

# DP IB Maths: AA SL

## 4.5 Binomial Distribution

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## 4.5.1 The Binomial Distribution

### Properties of Binomial Distribution

#### What is a binomial distribution?

- A binomial distribution is a **discrete probability distribution**
- A **discrete random variable**  $X$  follows a **binomial distribution** if it **counts the number of successes** when an experiment satisfies the following conditions:
  - There are a **fixed finite number of trials** ( $n$ )
  - The outcome of each trial is **independent** of the outcomes of the other trials
  - There are **exactly two outcomes** of each trial (**success or failure**)
  - The **probability of success is constant** ( $p$ )
- If  $X$  follows a binomial distribution then it is denoted  $X \sim B(n, p)$ 
  - $n$  is the **number of trials**
  - $p$  is the **probability of success**
- The **probability of failure** is  $1 - p$  which is sometimes denoted as  $q$
- The formula for the probability of  $r$  **successful trials** is given by:
  - $P(X = r) = {}^n C_r \times p^r (1 - p)^{n-r}$  for  $r = 0, 1, 2, \dots, n$
  - ${}^n C_r = \frac{n!}{r!(n-r)!}$  where  $n! = n \times (n-1) \times (n-2) \times \dots \times 3 \times 2 \times 1$
  - You will be expected to use the distribution function on your **GDC to calculate probabilities** with the binomial distribution

#### What are the important properties of a binomial distribution?

- The **expected number (mean)** of successful trials is
 
$$E(X) = np$$
  - You are given this in the **formula booklet**
- The **variance** of the number of successful trials is
 
$$\text{Var}(X) = np(1 - p)$$
  - You are given this in the **formula booklet**
  - Square root to get the **standard deviation**
- The distribution can be represented visually using a vertical line graph
  - If  $p$  is **close to 0** then the graph has a **tail to the right**
  - If  $p$  is **close to 1** then the graph has a **tail to the left**
  - If  $p$  is **close to 0.5** then the graph is **roughly symmetrical**
  - If  $p = 0.5$  then the graph is **symmetrical**

## Modelling with Binomial Distribution

### How do I set up a binomial model?

- **Identify** what a **trial** is in the scenario
  - For example: rolling a dice, flipping a coin, checking hair colour
- **Identify** what the **successful outcome** is in the scenario
  - For example: rolling a 6, landing on tails, having black hair
- **Identify** the **parameters**
  - $n$  is the number of trials and  $p$  is the probability of success in each trial
- Make sure you **clearly state** what your **random variable** is
  - For example, let  $X$  be the number of students in a class of 30 with black hair

### What can be modelled using a binomial distribution?

- Anything that satisfies the **four conditions**
- For example: let  $T$  be the number of times a fair coin lands on tails when flipped 20 times:
  - A trial is flipping a coin: There are 20 trials so  $n = 20$
  - We can assume each coin flip does not affect subsequent coin flips: they are **independent**
  - A success is when the coin lands on tails: **Two outcomes** – tails or not tails (heads)
  - The coin is fair: The probability of tails is constant with  $p = 0.5$
- Sometimes it might **seem like there are more than two outcomes**
  - For example: let  $Y$  be the number of yellow cars that are in a car park full of 100 cars
    - Although there are more than two possible colours of cars, here the trial is whether a car is yellow so there are two outcomes (yellow or not yellow)
    - $Y$  would still need to fulfil the other conditions in order to follow a binomial distribution
- Sometimes a **sample may be taken from a population**
  - For example: 30% of people in a city have blue eyes, a sample of 30 people from the city is taken and  $X$  is the number of them with blue eyes
    - As long as the population is large and the sample is random then it can be assumed that each person has a 30% chance of having blue eyes

### What can not be modelled using a binomial distribution?

- Anything where the number of trials is **not fixed** or is **infinite**
  - The number of emails received in an hour
  - The number of times a coin is flipped until it lands on heads
- Anything where the outcome of **one trial affects** the outcome of the **other trials**
  - The number of caramels that a person eats when they eat 5 sweets from a bag containing 6 caramels and 4 marshmallows
    - If you eat a caramel for your first sweet then there are less caramels left in the bag when you choose your second sweet
- Anything where there are **more than two outcomes** of a trial
  - A person's shoe size
  - The number a dice lands on when rolled

- Anything where the **probability of success changes**
  - The number of times that a person can swim a length of a swimming pool in under a minute when swimming 50 lengths
    - The probability of swimming a lap in under a minute will decrease as the person gets tired
    - The probability is **not constant**



### Worked example

It is known that 8% of a large population are immune to a particular virus. Mark takes a sample of 50 people from this population. Mark uses a binomial model for the number of people in his sample that are immune to the virus.

- a) State the distribution that Mark uses.

A trial is checking if a person is immune to the virus

A success is if the person is immune.

Let  $X$  be the number of people in the sample immune to the virus

$$X \sim B(50, 0.08)$$

Number of  
people in sample

Probability of  
being immune to the virus

- b) State two assumptions that Mark must make in order to use a binomial model.

Mark needs to assume that:

- each person in the population has an 8% chance of being immune
- the sample is random and the people are independent  
a person being immune does not affect the immunity of others

For example:

If all 50 came from the same family then they would not be independent

- c) Calculate the expected number of people in the sample that are immune to the virus.

Formula booklet

$$E(X) = 50 \times 0.08$$

4 people

Binomial distribution $X \sim B(n, p)$	
Mean	$E(X) = np$

## 4.5.2 Calculating Binomial Probabilities

### Calculating Binomial Probabilities

Throughout this section we will use the random variable  $X \sim B(n, p)$ . For binomial, the probability of  $X$  taking a non-integer or negative value is always zero. Therefore any values of  $X$  mentioned in this section will be assumed to be non-negative integers.

#### How do I calculate $P(X = x)$ : the probability of a single value for a binomial distribution?

- You should have a **GDC** that can calculate **binomial probabilities**
- You want to use the "**Binomial Probability Distribution**" function
  - This is sometimes shortened to BPD, Binomial PD or Binomial Pdf
- You will need to enter:
  - The 'x' value - the value of  $x$  for which you want to find  $P(X = x)$
  - The 'n' value - the **number of trials**
  - The 'p' value - the **probability of success**
- Some calculators will give you the option of **listing the probabilities** for **multiple values of  $x$  at once**
- There is a formula that you can use but you are expected to be able to use the distribution function on your GDC
  - $P(X = x) = {}^nC_x \times p^x(1 - p)^{n - x}$
  - ${}^nC_x = \frac{n!}{x!(n - x)!}$

#### How do I calculate $P(a \leq X \leq b)$ : the cumulative probabilities for a binomial distribution?

- You should have a **GDC** that can calculate **cumulative binomial probabilities**
  - Most calculators will find  $P(a \leq X \leq b)$
  - Some calculators can only find  $P(X \leq b)$ 
    - The identities below will help in this case
- You should use the "**Binomial Cumulative Distribution**" function
  - This is sometimes shortened to BCD, Binomial CD or Binomial Cdf
- You will need to enter:
  - The lower value - this is the **value a**
    - This can be zero in the case  $P(X \leq b)$
  - The upper value - this is the **value b**
    - This can be  $n$  in the case  $P(X \geq a)$
  - The 'n' value - the **number of trials**
  - The 'p' value - the **probability of success**

#### How do I find probabilities if my GDC only calculates $P(X \leq x)$ ?

- To calculate  $P(X \leq x)$  just enter  $x$  into the cumulative distribution function
- To calculate  $P(X < x)$  use:
  - $P(X < x) = P(X \leq x - 1)$  which works when  $X$  is a binomial random variable
    - $P(X < 5) = P(X \leq 4)$
- To calculate  $P(X > x)$  use:
  - $P(X > x) = 1 - P(X \leq x)$  which works for any random variable  $X$ 
    - $P(X > 5) = 1 - P(X \leq 5)$
- To calculate  $P(X \geq x)$  use:
  - $P(X \geq x) = 1 - P(X \leq x - 1)$  which works when  $X$  is a binomial random variable
    - $P(X \geq 5) = 1 - P(X \leq 4)$
- To calculate  $P(a \leq X \leq b)$  use:
  - $P(a \leq X \leq b) = P(X \leq b) - P(X \leq a - 1)$  which works when  $X$  is a binomial random variable
    - $P(5 \leq X \leq 9) = P(X \leq 9) - P(X \leq 4)$

### What if an inequality does not have the equals sign (strict inequality)?

- For a binomial distribution (as it is discrete) you could **rewrite all strict inequalities** ( $<$  and  $>$ ) as **weak inequalities** ( $\leq$  and  $\geq$ ) by using the identities for a binomial distribution
  - $P(X < x) = P(X \leq x - 1)$  and  $P(X > x) = P(X \geq x + 1)$ 
    - For example:  $P(X < 5) = P(X \leq 4)$  and  $P(X > 5) = P(X \geq 6)$
- It helps to think about the **range of integers** you want
  - Identify the smallest and biggest integers in the range
- If your range has no minimum or maximum then use 0 or  $n$ 
  - $P(X \leq b) = P(0 \leq X \leq b)$
  - $P(X \geq a) = P(a \leq X \leq n)$
- $P(a < X \leq b) = P(a + 1 \leq X \leq b)$ 
  - $P(5 < X \leq 9) = P(6 \leq X \leq 9)$
- $P(a \leq X < b) = P(a \leq X \leq b - 1)$ 
  - $P(5 \leq X < 9) = P(5 \leq X \leq 8)$
- $P(a < X < b) = P(a + 1 \leq X \leq b - 1)$ 
  - $P(5 < X < 9) = P(6 \leq X \leq 8)$

**Worked example**

The random variable  $X \sim B(40, 0.35)$ . Find:

i)  $P(X = 10)$ .

Identify  $n$  and  $p$      $n = 40$      $p = 0.35$

Use binomial probability distribution on GDC

$P(X = 10) = 0.057056...$

$P(X = 10) = 0.057 \text{ (3sf)}$

ii)  $P(X \leq 10)$ .

Identify upper and lower values

$P(X \leq 10) = P(0 \leq X \leq 10)$

Use binomial cumulative distribution on GDC

$P(X \leq 10) = 0.121491...$

$P(X \leq 10) = 0.121 \text{ (3sf)}$

iii)  $P(8 < X < 15)$ .

Identify upper and lower values

$P(8 < X < 15) = P(9 \leq X \leq 14)$

Use binomial cumulative distribution on GDC

$P(9 \leq X \leq 14) = 0.541827...$

$P(8 < X < 15) = 0.542 \text{ (3sf)}$