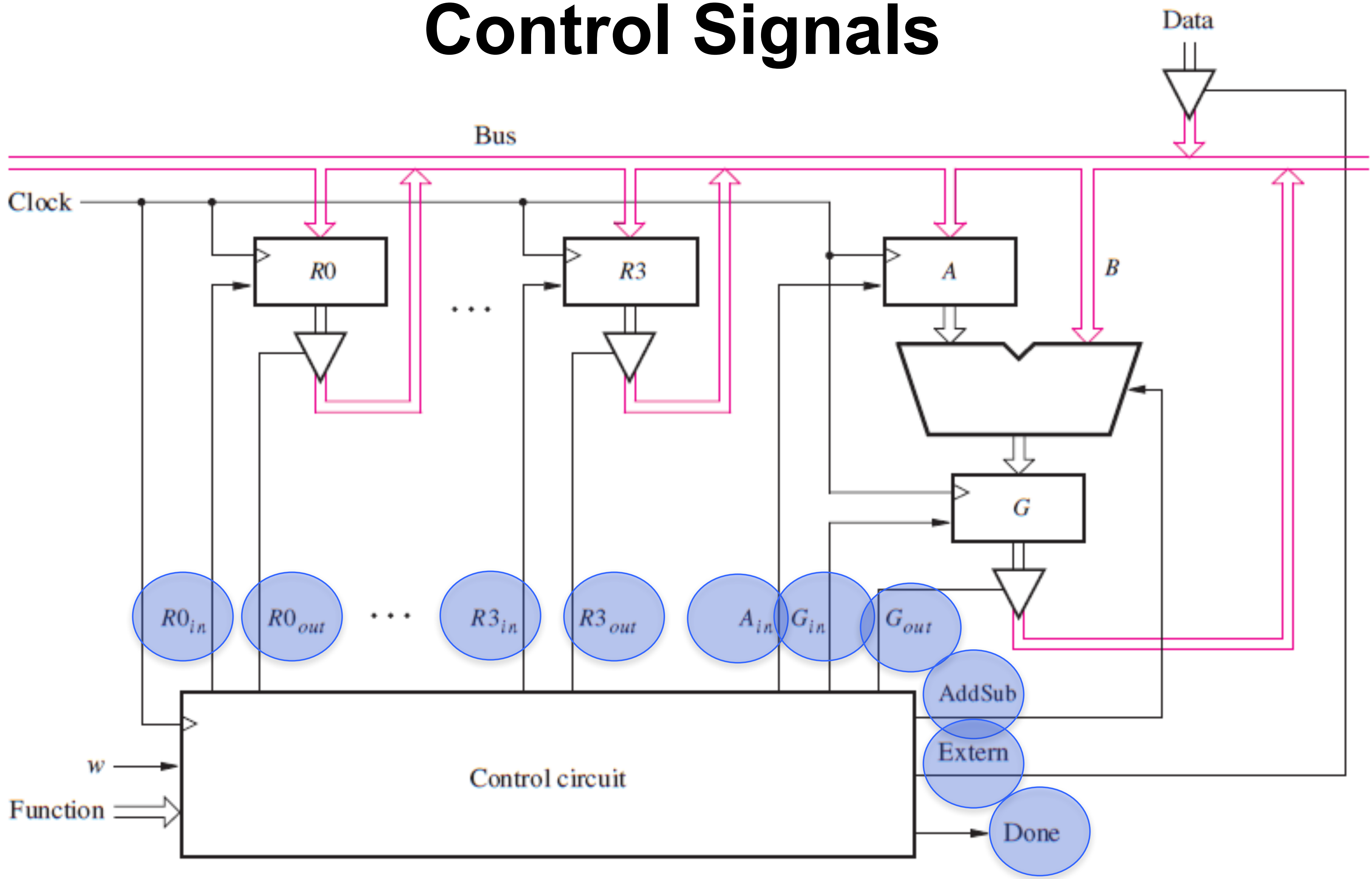
These are helper outputs that are one-hot encoded. They are used to simplify the expressions for the other outputs.

Control Signals



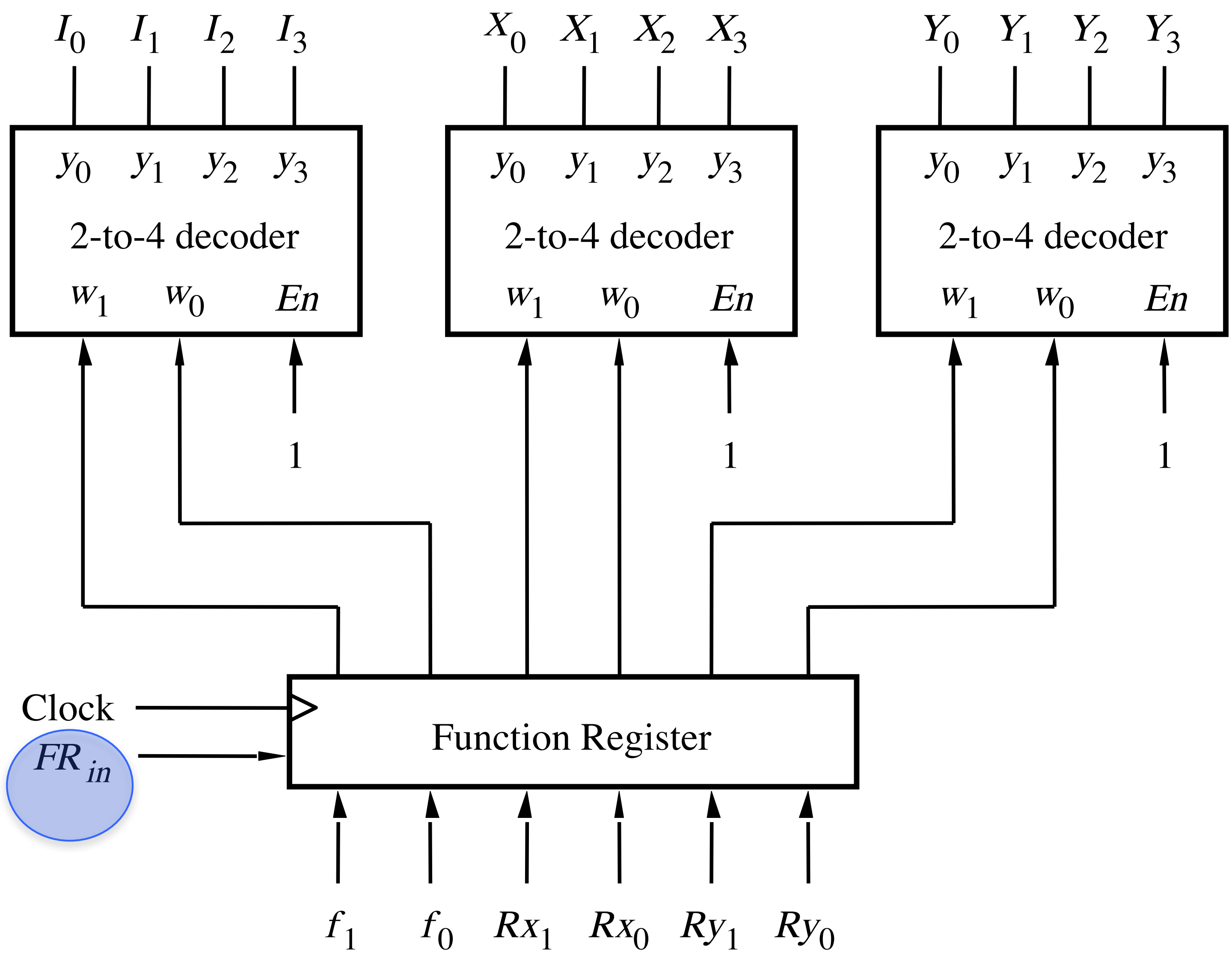
[Figure 7.9 from the textbook]

Control Signals



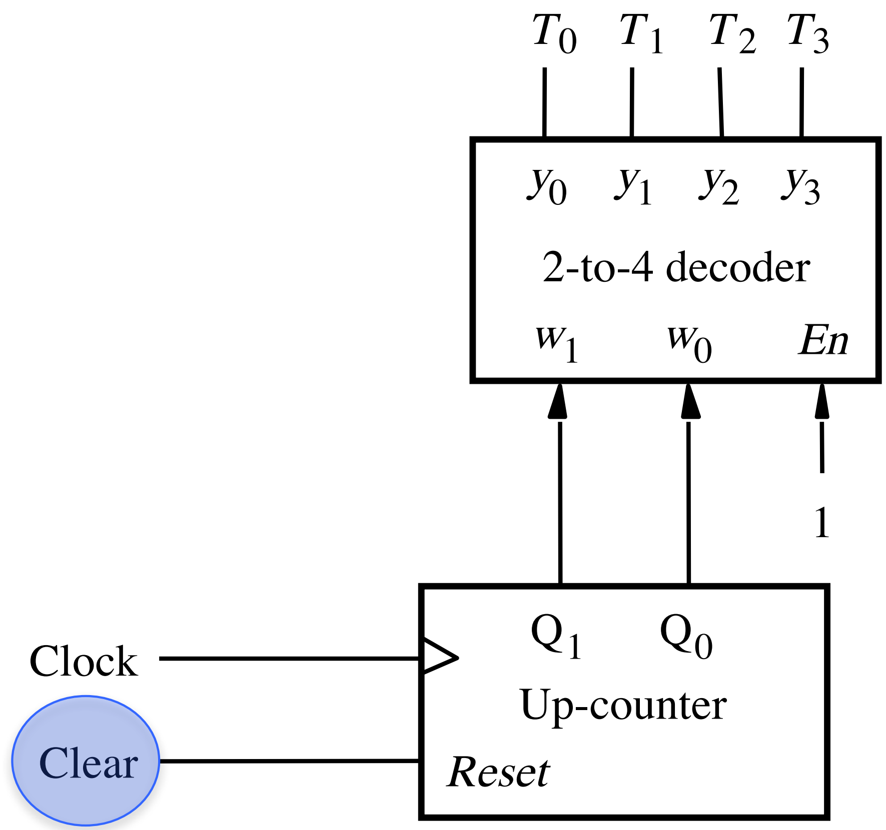
[Figure 7.9 from the textbook]

Another Control Signal



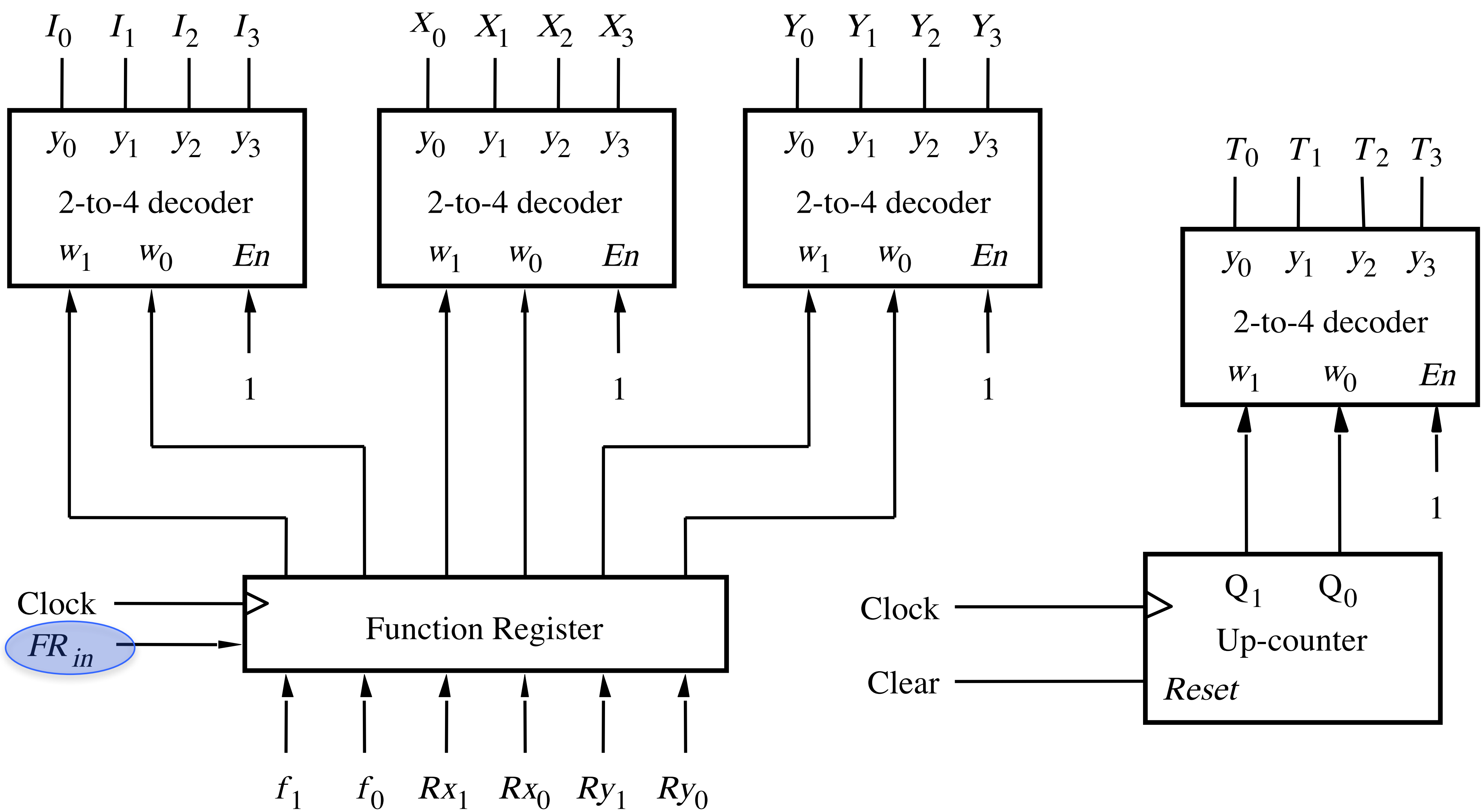
[Figure 7.11 from the textbook]

Yet Another Control Signal



[Figure 7.10 from the textbook]

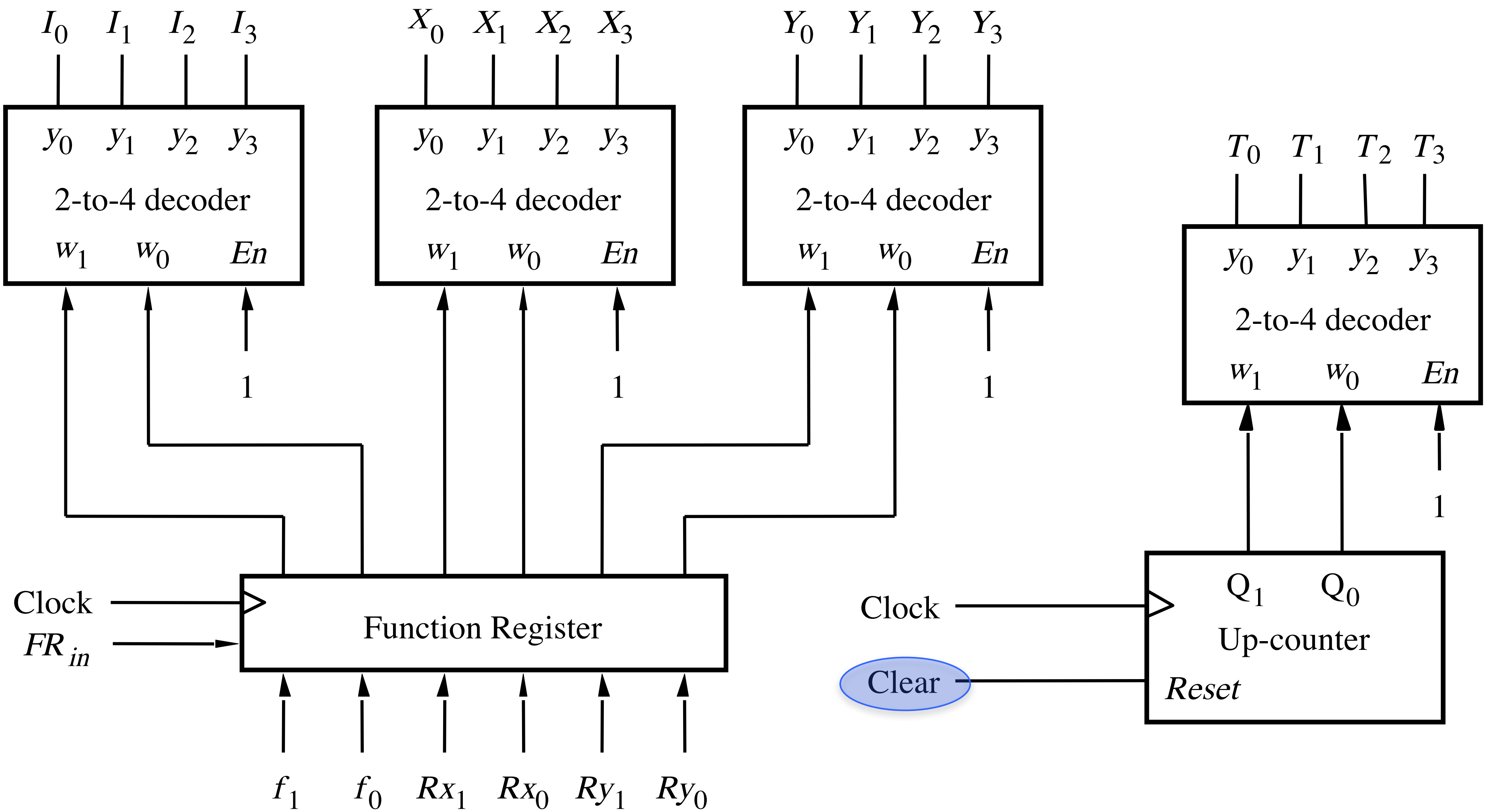
Expressing the 'FR_{in}' signal



$$FR_{in} = w\,T_0$$

Load a new operation into the function register

Expressing the 'Clear' signal



$$\text{Clear} = \overline{w}\, T_0 + \text{Done}$$

Reset the counter when Done or when w=0 and no operation is being executed (i.e., T_0=1).

Control signals asserted in each time step

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

[Table 7.2 from the textbook]

Control signals asserted in each time step

Time →

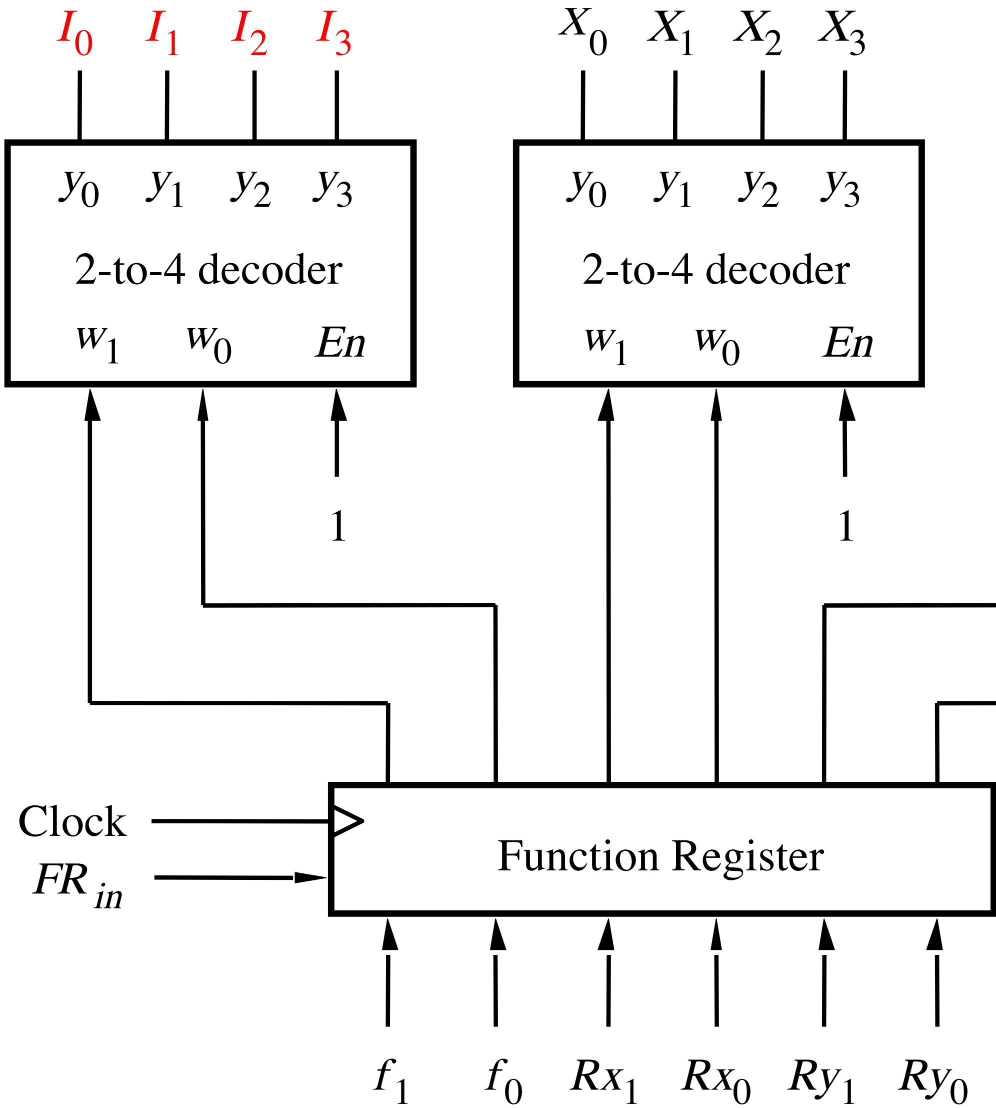
	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

These come from the outputs of the 2-to-4 decoder in Figure 7.10. They are also one-hot encoded.

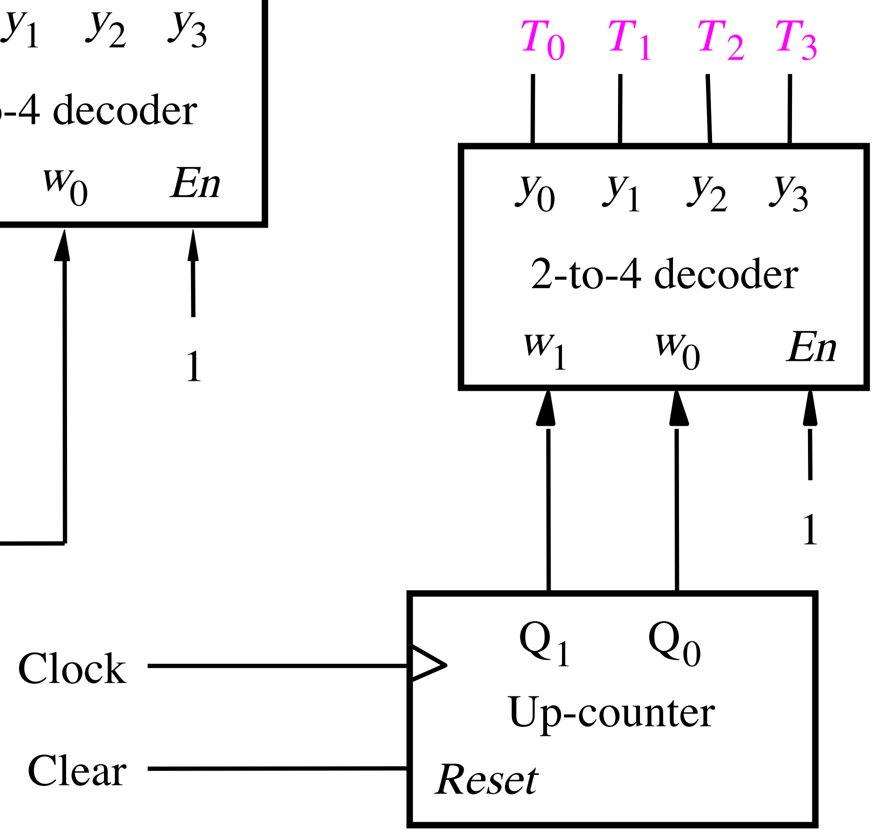
These are the outputs of the first 2-to-4 decoder that is connected to the two most significant bits of the function register. They are one-hot encoded so only one of them is active at any given time (see Fig 7.11).

[Table 7.2 from the textbook]

The I_0, I_1 ,I_2, I_3 and T_0,T_1,T_2,T_3 Signals



[Figure 7.11 from the textbook]



[Figure 7.10 from the textbook]

Different Operations Take Different Amount of Time

	T_1	T_2	T_3	
(Load): I_0	Extern $R_{in} = X$ Done			1 clock cycle
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done			1 clock cycle
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done	3 clock cycles
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done	3 clock cycles

[Table 7.2 from the textbook]

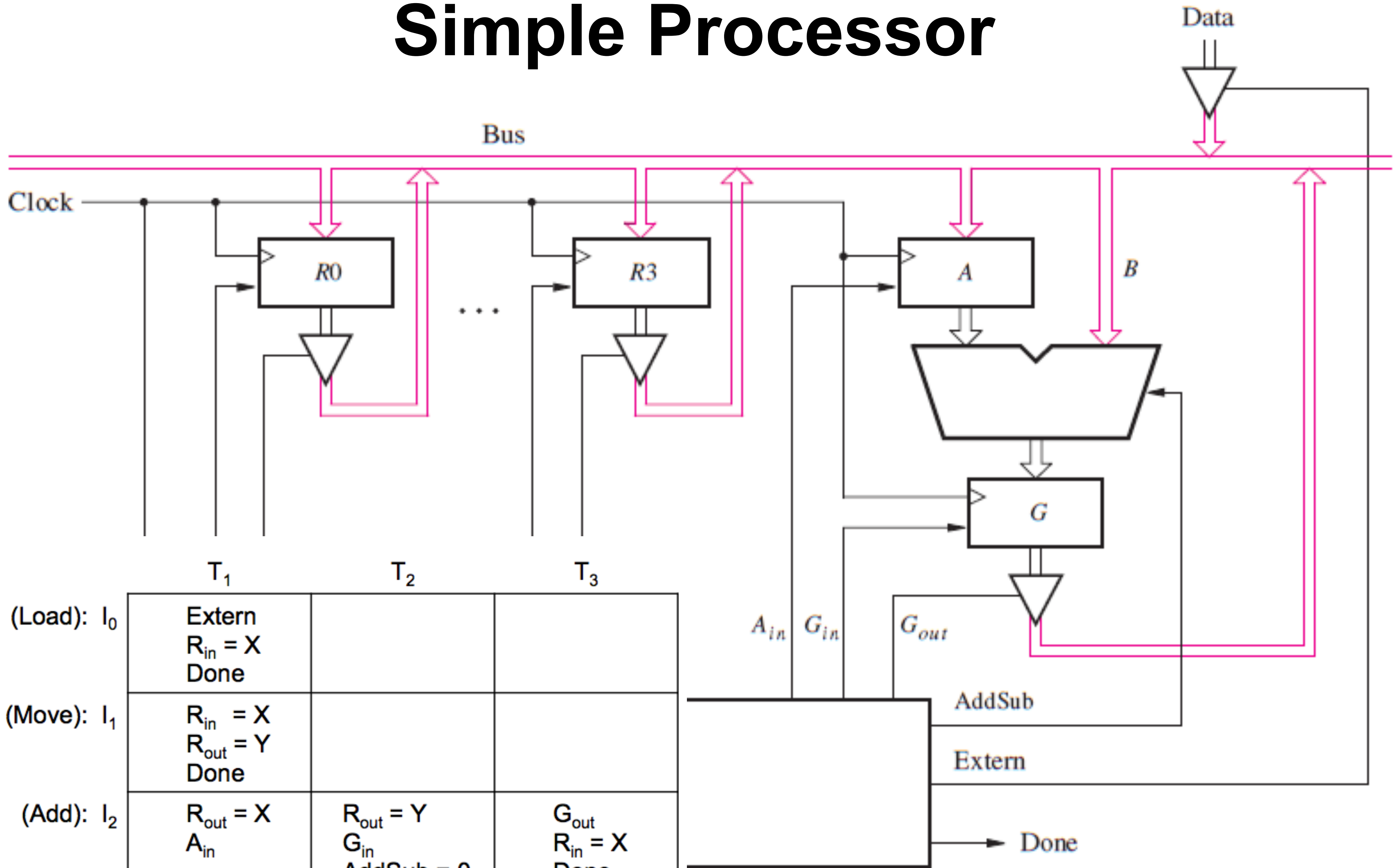
Operations performed by this processor

Operation	Function Performed
Load Rx, Data	Rx ← Data
Move Rx, Ry	Rx ← [Ry]
Add Rx, Ry	Rx ← [Rx] + [Ry]
Sub Rx, Ry	Rx ← [Rx] – [Ry]

Where Rx and Ry can be one of four possible options: R0, R1, R2, and R3

[Table 7.1 from the textbook]

Simple Processor



	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

[Figure 7.9 from the textbook]

Expressing the 'Extern' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

$$\text{Extern} = I_0 \, T_1$$

Expressing the 'Done' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$\text{Done} = (I_0 + I_1)T_1 + (I_2 + I_3)T_3$$

Expressing the 'A_{in}' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$A_{in} = (I_2 + I_3)T_1$$

Expressing the 'G_{in}' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$G_{in} = (I_2 + I_3)T_2$$

Expressing the 'G_{out}' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$G_{out} = (I_2 + I_3)T_3$$

Expressing the 'AddSub' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$AddSub = I_3$$

Expressing the '$R0_{in}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

$$R0_{in} = (I_0 + I_1)T_1 X_0 + (I_2 + I_3)T_3 X_0$$

Expressing the '$R1_{in}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$R1_{in} = (I_0 + I_1)T_1 X_1 + (I_2 + I_3)T_3 X_1$$

Expressing the 'R2$_{in}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

$$R2_{in} = (I_0 + I_1)T_1 X_2 + (I_2 + I_3)T_3 X_2$$

Expressing the 'R3$_{in}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern $R_{in} = X$ Done		
(Move): I_1	$R_{in} = X$ $R_{out} = Y$ Done		
(Add): I_2	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 0	G_{out} $R_{in} = X$ Done
(Sub): I_3	$R_{out} = X$ A_{in}	$R_{out} = Y$ G_{in} AddSub = 1	G_{out} $R_{in} = X$ Done

$$R3_{in} = (I_0 + I_1)T_1 X_3 + (I_2 + I_3)T_3 X_3$$

Expressing the 'R0$_{out}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

$$R0_{out} = I_1 T_1 Y_0 + (I_2 + I_3)(T_1 X_0 + T_2 Y_0)$$

Expressing the 'R1$_{out}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

$$R1_{out} = I_1 T_1 Y_1 + (I_2 + I_3)(T_1 X_1 + T_2 Y_1)$$

Expressing the '$R2_{out}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

$$R2_{out} = I_1 T_1 Y_2 + (I_2 + I_3)(T_1 X_2 + T_2 Y_2)$$

Expressing the 'R3$_{out}$' signal

	T_1	T_2	T_3
(Load): I_0	Extern R_{in} = X Done		
(Move): I_1	R_{in} = X R_{out} = Y Done		
(Add): I_2	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 0	G_{out} R_{in} = X Done
(Sub): I_3	R_{out} = X A_{in}	R_{out} = Y G_{in} AddSub = 1	G_{out} R_{in} = X Done

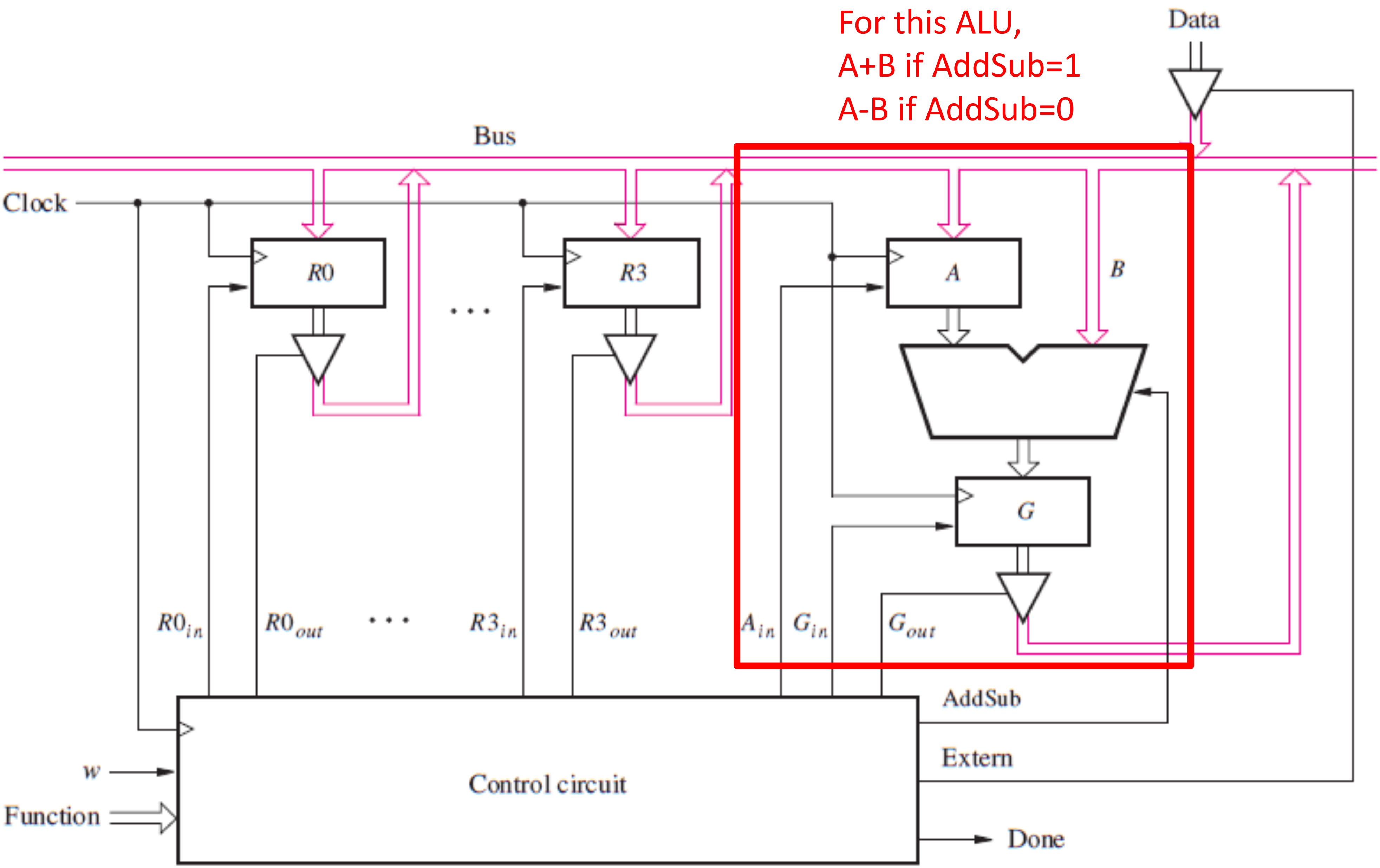
$$R3_{out} = I_1 T_1 Y_3 + (I_2 + I_3)(T_1 X_3 + T_2 Y_3)$$

Derivation of the Control Inputs

- For more insights into these derivations
  see pages 434 and 435 in the textbook

Some Additional Topics

The ALU for the Simple Processor

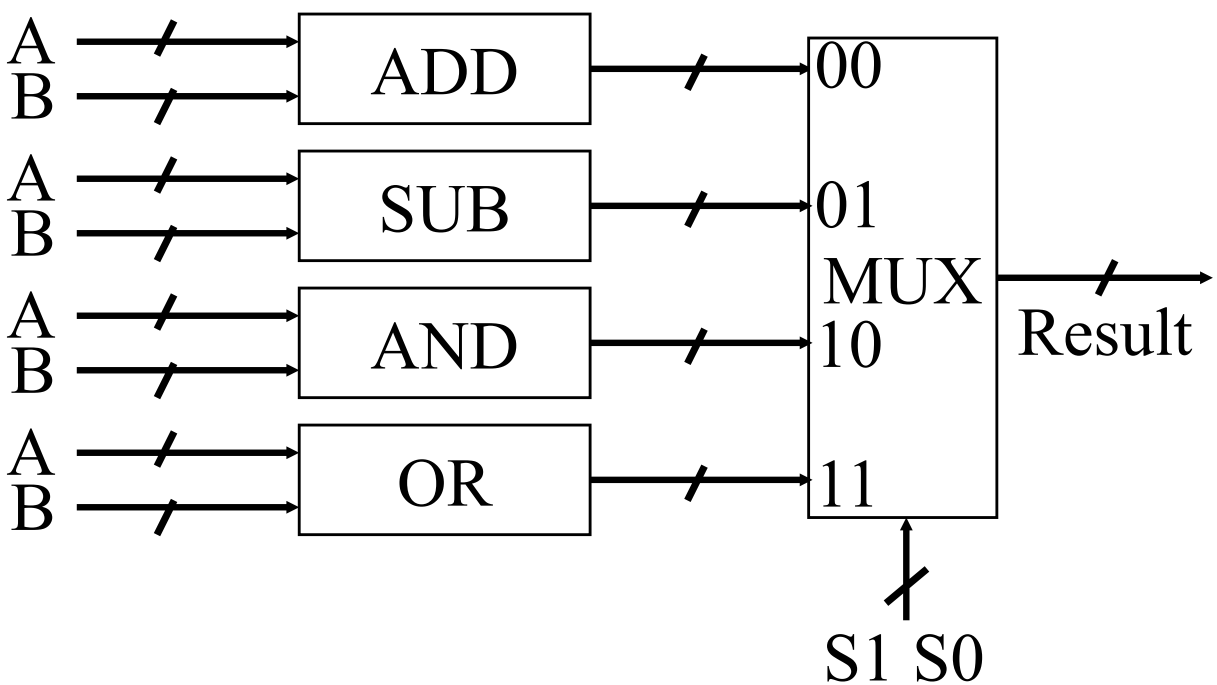


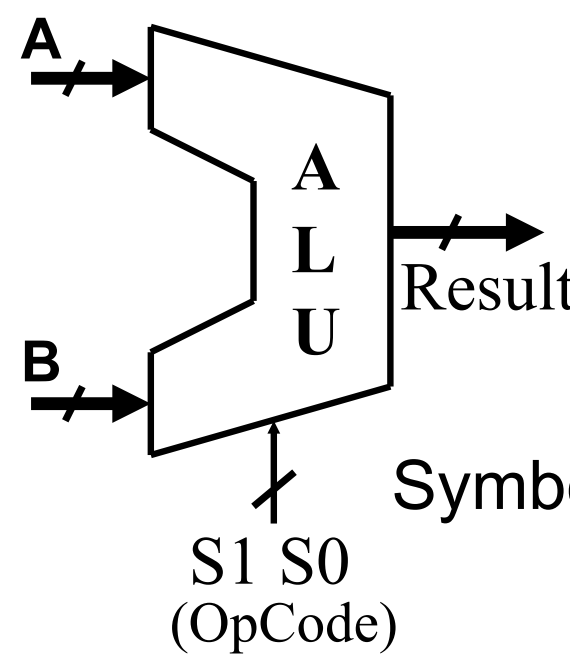
[Figure 7.9 from the textbook]

Another Arithmetic Logic Unit (ALU)

- Arithmetic Logic Unit (ALU) computes arithmetic or logic functions
- Example: A four-function ALU has two selection bits S1 S0 (also called OpCode) to specify the function
  - 00 (ADD), 01 (SUB), 10 (AND), 11 (OR)
- Then the following set up will work

S1	S0	Function
0	0	ADD
0	1	SUB
1	0	AND
1	1	OR

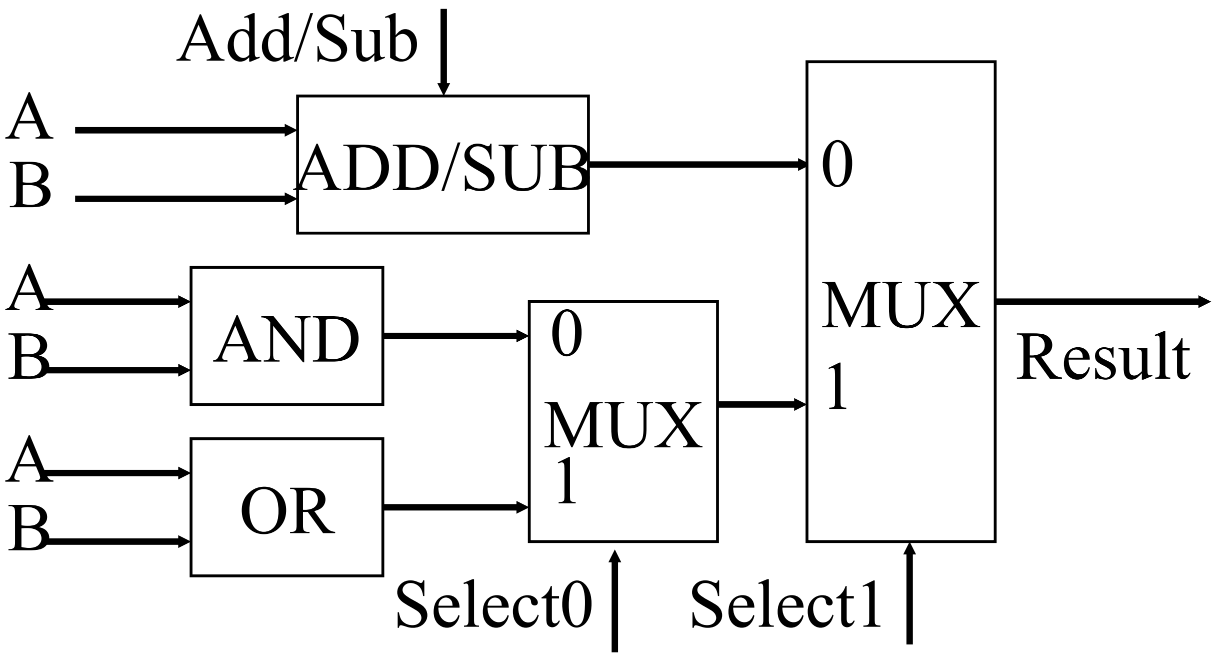




Symbol

An Alternative Design of Four-Function ALU

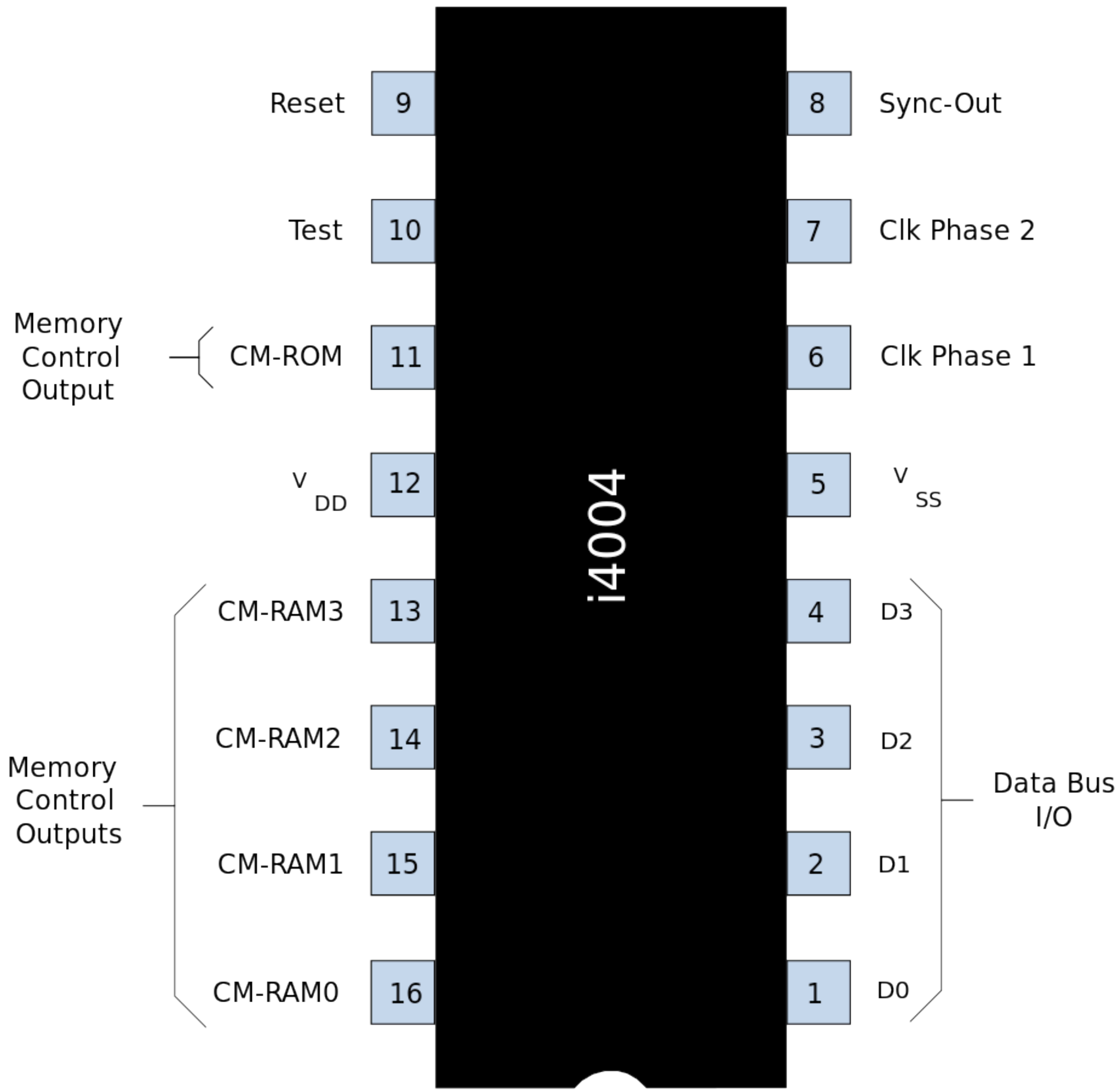
- The previous design is not very efficient as it uses an adder and a subtractor circuit
- We can design an add/subtract unit as discussed earlier
- Then we can design a logical unit (AND and OR) separately
- Then select appropriate output as result
- What are the control signals, Add/Sub, Select0, and Select1?



S1	S0	Function
0	0	ADD
0	1	SUB
1	0	AND
1	1	OR

Examples of Some Famous Microprocessors

Intel's 4004 Chip



[http://en.wikipedia.org/wiki/Intel_4004]

Technical specifications

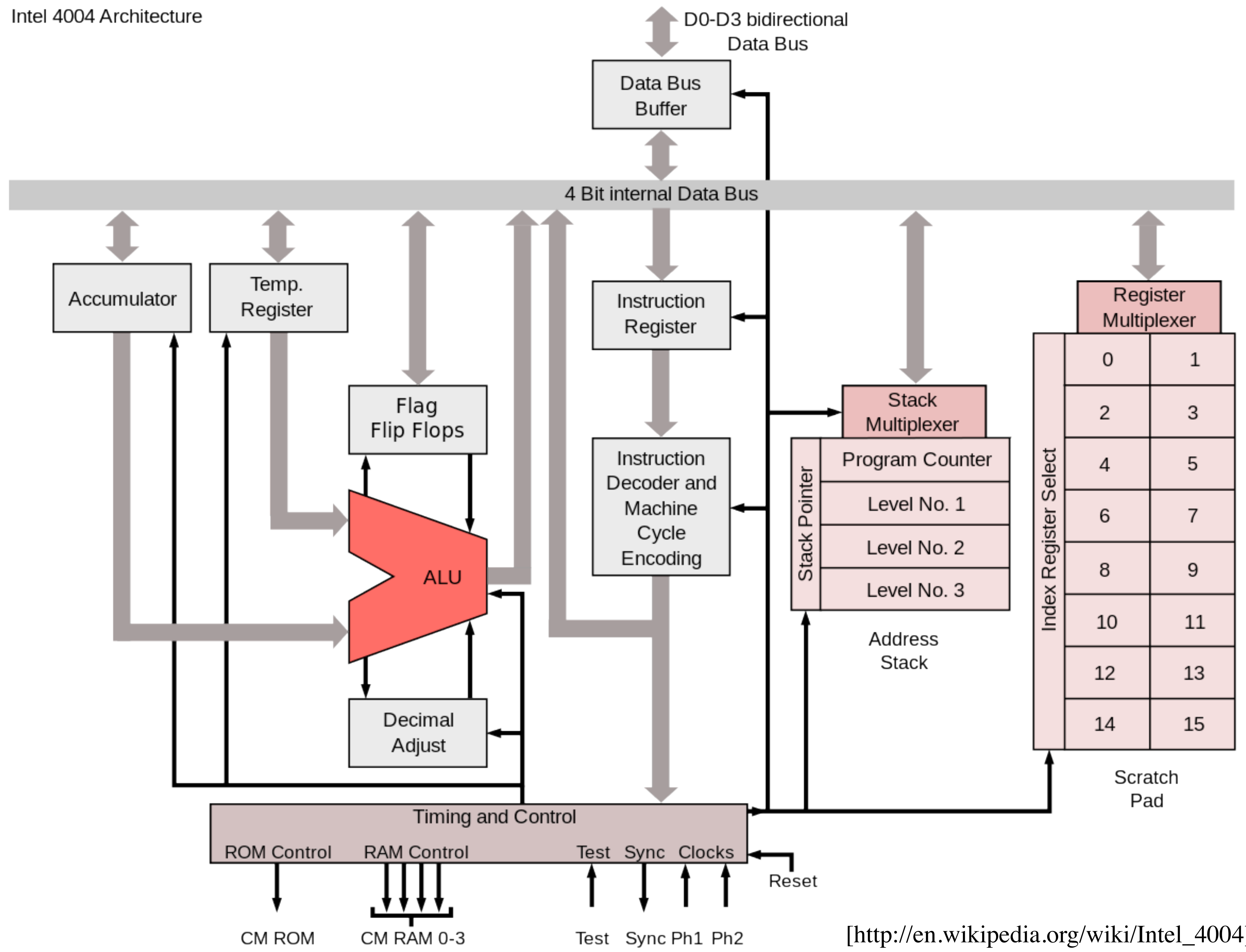
- **Maximum clock speed was 740 kHz**
- **Instruction cycle time: 10.8 μs**
  (8 clock cycles / instruction cycle)
- **Instruction execution time 1 or 2 instruction cycles (10.8 or 21.6 μs), 46300 to 92600 instructions per second**
- **Built using 2,300 transistors**

[http://en.wikipedia.org/wiki/Intel_4004]

Technical specifications

- Separate program and data storage.
- The 4004, with its need to keep pin count down, used a single multiplexed 4-bit bus for transferring:
  - 12-bit addresses
  - 8-bit instructions
  - 4-bit data words
- Instruction set contained 46 instructions (of which 41 were 8 bits wide and 5 were 16 bits wide)
- Register set contained 16 registers of 4 bits each
- Internal subroutine stack, 3 levels deep.

[http://en.wikipedia.org/wiki/Intel_4004]



[http://en.wikipedia.org/wiki/Intel_4004]

Intel 4004 registers

11 10 09 08 07 06 05 04 03 02 01 00 *(bit position)*

Main registers

		A	**A**ccumulator
	R0	R1	
	R2	R3	
	R4	R5	
	R6	R7	
	R8	R9	
	R10	R11	
	R12	R13	
	R14	R15	

Program counter

PC	**P**rogram **C**ounter

Push-down address call stack

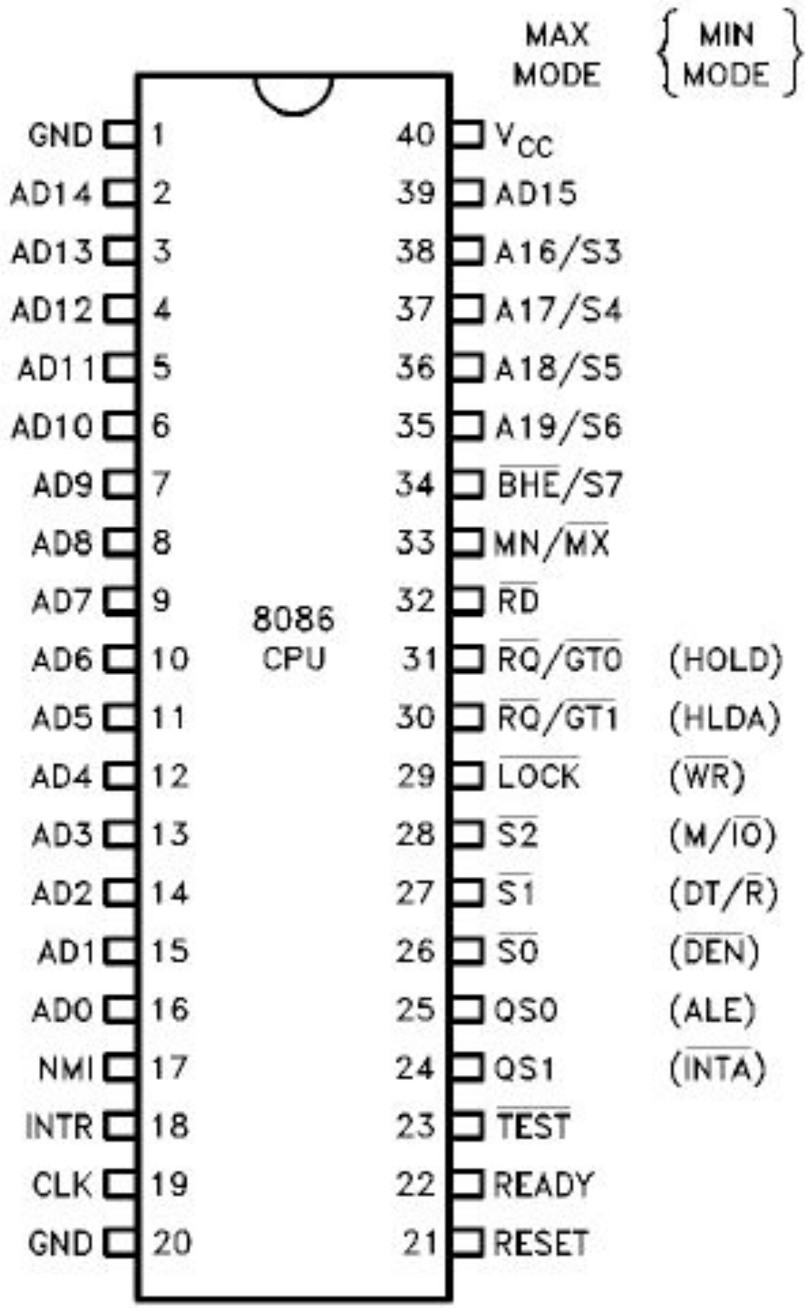
PC1	Call level 1
PC2	Call level 2
PC3	Call level 3

Status register

	C	P	Z	S	Flags

[http://en.wikipedia.org/wiki/Intel_4004]

Intel's 8086 Chip



[http://en.wikipedia.org/wiki/Intel_8086]

Intel 8086 registers

19	18	17	16	15	14	13	12	11	10	09	08	07	06	05	04	03	02	01	00	*(bit position)*
Main registers																				
				AH								AL								**AX** (primary accumulator)
				BH								BL								**BX** (base, accumulator)
				CH								CL								**CX** (counter, accumulator)
				DH								DL								**DX** (accumulator, other functions)
Index registers																				
0	0	0	0	SI																**S**ource **I**ndex
0	0	0	0	DI																**D**estination **I**ndex
0	0	0	0	BP																**B**ase **P**ointer
0	0	0	0	SP																**S**tack **P**ointer
Program counter																				
0	0	0	0	IP																**I**nstruction **P**ointer
Segment registers																				
CS																0	0	0	0	**C**ode **S**egment
DS																0	0	0	0	**D**ata **S**egment
ES																0	0	0	0	**E**xtra**S**egment
SS																0	0	0	0	**S**tack **S**egment
Status register																				
				-	-	-	-	O	D	I	T	S	Z	-	A	-	P	-	C	Flags

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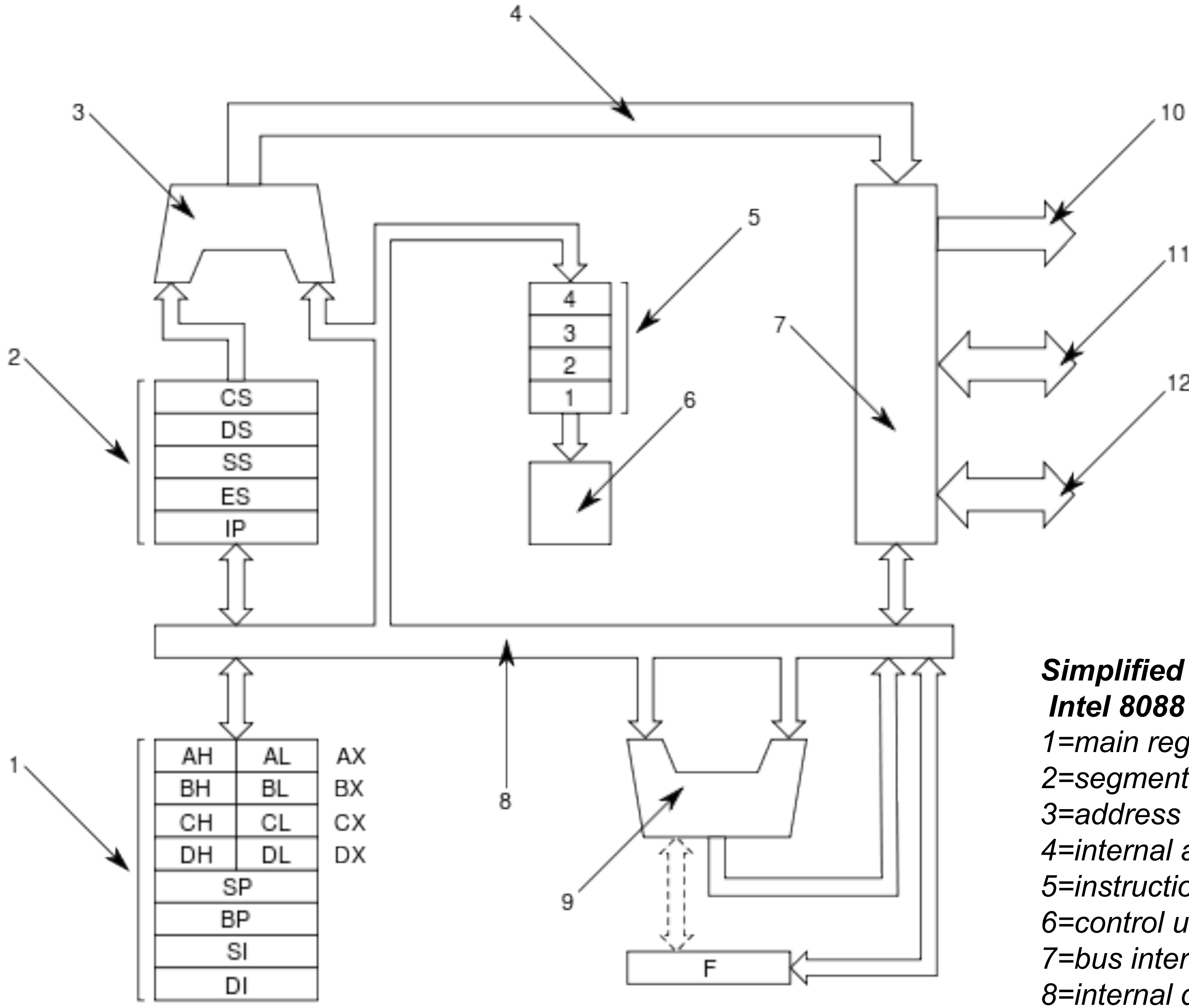

Simplified block diagram of
Intel 8088 (a variant of 8086);
1=main registers;
2=segment registers and IP;
3=address adder;
4=internal address bus;
5=instruction queue;
6=control unit (very simplified!);
7=bus interface;
8=internal databus;
9=ALU;
10/11/12=external address/ data/control bus.

[http://en.wikipedia.org/wiki/Intel_8086]

Questions?

THE END