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Undergraduate Natural Sciences B/C

Mathematics B Worked Solutions

Embassy recommendation 2016–2019

12 major problems / 47 questions Mathematics volume

Questions are not included. Use with the official papers.
Official public examination papers, 2016–2019

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Problem 6　2017 Mathematics B / 3

Official question PDF: page 3. Read alongside the original paper.

For the intersection of two perpendicular cylinders, a horizontal slice is a square. Derive that square from both cylinder inequalities before integrating; two circular-looking constraints do not make a circular slice.

3(1) A square horizontal section

Solution

Fix $z = t$. The two cylinder inequalities become

$$x^2 \le r^2 - t^2, \qquad y^2 \le r^2 - t^2.$$

For $-r \le t \le r$, let $s = \sqrt{r^2 - t^2}$. The permitted points form the square

$$-s \le x \le s, \qquad -s \le y \le s.$$

Its side length is $2s$, so

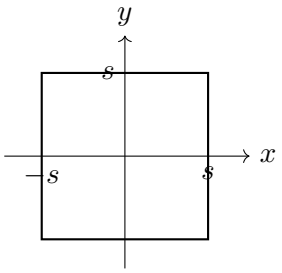
$$A(t) = (2s)^2 = 4(r^2 - t^2).$$

Answer $A(t) = 4(r^2 - t^2)$.

Explanation

Intersection, not union　Each point must satisfy both bounds. One cylinder restricts x and the other restricts y, so the common section is their Cartesian-product square.

A normalized section　The sketch uses $s = 1$. Its four corners all satisfy both cylinder bounds.



A diagnostic corner　The point (s, s) would fail the disk inequality $x^2 + y^2 \le s^2$, but it satisfies the actual pair of separate bounds. Replacing them by a disk is therefore not an innocent simplification; it removes valid points.

3(2) Volume of the common solid

Solution

Integrate the square area over its full vertical range:

$$V = \int_{-r}^{r} 4(r^2 - t^2)\,dt.$$

By symmetry and a polynomial antiderivative,

$$V = 8\int_{0}^{r} (r^2 - t^2)\,dt = 8\left[r^2 t - \frac{t^3}{3}\right]_0^r = 8\left(r^3 - \frac{r^3}{3}\right) = \frac{16}{3}r^3.$$

Answer $V = 16r^3/3$.

Explanation

A geometric upper bound The intersection lies inside a cube of side $2r$, whose volume is $8r^3$. The answer is two-thirds of that cube volume, consistent with the sections shrinking to zero at the top and bottom.

Track the symmetry factor The section formula already contains 4 from the square's side length. Restricting the integral to $0 \le t \le r$ adds a separate factor 2. Confusing those two factors commonly halves the volume.

What the question tests The integral is elementary once the right section is identified. A three-dimensional solid with curved boundaries does not automatically require cylindrical coordinates or a difficult multiple integral. Here the common z^2 in both inequalities suggests horizontal slices immediately.

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Chemistry Worked Solutions

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28 major problems / 156 answer fields Chemistry volume

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Problem 27 2019 Chemistry / VI

Official question PDF: page 6. Read alongside the original paper.

Acid–base extraction changes the charge of a compound and hence the layer in which it is preferentially retained. Keep the extracted ion distinct from the neutral compound recovered after the second reagent is added.

VI(1) Recovering aniline from the acidic layer

Solution

Aniline accepts a proton from hydrochloric acid:

$$C_6H_5NH_2 + H^+ \longrightarrow C_6H_5NH_3{}^+.$$

The resulting anilinium ion is retained in the aqueous layer. Adding sodium hydroxide removes that proton:

$$C_6H_5NH_3{}^+ + OH^- \longrightarrow C_6H_5NH_2 + H_2O.$$

The regenerated neutral aniline can then be extracted into ether.

Answer (3), aniline.

Explanation

Track two chemical forms The first aqueous layer contains the protonated form; the final ether layer contains the free amine. Reporting anilinium chloride as the recovered organic compound would stop the sequence one step too early.

Why hydrochloric acid selects the amine The nitrogen lone pair can accept a proton. Under this extraction scheme the other listed compounds do not become comparable water-soluble cations, so the amine is separated from them.

Extraction is an equilibrium separation Neutral and ionic forms have different preferences for the two solvents. The usual exam model treats this redistribution as an effective separation; it is not a claim that a single extraction gives literally zero solute in the other layer.

VI(2) Bicarbonate separates the carboxylic acid

Solution

Benzoic acid reacts with bicarbonate to form benzoate, carbon dioxide and water:

$$C_6H_5COOH + HCO_3{}^- \longrightarrow C_6H_5COO^- + CO_2 + H_2O.$$

Benzoate enters the aqueous phase. Acidifying this separated phase reverses its ionisation:

$$C_6H_5COO^- + H^+ \longrightarrow C_6H_5COOH.$$

The neutral benzoic acid is then recovered in ether.

Answer (1), benzoic acid.

Explanation

Bicarbonate is deliberately the weaker base It deprotonates the carboxylic acid effectively under these conditions, but does not extract phenol in the same way. Replacing it with a strong base at this stage would remove both acidic compounds and lose the intended separation.

Gas formation helps drive the reaction The initial proton transfer gives carbonic acid, which yields carbon dioxide and water. The written net equation makes both the acid–base change and the gas evolution visible.

Do not confuse salt and free acid The water-soluble intermediate is a benzoate salt. The answer requested after acidification and ether extraction is the parent acid, with $-\mathrm{COOH}$, not $-\mathrm{COO}-$.

VI(3) Strong base extracts phenol

Solution

After the carboxylic acid has been removed, sodium hydroxide converts phenol into phenoxide:

$$\mathrm{C_6H_5OH + OH^- \longrightarrow C_6H_5O^- + H_2O.}$$

This ion is transferred to the aqueous phase. Subsequent acidification regenerates neutral phenol:

$$\mathrm{C_6H_5O^- + H^+ \longrightarrow C_6H_5OH.}$$

The final ether extract therefore contains phenol.

Answer (2), phenol.

Explanation

The sequence distinguishes two kinds of acid Phenol remains after bicarbonate treatment but reacts with the stronger base. These observations are compatible: a compound need not react to the same extent with every base in order to be acidic.

Charge supplies the useful solubility change The neutral aromatic compound favours the organic solvent more strongly than its ionic salt does. Merely saying that phenol is soluble in one solvent misses the reason the reagent changes its layer.

The isolated aqueous layer must be treated Acid is added to the phenoxide-containing layer after it has been separated. Acidifying the original mixture without separation would regenerate the compounds together and would not accomplish the stated purification.

VI(4) The compound left in ether

Solution

Aniline has been removed by acid, benzoic acid by bicarbonate and phenol by hydroxide. Nitrobenzene remains neutral in this sequence and is retained in the final ether layer.

Answer (4), nitrobenzene.

Explanation

A nitrogen atom does not always imply an amine The nitrogen in a nitro group has a different bonding arrangement from that in $-NH_2$. Nitrobenzene therefore does not follow the protonation-and-extraction behaviour of aniline.

Elimination gives a complete material map The extracted fractions correspond in order to aniline, benzoic acid and phenol. Accounting for these three leaves exactly the fourth listed compound; none should appear as the main recovered compound in two different fractions.

The conclusion is specific to these reagents Remaining unchanged in an acid–base extraction does not mean nitrobenzene is chemically inert. Its nitro group can undergo a redox transformation, as the final part of this problem uses.

VI(5) Comparing the acidic compounds

Solution

Benzoic acid is the strongest acid among the four compounds. Its conjugate base is the benzoate ion:

$$C_6H_5COOH \rightleftharpoons H^+ + C_6H_5COO^-.$$

The negative charge of the carboxylate group is shared between two oxygen atoms through equivalent resonance contributors. This stabilisation makes proton loss more favourable than in phenol.

Answer (1), benzoic acid.

Explanation

Compare conjugate bases Both benzoate and phenoxide are resonance-stabilised, so saying only that one has resonance is insufficient. In a carboxylate the principal equivalent contributors keep the negative charge on oxygen atoms; the phenoxide comparison involves non-equivalent contributors extending into the ring.

The extraction results are an independent clue Bicarbonate removes benzoic acid but not phenol, whereas hydroxide removes phenol. That order supplies experimental evidence within the problem for the difference in acid strength.

Do not confuse acid strength with concentration The question compares the tendency of the molecular species to donate a proton under comparable conditions. The mass used or the volume of solvent is not an intrinsic measure of acid strength.

VI(6) Reduction changes nitrobenzene into aniline

Solution

Reduction converts an aromatic nitro group into an amino group without removing the benzene ring. The redox change can be represented by the half-equation

$$C_6H_5NO_2 + 6\,H^+ + 6\,e^- \longrightarrow C_6H_5NH_2 + 2\,H_2O.$$

Thus X is nitrobenzene and Y is aniline.

Answer X: (4); Y: (3).

Explanation

Check atoms and charge Both sides contain six carbons and one nitrogen. The two oxygen atoms appear in two water molecules; the six protons and six electrons balance both hydrogen and charge.

Reduction is not the extraction step Tin provides a route for changing the functional group. Acid–base extraction only interconverts protonated and unprotonated forms; it does not turn a nitro group into an amino group.

The isolated form depends on work-up In an acidic reduction mixture the amine may be present as anilinium. The compound identification is aniline after neutralisation, consistent with the free compound named in the options.

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Biology Worked Solutions

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20 major problems / 4 exam years Biology volume

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Problem 17 2019 Biology / II: cellular respiration and respiratory quotient

Official question PDF: page 5–7. Read alongside the original paper.

Passage 1 traces carbon, electrons and protons through respiration. Paired respirometers then separate oxygen uptake from net gas-volume change.

Solution

1. Respiration passage The three stages are **glycolysis** (L), the citric acid cycle and the **electron transport chain** (I). Glycolysis occurs in the **cytosol** (H) and converts glucose into **pyruvate** (W), a three-carbon compound. It neither requires **oxygen** (V) nor releases **carbon dioxide** (F).

Pyruvate is converted to **acetyl-CoA** (A), releasing carbon dioxide. Its acetyl group joins **oxaloacetate** (U) to form **citrate** (G). The cycle occurs in the mitochondrial **matrix** (R).

Electrons carried by NADH and **$FADH_2$** (J) enter the electron transport chain. Proton pumping creates a gradient between the matrix and the **intermembrane space** (O). The gradient drives **ATP** synthase to make ATP (D), while oxygen is reduced to **water** (X).

2. Carbon number One six-carbon glucose is split into two pyruvate molecules, each with three carbons. Therefore $a = 3$.

3. Glucose structure The correct displayed glucose structure is C, as recorded by the official key. Check the six-carbon aldose skeleton and the stereochemistry of the hydroxyl groups rather than relying on the drawing's overall silhouette.

4. Respiratory quotient KOH in flask A absorbs released CO_2, so its decrease is oxygen consumption. Flask B instead records $V_{O_2} - V_{CO_2} = 19$ mL. Therefore

$$V_{O_2} = 969 \text{ mL}, \qquad V_{CO_2} = 969 - 19 = 950 \text{ mL},$$
$$RQ = \frac{V_{CO_2}}{V_{O_2}} = \frac{950}{969} = 0.980\ldots \approx 0.98.$$

The answer is D.

5. Interpretation An RQ close to 1 indicates predominant carbohydrate use. Choice D, which says proteins were the respiratory substrate in this experiment, is therefore the incorrect statement.

Answer II–1 (1)–(14): L, I, H, W, V, F, A, U, G, R, J, O, D, X; II–2: 3; II–3: C; II–4: D (0.98); II–5: D.

Explanation

Direction check Flask B still contracts, so oxygen use exceeds carbon-dioxide release and the RQ must be just below 1, consistent with 0.98.

Problem 18 2019 Biology / III: circadian clocks and a sun compass

Official question PDF: page 7–10. Read alongside the original paper.

The actogram tests whether activity is driven directly by sunrise or by an internal oscillator. The orientation questions then combine the bird's internal time with the apparent position of the sun.

Solution

1. Reading the actogram Under constant light, activity onset continues but advances on successive days. Persistence without sunrise shows control by an endogenous circadian clock, and the advance means its free-running period is *shorter* than 24 hours. When light–dark cycles return, activity onset becomes synchronized with sunrise again.

Therefore B is incorrect because sunrise does not directly initiate every activity onset, and D is incorrect because the observed advance is not produced by a period longer than 24 hours. A, C and E are consistent with the record.

2. Orientation at the two marked dates At point (1), free running has shifted the bird's internal clock ahead of local solar time. A time-compensated sun compass then applies the wrong time correction to the observed sun, producing the westward choice D in the diagram. After several days back in a natural light–dark cycle, the clock is re-entrained; at point (2) the trained northward response returns, A.

3. Fixed artificial light The bird treats the eastern lamp as the sun while still applying time-of-day compensation.

- In the morning, the real sun would be east. Keeping that cue to the right gives north.
- At noon, the real sun would be south. Keeping the east lamp in the corresponding "behind" relation rotates the heading to west.
- In the evening, the real sun would be west. Keeping the east lamp in the corresponding left-side relation rotates the heading to south.

The north–west–south sequence is D.

Answer III–1: B and D; III–2: (1) D, (2) A; III–3: D.

Explanation

Slope gives period length In an actogram plotted against clock time, a daily onset that moves earlier has a period below 24 hours; an onset that moves later would indicate a period above 24 hours.

Entrainment and compass are separate operations Light–dark cycles set the clock's phase. The sun compass uses that clock to interpret a directional cue. A clock error can therefore rotate orientation even when the bird can see a clear light source.

Problem 19 2019 Biology / IV: ecosystem carbon flows and production

Official question PDF: page 11–12. Read alongside the original paper.

Treat each arrow as a carbon transfer: identify its source and destination before naming the process.

Solution

1. Atmospheric carbon into producers Arrow 1 moves carbon from atmospheric carbon dioxide into producers. The process is photosynthesis, E.

2. Other respiration arrows Like producer respiration at arrow 2, respiration by primary consumers, secondary consumers and decomposers is shown by arrows 3, 4 and 14.

3. Primary consumers The butterfly (A), honeybee (E) and rabbit (G) feed directly on producers. Dandelion and rice are producers; the other listed animals consume animals.

4. Gross production Net primary production is the producer carbon allocated to new growth or leaving producers as grazing and dead tissue:

$$NPP = 500 + 100 + 600 = 1200 \text{ g m}^{-2} \text{ year}^{-1}.$$

Gross primary production includes plant respiration:

$$GPP = NPP + R = 1200 + 1500 = 2700 \text{ g m}^{-2} \text{ year}^{-1}.$$

Thus E is correct.

5. Recent human amplification Arrow 13 transfers fossil-fuel carbon to atmospheric carbon dioxide. Combustion has greatly increased this flux, so the arrow is 13. The linked outcomes are an increased atmospheric carbon-dioxide concentration (C) and greenhouse warming of Earth's surface (D).

6. Marine ecosystem B and D are incorrect. Dissolved inorganic carbon exchanges with the atmosphere, and microscopic phytoplankton rather than large seaweeds perform most oceanic primary production. Carbonate formation and coral–zooxanthella symbiosis make C and E valid here.

Answer IV–1: E; IV–2: 3, 4 and 14; IV–3: A, E and G; IV–4: E (2700 g m^{-2} year^{-1}); IV–5: 13, C and D; IV–6: B and D.

Explanation

Production balance The calculation closes: $2700 - 1500 = 1200 = 500 + 100 + 600$, so every carbon flow in the table is accounted for.