



DISCRETE MATHEMATICS FOR COMPUTER SCIENCE

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Important Logical Equivalences

■ *Identity laws*

$$\diamond p \wedge T \equiv p$$

$$\diamond p \vee F \equiv p$$

■ *Domination laws*

$$\diamond p \vee T \equiv T$$

$$\diamond p \wedge F \equiv F$$

■ *Idempotent laws*

$$\diamond p \vee p \equiv p$$

$$\diamond p \wedge p \equiv p$$



Important Logical Equivalences

■ *Double negation laws*

$$\diamond \neg(\neg p) \equiv p$$

■ *Commutative laws*

$$\diamond p \vee q \equiv q \vee p$$

$$\diamond p \wedge q \equiv q \wedge p$$

■ *Associative laws*

$$\diamond (p \vee q) \vee r \equiv p \vee (q \vee r)$$

$$\diamond (p \wedge q) \wedge r \equiv p \wedge (q \wedge r)$$



Important Logical Equivalences

■ *Distributive laws*

$$\diamond p \vee (q \wedge r) \equiv (p \vee q) \wedge (p \vee r)$$

$$\diamond p \wedge (q \vee r) \equiv (p \wedge q) \vee (p \wedge r)$$

■ *De Morgan's laws*

$$\diamond \neg(p \vee q) \equiv \neg p \wedge \neg q$$

$$\diamond \neg(p \wedge q) \equiv \neg p \vee \neg q$$

■ *Others*

$$\diamond p \vee (p \wedge q) \equiv p$$

$$\diamond p \wedge (p \vee q) \equiv p$$

Absorption laws

$$\diamond p \vee \neg p \equiv T$$

$$\diamond p \wedge \neg p \equiv F$$

Negation laws

$$\diamond p \rightarrow q \equiv \neg p \vee q$$



Summary of Quantified Statements

- When $\forall x P(x)$ and $\exists x P(x)$ are true and false?

Statement	When true?	When false?
$\forall x P(x)$	$P(x)$ true for all x	There is an x where $P(x)$ is false.
$\exists x P(x)$	There is some x for which $P(x)$ is true.	$P(x)$ is false for all x .

- Suppose that the elements in the universe can be enumerated as x_1, x_2, \dots, x_n then:
 - ◇ $\forall x P(x)$ is true whenever $P(x_1) \wedge P(x_2) \wedge \dots \wedge P(x_n)$ is true
 - ◇ $\exists x P(x)$ is true whenever $P(x_1) \vee P(x_2) \vee \dots \vee P(x_n)$ is true.



Order of Quantifiers

- The order of nested quantifiers **matters** if quantifiers are of **different** type.



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Example: $\forall x \exists y L(x, y) \not\equiv \exists y \forall x L(x, y)$

◇ $L(x, y)$ denotes “ x loves y ”



Order of Quantifiers

- The order of nested quantifiers **matters** if quantifiers are of **different** type.

Example: $\forall x \exists y L(x, y) \not\equiv \exists y \forall x L(x, y)$

- ◇ $L(x, y)$ denotes “ x loves y ”
- ◇ $\forall x \exists y L(x, y)$: Everybody loves somebody.
- ◇ $\exists y \forall x L(x, y)$: There is someone who is loved by everyone.



Translation Exercise

- Suppose that variables x, y denote people, and $L(x, y)$ denotes x loves y .

Translate:

- ◇ Everybody loves Raymond.
- ◇ Everybody loves somebody.
- ◇ There is somebody whom everybody loves.
- ◇ There is somebody whom Raymond doesn't love.
- ◇ There is somebody whom no one loves.



Translation Exercise

- Suppose that variables x, y denote people, and $L(x, y)$ denotes x loves y .

Translate:

- ◇ Everybody loves Raymond. $\forall x L(x, \text{Raymond})$
- ◇ Everybody loves somebody. $\forall x \exists y L(x, y)$
- ◇ There is somebody whom everybody loves.
 $\exists y \forall x L(x, y)$
- ◇ There is somebody whom Raymond doesn't love.
 $\exists y \neg L(\text{Raymond}, y)$
- ◇ There is somebody whom no one loves.
 $\exists y \forall x \neg L(x, y)$



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 $\exists y \neg L(\text{Raymond}, y)$
- ◇ There is somebody whom no one loves.
 $\exists y \forall x \neg L(x, y)$
- ◇ There is **exactly** one person whom everybody loves.



Translation Exercise

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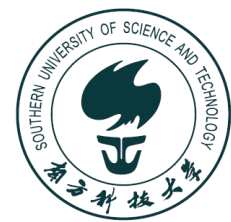
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- ◇ There is somebody whom no one loves.
 $\exists y \forall x \neg L(x, y)$
- ◇ There is **exactly** one person whom everybody loves.
 $\exists y (\forall x L(x, y) \wedge \forall z (\forall x L(x, z) \rightarrow z = y))$



Quantifications of Two Variables

Statement	When True?	When False
$\forall x \forall y P(x, y)$ $\forall y \forall x P(x, y)$	$P(x, y)$ is true for every pair x, y .	There is a pair x, y for which $P(x, y)$ is false.
$\forall x \exists y P(x, y)$	For every x there is a y for which $P(x, y)$ is true.	There is an x such that $P(x, y)$ is false for every y .
$\exists x \forall y P(x, y)$	There is an x for which $P(x, y)$ is true for every y .	For every x there is a y for which $P(x, y)$ is false.
$\exists x \exists y P(x, y)$ $\exists y \exists x P(x, y)$	There is a pair x, y for which $P(x, y)$ is true.	$P(x, y)$ is false for every pair x, y



Negating Nested Quantifiers

- Sentence: for every real number x , there exists a real number y such that $xy = 1$.



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◇ $\forall x \exists y (xy = 1)$



Negating Nested Quantifiers

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$$\diamond \forall x \exists y (xy = 1)$$

$$\neg \forall x \exists y (xy = 1)$$

$$\equiv \exists x \neg \exists y (xy = 1)$$

$$\equiv \exists x \forall y \neg (xy = 1)$$

$$\equiv \exists x \forall y (xy \neq 1)$$



Theorems and Proofs

- An *axiom* or *postulate* is a statement or proposition which is regarded as being established, accepted, or self-evidently *true*.



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- A *theorem* is a statement that can be proved to be **true**.



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Example:

- ◇ There are infinitely many prime numbers.



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Example:

- ◇ There are infinitely many prime numbers.

- A *lemma* is a statement that can be proved to be **true**, and is used in proving a theorem or proposition.



Theorems and Proofs

Journal of Combinatorial Theory, Series A 131 (2015) 61–70



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Difference balanced functions and their generalized difference sets



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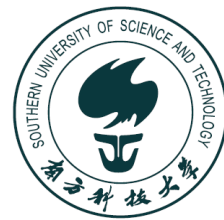


Lemma 3.1. (See [16].) For $q = p$ prime, every difference balanced function f from $\mathbb{F}_{p^n}^*$ to \mathbb{F}_p must be balanced, or an affine shift of a balanced function.

Remark 3.2. Without loss of generality, we may always assume that a difference balanced function f from $\mathbb{F}_{p^n}^*$ to \mathbb{F}_p is balanced (otherwise, replace f by $f - b$ for a suitable $b \in \mathbb{F}_p^*$).

By Lemma 3.1, $(1, t)$ is a multiplier of D implies that $D^{(1,t)} = (a_t, 0)D$ for some $a_t \in \mathbb{F}_{p^n}^*$ by the balance property. Then the equivalence relation in Theorem 2.2 could be formulated as follows for $q = p$ prime.

Corollary 3.3. Suppose that $D := \{(x, f(x)) : x \in \mathbb{F}_{p^n}^*\} \subseteq G = (\mathbb{F}_{p^n}^*, \cdot) \times (\mathbb{F}_p, +)$, where $f : \mathbb{F}_{p^n}^* \rightarrow \mathbb{F}_p$ is difference balanced. Then $(1, t)$ is a multiplier of D for every $t \in \mathbb{F}_p^*$ if and only if f is a d -homogeneous function for some d with $\gcd(d, p-1) = 1$.



Theorems and Proofs

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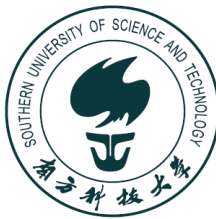
Theorem 3.5. *Let $D = \{(x, f(x)) : x \in \mathbb{F}_{p^n}^*\}$ be a difference set satisfying (2.1) in the group $G = N_2 \times N_1$, where $N_2 = (\mathbb{F}_{p^n}^*, \cdot)$, $N_1 = (\mathbb{F}_p, +)$ and p is a prime. Then $(1, t)$ is a multiplier of D for every $t \in \mathbb{F}_p^*$.*

Proof. We may assume that f is balanced, see Remark 3.2: Note that the difference sets defined by f and by affine shifts $f - b$ admit the same multipliers. Let $w = (p^n - 1)p$, let ζ_p be a complex p -th root of unity, and ζ_{p^n-1} be a complex $(p^n - 1)$ -st root of unity. In the ring $\mathbb{Z}[\zeta_p, \zeta_{p^n-1}]$, the prime ideal (p) decomposes as $(p) = (\pi_1 \dots \pi_v)^{\phi(p)}$, where the π_i 's are distinct prime ideals and $v = \phi(p^n - 1)/n$ (see [12]). If χ is a character of $N_2 \times N_1$ and $1 \leq t \leq p - 1$, then

$$\chi((x, y)^{(1, t)}) = \chi(x, ty) \equiv \chi(x, y) \pmod{p},$$

since the ring automorphism induced by $\zeta_p \mapsto \zeta_p^t$ and $\zeta_{p^n-1} \mapsto \zeta_{p^n-1}$ fixes the ideals π_i (see [12], again). Therefore by (2.2), we have

$$\chi(D^{(1, t)})\chi(D^{(-1)}) \equiv \chi(D)\chi(D^{(-1)}) \equiv 0 \pmod{p^n}$$



Theorems and Proofs

- To show the **truth value** of such a statement following from other statements, we need to provide **a correct supporting argument** (*proof*)



Theorems and Proofs

- To show the **truth value** of such a statement following from other statements, we need to provide **a correct supporting argument** (*proof*)
- **Important** questions:
 - ◇ **Why** is the argument correct?
 - ◇ **How** to construct a correct argument?



Theorems and Proofs

- Typically, a theorem looks like this:

$$(p_1 \wedge p_2 \wedge \dots \wedge p_n) \rightarrow q$$

premises conclusion



Theorems and Proofs

- Typically, a theorem looks like this:

$$\underbrace{(p_1 \wedge p_2 \wedge \dots \wedge p_n)}_{\text{premises}} \rightarrow \underbrace{q}_{\text{conclusion}}$$

Example: (Fermat's little theorem)

◇ If p is a prime and a is an integer not divisible by p , then $a^{p-1} \equiv 1 \pmod{p}$.



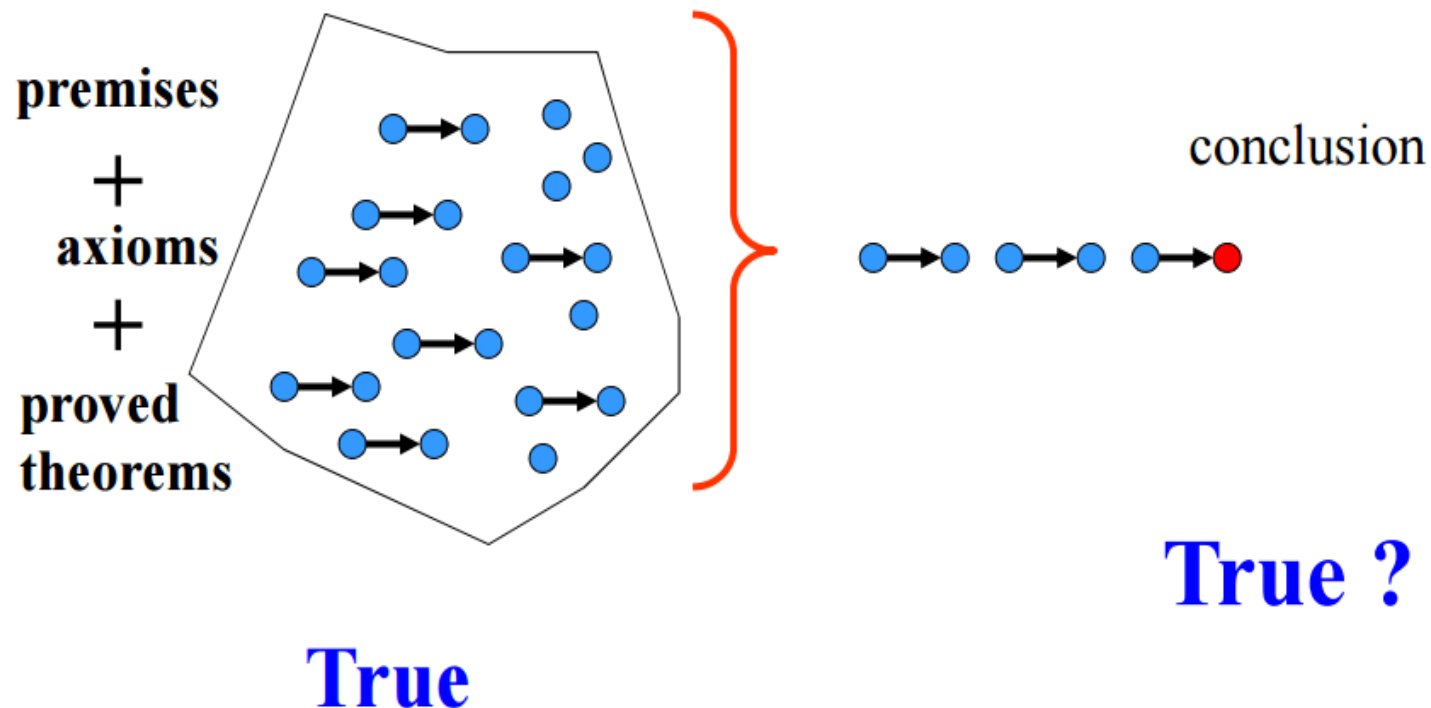
Formal Proofs

- A *proof* provides an argument supporting the validity of the statement, and may use *premises*, *axioms*, *lemmas*, *results of other theorems*, etc.
- In *formal proofs*, steps follow *logically* from the set of premises, axioms, lemmas, and other theorems.



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Using Logical Equivalence Rules

- (Proofs based on logical equivalences): A proposition can be transformed using a sequence of equivalence rewrites until some conclusion can be reached.



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Example: Show that $(p \wedge q) \rightarrow p$ is a tautology.

Proof: $(p \wedge q) \rightarrow p \equiv \neg(p \wedge q) \vee p$	Useful
$\equiv (\neg p \vee \neg q) \vee p$	De Morgan's
$\equiv (\neg q \vee \neg p) \vee p$	Commutative
$\equiv \neg q \vee (\neg p \vee p)$	Associative
$\equiv \neg q \vee T$	Negation
$\equiv T$	Domination



Rules of Inference for Propositional Logic

- Allow us to infer new **true** statements from existing true statements.
- Represent **logically valid** inference patterns

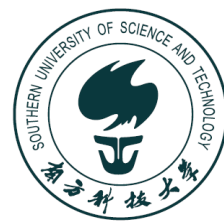


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- **modus ponens** (*law of detachment*) 肯定前件式

$$\frac{p \rightarrow q \quad p}{\therefore q}$$

corresponding tautology:
 $(p \wedge (p \rightarrow q)) \rightarrow q$



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$$\frac{p \rightarrow q \quad p}{\therefore q} \quad \text{corresponding tautology: } (p \wedge (p \rightarrow q)) \rightarrow q$$

Example:

p – “It is raining.”

q – “I will study discrete math.”

$p \rightarrow q$ – “If it is raining, then I will study discrete math.”

p – “It is raining.”

q – “Therefore, I will study discrete math.”



Rules of Inference for Propositional Logic

■ **modus tollens** 否定后件式

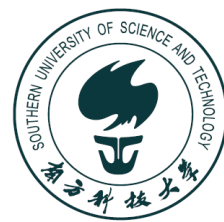
$$\frac{p \rightarrow q \quad \neg q}{\therefore \neg p}$$

corresponding tautology:
 $(\neg q \wedge (p \rightarrow q)) \rightarrow \neg p$

■ **hypothetical syllogism** 假言三段论

$$\frac{p \rightarrow q \quad q \rightarrow r}{\therefore p \rightarrow r}$$

corresponding tautology:
 $((p \rightarrow q) \wedge (q \rightarrow r)) \rightarrow (p \rightarrow r)$



Rules of Inference for Propositional Logic

■ **disjunctive syllogism** 选言三段论

$$\frac{p \vee q \quad \neg p}{\therefore q}$$

corresponding tautology:
 $(\neg p \wedge (p \vee q)) \rightarrow q$

■ **Addition**

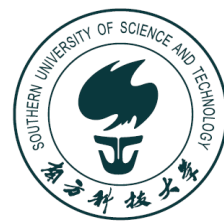
$$\frac{p}{\therefore p \vee q}$$

corresponding tautology:
 $p \rightarrow (p \vee q)$

■ **Simplification**

$$\frac{p \wedge q}{\therefore q}$$

corresponding tautology:
 $(p \wedge q) \rightarrow p$



Rules of Inference for Propositional Logic

■ Conjunction

$$\frac{p \quad q}{\therefore p \wedge q}$$

corresponding tautology:
 $((p) \wedge (q)) \rightarrow (p \wedge q)$

■ Resolution

$$\frac{\neg p \vee r \quad p \vee q}{\therefore q \vee r}$$

corresponding tautology:
 $((p \vee q) \wedge (\neg p \vee r)) \rightarrow (q \vee r)$



Applying Rules of Inference for Propositional Logic

- “It is not sunny this afternoon and it is colder than yesterday.”

“We will go swimming only if it is sunny.”

“If we do not go swimming then we will take a canoe trip.”

“If we take a canoe trip, then we will be home by sunset.”

Show that all these lead to a conclusion:

- ◇ We will be home by sunset.



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Applying Rules of Inference for Propositional Logic

- “It is not sunny this afternoon and it is colder than yesterday.”

$$\neg p \wedge q$$

“We will go swimming only if it is sunny.”

$$r \rightarrow p$$

“If we do not go swimming then we will take a canoe trip.”

$$\neg r \rightarrow s$$

“If we take a canoe trip, then we will be home by sunset.”

$$s \rightarrow t$$

Show that all these lead to a conclusion:

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p – It is sunny this afternoon.

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Applying Rules of Inference for Propositional Logic

■ Translation:

- ◇ premises: $\neg p \wedge q, r \rightarrow p, \neg r \rightarrow s, s \rightarrow t$
- ◇ conclusion: t



Applying Rules of Inference for Propositional Logic

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◇ premises: $\neg p \wedge q, r \rightarrow p, \neg r \rightarrow s, s \rightarrow t$

◇ conclusion: t

Proof:

Step	Reason
1. $\neg p \wedge q$	Premise
2. $\neg p$	Simplification using (1)
3. $r \rightarrow p$	Premise
4. $\neg r$	Modus tollens using (2) and (3)
5. $\neg r \rightarrow s$	Premise
6. s	Modus ponens using (4) and (5)
7. $s \rightarrow t$	Premise
8. t	Modus ponens using (6) and (7)



Rules of Inference for Quantified Statements

- **Universal Instantiation (UI)**

$$\frac{\forall x P(x)}{\therefore P(c)}$$

- **Universal Generalization (UG)**

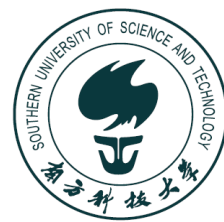
$$\frac{P(c) \text{ for an arbitrary } c}{\therefore \forall x P(x)}$$

- **Existential Instantiation (EI)**

$$\frac{\exists x P(x)}{\therefore P(c) \text{ for some element } c}$$

- **Existential Generalization (EG)**

$$\frac{P(c) \text{ for some element } c}{\therefore \exists x P(x)}$$



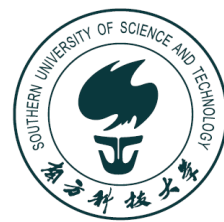
Applying Rules of Inference for Quantified Statements

- “A student in this class has not read the book.”

“Everyone in this class passed the first exam.”

Show that all these lead to a conclusion:

- ◇ Someone who passed the first exam has not read the book.



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- “A student in this class has not read the book.”

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$C(x)$ – x is in this class.

$B(x)$ – x has read the book.

$P(x)$ – x passed the first exam.



Applying Rules of Inference for Quantified Statements

- “A student in this class has not read the book.”

$$\exists x(C(x) \wedge \neg B(x))$$

“Everyone in this class passed the first exam.”

$$\forall x(C(x) \rightarrow P(x))$$

Show that all these lead to a conclusion:

- ◇ Someone who passed the first exam has not read the book.

$$\exists x(P(x) \wedge \neg B(x))$$

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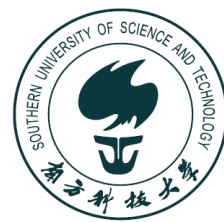
$P(x)$ – x passed the first exam.



Applying Rules of Inference for Quantified Statements

■ Translation:

- ◇ premises: $\exists x(C(x) \wedge \neg B(x)), \forall x(C(x) \rightarrow P(x))$
- ◇ conclusion: $\exists x(P(x) \wedge \neg B(x))$



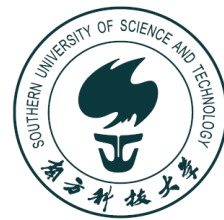
Applying Rules of Inference for Quantified Statements

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- ◇ conclusion: $\exists x(P(x) \wedge \neg B(x))$

Proof:

Step	Reason
1. $\exists x(C(x) \wedge \neg B(x))$	Premise
2. $C(a) \wedge \neg B(a)$	EI from (1)
3. $C(a)$	Simplification from (2)
4. $\forall x(C(x) \rightarrow P(x))$	Premise
5. $C(a) \rightarrow P(a)$	UI from (4)
6. $P(a)$	MP from (3) and (5)
7. $\neg B(a)$	Simplification from (2)
8. $P(a) \wedge \neg B(a)$	Conj from (6) and (7)
9. $\exists x(P(x) \wedge \neg B(x))$	EG from (8)



Informal Proofs

- Proving theorems *in practice*:
 - ◇ The steps of the proofs are *not expressed in any formal language of logic*.
 - ◇ One must always watch the *consistency* of the argument made, logic and its rules can often help us to decide the soundness of the argument.



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- Proving theorems *in practice*:
 - ◇ The steps of the proofs are *not expressed in any formal language of logic*.
 - ◇ One must always watch the *consistency* of the argument made, logic and its rules can often help us to decide the soundness of the argument.
- We use (*informal*) proofs to illustrate different methods of proving theorems.



Methods of Proving Theorems

■ Basic methods to prove theorems:

◇ *direct proof*

- $p \rightarrow q$ is proved by showing that if p is true then q follows

◇ *proof by contrapositive*

- show the contrapositive $\neg q \rightarrow \neg p$

◇ *proof by contradiction*

- show that $(p \wedge \neg q)$ contradicts the assumptions

◇ *proof by cases*

- give proofs for all possible cases

◇ *proof of equivalence*

- $p \leftrightarrow q$ is replaced with $(p \rightarrow q) \wedge (q \rightarrow p)$



Direct Proof

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Example: Prove that “if n is odd, then n^2 is odd”



Direct Proof

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Example: Prove that “if n is odd, then n^2 is odd”

Proof:

Assume that (the hypothesis is true, i.e., n is odd)
 $n = 2k + 1$ where k is an integer.

Then

$$n^2 = (2k + 1)^2 = 4k^2 + 4k + 1 = 2(2k^2 + 2k) + 1.$$

Therefore, n^2 is odd.



Proof by Contrapositive

- $p \rightarrow q$ is proved by showing the contrapositive $\neg q \rightarrow \neg p$



Proof by Contrapositive

- $p \rightarrow q$ is proved by showing the contrapositive $\neg q \rightarrow \neg p$

Example: Prove that “if $3n + 2$ is odd, then n is odd”



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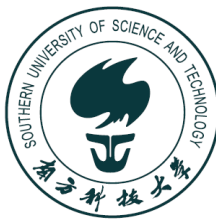
Example: Prove that “if $3n + 2$ is odd, then n is odd”

Proof:

Assume that n is even, i.e., $n = 2k$, where k is an integer. Then

$$3n + 2 = 3(2k) + 2 = 2(3k + 1).$$

Therefore, $3n + 2$ is even.



Proof by Contradiction

- Assume that p is true but q is false ($p \wedge \neg q$). Then show a contradiction to p , or $\neg q$, or other settled results.



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Assume that $3n + 2$ is odd and n is even, i.e., $n = 2k$, where k is an integer. Then

$$3n + 2 = 3(2k) + 2 = 2(3k + 1).$$

Thus, $3n + 2$ is even. This is a contradiction to the assumption that $3n + 2$ is odd. Therefore, n is odd.



Proof by Cases

- We want to show $(p_1 \vee p_2 \vee \dots \vee p_n) \rightarrow q$. This is equivalent to $(p_1 \rightarrow q) \wedge (p_2 \rightarrow q) \wedge \dots \wedge (p_n \rightarrow q)$. Why?



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Example: Prove that “ $|x||y| = |xy|$ for real numbers x, y ”

Proof: Four cases:

- ◇ $x \geq 0, y \geq 0$
- ◇ $x \geq 0, y < 0$
- ◇ $x < 0, y \geq 0$
- ◇ $x < 0, y < 0$



Proof of Equivalences

- To prove “ $p \leftrightarrow q$ ”, show $(p \rightarrow q) \wedge (q \rightarrow p)$.



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- To prove “ $p \leftrightarrow q$ ”, show $(p \rightarrow q) \wedge (q \rightarrow p)$.

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Proof:

- ◇ proof of $p \rightarrow q$: direct proof
- ◇ proof of $q \rightarrow p$: proof by contrapositive



Vacuous Proof

- To prove $p \rightarrow q$, suppose that p (the hypothesis) is always false, then $p \rightarrow q$ is always true.



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- To prove $p \rightarrow q$, suppose that p (the hypothesis) is always **false**, then $p \rightarrow q$ is always true.

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- To prove $p \rightarrow q$, suppose that p (the hypothesis) is always **false**, then $p \rightarrow q$ is **always true**.

Example: $P(n)$ – “if $n > 1$ then $n^2 > n$ ”. Show that $P(0)$

Proof: Since the premise $0 > 1$ is **always false**. Thus $P(0)$ is true.



Trivial Proof

- To prove $p \rightarrow q$, suppose that q (the conclusion) is always true, then $p \rightarrow q$ is always true.



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- To prove $p \rightarrow q$, suppose that q (the conclusion) is always true, then $p \rightarrow q$ is always true.

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Trivial Proof

- To prove $p \rightarrow q$, suppose that q (the conclusion) is always **true**, then $p \rightarrow q$ is **always true**.

Example: $P(n)$ – “if $a \geq b$ then $a^n \geq b^n$ ”. Show that $P(0)$

Proof: Since the conclusion $a^0 \geq b^0$ is **always true**. Thus $P(0)$ is true.



Proofs with Quantifiers

■ Universally quantified statements

- ◇ prove the property holds for all examples
 - proof by cases to divide the proof into different parts
- ◇ counterexamples
 - disprove universal statements



Proofs with Quantifiers

■ Existence proof

◇ constructive

- find a specific example to show the statement holds

◇ nonconstructive

- proof by contradiction



Proof Exercises

- Prove that “ $\sqrt{2}$ is *irrational*”. (*rational numbers* are those of the form $\frac{m}{n}$, where m, n are integers.)



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- Prove that “ $\sqrt{2}$ is *irrational*”. (*rational numbers* are those of the form $\frac{m}{n}$, where m, n are integers.)

Proof:

Suppose that $\sqrt{2}$ is rational. Then there exist two integers m and n such that $\gcd(m, n) = 1$ and $\sqrt{2} = m/n$. We have then $m^2 = 2n^2$. It then follows that m is even. Let $m = 2k$ for some integer k . It then follows that $n^2 = 2k^2$. Hence, n is also even. This means $\gcd(m, n)$ must have a factor 2, which contradicts to the assumption that $\gcd(m, n) = 1$.



Proof Exercises

- Prove that “There are infinitely many prime numbers”.



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Proof:

Suppose that there are only a finite number of primes. Then some prime number p is the largest of all the prime numbers, and we can list the prime numbers in ascending order:

$2, 3, 5, 7, 11, \dots, p.$

Let $n = (2 \times 3 \times 5 \times \dots \times p) + 1$. Then $n > 1$, and n cannot be divided by any prime number in the list above. This means that n is also a prime. Clearly, n is larger than all the primes in the list above. This is contrary to the assumption that all primes are in the list.



Words from Dijkstra



Edsger W. Dijkstra
(1930–2002)

– “... mathematical logic is and must be the basis for software design. ... mathematical analysis of designs and specifications have become central activities in computer science research...”

Announcements

■ Homework Assignment 1

- ◇ P13 Ex. 14, P15 Ex. 34 b) d) f), P16, Ex. 40, P35, Ex. 26, 30, 32, P53, Ex. 9, P65, Ex. 10, P67, Ex. 30 a) c) e), P79, Ex. 13 a) c) 14 b) d), P91, Ex. 26, P108, Ex. 7, 14, P109, Ex. 34, 36
- ◇ Due on *Oct. 10th, 2017 at the beginning of class*
- ◇ Please write your homework **neatly**, as a courtesy to graders.



Next Lecture

- Sets, functions ...

