Day 1: Proofs

Operational math bootcamp

Statistical Sciences
UNIVERSITY OF TORONTO

Emma Kroell

University of Toronto

May 12, 2022

Outline

- Logic
- Review of Proof Techniques
- Examples

Propositional logic

Propositions are statements that could be true or false. They have a corresponding **truth value**.

ex. "*n* is odd" and "*n* is divisible by 2" are propositions . Let's call them P and Q. Whether they are true or not depends on what n is.

Propositional logic

Propositions are statements that could be true or false. They have a corresponding **truth value**.

ex. "n is odd" and "n is divisible by 2" are propositions . Let's call them P and Q. Whether they are true or not depends on what n is.

We can negate statements: $\neg P$ is the statement "n is not odd"

Propositional logic

Propositions are statements that could be true or false. They have a corresponding **truth value**.

ex. "n is odd" and "n is divisible by 2" are propositions . Let's call them P and Q. Whether they are true or not depends on what n is.

We can negate statements: $\neg P$ is the statement "n is not odd"

We can combine statements:

- $P \wedge Q$ is the statement "n is odd and n is divisible by 2".
- $P \vee Q$ is the statement "n is odd or n is divisible by 2". We always assume the inclusive or unless specifically stated otherwise.

Examples

Symbol	Meaning
Capital letters	propositions
$\implies$	implies
$\wedge$	and
$\vee$	inclusive or
$\neg$	not

- If it's not raining, I won't bring my umbrella.
- I'm a banana or Toronto is in Canada.
- If I pass this exam, I'll be both happy and surprised.

Truth values

Example

If it is snowing, then it is cold out.
It is snowing.
Therefore, it is cold out.

Write this using propositional logic:

Truth values

Example

If it is snowing, then it is cold out.

It is snowing.

Therefore, it is cold out.

Write this using propositional logic:

$$P \implies Q$$
$$P$$
$$\text{Conclusion: } Q$$

How do we know if this statement is true or not?

Truth table

If it is snowing, then it is cold out.
It is snowing.
Therefore, it is cold out.

Truth table

$$P \implies Q$$

If it is snowing, then it is cold out.
It is snowing.
Therefore, it is cold out.

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

Logical equivalence

$$P \implies Q$$

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

Logical equivalence

$$P \implies Q$$

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

$$\neg P \vee Q$$

P	Q	$\neg P$	$\neg P \vee Q$
T	T	F	T
T	F	F	F
F	T	T	T
F	F	T	T

Logical equivalence

$P \implies Q$

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

$\neg P \vee Q$

P	Q	$\neg P$	$\neg P \vee Q$
T	T	F	T
T	F	F	F
F	T	T	T
F	F	T	T

What is $\neg(P \implies Q)$?

Types of proof

- Direct
- Contradiction
- Contrapositive
- Induction

Direct Proof

Approach: Use the definition and known results.

Example

Claim

The product of an even number with another integer is even.

Approach: use the definition of even.

Direct Proof

Claim

The product of an even number with another integer is even.

Definition

We say that an integer n is **even** if there exists another integer j such that $n = 2j$.
We say that an integer n is **odd** if there exists another integer j such that $n = 2j + 1$.

Proof.

Let $n, m \in \mathbb{Z}$, with n even. By definition, there $\exists\ j \in \mathbb{Z}$ such that $n = 2j$. Then

$$nm = (2j)m = 2(jm)$$

Therefore nm is even by definition. □

Claim

If an integer squared is even, then the integer is itself even.

How would you approach this proof?

Proof by contrapositive

$$P \implies Q$$

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

$$\neg P \implies \neg Q$$

P	Q	$\neg P$	$\neg Q$	$\neg Q \implies \neg P$
T	T	F	F	
T	F	F	T	
F	T	T	F	
F	F	T	T	

Statistical Sciences
UNIVERSITY OF TORONTO

Proof by contrapositive

$$P \implies Q$$

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

$$\neg Q \implies \neg P$$

P	Q	$\neg P$	$\neg Q$	$\neg Q \implies \neg P$
T	T	F	F	T
T	F	F	T	T
F	T	T	F	F
F	F	T	T	T

Proof by contrapositive

Claim

If an integer squared is even, then the integer is itself even.

Proof.

We prove the contrapositive. Let n be odd. Then there exists $k \in \mathbb{Z}$ such that $n = 2k + 1$. We compute

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

Thus n^2 is odd.

□

Proof by contradiction

Claim

The sum of a rational number and an irrational number is irrational.

Proof.

Let $q \in \mathbb{Q}$ and $r \in \mathbb{R} \setminus \mathbb{Q}$. Suppose in order to derive a contradiction that their sum is rational, i.e. $r + q = s$ where $s \in \mathbb{Q}$. But then $r = s - q \in \mathbb{Q}$. Contradiction. □

Summary

In sum, to prove $P \implies Q$:

Direct proof: assume P, prove Q

Proof by contrapositive: assume $\neg Q$, prove $\neg P$

Proof by contradiction: assume $P \wedge \neg Q$ and derive something that is impossible

Induction

Well-ordering principle for $\mathbb{N}$

Every nonempty set of natural numbers has a least element.

Principle of mathematical induction

Let n_0 be a non-negative integer. Suppose P is a property such that

1. (base case) $P(n_0)$ is true
2. (induction step) For every integer $k \geq n_0$, if $P(k)$ is true, then $P(k+1)$ is true.

Then $P(n)$ is true for every integer $n \geq n_0$

Note: Principle of strong mathematical induction: For every integer $k \geq n_0$, if $P(n)$ is true for every $n = n_0, \ldots, k$, then $P(k+1)$ is true.

Claim

$n! > 2^n$ if $n \geq 4$.

Proof.

We prove this by induction on n.

Base case: Let $n = 4$. Then $n! = 4! = 24 > 16 = 2^4$.

Claim

$n! > 2^n$ if $n \geq 4$.

Proof.

We prove this by induction on n.

Base case: Let $n = 4$. Then $n! = 4! = 24 > 16 = 2^4$.

Inductive hypothesis: Suppose for some $k \geq 4$, $k! > 2^k$.

Claim

$n! > 2^n$ if $n \geq 4$.

Proof.

We prove this by induction on n.

Base case: Let $n = 4$. Then $n! = 4! = 24 > 16 = 2^4$.

Inductive hypothesis: Suppose for some $k \geq 4$, $k! > 2^k$.

Then

$$(k+1)! = (k+1)k! > (k+1)2^k > 2(2^k) = 2^{k+1}.$$

□

Claim

Every integer $n \geq 2$ can be written as the product of primes.

Proof.

We prove this by induction on n.

Base case: $n = 2$ is prime.

Claim

Every integer $n \geq 2$ can be written as the product of primes.

Proof.

We prove this by induction on n.

Base case: $n = 2$ is prime.

Inductive hypothesis: Suppose for some $k \geq 2$ that one can write every integer n such that $2 \leq n \leq k$ as a product of primes.

Claim

Every integer $n \geq 2$ can be written as the product of primes.

Proof.

We prove this by induction on n.
Base case: $n = 2$ is prime.
Inductive hypothesis: Suppose for some $k \geq 2$ that one can write every integer n such that $2 \leq n \leq k$ as a product of primes.
We must show that we can write $k + 1$ as a product of primes.
First, if $k + 1$ is prime then we are done.

Claim

Every integer $n \geq 2$ can be written as the product of primes.

Proof.

We prove this by induction on n.
Base case: $n = 2$ is prime.
Inductive hypothesis: Suppose for some $k \geq 2$ that one can write every integer n such that $2 \leq n \leq k$ as a product of primes.
We must show that we can write $k + 1$ as a product of primes.
First, if $k + 1$ is prime then we are done.
Otherwise, if $k + 1$ is not prime, by definition it can be written as a product of some integers a, b such that $1 < a, b < k + 1$. By the induction hypothesis, a and b can both be written as products of primes, so we are done. □

Exercises

1. Prove De Morgan's Laws: $\neg(P \wedge Q) = \neg P \vee \neg Q$ and $\neg(P \vee Q) = \neg P \wedge \neg Q$.
2. Prove the Fundamental Theorem of Arithmetic, that every integer $n \geq 2$ has a unique prime factorization (i.e. prove that the prime factorization from the last proof is unique).