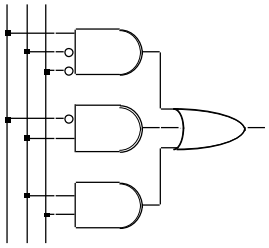
Combinational logic implementation

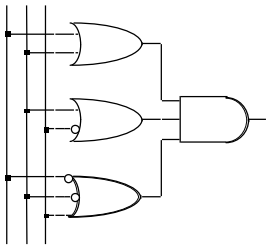
- Two-level logic
  - implementations of two-level logic
  - NAND/NOR
- Multi-level logic
  - factored forms
  - and-or-invert gates
- Time behavior
  - gate delays
  - hazards
- Regular logic
  - multiplexors
  - decoders
  - PAL/PLAs
  - ROMs

Implementations of two-level logic

- Sum-of-products
  - AND gates to form product terms (minterms)
  - OR gate to form sum

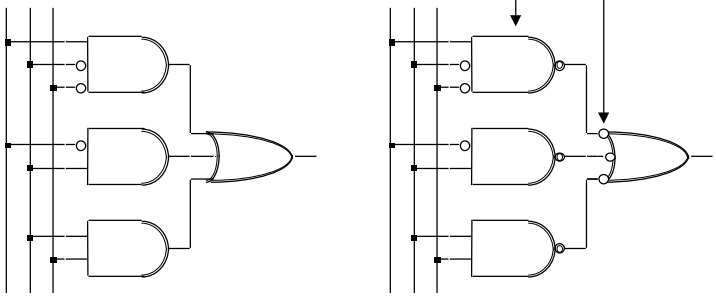


- Product-of-sums
  - OR gates to form sum terms (maxterms)
  - AND gates to form product



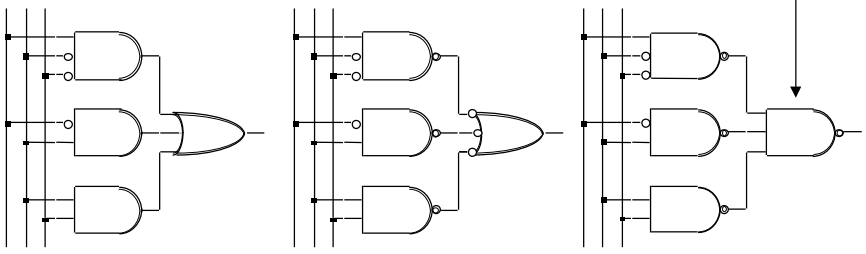
Two-level logic using NAND gates

- Replace minterm AND gates with NAND gates
- Place compensating inversion at inputs of OR gate



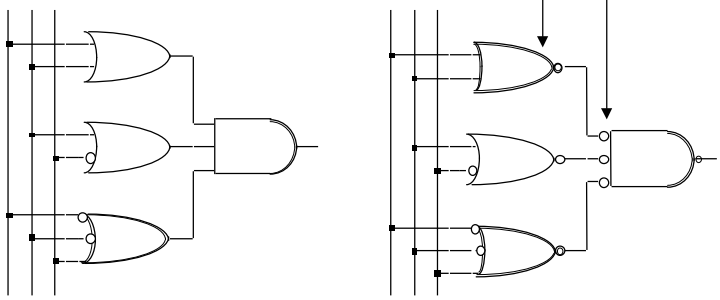
Two-level logic using NAND gates (cont'd)

- OR gate with inverted inputs is a NAND gate
  - de Morgan's: A' + B' = (A • B)'
- Two-level NAND-NAND network
  - inverted inputs are not counted
  - in a typical circuit, inversion is done once and signal distributed



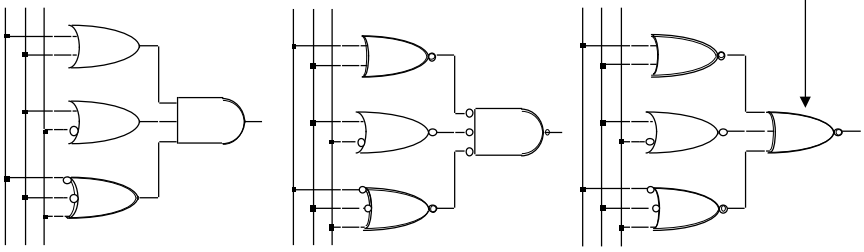
Two-level logic using NOR gates

- Replace maxterm OR gates with NOR gates
- Place compensating inversion at inputs of AND gate



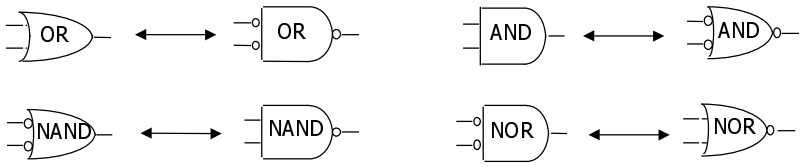
Two-level logic using NOR gates (cont'd)

- AND gate with inverted inputs is a NOR gate
  - de Morgan's: A' • B' = (A + B)'
- Two-level NOR-NOR network
  - inverted inputs are not counted
  - in a typical circuit, inversion is done once and signal distributed



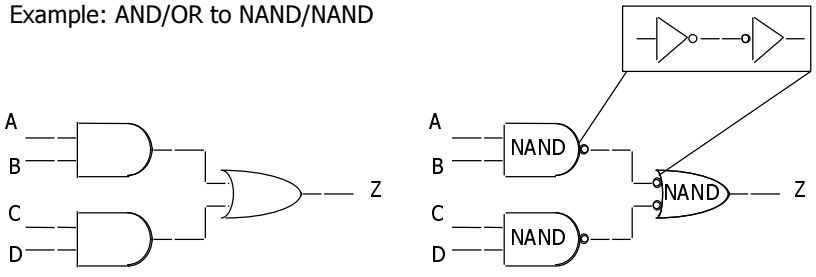
Two-level logic using NAND and NOR gates

- NAND-NAND and NOR-NOR networks
  - de Morgan's law: $(A + B)' = A' \bullet B'$ $(A \bullet B)' = A' + B'$
  - written differently: $A + B = (A' \bullet B')'$ $(A \bullet B) = (A' + B')'$
- In other words —
  - OR is the same as NAND with complemented inputs
  - AND is the same as NOR with complemented inputs
  - NAND is the same as OR with complemented inputs
  - NOR is the same as AND with complemented inputs



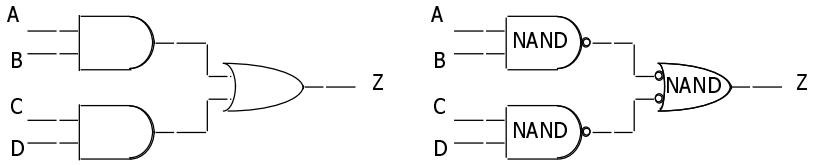
Conversion between forms

- Convert from networks of ANDs and ORs to networks of NANDs and NORs
  - introduce appropriate inversions ("bubbles")
- Each introduced "bubble" must be matched by a corresponding "bubble"
  - conservation of inversions
  - do not alter logic function
- Example: AND/OR to NAND/NAND



Conversion between forms (cont'd)

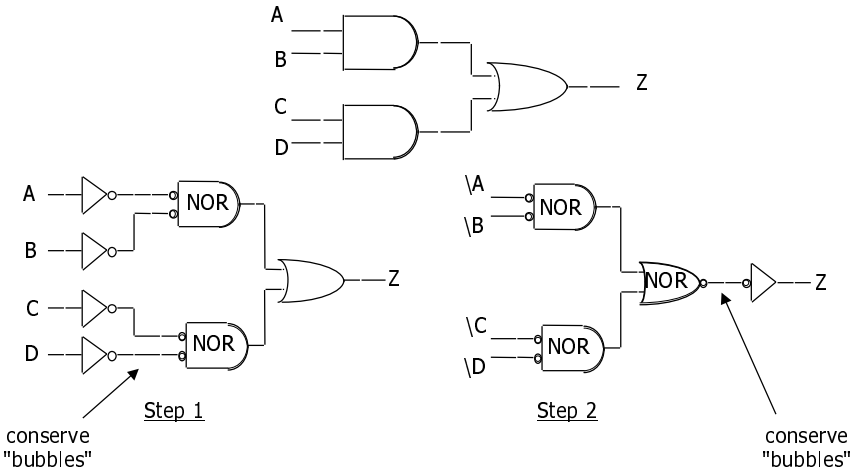
- Example: verify equivalence of two forms



$$Z = [\ (A \bullet B)' \bullet (C \bullet D)'\ ]'$$
$$= [\ (A' + B') \bullet (C' + D')\ ]'$$
$$= [\ (A' + B')' + (C' + D')'\ ]$$
$$= (A \bullet B) + (C \bullet D) \blacktriangleright$$

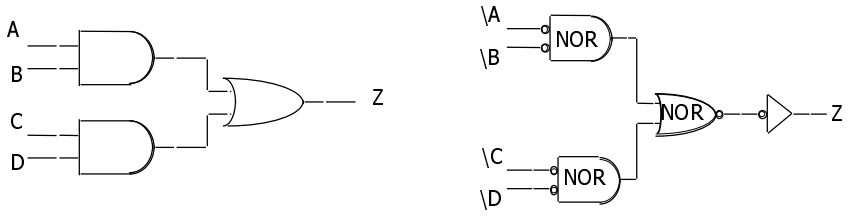
Conversion between forms (cont'd)

- Example: map AND/OR network to NOR/NOR network



Conversion between forms (cont'd)

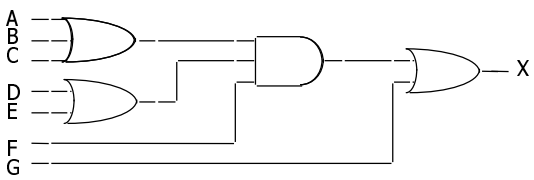
- Example: verify equivalence of two forms



$$
\begin{aligned}
Z &= \{\ [\ (A' + B')' + (C' + D')'\ ]'\ \}' \\
&= \{\ \ (A' + B')\ \bullet\ (C' + D')\ \ \}' \\
&= \quad (A' + B')' + (C' + D')' \\
&= \quad (A \bullet B)\ +\ (C \bullet D)\ \blacksquare
\end{aligned}
$$

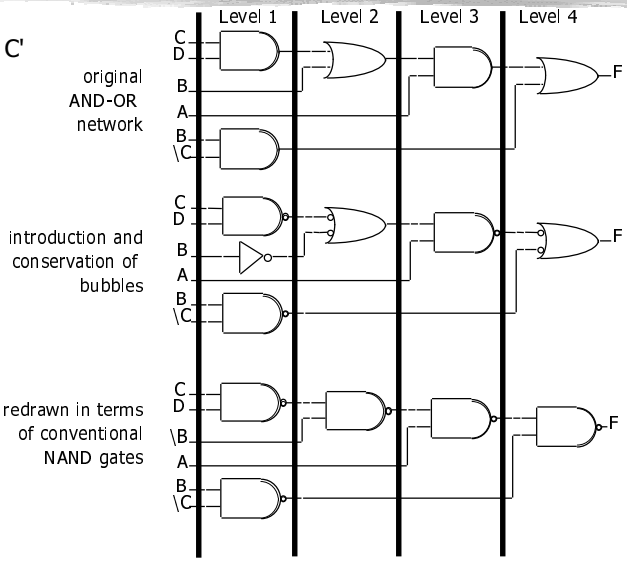
Multi-level logic

- x = A D F + A E F + B D F + B E F + C D F + C E F + G
  - reduced sum-of-products form – already simplified
  - 6 x 3-input AND gates + 1 x 7-input OR gate (that may not even exist!)
  - 25 wires (19 literals plus 6 internal wires)
- x = (A + B + C) (D + E) F + G
  - factored form – not written as two-level S-o-P
  - 1 x 3-input OR gate, 2 x 2-input OR gates, 1 x 3-input AND gate
  - 10 wires (7 literals plus 3 internal wires)



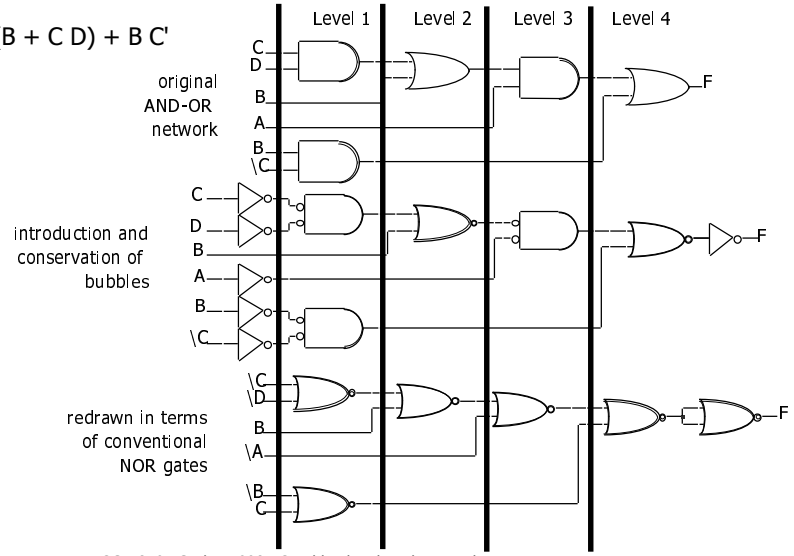
Conversion of multi-level logic to NAND gates

- F = A (B + C D) + B C'



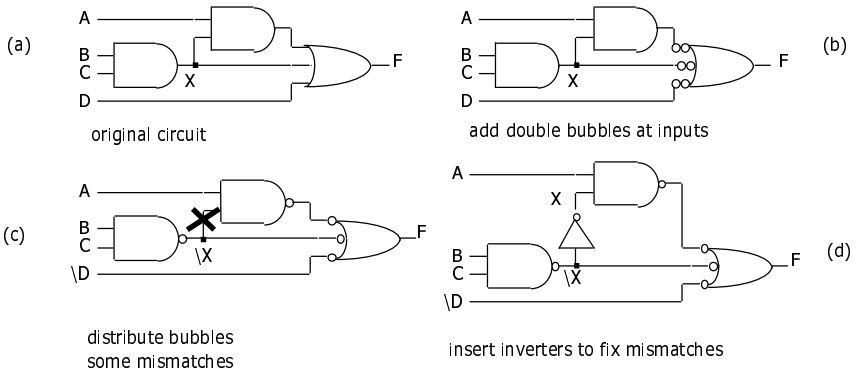
Conversion of multi-level logic to NORs

- F = A (B + C D) + B C'



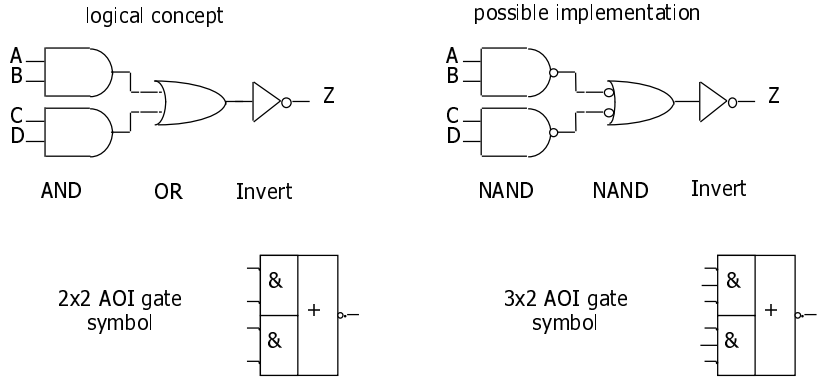
Conversion between forms

- Example



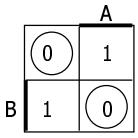
AND-OR-invert gates

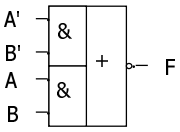
- AOI function: three stages of logic — AND, OR, Invert
  - multiple gates "packaged" as a single circuit block



Conversion to AOI forms

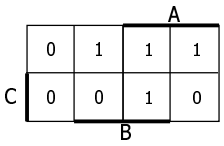
- General procedure to place in AOI form
  - compute the complement of the function in sum-of-products form
  - by grouping the 0s in the Karnaugh map
- Example: XOR implementation — A xor B = A' B + A B'
  - AOI form: F = (A' B' + A B)'





Examples of using AOI gates

- Example:
  - F = B C' + A C' + A B
  - F' = A' B' + A' C + B' C
  - Implemented by 2-input 3-stack AOI gate



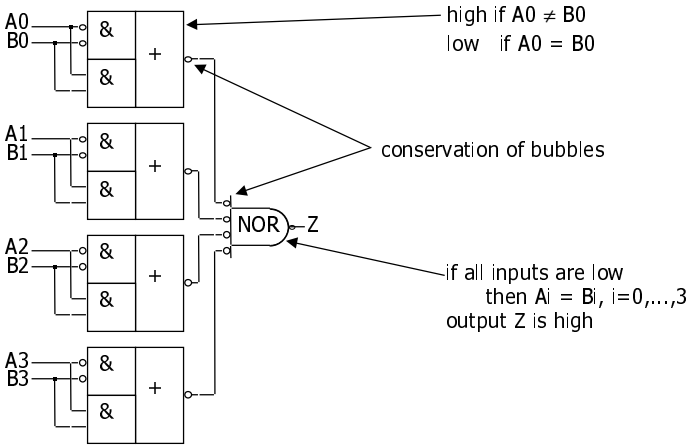
  - F = (A + B) (A + C') (B + C')
  - F' = (B' + C) (A' + C) (A' + B')
  - Implemented by 2-input 3-stack OAI gate

- Example: 4-bit equality function
  - Z = (A0 B0 + A0' B0')(A1 B1 + A1' B1')(A2 B2 + A2' B2')(A3 B3 + A3' B3')

each implemented in a single 2x2 AOI gate

Examples of using AOI gates (cont'd)

- Example: AOI implementation of 4-bit equality function



Summary for multi-level logic

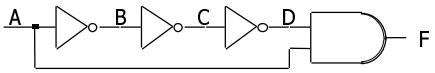
- Advantages
  - circuits may be smaller
  - gates have smaller fan-in
  - circuits may be faster
- Disadvantages
  - more difficult to design
  - tools for optimization are not as good as for two-level
  - analysis is more complex

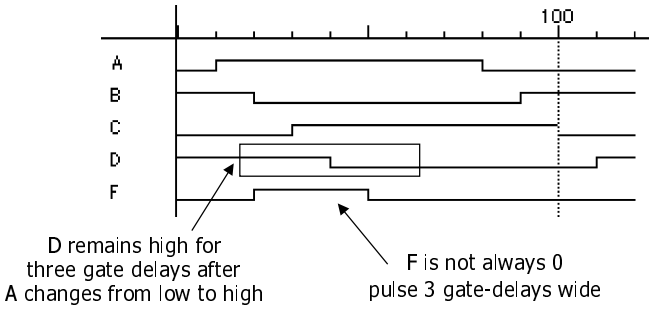
Time behavior of combinational networks

- Waveforms
  - visualization of values carried on signal wires over time
  - useful in explaining sequences of events (changes in value)
- Simulation tools are used to create these waveforms
  - input to the simulator includes gates and their connections
  - input stimulus, that is, input signal waveforms
- Some terms
  - gate delay — time for change at input to cause change at output
    - min delay – typical/nominal delay – max delay
    - careful designers design for the worst case
  - rise time — time for output to transition from low to high voltage
  - fall time — time for output to transition from high to low voltage
  - pulse width — time that an output stays high or stays low between changes

Momentary changes in outputs

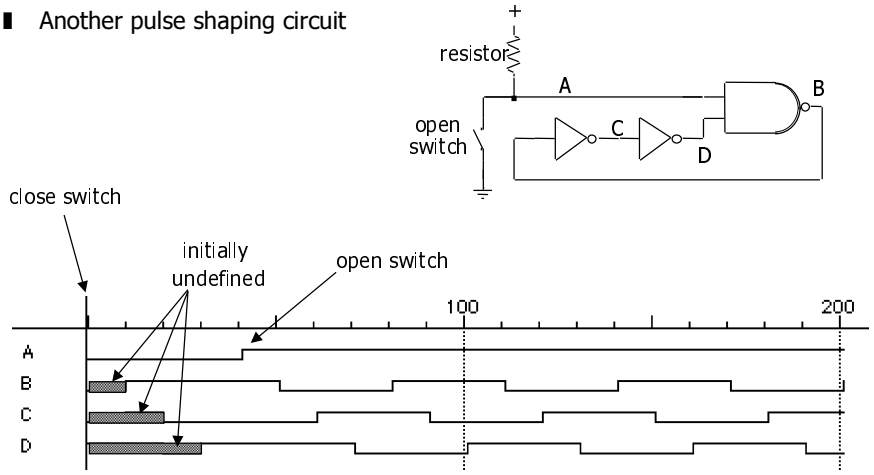
- Can be useful — pulse shaping circuits
- Can be a problem — incorrect circuit operation (glitches/hazards)
- Example: pulse shaping circuit
  - A' • A = 0
  - delays matter in function





Oscillatory behavior

- Another pulse shaping circuit



Hazards/glitches

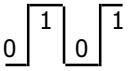
- Hazards/glitches: unwanted switching at the outputs
  - occur when different paths through circuit have different propagation delays
    - as in pulse shaping circuits we just analyzed
  - dangerous if logic causes an action while output is unstable
    - may need to guarantee absence of glitches
- Usual solutions
  - 1) wait until signals are stable (by using a clock)
    preferable (easiest to design when there is a clock – synchronous design)
  - 2) design hazard-free circuits
    sometimes necessary (clock not used – asynchronous design)

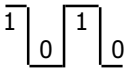
Types of hazards

- Static 1-hazard
  - input change causes output to go from 1 to 0 to 1

- Static 0-hazard
  - input change causes output to go from 0 to 1 to 0

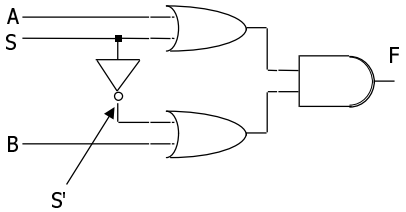
- Dynamic hazards
  - input change causes a double change from 0 to 1 to 0 to 1 OR from 1 to 0 to 1 to 0

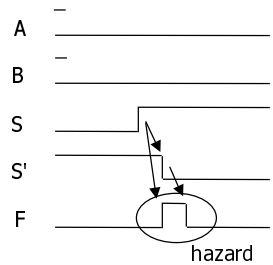




Static hazards

- Due to a literal and its complement momentarily taking on the same value
  - through different paths with different delays and reconverging
- May cause an output that should have stayed at the same value to momentarily take on the wrong value
- Example: multiplexer

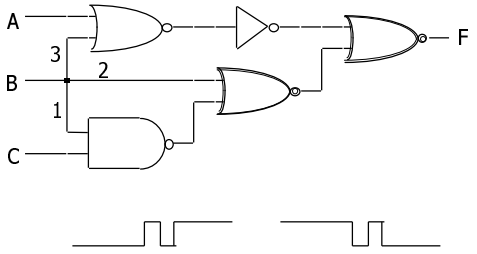




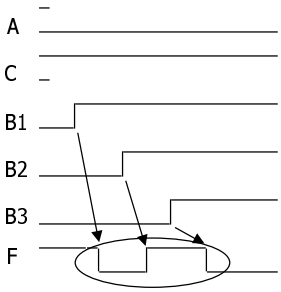
static-0 hazard static-1 hazard

Dynamic hazards

- Due to the same versions of a literal taking on opposite values
  - through different paths with different delays and reconverging
- May cause an output that was to change value
  to change 3 times instead of once
- Example:



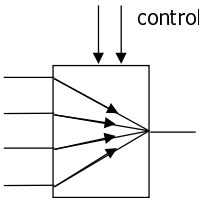
dynamic hazards



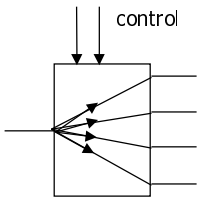
hazard

Making connections

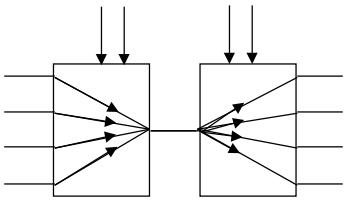
- Direct point-to-point connections between gates
  - wires we've seen so far
- Route one of many inputs to a single output --- multiplexer
- Route a single input to one of many outputs --- demultiplexer



multiplexer



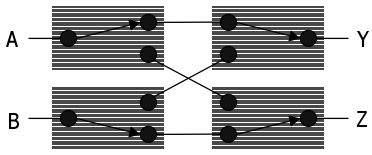
demultiplexer

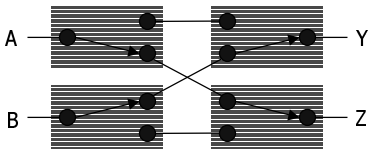


4x4 switch

Mux and demux

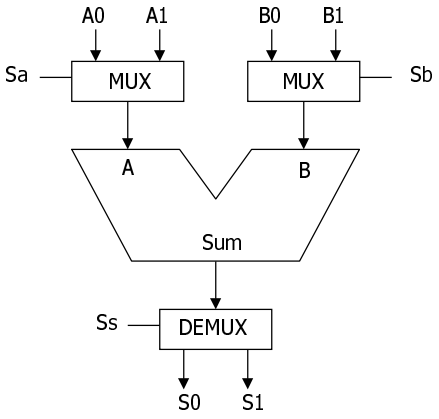
- Switch implementation of multiplexers and demultiplexers
  - can be composed to make arbitrary size switching networks
  - used to implement multiple-source/multiple-destination interconnections





Mux and demux (cont'd)

- Uses of multiplexers/demultiplexers in multi-point connections



multiple input sources

multiple output destinations

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

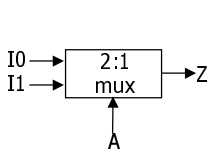
I_1	I_0	A	Z
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

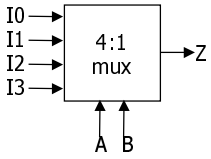
two alternative forms
for a 2:1 Mux truth table

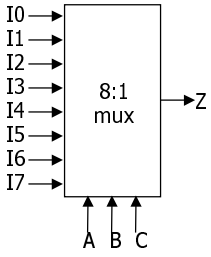
Multiplexers/selectors (cont'd)

- 2:1 mux: Z = A' I0 + A I1
- 4:1 mux: Z = A' B' I0 + A' B I1 + A B' I2 + A B I3
- 8:1 mux: Z = A' B' C' I0 + A' B' C I1 + A' B C' I2 + A' B C I3 + A B' C' I4 + A B' C I5 + A B C' I6 + A B C I7

- In general, $Z = \Sigma_{k=0}^{2^n-1} (m_k I_k)$
  - in minterm shorthand form for a 2^n:1 Mux

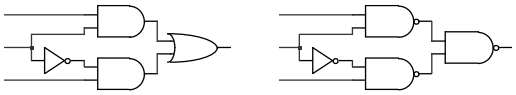




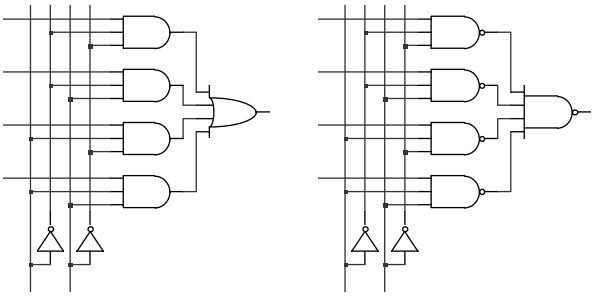


Gate level implementation of muxes

- 2:1 mux

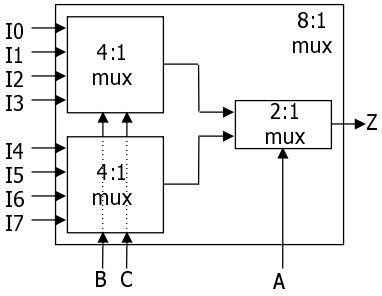


- 4:1 mux



Cascading multiplexers

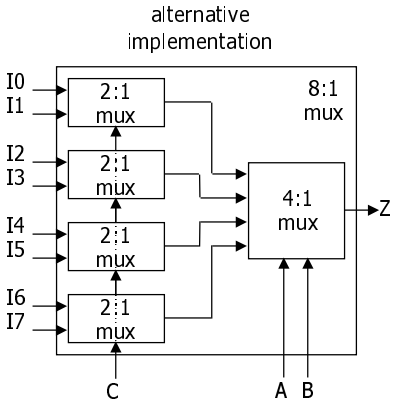
- Large multiplexers can be implemented by cascading smaller ones



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

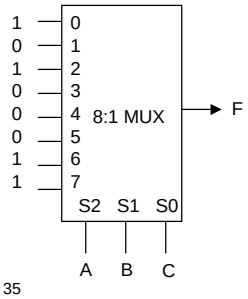
control signal A chooses which of the upper or lower mux's output to gate to Z

alternative implementation



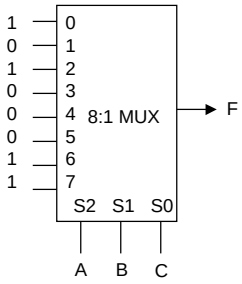
Multiplexers as general-purpose logic

- 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:
  - F(A,B,C) = m0 + m2 + m6 + m7
    = A'B'C' + A'BC' + ABC' + ABC
    = A'B'(C') + A'B(C') + AB'(0) + AB(1)

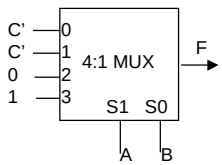


Multiplexers as general-purpose logic (cont'd)

- 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:
  - F(A,B,C) = m0 + m2 + m6 + m7
    = A'B'C' + A'BC' + ABC' + ABC
    = A'B'(C') + A'B(C') + AB'(0) + AB(1)

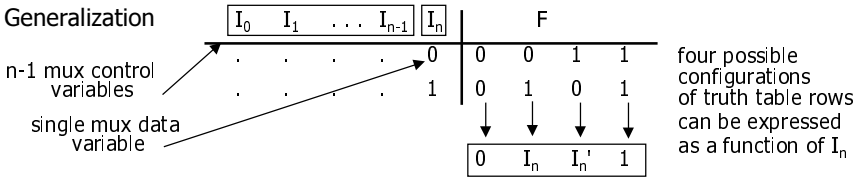


A	B	C	F	
0	0	0	1	C'
0	0	1	0	
0	1	0	1	C'
0	1	1	0	
1	0	0	0	0
1	0	1	0	
1	1	0	1	1
1	1	1	1	

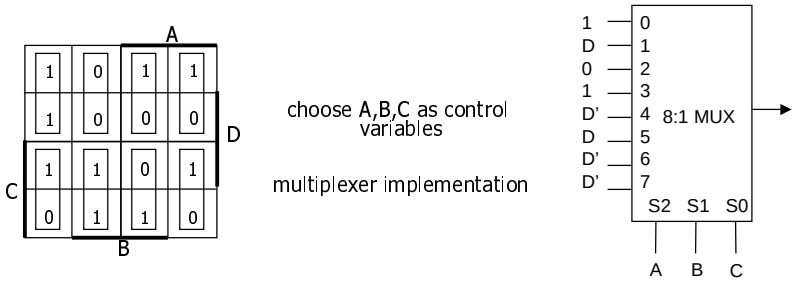


Multiplexers as general-purpose logic (cont'd)

- Generalization



- Example: F(A,B,C,D) can be implemented by an 8:1 MUX



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)

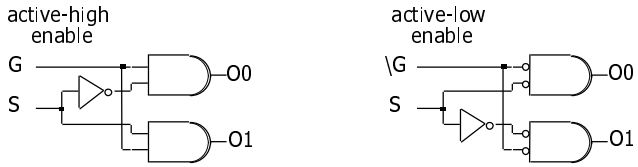
1:2 Decoder:
O0 = G • S'
O1 = G • S

2:4 Decoder:
O0 = G • S1' • S0'
O1 = G • S1' • S0
O2 = G • S1 • S0'
O3 = G • S1 • S0

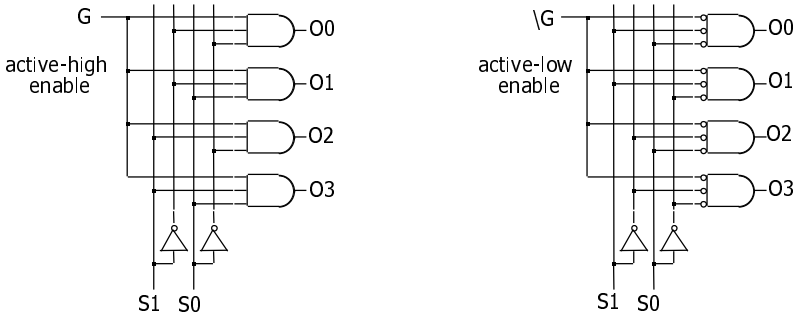
3:8 Decoder:
O0 = G • S2' • S1' • S0'
O1 = G • S2' • S1' • S0
O2 = G • S2' • S1 • S0'
O3 = G • S2' • S1 • S0
O4 = G • S2 • S1' • S0'
O5 = G • S2 • S1' • S0
O6 = G • S2 • S1 • S0'
O7 = G • S2 • S1 • S0

Gate level implementation of demultiplexers

- 1:2 decoders

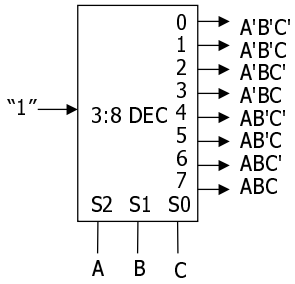


- 2:4 decoders



Demultiplexers as general-purpose logic

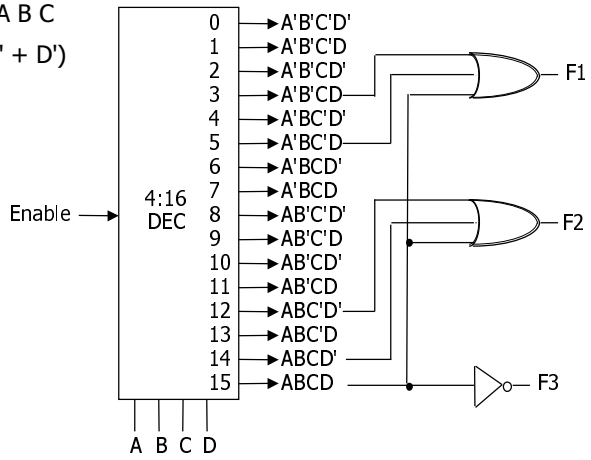
- A n:2^n decoder can implement any function of n variables
  - with the variables used as control inputs
  - the enable inputs tied to 1 and
  - the appropriate minterms summed to form the function



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

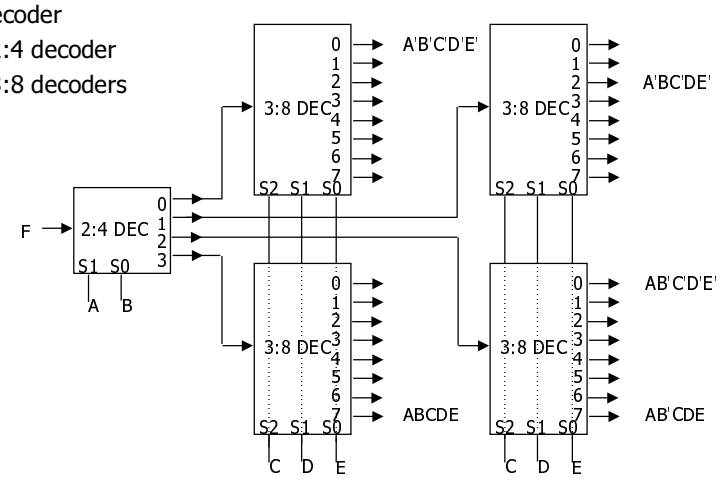
Demultiplexers as general-purpose logic (cont'd)

- F1 = A' B C' D + A' B' C D + A B C D
- F2 = A B C' D' + A B C
- F3 = (A' + B' + C' + D')



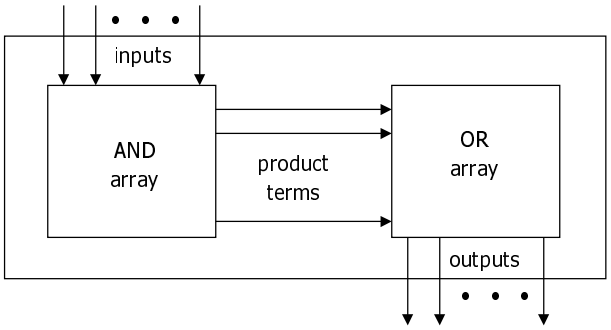
Cascading decoders

- 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 or breaking connections among the gates
  - programmable array block diagram for sum of products form



Enabling concept

- Shared product terms among outputs

example:

F0 = A + B' C'
F1 = A C' + A B
F2 = B' C' + A B
F3 = B' C + A

personality matrix

product term	inputs A	B	C	outputs 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

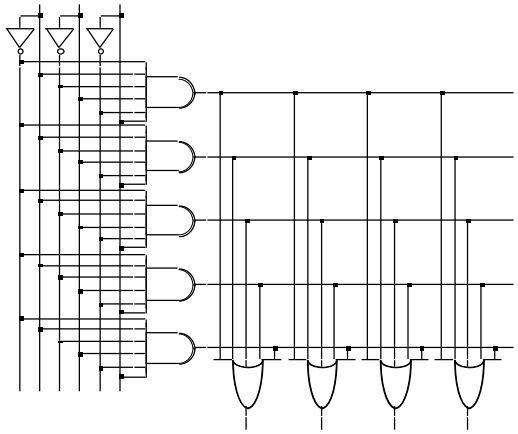
output side:

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

reuse of terms

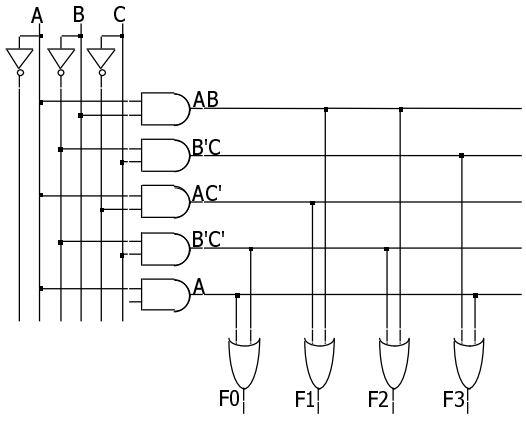
Before programming

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



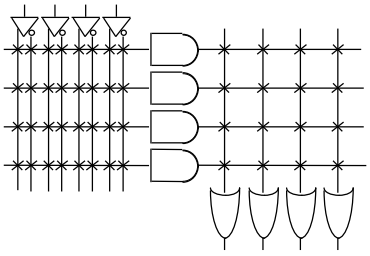
After programming

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

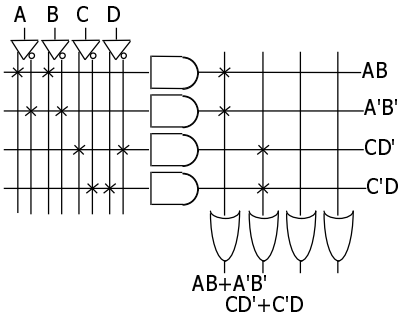


Alternate representation for high fan-in structures

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



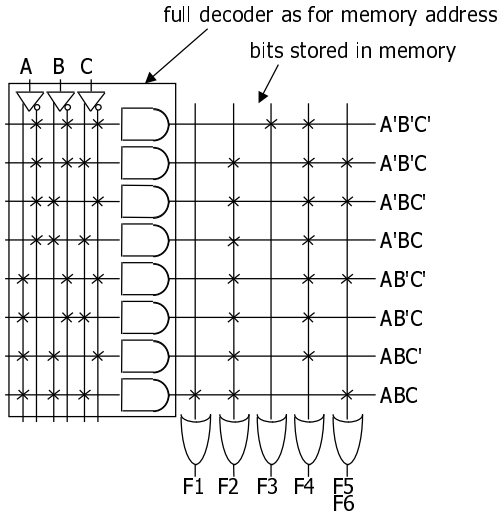
notation for implementing
F0 = A B + A' B'
F1 = C D' + C' D



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 xor B xor C
  - F6 = A xnor B xnor C

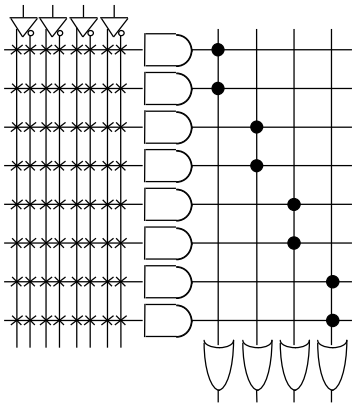
A	B	C	F1	F2	F3	F4	F5	F6
0	0	0	0	0	1	1	0	0
0	0	1	0	1	0	1	1	1
0	1	0	0	1	0	1	1	1
0	1	1	0	1	0	1	0	0
1	0	0	0	1	0	1	1	1
1	0	1	0	1	0	1	0	0
1	1	0	0	1	0	1	0	0
1	1	1	1	1	0	0	1	1



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



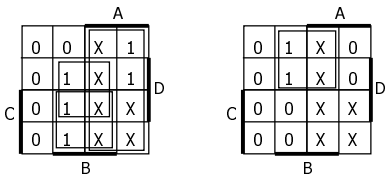
PALs and PLAs: design example

- 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	–	–	–	–	–	–

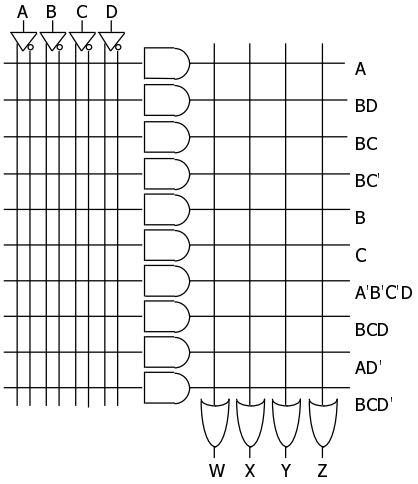
minimized functions:

W = A + B D + B C
X = B C'
Y = B + C
Z = A'B'C'D + B C D + A D' + B' C D'



PALs and PLAs: design example (cont'd)

- Code converter: programmed PLA



minimized functions:

W = A + B D + B C
X = B C'
Y = B + C
Z = A'B'C'D + B C D + A D' + B' C D'

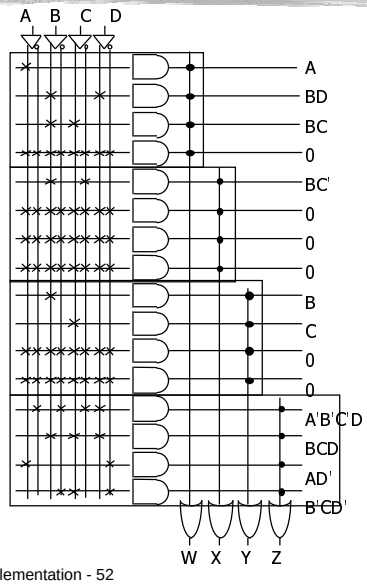
not a particularly good candidate for PAL/PLA implementation since no terms are shared among outputs

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

PALs and PLAs: design example (cont'd)

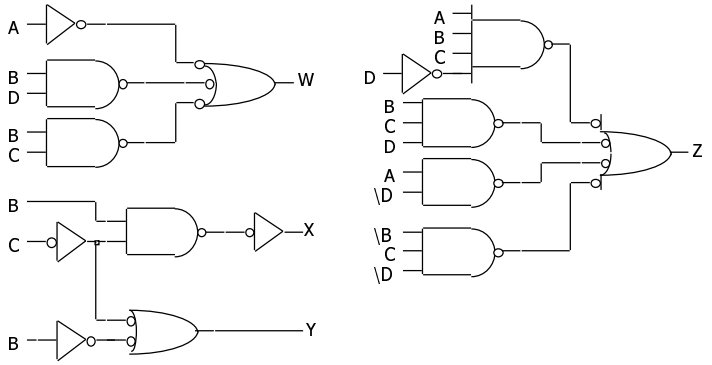
- Code converter: programmed PAL

4 product terms per each OR gate



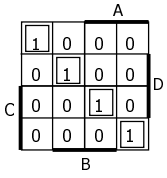
PALs and PLAs: design example (cont'd)

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

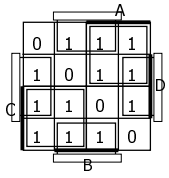


PALs and PLAs: another design example

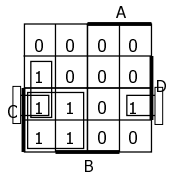
- Magnitude comparator



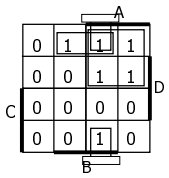
K-map for EQ



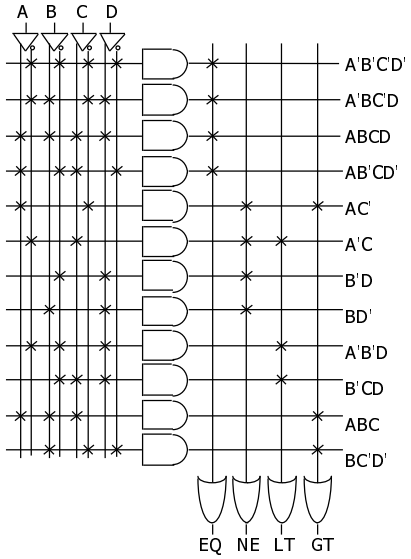
K-map for NE



K-map for LT

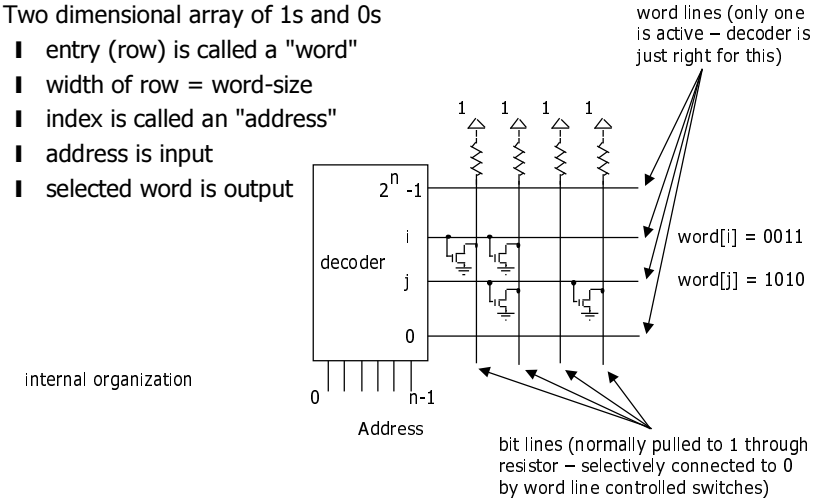


K-map for GT



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

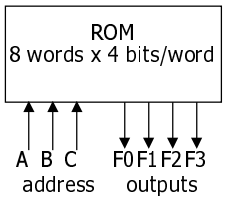
F1 = A' B' C + A' B C' + A B C

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

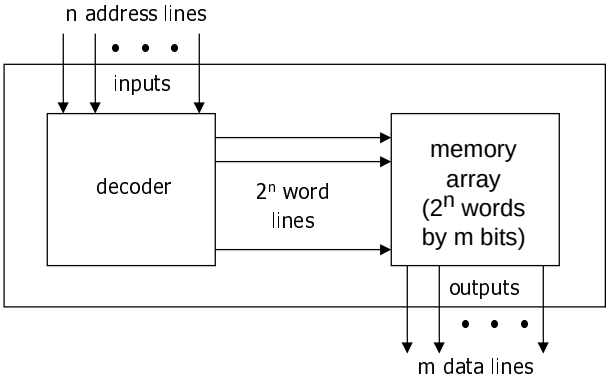
truth table



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 implementation summary

- Multi-level logic
  - 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