Unit 03 – Minimizing Formulas

Peter Bauer

Outline

Disjunctive Normal Form

Minimization of Propositional Logic Formulas
- KV-Diagrams – Motivation
- Quine-McCluskey Algorithm

Disjunctive Normal Form – Motivation

- Given the truth table of a propositional formula P
- Find a logically equivalent formula P'

Disjunctive Normal Form – Motivation

- Given the truth table of a propositional formula P
- Find a logically equivalent formula P'
- No unambiguous solution

Disjunctive Normal Form – Motivation

- Given the truth table of a propositional formula P
- Find a logically equivalent formula P'
- No unambiguous solution
- Disjunctive normal form is one (and easy to find) solution

Disjunctive Normal Form – Motivation

- Given the truth table of a propositional formula P
- Find a logically equivalent formula P'
- No unambiguous solution
- Disjunctive normal form is one (and easy to find) solution
- Is a basis for several methods of several algorithms for automated formula simplification

Disjunctive Normal Form

Definition

A propositional logic formula of the form

$$\begin{aligned}(A_{11} \wedge A_{12} \wedge \ldots \wedge A_{1n}) &\vee \\ (A_{21} \wedge A_{22} \wedge \ldots \wedge A_{2n}) &\vee \\ \ldots \\ (A_{m1} \wedge A_{m2} \wedge \ldots \wedge A_{mn})\end{aligned}$$

is called a *formula in disjunctive normal form* (DNF).

Procedure to Find the DNF

- Given a propositional formula $P(A_1, A_2, \ldots A_n)$ with n propositional variables

Procedure to Find the DNF

- Given a propositional formula $P(A_1, A_2, \ldots A_n)$ with n propositional variables
- Calculate the truth table of P
- For each row j in the truth table, where $P = t$ model a sub-formula Q_j as follows:

Procedure to Find the DNF

- Given a propositional formula $P(A_1, A_2, \ldots A_n)$ with n propositional variables
- Calculate the truth table of P
- For each row j in the truth table, where $P = t$ model a sub-formula Q_j as follows:

$$Q_j = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \ldots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right).$$

- Choose A_i for the i^{th} variable if the truth table holds a t and $\neg A_i$ otherwise.

Procedure to Find the DNF

- Given a propositional formula $P(A_1, A_2, \dots A_n)$ with n propositional variables
- Calculate the truth table of P
- For each row j in the truth table, where $P = t$ model a sub-formula Q_j as follows:

$$Q_j = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \dots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right).$$

- Choose A_i for the i^{th} variable if the truth table holds a t and $\neg A_i$ otherwise.
- The complete formula P' is realized by assembling all the sub-formulas $Q_1, Q_2, \dots, Q_m$ as follows:

$$P' = Q_1 \vee Q_2 \vee \dots \vee Q_m$$

Example

Example

Consider the formula $P(A,B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A,B)$	$Q_j(A,B)$
t	t		

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	$A \wedge B$
t	f		

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	$A \wedge B$
t	f	f	

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	$A \wedge B$
t	f	f	—
f	t		

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	$A \wedge B$
t	f	f	—
f	t	t	

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A,B)$	$Q_j(A,B)$
t	t	t	$A \wedge B$
t	f	f	—
f	t	t	$\neg A \wedge B$
f	f		

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	$A \wedge B$
t	f	f	—
f	t	t	$\neg A \wedge B$
f	f	t	

Example

Example

Consider the formula $P(A, B) = A \Rightarrow B$. The truth table would be as follows:

A	B	$P(A, B)$	$Q_j(A, B)$
t	t	t	$A \wedge B$
t	f	f	—
f	t	t	$\neg A \wedge B$
f	f	t	$\neg A \wedge \neg B$

Therefore, P could be rewritten in disjunctive normal form as $P'(A, B) = (A \wedge B) \vee (\neg A \wedge B) \vee (\neg A \wedge \neg B)$.

Minimizing Formulas – Motivation

- Easier to understand
- Save money when constructing integrated circuits

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = (A \wedge B) \vee (\neg A \wedge B) \vee (\neg A \wedge \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$		
B		

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = \boxed{(A \wedge B)} \vee (\neg A \wedge B) \vee (\neg A \wedge \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$		
B		

KV-Diagrams

Consider the following formula in DNF

$$P'(A,B) = \boxed{(A \land B)} \lor (\neg A \land B) \lor (\neg A \land \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$		
B		1

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = (A \wedge B) \vee \boxed{(\neg A \wedge B)} \vee (\neg A \wedge \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$		
B		1

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = (A \land B) \lor \boxed{(\neg A \land B)} \lor (\neg A \land \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$		
B	1	1

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = (A \wedge B) \vee (\neg A \wedge B) \vee (\neg A \wedge \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$		
B	1	1

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = (A \wedge B) \vee (\neg A \wedge B) \vee \boxed{(\neg A \wedge \neg B)}.$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$	1	
B	1	1

KV-Diagrams

Consider the following formula in DNF

$$P'(A,B) = (A \wedge B) \vee (\neg A \wedge B) \vee (\neg A \wedge \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$	1	
B	1	1

Now we try to find boxes of size 2 or 4 or 8, etc. These boxes should be as large as possible. The number of boxes should be as small as possible. The boxes may overlap.

KV-Diagrams

Consider the following formula in DNF

$$P'(A, B) = (A \land B) \lor (\neg A \land B) \lor (\neg A \land \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$	1	
B	1	1

$\neg A$

KV-Diagrams

Consider the following formula in DNF

$$P'(A,B) = (A \wedge B) \vee (\neg A \wedge B) \vee (\neg A \wedge \neg B).$$

In the two dimensional case we construct a diagram in the following way:

	$\neg A$	A
$\neg B$	1	
B	1	1

$\neg A \vee B$

KV-Diagrams – Another Example

Example

$$
\begin{aligned}
&(\neg A \land B \land C \land \neg D) \lor (A \land \neg B \land \neg C \land \neg D) &&\lor (A \land \neg B \land \neg C \land D) \lor \\
&\ (A \land \neg B \land C \land D) \lor (A \land \neg B \land C \land \neg D) &&\lor (A \land B \land \neg C \land \neg D) \lor \\
&\ (A \land B \land \neg C \land D) \lor (A \land B \land C \land \neg D)
\end{aligned}
$$

Another Example – Sample Solution

Another Example – Sample Solution

	A	A	$\neg A$	$\neg A$	
B		1			D
B	1	1		1	$\neg D$
$\neg B$	1	1			$\neg D$
$\neg B$	1	1			D
	C	$\neg C$	$\neg C$	C	

$$(A \wedge \neg C) \vee (A \wedge \neg B) \vee (B \wedge C \wedge \neg D)$$

KV-Table for Three Variables

	A	A	$\neg A$	$\neg A$	
B					
$\neg B$					
	C	$\neg C$	$\neg C$	C	

Minterm and Literal

Definition

Given a propositional logic formula $P = Q_1 \vee Q_2 \vee \ldots \vee Q_m$, where all $Q_j (1 \leq j \leq m)$ are of the form

$$Q_j = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \ldots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right)$$

we call Q_j a *minterm*. The A_i or $\neg A_i$ $(1 \leq i \leq n)$ are called *literals*.

Minterm and Literal

Definition

Given a propositional logic formula $P = Q_1 \vee Q_2 \vee \ldots \vee Q_m$, where all $Q_j (1 \leq j \leq m)$ are of the form

$$Q_j = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \ldots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right)$$

we call Q_j a *minterm*. The A_i or $\neg A_i$ $(1 \leq i \leq n)$ are called *literals*.

Remark

Sometimes we also call a row of a truth table which result is true a minterm.

Minterm and Literal

Definition

Given a propositional logic formula $P = Q_1 \vee Q_2 \vee \ldots \vee Q_m$, where all $Q_j (1 \leq j \leq m)$ are of the form

$$Q_j = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \ldots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right)$$

we call Q_j a *minterm*. The A_i or $\neg A_i$ $(1 \leq i \leq n)$ are called *literals*.

Remark

Sometimes we also call a row of a truth table which result is true a minterm.

Remark

In case of a multiple appearance of a literal A_i in a Q_j, Q_j is called a product term.

Implicant

Definition

Given a propositional logic formula $P = Q_1 \vee \ldots \vee Q_m$ with each minterm Q_i having n literals $A_1, A_2, \ldots, A_n$. Furthermore we have a product term

$$I = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \ldots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right).$$

Implicant

Definition

Given a propositional logic formula $P = Q_1 \vee \ldots \vee Q_m$ with each minterm Q_i having n literals $A_1, A_2, \ldots, A_n$. Furthermore we have a product term

$$I = \left(\begin{pmatrix} A_1 \\ \text{or} \\ \neg A_1 \end{pmatrix} \wedge \begin{pmatrix} A_2 \\ \text{or} \\ \neg A_2 \end{pmatrix} \wedge \ldots \wedge \begin{pmatrix} A_n \\ \text{or} \\ \neg A_n \end{pmatrix} \right).$$

I is called a *prime implicant* of P if $I \Rightarrow P$, i.e., that whenever the evaluation of I with a specific set of truth values for $A_1, A_2, \ldots, A_n$ yields true, the evaluation of P with the same set of truth values also yields true.

Example and Remark

Consider the following propositional logic formula P:

$$P \quad = \quad (A_1 \wedge A_2) \vee (A_2 \wedge A_3) \vee A_4$$

This formula is implied by the formulas $A_1 \wedge A_2$, $A_2 \wedge A_3$, A_4, $A_1 \wedge A_2 \wedge A_3$, $A_1 \wedge A2_{\wedge} A_4$ and many others. These are the implicants of P.

Example and Remark

Consider the following propositional logic formula P:

$$P \quad = \quad (A_1 \wedge A_2) \vee (A_2 \wedge A_3) \vee A_4$$

This formula is implied by the formulas $A_1 \wedge A_2$, $A_2 \wedge A_3$, A_4, $A_1 \wedge A_2 \wedge A_3$, $A_1 \wedge A2_{\wedge} A_4$ and many others. These are the implicants of P.

Remark

Implicants are sometimes called “coverings” of one or more minterms.

Prime Implicant

Definition

Given a propositional logic formula P. An implicant I is called a *prime implicant* if it can't be reduced any further, i.e., any removal of a literal would make it a "non-implicant".

Prime Implicant

Definition

Given a propositional logic formula P. An implicant I is called a *prime implicant* if it can't be reduced any further, i.e., any removal of a literal would make it a "non-implicant".

Example

Let $P = (A_1 \wedge A_2) \vee (A_2 \wedge A_3) \vee A_4$ be a propositional logic formula. The prime implicants of P would be $A_1 \wedge A_2$, $A_2 \wedge A_3$, and A_4 would be the prime implicants of P.

Prime Implicant and Minimal Formulas

Definition

A disjunction of prime implicants covering a complete formula P is called a minimal formula of P.

Remark

There may exist more than one minimal formula.

Example

Given the following truth table M:

x_1	x_2	x_3	y
f	f	f	f
f	f	t	f
f	t	f	f
f	t	t	t
t	f	f	t
t	f	t	t
t	t	f	f
t	t	t	t

Example continued

- $$\begin{array}{ccccc} \neg A_1 & \wedge & A_2 & \wedge & A_3 \\ A_1 & \wedge & \neg A_2 & \wedge & \neg A_3 \\ A_1 & \wedge & \neg A_2 & \wedge & A_3 \\ A_1 & \wedge & A_2 & \wedge & A_3 \end{array}$$
  are the minterms of M.

Example continued

- $$\begin{array}{ccccc} \neg A_1 & \wedge & A_2 & \wedge & A_3 \\ A_1 & \wedge & \neg A_2 & \wedge & \neg A_3 \\ A_1 & \wedge & \neg A_2 & \wedge & A_3 \\ A_1 & \wedge & A_2 & \wedge & A_3 \end{array}$$
  are the minterms of M.
- $A_1 \wedge \neg A_2$ and $A_2 \wedge A_3$ are prime implicants of M.

Example continued

- $$\begin{array}{ccccc} \neg A_1 & \wedge & A_2 & \wedge & A_3 \\ A_1 & \wedge & \neg A_2 & \wedge & \neg A_3 \\ A_1 & \wedge & \neg A_2 & \wedge & A_3 \\ A_1 & \wedge & A_2 & \wedge & A_3 \end{array}$$
  are the minterms of M.
- $A_1 \wedge \neg A_2$ and $A_2 \wedge A_3$ are prime implicants of M.
- $A_1 \wedge \neg A_2 \vee A_2 \wedge A_3$ is a minimal formula representing M.

Quine-McCluskey Algorithm

- An algorithm to find minimal formulas
- Finds all prime implicants of a given formula S
- Finds a combination of prime implicants which covers S
- Example as given in class