

# Combinational logic design case studies

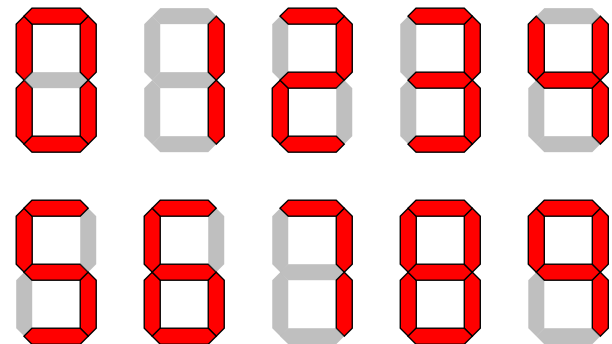
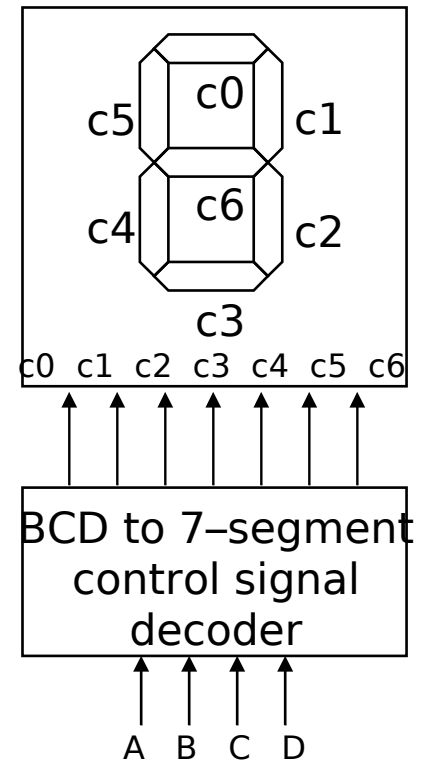
- General design procedure
- Case studies
  - BCD to 7-segment display controller
  - logical function unit
  - process line controller
  - calendar subsystem
- Arithmetic circuits
  - integer representations
  - addition/subtraction
  - arithmetic/logic units

# General design procedure for combinational logic

- 1. Understand the problem
  - what is the circuit supposed to do?
  - write down inputs (data, control) and outputs
  - draw block diagram or other picture
- 2. Formulate the problem using a suitable design representation
  - truth table or waveform diagram are typical
  - may require encoding of symbolic inputs and outputs
- 3. Choose implementation target
  - ROM, PAL, PLA
  - mux, decoder and OR-gate
  - discrete gates
- 4. Follow implementation procedure
  - K-maps for two-level, multi-level
  - design tools and hardware description language (e.g., Verilog)

# BCD to 7-segment display controller

- Understanding the problem
  - input is a 4 bit bcd digit (A, B, C, D)
  - output is the control signals for the display (7 outputs C0 – C6)
- Block diagram



# Formalize the problem

- Truth table
  - show don't cares
- Choose implementation target
  - if ROM, we are done
  - don't cares imply PAL/PLA may be attractive
- Follow implementation procedure
  - minimization using K-maps

A	B	C	D	C0	C1	C2	C3	C4	C5	C6
0	0	0	0	1	1	1	1	1	1	0
0	0	0	1	0	1	1	0	0	0	0
0	0	1	0	1	1	0	1	1	0	1
0	0	1	1	1	1	1	1	0	0	1
0	1	0	0	0	1	1	0	0	1	1
0	1	0	1	1	0	1	1	0	1	1
0	1	1	0	1	0	1	1	1	1	1
0	1	1	1	1	1	1	0	0	0	0
1	0	0	0	1	1	1	1	1	1	1
1	0	0	1	1	1	1	0	0	1	1
1	0	1	-	-	-	-	-	-	-	-
1	1	-	-	-	-	-	-	-	-	-

# Implementation as minimized sum-of-products

- 15 unique product terms when minimized individually

A			
1	0	X	1
0	1	X	1
1	1	X	X
1	1	X	X
B			

A			
1	1	X	1
1	0	X	1
1	1	X	X
1	0	X	X
B			

A			
1	1	X	1
1	1	X	1
1	1	X	X
0	1	X	X
B			

A			
1	0	X	1
0	1	X	0
1	0	X	X
1	1	X	X
B			

A			
1	0	X	1
0	0	X	0
0	0	X	X
1	1	X	X
B			

A			
1	1	X	1
0	1	X	1
0	0	X	X
0	1	X	X
B			

A			
0	1	X	1
0	1	X	1
1	0	X	X
1	1	X	X
B			

$$C0 = A + B D + C + B' D'$$

$$C1 = C' D' + C D + B'$$

$$C2 = B + C' + D$$

$$C3 = B' D' + C D' + B C' D + B' C$$

$$C4 = B' D' + C D'$$

$$C5 = A + C' D' + B D' + B C'$$

$$C6 = A + C D' + B C' + B' C$$

# Implementation as minimized S-o-P (cont'd)

- Can do better
  - 9 unique product terms (instead of 15)
  - share terms among outputs
  - each output not necessarily in minimized form

	A			
C2	1	1	X	1
	1	1	X	1
(	1	1	X	X
	0	1	X	X
	B			

	A			
C2	1	1	X	1
	1	1	X	1
(	1	1	X	X
	0	1	X	X
	B			

$$C0 = A + B D + C + B' D'$$

$$C1 = C' D' + C D + B'$$

$$C2 = B + C' + D$$

$$C3 = B' D' + C D' + B C' D + B' C$$

$$C4 = B' D' + C D'$$

$$C5 = A + C' D' + B D' + B C'$$

$$C6 = A + C D' + B C' + B' C$$

$$C0 = B C' D + C D + B' D' + B C D' + A$$

$$C1 = B' D + C' D' + C D + B' D'$$

$$C2 = B' D + B C' D + C' D' + C D + B C D'$$

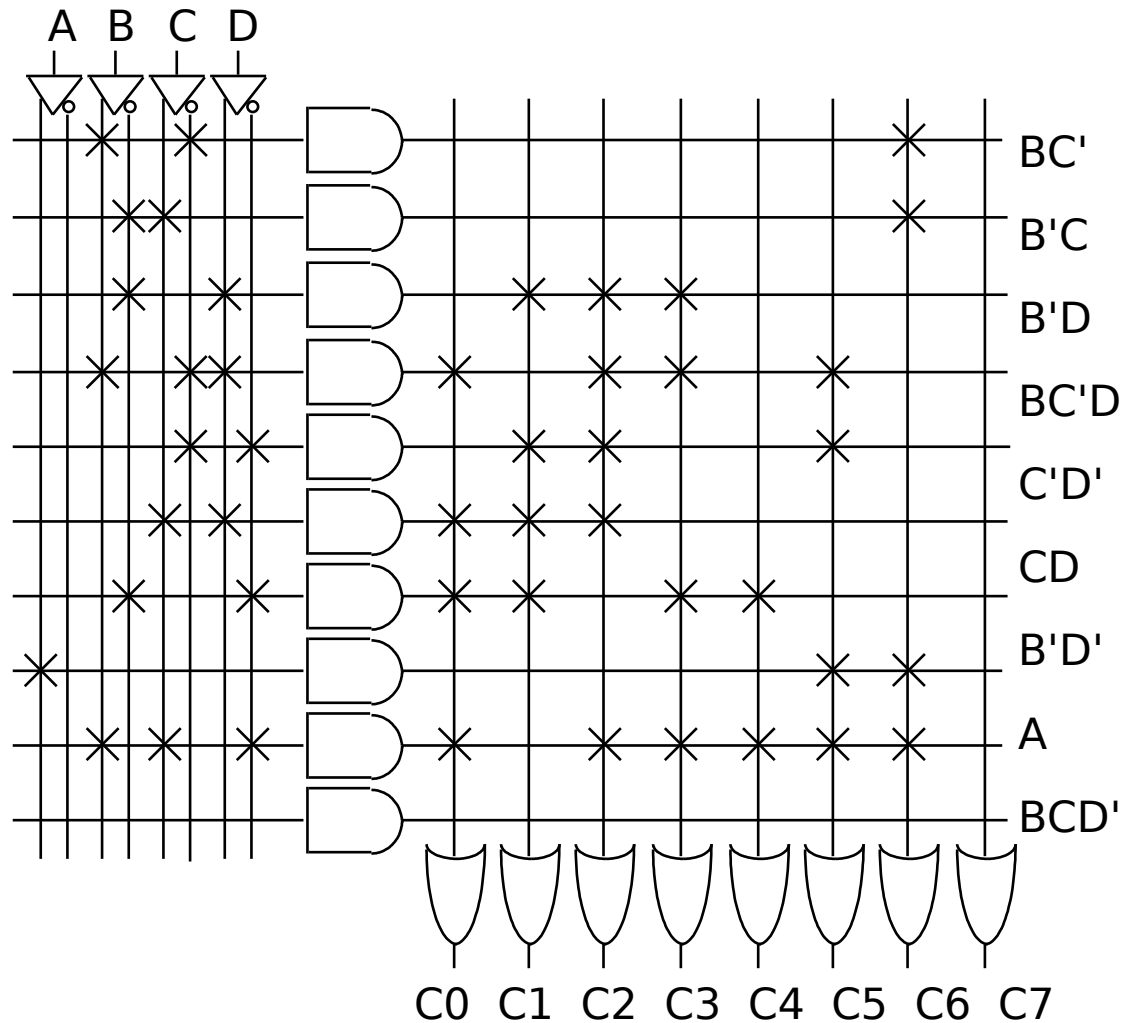
$$C3 = B C' D + B' D + B' D' + B C D'$$

$$C4 = B' D' + B C D'$$

$$C5 = B C' D + C' D' + A + B C D'$$

$$C6 = B' C + B C' + B C D' + A$$

# PLA implementation



# PAL implementation vs. Discrete gate implementation

- Limit of 4 product terms per output
  - decomposition of functions with larger number of terms
  - do not share terms in PAL anyway  
(although there are some with some shared terms)

$$C2 = B + C' + D$$

$$C2 = B' D + B C' D + C' D' + C D + B C D'$$

$$C2 = B' D + B C' D + C' D' + W \quad \text{need another input and another output}$$

$$W = C D + B C D'$$

- decompose into multi-level logic (hopefully with CAD support)
  - find common sub-expressions among functions

$$C0 = C3 + A' B X' + A D Y$$

$$C1 = Y + A' C5' + C' D' C6$$

$$C2 = C5 + A' B' D + A' C D$$

$$C3 = C4 + B D C5 + A' B' X'$$

$$C4 = D' Y + A' C D'$$

$$C5 = C' C4 + A Y + A' B X$$

$$C6 = A C4 + C C5 + C4' C5 + A' B' C$$

$$X = C' + D'$$

$$Y = B' C'$$



# Logical function unit

- Multi-purpose function block
  - 3 control inputs to specify operation to perform on operands
  - 2 data inputs for operands
  - 1 output of the same bit-width as operands

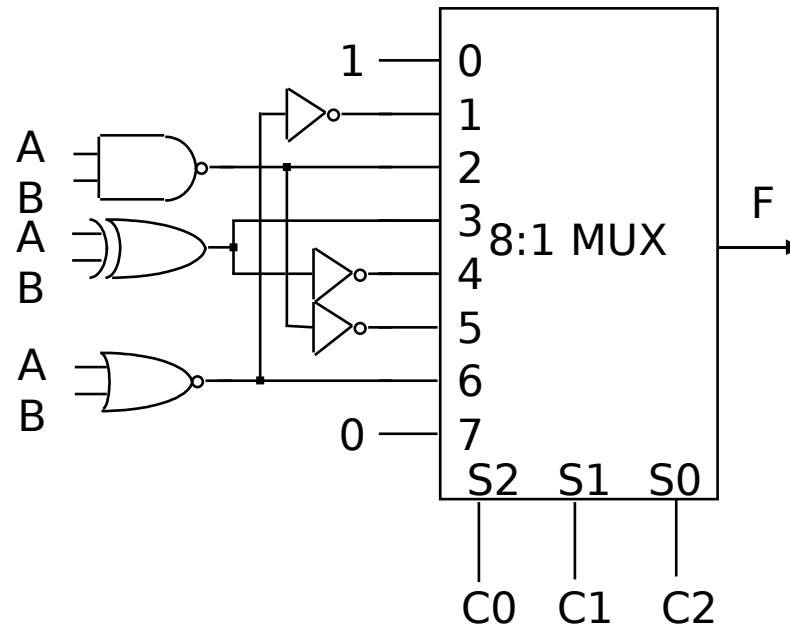
C0	C1	C2	Function	Comments
0	0	0	1	always 1
0	0	1	$A + B$	logical OR
0	1	0	$(A \cdot B)'$	logical NAND
0	1	1	$A \text{ xor } B$	logical xor
1	0	0	$A \text{ xnor } B$	logical xnor
1	0	1	$A \cdot B$	logical AND
1	1	0	$(A + B)'$	logical NOR
1	1	1	0	always 0

3 control inputs: C0, C1, C2  
2 data inputs: A, B  
1 output: F

# Formalize the problem

C0	C1	C2	A	B
F				
0	0	0	0	0
1	0	0	0	1
0	0	0	1	0
1	0	0	1	1
0	0	1	0	0
0	0	1	0	1
0	0	1	1	0
0	0	1	1	1
0	1	0	0	0
0	1	0	0	1
0	1	0	1	0
0	1	0	1	1
0	1	1	0	0
0	1	1	0	1
0	1	1	1	0
0	1	1	1	1
1	0	0	0	0
1	0	0	0	1
1	0	0	1	0
1	0	0	1	1
1	0	1	0	0
1	0	1	0	1
1	0	1	1	0
1	0	1	1	1
1	1	0	0	0
1	1	0	0	1
1	1	0	1	0
1	1	0	1	1
1	1	1	0	0
1	1	1	0	1
1	1	1	1	0
1	1	1	1	1

choose implementation technology  
5-variable K-map to discrete gates  
multiplexor implementation

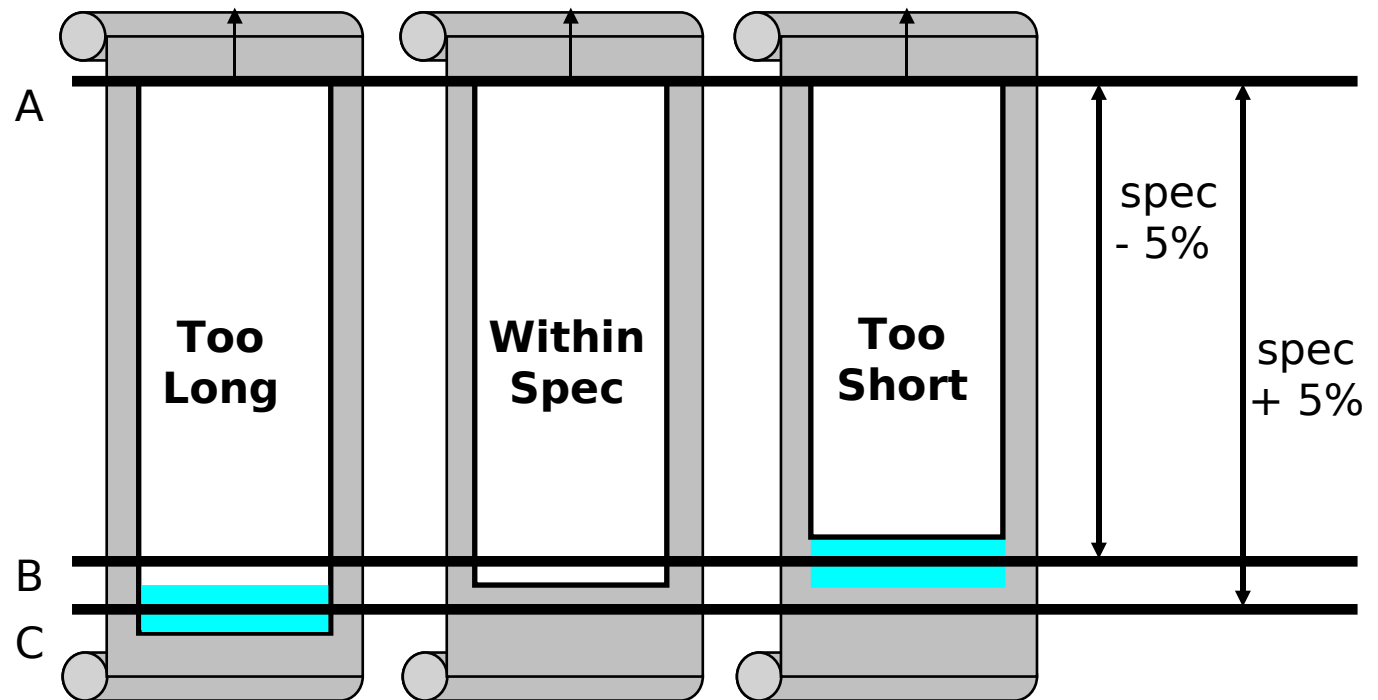


# Production line control

- Rods of varying length ( $\pm 10\%$ ) travel on conveyor belt
  - mechanical arm pushes rods within spec ( $\pm 5\%$ ) to one side
  - second arm pushes rods too long to other side
  - rods that are too short stay on belt
  - 3 light barriers (light source + photocell) as sensors
  - design combinational logic to activate the arms
- Understanding the problem
  - inputs are three sensors
  - outputs are two arm control signals
  - assume sensor reads "1" when tripped, "0" otherwise
  - call sensors A, B, C

# Sketch of problem

- Position of sensors
  - A to B distance = specification – 5%
  - A to C distance = specification + 5%



# Formalize the problem

- Truth table
  - show don't cares

A	B	C	Function
0	0	0	do nothing
0	0	1	do nothing
0	1	0	do nothing
0	1	1	do nothing
1	0	0	too short
1	0	1	don't care
1	1	0	in spec
1	1	1	too long

logic implementation now straightforward  
just use three 3-input AND gates

"too short" =  $AB'C'$   
(only first sensor tripped)

"in spec" =  $A B C'$   
(first two sensors tripped)

"too long" =  $A B C$   
(all three sensors tripped)

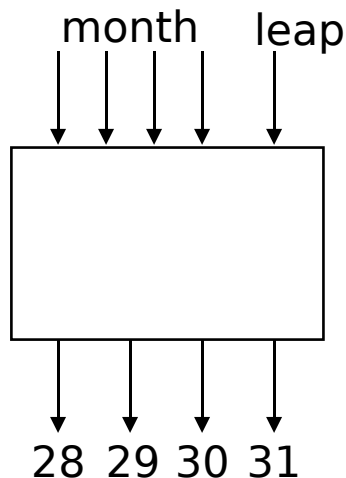
# Calendar subsystem

- Determine number of days in a month (to control watch display)
  - used in controlling the display of a wrist-watch LCD screen
  - inputs: month, leap year flag
  - outputs: number of days
- Use software implementation to help understand the problem

```
integer number_of_days ( month, leap_year_flag) {  
    switch (month) {  
        case 1: return (31);  
        case 2: if (leap_year_flag == 1)  
                then return (29)  
                else return (28);  
        case 3: return (31);  
        case 4: return (30);  
        case 5: return (31);  
        case 6: return (30);  
        case 7: return (31);  
        case 8: return (31);  
        case 9: return (30);  
        case 10: return (31);  
        case 11: return (30);  
        case 12: return (31);  
        default: return (0);  
    }  
}
```

# Formalize the problem

- Encoding:
  - binary number for month: 4 bits
  - 4 wires for 28, 29, 30, and 31  
one-hot – only one true at any time
- Block diagram:



month	leap	28	29	30	31
0000	–	–	–	–	–
0001	–	0	0	0	1
0010	0	1	0	0	0
0010	1	0	1	0	0
0011	–	0	0	0	1
0100	–	0	0	1	0
0101	–	0	0	0	1
0110	–	0	0	1	0
0111	–	0	0	0	1
1000	–	0	0	0	1
1001	–	0	0	1	0
1010	–	0	0	0	1
1011	–	0	0	1	0
1100	–	0	0	0	1
1101	–	–	–	–	–
111–	–	–	–	–	–

# Choose implementation target and perform mapping

- Discrete gates

- $28 = m8' m4' m2 m1' \text{ leap}'$

- $29 = m8' m4' m2 m1' \text{ leap}$

- $30 = m8' m4 m1' + m8 m1$

- $31 = m8' m1 + m8 m1'$

- Can translate to S-o-P or P-o-S

month	leap	28	29	30	31
0000	–	–	–	–	–
0001	–	0	0	0	1
0010	0	1	0	0	0
0011	1	0	1	0	0
0011	–	0	0	0	1
0100	–	0	0	1	0
0101	–	0	0	0	1
0110	–	0	0	1	0
0111	–	0	0	0	1
1000	–	0	0	0	1
1001	–	0	0	1	0
1010	–	0	0	0	1
1011	–	0	0	1	0
1100	–	0	0	0	1
1101	–	–	–	–	–
111–	–	–	–	–	–



# Leap year flag

- Determine value of leap year flag given the year
  - For years after 1582 (Gregorian calendar reformation),
  - leap years are all the years divisible by 4,
  - except that years divisible by 100 are not leap years,
  - but years divisible by 400 are leap years.
- Encoding the year:
  - binary – easy for divisible by 4,  
but difficult for 100 and 400 (not powers of 2)
  - BCD – easy for 100,  
but more difficult for 4, what about 400?
- Parts:
  - construct a circuit that determines if the year is divisible by 4
  - construct a circuit that determines if the year is divisible by 100
  - construct a circuit that determines if the year is divisible by 400
  - combine the results of the previous three steps to yield the leap year flag

# Activity: divisible-by-4 circuit

# Divisible-by-100 and divisible-by-400 circuits

- Divisible-by-100 just requires checking that all bits of two low-order digits are all 0:

$$YT8' YT4' YT2' YT1' \cdot YO8' YO4' YO2' YO1'$$

- Divisible-by-400 combines the divisible-by-4 (applied to the thousands and hundreds digits) and divisible-by-100 circuits

$$(YM1' YH2' YH1' + YM1 YH2 YH1')$$

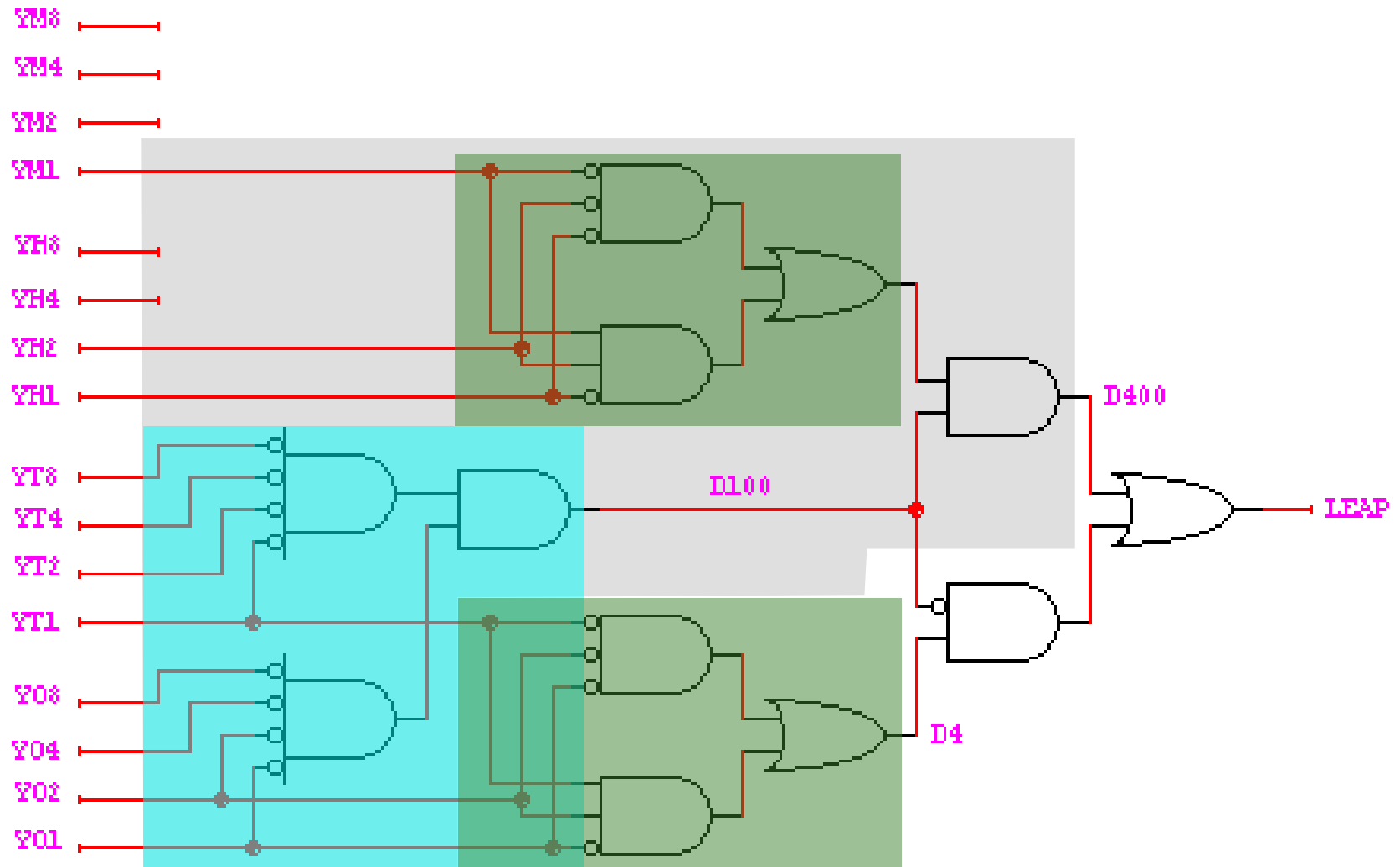
$$\cdot (YT8' YT4' YT2' YT1' \cdot YO8' YO4' YO2' YO1' )$$

# Combining to determine leap year flag

- Label results of previous three circuits: D4, D100, and D400

$$\begin{aligned}\text{leap\_year\_flag} &= D4 (D100 \cdot D400')' \\ &= D4 \cdot D100' + D4 \cdot D400 \\ &= D4 \cdot D100' + D400\end{aligned}$$

# Implementation of leap year flag



# Arithmetic circuits

- Excellent examples of combinational logic design
- Time vs. space trade-offs
  - doing things fast may require more logic and thus more space
  - example: carry lookahead logic
- Arithmetic and logic units
  - general-purpose building blocks
  - critical components of processor datapaths
  - used within most computer instructions

# Number systems

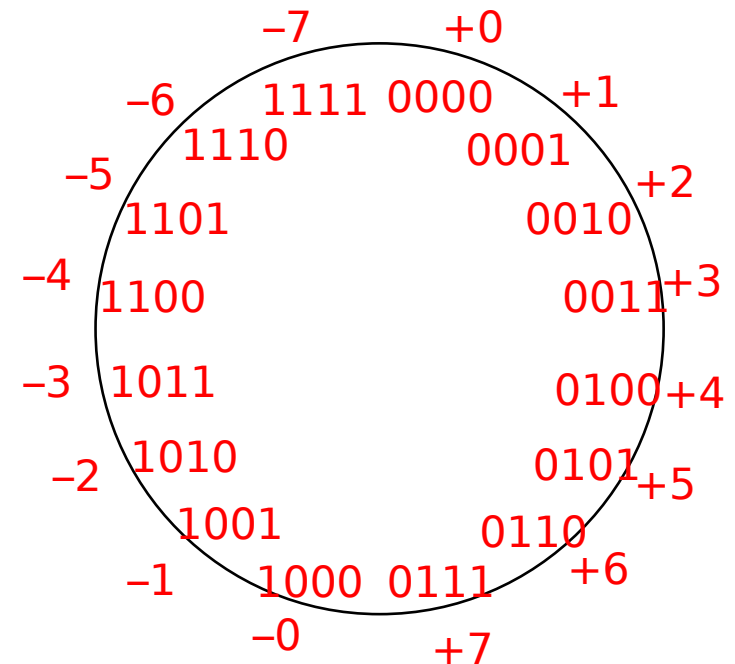
- Representation of positive numbers is the same in most systems
- Major differences are in how negative numbers are represented
- Representation of negative numbers come in three major schemes
  - sign and magnitude
  - 1s complement
  - 2s complement
- Assumptions
  - we'll assume a 4 bit machine word
  - 16 different values can be represented
  - roughly half are positive, half are negative

# Sign and magnitude

- One bit dedicate to sign (positive or negative)
  - sign: 0 = positive (or zero), 1 = negative
- Rest represent the absolute value or magnitude
  - three low order bits: 0 (000) thru 7 (111)
- Range for n bits
  - $\pm 2^{n-1} - 1$  (two representations for 0)
- Cumbersome addition/subtraction
  - must compare magnitudes to determine sign of result

0 100 = + 4

1 100 = - 4





# 1s complement

- If N is a positive number, then the negative of N (its 1s complement or N' ) is  $N' = (2^n - 1) - N$ 
  - example: 1s complement of 7

$$2^4 = 10000$$

$$1 = \underline{00001}$$

$$2^4 - 1 = 1111$$

$$7 = \underline{0111}$$

$$1000 = -7 \text{ in 1s complement form}$$

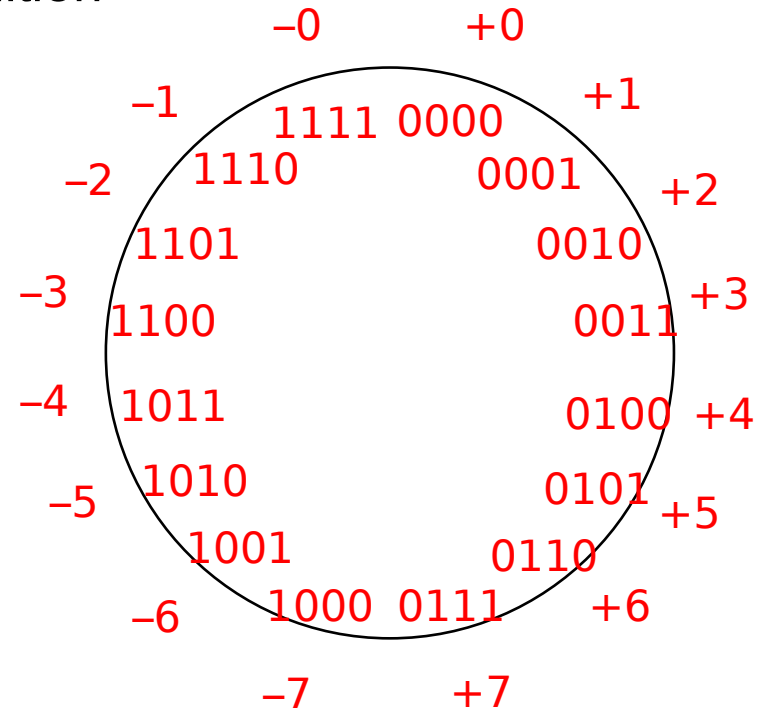
- shortcut: simply compute bit-wise complement ( 0111 -> 1000 )

# 1s complement (cont'd)

- Subtraction implemented by 1s complement and then addition
- Two representations of 0
  - causes some complexities in addition
- High-order bit can act as sign bit

0 100 = + 4

1 011 = - 4



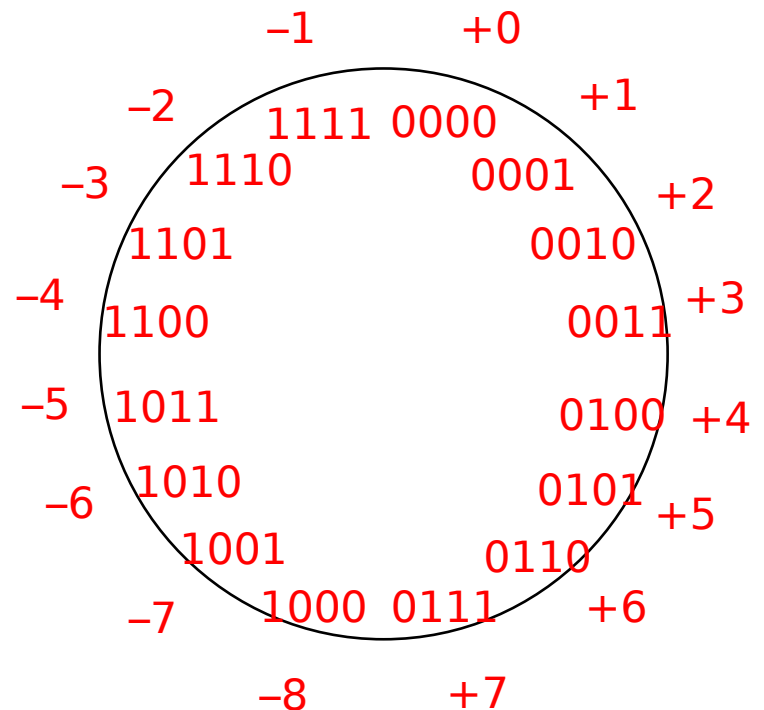
# 2s complement

- 1s complement with negative numbers shifted one position clockwise

- only one representation for 0
- one more negative number than positive numbers
- high-order bit can act as sign bit

0 100 = + 4

1 100 = - 4



# 2s complement (cont'd)

- If N is a positive number, then the negative of N (its 2s complement or  $N^*$ ) is  $N^* = 2^n - N$

- example: 2s complement of 7

$$\begin{array}{rcl} & 4 & \\ 2^4 & = & 10000 \\ \text{subtract } 7 & = & \underline{0111} \end{array}$$

1001 = repr. of -7

- example: 2s complement of -7

$$\begin{array}{rcl} & 4 & \\ 2^4 & = & 10000 \\ \text{subtract } -7 & = & \underline{1001} \end{array}$$

0111 = repr. of 7

- shortcut: 2s complement = bit-wise complement + 1

- 0111 -> 1000 + 1 -> 1001 (representation of -7)
- 1001 -> 0110 + 1 -> 0111 (representation of 7)

# 2s complement addition and subtraction

- Simple addition and subtraction
  - simple scheme makes 2s complement the virtually unanimous choice for integer number systems in computers

4	0100	- 4	1100
<u>+ 3</u>	<u>0011</u>	<u>+ (- 3)</u>	<u>1101</u>
7	0111	- 7	11001

4	0100	- 4	1100
<u>- 3</u>	<u>1101</u>	<u>+ 3</u>	<u>0011</u>
1	10001	- 1	1111

# Why can the carry-out be ignored?

- Can't ignore it completely
  - needed to check for overflow (see next two slides)
- When there is no overflow, carry-out may be true but can be ignored

–  $M + N$  when  $N > M$ :

$$M^* + N = (2^n - M) + N = 2^n + (N - M)$$

ignoring carry-out is just like subtracting  $2^n$

–  $M + -N$  where  $N + M \leq 2^{n-1}$

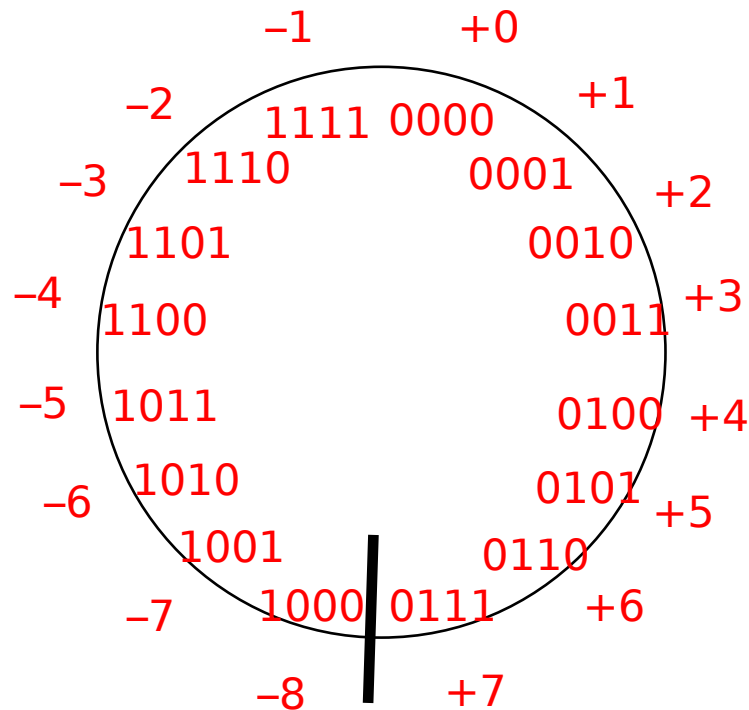
$$(-M) + (-N) = M^* + N^* = (2^n - M) + (2^n - N) = 2^n - (M + N) + 2^n$$

ignoring the carry, it is just the 2s complement representation for  $-(M + N)$

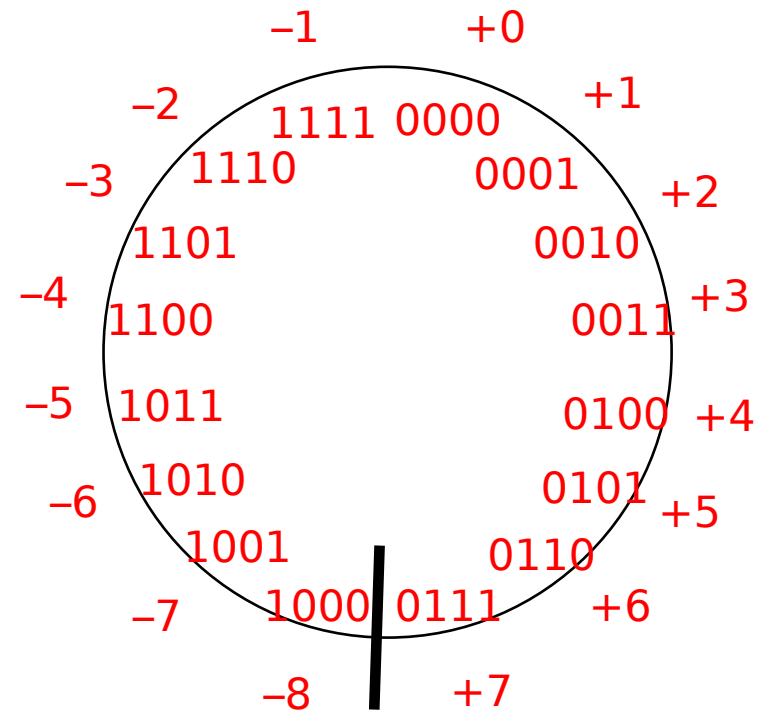
# Overflow in 2s complement addition/subtraction

## ■ Overflow conditions

- add two positive numbers to get a negative number
- add two negative numbers to get a positive number



$$5 + 3 = -8$$



$$-7 - 2 = +7$$

# Overflow conditions

- Overflow when carry into sign bit position is not equal to carry-out

$$\begin{array}{r}
 5 \\
 - 3 \\
 \hline
 -8
 \end{array}
 \quad
 \begin{array}{r}
 0111 \\
 0101 \\
 \hline
 0011 \\
 1000
 \end{array}$$

overflow

$$\begin{array}{r}
 -7 \\
 - 2 \\
 \hline
 7
 \end{array}
 \quad
 \begin{array}{r}
 1000 \\
 1001 \\
 \hline
 1110 \\
 10111
 \end{array}$$

overflow

$$\begin{array}{r}
 5 \\
 - 2 \\
 \hline
 7
 \end{array}
 \quad
 \begin{array}{r}
 0000 \\
 0101 \\
 \hline
 0010 \\
 0111
 \end{array}$$

no overflow

$$\begin{array}{r}
 -3 \\
 - 5 \\
 \hline
 -8
 \end{array}
 \quad
 \begin{array}{r}
 1111 \\
 1101 \\
 \hline
 1011 \\
 11000
 \end{array}$$

no overflow



# Circuits for binary addition

- Half adder (add 2 1-bit numbers)
  - $\text{Sum} = A_i' B_i + A_i B_i' = A_i \text{ xor } B_i$
  - $\text{Cout} = A_i B_i$
- Full adder (carry-in to cascade for multi-bit adders)
  - $\text{Sum} = C_i \text{ xor } A \text{ xor } B$
  - $\text{Cout} = B C_i + A C_i + A B = C_i (A + B) + A B$

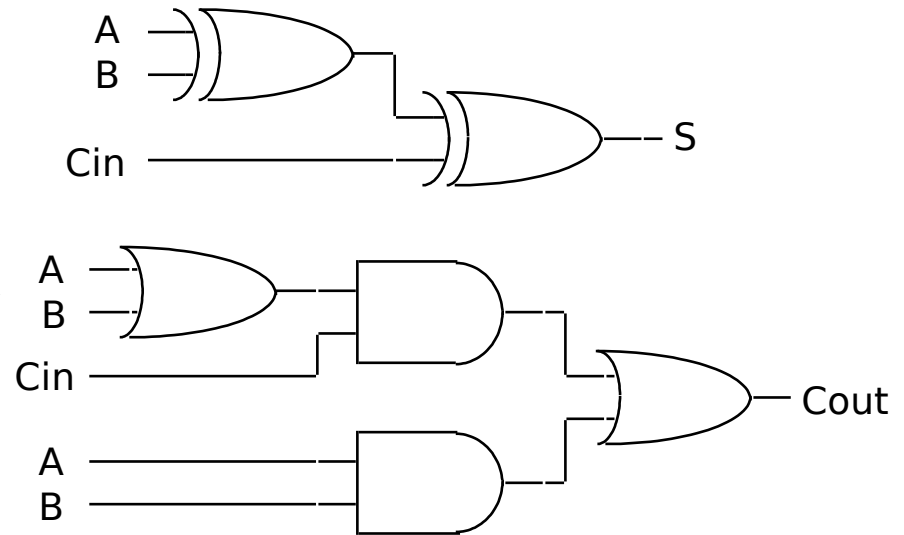
Ai	Bi	Sum	Cout
0	0	0	0
0	1	1	0
1	0	1	0
1	1	1	1

Ai	Bi	Cin	Sum	Cout
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

# Full adder implementations

## Standard approach

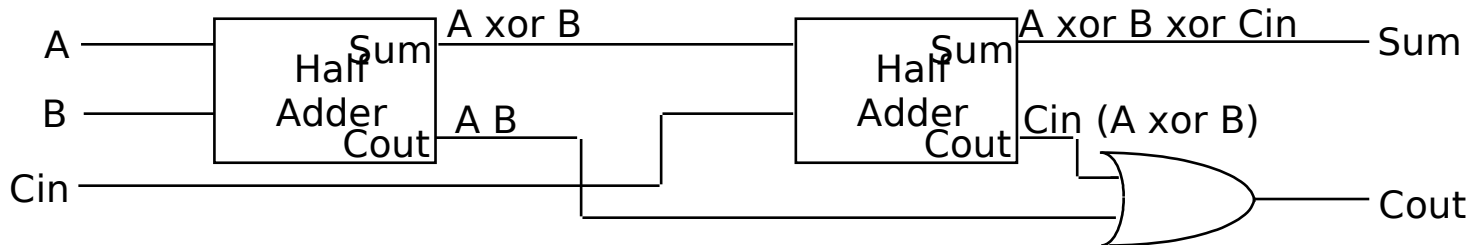
- 6 gates
- 2 XORs, 2 ANDs, 2 ORs



## Alternative implementation

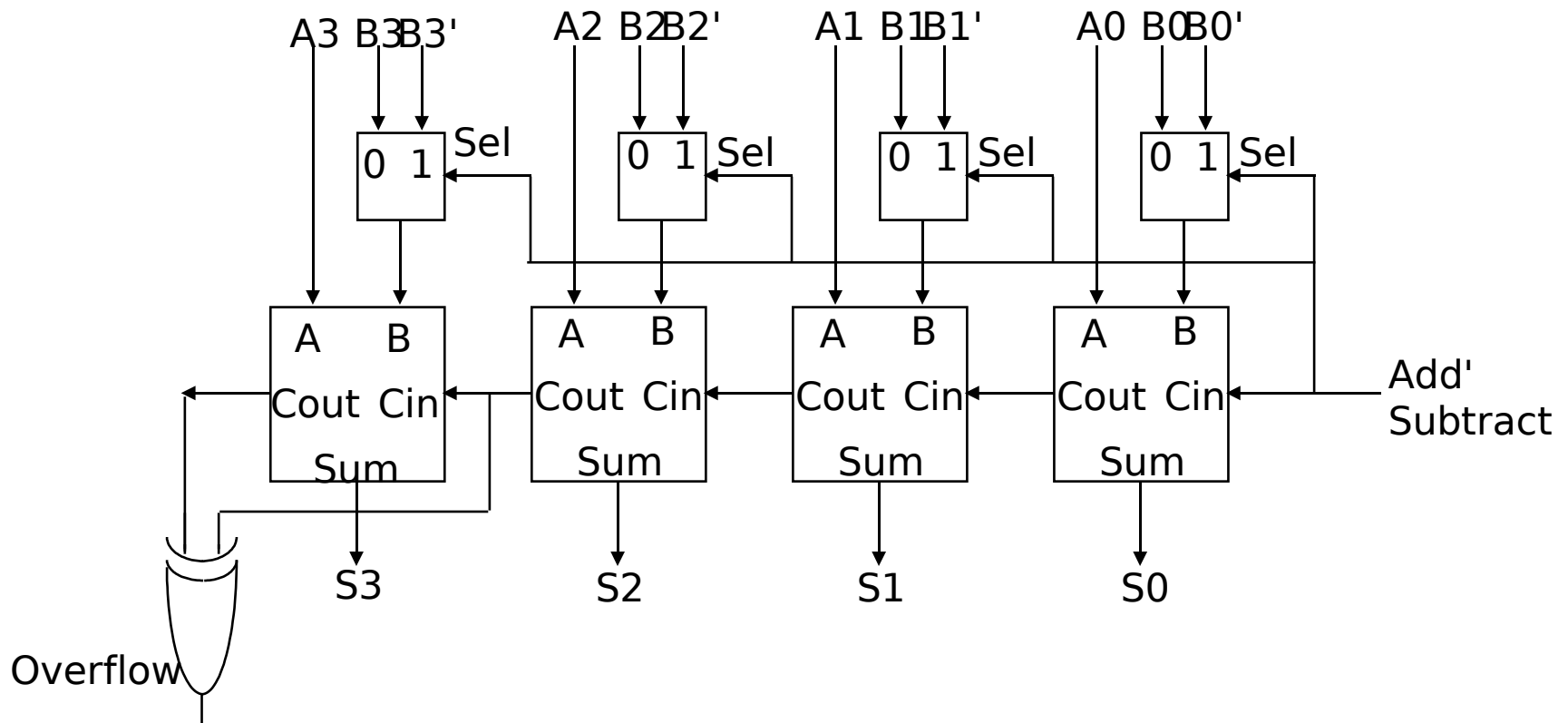
- 5 gates
- half adder is an XOR gate and AND gate
- 2 XORs, 2 ANDs, 1 OR

$$Cout = A B + Cin (A \text{ xor } B) = A B + B Cin + A Cin$$



# Adder/subtractor

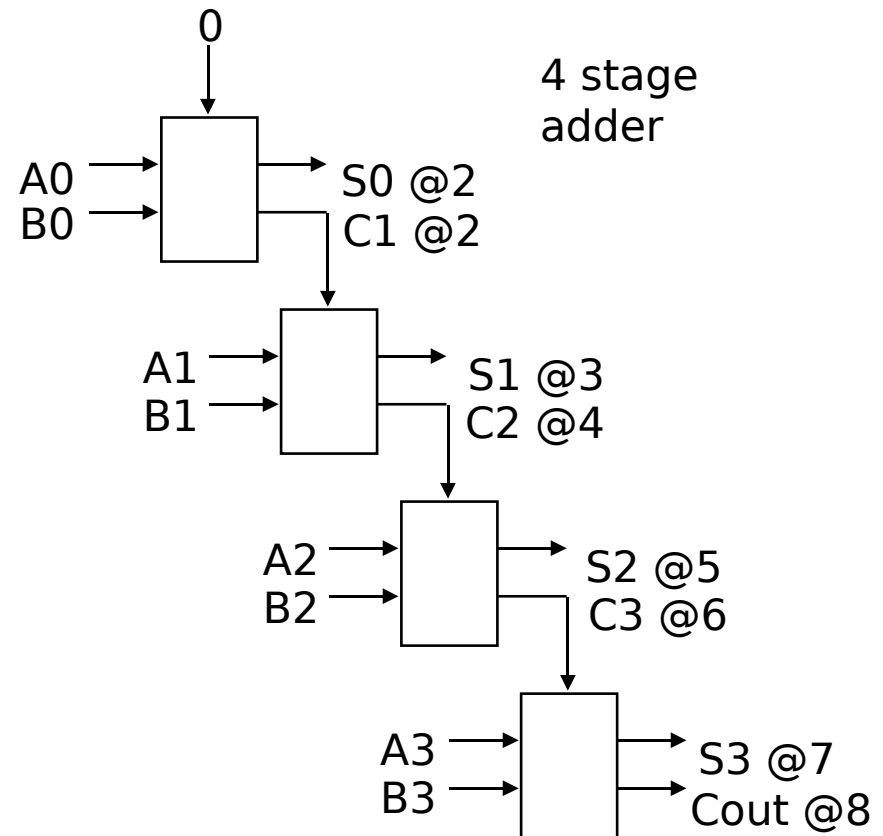
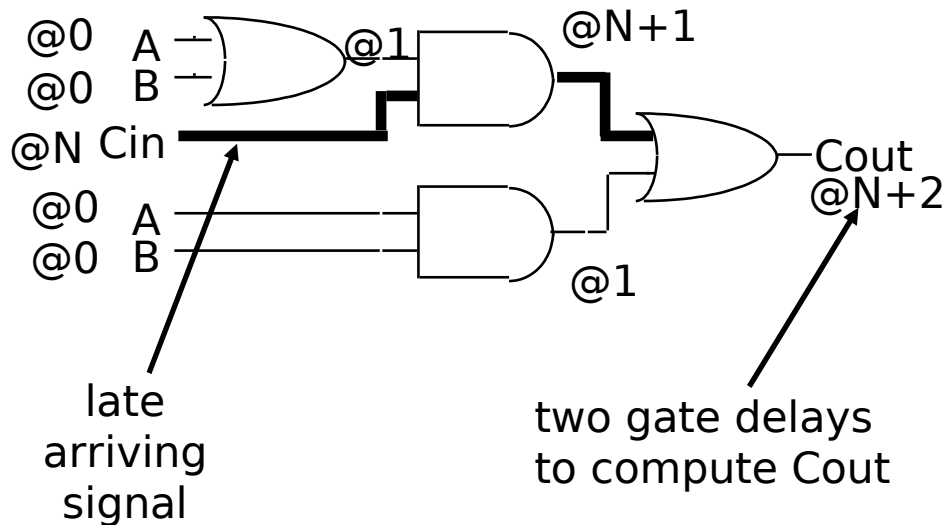
- Use an adder to do subtraction thanks to 2s complement representation
  - $A - B = A + (-B) = A + B' + 1$
  - control signal selects B or 2s complement of B



# Ripple-carry adders

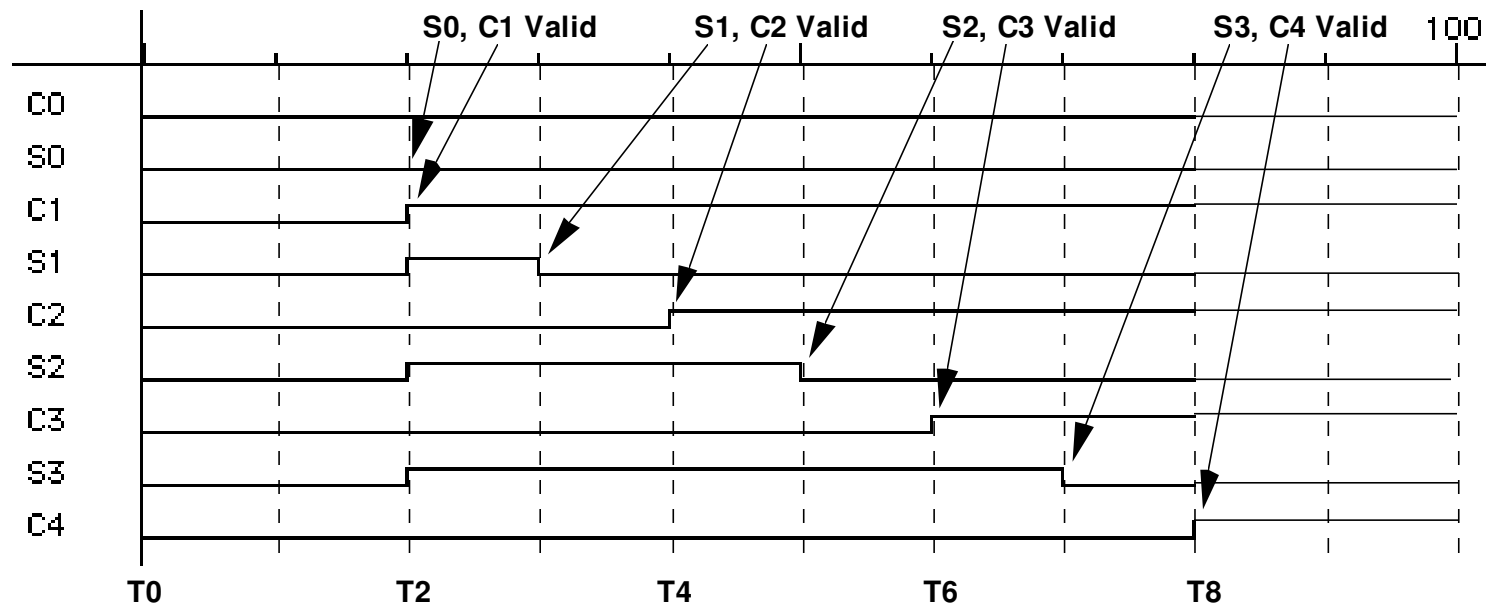
- Critical delay

- the propagation of carry from low to high order stages



# Ripple-carry adders (cont'd)

- Critical delay
  - the propagation of carry from low to high order stages
  - 1111 + 0001 is the worst case addition
  - carry must propagate through all bits



# Carry-lookahead logic

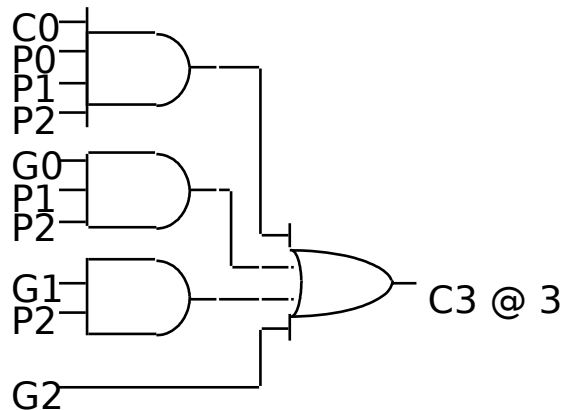
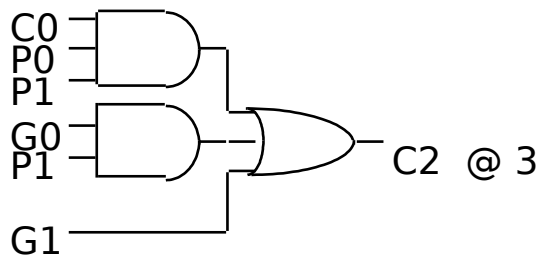
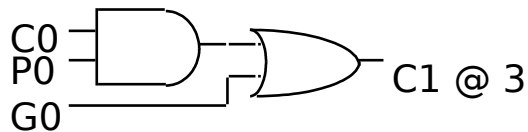
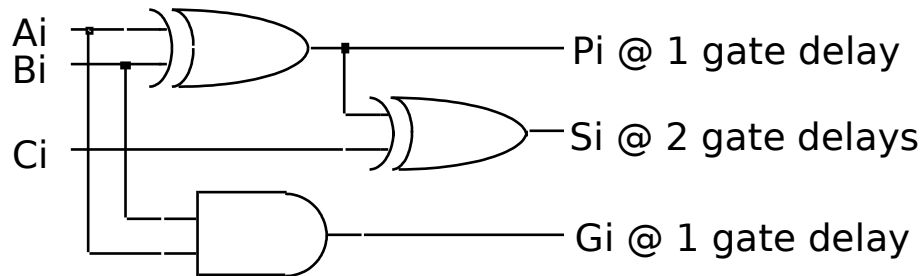
- Carry generate:  $G_i = A_i B_i$ 
  - must generate carry when  $A = B = 1$
- Carry propagate:  $P_i = A_i \text{ xor } B_i$ 
  - carry-in will equal carry-out here
- Sum and Cout can be re-expressed in terms of generate/propagate:
  - $S_i = A_i \text{ xor } B_i \text{ xor } C_i$   
 $= P_i \text{ xor } C_i$
  - $C_{i+1} = A_i B_i + A_i C_i + B_i C_i$   
 $= A_i B_i + C_i (A_i + B_i)$   
 $= A_i B_i + C_i (A_i \text{ xor } B_i)$   
 $= G_i + C_i P_i$

# Carry-lookahead logic (cont'd)

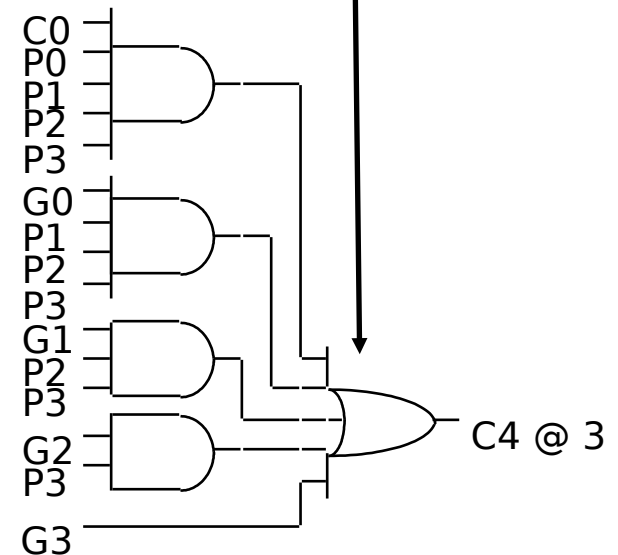
- Re-express the carry logic as follows:
  - $C_1 = G_0 + P_0 C_0$
  - $C_2 = G_1 + P_1 C_1 = G_1 + P_1 G_0 + P_1 P_0 C_0$
  - $C_3 = G_2 + P_2 C_2 = G_2 + P_2 G_1 + P_2 P_1 G_0 + P_2 P_1 P_0 C_0$
  - $C_4 = G_3 + P_3 C_3 = G_3 + P_3 G_2 + P_3 P_2 G_1 + P_3 P_2 P_1 G_0 + P_3 P_2 P_1 P_0 C_0$
- Each of the carry equations can be implemented with two-level logic
  - all inputs are now directly derived from data inputs and not from intermediate carries
  - this allows computation of all sum outputs to proceed in parallel

# Carry-lookahead implementation

- Adder with propagate and generate outputs



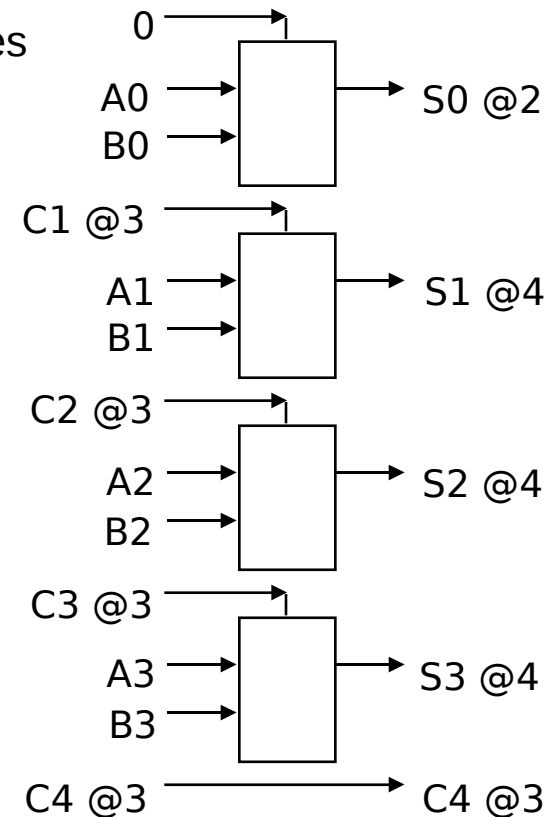
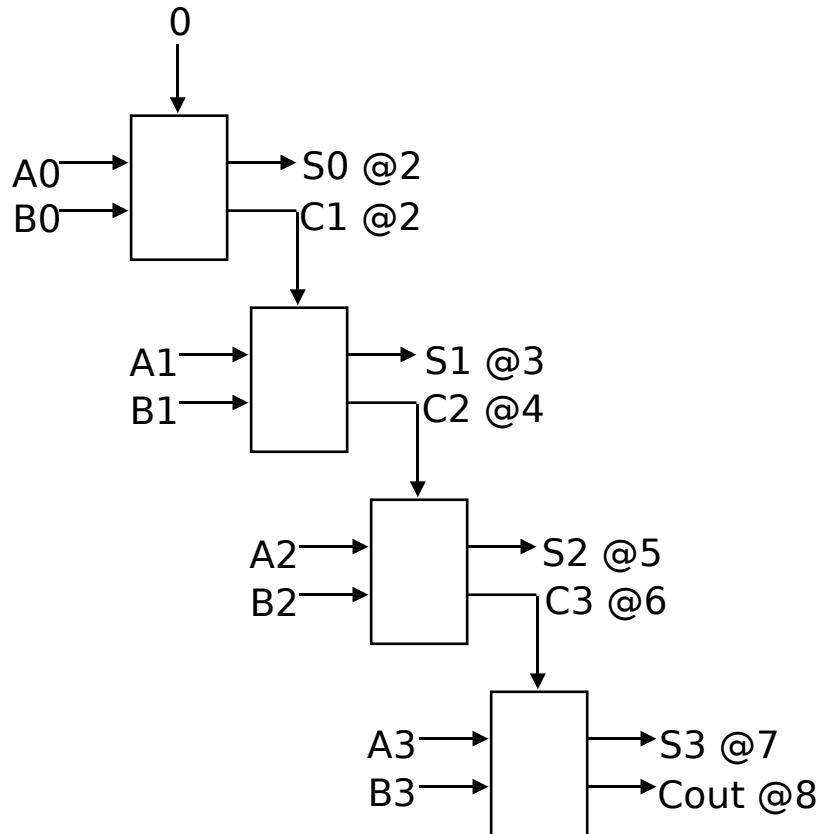
increasingly complex  
logic for carries





# Carry-lookahead implementation (cont'd)

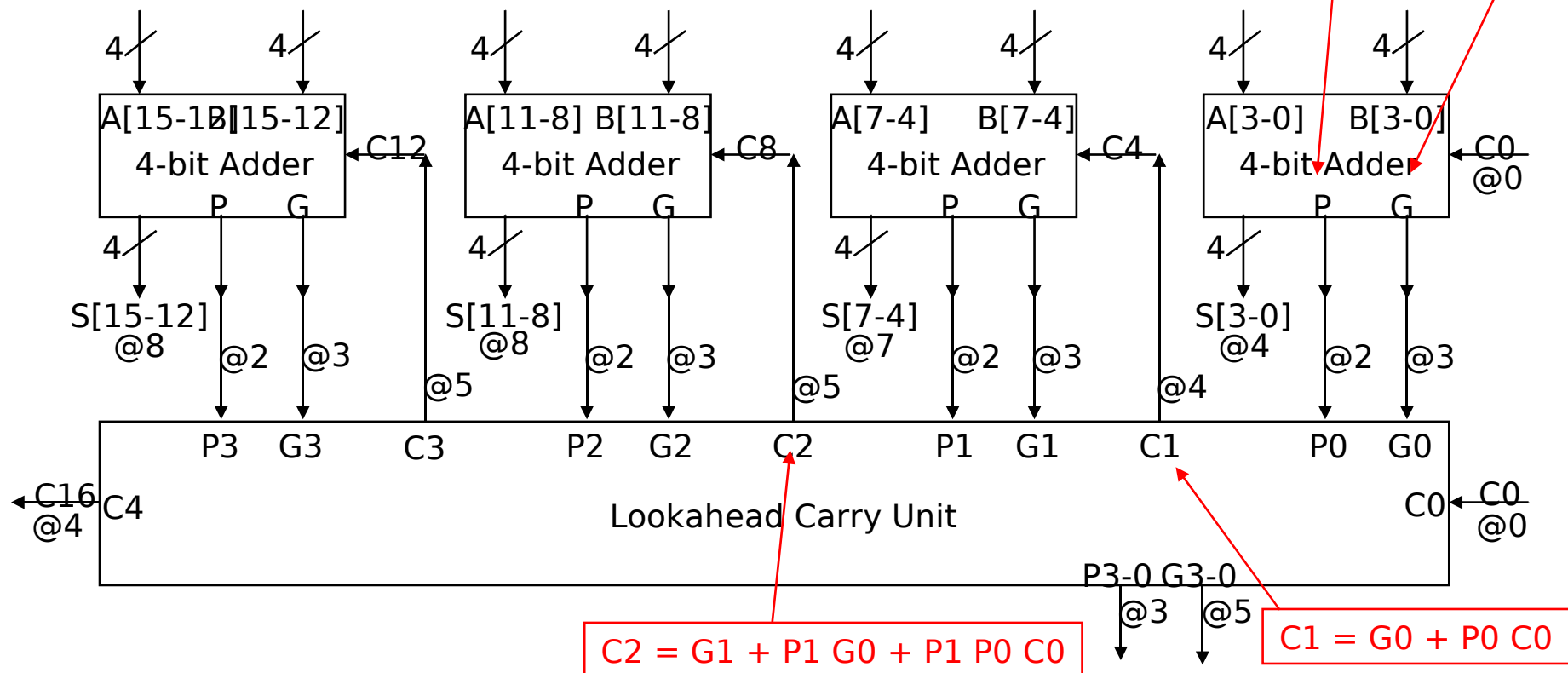
- Carry-lookahead logic generates individual carries
  - sums computed much more quickly in parallel
  - however, cost of carry logic increases with more stages



# Carry-lookahead adder with cascaded carry-lookahead logic

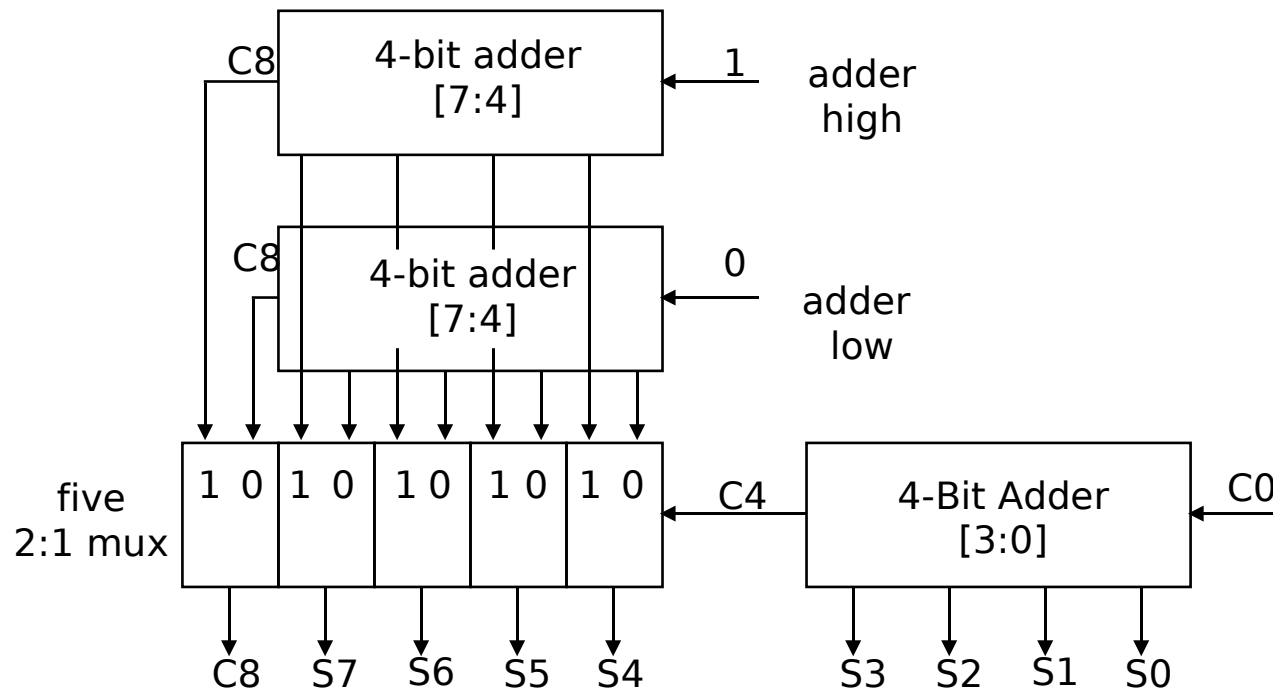
## ■ Carry-lookahead adder

- 4 four-bit adders with internal carry lookahead
- second level carry lookahead unit extends lookahead to 16 bits



# Carry-select adder

- Redundant hardware to make carry calculation go faster
  - compute two high-order sums in parallel while waiting for carry-in
  - one assuming carry-in is 0 and another assuming carry-in is 1
  - select correct result once carry-in is finally computed



# Arithmetic logic unit design specification

**M = 0, logical bitwise operations**

<b>S1</b>	<b>S0</b>	<b>Function</b>	<b>Comment</b>
0	0	<b><math>F_i = A_i</math></b>	<b>input <math>A_i</math> transferred to output</b>
0	1	<b><math>F_i = \text{not } A_i</math></b>	<b>complement of <math>A_i</math> transferred to output</b>
1	0	<b><math>F_i = A_i \text{ xor } B_i</math></b>	<b>compute XOR of <math>A_i, B_i</math></b>
1	1	<b><math>F_i = A_i \text{ xnor } B_i</math></b>	<b>compute XNOR of <math>A_i, B_i</math></b>

**M = 1, C0 = 0, arithmetic operations**

0	0	<b><math>F = A</math></b>	<b>input A passed to output</b>
0	1	<b><math>F = \text{not } A</math></b>	<b>complement of A passed to output</b>
1	0	<b><math>F = A \text{ plus } B</math></b>	<b>sum of A and B</b>
1	1	<b><math>F = (\text{not } A) \text{ plus } B</math></b>	<b>sum of B and complement of A</b>

**M = 1, C0 = 1, arithmetic operations**

0	0	<b><math>F = A \text{ plus } 1</math></b>	<b>increment A</b>
0	1	<b><math>F = (\text{not } A) \text{ plus } 1</math></b>	<b>twos complement of A</b>
1	0	<b><math>F = A \text{ plus } B \text{ plus } 1</math></b>	<b>increment sum of A and B</b>
1	1	<b><math>F = (\text{not } A) \text{ plus } B \text{ plus } 1</math></b>	<b>B minus A</b>

**logical and arithmetic operations**  
**not all operations appear useful, but "fall out" of internal logic**

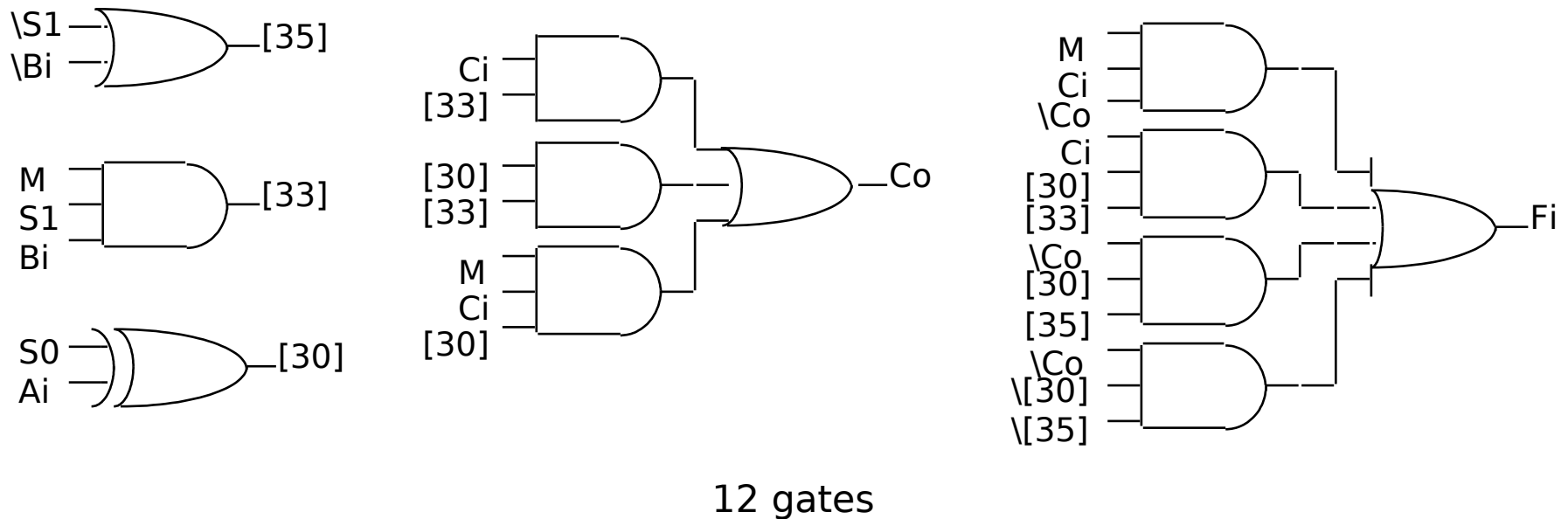
# Arithmetic logic unit design (cont'd)

- Sample ALU – truth table

M	S1	S0	Ci	Ai	Bi	Fi	Ci+1
0	0	0	X	0	X	0	X
			X	1	X	1	X
		1	X	0	X	1	X
			X	1	X	0	X
	1	0	X	0	0	0	X
			X	0	1	1	X
		1	X	1	0	1	X
			X	1	1	0	X
1	1	1	X	0	0	1	X
			X	0	1	0	X
		0	X	1	0	0	X
			X	1	1	1	X
	0	0	0	0	X	0	X
			0	1	X	1	X
		1	0	0	X	1	X
			0	1	X	0	X
1	1	0	0	0	0	0	0
			0	0	1	1	0
		1	0	1	0	0	1
			0	0	0	1	0
	0	0	1	0	X	1	0
			1	1	X	0	1
		1	1	0	X	0	1
			1	1	X	1	0
1	1	0	1	0	0	1	0
			1	0	1	0	1
		1	1	0	0	0	1
			1	0	1	0	1
	0	0	1	1	1	1	1
			1	1	0	1	1
		1	1	1	1	1	1
			1	1	0	1	1

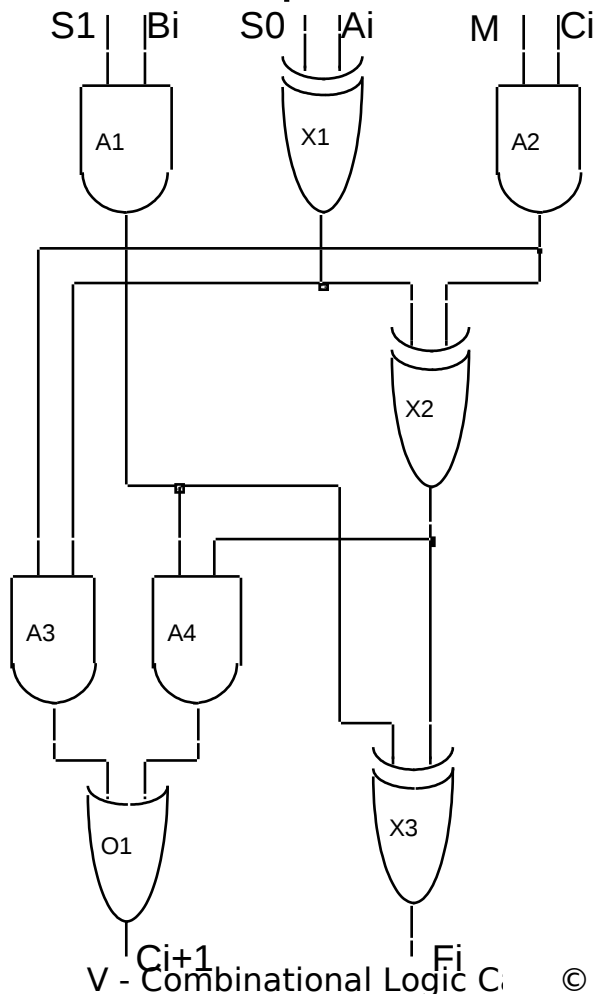
# Arithmetic logic unit design (cont'd)

- Sample ALU – multi-level discrete gate logic implementation



# Arithmetic logic unit design (cont'd)

## ■ Sample ALU – clever multi-level implementation



first-level gates

use S0 to complement Ai

S0 = 0 causes gate X1 to pass Ai

S0 = 1 causes gate X1 to pass Ai'

use S1 to block Bi

S1 = 0 causes gate A1 to make Bi go forward as 0  
(don't want Bi for operations with just A)

S1 = 1 causes gate A1 to pass Bi

use M to block Ci

M = 0 causes gate A2 to make Ci go forward as 0  
(don't want Ci for logical operations)

M = 1 causes gate A2 to pass Ci

other gates

for M=0 (logical operations, Ci is ignored)

$$F_i = S_1 B_i \text{ xor } (S_0 \text{ xor } A_i)$$

$$= S_1' S_0' (A_i) + S_1' S_0 (A_i') +$$

$$S_1 S_0' (A_i B_i' + A_i' B_i) + S_1 S_0 (A_i' B_i' + A_i B_i)$$

for M=1 (arithmetic operations)

$$F_i = S_1 B_i \text{ xor } ((S_0 \text{ xor } A_i) \text{ xor } C_i) =$$

$$C_{i+1} = C_i (S_0 \text{ xor } A_i) + S_1 B_i ((S_0 \text{ xor } A_i) \text{ xor } C_i) =$$

# Summary for examples of combinational logic

- Combinational logic design process
  - formalize problem: encodings, truth-table, equations
  - choose implementation technology (ROM, PAL, PLA, discrete gates)
  - implement by following the design procedure for that technology
- Binary number representation
  - positive numbers the same
  - difference is in how negative numbers are represented
  - 2s complement easiest to handle: one representation for zero, slightly complicated complementation, simple addition
- Circuits for binary addition
  - basic half-adder and full-adder
  - carry lookahead logic
  - carry-select
- ALU Design
  - specification, implementation