Youth STEM Cup 2023

Preliminary Round

Problems and Answers

23 March 2023

Contents

Committee and Contributions

Organising Committee

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Problem Selection Committee

The Problem Selection Committee (PSC) is responsible for setting and selecting problems for the contest. It makes collaborative decisions on the suitability and format of the questions, and performs cross-checks to ensure the questions are valid, clear, and well-posed. It also produces the *Problems and Answers* document, the *Problems and Solutions* document and the question paper.

Special thanks to the PSC for contributing 30 problem proposals for the Preliminary Round:

Biology
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Mathematics
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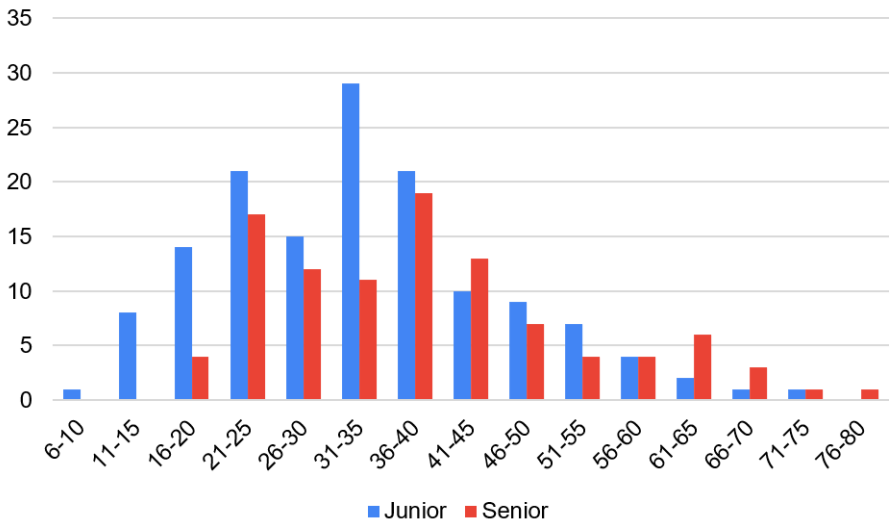
Astronomy and Astrophysics
Chooi Je Qin, Yap Yong Sheng, Ong Zhi Zheng, Chin Jia Yao

Preliminary Round Analysis

General Statistics

Full Score	115
Number of Teams	279
Average Score	35.60
Median Score	34
Range	8-78
Standard Deviation	13.39

Score Distribution



Breakdown of Correct Responses

Bio	
Q	Freq
1	87
2	126
3	19
4	15
5	165
6	36
Σ	448

Chem	
Q	Freq
1	71
2	160
3	137
4	89
5	255
6	181
Σ	893

Phy	
Q	Freq
1	96
2	68
3	47
4	101
5	48
6	90
Σ	450

Maths	
Q	Freq
1	194
2	3
3	17
4	28
5	49
6	151
Σ	442

Astro	
Q	Freq
1	98
2	63
3	57
4	51
5	81
6	102
Σ	452

Problems

Biology

1. Artificial selection is the process of the purposeful breeding of domesticated plants and animals by humans. People have been modifying various species for millions of years by selecting specific traits. This selection has improved food production, food quality, and variation. One example is wild mustard which can be artificially selected to form the following vegetables. Which of the following are **CORRECT** from this selection?

   I. Cabbage is developed from the end buds of wild mustard.

   II. Kohlrabi is developed from leaves of wild mustard.

   III. Broccoli is developed from flower clusters of wild mustard.

   IV. Brussels sprouts are developed from the side bus of wild mustard.

   A. I & II B. II & III C. III & IV D. IV & I

   (3 marks)

2. Life is diverse in nature. Biologists categorised organisms into three (3) domains: bacteria, archaea, and eukarya. Match the following organisms with the most likely domain and/or kingdom:

A	A foot-tall organism capable of producing its own food from sunlight
B	An inch-tall organism growing on the forest floor that consumes materials from dead leaves
C	A microscopic, simple, less membrane-bound organism found in a riverbed
D	A thimble-sized organism that feeds on algae growing in a pond

1	Eukarya/Animalia
2	Eukarya/Fungi
3	Eukarya/Plantae
4	Bacteria

   If your answer is A-1, B-2, C-3, D-4, type `A1,B2,C3,D4` with no spaces in between.

   (4 marks)

3. Simple sugars are from monosaccharides and disaccharides. They are commonly found in our food such as cereals, cakes, and fast foods. Overconsumption of simple sugars in diet can cause which of the following risks?

   I. Type I diabetes III. Heart disease V. Cancer

   II. Hypertension IV. Tooth decay

   If your answer is I, II, and III, type `I,II,III` with no spaces in between.

   (4 marks)

4. Lysosomes are a type of degradative organelles with hydrolases found in eukaryotic cells. Which of the following is **NOT** true about lysosomes?

   I. Lysosomes play an important role in endocytosis and exocytosis.

   II. Lysosomes are involved in apoptosis and autophagy.

   III. Lysosomes are found in both prokaryotic and eukaryotic cells.

   IV. Lysosomes help in the metamorphosis of frogs.

   V. Lysosome is one of the organelles involved in the secretion of extracellular enzymes.

   If your answer is I, II, and III, type `I,II,III` with no spaces in between.

   (5 marks)

5. The total solute concentration in a red blood cell is about 2%. Sucrose cannot pass through a red blood cell's plasma membrane, but water and urea can. Osmosis will cause such a cell to shrink the most when the cell is immersed in which of the following solution?

   A. a hypertonic urea solution

   B. a hypotonic urea solution

   C. a hypertonic sucrose solution

   D. a hypotonic sucrose solution

   (4 marks)

6. As a scientist, you wish to create a large batch of insulin using recombinant DNA technology. Arrange the following steps to enable the synthesis of insulin.

   I. Find the clone with the gene for insulin.

   II. Insert the plasmids into bacteria and grow the bacteria into clones.

   III. Isolate the gene for insulin.

   IV. Create recombinant plasmids, including one that carries the genes for insulin.

   If your answer is I, II, III, then IV, type `I,II,III,IV` with no spaces in between.

   (3 marks)

Chemistry

1. In a redox reaction between hydroxylammonium ions, $[NH_3OH]^+$, and acidified iron(III) ions, Fe^{3+}. The products are iron(II) ions, Fe^{2+}, H^+ ions, water and a compound of nitrogen. The mole ratio of reacting hydroxylammonium ions to reacting iron(III) ions is 1 : 1.
What is the oxidation state of the nitrogen containing the compound formed in this reaction?

A. +2 B. +1 C. 0 D. −1

(3 marks)

2. Phosphoric acid establishes the following equilibria in aqueous solution.

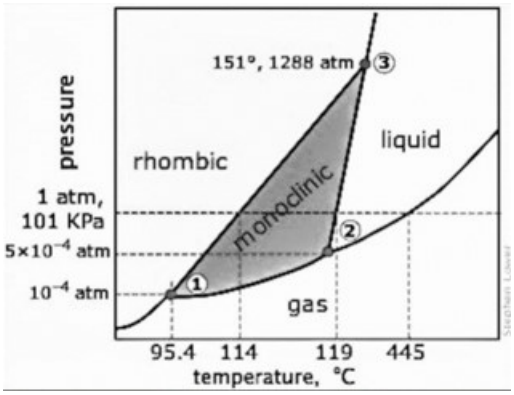
$$\begin{aligned} H_3PO_{4(aq)} + H_2O_{(l)} &\rightarrow H_3O^+_{(aq)} + H_2PO^-_{4\,(aq)} &&\longrightarrow K_1 \\ H_2PO^-_{4\,(aq)} + H_2O_{(l)} &\rightarrow H_3O^+_{(aq)} + HPO^{2-}_{4\,(aq)} &&\longrightarrow K_2 \\ HPO^{2-}_{4\,(aq)} + H_2O_{(l)} &\rightarrow H_3O^+_{(aq)} + PO^{3-}_{4\,(aq)} &&\longrightarrow K_3 \end{aligned}$$

What is the relationship among the K values?

A. $K_1 = K_2 = K_3$ B. $K_1 > K_2 = K_3$ C. $K_1 > K_2 > K_3$ D. $K_1 < K_2 < K_3$

(3 marks)

3. The phase diagram of sulphur is shown below:



Which of the statements below is **CORRECT**?

A. Monoclinic sulphur is denser than rhombic sulphur.

B. The conversion of monoclinic to rhombic sulphur is endothermic.

C. Liquid sulphur cannot equilibrate with gaseous sulphur at temperatures lower than 445°C.

D. At atmospheric pressure, rhombic sulphur cannot be converted to liquid sulphur without first converting to monoclinic sulphur.

(5 marks)

4. A reaction has $K_{eq} = 1.4 \times 10^{-5}$ at $T = 298$ K, and K_{eq} decreases with increasing temperature between 298 K and 350 K. What may be concluded from these observations?

   I. $\Delta G^{\circ}_{rxn} < 0$ at 330 K

   II. $\Delta S^{\circ}_{rxn} > 0$ at 330 K

   A. Both I and II B. I only C. II only D. Neither I nor II

   (4 marks)

5. Which statement below is **CORRECT** for an endothermic reaction?

   A. The reaction absorbs heat from its surroundings.

   B. It always involves a change of phase.

   C. It happens when the energy used to break bonds is less than the energy released during bond formation.

   D. It is not spontaneous.

   (3 marks)

6. Which statement best explains why phenol is more reactive than benzene in electrophilic aromatic substitution reactions?

   A. The presence of hydroxyl group increases electrophilicity of benzene ring.

   B. The hydroxyl group increases the electron density of a benzene ring, which stabilises the intermediate during an electrophilic aromatic substitution.

   C. The hydroxyl group increases the electron density of a benzene ring, which increases the stability of phenol.

   D. The acidity of phenol enables itself to act as a catalyst, which increases the rate of reaction.

   (5 marks)

Physics

1. An upright ring of radius R is spinning about its vertical diameter at angular speed ω and it always fixed to spin at this rate. A particle slides freely on the ring. The range of ω for which the particle has an equilibrium point (other than the topmost and bottommost point) relative to the ring is:

   A. $\omega > \sqrt{\frac{g}{2R}}$ B. $\omega > \sqrt{\frac{g}{R}}$ C. $\omega > \sqrt{\frac{2g}{R}}$ D. $\omega > 2\sqrt{\frac{g}{R}}$

   (4 marks)

2. A particle freely slides on a spoke of a horizontal wheel that is forced to spin at fixed angular velocity. By the centrifugal effect the particle slides away from the centre as the wheel spins. Its distance from the centre is _____ in time.

   A. linear B. quadratic C. exponential D. logarithmic

   (6 marks)

3. On a rough inclined plane of angle θ and coefficient of friction μ, 4 objects of equal masses and radii are rolled down without slipping. Given the expressions for their moments of inertia, which object reaches the bottom first? Rank the choices below in the order of reaching the bottom first.

   A. Solid Sphere $\left(I = \frac{2}{5}mR^2\right)$ C. Solid Cylinder $\left(I = \frac{1}{2}mR^2\right)$

   B. Hollow Sphere $\left(I = \frac{2}{3}mR^2\right)$ D. Hollow Cylinder $\left(I = mR^2\right)$

   If your answer is A, B, C, then D, type `A,B,C,D` with no spaces in between.

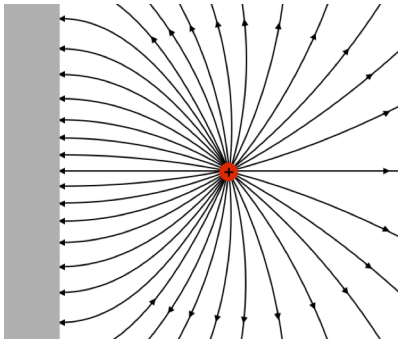
   (4 marks)

4. When a ball is dropped onto an immovable surface, it bounces back up but doesn't reach its original height due to the collision not being elastic. How does the wasted energy scale if the coefficient of restitution is constant at e?

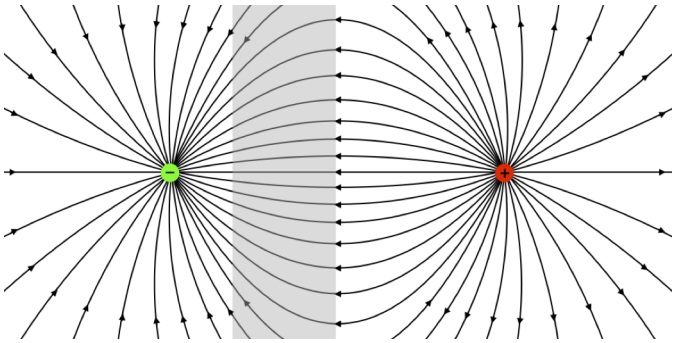
   A. $W \propto 1 - e$ B. $W \propto 1 - e^2$ C. $W \propto \sqrt{1 - e}$ D. $W \propto (1 - e)^{-1}$

   (3 marks)

5. We know that an electrically charged particle is attracted to a conductor due to the attraction of the particle and the induced charges on the conductor. Hence there must be a force that acts on the particle to provide the acceleration for the movement of the particle. The force can be found by using a method known as "image charges". This is a model of 2 oppositely charged particles that together give exactly the same electric field as that in the original configuration. For example,



can be modelled as



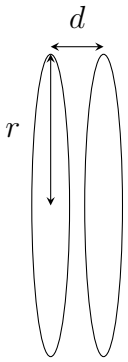
without considering the conductor anymore.

Find the force of an electron acted on by a nearby conducting plate which is a distance d from the electron. Take e as the elementary charge.

A. $\dfrac{e^2}{\pi\varepsilon_0 d^2}$ B. $\dfrac{e^2}{2\pi\varepsilon_0 d^2}$ C. $\dfrac{e^2}{4\pi\varepsilon_0 d^2}$ D. $\dfrac{e^2}{16\pi\varepsilon_0 d^2}$

(3 marks)

6. Two circular wires with radius r each containing current I are placed co-axially to each other as shown in the diagram, with a distance of d between them. You may assume that $r \gg d$, Find the force acting on one of the wires. (Hint: Since the distance between the loops is significantly shorter than the length of the wires, the force can be approximated as the force between two straight currents I at distance d apart)



A. $\dfrac{\mu_0 I^2 r}{d}$ B. $\dfrac{\mu_0 I^2 d}{r}$ C. $\dfrac{2\mu_0 I^2 r}{d}$ D. $\dfrac{2\mu_0 I^2 d}{r}$

(3 marks)

Mathematics

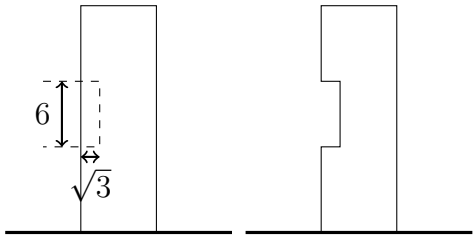
1. The numbers 1 to 1000 are written on a whiteboard. How many times is the number 7 written?

(3 marks)

2. Find the number of 2×2 matrices with entries in $\{0, 1, 2, 3, 4\}$ (can be repeated) whose determinant is divisible by 5.

(4 marks)

3. A notch is carved on a vertical cylindrical tree trunk of radius $2\sqrt{3}$. The notch is created by two rectangular horizontal planes 6 units apart and a vertical plane $\sqrt{3}$ units away from the central axis. Find $A + B$ if the volume of wood removed is $A\pi - B\sqrt{3}$ where A, B are integers.



(4 marks)

4. Find $\displaystyle\sum_{k\geq 1} \frac{k^3}{2^k} = \frac{1^3}{2^1} + \frac{2^3}{2^2} + \frac{3^3}{2^3} + \frac{4^3}{2^4} + \cdots$. Type `0` if it is divergent.

(4 marks)

5. How many ways are there to tile a 2×10 region with dominoes? (A domino is a 1×2 or 2×1 tile.)

(5 marks)

6. How many trailing zeros does 2023! have? (eg. 102300 has 2 trailing zeros)

(3 marks)

Astronomy and Astrophysics

1. The Moon is safe to look at with your naked eyes, but the Sun is not. Ashriq is making sunglasses that will allow observers to look at the Sun safely. What is the fraction of brightness that will be blocked by his new invention, so that the brightness of the Sun as seen through the sunglasses will be exactly that of the Moon? The apparent magnitude of the the Moon is -12.74, while that of the Sun is -26.74. Note: magnitudes m_1, m_2 are related to their brightness f_1, f_2 by $m_1 - m_2 = -2.5 \log \dfrac{f_1}{f_2}$.

   A. 0.0000025% B. 0.00025% C. 0.9999925% D. 99.99975% E. 99.75%

   (3 marks)

2. In one week, astronomers observed $2n$ supernovae for a sufficiently large sample of N galaxies nearby ($z \ll 1$), and n supernovae for another sample of N galaxies at redshift $z = 1$. It is believed this is caused by the expansion of the space between the redshifted galaxies and the astronomers at Earth, so that the astronomers perceive that time in galaxies further away passes slower, and therefore the number of supernovae in far galaxies observed by astronomers in a week is less than that of the galaxies nearby. Estimate the number of supernovae observed from sample of N galaxies at redshift $z = 3$. Hint: Consider the cosmological Doppler shift $z = \dfrac{\lambda_o}{\lambda_e} - 1$. What does the ratio of wavelengths tell us about the ratio of time passage?

   A. $\dfrac{n}{2}$ B. $\dfrac{n}{3}$ C. $\dfrac{n}{4}$ D. $3n$ E. $\dfrac{3n}{2}$

   (3 marks)

3. In the framework of General Relativity, massive objects can bend light just like optical lenses, a phenomenon named **gravitational lensing**. We quantify the magnification factor of a gravitational lens as μ, i.e. the brightness/flux of an object is amplified by a factor of μ. With the aid of a gravitational lens, we can see fainter sources. However, it also magnifies the region behind the lens, such that we see a smaller portion of the sky for a given field of view. Consider at a fixed distance behind the lens of magnification μ, we have a luminosity distribution $(\mathrm{d}n/\mathrm{d}L) \propto L^{-\alpha}$, where n is the volume number density of sources of luminosity L. What is the minimum value of α such that the number of sources increase for a given field of view?

   A. -2 B. -1 C. 0 D. 1 E. 2

   (6 marks)

4. In which of the following pairs of molecular clouds would cloud A be more likely to collapse than cloud B? You may assume only the stated variables differ between the two clouds.

	Cloud *A*	**Cloud *B***
A.	[Fe/H] = 0	[Fe/H] = -3
B.	$T = 30$ K	$T = 10$ K
C.	$M = 10^4\, M_\odot$, $R = 10$ pc	$M = 10^7\, M_\odot$, $R = 100$ pc
D.	Mainly neutral atomic H	Mainly molecular H_2
E.	None of the above	

(4 marks)

5. Since the Sun is made of plasma, it does not rotate as a whole like rigid bodies do. Instead, the differential angular velocity of the Sun, as measured by Doppler shift measurements, is given by

$$\frac{\Omega}{2\pi} = (450 - 65\sin^2\theta - 67\sin^4\theta) \text{ nHz}$$

where θ is the latitude (measured from the equator). An astronomer measures two sunspot groups, one clustered at the equator, and the other at latitude $\theta = +30°$. They are separated by 45° in longitude, with that on the equator group lagging behind. Assuming that the sunspot groups only transverse the Sun along the heliographic longitude. How long after would the sunspot groups be seen along the same heliographic longitude?

A. 45 hours B. 72 days C. 6.5 months D. 1.2 years E. Never

(4 marks)

6. Kepler's 3rd Law states a relationship between a planet's orbital period T and its orbital radius r as $T \propto r^{3/2}$. It was first formulated by Kepler as an empirical law from Tycho Brahe's data in 1621, and later mathematically proven by Newton in 1687 when he formulated his theory of gravity, which scaled as $F_g \propto r^{-2}$. In a hypothetical universe where $F_g \propto r^n$, what would Kepler's 3rd Law look like?

A. $T \propto r^{3/2}$ B. $T \propto r^{-3/n}$ C. $T \propto r^{(1-n)/2}$ D. $T \propto r^{(n-1)/n}$

(3 marks)

Answers

Biology

1. D
2. A3,B2,C4,D1
3. II,III,IV,V
4. I,III,V
5. C
6. III,IV,II,I

Chemistry

1. C
2. C
3. D
4. D
5. A
6. B

Physics

1. B
2. C
3. A,C,B,D
4. B
5. D
6. A

Mathematics

1. 300
2. 145
3. 42
4. 26
5. 89
6. 503

Astronomy and Astrophysics

1. D
2. A
3. E
4. A
5. B
6. C