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MARKSCHEME

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MATHEMATICS
SETS, RELATIONS AND GROUPS

Higher Level

Paper 3

9 pages

Instructions to Examiners

Abbreviations

M Marks awarded for attempting to use a correct **Method**; working must be seen.

(M) Marks awarded for **Method**; may be implied by **correct** subsequent working.

A Marks awarded for an **Answer** or for **Accuracy**: often dependent on preceding ***M*** marks.

(A) Marks awarded for an **Answer** or for **Accuracy**; may be implied by **correct** subsequent working.

R Marks awarded for clear **Reasoning**.

N Marks awarded for **correct** answers if **no** working shown.

AG Answer given in the question and so no marks are awarded.

Using the markscheme

1 General

Write the marks in red on candidates' scripts, in the right hand margin.

- Show the **breakdown** of individual marks awarded using the abbreviations ***M1***, ***A1***, *etc*.
- Write down the total for each **question** (at the end of the question) and **circle** it.

2 Method and Answer/Accuracy marks

- Do **not** automatically award full marks for a correct answer; all working **must** be checked, and marks awarded according to the markscheme.
- It is not possible to award ***M0*** followed by ***A1***, as ***A*** mark(s) depend on the preceding ***M*** mark(s), if any.
- Where ***M*** and ***A*** marks are noted on the same line, *e.g.* ***M1A1***, this usually means ***M1*** for an **attempt** to use an appropriate method (*e.g.* substitution into a formula) and ***A1*** for using the **correct** values.
- Where the markscheme specifies ***(M2)***, ***N3***, *etc.*, do **not** split the marks.
- Once a correct answer to a question or part-question is seen, ignore further working.

3 *N* marks

*Award **N** marks for **correct** answers where there is **no** working.*

- Do **not** award a mixture of ***N*** and other marks.
- There may be fewer ***N*** marks available than the total of ***M***, ***A*** and ***R*** marks; this is deliberate as it penalizes candidates for not following the instruction to show their working.

4 Implied marks

Implied marks appear in ***brackets e.g. (M1)****, and can only be awarded if* ***correct*** *work is seen or if implied in subsequent working.*

- Normally the correct work is seen or implied in the next line.
- Marks **without** brackets can only be awarded for work that is **seen**.

5 Follow through marks

*Follow through (****FT****) marks are awarded where an incorrect answer from one* ***part*** *of a question is used correctly in* ***subsequent*** *part(s). To award* ***FT*** *marks,* ***there must be working present*** *and not just a final answer based on an incorrect answer to a previous part.*

- If the question becomes much simpler because of an error then use discretion to award fewer ***FT*** marks.
- If the error leads to an inappropriate value (*e.g.* $\sin\theta = 1.5$), do not award the mark(s) for the final answer(s).
- Within a question part, once an error is made, no further **dependent *A*** marks can be awarded, but ***M*** marks may be awarded if appropriate.
- Exceptions to this rule will be explicitly noted on the markscheme.

6 Mis-read

*If a candidate incorrectly copies information from the question, this is a mis-read (****MR****). Apply a* ***MR*** *penalty of 1 mark to that question. Award the marks as usual and then write –1(****MR****) next to the total. Subtract 1 mark from the total for the question. A candidate should be penalized only once for a particular mis-read.*

- If the question becomes much simpler because of the ***MR***, then use discretion to award fewer marks.
- If the ***MR*** leads to an inappropriate value (*e.g.* $\sin\theta = 1.5$), do not award the mark(s) for the final answer(s).

7 Discretionary marks *(d)*

An examiner uses discretion to award a mark on the rare occasions when the markscheme does not cover the work seen. The mark should be labelled ***(d)*** *and a brief* ***note*** *written next to the mark explaining this decision.*

8 Alternative methods

Candidates will sometimes use methods other than those in the markscheme. Unless the question specifies a method, other correct methods should be marked in line with the markscheme. If in doubt, contact your team leader for advice.

- Alternative methods for complete questions are indicated by **METHOD 1**, **METHOD 2**, *etc*.
- Alternative solutions for part-questions are indicated by **EITHER** . . . **OR**.
- Where possible, alignment will also be used to assist examiners in identifying where these alternatives start and finish.

9 Alternative forms

Unless the question specifies otherwise, ***accept*** *equivalent forms.*

- As this is an international examination, accept all alternative forms of **notation**.
- In the markscheme, equivalent **numerical** and **algebraic** forms will generally be written in brackets immediately following the answer.
- In the markscheme, **simplified** answers, (which candidates often do not write in examinations), will generally appear in brackets. Marks should be awarded for either the form preceding the bracket or the form in brackets (if it is seen).

  Example: for differentiating $f(x) = 2\sin(5x-3)$, the markscheme gives:

  $f'(x) = \left(2\cos(5x-3)\right)5 \quad \left(=10\cos(5x-3)\right)$ ***A1***

  Award ***A1*** for $\left(2\cos(5x-3)\right)5$, even if $10\cos(5x-3)$ is not seen.

10 Accuracy of Answers

If the level of accuracy is specified in the question, a mark will be allocated for giving the answer to the required accuracy.

- **Rounding errors**: only applies to final answers not to intermediate steps.
- **Level of accuracy**: when this is not specified in the question the general rule applies: *unless otherwise stated in the question all numerical answers must be given exactly or correct to three significant figures*.

Candidates should be penalized ***once only IN THE PAPER*** *for an accuracy error* ***(AP)***. *Award the marks as usual then write* ***(AP)*** *against the answer. On the* **front** *cover write –1****(AP)***. *Deduct 1 mark from the total for the paper, not the question.*

- If a final correct answer is incorrectly rounded, apply the ***AP***.
- If the level of accuracy is not specified in the question, apply the ***AP*** for correct answers not given to three significant figures.

If there is no working shown, and answers are given to the correct two significant figures, apply the ***AP***. However, do **not** accept answers to one significant figure without working.

11 Crossed out work

If a candidate has drawn a line through work on their examination script, or in some other way crossed out their work, do not award any marks for that work.

1. (a) (i) It is not closed because
$1 * 1 = 0 \notin \mathbb{Z}^+$. ***R2***

(ii) $a * b = a + b - 2$
$b * a = b + a - 2 = a * b$ ***M1***
It is commutative. ***A1***

(iii) It is not associative. ***A1***
Consider $(1 * 1) * 5$ and $1 * (1 * 5)$.
The first is undefined because $1 * 1 \notin \mathbb{Z}^+$.
The second equals 3. ***R2***

Notes: Award ***A1R2*** for stating that non-closure implies non-associative.   Award ***A1R1*** to candidates who show that $a * (b * c) = (a * b) * c = a + b + c - 4$ and therefore conclude that it is associative, ignoring the non-closure.

[7 marks]

(b) (i) The identity e satisfies
$a * e = a + e - 2 = a$ ***M1***
$e = 2$ (and $2 \in \mathbb{Z}^+$) ***A1***

(ii) $a * a^{-1} = a + a^{-1} - 2 = 2$ ***M1***
$a + a^{-1} = 4$ ***A1***
So the only elements having an inverse are 1, 2 and 3. ***A1***

Note: Due to commutativity there is no need to check two sidedness of identity and inverse.

[5 marks]

Total [12 marks]

2. (a) $]-1, 1[$ ***A1A1***

Note: Award ***A1*** for the values –1, 1 and ***A1*** for the open interval.

[2 marks]

(b) **EITHER**

Let $\dfrac{1-e^{-x}}{1+e^{-x}} = \dfrac{1-e^{-y}}{1+e^{-y}}$ ***M1***

$1-e^{-x}+e^{-y}-e^{-(x+y)} = 1+e^{-x}-e^{-y}-e^{-(x+y)}$ ***A1***

$e^{-x}=e^{-y}$

$x=y$ ***A1***

Therefore f is an injection ***AG***

OR

Consider

$$f'(x)=\frac{e^{-x}(1+e^{-x})+e^{-x}(1-e^{-x})}{(1+e^{-x})^2}$$ ***M1***

$$=\frac{2e^{-x}}{(1+e^{-x})^2}$$ ***A1***

>0 for all x. ***A1***

Therefore f is an injection. ***AG***

Note: Award ***M1A1A0*** for a graphical solution.

[3 marks]

(c) Let $y=\dfrac{1-e^{-x}}{1+e^{-x}}$ ***M1***

$y(1+e^{-x})=1-e^{-x}$ ***A1***

$e^{-x}(1+y)=1-y$ ***A1***

$e^{-x}=\dfrac{1-y}{1+y}$

$x=\ln\left(\dfrac{1+y}{1-y}\right)$ ***A1***

$f^{-1}(x)=\ln\left(\dfrac{1+x}{1-x}\right)$ ***A1***

[5 marks]

Total [10 marks]

3. (a) $z^6 = 1 = \text{cis}\,2n\pi$ *(M1)*

The six roots are

$$\text{cis}\,0\ (1),\ \text{cis}\frac{\pi}{3},\ \text{cis}\frac{2\pi}{3},\ \text{cis}\,\pi\ (-1),\ \text{cis}\frac{4\pi}{3},\ \text{cis}\frac{5\pi}{3}$$ ***A3***

Note: Award ***A2*** for 4 or 5 correct roots, ***A1*** for 2 or 3 correct roots.

[4 marks]

(b) (i) Closure: Consider any two roots $\text{cis}\frac{m\pi}{3}, \text{cis}\frac{n\pi}{3}$. ***M1***

$$\text{cis}\frac{m\pi}{3} \times \text{cis}\frac{n\pi}{3} = \text{cis}(m+n)(\text{mod}\,6)\frac{\pi}{3} \in G$$ ***A1***

Note: Award ***M1A1*** for a correct Cayley table showing closure.

Identity: The identity is 1. ***A1***

Inverse: The inverse of $\text{cis}\frac{m\pi}{3}$ is $\text{cis}\frac{(6-m)\pi}{3} \in G$. ***A2***

Associative: This follows from the associativity of multiplication. ***R1***

The 4 group axioms are satisfied. ***R1***

(ii) Successive powers of $\text{cis}\frac{\pi}{3}\left(\text{or cis}\frac{5\pi}{3}\right)$

generate the group which is therefore cyclic. ***R2***

The (only) other generator is $\text{cis}\frac{5\pi}{3}\left(\text{or cis}\frac{\pi}{3}\right)$. ***A1***

Note: Award ***A0*** for any additional answers.

(iii) The group of the integers 0, 1, 2, 3, 4, 5 under addition modulo 6. ***R2***

The correspondence is

$$m \to \text{cis}\frac{m\pi}{3}$$ ***R1***

Note: Accept any other cyclic group of order 6.

[13 marks]

Total [17 marks]

4. (a) Reflexive: $(a, b)R(a, b)$ because $ab = ba$ ***R1***

Symmetric: $(a, b)R(c, d) \Rightarrow ad = bc \Rightarrow cb = da \Rightarrow (c, d)R(a, b)$ ***M1A1***

Transitive: $(a, b)R(c, d) \Rightarrow ad = bc$ ***M1***

$(c, d)R(e, f) \Rightarrow cf = de$

Therefore

$$\frac{ad}{de} = \frac{bc}{cf} \text{ so } af = be$$ ***A1***

It follows that $(a, b)R(e, f)$ ***R1***

[6 marks]

(b) $(a, b)R(c, d) \Rightarrow \frac{a}{b} = \frac{c}{d}$ ***(M1)***

Equivalence classes are therefore points lying, in the first quadrant, on straight lines through the origin. ***A2***

Notes: Accept a correct sketch.

Award ***A1*** if "in the first quadrant" is omitted.

Do not penalise candidates who fail to exclude the origin.

[3 marks]

Total [9 marks]

5. The identity is 1. ***(R1)***

Consider

$2^1, 2^2, 2^3, \ldots, 2^k$

$2^k = p - 1$ ***R1***

Therefore all the above powers of two are different ***R1***

Now consider

$2^{k+1} \equiv 2p - 2 (\text{mod } p) = p - 2$ ***M1A1***

$2^{k+2} \equiv 2p - 4 (\text{mod } p) = p - 4$ ***A1***

$2^{k+3} = p - 8$

etc.

$2^{2k-1} = p - 2^{k-1}$

$2^{2k} = p - 2^k$ ***A1***

$= 1$ ***A1***

and this is the first power of 2 equal to 1. ***R2***

The order of 2 is therefore $2k$. ***AG***

Using Lagrange's Theorem, it follows that $2k$ is a factor of 2^k, the order of the group, in which case k must be as given. ***R2***

[12 marks]