DP IB Maths: AA HL

Your notes

1.5 Further Proof & Reasoning

Contents

Your notes

1.5.1 Proof by Induction

Proof by Induction

What is proof by induction?

- **Proof by induction** is a way of proving a **result is true for a set of integers** by showing that if it is **true for one integer then it is true for the next integer**
- It can be thought of as dominoes:
  - All dominoes will fall down if:
    - The first domino falls down
    - Each domino falling down causes the next domino to fall down

What are the steps for proof by induction?

- **STEP 1: The basic step**
  - **Show** the result is true for the **base case**
  - This is **normally *n* = 1 or 0** but it could be any integer
    - For example: To prove $\sum_{r=1}^{n} r^2 = \frac{1}{6}n(n+1)(2n+1)$ is true for all integers $n \geq 1$ you would first need to show it is true for $n = 1$:
    - $\sum_{r=1}^{1} r^2 = \frac{1}{6}(1)((1)+1)(2(1)+1)$
- **STEP 2: The assumption step**
  - **Assume** the result is true for ***n* = *k*** for some integer *k*
    - For example: Assume $\sum_{r=1}^{k} r^2 = \frac{1}{6}k(k+1)(2k+1)$ is true
  - There is nothing to do for this step apart from writing down the assumption
- **STEP 3: The inductive step**
  - **Using the assumption show** the result is true for ***n* = *k* + 1**
  - It can be helpful to simplify LHS & RHS separately and show they are identical
  - The assumption from STEP 2 will be needed at some point
    - For example: $LHS = \sum_{r=1}^{k+1} r^2$ and $RHS = \frac{1}{6}(k+1)((k+1)+1)(2(k+1)+1)$
- **STEP 4: The conclusion step**
  - **State** the result is true
  - **Explain in words** why the result is true
  - It must include:
    - If true for $n = k$ then it is true for $n = k + 1$
    - Since true for $n = 1$ the statement is true for all $n \in \mathbb{Z}, n \geq 1$ by mathematical induction

- The sentence will be the same for each proof just change the base case from $n = 1$ if necessary

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What type of statements might I be asked to prove by induction?

- **Sums of sequences**
  - If the terms involve factorials then $(k+1)! = (k+1) \times (k!)$ is useful
  - These can be written in the form $\sum_{r=1}^{n} f(r) = g(n)$
  - A useful trick for the inductive step is using $\sum_{r=1}^{k+1} f(r) = f(k+1) + \sum_{r=1}^{k} f(r)$
- **Divisibility** of an expression by an integer
  - These can be written in the form $f(n) = m \times q_n$ where m & q_n are integers
  - A useful trick for the inductive step is using $a^{k+1} = a \times a^k$
- **Complex numbers**
  - You can use proof by induction to prove de Moivre's theorem
- **Derivatives**
  - Such as chain rule, product rule & quotient rule
  - These can be written in the form $f^{(n)}(x) = g(x)$
  - A useful trick for the inductive step is using $f^{(k+1)}(x) = \frac{\mathrm{d}}{\mathrm{d}x}\left(f^{(k)}(x)\right)$
  - You will have to use the differentiation rules

Examiner Tip

- Learn the steps for proof by induction and make sure you can use the method for a number of different types of questions before going into the exam
- The trick to answering these questions well is practicing the pattern of using each step regularly

Your notes

Worked example

Prove by induction that $\sum_{r=1}^{n} r(r-3) = \frac{1}{3}n(n-4)(n+1)$ for $n \in \mathbb{Z}^+$.

Want to prove $\sum_{r=1}^{n} r(r-3) = \frac{1}{3}n(n-4)(n+1)$

Basic step
Show true for $n=1$

$LHS = \sum_{r=1}^{1} r(r-3) = (1)(1-3) = -2$

$RHS = \frac{1}{3}(1)(1-4)(1+1) = -2$ $\therefore$ LHS = RHS so true for $n=1$

Assumption step
Assume true for $n=k$

Assume $\sum_{r=1}^{k} r(r-3) = \frac{1}{3}k(k-4)(k+1)$

Inductive step
Show true for $n=k+1$

$RHS = \frac{1}{3}(k+1)((k+1)-4)((k+1)+1) = \frac{1}{3}(k+1)(k-3)(k+2)$

$LHS = \sum_{r=1}^{k+1} r(r-3) = (k+1)((k+1)-3) + \sum_{r=1}^{k} r(r-3)$

$= (k+1)(k-2) + \frac{1}{3}k(k-4)(k+1)$ ← Using assumption

$= \frac{1}{3}(k+1)[3(k-2) + k(k-4)]$ ← Factorise $\frac{1}{3}(k+1)$

$= \frac{1}{3}(k+1)[k^2 - k - 6]$

$= \frac{1}{3}(k+1)(k-3)(k+2)$

$\therefore$ LHS = RHS so true for $n=k+1$

Conclusion step
Explain

If true for $n=k$ then true for $n=k+1$.
Since it is true for $n=1$, the statement is true for all $n \in \mathbb{Z}^+$

$\sum_{r=1}^{n} r(r-3) = \frac{1}{3}n(n-4)(n+1)$

1.5.2 Proof by Contradiction

Your notes

Proof by Contradiction

What is proof by contradiction?

- **Proof by contradiction** is a way of proving a **result is true** by showing that **the negation can not be true**
- It is done by:
  - Assuming the negation (opposite) of the result is true
  - Showing that this then leads to a contradiction

How do I determine the negation of a statement?

- The **negation** of a statement is the **opposite**
  - It is the statement that makes the original statement false
- To negate statements that mention "all", "every", "and" "both":
  - Replace these phrases with "there is at least one", "or" or "there exists" and include the opposite
- To negate statements that mention "there is at least one", "or" or "there exists":
  - Replace these phrases with "all", "every", "and" or "both" and include the opposite
- To negate a statement with "if A occurs then B occurs":
  - Replace with "A occurs and the negation of B occurs"
- Examples include:

Statement	Negation
a is rational	a is irrational
every even number bigger than 2 can be written as the sum of two primes	there exists an even number bigger than 2 which cannot be written as a sum of two primes
n is even and prime	n is not even or n is not prime
there is at least one odd perfect number	all perfect numbers are even
n is a multiple of 5 or a multiple of 3	n is not a multiple of 5 and n is not a multiple of 3
if n^2 is even then n is even	n^2 is even and n is odd

What are the steps for proof by contradiction?

- **STEP 1: Assume the negation** of the statement is **true**
  - You assume it is true but then try to prove your assumption is wrong

Your notes

        - For example: To prove that there is no smallest positive number you start by assuming there is a smallest positive number called *a*
- **STEP 2:** Find **two results which contradict** each other
    - Use algebra to help with this
    - Consider how a contradiction might arise
        - For example: ½*a* is positive and it is smaller than *a* which contradicts that *a* was the smallest positive number
- **STEP 3**: **Explain** why the **original statement is true**
    - In your explanation mention:
        - The **negation can't be true** as it led to a contradiction
        - Therefore the **original statement must be true**

What type of statements might I be asked to prove by contradiction?

- **Irrational numbers**
    - To show $\sqrt[n]{p}$ is irrational where p is a prime
        - Assume $\sqrt[n]{p} = \frac{a}{b}$ where a & b are integers with no common factors and $b \neq 0$
        - Use algebra to show that p is a factor of both a & b
    - To show that $\log_p(q)$ is irrational where p & q are different primes
        - Assume $\log_p(q) = \frac{a}{b}$ where a & b are integers with no common factors and $b \neq 0$
        - Use algebra to show $q^b = p^a$
    - To show that a or b must be irrational if their sum or product is irrational
        - Assume a & b are rational and write as fractions
        - Show that $a + b$ or ab is rational
- **Prime numbers**
    - To show a polynomial is never prime
        - Assume that it is prime
        - Show there is at least one factor that cannot equal 1
    - To show that there is an infinite number of prime numbers
        - Assume there are n primes $p_1, p_2, \ldots, p_n$
        - Show that $p = 1 + p_1 \times p_2 \times \ldots \times p_n$ is a prime that is bigger than the n primes
- **Odds and evens**
    - To show that n is even if n^2 is even
        - Assume n^2 is even and n is odd
        - Show that n^2 is odd
- **Maximum and minimum values**
    - To show that there is no maximum multiple of 3
        - Assume there is a maximum multiple of 3 called *a*
        - Multiply *a* by 3

Examiner Tip

- A question won't always state that you should use proof by contradiction, you will need to recognise that it is the correct method to use
  - There will only be two options (e.g. a number is rational or irrational)
  - Contradiction is often used when no other proof seems reasonable

Your notes

Your notes

Worked example

Prove the following statements by contradiction.

a) For any integer n, if n^2 is a multiple of 3 then n is a multiple of 3.

Assume the negation is true for a contradiction.

Assume n^2 is a multiple of 3 and n is not a multiple of 3.

Every integer can be written as one of $3k-1, 3k, 3k+1$ for some $k \in \mathbb{Z}$

As n is not a multiple of 3 then $n = 3k+1$ or $n = 3k-1$ for some $k \in \mathbb{Z}$

If $n = 3k+1$: $n^2 = (3k+1)^2 = 9k^2 + 6k + 1 = 3(3k^2 + 2k) + 1$ so not a multiple of 3

If $n = 3k-1$: $n^2 = (3k-1)^2 = 9k^2 - 6k + 1 = 3(3k^2 - 2k) + 1$ so not a multiple of 3

$\therefore n^2$ is not a multiple of 3

This contradicts the statement "n^2 is a multiple of 3".
Therefore the assumption is incorrect.
Therefore if n^2 is a multiple of 3 then n is a multiple of 3.

b) $\sqrt{3}$ is an irrational number.

Your notes

Assume the negation is true for a contradiction.

Assume $\sqrt{3}$ is rational so can be written $\sqrt{3} = \frac{a}{b}$ where a and b are integers with no common factors and $b \neq 0$.

Square both sides and rearrange

$3 = \frac{a^2}{b^2} \Rightarrow 3b^2 = a^2 \Rightarrow a^2$ is a multiple of 3 $\Rightarrow a$ is a multiple of 3

Let $a = 3k$ for some $k \in \mathbb{Z}$

$3b^2 = a^2 \Rightarrow 3b^2 = 9k^2 \Rightarrow b^2 = 3k^2 \Rightarrow b^2$ is a multiple of 3

$\therefore$ b and a are multiples of 3

This contradicts the statement "a and b have no common factors".
Therefore the assumption is incorrect.
Therefore $\sqrt{3}$ is irrational.