

1. Perform the following steps:

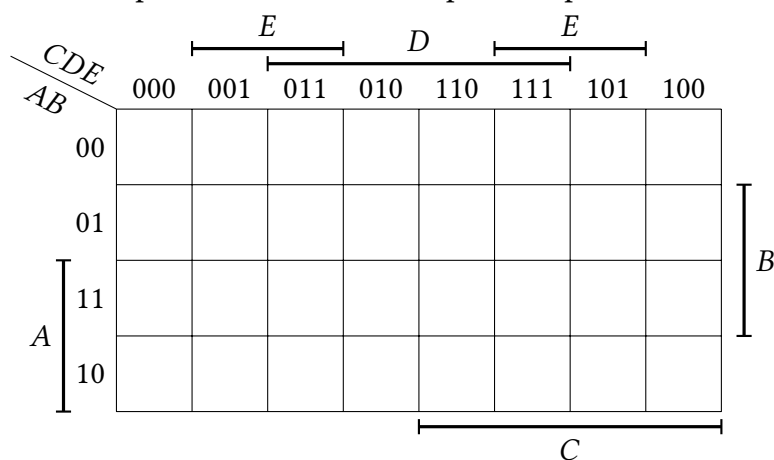
- (a) Calculate the SHA-256 hash h of the string $s = \text{"DM Fall 2023 HW3"}$ (without quotes, with all spaces, encoded in UTF-8). Convert hash h to a 256-bit binary string b (prepend leading zeros if necessary). Cut the binary string b into eight 32-bit slices r_1, \dots, r_8 , e.g. $r_2 = b_{33..64}$. Xor all slices into a 32-bit string $d = r_1 \oplus \dots \oplus r_8$. Compute $w = d \oplus 0x24d03294$.

Hint: last (least significant) bits of h are ...01001001, last bits of d are ...0001.

- (b) Draw the Karnaugh map (use a template below) for a function $f(A, B, C, D, E)$ defined by the truth table $w = (w_1 \dots w_{32})$, where MSB corresponds to $f(0) = w_1$ and LSB to $f(1) = w_{32}$.

- (c) Use K-map to find the minimal DNF and minimal CNF for the function f .

- (d) Use K-map to find the number of prime implicants, i.e. the size of BCF.



2. For each given function f_i of 4 arguments, draw the Karnaugh map and use it to find BCF, minimal DNF, and minimal CNF. Additionally, construct ANF (Zhegalkin polynomial) using either the K-map, the tabular ("triangle") method or the Pascal method – use each method at least once.

Note: WolframAlpha¹ interprets the query " n -th Boolean function of k variables" in a reverse manner. In order to employ WolframAlpha properly, manually flip the truth table beforehand, e.g. the correct query for $f_{10}^{(2)}$ is "5th Boolean function of 2 variables"², which gives $f_{10}^{(2)} = \neg x_2$, since $\text{rev}(1010_2) = 0101_2 = 5_{10}$.

(a) $f_1 = f_{47541}^{(4)}$

(b) $f_2 = \sum m(1, 4, 5, 6, 8, 12, 13)$

(c) $f_3 = f_{51011}^{(4)} \oplus f_{40389}^{(4)}$

(d) $f_4 = ABD + \bar{A}\bar{C}D + \bar{B}C\bar{D} + A\bar{C}D$

3. Convert the following formulae to CNF.

(a) $X \leftrightarrow (A \wedge B)$

(b) $Z \leftrightarrow \bigvee_i C_i$

(c) $D_1 \oplus \dots \oplus D_n$

(d) $\text{majority}(X_1, X_2, X_3)$ ¹

(e) $R \rightarrow (S \rightarrow (T \rightarrow \bigwedge_i F_i))$

(f) $M \rightarrow (H \leftrightarrow \bigvee_i D_i)$

4. For each given system of functions F_i , determine whether it is functionally complete using Post's criterion. For each basis F_i , use it to represent the majority(A, B, C) function. Draw a combinational Boolean circuit for each resulting formula.

(a) $F_1 = \{\wedge, \vee, \neg\}$

(b) $F_2 = \{f_{14}^{(2)}\}$

(c) $F_3 = \{\rightarrow, \nrightarrow\}$

(d) $F_4 = \{1, \leftrightarrow, \wedge\}$

5. Show – without using Post's criterion – that the Zhegalkin basis $\{\oplus, \wedge, 1\}$ is functionally complete.

¹ Majority function² is a Boolean function that is 1 iff the majority (more than half) of the inputs are 1.

6. Compute the truth table for the function $f: \mathbb{B}^3 \rightarrow \mathbb{B}^2$ (with the semantics $\langle A, B, C \rangle \mapsto \langle f_{(1)}, f_{(2)} \rangle$) represented with the following circuit.



7. Construct a minimal Boolean circuit that implements the conversion of 4-bit binary numbers to Gray code², i.e. the function $f: \mathbb{B}^4 \rightarrow \mathbb{B}^4$ with the semantics $(b_3, b_2, b_1, b_0) \mapsto (g_3, g_2, g_1, g_0)$, e.g., $0000_2 \mapsto 0000_{\text{Gray}}$, and $1001_2 \mapsto 1101_{\text{Gray}}$. Use only NAND and NOR logic gates.
8. A *half subtractor* is a circuit that has two bits as input and produces as output a difference bit and a borrow. A *full subtractor* is a circuit that has two bits and a borrow as input, and produces as output a difference bit and a borrow.
- Construct a circuit for a half subtractor using AND gates, OR gates, and inverters.
 - Construct a circuit for a full subtractor using half subtractors and NAND gates.
 - Construct a circuit that computes the *saturating* difference of two four-bit integers $(x_3x_2x_1x_0)_2$ and $(y_3y_2y_1y_0)_2$ using half/full subtractors, AND gates, OR gates, and inverters. When $x \geq y$, the output bits d_3, \dots, d_0 should represent $d = x - y$, and when $x < y$, the output must be zero.
9. Construct a circuit that compares the two-bit integers $(x_1x_0)_2$ and $(y_1y_0)_2$, and outputs 1 when $x > y$ and 0 otherwise.
10. Construct a circuit that computes the product of the two-bit integers $(x_1x_0)_2$ and $(y_1y_0)_2$. The circuit should have four-bit output $(p_3p_2p_1p_0)_2$ representing the product $p = x \cdot y$.
11. Consider a Boolean function ITE: $\mathbb{B}^3 \rightarrow \mathbb{B}$ defined as follows: $\text{ITE}(c, x, y) = \begin{cases} x & \text{if } c=0 \\ y & \text{if } c=1 \end{cases}$. Construct a formula for it using the standard Boolean basis $\{\wedge, \vee, \neg\}$. Determine whether the set $\{\text{ITE}\}$ is functionally complete.
12. For each given function f_i , construct a Reduced Ordered Binary Decision Diagram (ROBDD) using the natural variable order $x_1 \prec x_2 \prec \dots \prec x_n$. Determine whether the ROBDD can be reduced even further by using a different variable order – if so, show it.

Binary Decision Diagram² (BDD) is a representation of a Boolean function as a directed acyclic graph, which consists of *decision* nodes and two *terminal* nodes (0 and 1). Each decision node is labeled by a Boolean variable x_i and has two child nodes called *low* and *high*. The edge from node to a low (high) child represents an assignment of the value FALSE (TRUE) to variable x_i . A path from the root node to the 1-terminal (0-terminal) corresponds to an assignment for which the represented Boolean function is true (false). BDD is called *ordered* if variables appear in the same order on all paths from the root. BDD is called *reduced* if it does not contain a node v with $\text{high}(v) = \text{low}(v)$, and there does not exist a pair of nodes u, v such that the sub-OBDDs rooted in u and v are isomorphic.

- $f_1(x_1, \dots, x_4) = x_1 \oplus x_2 \oplus x_3 \oplus x_4$
- $f_2(x_1, \dots, x_5) = \text{majority}(x_1, \dots, x_5)$
- $f_3(x_1, \dots, x_4) = \sum m(1, 2, 5, 12, 15)$
- $f_4(x_1, \dots, x_6) = x_1x_4 + x_2x_5 + x_3x_6$