DIGITAL LOGIC

Chapter 3: Gate-Level Minimization

2025 Fall

baiyh@sustech.edu.cn

Today’s Agenda

- Recap
- Context
  - Gate level minimization using the Map Method
  - Product of sums simplification
  - Don’t Care Conditions
- Reading: Textbook, Chapter 3.1-3.5

Recap

- Boolean Algebra
  - DeMorgan's Law: $(x+y)'=x'y'$, $(xy)'=x'+y'$
  - Distributivity: $x(y+z)=xy+xz$; $x+yz=(x+y)(x+z)$
  - Complements: $x+x'=1$, $x \bullet x'=0$
  - etc
- Boolean Functions
  - Literals, Product term, Sum term
  - Unique: Truth table (2^n entries for n variables)
  - Not unique: Algebraic forms (simplifiable to reduce literals/terms for cheaper circuits).
- Canonical & Standard Forms
  - Canonical (unique)
    - Sum of Minterms (som: $\sum m_i$, all variables)
    - Product of Maxterms (pom: $\prod M_i$, $M_i=m_i'$)
  - Standard (not unique)
    - Sum of Products (SOP)
    - Product of Sums (POS)
- Other Logic Operations
  - Multi-input extension: AND/OR/XOR are associative; NAND/NOR are not.

Outline

- **Map Method Simplification**
- Product of sums simplification
- Don’t Care Conditions

Boolean function simplification

- A function’s truth-table representation is unique, while its algebraic expression is not unique.
- Complexity of digital circuit (gate count) $\propto$ complexity of algebraic expression (literal count)
  - F=x’y’z+x’yz+xy’ (3 Product/AND term, 8 literals)
  - F=x’z+xy’ (2 AND terms, 4 literals)
- The simplest algebraic expression is one that has minimum number of terms with the smallest possible number of literals in each term
- Methods for gate-level minimization:
  - **Algebraic method**(逻辑代数): Boolean algebra (Last lecture)
  - **Karnaugh map**(卡诺图): the map method (This lecture)

Karnaugh Map (K-map)

- An array of squares each representing one minterm to be minimized
- Each K-map defines a unique Boolean function
  - A Boolean function can be represented by a truth table, a Boolean expression, or a map
- K-map is a visual diagram of all possible ways a function may be expressed
- Used for manual minimization of Boolean functions

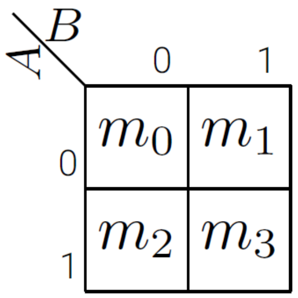
Merging Minterms

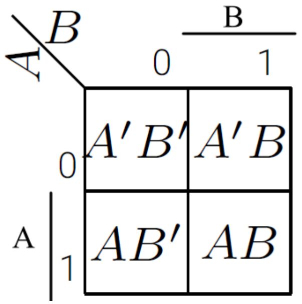
- In function F, m_1 and m_3 in the truth table differ only in one position
  - 001 → x'y'z
  - 011 → x'yz
  - 0?1, with ? matching either 0 or 1, meaning the value of input y does not affect the function's output.
- The minterms in a function can be merged to form a simpler product term
  - F = x'y'z+x'yz = x'z(y'+y) = x'z

x	y	z	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	0

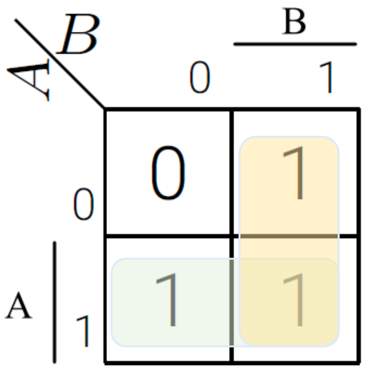
Two-Variable Map

- A two-variable map
  - is A truth table in square diagram
  - 4 minterms: A’B’, A’B, AB’, AB
  - row 0 stands for A’; row 1 stands for A
  - column 0 stands for B'; column 1 stands for B





	A	B	F
m_0	0	0	0
m_1	0	1	1
m_2	1	0	1
m_3	1	1	1



It’s ok for groups to overlap, if that makes them larger

$m_1+m_2+m_3 = A'B+AB'+AB = A+B$

Three-variable Map

- Minterms are arranged in the Gray-code sequence
- Any 2 (horizontally or vertically) adjacent squares differ by exactly 1 variable, which is complemented in one square and uncomplemented in the other.
- Any 2 minterms in adjacent squares that are ORed together will cause a removal of the different variable (adjacent applies not only the middle squares but also the boundary squares)

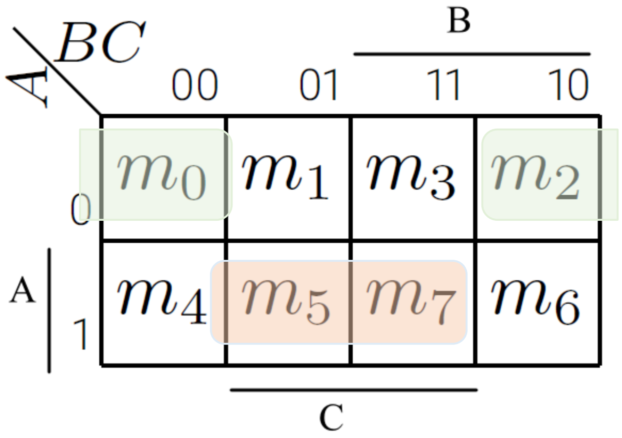
A \ BC	00	01	11	10
0	m_0	m_1	m_3	m_2
1	m_4	m_5	m_7	m_6

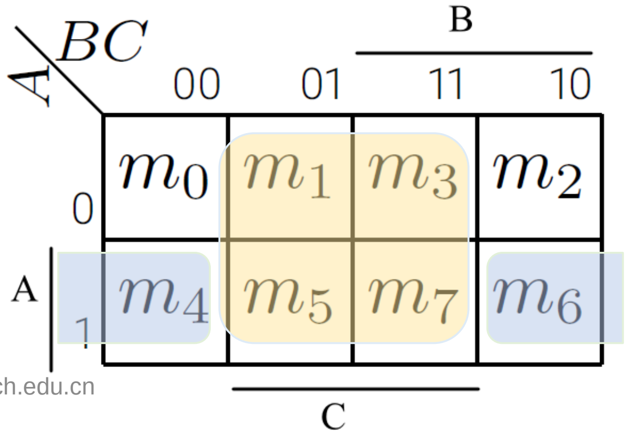
Three-variable Map

- Example (adjacent squares)
- m_5+m_7 = AB'C+ABC = AC(B+B') = AC
- m_0+m_2 = A'B'C'+A'BC' = A'C'(B+B') = A'C'
- m_4+m_6 = AB'C' + ABC' = AC' (B'+B) = AC'
- $m_1+m_3+m_5+m_7$

  = A'B'C+A'BC+AB'C+ABC=A'C(B+B')+AC(B+B')

  = A'C+AC=C





Example

- Simplify the following Boolean functions.

F = A’BC+A’BC’+AB’C’+AB’C
= A'B + AB’

A \ BC	00	01	11	10
0	0	0	1	1
1	1	1	0	0

Green circle: A’BC+A’BC’ = A’B
Red circle: AB’C’+AB’C = AB’

F = A’BC+AB’C’+ABC’+ABC
= BC + AC’

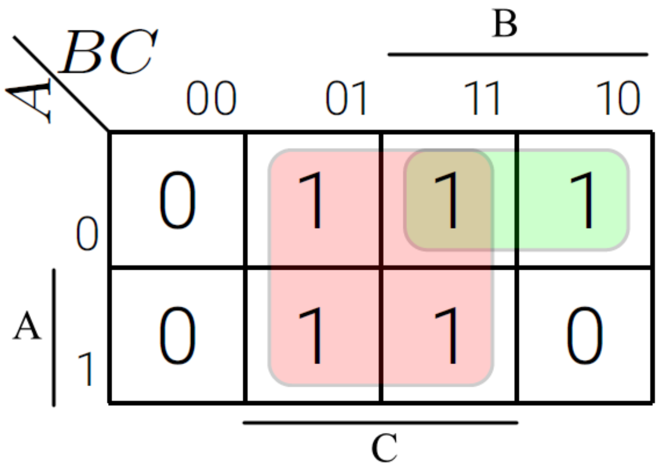
A \ BC	00	01	11	10
0	0	0	1	0
1	1	0	1	1

Green circle: A’BC + ABC = BC
Red circle: AB’C’ + ABC’ = AC’

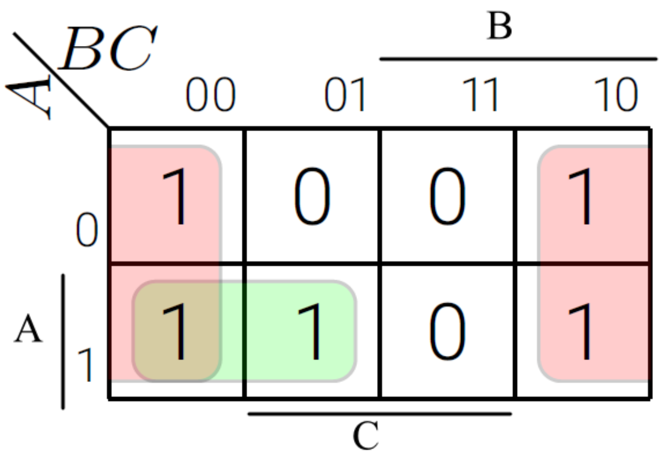
Example

- Simplify the following Boolean functions.

$F = \sum(1, 2, 3, 5, 7) = C + A'B$



$F = \sum(0, 2, 4, 5, 6) = C' + AB'$



It’s ok for groups to overlap,
if that makes them larger

Exercise

- Simplify the following Boolean function.
  - F = A'C + A'B + AB'C + BC

    = ?

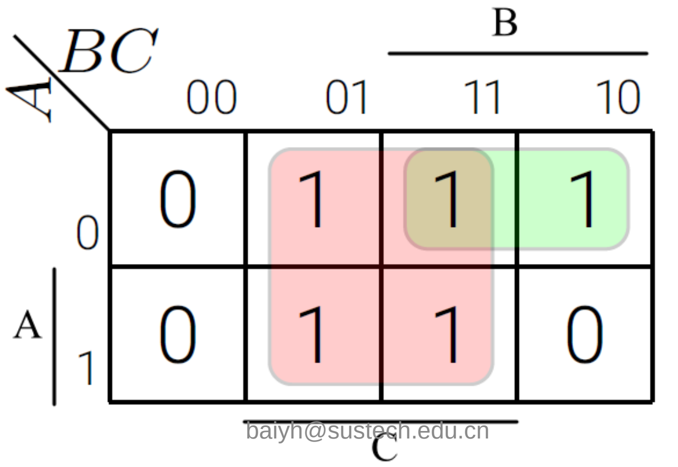
Exercise

- Simplify the following Boolean function.
  - $F = A'C + A'B + AB'C + BC = ?$
- Solution:
  - Express it in sum of minterms.
  - Find the minimal sum of products expression.
  - $F = A'C + A'B + AB'C + BC$

    $= A'C(B+B') + A'B(C+C') + AB'C + (A+A')BC$

    $= A'BC + A'B'C + \cancel{A'BC} + A'BC' + AB'C + ABC + \cancel{A'BC}$

    $= \sum(1, 2, 3, 5, 7) = C + A'B$



Four-Variable Map

- The map
  - 16 minterms
  - Combinations of 2, 4, 8, and 16 adjacent squares

$AB \backslash CD$	00	01	11	10
00	m_0	m_1	m_3	m_2
01	m_4	m_5	m_7	m_6
11	m_{12}	m_{13}	m_{15}	m_{14}
10	m_8	m_9	m_{11}	m_{10}

Implicants

- Implicant: any product term that implies the function
  - A product term that makes a function to be true

	minterm	implicant	
m_1	√	√	1-minterm
m_2	√	X	0-minterm
x'z	X	√	1 product term

x	y	z	F	
0	0	0	0	m_0
0	0	1	1	m_1
0	1	0	0	m_2
0	1	1	1	m_3
1	0	0	1	m_4
1	0	1	1	m_5
1	1	0	0	m_6
1	1	1	0	m_7

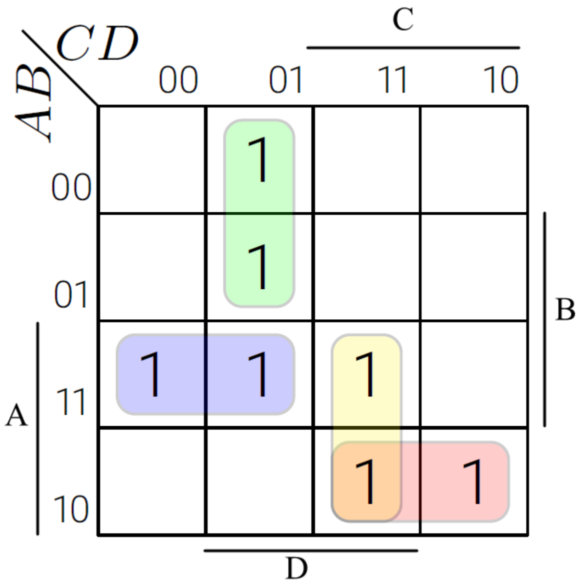
- Prime implicant (PI) (质蕴含)
  - A 1-product term obtained by combining the maximum possible number of adjacent squares in the map.
- Essential prime implicant (EPI) (基本质蕴含)
  - If a minterm in a square is covered by only one prime implicant

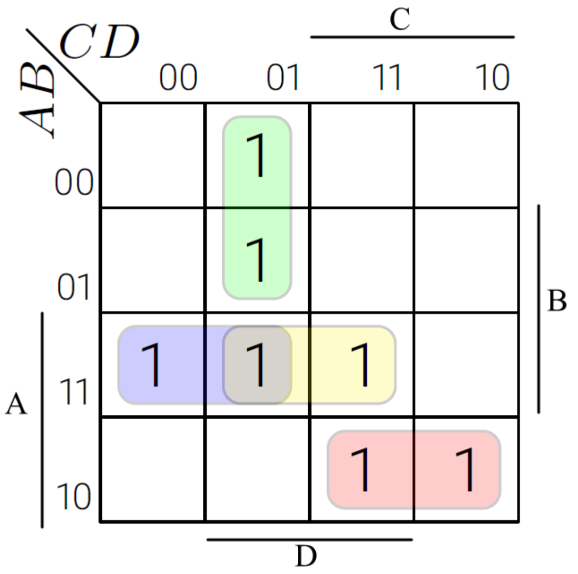
Tips for simplification

- Simplification Steps:
  - Determine all essential prime implicants.
  - Find other prime implicants that cover remaining minterms.
  - Logical sum all prime implicants.
- Tips:
  1. Adjacent Coverage(相邻覆盖): Loop adjacent 1s, making each loop as large as possible.
  2. Minimal Loops(最少圈数): Use the fewest loops to cover all 1s for simplification.
  3. Avoid Redundancy(避免冗余): Ensure each loop covers at least one unique 1 not covered by other loops.
  4. Boundary Connectivity(边界连通): Treat the map as continuous—left/right and top/bottom edges are adjacent.
  5. Power-of-Two Priority(幂次优先): Prioritize looping groups of 2^n 1s (e.g., 8, 4, 2, 1) for maximum simplification.

Example

- Simplify the following Boolean functions
- $F = m_1+m_5+m_{10}+m_{11}+m_{12}+m_{13}+m_{15}$
    - start with EPIs
    - Green circle: A′B′C′D + A′BC′D = A′C′D
    - Purple circle: ABC′D′ + ABC′D = ABC′
    - Red circle: …
    - …
  - F = A′C′D + ABC′ + ACD + AB′C
- This reduced expression is not a unique one
  - If pairs are formed in different ways, the simplified expression will be different.
  - F = A′C′D + ABC′ + ABD + AB′C

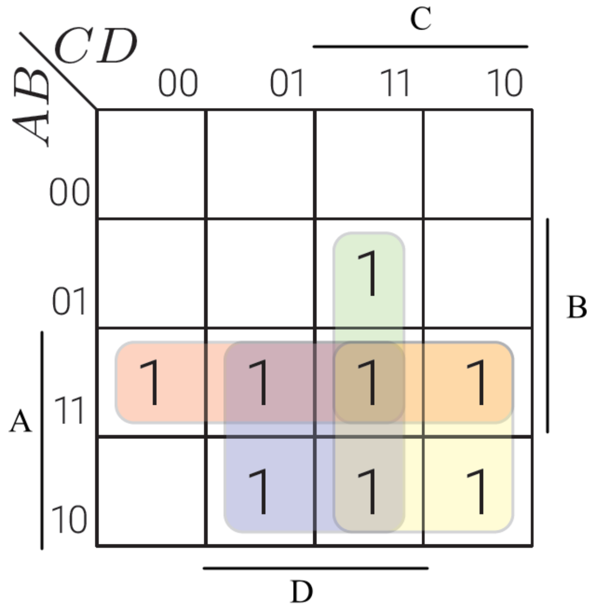




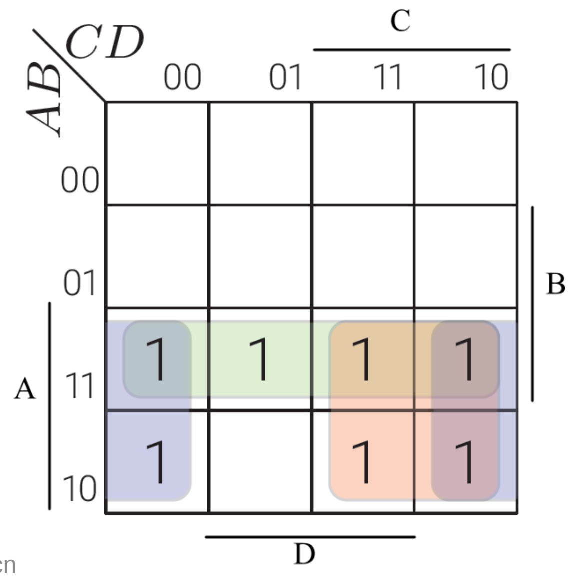
Example

- Simplify the following Boolean functions.

$F = \sum(7, 9, 10, 11, 12, 13, 14, 15)$
$= AB + AC + AD + BCD$



$F(A,B,C,D) = ABCD + AB'C'D' + AB'C + AB$
$= ABCD + AB'C'D' + AB'C(D + D')$
$+AB(C + C')(D + D')$
$= \ldots$
$= \sum(8, 10, 11, 12, 13, 14, 15)$
$=AB + AC + AD'$



Exercise

- Simplify the following Boolean functions.

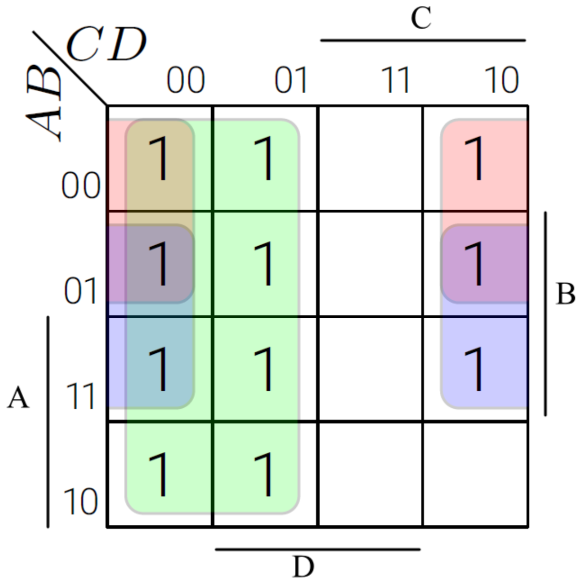
F(A,B,C,D)
$= \sum(0, 1, 2, 4, 5, 6, 8, 9, 12, 13, 14)$
= ?

F(A,B,C,D)
$= A'B'C' + B'CD' + A'BCD' + AB'C'$
= ?

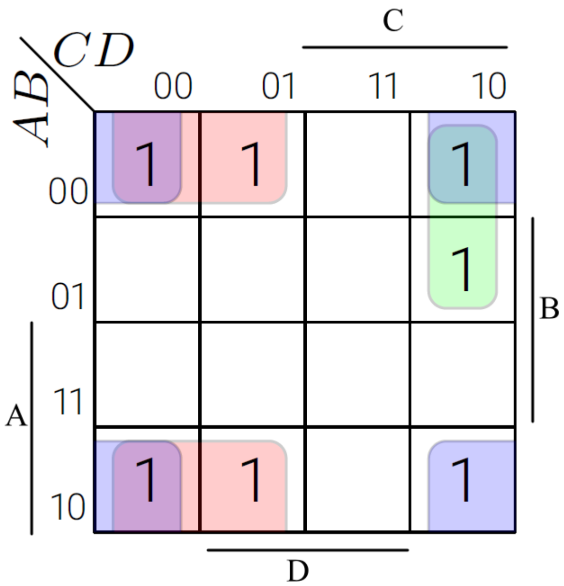
Exercise

- Simplify the following Boolean functions.

$F(A,B,C,D)$
$= \sum(0, 1, 2, 4, 5, 6, 8, 9, 12, 13, 14)$
$= C' + A'D' + BD'$



$F = A'B'C' + B'CD' + A'BCD' + AB'C'$
$= A'B'C'(D + D') + B'CD'(A + A') +$
$A'BCD' + AB'C'(D + D')$
$= A'B'C'D + A'B'C'D' + AB'CD' + A'B'CD' +$
$A'BCD' + AB'C'D + AB'C'D'$
$= \sum(0, 1, 2, 6, 8, 9, 10)$
$= B'C' + B'D' + A'CD'$



K-map Summary

- Any 2^k adjacent squares, k=0,1,...,n, in an n-variable map represent an area that gives a product term of n-k literals

K	# of adjacent squares	# of literals left in a term in an n-variable map		
		n=2	n=3	n=4
0	1	2	3	4
1	2	1	2	3
2	4	0	1	2
3	8		0	1
4	16			0

- Five-Variable Map
  - Map for more than four variables becomes complicated
  - Five-variable map: two four-variable map (one on the top of the other), contains 2^5 or 32 cells.

Outline

- Map Method Simplification
- **Product of sums simplification**
- Don’t Care Conditions

Product of Sums Simplification

- Previous Examples are Sum of Product Simplification
  - E.g. F = AB + A'D + AB'C (Product of sum form)
- How to find Product of Sum simplification
  - E.g. F = (A+B)(B+C') (Sum of Product form)
- POS simplification Steps
  - Simplified F' in the form of sum of products
    - Group adjacent 0-minterms squares together
  - Apply DeMorgan's theorem F = (F')'
  - F': sum of products → F: product of sums

Example

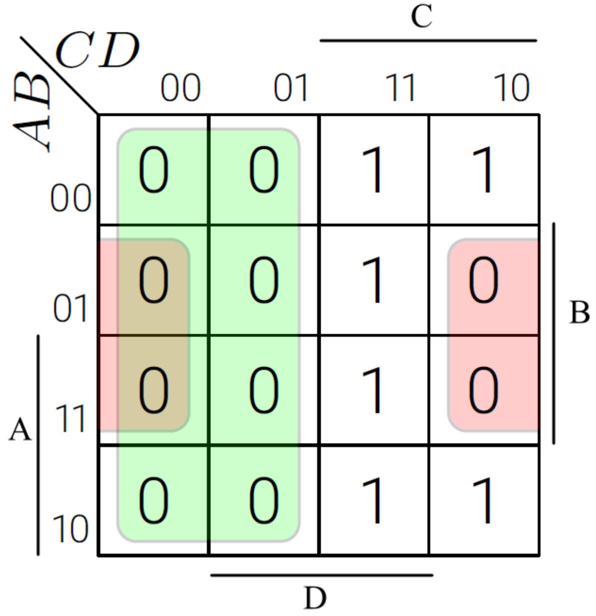
- Simplify the Boolean function into product of sums form:
  - F(A,B,C,D) = ∑(2, 3, 7, 10, 11, 15)
- Solution
  - Step1: group the 0-minterms to find F complement

    F’ = ∑(0, 1, 4, 5, 6, 8, 9, 12, 13, 14)

    = C’ + BD’ (Group 0 minterms)
  - Step2: find the complement again to get original F

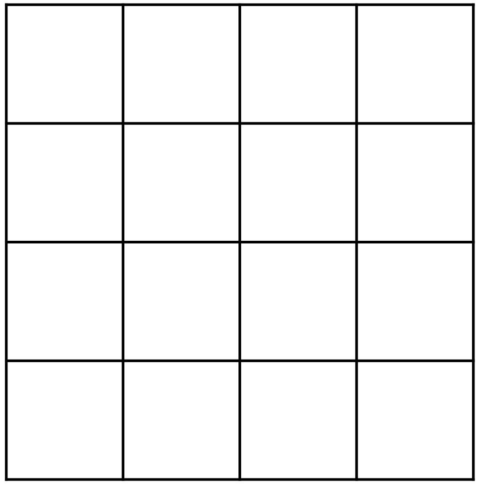
    F = (F’)’ = (C’ + BD’)’

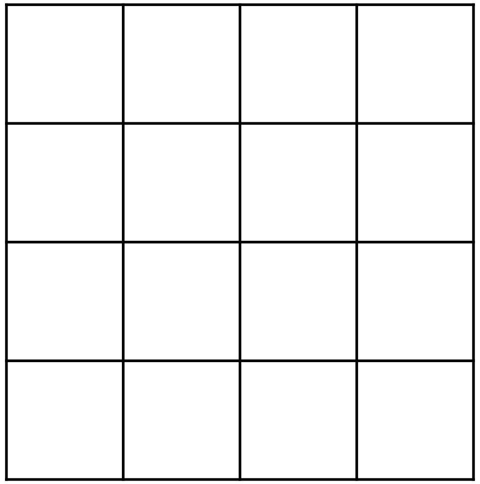
    = C(B’+D) (DeMorgan’s)



Exercise

- simplify $F(A, B, C, D) = \sum(0, 1, 2, 5, 8, 9, 10)$ into
  - sum-of-products form
    - F = ?
  - product-of-sums form
    - F = ?





Exercise

- simplify $F(A, B, C, D) = \sum(0, 1, 2, 5, 8, 9, 10)$ into
  - sum-of-products form
    - F = B'D' + B'C' + A'C'D (Group 1-minterms)
  - product-of-sums form
    - F' = AB+CD+BD'   (Group 0-minterms)
    - F = (A'+B')(C'+D')(B'+D) (DeMorgan's)

AB \ CD	00	01	11	10
00	1	1	0	1
01	0	1	0	0
11	0	0	0	0
10	1	1	0	1

AB \ CD	00	01	11	10
00	1	1	0	1
01	0	1	0	0
11	0	0	0	0
10	1	1	0	1

baiyh@sustech.edu.cn

Outline

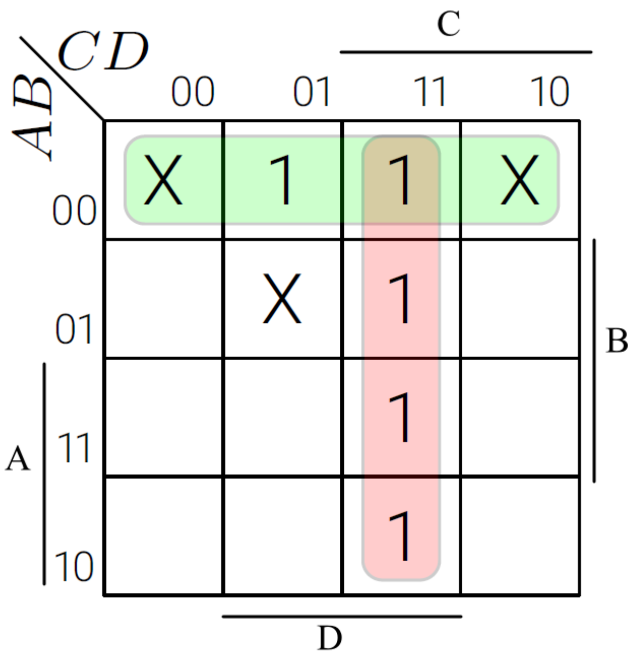
- Map Method Simplification
- Product of sums simplification
- **Don’t Care Conditions**

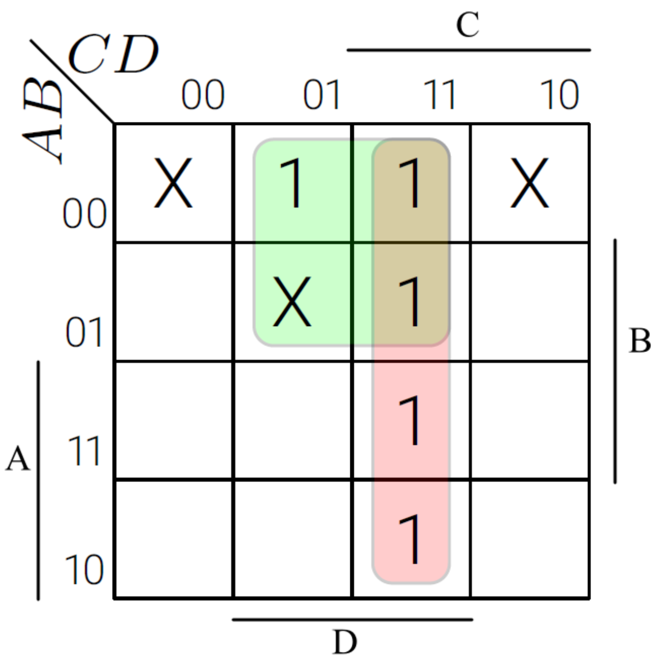
Don’t care conditions

- Incompletely specified functions
  - Functions that have unspecified outputs for some input combinations
  - E.g. output are unspecified for 1010 to 1111 in 4-bit BCD code
- Don’t-care conditions
  - Unspecified minterms of a function, don’t-cares, Xs
  - Can be used on a map to provide further simplifications of the Boolean expression
  - Each X can be assigned an arbitrary value, 0 or 1, to help simplification procedure

Example

- Simplify F(A, B, C, D) = ∑(1, 3, 7, 11, 15) with don't-care conditions d(A, B, C, D) = ∑(0, 2, 5).
  - F = A’B’ + CD
  - or F = A’D + CD
  - Just make sure all 1 minterms are circled, thus both simplifications are acceptable





Exercise

- Using the Karnaugh map method obtain the minimal sum of the products expression for the function $F(A,B,C,D) = \Sigma(0, 2, 3, 6, 7) + d(8, 10, 11, 15)$

Exercise

- Using the Karnaugh map method obtain the minimal sum of the products expression for the function F(A,B,C,D) = Σ(0, 2, 3, 6, 7) + d(8, 10, 11, 15)
- F = A'C + B'D'

AB \ CD	00	01	11	10
00	1	0	1	1
01	0	0	1	1
11	0	0	X	0
10	X	0	X	X

C B A D