

Mathematical Induction

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Chapter 1

Mathematical Induction

1.1 Introduction

Definition 1.1.1: Mathematical Induction

Mathematical induction can be used to prove statements that assert $P(n)$ is true for all positive integers n , where $P(n)$ is a propositional function. A proof by mathematical induction has two parts, a **basis step**, where we show that $P(1)$ is true and an **inductive step**, where we show that for all positive integers k if $P(k)$ is true then $P(k+1)$ is also true.

Mathematical Induction can be expressed as the rule of inference $P(1) \wedge (P(k) \rightarrow P(k+1)) \rightarrow \forall n P(n)$, where the domain is the set of positive integers.

Example 1.1.1

Question 1

Show that

$$P(n) : 1 + 2 + 3 + \dots + n = \frac{n(n+1)}{2}$$

Solution: We first start with the basis step, $P(1)$, which is

$$\begin{aligned} P(1) : 1 &= \frac{1(1+1)}{2} \\ 1 &= 1 \end{aligned}$$

$\therefore P(1)$ is true.

Next is the inductive step, where we need to show that $P(k) \rightarrow P(k+1)$

We assume

$$P(k) : 1 + 2 + 3 + \dots + k = \frac{k(k+1)}{2}$$

and prove

$$P(k+1) : 1 + 2 + 3 + \dots + (k+1) = \frac{(k+1)(k+2)}{2}$$

To prove this we need to relate these two predicates. And because $P(k+1)$ can be expressed as $P(k) + (k+1)$ we can write

$$P(k+1) : 1 + 2 + 3 + \dots + (k+1) = \frac{k(k+1)}{2} + (k+1)$$

So we simplify

$$\begin{aligned}\frac{k(k+1)}{2} + (k+1) &= \frac{k(k+1) + 2(k+1)}{2} \\ &= \frac{(k+1)(k+2)}{2}\end{aligned}$$

Example 1.1.2

Question 2

Show that

$$P(n) : 1 + 3 + 5 + \dots + (2n - 1) = n^2 \quad \forall n \in \mathbb{Z}$$

Solution: The basis step is $P(1)$

$$P(1) : 1 = 1^2$$

Assume

$$P(k) : 1 + 3 + 5 + \dots + (2k - 1) = k^2$$

and show that

$$P(k+1) : 1 + 3 + 5 + \dots + (2(k+1) - 1) = (k+1)^2$$

$P(k+1)$ can be expressed as $P(k) + (2k+1)$

$$\begin{aligned}P(k+1) : 1 + 3 + 5 + \dots + (2k - 1) + (2k + 1) \\ &= k^2 + 2k + 1 \\ &= (k+1)^2\end{aligned}$$

$\therefore P(k+1)$ is true

Conclusion: Having completed the basis and induction steps we can conclude that $1 + 3 + 5 + \dots + (2n - 1) = n^2$

1.2 Why Mathematical Induction is Valid

Definition 1.2.1: Well Ordering Property of Positive Integers

This axiom states that every non-empty subset of positive integers has a least element

The validity of mathematical induction as a proof technique comes from the well ordering property, as an axiom of positive integers. So suppose we know that $P(1)$ is true for all positive integers n and that the proposition $P(k) \rightarrow P(k+1)$ is true for all positive integers k . To show that $P(n)$ must be true for all positive integers n we can use a proof by contradiction.

We first assume that there is at least positive integer for which $P(n)$ is false, i.e. $\exists x \in \mathbb{Z}^+ \neg P(x)$

Then the set of positive integers for which $P(n)$ is false, let this be S , is non-empty. Thus by the well ordering property, S has a least element, which we will denote as m .

We know that m cannot be 1, because $P(1)$ is true, and since m is a positive integer it must be greater than one ergo $m - 1$ is also a positive integer.

Again due to well ordering property we know the least value in S is m therefore $m - 1$ is not in set S , as a result $P(m - 1)$ is true.

Because the statements $P(m - 1) \rightarrow P(m)$ is also true, it must be the case that $P(m)$ is true, which is a contradiction of the statement that $P(m)$ must be false.

Hence $P(n)$ must be true for every positive integer.

1.3 Examples of Proofs by Mathematical Induction

1.3.1 Proving Summation Formulae

Question 3

Conjecture a formula for the sum of the first n positive odd integers. Then prove your conjecture using mathematical induction.

Solution: The sums of the first n positive odd integers for $n = 1, 2, 3, 4, 5$ are

$$\begin{aligned} 1 &= 1 \\ 1 + 3 &= 4 \\ 1 + 3 + 5 &= 9 \\ 1 + 3 + 5 + 7 &= 16 \\ 1 + 3 + 5 + 7 + 9 &= 25 \end{aligned}$$

From these values it is reasonable to conjecture that the sum of the first n odd integers is n^2 , i.e.

$$1 + 3 + 5 + \dots + (2n - 1) = n^2$$

Let $P(n)$ be $1 + 3 + 5 + \dots + (2n - 1) = n^2$

Basis Step:

$$P(1) : 1 = 1^2$$

Inductive Step:

To complete this step we need to prove that $\forall k \in \mathbb{Z}^+ (P(k) \rightarrow P(k + 1))$

Assume $\exists k \in \mathbb{Z}^+ P(k) = T$, then

$$P(k) : 1 + 3 + 5 + \dots + (2k - 1) = k^2$$

$$P(k+1) : 1 + 3 + 5 + \dots + (2k+1) = (k+1)^2$$

$$P(k+1) : 1 + 3 + 5 + \dots + (2k-1) + (2k+1) = (k+1)^2$$

$$P(k+1) : P(k) + (2k+1)$$

$$1 + 3 + 5 + \dots + (2k+1) = k^2 + 2k + 1$$

$$= (k+1)(k+1)$$

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

$\therefore P(k+1)$ is T

Hence we can conclude that $P(n)$ is true for all positive integers n .

Question 4

Use mathematical induction to show that

$$1 + 2 + 2^2 + \dots + 2^n = 2^{n+1} - 1$$

For all non-negative integers n

Solution:

Let $P(n)$ be $1 + 2 + 2^2 + \dots + 2^n = 2^{n+1} - 1$

Basis Step:

$$P(0) : 2^0 = 2^{0+1} - 1$$

$$1 = 2 - 1$$

$$1 = 1$$

Induction Step

To complete this step I must prove $P(k) \rightarrow P(k+1)$ where k is any non-negative integer.

Assume $P(k)$ is true for some non-negative integer k , then

$$P(k) : 1 + 2 + 2^2 + \dots + 2^k = 2^{k+1} - 1$$

Then $P(k+1)$ is

$$P(k+1) : 1 + 2 + 2^2 + \dots + 2^k + 2^{k+1} = 2^{k+2} - 1$$

$P(k+1)$ can also be expressed as $P(k+1) = P(k) + 2^{k+1}$

$$\begin{aligned}
P(k+1) : 1 + 2 + 2^2 + \dots + 2^{k+1} &= 2^{k+1} - 1 + 2^{k+1} \\
&= 2^k \times 2^1 + 2^k \times 2^1 - 1 \\
&= 2^k (2^1 + 2^1) - 1 \\
&= 2^k (2^2) - 1 \\
&= 2^{k+2} - 1
\end{aligned}$$

$\therefore P(k+1)$ is T

Hence we can conclude that $P(n)$ is true for all non-negative integers n .

1.3.1.0.1 Sums of Geometric Progressions

Question 5

Use mathematical induction to prove this formula for the sum of a finite number of terms of a geometric progression with initial term a and a common ratio r

$$\sum_{j=0}^n ar^j = a + ar + ar^2 + \dots + ar^n = \frac{ar^{n+1} - a}{r - 1} \quad \text{where } r \neq 1$$

where n is a non-negative integer.

Solution: Let $P(n)$ be "the sum of the first $n+1$ terms of a geometric progression in this formula is correct".

Basis Step

$$\begin{aligned}
P(0) : \sum_{j=0}^0 ar^j &= \frac{ar^{0+1} - a}{r - 1} \\
a &= \frac{ar - a}{r - 1} \\
a &= \frac{a(r - 1)}{r - 1} \\
a &= a
\end{aligned}$$

Induction Step

To complete this step I must prove $P(k) \rightarrow P(k+1)$ where k is any non-negative integer.

Assume $P(k)$ for some non-negative integer k , then

$$P(k) : \sum_{j=0}^k ar^j = a + ar + ar^2 + \dots + ar^k = \frac{ar^{k+1} - a}{r - 1}$$

Then $P(k+1)$ is

$$P(k+1) : \sum_{j=0}^{k+1} ar^j = a + ar + ar^2 + \dots + ar^{k+1} = \frac{ar^{k+2} - a}{r - 1}$$

And can be expressed as $P(k+1) = P(k) + ar^{k+1}$, therefore:

$$\begin{aligned} P(k+1) : \sum_{j=0}^{k+1} ar^j &= a + ar + ar^2 + \dots + ar^k + ar^{k+1} = \frac{ar^{k+1} - a}{r - 1} + ar^{k+1} \\ &= \frac{ar^{k+1} - a}{r - 1} + \frac{ar^{k+1}}{1} \\ &= \frac{ar^{k+1} - a + (ar^{k+1})(r - 1)}{r - 1} \\ &= \frac{ar^{k+1} + ar^{k+2} - ar^{k+1} - a}{r - 1} \\ &= \frac{ar^{k+2} - a}{r - 1} \end{aligned}$$

$\therefore P(k+1)$ is T

Hence we can conclude that $P(n)$ is true for all non-negative integers n

1.4 Exercises

Question 6

Prove that

$$3 + 3 \times 5 + 3 \times 5^2 + \dots + 3 \times 5^n = \frac{3(5^{n+1} - 1)}{4}$$

whenever n is non-negative integer

Solution:

Let $P(n)$ be $3 + 3 \times 5 + 3 \times 5^2 + \dots + 3 \times 5^n = \frac{3(5^{n+1}-1)}{4}$

Basis Step

$$\begin{aligned} P(0) : 3 &= \frac{3(5^1 - 1)}{4} \\ 3 &= \frac{12}{4} \\ 3 &= 3 \end{aligned}$$

Induction Step

To complete this step I must prove $P(k) \rightarrow P(k+1)$ for any non-negative integer k

Assume $P(k)$ is T for some non-negative integer k , then

$$P(k) : 3 + 3 \times 5 + 3 \times 5^2 + \dots + 3 \times 5^k = \frac{3(5^{k+1} - 1)}{4}$$

Then $P(k+1)$ is

$$P(k+1) : 3 + 3 \times 5 + 3 \times 5^2 + \dots + 3 \times 5^{k+1} = \frac{3(5^{k+2} - 1)}{4}$$

And can be expressed as $P(k+1) = P(k) + 3 \times 5^{k+1}$, therefore:

$$\begin{aligned} P(k+1) : 3 + 3 \times 5 + 3 \times 5^2 + \dots + 3 \times 5^k + 3 \times 5^{k+1} &= \frac{3(5^{k+1} - 1)}{4} + (3 \times 5^{k+1}) \\ &= \frac{3(5^{k+1} - 1) + 4(3 \times 5^{k+1})}{4} \\ &= \frac{3 \times 5^{k+1} - 3 + 12 \times 5^{k+1}}{4} \\ &= \frac{3(5^{k+1} + 4 \times 5^{k+1} - 1)}{4} \end{aligned}$$

Let $x = 5^{k+1}$

$$\begin{aligned} &= \frac{3(x + 4x - 1)}{4} \\ &= \frac{3(5x - 1)}{4} \\ &= \frac{3(5^1 \times 5^{k+1}) - 1}{4} \\ &= \frac{3(5^{k+2} - 1)}{4} \end{aligned}$$

$\therefore P(k+1)$ is T

Hence we can conclude that $P(n)$ is true for all non-negative integers n

Question 7

Prove that

$$1 \times 1! + 2 \times 2! + \dots + n \times n! = (n+1)! - 1$$

Whenever n is a positive integer.

Solution:

Let $P(n)$ be $1 \times 1! + 2 \times 2! + \dots + n \times n! = (n+1)! - 1$

Basis Step

$$\begin{aligned} P(1) : 1 \times 1! &= (1+1)! - 1 \\ 1 &= 2 - 1 \end{aligned}$$

Induction Step

To conclude this step I need to prove $P(k) \rightarrow P(k+1)$ for any positive integer k

Assume $P(k)$ is T for some positive integer k , then

$$P(k) : 1 \times 1! + 2 \times 2! + \dots + k \times k! = (k+1)! - 1$$

Then $P(k+1)$ is:

$$P(k+1) : 1 \times 1! + 2 \times 2! + \dots + (k+1) \times (k+1)! = (k+2)! - 1$$

And can be expressed as $P(k+1) : P(k) + (k+1) \times (k+1)!$, therefore

$$\begin{aligned} P(k+1) : 1 \times 1! + 2 \times 2! + \dots + k \times k! + (k+1) \times (k+1)! &= ((k+1)! - 1) + ((k+1) \times (k+1)!) \\ &= (k+1)! + (k+1) \times (k+1)! - 1 \\ &= (k+1)! (k+2) - 1 \\ &= (k+2)! - 1 \end{aligned}$$

Question 8

1. Find a formula for

$$\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^n}$$

by examining the values of this expression for small values of n

2. Prove the formula you conjectured in part 1.

Solution:

- 1.

$$\begin{aligned} S_n &= \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^n} \\ S_1 &= \frac{1}{2} \\ S_2 &= \frac{3}{4} \\ S_3 &= \frac{7}{8} \\ S_4 &= \frac{15}{16} \\ S_n &= \frac{2^n - 1}{2^n} \end{aligned}$$

2. **Proof:** Let $P(n)$ be $\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^n} = \frac{2^n - 1}{2^n}$

Basis Step

$$P(1) : \frac{1}{2} = \frac{2^1 - 1}{2^1}$$

$$\frac{1}{2} = \frac{1}{2}$$

Induction Step

To complete this step I need to prove $P(k) \rightarrow P(k+1)$ for any positive integer k .

Assume $P(k)$ is T for some positive integer k . Then:

$$P(k) : \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^k} = \frac{2^k - 1}{2^k}$$

Then $P(k+1)$ is:

$$P(k+1) : \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^{k+1}} = \frac{2^{k+1} - 1}{2^{k+1}}$$

And can be expressed as $P(k+1) : P(k) + \frac{1}{2^{k+1}}$, therefore

$$P(k+1) : \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^{k+1}} = \frac{2^k - 1}{2^k} + \frac{1}{2^{k+1}}$$

$$= \frac{(2^k - 1)(2^{k+1}) + 2^k}{(2^k)(2^{k+1})}$$

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Question 9

Show that 3 divides $n^3 + 2n$, whenever $n \in \mathbb{Z}^+$

Proof: This has the same meaning as:

" $n^3 + 2n$ is divisible by 3"

" $n^3 + 2n$ is a multiple of 3"

Let $P(n)$ be $n^3 + 2n$ is a multiple of 3

Basis Step

$$P(1) : 1^3 + 2 + 1 \text{ is a multiple of 3}$$

True because 3 is a multiple of three.

Induction Step

Assume $P(k)$ is T then

$$”k^3 + 2k \text{ is multiple of } 3” - \exists m \in \mathbb{Z}, k^3 + 2k = 3m$$

And show $P(k+1)$ is

$$”(k+1)^3 + 2(k+1) \text{ is a multiple of } 3”$$

We have

$$\begin{aligned}(k+1)^3 + 2(k+1) &= k^3 + 3k^2 + 3k + 1 + 2k + 2 \\ &= (k^3 + 2k) + 3k^2 + 3k + 3 \\ &= 3m + 3k^2 + 3k + 3 \\ &= 3(m + k^2 + k + 1)\end{aligned}$$

$$\begin{aligned}\text{Let } z &= m + k^2 + k + 1 \\ &= 3z\end{aligned}$$

Since z is made up of positive integers z is a positive integer

$\therefore P(k+1)$

Hence we can conclude that $P(n)$ is true for all positive integers.

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