



Youth STEM Cup 2024

(Senior Category)

Final Round

Problems and Answers

22 June 2024

In collaboration with



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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 19 problem proposals for the Final Round:

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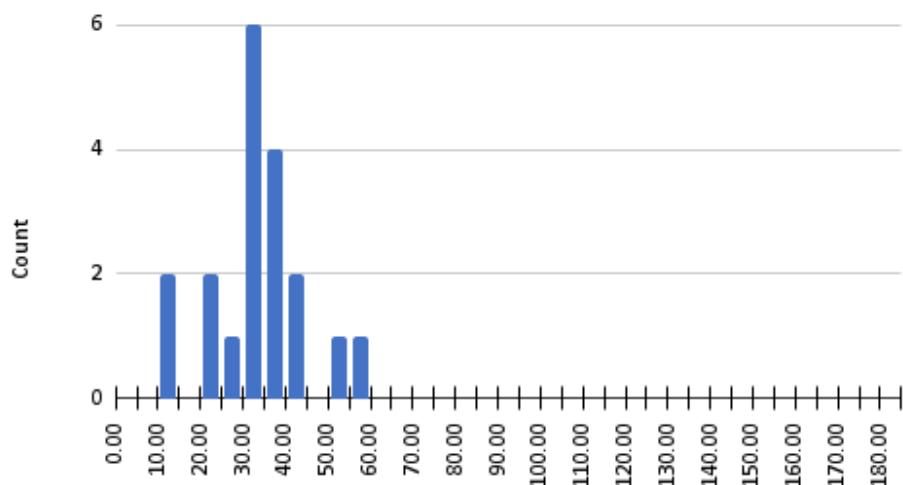
Final Round Analysis

General Statistics

Duration	120 minutes
Full Score	182
Number of Teams	19
Average Score	33.50
Median Score	33.45
Range	12.2 – 58.4
Standard Deviation	11.55

Score Distribution

Histogram of Score (Seniors)



Breakdown of Responses

Bio			
Section	Question	Total Score per Question	Range of Scores obtained by participants
A	3	6	0 – 4.5
B	1	6	0 – 6
C	1	5	0 – 5
D	–	–	–
E	–	–	–

Chem			
Section	Question	Total Score per Question	Range of Scores obtained by participants
A	2	12	0 – 4
B	5	15	0 – 8
C	–	–	–
D	1 – <i>Part I</i>	12	0 – 11
E	–	–	–

Phy			
Section	Question	Total Score per Question	Range of Scores obtained by participants
A	7	15	0 – 1.5
B	3	7.5	0 – 3.5
C	–	–	–
D	2	10	0 – 2.5
E	–	–	–

Maths			
Section	Question	Total Score per Question	Range of Scores obtained by participants
A	1	5	0 – 5
B	4	5	0 – 3
C	–	–	–
D	1 – Part II	10	0 – 4
E	–	–	–

Earth			
Section	Question	Total Score per Question	Range of Scores obtained by participants
A	5	4	0 – 2
B	2	7	0 – 3.2
C	–	–	–
D	3	8	0 – 3
E	–	–	–

Social			
Section	Question	Total Score per Question	Range of Scores obtained by participants
A	4 & 6	34	0 – 13
B	–	–	–
C	–	–	–
D	–	–	–
E	1	20.5	1 – 13.5

Problems

Section A: Asia

1. China - Advancement in Twin Prime Conjecture

Nearly a decade ago, in 2013, Chinese mathematician Yitang Zhang made a significant advancement in the twin prime conjecture. This conjecture states that there are infinitely many pairs of prime numbers that differ by exactly 2, such as (3, 5) and (11, 13). Zhang's breakthrough showed that there are infinitely many pairs of primes that differ by less than 70 million (later improved to less than or equal to 246). Although the nature of twin primes remains mysterious, we will explore a small part of this mystery. **Determine with proof** if there is a pair of twin primes whose sum is a power of 2024.

5 marks

2. Nepal - Malaysian climber rescued by Nepali sherpa from the Everest

On 18 May 2023, a Malaysian climber was rescued by a Nepali sherpa from the Everest “death zone,” where temperatures can plunge to minus 30 degrees Celsius or lower. He was wrapped in a sleeping mat while being carried down by the sherpa to the 7,162 m-high Camp III, where he was subsequently lifted down to the base camp by a helicopter.



While ascending Mount Everest, Clausius and his friend Clapeyron happened to witness this rare high-altitude rescue operation. After hours of climbing, they arrived at the peak of Mount Everest, which has an atmospheric pressure of 0.33 bar. Exhausted from their trip, they decided to boil a nice hot glass of water while savoring the sights on the peak.

When an ideal gas is isothermally expanded from pressure p [bar] to p' [bar] ($p > p'$), the entropy change ΔS of the gas is

$$\Delta S = -R \ln \left(\frac{p'}{p} \right)$$

The enthalpy change when liquid water evaporates to water vapor at p_0 [bar] is ΔH_0° , and the entropy change is ΔS_0° . Let us suppose these values do not depend on temperature, and the gas is an ideal gas. In this case, when liquid water evaporates to water vapor at p_1 [bar], the enthalpy change is $\Delta H_v = \Delta H_0^\circ$, and the entropy change is

$$\Delta S_v = \Delta S_0^\circ - R \ln \left(\frac{p'}{p} \right)$$

- (a) Assuming that $\Delta H_0^\circ = 4.070 \times 10^4 \text{ J mol}^{-1}$ and $\Delta S_0^\circ = 1.091 \times 10^2 \text{ JK}^{-1} \text{ mol}^{-1}$ at $p_0 = 1 \text{ bar}$, calculate the boiling point of water at 0.33 bar in $^\circ\text{C}$. 4 marks

Useful constants and formulae

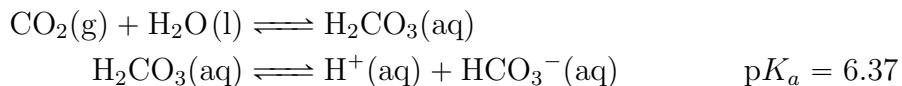
$$R = 8.314 \text{ JK}^{-1} \text{ mol}^{-1}$$

Gibbs free energy equation: $\Delta G = \Delta H - T\Delta S$

$$\text{Clausius-Clapeyron equation: } \ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{vap}}{R} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Due to the extremely low levels of O_2 at the peak of Mount Everest, Clausius hyperventilated and developed subsequent respiratory alkalosis, a condition where the body pH is abnormally high due to excessive CO_2 being expelled from the body. Frantic to help his friend in any way possible, Clapeyron attempted to calculate Clausius' body pH.

He recalled some key equations:



- (b) The bicarbonate ion HCO_3^- (aq) is the main chemical buffer of the human body. Given that water is largely abundant in Clausius' body, he has a body temperature of 37°C , and the buffering effects of other ions in his blood are negligible, calculate Clausius' body pH when $P_{\text{CO}_2} = 0.1 \text{ Pa}$ and $[\text{HCO}_3^-] = 3.64 \times 10^{-5} \text{ M}$. 8 marks

Thermodynamic data:

Compound	$\Delta H_f^\circ(298 \text{ K})/\text{kJ mol}^{-1}$	$S^\circ(298 \text{ K})/\text{JK}^{-1} \text{ mol}^{-1}$
$\text{CO}_2(\text{g})$	-394	214
$\text{H}_2\text{O}(\text{l})$	-286	70
$\text{H}_2\text{CO}_3(\text{aq})$	-699	187
$\text{H}^+(\text{aq})$	0	0
$\text{HCO}_3^-(\text{aq})$	-691	92

*In equilibrium constant calculations, all concentrations have the unit of mol dm^{-3} and all pressures have the unit of kPa.

3. Malaysia - Mussels in Port Dickson tainted by biotoxins, unsafe to eat

PORT DICKSON – Mussels found in waters off the resort town of Port Dickson have been contaminated by dangerous biotoxins and are not safe for consumption, said Malaysia's Fisheries Department. The public has also been advised against eating mussels and other bivalves, such as lokan and lala, harvested in the town for three weeks till they are certified safe to eat. Fisheries Department deputy director-general of management Wan Aznan Abdullah said tests carried out by the Fisheries Biosecurity Centre showed that the mussels harvested in the area have been contaminated by the *Prorocentrum*, *Alexandrium* and *Pseudonitzschia* algae species. Mr. Wan Aznan said preliminary findings revealed that the algae population has increased drastically due to the unusually hot weather. Mr Wan Aznan said tests carried out by the department showed that bivalves farmed and fished in other states such as Melaka and Johor are safe to eat.

“Only the ones harvested in PD (Port Dickson) are not safe to eat for now,” he said.

Asked if there was a possibility that the contamination was caused by sea pollution, Mr Wan Aznan said there are no leads to suggest this.

Indicate whether each of the following statements is **TRUE** or **FALSE**.

[6 marks]

- (a) Algae are considered as the main source of food for water filtering mussels, this means that marine biotoxins such as yessotoxins too are ingested and accumulate in the flesh of the mussels, resulting in the typical diarrhoeic mussel poisoning.
- (b) Paralytic shellfish poisoning is a foodborne illness that typically develops after consumption of shellfish contaminated with saxitoxin.
- (c) *Alexandrium*, one of the most common dinoflagellates, is well known for being responsible for harmful algal blooms.
- (d) Diarrhetic shellfish poisoning is an alimentary intoxication caused by the production of okadaic acid and dinophysistoxins, which are produced by the dinoflagellates *Dinophysis fortii* or *Prorocentrum lima*, consumed by mollusks.

4. Malaysia - Ministry of Finance Malaysia announced targeted subsidies for diesel

Recently, YB Senator Datuk Seri Amir Hamzah Azizan, Finance Minister II, has announced the implementation of targeted subsidies for diesel, which involve setting the diesel fuel price to align with market price. This entails setting retail price for diesel fuel at RM3.35 per litre effective on 10th June 2024.

Targeted subsidies are a hot topic in Malaysia right now, especially with the government planning to implement them for petrol and diesel due to unsustainable costs being incurred by blanket subsidies. Moreover, there is also a suggestion to expand targeted subsidies to the EV & RE industry to boost them further in their initial stages.

- (a) How does the introduction of a targeted subsidy for electric vehicles (EVs) affect the market equilibrium in the EV market? Assume the subsidy is given directly to consumers in the form of a rebate.

[3 marks]

- (b) Consider a government that provides a targeted subsidy for renewable energy producers. Analyse the welfare effects of this subsidy on consumers, producers, and the overall economy. What are the potential deadweight losses or gains associated with this subsidy? 3 marks
- (c) Evaluate the fiscal implications of implementing a targeted subsidy for low-income families to purchase healthy food. What are the potential short-term and long-term fiscal impacts on the government's budget? 4 marks

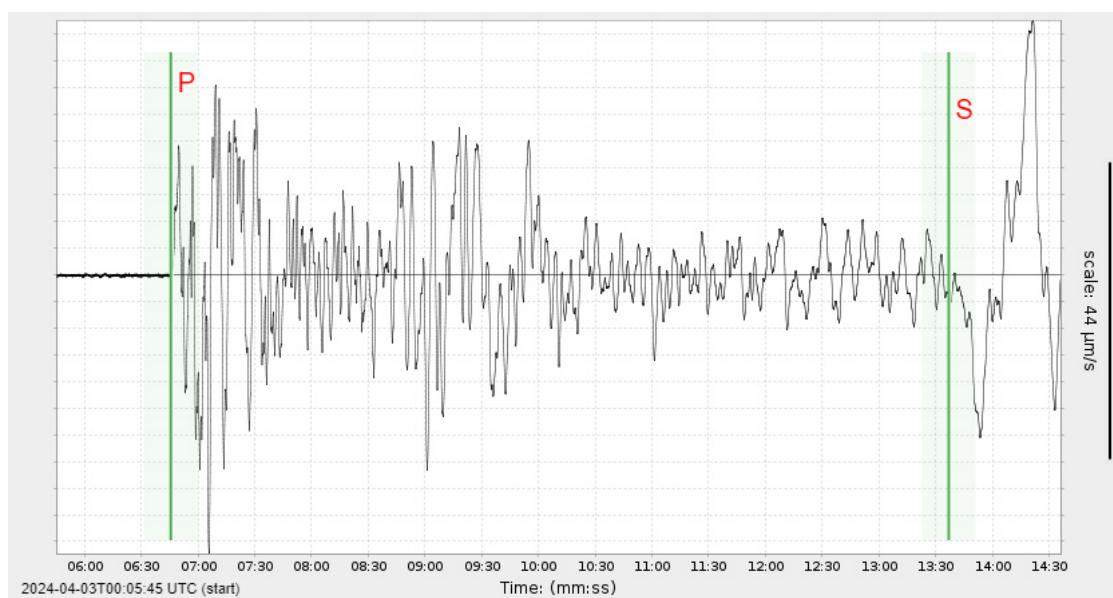
5. Taiwan - Taiwan hit by strongest earthquake in 25 years

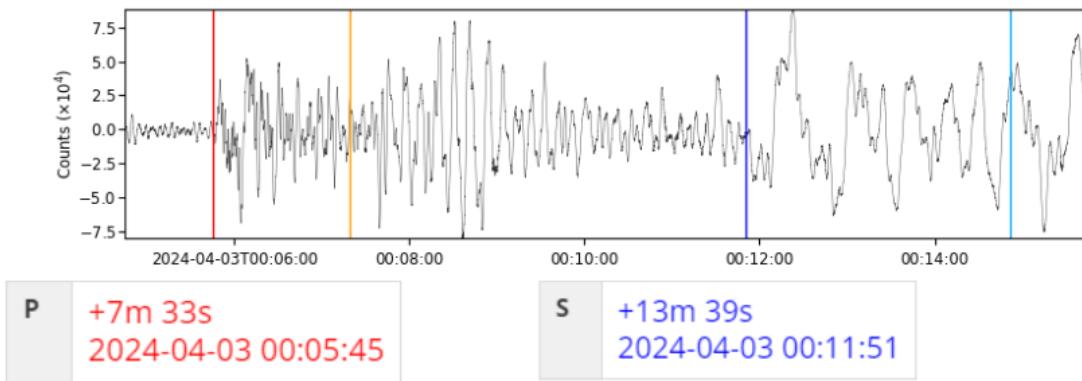
Taiwan was hit by an earthquake on 3 April 2024, at 07:58:11 NST. At least 18 people were killed and over 1000 people were injured. Most of the destruction – and deaths – occurred in remote rural areas in the wider Hualien County. The victims were mostly killed outdoors by falling rocks or landslides.



The earthquake was of magnitude 7.2 M_L on the Richter scale and the previous time such a big earthquake hit Taiwan was the 7.3 M_L Jiji earthquake which killed 2415 people in 1999.

Given below are the seismographs from two locations in Taiwan during the 3rd April earthquake.



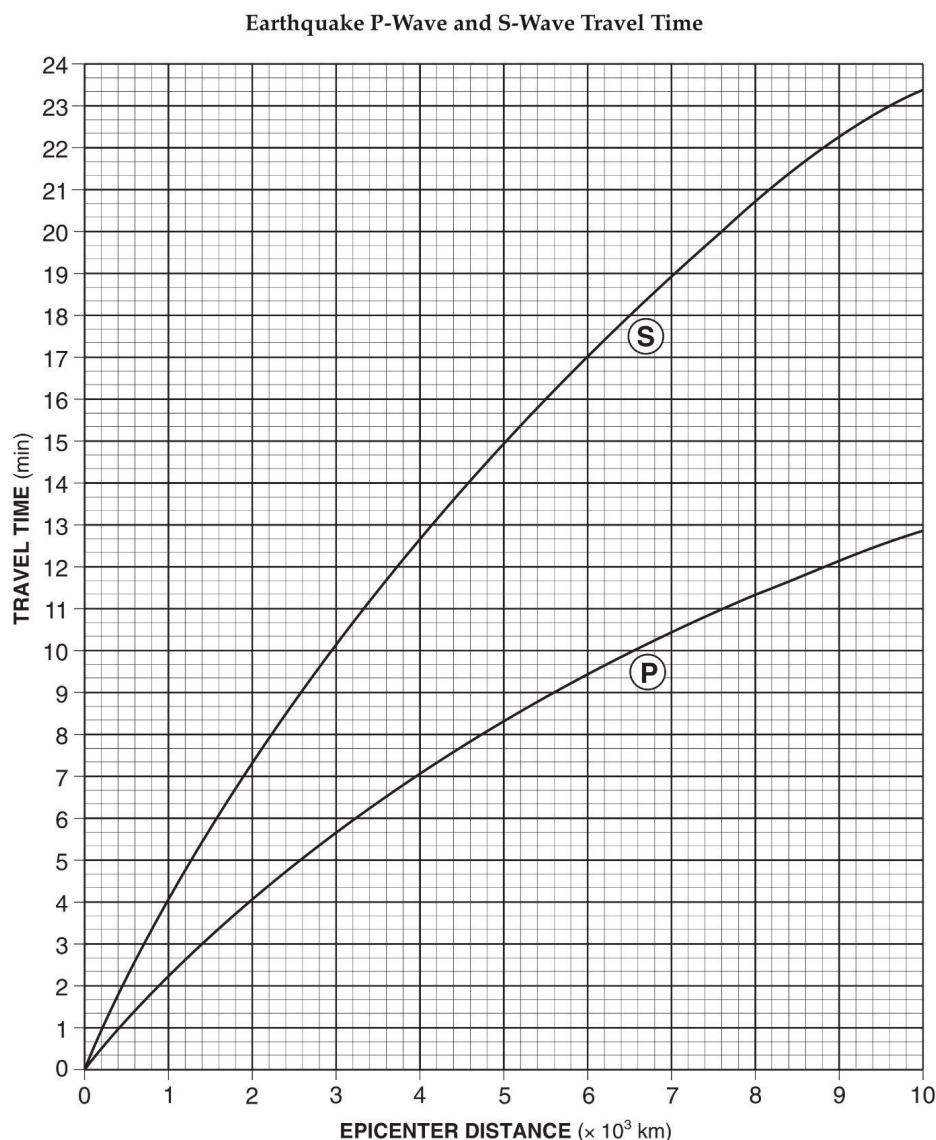


Seismograph from Station B (53.02°N , 158.65°W)

- (a) Using the travel time graph provided (Graph 1 below), calculate the distance of stations A and B from the epicentre in kilometre (km). [3 marks]

(i) Station A: _____

(ii) Station B: _____



Graph 1. Travel time graph.

- (b) What are the reasons why the 3rd April earthquake (Hualien earthquake) was less harmful than the Jiji Earthquake? 1 mark
- I. There was a successful warning system during the Hualien Earthquake.
 - II. Strict building codes were imposed only after the Jiji earthquake.
 - III. The Earthquake hit a less populated area on 3 April.
 - IV. Taiwan moved people out of places with higher risk of Earthquakes before earthquakes can happen.
- | | |
|--------------------|--------------------|
| A. I and IV only | C. III and IV only |
| B. II and III only | D. I and II only |

6. Bhutan - Liberal PDP won parliamentary elections in Bhutan

Earlier this year, Bhutan, a country nestled between India and China which pioneered the usage of Gross National Happiness (GNH) in gauging its economic growth, held a general election. Results of the election revealed that People's Democratic Party (PDP) successfully secured 30 out of 47 parliamentary seats. Thanks to the party's victory, Tshering Tobgay becomes the prime minister of Bhutan for the second time.

Dzongkha is the national language of Bhutan. It belongs to the Sino-Tibetan language family and is spoken by approximately 640 000 people.

Here are some equalities written in the Dzongkha language:

1.	gu: × cu-ci	=	khe zi da cy-gu
2.	khe ci: da zi + khe ko-da sum	=	khe sum da cy-gu
3.	(ci: + ge:)^2	=	khe zi da ci:
4.	khe ko-da 'ni - ce-ja	=	khe ci:
5.	cu-du × 'ŋa	=	khe zi
6.	khe 'ni da zi + khe ci: da qhu:	=	khe p̥he-da zi
7.	cop-ge + cy-zi	=	khe ci: da cu-ŋi
8.	khe p̥he-da 'ni: + dyn	=	khe ci: da cup-dy
9.	khe zi da cu-du - khe 'ni da cu-sum	=	khe 'ni da sum

Note (Please read very carefully):

- 1) “ ‘ ” indicates stress
- 2) “ : ” indicates that the vowel is long
- 3) “ ~ ” indicates that the vowel is nasalised
- 4) “ z ”, “ q ”, “ n ”, “ ŋ ”, “ ŋ ” are consonants

- (a) **Write** the equalities (1–9) in digits, given that all words have a numerical value of less than 100. 18 marks
- (b) **Write** the following numbers in the Dzongkha language. 6 marks

(i) 10

(ii) 34

(iii) 75

(iv) 90

7. Macao, China - ITTF World Cup Macao 2024: The competition that united globe's top table tennis talents

From the 15th to the 21st of April, the International Table Tennis Federation (ITTF) hosted the 2024 Singles' World Cup in Macao, China after a hiatus of three years since 2021.

- (a) Some players may argue that the essence of table tennis lies in the art of producing 'spins' which can dramatically alter the ball's trajectory. These spinning effects are created when players brush the balls with their rubber-padded paddle. Here, we will consider a simple model of the collision between a spinning table tennis ball with a paddle.

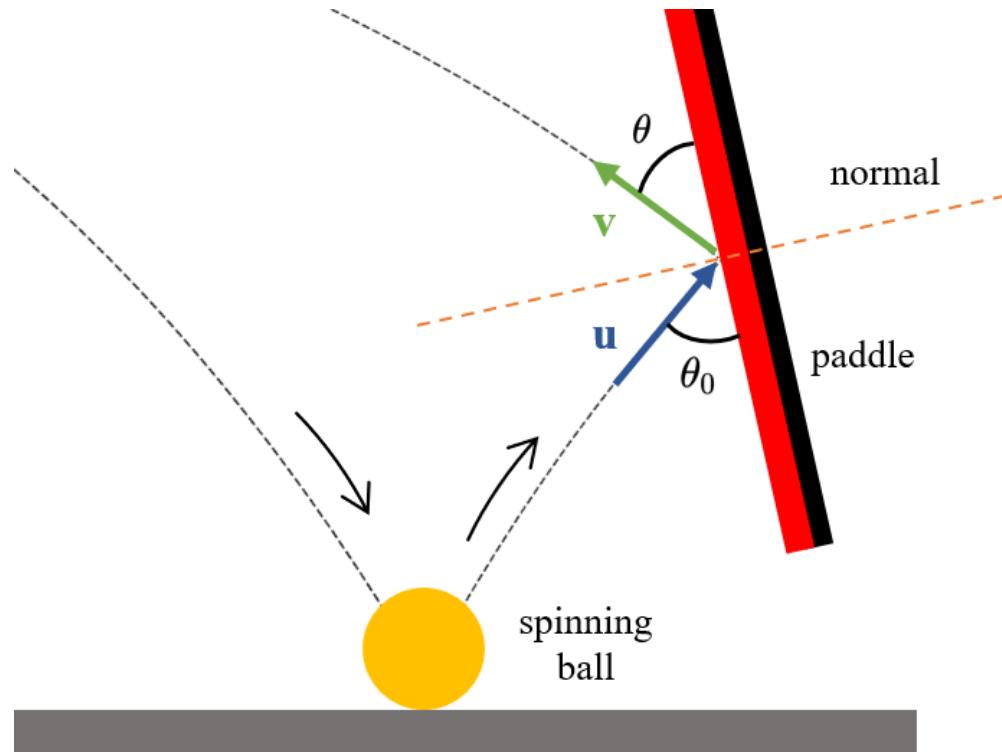


Figure 1. Spinning a ball

Assume that the paddle is held stationary, whereas the incoming ball has an initial clockwise angular velocity of ω and speed u . The initial velocity vector \mathbf{u} subtends an angle θ_0 from the paddle. Your task is to find the angle of departure θ in terms of any of the following quantities: u , ω , θ_0 , m , r .

4 marks

You may use the following assumptions:

- The collision is near-instantaneous and the friction between the ball and the rubber surface is sufficiently high to prevent any slipping
- The speed component in the *normal* direction remains unchanged after the collision
- The ball can be modelled as a hollow sphere of mass m and radius r

- (b) In any competitive sport, you need both skill and some luck. In table tennis, luck can come in the form of ‘edge-balls’ (see **Figure 2**). An edge-ball occurs when the ball nicely clips the edge of the table, resulting in an unanticipated trajectory.

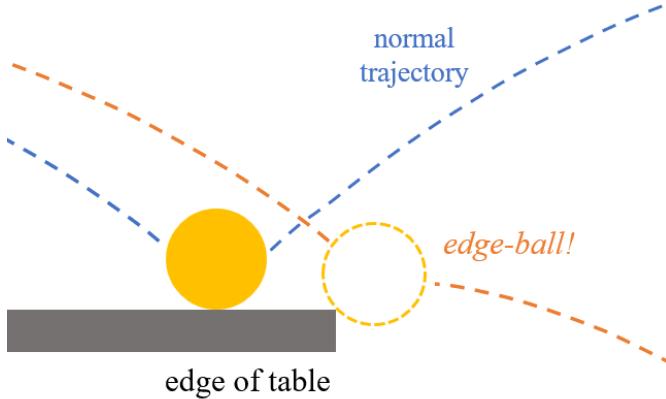


Figure 2. An edge-ball

For the following parts, assume that the ball is hit at a distance $d = 20\text{ cm}$ from the left edge of the table (see **Figure 3**). The center of the ball is at the same level as the edges of the table. The table has a length $L = 270\text{ cm}$ and the ball has a radius of $R = 20\text{ mm}$. The initial speed is u and the launch angle is θ , both of which can vary. You may neglect air drag and the existence of a net in the middle of the table, but you cannot treat the ball as a point mass.

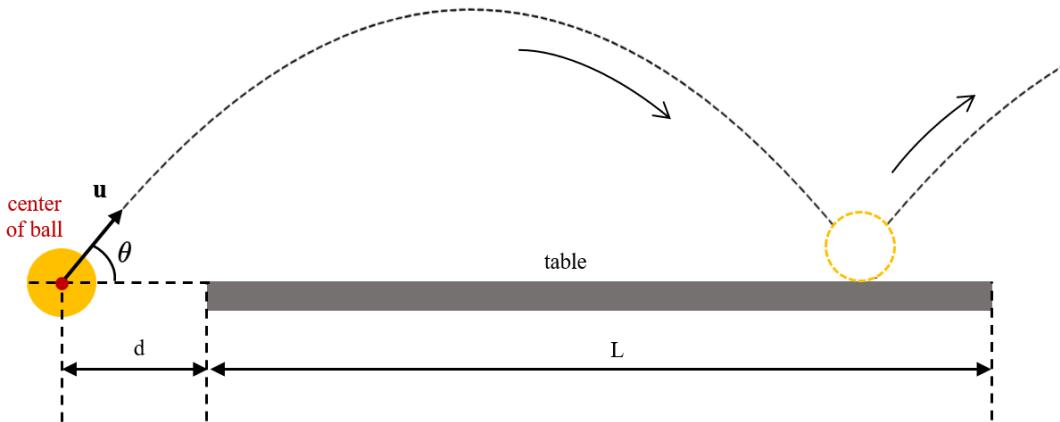


Figure 3. Launch setup (not drawn to scale)

- (i) **Find** the minimum possible speed u in order to produce an edge-ball, **and** the corresponding launch angle θ .

[3 marks]

It turns out that there is an upper limit u_{\max} on the speed u such that the ball will always hit the table (an edge ball is also counted) regardless of the launch angle. (Of course, if the launch is too vertical, the ball might just fall through the gap d ; you may ignore such cases.)

- (ii) As a preliminary step, let us start with a separate problem. For a pointlike object, consider the family of parabolae, all with the launch speed of v , but of different launch angles. These parabolae fill a region \mathcal{R} (shaded orange in **Figure 4**) of points that can possibly be hit by a projectile of launch speed v .

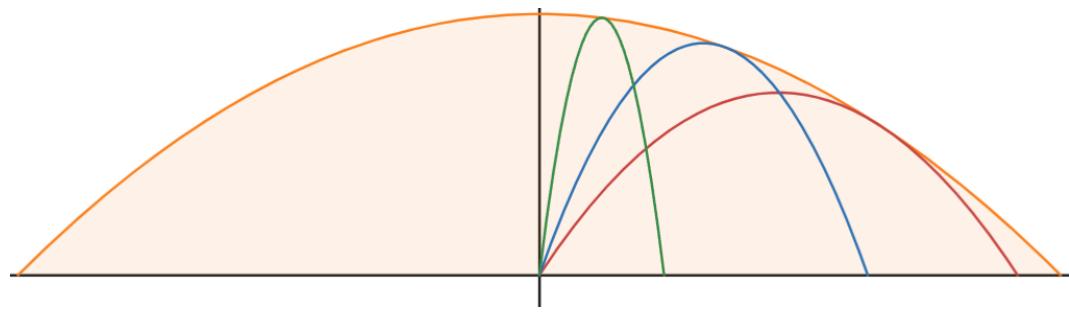


Figure 4. The region \mathcal{R} (orange); the other three parabolae are possible trajectories with the same launch speed

Show that \mathcal{R} is bounded above by a parabola with the equation:

1.5 marks

$$y_s = \frac{v^2}{2g} - \frac{gx^2}{2v^2}.$$

This is known as the *safety parabola* for a given launch speed v . (Note that the projectile is launched from the origin.)

Hint: You may use results from your working in part b(i).

(iii) **Show** that the *focus* of the safety parabola is at the origin.

1.5 marks

(iv) We are now ready to solve the original problem. Using what you have learned or otherwise, **find** the value of u_{\max} .

5 marks

Section B: North America

1. United States (Northern Illinois) - 2024: The Year of the Once-in-a-Lifetime Synchronized Emergence of Brood XIII and Brood XIX Cicadas

Billions of cicadas are emerging from the soil across a large swath of the United States in a natural phenomenon last witnessed in 1803. The Northern Illinois brood spends 17 years underground before surfacing and is known as Brood XIII (*Magicicada septendecim*), while the Great Southern Brood (*Magicicada tredecula*), or Brood XIX, lives underground for 13 years. The synchronous dual emergence of these two particular broods, which happens once every 221 years, is underway in 2024.

M. septendecim is one of the most abundant and common cicadas in the United States. They will spend their years underground feeding on plant roots. Then they climb on trees where they transform into adults, complete with rings and bright red eyes. A few days later, the males start to sing. Males of the species show intense acoustic behaviour. The analysis of the structure of the calling song in *Magicicada* over a wide distribution range of the species in the Mediterranean region was performed to better understand the pattern of its geographic variation. **Diagram 3** shows some of the studied acoustic variables. These acoustic variables revealed some variation among specimens from different regions, such as shown in **Diagram 3**.

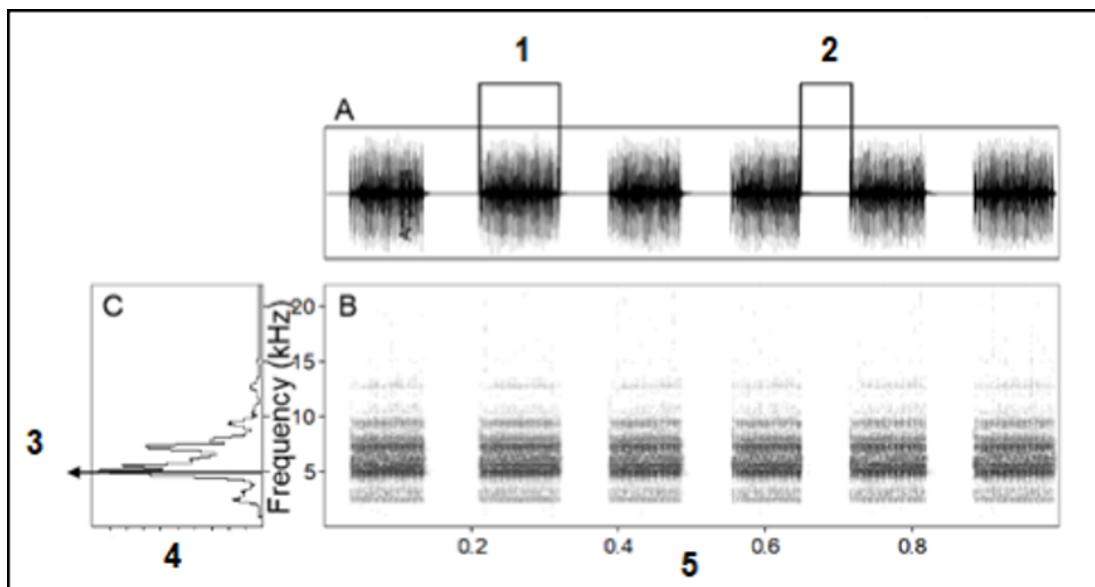


Diagram 3. Calling song of *C. ornata*. **A.** Oscillogram (amplitude vs time); **B.** Sonogram (frequency vs time); **C.** Mean amplitude spectrum (frequency vs amplitude). **1.** Echeme duration (s); **2.** Inter-echeme interval (s); **3.** Peak frequency (Hz). **4.** Intensity (V) **5.** Time (s). The echemes are composed of groups of pulses, and the duration of the interval between them is the inter-echeme.

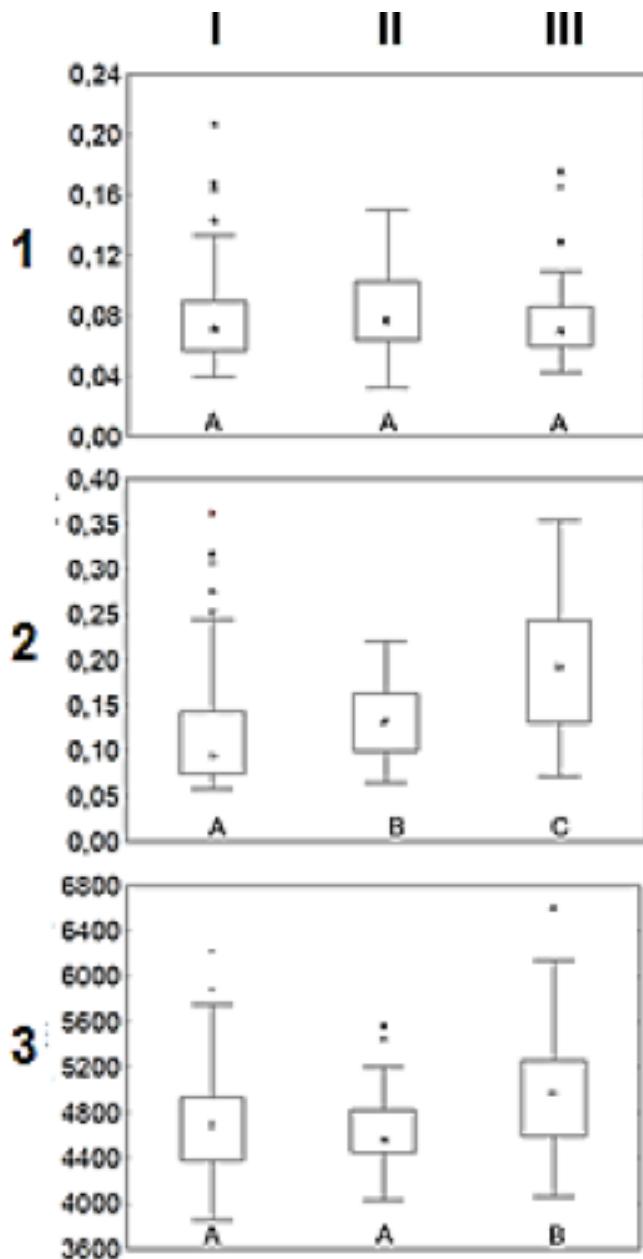


Diagram 4. Boxplots of three acoustic variables of the calling song of *C.orni* in (I) Iberian Peninsula, (II) France and (III) Greece. Regions with significant differences (Mann-Whitney, $p \ll 0.05$) share no letters. **1.** Echeme duration (s); **2.** Inter-echeme interval (s); **3.** Peak frequency (Hz). The echemes are composed by groups of pulses, and the duration of the interval between them is the inter-echeme.

Indicate which of the following statements is **TRUE** or **FALSE**.

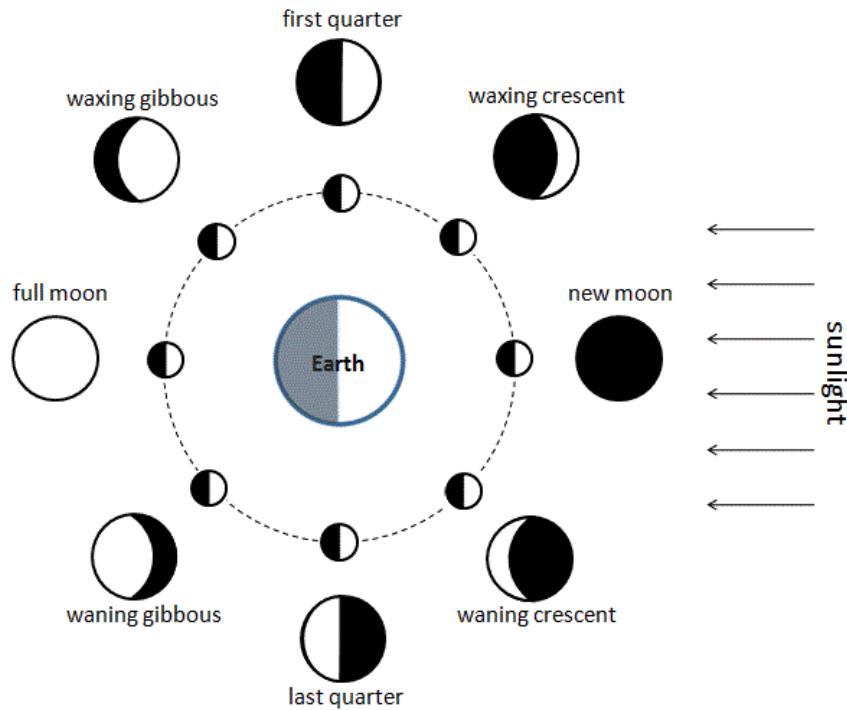
6 marks

- Echeme duration is not important in species recognition.
- Inter-echeme interval is probably not important in species recognition.
- Greece appears as the most differentiated area.
- Differentiation in Greek specimens might have been the result of strong geographic isolation.

2. USA, Mexico, Canada - Rare total solar eclipse swept across North America



Solar, Saros, Syzygy, bet you can't pronounce those Ss! The month of April saw the arrival of a once-in-a-lifetime astronomical event in North America - the Total Solar Eclipse of April 8, 2024. It is widely known that eclipses occur when the Sun, Moon and Earth align (called a syzygy!)



However, from textbook astronomy, it might at first sight seem like eclipses should happen every new moon (every month!), because of the apparent alignment of the three heavenly bodies. In reality, what makes eclipses so rare is actually because of the tilted orbit of the Moon - it doesn't orbit in the same plane as the Earth's orbit, but tilted at an angle of 5.1° ! Hence there are actually different definitions of a month:

- **Synodic Month:** the time between successive new Moons (29.53 days). This is what Lunar calendars are based off, and controls tides, etc.

- **Anomalistic Month:** the time between successive “closest approaches” to the Earth (because the Moon’s orbit has eccentricity $e = 0.055$, 27.55 days)
 - **Draconic Month:** the period between successive passages of the Moon through the node of the intersection of orbital planes (27.21 days)
- (a) Sketch a diagram showing the alignment of the Sun, Earth and Moon during the solar eclipse. Label the umbra and penumbra area clearly. 1 mark
- (b) The Sun’s declination varies throughout the year. Estimate the declination of the Sun on that day. 2 marks
- (c) Successive eclipses occur when the Moon seems about the same size, and aligns perfectly with the Sun as seen from Earth. Based on long-term observations, eclipses are found to have a periodicity of around 18 years. Based on the information given, calculate more accurately the date of the next eclipse, down to the week. 4 marks

Extra info:

This result is known as the Saros Cycle, and has been known to the ancients since the Babylonians - hopefully this shows that being ancient does not equate to being primitive!

3. USA - Fermilab’s Muon $g - 2$ experiment unveiled new insights into particle physics

The Muon $g - 2$ experiment is a highly sensitive experiment done over the course of 6 years (data collection ended in 2023) to measure the anomalous magnetic dipole moment of a muon. As published recently, the results are highly suggestive of new physics beyond the Standard Model.

- (a) To better analyse the behaviour of muons, it is desirable to ‘confine’ them by means of a storage ring.

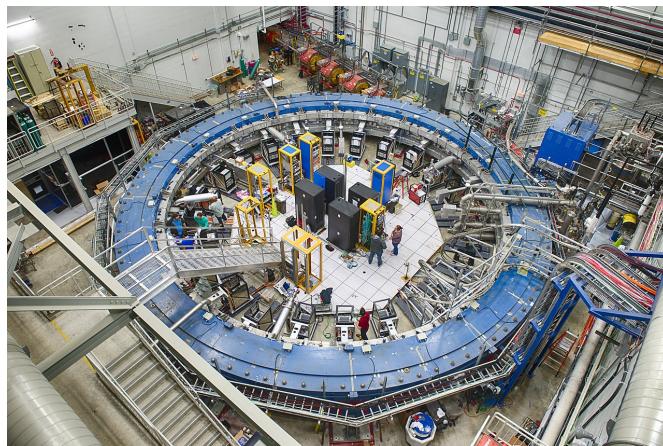


Figure 1. The $g - 2$ storage-ring magnet.

In some designs, this is achieved by using a quadrupole-magnet configuration. A simplified diagram is shown in **Figure 2**.

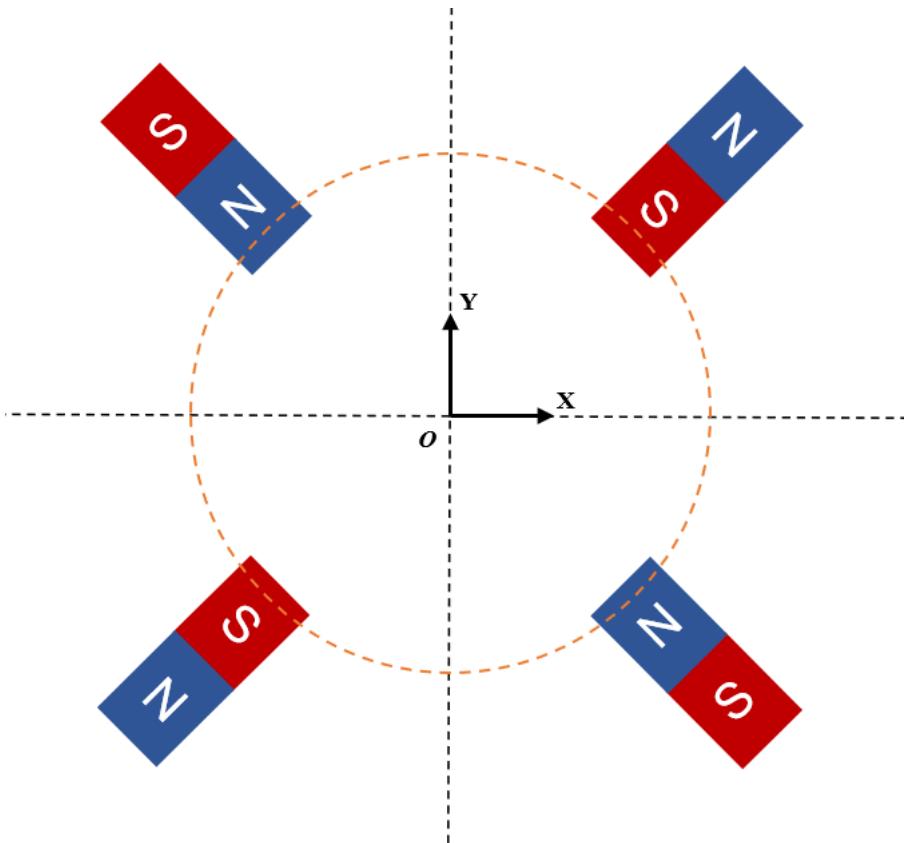


Figure 2. A cross-section of a storage ring containing a simplified quadrupole magnet schematic (drawn to scale). O is the center of the cross-section.

- (i) On **Figure 2** in the **answer sheet**, **draw** 4 magnetic field lines within the dotted circle. Each line should be symmetric across the four quadrants. Remember to **indicate** the direction of the field lines for which you will primarily be graded. 1.5 marks
- (ii) A centered beam of *negative muons* (which have a charge equal to an electron's) is shot into the storage ring perpendicularly into the page. Along which direction(s) (x or y) will the beam be *focused* (i.e. the particles in the beam tend to converge together along that direction)? Explain your reasoning clearly. 2 marks
- (b) Muons almost always decay into at least three particles. The trio must include an electron (or a positron if it's a positive muon μ^+) and two types of neutrinos. Apparently, some modes of decay are highly unlikely that they are effectively 'prohibited'. An example is

$$\mu^- \rightarrow e^- + \gamma$$

where a negative muon decays into an electron and a photon. One day, your physicist colleague insists that he observed such a decay. Assuming that the muon has an initial energy of E_μ , and it is observed that the photon departs at an angle θ from the muon's line of motion, what frequency must the photon have? Electrons have a mass of m_e whereas muons have a mass of $m_\mu > m_e$. 4 marks

4. USA - Creation of AlphaGeometry: An AI system for Mathematics Olympiad

AlphaGeometry is an Olympiad-level AI system for geometry, developed by Trieu Trinh and Thang Luong on January 17, 2024. This advanced system can solve complex geometry problems at a level comparable to a human Olympiad gold medalist, representing a significant breakthrough in AI performance. However, despite its impressive capabilities, AlphaGeometry relies exclusively on pure angle chasing and length chasing techniques, even for challenging problems such as IMO P3 and P6. This limitation prevents it from solving geometric inequality problems.

Now, can you beat AlphaGeometry by solving the following problem?

5 marks

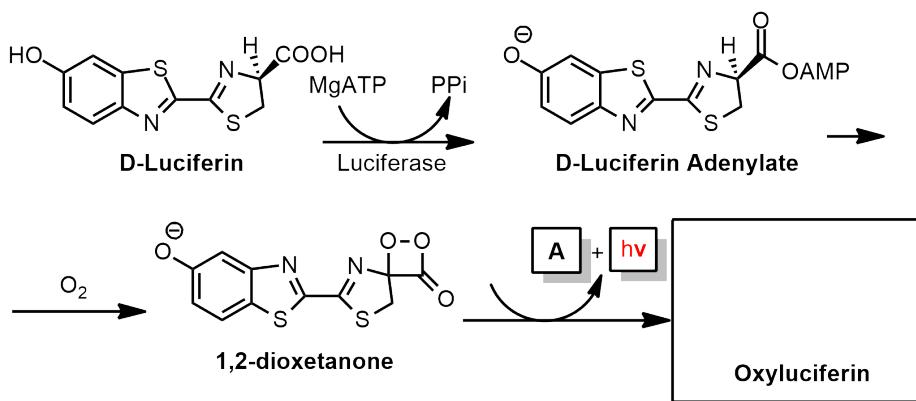
In triangle $\triangle ABC$, given that $2AB^3 = BC^3 + CA^3$, determine with proof the maximum value of $\angle ACB$.

5. USA - Increasing Sightings of Blue Waves in California Waters

As reported in The New York Times, sightings of mesmerizing glowing neon blue waves are becoming more frequent in California's waters. The water is so luminescent when it is disturbed at night that it seems like surfers are riding waves in "Avatar: The Way of Water." This mesmerizing sight is caused by an algal bloom involving a type of phytoplankton known as bioluminescent dinoflagellates, which are able to produce light through an enzyme called luciferase.



Luciferase is present in many bioluminescing organisms, including the firefly, the sea pansy *Renilla reniformis*, the copepod *Gaussia princeps*, and the ostracod *Cypridina noctiluca*. It catalyzes the conversion of luciferin to oxyluciferin, producing visible light in the process. In fireflies, this reaction produces a green-yellow light. The steps for this conversion in **fireflies** are shown below:



- (a) Firefly 1,2-dioxetanone is a high-energy intermediate which undergoes [2+2] cycloelimination to form oxyluciferin and compound **A**, releasing visible light in the process. **Draw** the chemical structures of oxyluciferin and compound **A**. 6 marks

Hint: Compound **A** has molar mass of 44.01 g mol^{-1} .

- (b) Prior to forming excited oxyluciferin, 1,2-dioxetanone overcomes an energy barrier to form a transition state. Excited oxyluciferin then decomposes into oxyluciferin, releasing visible light in the process.

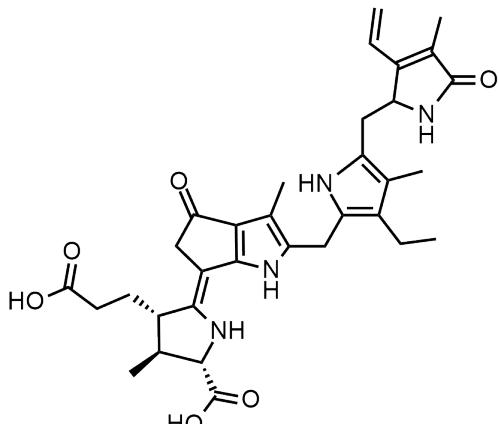
Arrange the following compounds in descending order of their free energies: 3 marks

- (i) Firefly 1,2-dioxetanone
- (ii) Transition state between 1,2-dioxetanone and excited oxyluciferin
- (iii) Excited oxyluciferin
- (iv) Oxyluciferin

- (c) Which of the following best explains why the [2+2] cycloelimination step results in oxyluciferin being in an excited state, as opposed to compound **A**? 3 marks

- A. Oxyluciferin has a specific orbital arrangement that makes it more likely to be excited.
 - B. The formation of oxyluciferin involves a greater release of energy, which is retained as electronic excitation.
 - C. Oxyluciferin's aromatic structure allows it to better stabilize the extra energy, resulting in an excited state.
 - D. Oxyluciferin's unique bonding and resonance structures stabilize the excited state more effectively.
 - E. The energy released during the cycloelimination is primarily absorbed by oxyluciferin due to its electronic structure.
- (d) While the same luciferase enzyme is present in both fireflies and bioluminescent dinoflagellates, both species emit different wavelengths of light. Fireflies mainly emit a green-yellow light (560-570 nm), while bioluminescent dinoflagellates mainly emit a blue light (470-480 nm).

The chemical structure of dinoflagellate oxyluciferin is shown below.



Dinoflagellate oxyluciferin

Based on the information above, which of the following statements are **TRUE** (select 3 options)?

[3 marks]

- A. The difference in emitted wavelengths is due to the different cofactors or microenvironments provided by the luciferase enzymes in fireflies and dinoflagellates.
- B. The luciferase enzyme in fireflies has an active site that stabilizes the excited state of oxyluciferin differently compared to dinoflagellates, leading to emission at a longer wavelength.
- C. The blue light emitted by dinoflagellates is due to a higher energy transition state of the excited oxyluciferin compared to that in fireflies.
- D. Differences in the chemical structure of the luciferin substrate between fireflies and dinoflagellates result in different wavelengths of emitted light.
- E. The presence of specific amino acid residues in the luciferase active site influences the electronic environment of the oxyluciferin, altering the wavelength of the emitted light.

Section C: South America

1. Ecuador - Gigantic New Anaconda Species Discovered in Amazon

Researchers in the Amazon have discovered the world's largest snake species — an enormous green anaconda — in Ecuador's rainforest that split off from its closest relatives 10 million years ago, though they still look nearly identical to this day. It was thought that there was only one species of green anaconda in the wild, the *Eunectes murinus*, but the scientific journal *Diversity* this month revealed that the new "northern green anaconda" belongs to a different, new species, *Eunectes akiyama*.

"What we were there to do was use the anacondas as an indicator species for what kind of damage is being done by the oil spills that are plaguing the Yasuni in Ecuador because the oil extraction is absolutely out of control," University of Queensland professor of biology Bryan Fry said.



Diagram 1. Footage of the world's biggest snake species ever discovered.
(Credits to: Story Freek via Storyful)

Professor Fry, who for almost 20 years has been investigating anaconda species found in South America, said the discovery allows them to show that the two species split from each other almost 10 million years ago.

"But the really amazing part was, despite this genetic difference, and despite their long period of divergence, the two animals are completely identical," he said.

Although green anaconda snakes are very similar visually, there is a genetic difference of 5.5 per cent, which surprised the scientists.

"Which is an incredible amount of genetic difference, particularly when you put it in the context that we're only 2 per cent different from chimpanzees," Professor Fry said. **Diagram 2** below shows an inferred phylogeny from the genomic region of *Eunectes akiyama*.

Anacondas are useful sources of information for the ecological health of the area and the potential impacts on human health of oil spills in the region, he said. Some of the snakes they studied in parts of Ecuador were heavily polluted by oil spills, and the anacondas and arapaima fish are accumulating a large amount of the petrochemical metals, he added.

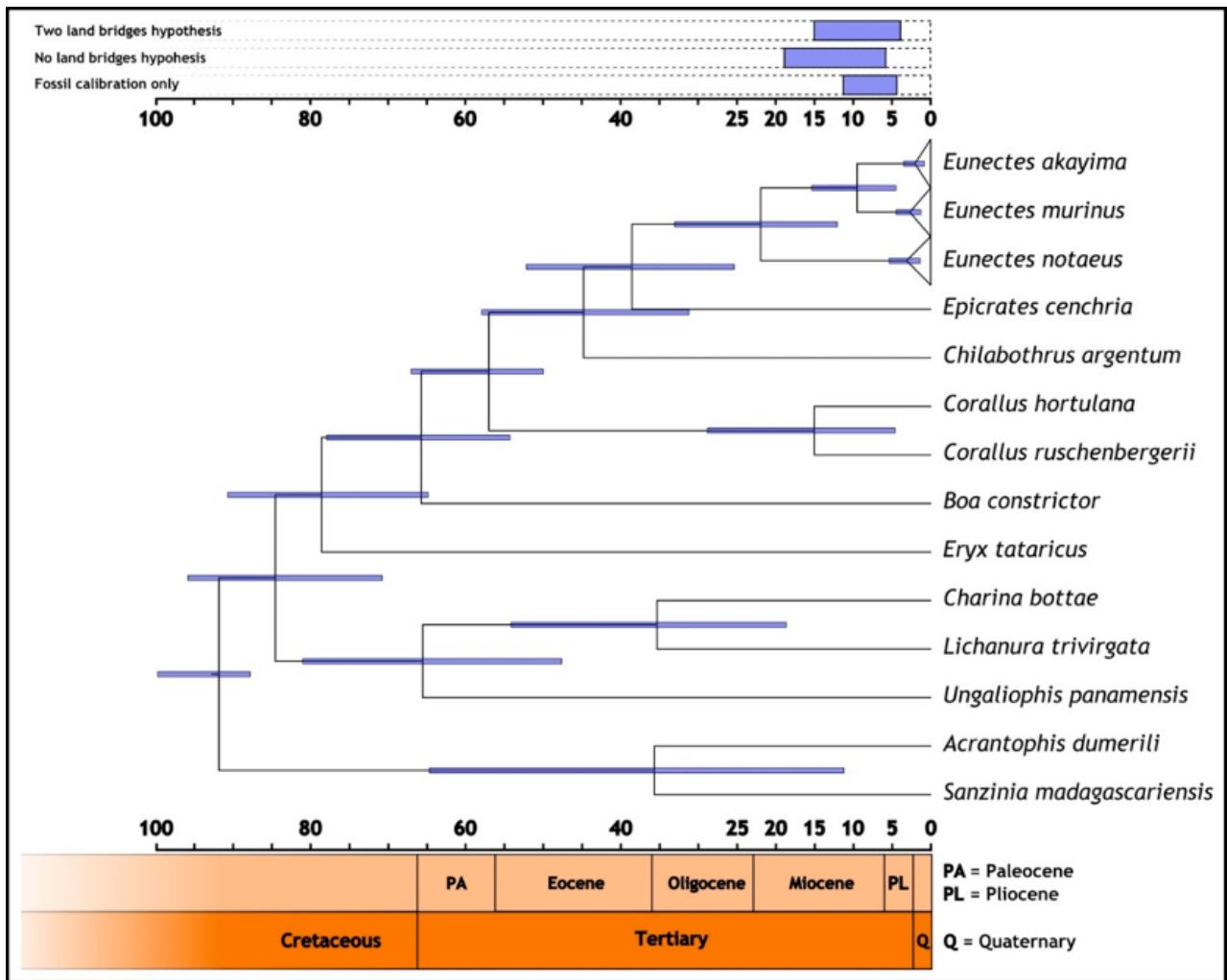


Diagram 2. Cladogram of Boidae diversification with timeline, showing estimates of the split between *Eunectes akayima* and *E. murinus* according to different paleogeographical scenarios (Source: Disentangling the Anacondas: Revealing a New Green Species and Rethinking Yellows †, 2024)

Based on the phylogeny tree, indicate whether the following statements are **TRUE** or **FALSE**. 5 marks

- The most recent common ancestor of both *E. akayima* and *E. murinus* lived during an epoch when continental configurations and mountain topography transitioned toward modern conditions, and many flora and fauna evolved into the same taxa that exist today.
- The lineages that are most closely related to the *E. murinus* are both *E. akayima* and *E. notaeus*.
- Charina bottae* and *Ungaliophis panamensis* are considered sister taxa.
- The ancestor of *Acrantophis dumerili* and *Sanzinia madagascariensis* lineages gave rise to all other Boidae shown in the cladogram.

Section D: Europe

1. France - Paris is the host city for the Summer Olympic Games 2024

Part I.

On 8 February 2024, the organizing committee of Paris 2024 Olympic Games unveiled the medal designs for this year's Summer Olympic Games. Each medal is embellished with a hexagon-shaped iron - weighing 18 grams - that is taken originally from the Eiffel Tower itself.

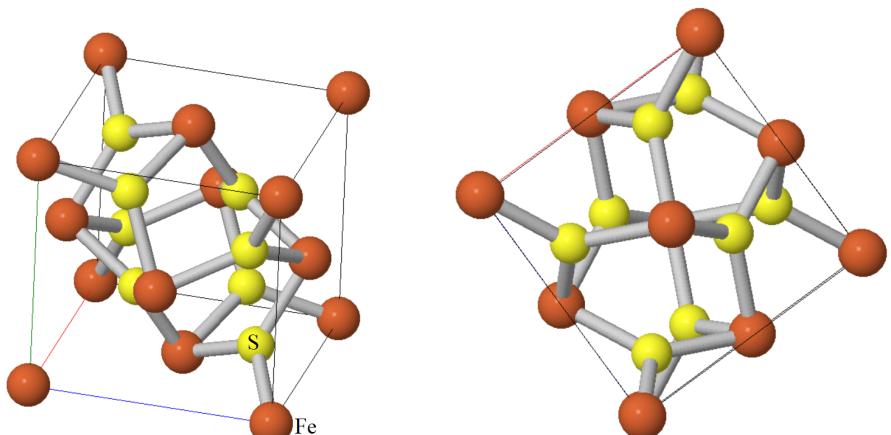


Quincy thought it would be intriguing to replace the entire gold medal (excluding the iron) with pyrite.

Pyrite is famously known as the Fool's Gold due to its gold-like appearance which mimics gold. The two images below show gold and pyrite respectively.



Pyrite is made up of iron (Fe) and sulphur (S), and crystallises in a cubic unit cell as depicted below:



Top view of the pyrite unit cell

- (a) What is the chemical formula of pyrite? 2 marks
- (b) What is the coordination number of iron in pyrite? 1 mark
- (c) Given the density of pyrite is 5.016 g/cm^3 , calculate the side length (denoted by a) of the unit cell of pyrite in Å. Give your answer to the nearest **4 significant figures**.
 $(1 \text{ \AA} = 10^{-10} \text{ m})$ 3 marks

In crystallography, Atomic Packing Factor (APF) is defined as the fraction of volume in a crystal structure that is occupied by atoms. APF is determined with the assumption that all atoms are rigid spheres and has the formula below:

$$APF = \frac{\text{Total volume of atoms in a unit cell}}{\text{Volume of a unit cell}}$$

- (d) Given that the atomic radii of iron and sulphur atoms are 132 pm and 105 pm respectively, what is the APF of pyrite crystal structure? Give your answer to the nearest **3 significant figures**. 3 marks

It is assumed that the Paris 2024 Olympic gold medal is a perfect cylinder with thickness of 9.2 mm and diameter of 85 mm.

- (e) To replace the entire gold medal with pyrite, what is the mass of pyrite needed? 2 marks
- (f) Hence, what will be the final mass of the “gold” medal when it is embellished with the piece of iron? 1 mark

Part II.

The 2024 Summer Olympics will be held in Paris this July and August! As the welcoming coordinator for team arrivals, you wish to understand the order in which the participating countries from each *continent* arrive at the venue.

- (a) You safely assume that the order of arrival of all countries is uniformly random. 12 out of the 162 participating countries are from South America, and the first South American country that arrives is the N -th country to arrive ($1 \leq N \leq 162$). Determine with proof the expected value of N . Write your answer as a simplified fraction $\frac{b}{c}$. 6 marks

You are at one of the events filled with supporters from all 12 South American countries (and from no other countries), each with an equal number of supporters. You hope to interview at least one supporter from each South American country, but the only way to know which country a supporter is from is to directly interview them and ask.

- (b) You randomly select supporters to interview and stop after you accomplish your goal (i.e. all 12 countries have at least one interviewee). Determine with proof the expected number of people that you reach out to, rounded to the nearest integer? Assume that there are a huge number of supporters and the event is chaotic, so you may reach out to the same person twice (i.e. random selections with replacement). 4 marks

2. France - European Space Agency (ESA) officially adopted LISA in search for gravitational waves

On 25 January 2024, the European Space Agency (ESA) officially adopted LISA as a project, of which construction will begin in January 2025. LISA is an acronym for “Laser Interferometer Space Antenna”, and differs from conventional telescopes as it will not be observing electromagnetic waves, but rather low frequency **gravitational waves!**

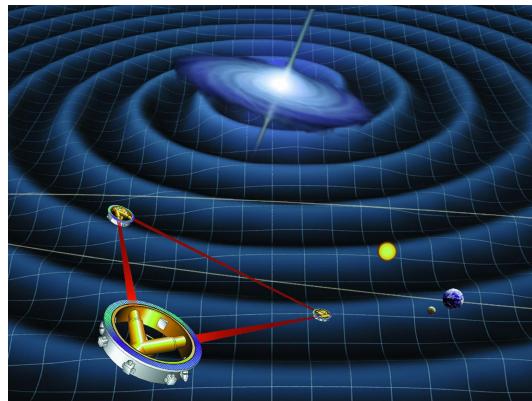


Figure 1. Artist's conception of LISA spacecraft, taken from Wikipedia.

In principle, it works because light is a wave - and waves can be superposed together to give bright and dark spots when certain conditions are met. These setups allow the minute changes in the fabric of spacetime to be analyzed accurately, becoming the subject of the 2017 Nobel Prize in Physics! Let's first find out why scientists want to send LISA to space. A model for an Earth-based gravitational wave detector consists of two metal rods each a length L , held at right angles to each other. The laser has wavelength $\lambda = 656 \text{ nm}$.

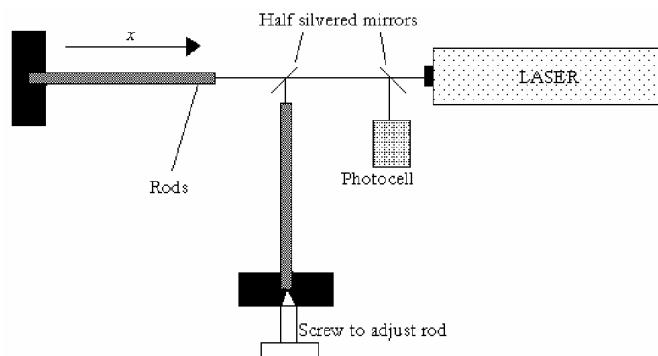


Figure 2. A simplified model of a Gravitational Wave detector

One end of each rod is polished optically flat and the other end is held rigidly. The position of one rod is adjusted so there is a minimum signal received from the photocell. Let's suppose the rods are made of aluminium with density $\rho = 2700 \text{ kg m}^{-3}$ and Young modulus $E = 7.1 \times 10^{10} \text{ Pa}$. The rods are subject to a gravitational field g that need not point downwards, but instead across one of the rods.

- (a) Suppose that the gravitational field changes by Δg . What is the corresponding change in the strain $\Delta\varepsilon$ of a segment of the rod of length ℓ ? 2 marks

- (b) This change in strain causes each segment of $\Delta\ell$ to turn become $(1 + \Delta\varepsilon)\Delta\ell$. Based on this, show that the change in the total length of the rod is $\Delta L = (\rho L^2/2E)\Delta g$ where L is the total length. 2 marks
- (c) Suppose that the light bouncing off the changing rod has a path difference of Δx caused by ΔL as derived from above. Suppose the waves currently interfere destructively. What is the condition for ΔL such that the minimum is observed? Express this relation solely in terms of the wavelength λ . 1 mark
- (d) If the minimum fringe shift that can be detected is 10^{-4} of the wavelength of the laser, what is the minimum value of L necessary if such a system were to be capable of detecting Δg of $10^{-19} \text{ N kg}^{-1}$? 2 marks

Being so delicate is the reason why LISA should be in space, as it would be free of all Earthly noise such as vibrations from earthquakes, nearby construction, etc. LISA is a group of three identical spacecrafts, each placed at the corners of an equilateral triangle as shown. The sides (or “arms” of the interferometer on which the path of the lasers propagate) are about $l = 5 \times 10^9 \text{ m}$ long. The LISA constellation is in orbit around the Sun, trailing behind Earth by 20° . Effectively, the three spacecrafts appear to roll about their common centre **one revolution per year**.

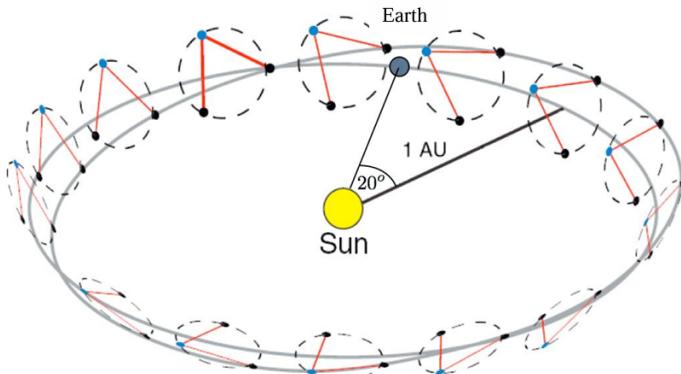


Figure 3. Illustration of the LISA orbit. The three spacecraft roll about their centre of mass with a period of 1 year. (Credit: Astronomical Society of Australia)

- (e) What is the orbital velocity of the three spacecrafts v about the circle that they trace out? 1 mark
- (f) In the plane containing the three spacecrafts, what is the relative speed of one spacecraft with respect to another? 2 marks

Hint: Consider their velocity vectors.



Figure 4. A, B and C are the three spacecrafts at the corners of the equilateral triangle.

3. United Kingdom - Rare heavenly glow over the skies of countries in the North

Engineering PhD student, Jamie Clarkson, who is studying at the University of Cambridge took a magnificent shot of the Northern Lights over Cambridge last month. “Never in my wildest dreams did I think I would see the aurora this well in Cambridge! A once in a lifetime event.” they commented afterwards. In fact, Jamie is not exaggerating, the aurora borealis that was visible in several European countries and in parts of the northern United States is an unusual sight. It is believed to be the consequence of a severe solar storm.



Figure 5. Photo taken by Jamie Clarkson.

- (a) Auroras are caused by charged particles ejected from the Sun’s corona. The particles are deflected towards the poles of Earth by our planet’s magnetic field and interact with our atmosphere, depositing energy and causing the atmosphere to fluoresce. Assume a 30% efficiency, **determine** the energy transferred to the gas molecules in the atmosphere by a charged electron which is travelling at the speed of light. 2 marks
- (b) Based on your knowledge about the composition of the atmosphere, **name** the types of gas molecules that are likely to radiate the pink hue as seen in the picture above.

Hint: The pink colour is actually a mix of red and blue colours.

1 mark

- (c) Late at night on May 7 2024 and in the wee hours of May 8 2024, the Sun emitted a powerful pair of solar flares. Both are classified as X-class, which are among the strongest flares the Sun has ever emitted, thus explaining the unusual sightings of auroras in regions with lower latitudes.



Figure 6. Pair of solar flares captured by NASA.

The existence of the solar wind was first proposed by Eugene Parker who described a theory that in the sun's corona, plasma in this region can reach a blistering 2 million Kelvin. Eventually, the plasma becomes so hot that the sun's gravity can no longer hold it down so it is "ejected" into space as the solar wind. Let's assume a simplified model of solar flares, in which the particles on the Sun's surface gain sufficient kinetic energy from their thermal surroundings. To fulfil the conditions stated above, what is the maximum initial temperature of the plasma on the Sun's surface? 3 marks

These are the assumptions that you can make:

- No heat is lost to the surroundings.
- The process of particle ejection is slow, such that one can model it as an isovolumetric process.
- Particles are at rest on the Sun's surface (i.e. ignore thermal speed).

Useful constant:

The plasma is made of hydrogen which has a specific heat capacity of $14.30 \text{ J g}^{-1} \text{ K}^{-1}$.

- (d) The number of solar flares increases every 11 years until the Sun's magnetic field flips and starts a new solar cycle. Scientists expect the Sun's activity to ramp up as we approach solar maximum; there have been 13 X-class solar flares so far this year. Briefly **explain** how the solar flares affect spacecraft and telecommunication. 2 marks

Section E: Oceania

1. Vanuatu - Nine small island states including Vanuatu secured historic climate win at international ocean court

On 21st May 2024, nine small island states won a historic climate change case at the International Tribunal for the Law of the Sea (ITLOS). The win had successfully redefined marine pollution by which it includes greenhouse gas emissions absorbed by the ocean. This urged countries to enhance their protection of marine environments beyond the obligations set by the Paris climate agreement.

Vanuatu was one of the nine island states that secured the historic win. Vanuatu has three official languages with Bislama being one of them. It is spoken by approximately 200 000 people.

- (a) **Match** the words in Bislama (1-13) to their English Translations (A-M). Write down the answers only, for example **1. A.**

6.5 marks

Words in Bislama		English Translations	
1.	mitufala	A.	Yawn
2.	olgeta	B.	We two (Exclusive)
3.	yumi	C.	They three
4.	smolpima	D.	Dugong
5.	mifala	E.	We (Exclusive)
6.	kaofis	F.	You (Plural)
7.	ol nani	G.	Chickens
8.	luksave	H.	They (Plural)
9.	yufala	I.	We (Inclusive)
10.	wantem silip	J.	Goats
11.	ol faol	K.	Bird's eye chilli
12.	trifala	L.	We two (Inclusive)
13.	yumitu	M.	Recognise

(Note: Inclusive / Exclusive **means** Including / Excluding addressee)

- (b) **Translate** the following words in English to Bislama.

4 marks

- (i) Goat
- (ii) You three
- (iii) Chilli
- (iv) Fish

2. New Zealand: New Zealand's new government plans to scrap tobacco endgame policy to fund tax cuts

Last December, New Zealand's new government announced their plan to reverse their ambitious tobacco endgame policy to fund tax cuts - a move which will potentially affect the Māori communities the most.

Generational endgame for smoking is a policy piloted by New Zealand to prevent younger generations from smoking to create a smoking-free society in the future. However, there are major implications to this, not least the lobbying from the tobacco industry. As of now, only 3 countries have started work on the proposal: New Zealand, Malaysia and the UK.

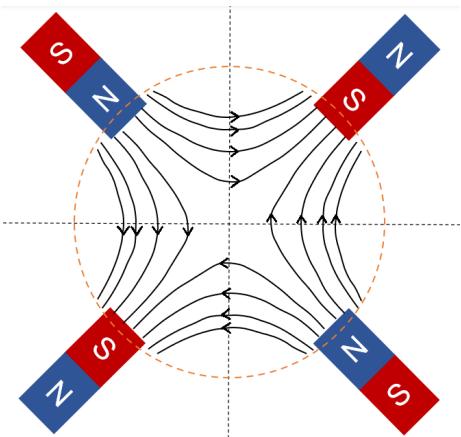
- (a) How will New Zealand's generational endgame smoking plan, which aims to prohibit the sale of tobacco to individuals born after 2008, impact the country's tobacco industry in terms of employment, production, and sales? 3 marks
- (b) Analyse the potential long-term healthcare cost savings for New Zealand's public health system resulting from the generational endgame smoking plan. Consider the impact on the prevalence of smoking-related diseases and the associated treatment costs. 3 marks
- (c) Evaluate the effects of New Zealand's generational endgame smoking plan on government tax revenue from tobacco sales. What alternative fiscal strategies could the government implement to compensate for the expected decrease in tobacco tax revenue? 4 marks

Answers

Section A: Asia

Section B: North America

3. (a) (i)

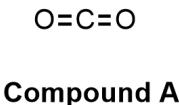
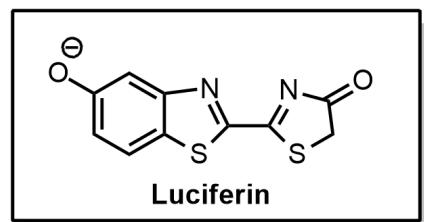


(ii) x-direction

$$(b) f = \frac{(m_\mu^2 - m_e^2)c^4}{2h(E_\mu - \sqrt{E_\mu^2 - m_\mu^2 c^4} \cos \theta)}$$

4. $\frac{\pi}{3}$ or 60°

5. (a)



(b) ii, iii, i, iv

(c) E

(d) A, B, E

Section C: South America

1. (a) True

(b) False

(c) False

(d) False

Section D: Europe

1. **Part I.**

(a) FeS_2

(b) 6

(c) 5.417 \AA

(d) 0.487

(e) 261.8 g

(f) 279.8 g or 280 g

(c) $\frac{\lambda}{4}$

(d) 92900 km

(e) 575 ms^{-1}

(f) 996 ms^{-1}

3. (a) $1.23 \times 10^{-14} \text{ J}$

(b) Nitrogen (Red) and Oxygen (Blue)

(c) $1.54 \times 10^7 \text{ K}$

(d) Accept any points that explain how the solar flares affect electronic appliances in the spacecraft, astronauts' health and telecommunication.

Part II.

(a) $\frac{163}{13}$

(b) 37

2. (a) $\Delta\varepsilon = \frac{\rho\ell\Delta g}{E}$

(b) Accept any plausible workings that lead to $\Delta L = \frac{\rho L^2 \Delta g}{2E}$.

Section E: Oceania

- | | | | |
|-------------|-------|-------|--|
| 1. (a) 1. B | 6. D | 11. G | |
| 2. H | 7. J | 12. C | |
| 3. I | 8. M | 13. L | |
| 4. K | 9. F | | |
| 5. E | 10. A | | |
- (b) (i) nani
(ii) yutrifala
(iii) pima
(iv) fis
2. (a) Accept any points that relate to the effect of the plan to the country's tobacco industry in terms of employment, production and sales correctly. Award marks for additional explanation if applicable.
- (b) Accept points that relate to a reduction in smoking-related diseases, savings to healthcare costs and additional analysis that are correctly linked.
- (c) Accept any points that relate to a decrease in tax revenue. Accept any alternative fiscal strategies mentioned that are realistic to implement. Award marks for additional analysis and explanation.

References

Section A: Asia

1. The image in **Q2** is sourced from:
Sharma G. Nepali sherpa saves Malaysian climber in rare Everest ‘death zone’ rescue. Reuters [Image on the internet]. 2023 June 2 [cited 2024 May 30]. Available from: <https://www.reuters.com/world/asia-pacific/nepali-sherpa-saves-malaysian-climber-rare-everest-death-zone-rescue-2023-05-31/>
2. The image in **Q5** is sourced from:
Bush E. Earthquake showed Taiwan was well prepared for a big one — more so than parts of U.S. NBC News [Image on the internet]. 2024 April 4 [cited 2024 May 30]. Available from: <https://www.nbcnews.com/science/science-news/taiwan-earthquake-well-prepared-rcna146243>
3. The seismographs in **Q5** are sourced from:
NSF SAGE. Station Monitor [Dataset on the internet]. VA: U.S. National Science Foundation; 2024 [cited 2024 June 3]. Available from: https://www.iris.edu/app/station_monitor/#Today//welcome/
4. The travel time graph in **Q5** is sourced from:
The University of the State of New York. Reference Tables for Physical Setting/EARTH SCIENCE [Graph]. New York: The University of the State of New York; 2011 [cited 2024 June 3]. Available from: <https://www.nysesd.gov/sites/default/files/programs/state-assessment/earth-science-reference-tables-english-2011.pdf>

Section B: North America

1. **Q1** is sourced from:
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2. The images in **Q2** are sourced from:
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4. The image in **Q5** is sourced from:
Fedschun T. Rare neon-blue waves attract crowds to California beaches, despite stay-at-home

orders. Fox News [Image on the internet]. 2020 May 12 [cited 2024 June 5]. Available from: <https://www.foxnews.com/us/rare-neon-blue-bioluminescent-waves-southern-california-beach-closure-stay-at-home>

Section D: Europe

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2. The images in **Q2** are sourced from:

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3. The images in **Q3** are sourced from:

- j.clarkson.photography. Aurora borealis [Online image]. Instagram; 2024 May 12 [cited 2024 June 10]. Available from: https://www.instagram.com/p/C6383n_qbI4/?img_index=1
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