

DP IB Maths: AA SL

4.6 Normal Distribution

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4.6.1 The Normal Distribution

Properties of Normal Distribution

The binomial distribution is an example of a discrete probability distribution. The normal distribution is an example of a **continuous** probability distribution.

What is a continuous random variable?

- A continuous random variable (often abbreviated to CRV) is a random variable that can take **any value** within a range of infinite values
 - Continuous random variables **usually measure** something
 - For example, height, weight, time, etc

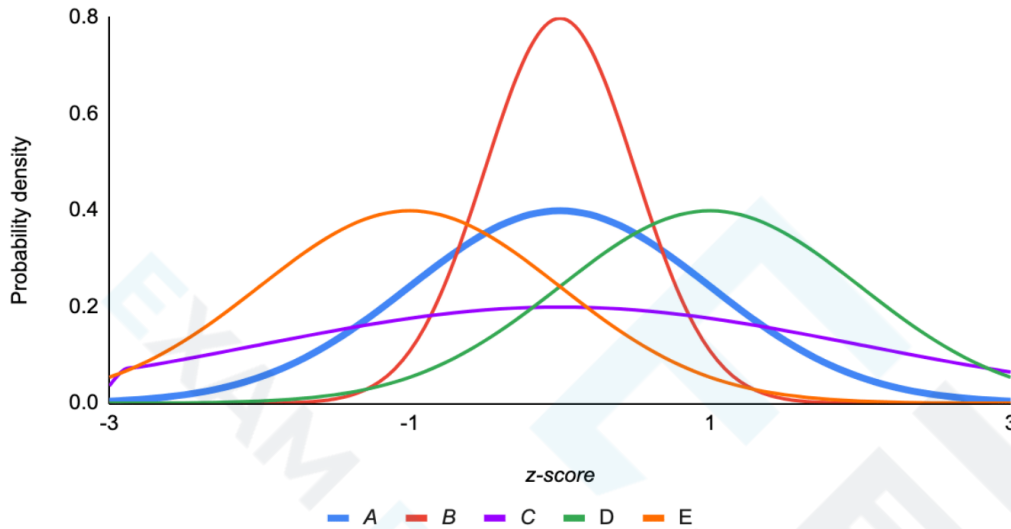
What is a continuous probability distribution?

- A continuous probability distribution is a probability distribution in which the random variable X is continuous
- The probability of X being a **particular value is always zero**
 - $P(X = k) = 0$ for any value k
 - Instead we define the **probability density function** $f(x)$ for a specific value
 - This is a function that describes the **relative likelihood** that the random variable would be close to that value
 - We talk about the **probability** of X being within a **certain range**
- A continuous probability distribution can be represented by a continuous graph (the values for X along the horizontal axis and probability **density** on the vertical axis)
- The **area under the graph** between the points $X = a$ and $X = b$ is equal to $P(a \leq X \leq b)$
 - The **total area under the graph equals 1**
- As $P(X = k) = 0$ for any value k , it does not matter if we use strict or weak inequalities
 - $P(X \leq k) = P(X < k)$ for any value k when X is a **continuous random variable**

What is a normal distribution?

- A normal distribution is a **continuous probability distribution**
- The **continuous random variable** X can follow a normal distribution if:
 - The distribution is **symmetrical**
 - The distribution is **bell-shaped**
- If X follows a normal distribution then it is denoted $X \sim N(\mu, \sigma^2)$
 - μ is the **mean**
 - σ^2 is the **variance**
 - σ is the **standard deviation**
- If the **mean** changes then the graph is **translated horizontally**

- If the **variance** increases then the graph is **widened horizontally** and **made shorter vertically** to maintain the same area
 - A **small variance** leads to a **tall** curve with a **narrow** centre
 - A **large variance** leads to a **short** curve with a **wide** centre



What are the important properties of a normal distribution?

- The **mean** is μ
- The **variance** is σ^2
 - If you need the **standard deviation** remember to square root this
- The normal distribution is symmetrical about $X = \mu$
 - Mean = Median = Mode = μ
- There are the results:
 - Approximately **two-thirds (68%)** of the data lies within **one standard deviation** of the mean ($\mu \pm \sigma$)
 - Approximately **95%** of the data lies within **two standard deviations** of the mean ($\mu \pm 2\sigma$)
 - Nearly **all of the data (99.7%)** lies within **three standard deviations** of the mean ($\mu \pm 3\sigma$)

Modelling with Normal Distribution

What can be modelled using a normal distribution?

- A lot of real-life continuous variables can be modelled by a normal distribution provided that the population is large enough and that the variable is **symmetrical** with **one mode**
- For a normal distribution X can take any real value, however values far from the mean (more than 4 standard deviations away from the mean) have a probability density of **practically zero**
 - This fact allows us to model variables that are not defined for all real values such as height and weight

What can not be modelled using a normal distribution?

- Variables which have **more than one mode** or **no mode**
 - For example: the number given by a random number generator
- Variables which are **not symmetrical**
 - For example: how long a human lives for

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Worked example

The random variable S represents the speeds (mph) of a certain species of cheetahs when they run. The variable is modelled using $N(40, 100)$.

- a) Write down the mean and standard deviation of the running speeds of cheetahs.

$$\mu = 40 \text{ and } \sigma^2 = 100$$



Square root to get standard deviation

Mean $\mu = 40$
Standard deviation $\sigma = 10$

- b) State two assumptions that have been made in order to use this model.

We assume that the distribution of the speeds is

- symmetrical
- bell-shaped

4.6.2 Calculations with Normal Distribution

Calculating Normal Probabilities

Throughout this section we will use the random variable $X \sim N(\mu, \sigma^2)$. For X distributed normally, X can take any real number. Therefore any values mentioned in this section will be assumed to be real numbers.

How do I find probabilities using a normal distribution?

- The **area under a normal curve** between the points $x = a$ and $x = b$ is equal to the **probability** $P(a < X < b)$
 - Remember for a normal distribution you do not need to worry about whether the inequality is strict ($<$ or $>$) or weak (\leq or \geq)
 - $P(a < X < b) = P(a \leq X \leq b)$
- You will be **expected to use** distribution functions on your **GDC** to find the probabilities when working with a normal distribution

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

- The probability of a **single value** is **always zero** for a normal distribution
 - You can picture this as the area of a single line is zero
- $P(X = x) = 0$
- Your GDC is likely to have a "**Normal Probability Density**" function
 - This is sometimes shortened to NPD, Normal PD or Normal Pdf
 - **IGNORE THIS FUNCTION** for this course!
 - This calculates the **probability density function** at a point **NOT** the probability

How do I calculate $P(a < X < b)$: the probability of a range of values for a normal distribution?

- You need a **GDC** that can calculate **cumulative normal probabilities**
- You want to use the "**Normal Cumulative Distribution**" function
 - This is sometimes shortened to NCD, Normal CD or Normal Cdf
- You will need to enter:
 - The 'lower bound' - this is the value a
 - The 'upper bound' - this is the value b
 - The ' μ ' value - this is the mean
 - The ' σ ' value - this is the standard deviation
- **Check the order carefully** as some calculators ask for standard deviation before mean
 - Remember it is the standard deviation
 - so if you have the **variance** then **square root it**
- **Always sketch** a quick diagram to visualise which area you are looking for

How do I calculate $P(X > a)$ or $P(X < b)$ for a normal distribution?

- You will still use the "**Normal Cumulative Distribution**" function
- $P(X > a)$ can be estimated using an **upper bound that is sufficiently bigger** than the **mean**
 - Using a value that is more than 4 standard deviations **bigger than the mean** is quite accurate
 - Or an easier option is just to input lots of 9's for the upper bound (**99999999...** or **10^{99}**)
- $P(X < b)$ can be estimated using a **lower bound that is sufficiently smaller** than the **mean**
 - Using a value that is more than 4 standard deviations **smaller than the mean** is quite accurate
 - Or an easier option is just to input lots of 9's for the lower bound with a negative sign (**-99999999...** or **-10^{99}**)

Are there any useful identities?

- $P(X < \mu) = P(X > \mu) = 0.5$
- As $P(X = a) = 0$ you can use:
 - $P(X < a) + P(X > a) = 1$
 - $P(X > a) = 1 - P(X < a)$
 - $P(a < X < b) = P(X < b) - P(X < a)$
- These are useful when:
 - The mean and/or standard deviation are unknown
 - You only have a diagram
 - You are working with the **inverse distribution**

Worked example

The random variable $Y \sim N(20, 5^2)$. Calculate:

i) $P(Y = 20)$.

Identify μ and σ
 $\mu = 20$ $\sigma^2 = 5^2$ so $\sigma = 5$

Sketch!



$$P(Y = 20) = 0$$

ii) $P(18 \leq Y < 27)$.

Sketch!



Using GDL
 Lower = 18
 Upper = 27

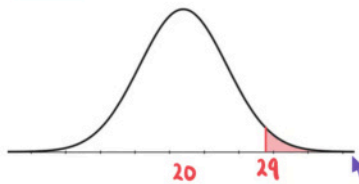
We can use \leq or $<$

$$P(18 < Y < 27) = 0.574665...$$

$$0.575 \text{ (3sf)}$$

iii) $P(Y > 29)$

Sketch!



Using GDL
 Lower = 29
 Upper = 99999

$$P(Y > 29) = 0.035930...$$

$$0.0359 \text{ (3sf)}$$

No upper bound so
 choose a big number

Inverse Normal Distribution

Given the value of $P(X < a)$ how do I find the value of a ?

- Your **GDC** will have a function called "**Inverse Normal Distribution**"
 - Some calculators call this InvN
- Given that $P(X < a) = p$ you will need to enter:
 - The 'area' - this is the value p
 - Some calculators might ask for the 'tail' - this is the left tail as you know the area to the left of a
 - The ' μ ' value - this is the mean
 - The ' σ ' value - this is the standard deviation

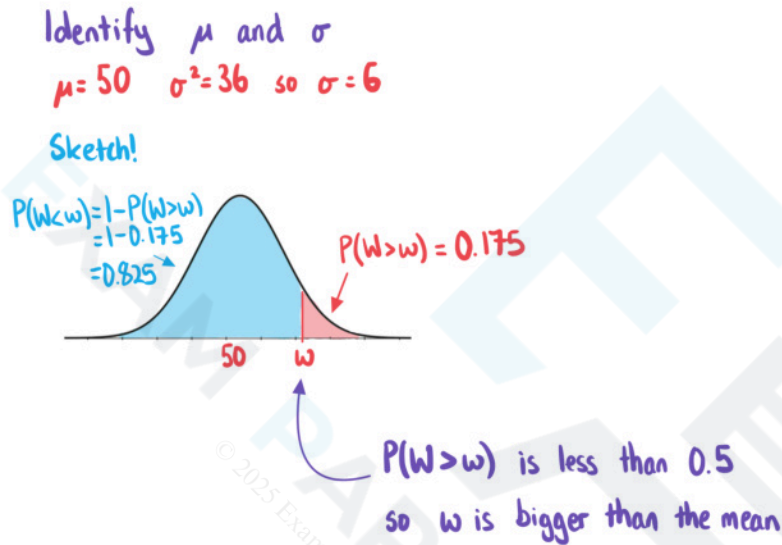
Given the value of $P(X > a)$ how do I find the value of a ?

- If your calculator **does** have the **tail option** (left, right or centre) then you can use the "Inverse Normal Distribution" function straightaway by:
 - Selecting 'right' for the tail
 - Entering the area as ' p '
- If your calculator **does not** have the **tail option** (left, right or centre) then:
 - Given $P(X > a) = p$
 - Use $P(X < a) = 1 - P(X > a)$ to rewrite this as
 - $P(X < a) = 1 - p$
 - Then use the **method for $P(X < a)$** to find a

Worked example

The random variable $W \sim N(50, 36)$.

Find the value of w such that $P(W > w) = 0.175$.



Area from left is 0.825

Use Inverse Normal Distribution function on GDC

$w = 55.6075...$

$w = 55.6$ (3sf)

4.6.3 Standardisation of Normal Variables

Standard Normal Distribution

What is the standard normal distribution?

- The **standard normal distribution** is a normal distribution where the **mean is 0** and the **standard deviation is 1**
 - It is denoted by Z
 - $Z \sim N(0, 1^2)$

Why is the standard normal distribution important?

- Any **normal distribution curve** can be transformed to the standard normal distribution curve by a **horizontal translation** and a **horizontal stretch**
- Therefore we have the relationship:
 - $Z = \frac{X - \mu}{\sigma}$
 - Where $X \sim N(\mu, \sigma^2)$ and $Z \sim N(0, 1^2)$
- Probabilities are related by:
 - $P(a < X < b) = P\left(\frac{a - \mu}{\sigma} < Z < \frac{b - \mu}{\sigma}\right)$
 - This will be useful when the mean or variance is unknown
- Some mathematicians use the function $\Phi(z)$ to represent $P(Z < z)$

z-values

What are z-values (standardised values)?

- For a normal distribution $X \sim N(\mu, \sigma^2)$ the z-value (standardised value) of an x-value tells you how many standard deviations it is away from the mean
 - If $z = 1$ then that means the x-value is 1 standard deviation bigger than the mean
 - If $z = -1$ then that means the x-value is 1 standard deviation smaller than the mean
- If the x-value is **more than the mean** then its corresponding z-value will be **positive**
- If the x-value is **less than the mean** then its corresponding z-value will be **negative**
- The z-value can be calculated using the formula:
 - $Z = \frac{X - \mu}{\sigma}$
 - This is given in the **formula booklet**
- z-values can be used to compare values from different distributions

Finding Sigma and Mu

How do I find the mean (μ) or the standard deviation (σ) if one of them is unknown?

- If the **mean** or **standard deviation** of $X \sim N(\mu, \sigma^2)$ is **unknown** then you will need to use the **standard normal distribution**
- You will need to use the formula
 - $Z = \frac{X - \mu}{\sigma}$ or its rearranged form $X = \mu + \sigma Z$
- You will be given a **probability for a specific value** of
 - $P(X < x) = p$ or $P(X > x) = p$
- To find the unknown parameter:
- **STEP 1: Sketch** the normal curve
 - Label the known value and the mean
- **STEP 2: Find the z-value** for the given value of x
 - Use the **Inverse Normal Distribution** to find the value of Z such that $P(Z < z) = p$ or $P(Z > z) = p$
 - Make sure the direction of the inequality for Z is consistent with the inequality for X
 - Try to **use lots of decimal places** for the z-value or **store your answer** to **avoid rounding errors**
 - You should use at least one extra decimal place within your working than your intended degree of accuracy for your answer
- **STEP 3: Substitute** the known values into $Z = \frac{X - \mu}{\sigma}$ or $X = \mu + \sigma Z$
 - You will be given and one of the parameters (μ or σ) in the question
 - You will have calculated z in STEP 2
- **STEP 4: Solve** the equation

How do I find the mean (μ) and the standard deviation (σ) if both of them are unknown?

- If **both** of them are **unknown** then you will be given two probabilities for two specific values of x
- The process is the same as above
 - You will now be able to **calculate two z-values**
 - You can form **two equations** (rearranging to the form $X = \mu + \sigma Z$ is helpful)
 - You now have to **solve the two equations simultaneously** (you can use your calculator to do this)
 - Be careful not to mix up which z-value goes with which value of x

Worked example

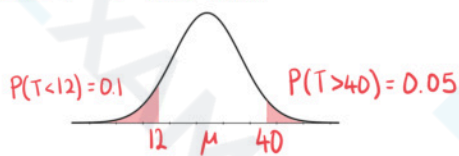
It is known that the times, in minutes, taken by students at a school to eat their lunch can be modelled using a normal distribution with mean μ minutes and standard deviation σ minutes.

Given that 10% of students at the school take less than 12 minutes to eat their lunch and 5% of the students take more than 40 minutes to eat their lunch, find the mean and standard deviation of the time taken by the students at the school.

Let $T \sim N(\mu, \sigma^2)$ be the time taken to eat lunch

STEP 1

Sketch the information



STEP 2

Find the corresponding z-values using inverse normal on GDC

$Z \sim N(0, 1^2)$

$$P(Z < z_1) = 0.1 \Rightarrow z_1 = -1.2815...$$

$$P(Z > z_2) = 0.05 \Rightarrow P(Z < z_2) = 0.95 \Rightarrow z_2 = 1.6448...$$

STEP 3

Form equations using $z = \frac{x - \mu}{\sigma}$ or $x = \mu + \sigma z$

$$12 = \mu - (1.2815...) \sigma$$

$$40 = \mu + (1.6448...) \sigma$$

STEP 4

Solve equations using GDC

$$\mu = 24.26... \quad \sigma = 9.568...$$

$$\text{Mean} = 24.3 \text{ mins (3sf)}$$

$$\text{Standard deviation} = 9.57 \text{ mins (3sf)}$$