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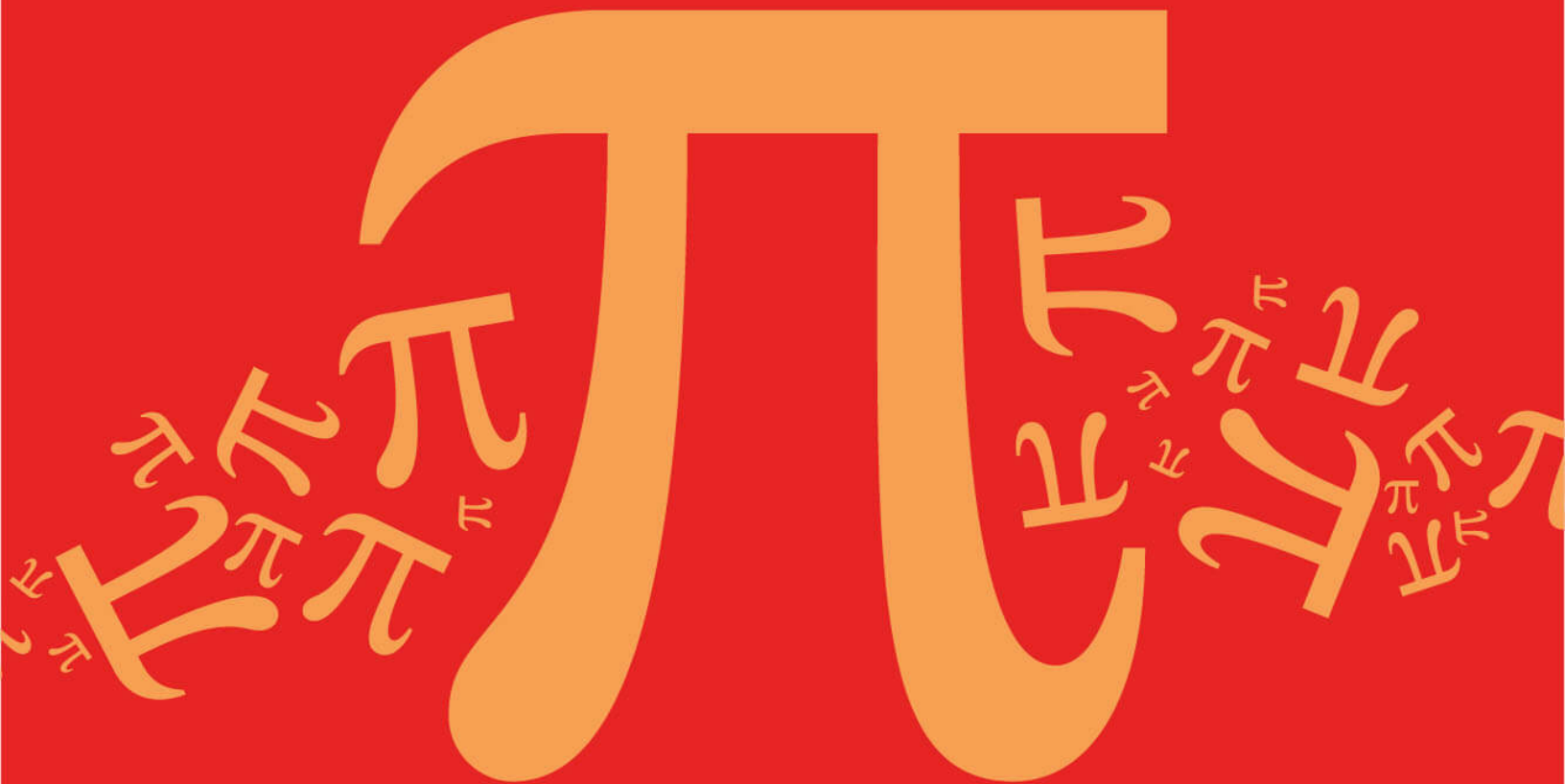
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## 4.6 Normal Distribution



# IB Maths - Revision Notes

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**AA SL**

## 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?

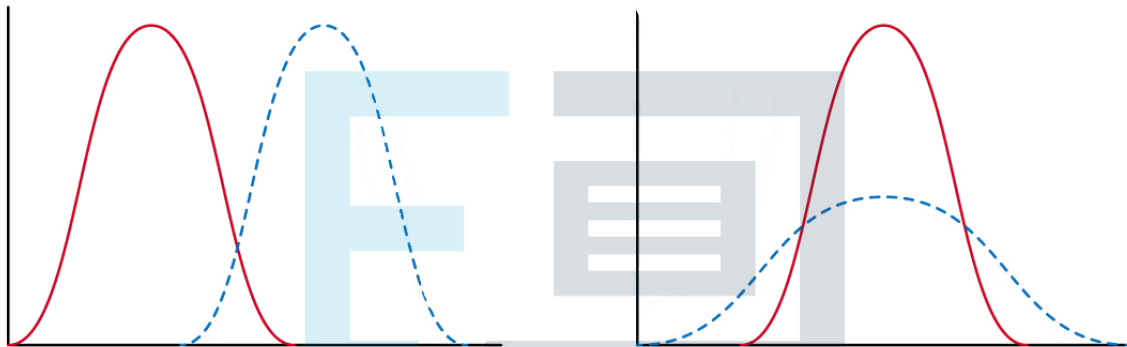
- A normal distribution is a **continuous probability distribution**
- The **continuous random variable**  $X$  can follow a normal distribution if:
  - The distribution is **symmetrical**
  - The distribution is **bell-shaped**
- If  $X$  follows a normal distribution then it is denoted  $X \sim N(\mu,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



- $\sigma$  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 taller 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

SAME VARIANCES  
DIFFERENT MEANS

SAME MEANS  
DIFFERENT VARIANCES



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

- The **mean** is  $\mu$
- The **variance** is  $\sigma^2$ 
  - If you need the **standard deviation** remember to square root this
- The normal distribution is symmetrical about
  - Mean = Median = Mode =  $\mu$
- 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 ( $\mu \pm 3\sigma$ )

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## 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

#### Exam Tip

- An exam question might involve different types of distributions so make it clear which distribution is being used for each variable



### 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 ' $\mu$ ' value - this is the mean
  - The ' $\sigma$ ' 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**

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## Exam Tip

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- Check carefully whether you have entered the standard deviation or variance into your GDC



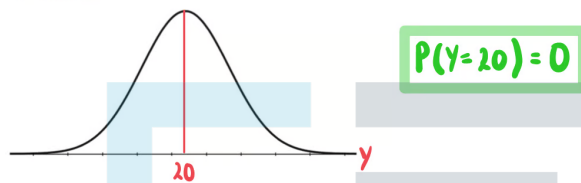
**Worked example**

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

i)  $P(Y = 20)$ .

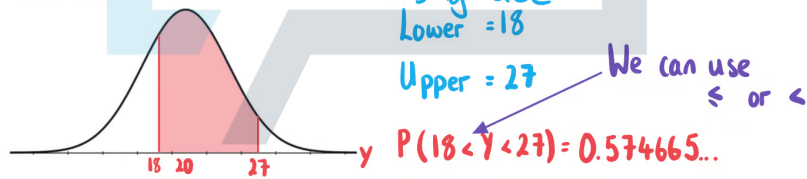
Identify  $\mu$  and  $\sigma$   
 $\mu = 20$   $\sigma^2 = 5^2$  so  $\sigma = 5$

Sketch!



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

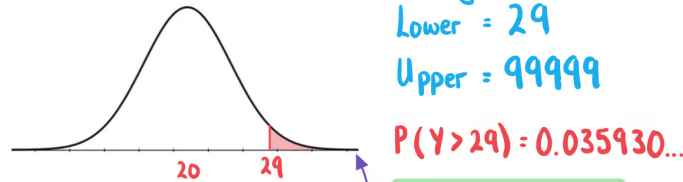
Sketch!



**0.575 (3sf)**

iii)  $P(Y > 29)$

Sketch!



**0.0359 (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 ' $\mu$ ' value - this is the mean
  - The ' $\sigma$ ' 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  $a$

#### Exam Tip

- Always check your **answer makes sense**
  - If  $P(X < a)$  is **less than 0.5** then  $a$  should be **smaller than the mean**
  - If  $P(X < a)$  is **more than 0.5** then  $a$  should be **bigger than the mean**
  - A sketch will help you see this

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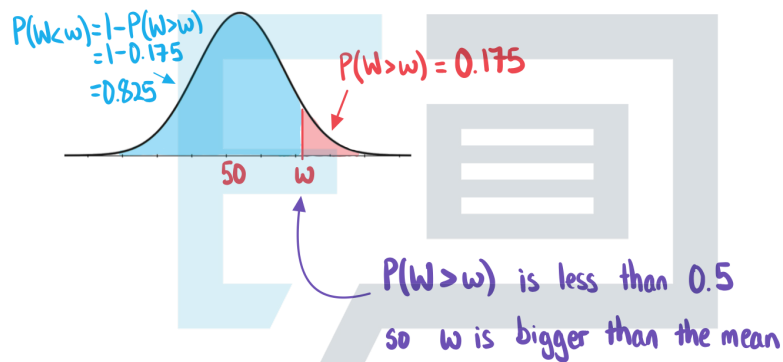
**Worked example**

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

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

Identify  $\mu$  and  $\sigma$   
 $\mu = 50$   $\sigma^2 = 36$  so  $\sigma = 6$

Sketch!



Area from left is 0.825

Use Inverse Normal Distribution function on GDC

$w = 55.6075\dots$

**$w = 55.6$  (3sf)**

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## 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 ( $\mu$ ) or the standard deviation ( $\sigma$ ) 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 ( $\mu$  or  $\sigma$ ) in the question
  - You will have calculated  $z$  in STEP 2
- **STEP 4: Solve** the equation

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### How do I find the mean ( $\mu$ ) and the standard deviation ( $\sigma$ ) 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

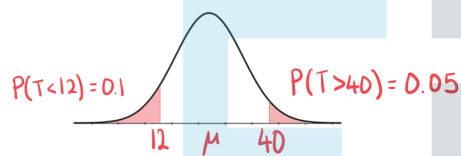
It is known that the times, in minutes, taken by students at a school to eat their lunch can be modelled using a normal distribution with mean  $\mu$  minutes and standard deviation  $\sigma$  minutes.

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

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

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

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

STEP 3

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

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

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

STEP 4

Solve equations using GDC

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

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

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