COS 140: Foundations of Computer Science

Boolean Algebra

Fall 2018

Computer
Science
Foundations

Homework and announcements!

- Reading: Chapter 5
- Homework: exercises 1–6
  - Exercise 7 for extra credit
  - Due: 1 week + 1 class from today (i.e., 9/21)
- Don't forget – **recitation this week**!
- Slides: online now

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Problem

- Computers compute digital logic functions
- Need some way to describe those functions
- For some ordinary mathematical functions, algebra works well
- But the functions we want aren't numeric, but give true/false (1/0) values
- What can we use?

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Boolean algebra

- Boolean algebra is analogous to “regular” algebra, but for true/false values
- Well-known, well-developed mathematical foundation for digital logic.
- Provides a formalism for specifying the functions that we wish to have performed.
- Provides a mechanism for proving circuits are equivalent.
- Named for George Boole, a 19^{th}-century mathematician.

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Operators

Boolean operators correspond to gates and have same truth tables as corresponding gate.

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Boolean operators correspond to gates and have same truth tables as corresponding gate.

- NOT: NOT A, $\neg A$, $\overline{A}$, A'

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Operators

Boolean operators correspond to gates and have same truth tables as corresponding gate.

- NOT: NOT $A,\ \neg A,\ \overline{A},\ A'$
- AND: A AND $B,\ A \cdot B,\ AB,\ A \wedge B$

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Operators

Boolean operators correspond to gates and have same truth tables as corresponding gate.

- NOT: NOT A, $\neg A$, $\overline{A}$, A'
- AND: A AND B, $A \cdot B$, AB, $A \wedge B$
- OR: A OR B, $A + B$, $A \vee B$

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Operators

Boolean operators correspond to gates and have same truth tables as corresponding gate.

- NOT: NOT A, $\neg A$, $\overline{A}$, A'
- AND: A AND B, $A \cdot B$, AB, $A \wedge B$
- OR: A OR B, $A + B$, $A \vee B$
- NAND: A NAND B, $A|B$, $A \uparrow B$, $\overline{AB}$

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Operators

Boolean operators correspond to gates and have same truth tables as corresponding gate.

- NOT: NOT A, $\neg A$, $\overline{A}$, A'
- AND: A AND B, $A \cdot B$, AB, $A \wedge B$
- OR: A OR B, $A + B$, $A \vee B$
- NAND: A NAND B, $A|B$, $A \uparrow B$, $\overline{AB}$
- NOR: A NOR B, $A \downarrow B$, $\overline{(A + B)}$

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Operators

Boolean operators correspond to gates and have same truth tables as corresponding gate.

- NOT: NOT $A,\ \neg A,\ \overline{A},\ A'$
- AND: A AND $B,\ A \cdot B,\ AB,\ A \wedge B$
- OR: A OR $B,\ A + B,\ A \vee B$
- NAND: A NAND $B,\ A|B,\ A \uparrow B,\ \overline{AB}$
- NOR: A NOR $B,\ A \downarrow B,\ \overline{(A + B)}$
- XOR: A XOR $B,\ A \oplus B$

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Boolean Algebra Expressions

- What is an *expression*?
- Value of an expression $\Leftarrow$ depends on the values of the variables
- Evaluate expression: assign values to variables, performing the operations
- Can create an expression for a function by determining when the function should be 1, then writing an expression that is 1 in only those cases.

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Boolean Algebra Expressions

- What is an *expression*?
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Example: Create a 3-variable expression that equals 1 when all of the inputs are 1, or when one, and only one, input is 0.

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Boolean Algebra Expressions

- What is an *expression*?
- Value of an expression $\Leftarrow$ depends on the values of the variables
- Evaluate expression: assign values to variables, performing the operations
- Can create an expression for a function by determining when the function should be 1, then writing an expression that is 1 in only those cases.

Example: Create a 3-variable expression that equals 1 when all of the inputs are 1, or when one, and only one, input is 0.

$$ABC + \overline{A}BC + A\overline{B}C + AB\overline{C}$$

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Operator Precedence for Boolean Algebra

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Operator Precedence for Boolean Algebra

- Subexpressions inside of parentheses, beginning with innermost parentheses.
- NOT
- AND
- OR
- Evaluate A NAND B as NOT($A \wedge B$) and A NOR B as NOT($A \vee B$)
- Evaluate subexpressions of equal precedence from left to right.

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Proofs of Equivalence

- Two ways: truth tables and algebraic substitution
- Truth table method: if truth table for expression A same as for expression B, then $A \equiv B$
- Algebraic substitution method:
  - Use laws of Boolean algebra to transform one expression into the other
  - Proofs have to be convincing to others
  - Have to provide enough detail to show how one step follows from another
  - Have to provide justification for each step

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Proof by Truth Table

Best to have column for each input and results of each operator

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Proof by Truth Table

Best to have column for each input and results of each operator

Prove that $A \oplus B$ is equivalent to $(\overline{A}B) + (A\overline{B})$

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Proof by Truth Table

Best to have column for each input and results of each operator

Prove that $A \oplus B$ is equivalent to $(\overline{A}B) + (A\overline{B})$

A	B	$A \oplus B$	$\overline{A}$	$\overline{B}$	$\overline{A}B$	$A\overline{B}$	$(\overline{A}B) + (A\overline{B})$
0	0	0	1	1	0	0	0
0	1	1	1	0	1	0	1
1	0	1	0	1	0	1	1
1	1	0	0	0	0	0	0

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Proof by Algebraic Substitution

- If you are trying to prove that expression 1 is equivalent to expression 2:
  - Start with one of the expressions, let's say 1.
  - Change it into another expression (say $1'$) using an *identity postulate* (law).
  - Continue the process with $1'$ until you arrive at 2.
- You must justify *every* change to the current expression by listing the identity postulate used.
- Some identity postulates: double negation law, identity law, null law, idempotent law, and inverse law

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Double Negation Law

- $A = \overline{\overline{A}}$

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Identity Law

- AND form: $1A = A$
- OR form: $0 + A = A$

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Null Law

- AND form: $0A = 0$
- OR form: $1 + A = 1$

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Idempotent Law

- AND form: $AA = A$
- OR form: $A + A = A$

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Inverse Law

- AND form: $A\overline{A} = 0$
- OR form: $A + \overline{A} = 1$

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Example: Finding Equivalent Circuits

Starting with the following expression, find the equivalent expression that uses the least number of gates (has the smallest number of boolean operators) and the least number of inputs

$$(A + \overline{A})\overline{(B\overline{\overline{B}})}$$

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Example: Finding Equivalent Circuits

Starting with the following expression, find the equivalent expression that uses the least number of gates (has the smallest number of boolean operators) and the least number of inputs

$$(A + \overline{A})\overline{(B\overline{\overline{B}})}$$

- Don't know what the final result will be so use algebraic substitution instead of truth tables

Example: Finding Equivalent Circuits

Starting with the following expression, find the equivalent expression that uses the least number of gates (has the smallest number of boolean operators) and the least number of inputs

$$(A + \overline{A})\overline{(B\overline{\overline{B}})}$$

- Don't know what the final result will be so use algebraic substitution instead of truth tables
- Follow your intuition about what should be the case and what makes sense, then justify with a law.
- In other words, have a plan based on what makes sense.
- Sometimes you need to try things to make the plan.

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Example: Finding Equivalent Circuits

$$(A + \overline{A})\overline{(B\overline{\overline{B}})}$$

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Introduction
Proofs
Laws
- Double Negation Law
- Identity Law
- Null Law
- Idempotent Law
- Inverse Law
- Example
- Commutative Law
- Associative Law
- Distributive Law
- Absorption Law
- DeMorgan's Law

Using the Laws

Example: Finding Equivalent Circuits

$$(A + \overline{A})\overline{(B\overline{\overline{B}})}$$

$$(A + \overline{A})\overline{(BB)}$$ *Double Negation Law*

Example: Finding Equivalent Circuits

$$(A + \overline{A})\overline{(B\overline{\overline{B}})}$$

$$(A + \overline{A})\overline{(BB)}$$ *Double Negation Law*

$$(A + \overline{A})\overline{B}$$ *Idempotent Law*

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Example: Finding Equivalent Circuits

$(A + \overline{A})\overline{(B\overline{\overline{B}})}$	
$(A + \overline{A})\overline{(BB)}$	*Double Negation Law*
$(A + \overline{A})\overline{B}$	*Idempotent Law*
$1\overline{B}$	*Inverse Law*

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Example: Finding Equivalent Circuits

$(A + \overline{A})\overline{(B\overline{\overline{B}})}$	
$(A + \overline{A})\overline{(BB)}$	*Double Negation Law*
$(A + \overline{A})\overline{B}$	*Idempotent Law*
$1\overline{B}$	*Inverse Law*
$\overline{B}$	*Identity Law*

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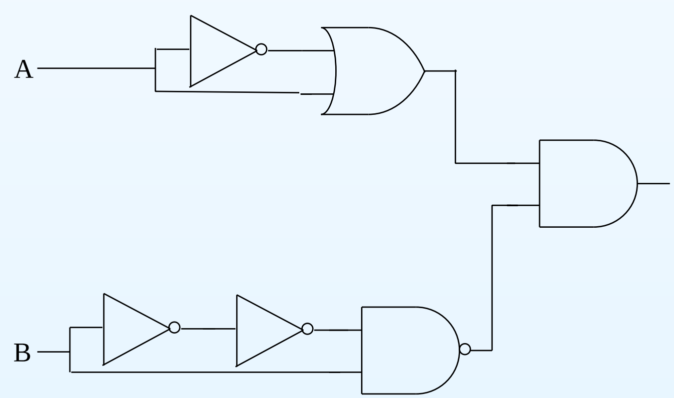
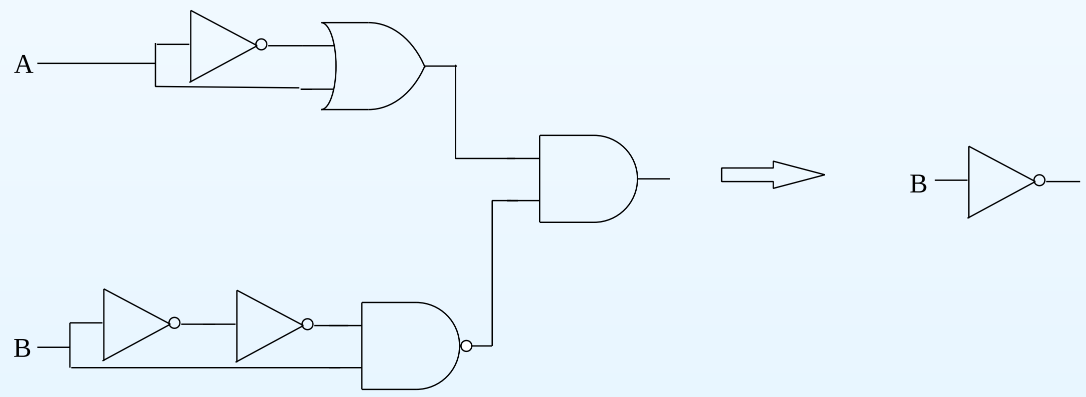
Example: Finding Equivalent Circuits

$(A + \overline{A})\overline{(B\overline{\overline{B}})}$	
$(A + \overline{A})\overline{(BB)}$	*Double Negation Law*
$(A + \overline{A})\overline{B}$	*Idempotent Law*
$1\overline{B}$	*Inverse Law*
$\overline{B}$	*Identity Law*



Example: Finding Equivalent Circuits

$(A + \overline{A})\overline{(B\overline{\overline{B}})}$	
$(A + \overline{A})\overline{(BB)}$	*Double Negation Law*
$(A + \overline{A})\overline{B}$	*Idempotent Law*
$1\overline{B}$	*Inverse Law*
$\overline{B}$	*Identity Law*



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Commutative Law

- AND form: $AB = BA$
- OR form: $A + B = B + A$

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Associative Law

- AND form: $(AB)C = A(BC)$
- OR form: $(A + B) + C = A + (B + C)$

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Distributive Law

- AND form: $A(B + C) = AB + AC$

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Distributive Law

- AND form: $A(B + C) = AB + AC$
- OR form: $A + BC = (A + B)(A + C)$

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Distributive Law

- AND form: $A(B + C) = AB + AC$
- OR form: $A + BC = (A + B)(A + C)$
- ...or $A \vee (B \wedge C) = (A \vee B) \wedge (A \vee C)$

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Absorption Law

- AND form: $A(A + B) = A$
- OR form: $A + AB = A$

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DeMorgan's Law

- AND form: $\overline{AB} = \overline{A} + \overline{B}$
- OR form: $\overline{A + B} = \overline{A} \cdot \overline{B}$

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DeMorgan's Law

- AND form: $\overline{AB} = \overline{A} + \overline{B}$
- OR form: $\overline{A+B} = \overline{A} \cdot \overline{B}$

Aside: recall that $\overline{AB} = A$ NAND B, and $\overline{A+B} = A$ NOR B

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DeMorgan's Law

- AND form: $\overline{AB} = \overline{A} + \overline{B}$
- OR form: $\overline{A + B} = \overline{A} \cdot \overline{B}$

Aside: recall that $\overline{AB} = A$ NAND B, and $\overline{A+B} = A$ NOR B

NOTE:

$$\overline{AB} \neq \overline{A}\,\overline{B}$$

$$\overline{A+B} \neq \overline{A} + \overline{B}$$

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How would you prove DeMorgan's Law?

What approach would you use? Why?

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Example: Proof by Algebraic Substitution

Introduction
Proofs
Laws
Using the Laws
- Proving DeMorgan's Law
- Proof 1
- Proof 1a
- Proof 1b
- Proof 2
- Proof 3

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B \; + \; A\overline{B} \; = \; \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$
- $\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$ *DeMorgan's Law*

Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$
- $\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$ *DeMorgan's Law*
- $(\overline{A}B) + \overline{\overline{(A\overline{B})}}$ *Double Negation*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B \; + \; A\overline{B} \; = \; \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$
- $\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$ *DeMorgan's Law*
- $(\overline{A}B) + \overline{\overline{(A\overline{B})}}$ *Double Negation*
- $(\overline{A}B) + (A\overline{B})$ *Double Negation*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$
- $\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$ *DeMorgan's Law*
- $(\overline{A}B) + \overline{\overline{(A\overline{B})}}$ *Double Negation*
- $(\overline{A}B) + (A\overline{B})$ *Double Negation*
- $\overline{A}B + A\overline{B}$ *Def. of parentheses/precedence*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$$\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$\overline{XY}$ *Let* $X = (\overline{\overline{A}B}),\ Y = (\overline{A\overline{B}})$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$	
$\overline{XY}$	*Let* $X = (\overline{\overline{A}B})$, $Y = (\overline{A\overline{B}})$
$\overline{X} + \overline{Y}$	*DeMorgan's Law*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$	
$\overline{XY}$	*Let* $X = (\overline{\overline{A}B}),\ Y = (\overline{A\overline{B}})$
$\overline{X} + \overline{Y}$	*DeMorgan's Law*
$\overline{(\overline{\overline{A}B})} + \overline{(\overline{A\overline{B}})}$	*Substitution for* $X,\ Y$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$	
$\overline{XY}$	*Let* $X = (\overline{\overline{A}B}),\ Y = (\overline{A\overline{B}})$
$\overline{X} + \overline{Y}$	*DeMorgan's Law*
$\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$	*Substitution for* $X,\ Y$
$(\overline{A}B) + (A\overline{B})$	*Double Negation*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{\overline{(\overline{A}B)}\,\overline{(A\overline{B})}}$

$\overline{\overline{(\overline{A}B)}\,\overline{(A\overline{B})}}$	
$\overline{XY}$	*Let* $X = \overline{(\overline{A}B)},\ Y = \overline{(A\overline{B})}$
$\overline{X} + \overline{Y}$	*DeMorgan's Law*
$\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$	*Substitution for* $X,\ Y$
$(\overline{A}B) + \overline{\overline{(A\overline{B})}}$	*Double Negation*
$(\overline{A}B) + (A\overline{B})$	*Double Negation*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

$\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$	
$\overline{XY}$	*Let* $X = (\overline{\overline{A}B}),\ Y = (\overline{A\overline{B}})$
$\overline{X} + \overline{Y}$	*DeMorgan's Law*
$\overline{\overline{(\overline{A}B)}} + \overline{\overline{(A\overline{B})}}$	*Substitution for* $X,\ Y$
$(\overline{A}B) + \overline{\overline{(A\overline{B})}}$	*Double Negation*
$(\overline{A}B) + (A\overline{B})$	*Double Negation*
$\overline{A}B + A\overline{B}$	*Def. of parentheses/precedence*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B + A\overline{B} = \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{A}B + A\overline{B}$

Introduction
Proofs
Laws
Using the Laws
- Proving DeMorgan's Law
- Proof 1
- Proof 1a
- Proof 1b
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Example: Proof by Algebraic Substitution

Prove $\overline{A}B \;+\; A\overline{B} \;=\; \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{A}B \;+\; A\overline{B}$
- $\overline{\overline{\overline{A}B \;+\; A\overline{B}}}$ *Double Negation*

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Example: Proof by Algebraic Substitution

Prove $\overline{A}B \; + \; A\overline{B} \; = \; \overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$

- $\overline{A}B \; + \; A\overline{B}$
- $\overline{\overline{\overline{A}B \; + \; A\overline{B}}}$ *Double Negation*
- $\overline{(\overline{\overline{A}B})(\overline{A\overline{B}})}$ *DeMorgan's Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $CB + ACB + C$ *Commutative Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $CB + ACB + C$ *Commutative Law*
- $CB + CBA + C$ *Commutative Law*

Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $CB + ACB + C$ *Commutative Law*
- $CB + CBA + C$ *Commutative Law*
- $CB + C + CBA$ *Commutative Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $CB + ACB + C$ *Commutative Law*
- $CB + CBA + C$ *Commutative Law*
- $CB + C + CBA$ *Commutative Law*
- $CB + C$ *Absorption Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $CB + ACB + C$ *Commutative Law*
- $CB + CBA + C$ *Commutative Law*
- $CB + C + CBA$ *Commutative Law*
- $CB + C$ *Absorption Law*
- $C + CB$ *Commutative Law*

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Example: Another Proof by Algebraic Substitution

Prove $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $CB + ACB + C$ *Commutative Law*
- $CB + CBA + C$ *Commutative Law*
- $CB + C + CBA$ *Commutative Law*
- $CB + C$ *Absorption Law*
- $C + CB$ *Commutative Law*
- C *Absorption Law*

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

- $ACB + C(B + C)$

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $ABC + CB + 1C$ *Identity Law*

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $ABC + CB + 1C$ *Identity Law*
- $CAB + CB + C1$ *Commutative Law, twice*

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Example: Another Proof by Algebraic Substitution

Alternate proof of $ACB + C(B + C) = C$

- $ACB + C(B + C)$
- $ACB + CB + CC$ *Distributive Law*
- $ACB + CB + C$ *Idempotent Law*
- $ABC + CB + 1C$ *Identity Law*
- $CAB + CB + C1$ *Commutative Law, twice*
- $C(AB + B + 1)$ *Distributive Law*

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$\Rightarrow$ Often more than one way to do proof!

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