Methods of Proof

This Lecture

Now we have learnt the basics in logic.

We are going to apply the logical rules in proving mathematical theorems.

- Direct proof
- Contrapositive
- Proof by contradiction
- Proof by cases

Basic Definitions

An integer n is an even number
if there exists an integer k such that $n = 2k$.

An integer n is an odd number
if there exists an integer k such that $n = 2k+1$.

Proving an Implication

Goal: If P, then Q. (P implies Q)

Method 1: Write assume P, then show that Q logically follows.

The sum of two even numbers is even.

Proof

$x = 2m, y = 2n$

$x+y = 2m+2n$

$= 2(m+n)$

Direct Proofs

The product of two odd numbers is odd.

Proof $x = 2m+1$, $y = 2n+1$

$$xy = (2m+1)(2n+1)$$
$$= 4mn + 2m + 2n + 1$$
$$= 2(2mn+m+n) + 1.$$

If m and n are perfect squares, then $m+n+2\sqrt{(mn)}$ is a perfect square.

Proof $m = a^2$ and $n = b^2$ for some integers a and b

Then $m + n + 2\sqrt{(mn)} = a^2 + b^2 + 2ab$
$$= (a + b)^2$$

So $m + n + 2\sqrt{(mn)}$ is a perfect square.

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Proving an Implication

Goal: If P, then Q. (P implies Q)

Method 1: Write assume P, then show that Q logically follows.

Claim: If r is irrational, then $\sqrt{r}$ is irrational.

How to begin with?

What if I prove "If $\sqrt{r}$ is rational, then r is rational", is it equivalent?

Yes, this is equivalent, because it is the **contrapositive** of the statement, so proving "if P, then Q" is equivalent to proving "if not Q, then not P".

Rational Number

A real number *r* is rational if there are integers a and b such that

numerator

$$r = \frac{a}{b}$$

denominator

and b ≠ 0.

Is 0.281 a rational number? Yes, 281/1000

Is 0 a rational number? Yes, 0/1

If m and n are non-zero integers, is (m+n)/mn a rational number? Yes

Is the sum of two rational numbers a rational number? Yes, a/b+c/d=(ad+bc)/bd

Is x=0.12121212…… a rational number? Note that 100x-x=12, and so x=12/99.

Proving the Contrapositive

Goal: If P, then Q. (P implies Q)

Method 2: Prove the ***contrapositive***, i.e. prove "not Q implies not P".

Claim: If r is irrational, then $\sqrt{r}$ is irrational.

Proof:

We shall prove the contrapositive –

"if $\sqrt{r}$ is rational, then r is rational."

Since $\sqrt{r}$ is rational, $\sqrt{r} = a/b$ for some integers a,b.

So $r = a^2/b^2$. Since a,b are integers, a^2,b^2 are integers.

Therefore, r is rational. □ Q.E.D.

(Q.E.D.) "thus it has been demonstrated", or "quite easily done". ☺

Proving an "if and only if"

Goal: Prove that two statements P and Q are "**logically equivalent**", that is, one holds if and only if the other holds.

Example: For an integer n, n is even if and only if n^2 is even.

Method 1a: Prove P implies Q **and** Q implies P.

Method 1b: Prove P implies Q **and** not P implies not Q.

Method 2: Construct a chain of if and only if statement.

Proof the Contrapositive

For an integer n, n is even if and only if n^2 is even.

Method 1a: Prove P implies Q **and** Q implies P.

Statement: If n is even, then n^2 is even

Proof: $n = 2k$

$n^2 = 4k^2$

Statement: If n^2 is even, then n is even

Proof: $n^2 = 2k$

$n = \sqrt{(2k)}$

??

Proof the Contrapositive

For an integer n, n is even if and only if n^2 is even.

Method 1b: Prove P implies Q **and** not P implies not Q.

Statement: If n^2 is even, then n is even

Contrapositive: If n is odd, then n^2 is odd.

Proof (the contrapositive):

Since n is an odd number, $n = 2k+1$ for some integer k.

So $n^2 = (2k+1)^2$

$= (2k)^2 + 2(2k) + 1 \quad = 2(2k^2 + 2k) + 1$

So n^2 is an odd number.

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Proof by Contradiction

$$\frac{\overline{P} \rightarrow \textcolor{red}{\mathrm{F}}}{P}$$

To prove P, you prove that not P would lead to a ridiculous result, and so P must be true.

Proof by Contradiction

Theorem: $\sqrt{2}$ is irrational.

Proof (by contradiction):

- Suppose $\sqrt{2}$ was rational.
- Choose *m*, *n* integers without common prime factors (always possible)

  such that $\sqrt{2} = \dfrac{m}{n}$

- Show that *m* and *n* are both even, thus having a common factor 2,

  a **contradiction**!

Proof by Contradiction

Theorem: $\sqrt{2}$ is irrational.

Proof (by contradiction):

Want to prove both m and n are even.

$$\sqrt{2} = \frac{m}{n}$$

$$\sqrt{2}n = m$$

$$2n^2 = m^2$$

so m is even.

so we have $m = 2l$

$$m^2 = 4l^2$$

$$2n^2 = 4l^2$$

$$n^2 = 2l^2$$

so n is even.

Recall that m is even if and only if m^2 is even.

Infinitude of the Primes

Theorem. There are infinitely many prime numbers.

Proof (by contradiction):

Assume there are only finitely many primes.

Let $p_1, p_2, \ldots, p_k$ be all the primes.

(1) We will construct a number N so that N is not divisible by any p_i.

By our assumption, it means that N is not divisible by any prime number.

(2) On the other hand, we show that any number is divisible by *some* prime.

This will lead to a contradiction, and therefore the assumption must be false.

So there must be infinitely many primes.

Infinitude of the Primes

Theorem. There are infinitely many prime numbers.

Proof (by contradiction):

Let $p_1, p_2, \ldots, p_k$ be all the primes.

Consider $p_1p_2\ldots p_k + 1$.

Claim: if p divides a, then p does not divide a+1.

Proof (by contradiction):

a = cp for some integer c

a+1 = dp for some integer d

=> 1 = (d-c)p, contradiction because p>=2.

So, by the claim, none of $p_1, p_2, \ldots, p_k$ can divide $p_1p_2\ldots p_k + 1$, a contradiction.

Divisibility by a Prime

Theorem. Any integer $n > 1$ is divisible by a prime number.

- Let n be an integer.
- If n is a prime number, then we are done.
- Otherwise, $n = ab$, both a,b are smaller than n.
- If a or b is a prime number, then we are done.
- Otherwise, $a = cd$, both c,d are smaller than a.
- If c or d is a prime number, then we are done.
- Otherwise, repeat this argument, since the numbers are getting smaller and smaller, this will eventually stop and we will find a prime factor of n.

We will see a better proof by mathematical induction later.

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Proof by Cases

$$p \vee q$$
$$p \rightarrow r$$
$$q \rightarrow r$$
$$\therefore \; r$$

e.g. want to prove the square of a nonzero number is always positive.

x is positive or x is negative

if x is positive, then $x^2 > 0$.

if x is negative, then $x^2 > 0$.

$\therefore$ $x^2 > 0$.

The Square of an Odd Integer

$$\boxed{\forall \text{ odd } n, \exists m, n^2 = 8m + 1?}$$

Idea 0: find counterexample.

$3^2 = 9 = 8+1$, $5^2 = 25 = 3 \times 8+1$ …… $131^2 = 17161 = 2145 \times 8 + 1$, ………

Idea 1: prove that $n^2 - 1$ is divisible by 8.

$n^2 - 1 = (n-1)(n+1) = ??$…

Idea 2: consider $(2k+1)^2$

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

If k is even, then both k^2 and k are even, and so we are done.

If k is odd, then both k^2 and k are odd, and so k^2+k even, also done.

Rational vs Irrational

Question: If a and b are irrational, can a^b be rational??

We (only) know that $\sqrt{2}$ is irrational, what about $\sqrt{2}^{\sqrt{2}}$?

Case 1: $\sqrt{2}^{\sqrt{2}}$ is rational

Then we are done, $a=\sqrt{2}$, $b=\sqrt{2}$.

Case 2: $\sqrt{2}^{\sqrt{2}}$ is irrational

Then $(\sqrt{2}^{\sqrt{2}})^{\sqrt{2}} = \sqrt{2}^2 = 2$, a rational number

So $a=\sqrt{2}^{\sqrt{2}}$, $b= \sqrt{2}$ will do.

So in either case there are a,b irrational and a^b be rational.

We don't (need to) know which case is true!

Summary

We have learnt different techniques to prove mathematical statements.

- Direct proof
- Contrapositive
- Proof by contradiction
- Proof by cases

Next time we will focus on a very important technique, proof by induction.