

## Combinational Logic Technologies

- Standard gates
  - gate packages
  - cell libraries
- Regular logic
  - multiplexers
  - decoders
- Two-level programmable logic
  - PALs
  - PLAs
  - ROMs

## Random logic

- Transistors quickly integrated into logic gates (1960s)
- Catalog of common gates (1970s)
  - Texas Instruments Logic Data Book – the yellow bible
  - all common packages listed and characterized (delays, power)
  - typical packages:
    - in 14-pin IC: 6-inverters, 4 NAND gates, 4 XOR gates
- Today, very few parts are still in use
- However, parts libraries exist for chip design
  - designers reuse already characterized logic gates on chips
  - same reasons as before
  - difference is that the parts don't exist in physical inventory – created as needed

## Random logic

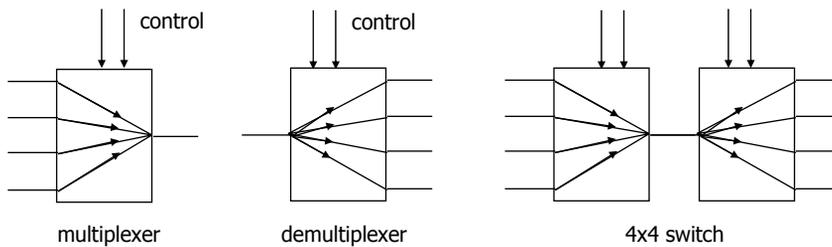
- Too hard to figure out exactly what gates to use
  - map from logic to NAND/NOR networks
  - determine minimum number of packages
    - slight changes to logic function could decrease cost
- Changes to difficult to realize
  - need to rewire parts
  - may need new parts
  - design with spares (few extra inverters and gates on every board)

## Regular logic

- Need to make design faster
- Need to make engineering changes easier to make
- Simpler for designers to understand and map to functionality
  - harder to think in terms of specific gates
  - better to think in terms of a large multi-purpose block

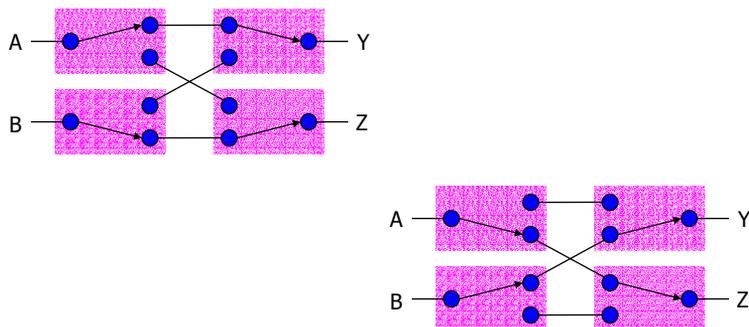
## Making connections

- Direct point-to-point connections between gates
  - wires we've seen so far
- Route one of many inputs to a single output --- multiplexer
- Route a single input to one of many outputs --- demultiplexer



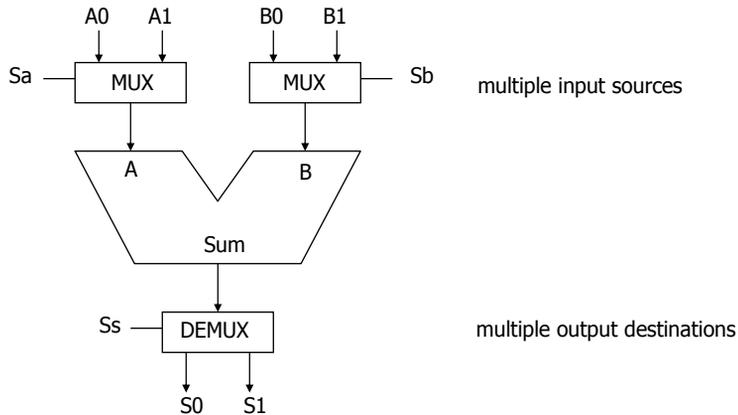
## Mux and demux

- Switch implementation of multiplexers and demultiplexers
  - can be composed to make arbitrary size switching networks
  - used to implement multiple-source/multiple-destination interconnections



## Mux and demux (cont'd)

- Uses of multiplexers/demultiplexers in multi-point connections



## Multiplexers/selectors

- Multiplexers/selectors: general concept
  - $2^n$  data inputs,  $n$  control inputs (called "selects"), 1 output
  - used to connect  $2^n$  points to a single point
  - control signal pattern forms binary index of input connected to output

$Z = A' I_0 + A I_1$

A	Z
0	$I_0$
1	$I_1$

functional form

logical form

two alternative forms for a 2:1 Mux truth table

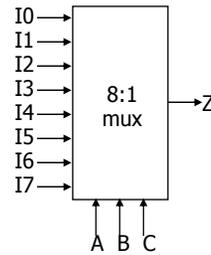
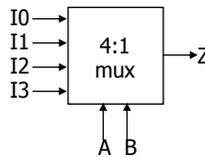
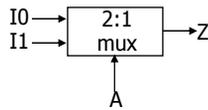
$I_1$	$I_0$	A	Z
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

## Multiplexers/selectors (cont'd)

- 2:1 mux:  $Z = A'I_0 + AI_1$
- 4:1 mux:  $Z = A'B'I_0 + A'BI_1 + AB'I_2 + ABI_3$
- 8:1 mux:  $Z = A'B'C'I_0 + A'B'CI_1 + A'BC'I_2 + A'BCI_3 + AB'C'I_4 + AB'CI_5 + ABC'I_6 + ABCI_7$

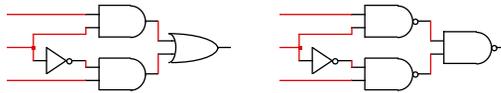
- In general:  $Z = \sum_{k=0}^{2^n-1} (m_k I_k)$

- in minterm shorthand form for a  $2^n:1$  Mux

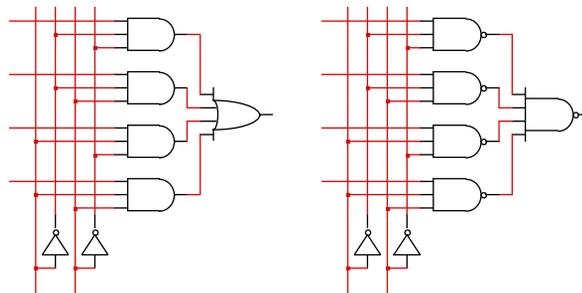


## Gate level implementation of muxes

- 2:1 mux

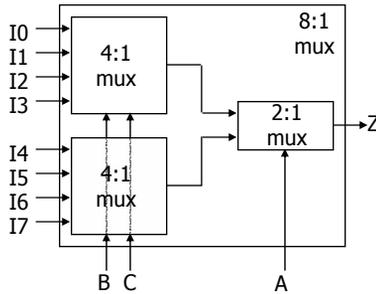


- 4:1 mux



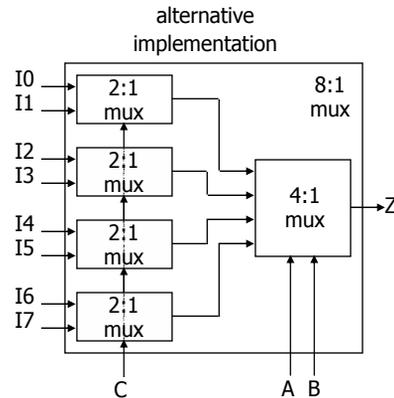
## Cascading multiplexers

- Large multiplexers can be made by cascading smaller ones



control signals B and C simultaneously choose one of I0, I1, I2, I3 and one of I4, I5, I6, I7

control signal A chooses which of the upper or lower mux's output to gate to Z

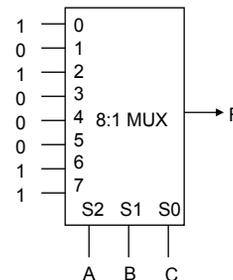


## Multiplexers as general-purpose logic

- A  $2^n:1$  multiplexer can implement any function of  $n$  variables
  - with the variables used as control inputs and
  - the data inputs tied to 0 or 1
  - in essence, a lookup table

- Example:

$$\begin{aligned}
 F(A,B,C) &= m_0 + m_2 + m_6 + m_7 \\
 &= A'B'C' + A'BC' + ABC' + ABC \\
 &= A'B'C'(1) + A'B'C(0) \\
 &\quad + A'BC'(1) + A'BC(0) \\
 &\quad + AB'C'(0) + AB'C(0) \\
 &\quad + ABC'(1) + ABC(1)
 \end{aligned}$$



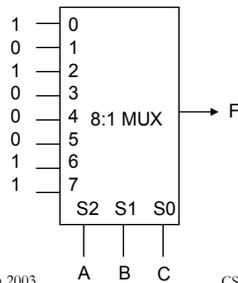
$$\begin{aligned}
 Z &= A'B'C'I_0 + A'B'CI_1 + A'BC'I_2 + A'BCI_3 + \\
 &\quad AB'C'I_4 + AB'CI_5 + ABC'I_6 + ABCI_7
 \end{aligned}$$

## Multiplexers as general-purpose logic (cont'd)

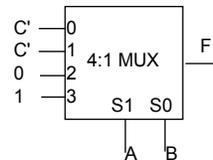
- A  $2^{n-1}:1$  multiplexer can implement any function of  $n$  variables
  - with  $n-1$  variables used as control inputs and
  - the data inputs tied to the last variable or its complement

■ Example:

$$\begin{aligned}
 F(A,B,C) &= m_0 + m_2 + m_6 + m_7 \\
 &= A'B'C' + A'BC' + ABC' + ABC \\
 &= A'B'(C') + A'B(C') + AB'(0) + AB(1)
 \end{aligned}$$



A	B	C	F
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1



## Multiplexers as general-purpose logic (cont'd)

■ Generalization

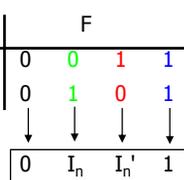
$n-1$  mux control variables

single mux data variable

$I_0$	$I_1$	...	$I_{n-1}$	$I_n$	F
.	.	.	.	0	0
.	.	.	.	1	$I_n$

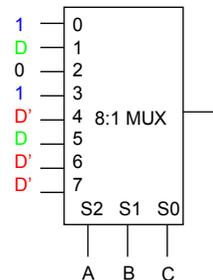
A	B	C	D	G
0	0	0	0	1
0	0	0	1	1
0	0	1	0	0
0	0	1	1	0
0	1	0	0	1
0	1	1	1	1
1	0	0	0	1
1	0	0	1	0
1	0	1	0	0
1	0	1	1	0
1	1	0	0	1
1	1	0	1	0
1	1	1	0	1
1	1	1	1	0



four possible configurations of truth table rows can be expressed as a function of  $I_n$

■ Example:  
 $G(A,B,C,D)$   
 can be realized  
 by an 8:1 MUX

choose A,B,C as control variables



## Activity

- Realize  $F = B'CD' + ABC'$  with a 4:1 multiplexer and a minimum of other gates:

## Demultiplexers/decoders

- Decoders/demultiplexers: general concept
  - single data input, n control inputs,  $2^n$  outputs
  - control inputs (called “selects” (S)) represent binary index of output to which the input is connected
  - data input usually called “enable” (G)

### 1:2 Decoder:

$$O0 = G \cdot S'$$

$$O1 = G \cdot S$$

### 2:4 Decoder:

$$O0 = G \cdot S1' \cdot S0'$$

$$O1 = G \cdot S1' \cdot S0$$

$$O2 = G \cdot S1 \cdot S0'$$

$$O3 = G \cdot S1 \cdot S0$$

### 3:8 Decoder:

$$O0 = G \cdot S2' \cdot S1' \cdot S0'$$

$$O1 = G \cdot S2' \cdot S1' \cdot S0$$

$$O2 = G \cdot S2' \cdot S1 \cdot S0'$$

$$O3 = G \cdot S2' \cdot S1 \cdot S0$$

$$O4 = G \cdot S2 \cdot S1' \cdot S0'$$

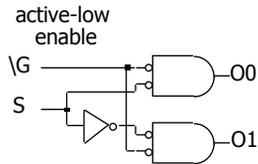
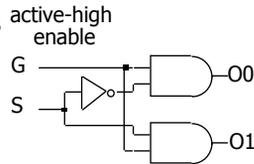
$$O5 = G \cdot S2 \cdot S1' \cdot S0$$

$$O6 = G \cdot S2 \cdot S1 \cdot S0'$$

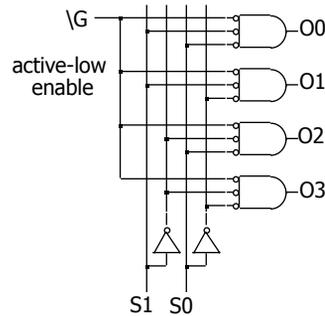
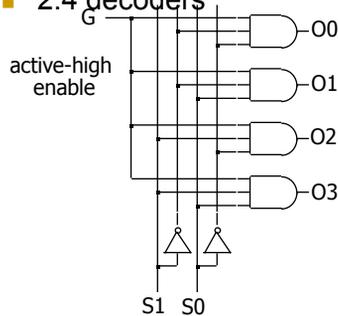
$$O7 = G \cdot S2 \cdot S1 \cdot S0$$

## Gate level implementation of demultiplexers

### 1:2 decoders

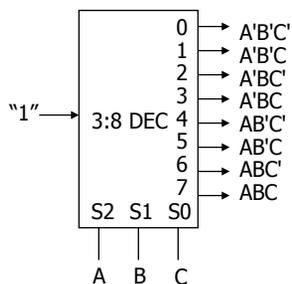


### 2:4 decoders



## Demultiplexers as general-purpose logic

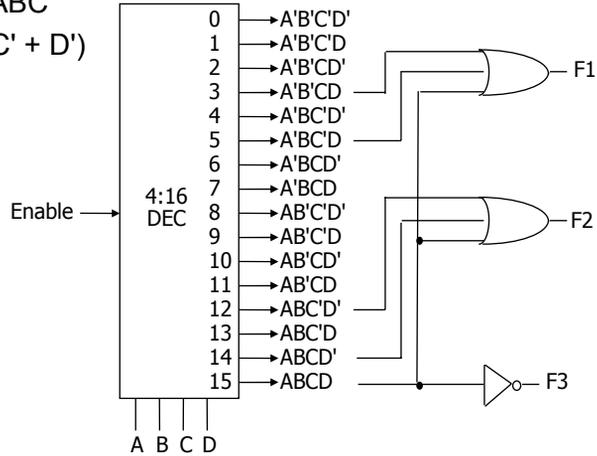
- A  $n:2^n$  decoder can implement any function of  $n$  variables
  - with the variables used as control inputs
  - the enable inputs tied to 1 and
  - the appropriate minterms summed to form the function



demultiplexer generates appropriate minterm based on control signals (it "decodes" control signals)

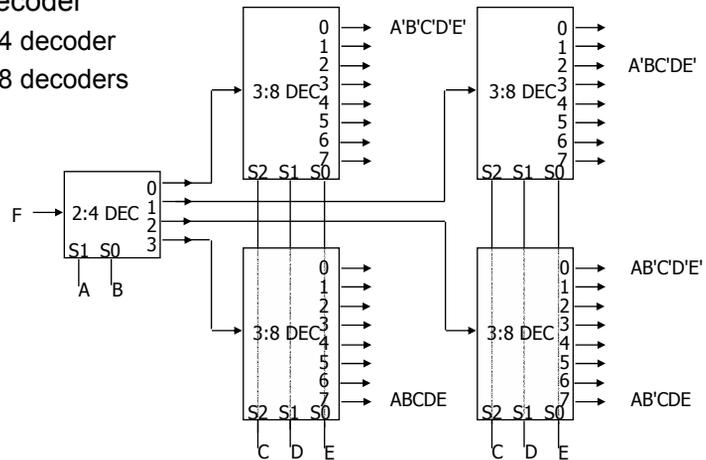
## Demultiplexers as general-purpose logic (cont'd)

- $F1 = A'BC'D + A'B'CD + ABCD$
- $F2 = ABC'D' + ABC$
- $F3 = (A' + B' + C' + D')$



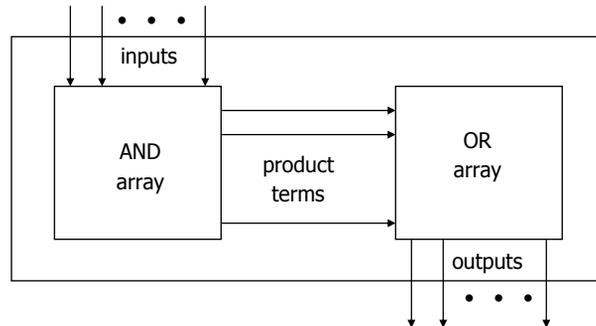
## Cascading decoders

- 5:32 decoder
  - 1x2:4 decoder
  - 4x3:8 decoders



## Programmable logic arrays

- Pre-fabricated building block of many AND/OR gates
  - actually NOR or NAND
  - "personalized" by making/breaking connections among the gates
  - programmable array block diagram for sum of products form



## Enabling concept

- Shared product terms among outputs

example:

$$F_0 = A + B' C'$$

$$F_1 = A C' + A B$$

$$F_2 = B' C' + A B$$

$$F_3 = B' C + A$$

personality matrix

product term	inputs			outputs			
	A	B	C	F0	F1	F2	F3
AB	1	1	-	0	1	1	0
B'C	-	0	1	0	0	0	1
AC'	1	-	0	0	1	0	0
B'C'	-	0	0	1	0	1	0
A	1	-	-	1	0	0	1

input side:

1 = uncomplemented in term  
 0 = complemented in term  
 - = does not participate

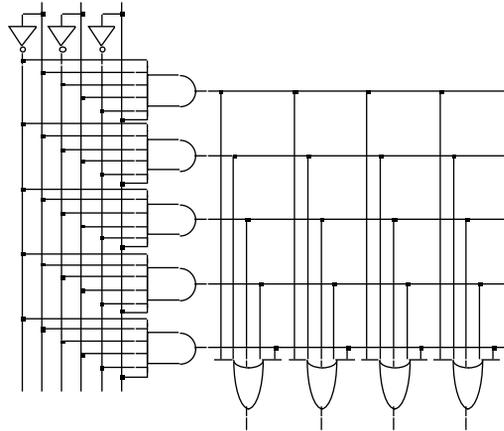
output side:

1 = term connected to output  
 0 = no connection to output

reuse of terms

## Before programming

- All possible connections are available before "programming"
  - in reality, all AND and OR gates are NANDs



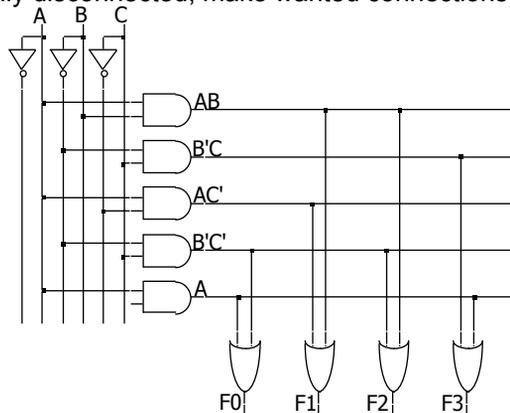
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## After programming

- Unwanted connections are "blown"
  - fuse (normally connected, break unwanted ones)
  - anti-fuse (normally disconnected, make wanted connections)



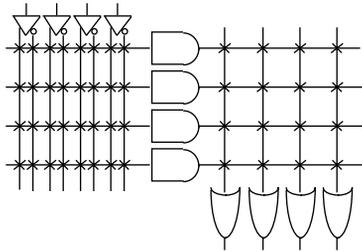
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## Alternate representation for high fan-in structures

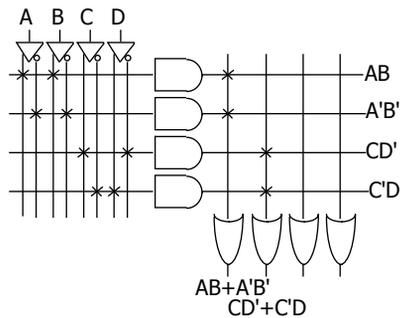
- Short-hand notation so we don't have to draw all the wires
  - $\times$  signifies a connection is present and perpendicular signal is an input to gate



notation for implementing

$$F0 = A B + A' B'$$

$$F1 = C D' + C' D$$

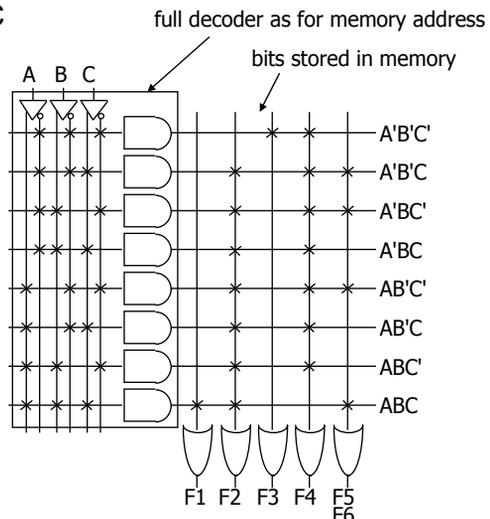


## Programmable logic array example

- Multiple functions of A, B, C

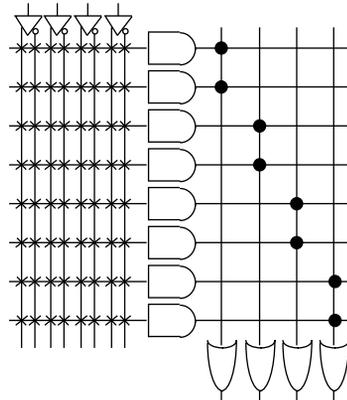
- $F1 = A B C$
- $F2 = A + B + C$
- $F3 = A' B' C'$
- $F4 = A' + B' + C'$
- $F5 = A \text{ xor } B \text{ xor } C$
- $F6 = A \text{ xnor } B \text{ xnor } C$

A	B	C	F1	F2	F3	F4	F5	F6
0	0	0	0	0	1	1	0	0
0	0	1	0	1	0	1	1	1
0	1	0	0	1	0	1	1	1
0	1	1	0	1	0	1	0	0
1	0	0	0	1	0	1	1	1
1	0	1	0	1	0	1	0	0
1	1	0	0	1	0	1	0	0
1	1	1	1	1	0	0	1	1



## PALs and PLAs

- Programmable logic array (PLA)
  - what we've seen so far
  - unconstrained fully-general AND and OR arrays
- Programmable array logic (PAL)
  - constrained topology of the OR array
  - innovation by Monolithic Memories
  - faster and smaller OR plane



a given column of the OR array has access to only a subset of the possible product terms

## PALs and PLAs: design example

- BCD to Gray code converter

A	B	C	D	W	X	Y	Z
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	1
0	0	1	0	0	0	1	1
0	0	1	1	0	0	1	0
0	1	0	0	0	1	1	0
0	1	0	1	1	1	1	0
0	1	1	0	1	0	1	0
0	1	1	1	1	0	1	1
1	0	0	0	1	0	0	1
1	0	0	1	1	0	0	0
1	0	1	-	-	-	-	-
1	1	-	-	-	-	-	-

minimized functions:

$$W = A + BD + BC$$

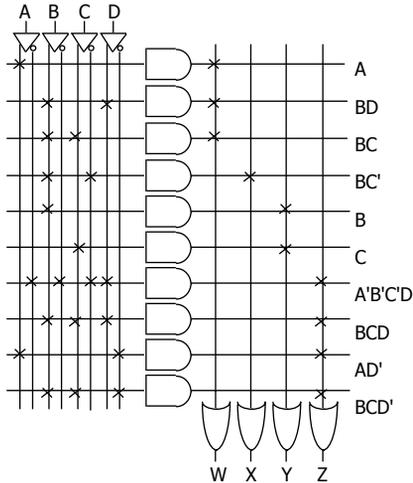
$$X = BC'$$

$$Y = B + C$$

$$Z = A'B'C'D + BCD + AD' + B'CD'$$

## PALs and PLAs: design example (cont'd)

- Code converter: programmed PLA



minimized functions:

$$\begin{aligned} W &= A + BD + BC \\ X &= B C' \\ Y &= B + C \\ Z &= A'B'C'D + BCD + AD' + B'CD' \end{aligned}$$

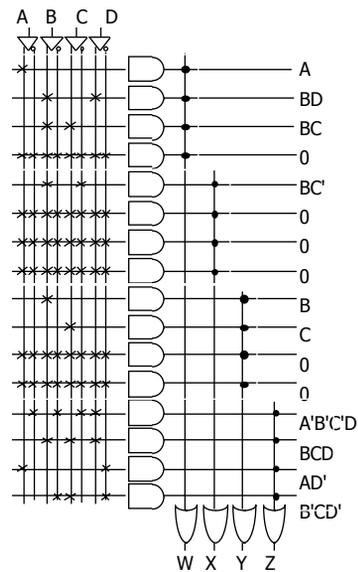
not a particularly good candidate for PAL/PLA implementation since no terms are shared among outputs

however, much more compact and regular implementation when compared with discrete AND and OR gates

## PALs and PLAs: design example (cont'd)

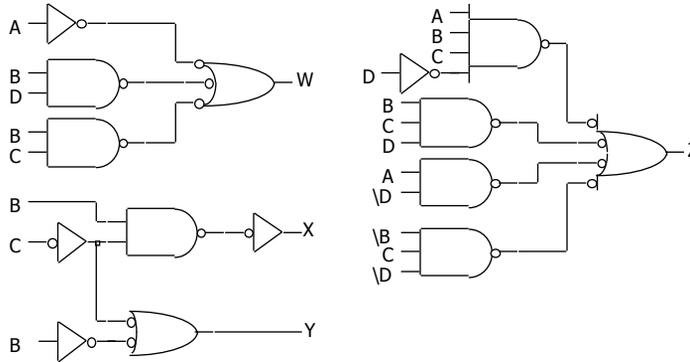
- Code converter: programmed PAL

4 product terms per each OR gate



## PALs and PLAs: design example (cont'd)

- Code converter: NAND gate implementation
  - loss of regularity, harder to understand
  - harder to make changes



## PALs and PLAs: another design example

- Magnitude comparator

A	B	C	D	EQ	NE	LT	GT
0	0	0	0	1	0	0	0
0	0	0	1	0	1	1	0
0	0	1	0	0	1	1	0
0	0	1	1	0	1	1	0
0	1	0	0	0	1	0	1
0	1	0	1	1	0	0	0
0	1	1	0	0	1	1	0
0	1	1	1	0	1	1	0
1	0	0	0	0	1	0	1
1	0	0	1	0	1	0	1
1	0	1	0	1	0	0	0
1	0	1	1	0	1	1	0
1	1	0	0	0	1	0	1
1	1	0	1	0	1	0	1
1	1	1	0	0	1	0	1
1	1	1	1	1	0	0	0

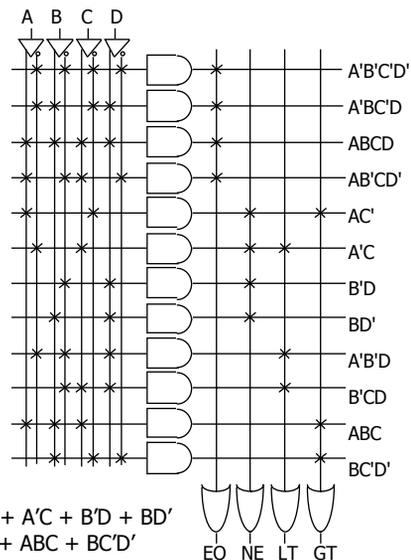
minimized functions:

$$EQ = A'B'C'D' + A'BC'D + ABCD + AB'CD'$$

$$LT = A'C + A'B'D + B'CD$$

$$NE = AC' + A'C + B'D + BD'$$

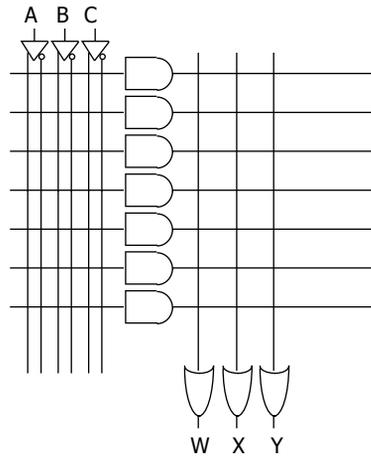
$$GT = AC' + ABC + BC'D'$$



## Activity

- Map the following functions to the PLA below:

- $W = AB + A'C' + BC'$
- $X = ABC + AB' + A'B$
- $Y = ABC' + BC + B'C'$

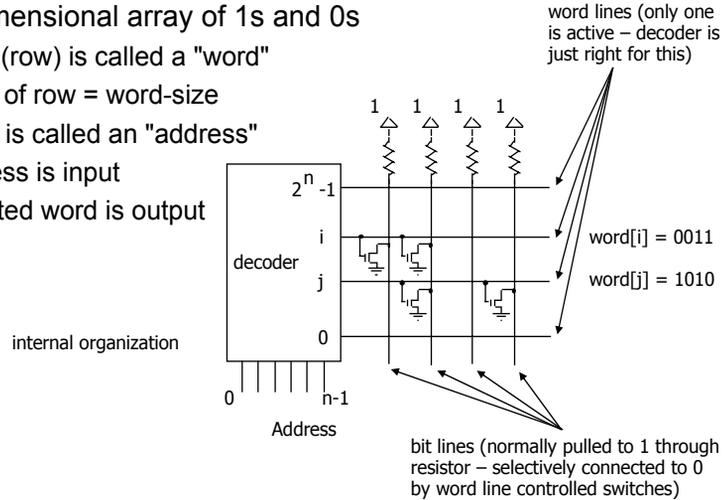


## Activity (cont'd)

## Read-only memories

- Two dimensional array of 1s and 0s

- entry (row) is called a "word"
- width of row = word-size
- index is called an "address"
- address is input
- selected word is output



## ROMs and combinational logic

- Combinational logic implementation (two-level canonical form) using a ROM

$$F0 = A' B' C + A' B C' + A B' C$$

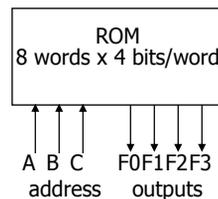
$$F1 = A' B' C + A' B C' + A B C$$

$$F2 = A' B' C' + A' B' C + A B' C'$$

$$F3 = A' B C + A B' C' + A B C'$$

A	B	C	F0	F1	F2	F3
0	0	0	0	0	1	0
0	0	1	1	1	1	0
0	1	0	0	1	0	0
0	1	1	0	0	0	1
1	0	0	1	0	1	1
1	0	1	1	0	0	0
1	1	0	0	0	0	1
1	1	1	0	1	0	0

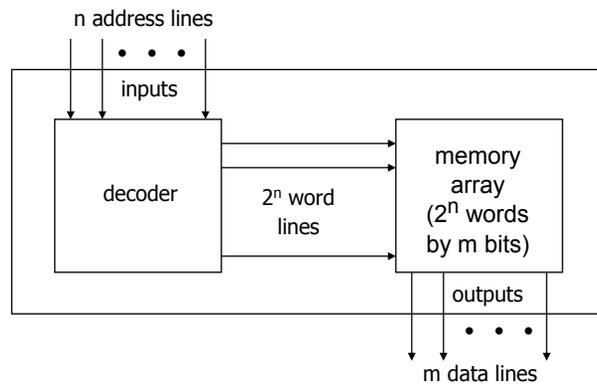
truth table



block diagram

## ROM structure

- Similar to a PLA structure but with a fully decoded AND array
  - completely flexible OR array (unlike PAL)



## ROM vs. PLA

- ROM approach advantageous when
  - design time is short (no need to minimize output functions)
  - most input combinations are needed (e.g., code converters)
  - little sharing of product terms among output functions
- ROM problems
  - size doubles for each additional input
  - can't exploit don't cares
- PLA approach advantageous when
  - design tools are available for multi-output minimization
  - there are relatively few unique minterm combinations
  - many minterms are shared among the output functions
- PAL problems
  - constrained fan-ins on OR plane

## Regular logic structures for two-level logic

- ROM – full AND plane, general OR plane
  - cheap (high-volume component)
  - can implement any function of  $n$  inputs
  - medium speed
- PAL – programmable AND plane, fixed OR plane
  - intermediate cost
  - can implement functions limited by number of terms
  - high speed (only one programmable plane that is much smaller than ROM's decoder)
- PLA – programmable AND and OR planes
  - most expensive (most complex in design, need more sophisticated tools)
  - can implement any function up to a product term limit
  - slow (two programmable planes)

## Regular logic structures for multi-level logic

- Difficult to devise a regular structure for arbitrary connections between a large set of different types of gates
  - efficiency/speed concerns for such a structure
  - in 467 you'll learn about field programmable gate arrays (FPGAs) that are just such programmable multi-level structures
    - programmable multiplexers for wiring
    - lookup tables for logic functions (programming fills in the table)
    - multi-purpose cells (utilization is the big issue)
- Use multiple levels of PALs/PLAs/ROMs
  - output intermediate result
  - make it an input to be used in further logic

## Combinational logic technology summary

- Random logic
  - Single gates or in groups
  - conversion to NAND-NAND and NOR-NOR networks
  - transition from simple gates to more complex gate building blocks
  - reduced gate count, fan-ins, potentially faster
  - more levels, harder to design
- Time response in combinational networks
  - gate delays and timing waveforms
  - hazards/glitches (what they are and why they happen)
- Regular logic
  - multiplexers/decoders
  - ROMs
  - PLAs/PALs
  - advantages/disadvantages of each