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Topic 3.9: Separation of Solutions and Mixtures

Worksheet · AP Chemistry

UNIT 3 · PROPERTIES OF SUBSTANCES AND MIXTURES

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How to Use This Worksheet

Work in order. Section A checks the ideas: the two phases, polarity and boiling point. Section B builds R_f calculations, identification and choosing a technique. Section C combines chromatograms, columns and distillation in exam style.

Every chromatogram is described completely in words, with front and spot distances stated, so each question can be answered from the text alone.

Do not look at the answer key until you have attempted every question.

Section A: Recall and Concepts

A1. A paper chromatogram has a solvent front 9.0 cm from the baseline. It shows a red spot 2.7 cm from the baseline, a blue spot 5.4 cm, and a yellow spot 8.1 cm. The paper is polar cellulose. (a) Calculate the R_f value of each spot, showing each division. (b) Rank the spots by increasing attraction to the stationary phase, with a reason. (c) State which spot was most attracted to the mobile phase, and what its R_f shows. (d) State why no R_f value carries a unit, and why a value above 1.00 is impossible.

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A2. A polar dye and a nonpolar dye are spotted on polar cellulose paper. The mobile phase is a nonpolar solvent. (a) Predict which dye travels further, justifying it by the attraction holding the other dye back. (b) State where the dye that travels less sits relative to the baseline and the solvent front. (c) The solvent is changed to a polar one, everything else kept the same. Predict the effect on the polar dye, explained as a change in the competition between the phases. (d) State one other condition that must be kept the same before R_f values from the two runs can be compared.

A3. A student makes three mistakes. The baseline is drawn in ink. The paper is lowered so the baseline sits below the solvent surface. The paper is left until the front has run off the top edge. (a) Explain what the ink does once the solvent reaches it, and why the baseline should be pencil. (b) Explain what happens to the spotted mixture in the second mistake, and why no separation follows. (c) Explain why the third mistake makes every R_f value unusable, naming the lost measurement. (d) State the corrected position of the baseline relative to the solvent surface.

A4. A column is packed with polar silica. A mixture of a polar compound and a nonpolar compound is added at the top, and a nonpolar solvent is poured through. (a) State which compound elutes first, and which is collected in the later fraction. (b) Explain the order using attractions to the stationary phase and solubility in the mobile phase. (c) The solvent is changed to a more polar one part way through. State what this does to the compound still held in the column, and why. (d) State how this elution order compares with the order of distances on a TLC plate using the same two phases.

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A5. A mixture of ethanol, boiling point 78 °C, and water, boiling point 100 °C, both stated in the question, is heated in a distillation apparatus. (a) State which liquid vaporises first, and what the thermometer reads while it distils. (b) State what the condenser does, and what the collected liquid is richer in than the original mixture. (c) State which of the two has the highest vapour pressure at a given temperature, and link that to why it boils first. (d) State which attractions are overcome when the mixture boils, and which bonds inside the H_2O and C_2H_5OH molecules stay intact.

Section B: Core Practice

B1. On a TLC plate the solvent front reached 12.0 cm from the baseline. Three spots reached 3.6 cm, 7.2 cm and 9.6 cm. (a) Calculate the R_f value of each spot. (b) State the distance between the lowest and highest spots. (c) A fourth spot is reported with R_f = 1.25 on this plate. Calculate the distance that would imply, and state why the report must be wrong. (d) State which spot spent the greatest fraction of the run moving with the mobile phase, and how its R_f value shows it.

B2. Three known dyes and an unknown mixture are run on the same paper, under identical conditions, and the front reaches 7.5 cm. Dye P reaches 1.5 cm, dye Q reaches 4.5 cm, and dye R reaches 6.0 cm. The unknown separates into two spots, at 1.5 cm and 4.5 cm. (a) Calculate the R_f value of each known dye. (b) Calculate the R_f values of the two unknown spots. (c) State which known dyes the unknown appears to contain, and which is absent, with the matching evidence. (d) State why the matches are not proof of identity, and name one further test that strengthens the identification.

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B3. A dye is run twice on the same paper with the same solvent. In the first run the front reaches 6.0 cm and the spot reaches 4.2 cm. In the second run the front reaches 10.0 cm. (a) Calculate the R_f value in the first run. (b) Predict the spot distance in the second run, assuming identical conditions apart from the distance climbed, showing the calculation. (c) In a third run, with a different solvent, the front again reaches 10.0 cm but the spot reaches only 5.0 cm. Calculate the new R_f value. (d) Explain what the change in part (c) shows, and why R_f values from different solvents cannot be matched against a table from the first solvent.

B4. Two dyes, P and Q, are run on polar paper with two solvents. The front reaches 8.0 cm in every run. In a less polar solvent, P reaches 2.0 cm and Q reaches 6.4 cm. In a more polar solvent, P reaches 6.0 cm and Q reaches 6.8 cm. (a) Calculate all four R_f values. (b) State which dye changes more between the solvents, and calculate that change. (c) Deduce which dye is more polar, justifying it from the size of its change. (d) State which solvent separates the two dyes better, comparing the gap between their R_f values in each solvent.

B5. Three miscible liquids have boiling points stated in the question: X, 69 °C; Y, 78 °C; Z, 126 °C. (a) State the order in which they are collected, and which is left in the flask last. (b) Calculate the boiling point gap between X and Y, and between Y and Z. (c) State which pair separates well by simple distillation, and which pair needs a fractionating column, using the gaps from part (b). (d) Rank the liquids by strength of intermolecular forces, and name the one with the highest vapour pressure at a given temperature.

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B6. Four mixtures must be separated. Mixture 1 is sodium chloride dissolved in water, the solid being needed. Mixture 2 is sand in water. Mixture 3 is three soluble dyes. Mixture 4 is two miscible liquids with boiling points differing by 50 °C, stated in the question. (a) Name the best technique for mixture 1, and explain why filtration fails. (b) Name the best technique for mixture 2, and state what passes through and what stays behind. (c) Name the best technique for mixture 3, and state the property difference it uses. (d) Name the best technique for mixture 4, state which liquid is collected first, and what happens to the covalent bonds.

Section C: Exam Style

C1. A food colouring is run alongside three single known colourings, on the same paper with the same solvent. The front reaches 8.4 cm. The food colouring gives two spots, at 2.1 cm and 6.3 cm. The known colourings give single spots at 2.1 cm, 4.2 cm and 6.3 cm. (a) Calculate the R_f value of every spot described. (b) State which known colourings the food colouring appears to contain, and which it does not, with evidence. (c) Rank the known colourings by attraction to the stationary phase, strongest first. (d) A student writes that the food colouring is proved to contain the first and third colourings. Evaluate that claim, and describe one further run that tests it. (e) The run is repeated with the baseline below the solvent surface. Predict what is observed, and why no R_f values can be obtained.

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C2. On a TLC plate of polar silica, with a nonpolar solvent, the front reaches 9.0 cm. Compound A reaches 1.8 cm, compound B reaches 7.2 cm, and compound C reaches 4.5 cm. The same mixture, phases and solvent are then used in a column. (a) Calculate the R_f value of each compound. (b) Rank the compounds by polarity, most polar first, justifying it from travel on polar silica. (c) Predict the elution order from the column, first to last. (d) Explain the link between plate results and column order, in terms of time spent held. (e) The column solvent is switched to a more polar one. State which compound is affected most, and the effect on its elution time.

C3. Methane, ethane and propane are separated by fractional distillation. Their boiling points, stated in the question, are: CH_4, −162 °C; C_2H_6, −89 °C; C_3H_8, −42 °C. (a) State the order in which they are collected, first to last. (b) Calculate the boiling point gap between CH_4 and C_2H_6, and between C_2H_6 and C_3H_8. (c) Explain the order in terms of molecule size, polarizability and London dispersion forces. (d) State which compound has the strongest intermolecular forces and which has the highest vapour pressure at a given temperature, with a reason for each. (e) Explain what the fractionating column does, and why repeated condensation and vaporisation improve the purity of the first fraction.

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Answer Key

A1. (a) Red: 2.7 ÷ 9.0 = 0.30. Blue: 5.4 ÷ 9.0 = 0.60. Yellow: 8.1 ÷ 9.0 = 0.90. (b) Increasing attraction: yellow, then blue, then red. Red travelled least, so it spent most time held by the polar paper. (c) Yellow: it travelled 8.1 cm against a 9.0 cm front, so it spent most of the run moving with the mobile phase. (d) A ratio of two distances in the same unit has no unit. A spot cannot pass the front carrying it, so its distance can at most equal the front distance, giving at most 1.00.

A2. (a) The nonpolar dye travels further. The polar dye is held back by strong attractions, including hydrogen bonding, to the polar cellulose, while the nonpolar dye is held weakly and dissolves well in the nonpolar solvent. (b) Close to the baseline, far below the front, with a low R_f value. (c) The polar dye travels further and its R_f rises: a polar solvent dissolves it better and competes for it, so the mobile phase wins a larger share. (d) The stationary phase must be the same material, and the temperature must match.

A3. (a) Ink dyes dissolve in the solvent, climb the paper and separate into extra spots that hide the real ones. Pencil graphite is insoluble, so the baseline stays put and adds no spots. (b) The spotted dyes dissolve straight into the solvent pool. Diluted into the pool, they are never carried up the paper different distances, so no separation occurs. (c) R_f needs the front distance, which must be marked as soon as the paper is removed. Once the front has run off the top, it cannot be measured. (d) The baseline sits above the solvent surface, with only the bottom edge of the paper dipping in.

A4. (a) The nonpolar compound elutes first; the polar compound is in the later fraction. (b) Polar silica holds the polar compound strongly, so it spends most time held and moves slowly. The nonpolar compound is held weakly, dissolves in the nonpolar solvent, and is carried through quickly. (c) It elutes sooner: a more polar solvent dissolves it better and competes with the silica, so it spends less time held. (d) The orders are reversed: the compound travelling furthest on the plate leaves the column first, because both follow from weak holding.

A5. (a) Ethanol vaporises first, and the thermometer reads 78 °C while it distils, holding there until the ethanol has mostly boiled away before rising toward 100 °C. (b) The condenser removes thermal energy and turns the vapour back into a liquid, collected separately. That liquid is richer in ethanol than the original mixture, because the first vapour was richer in the more volatile component. (c) Ethanol: its molecules escape most readily, so it vaporises first. (d) Intermolecular forces between molecules are overcome. The covalent bonds inside H_2O and C_2H_5OH stay intact, because boiling is a physical change.

B1. (a) 3.6 ÷ 12.0 = 0.30; 7.2 ÷ 12.0 = 0.60; 9.6 ÷ 12.0 = 0.80. (b) 9.6 − 3.6 = 6.0 cm. (c) Distance = 1.25 × 12.0 = 15.0 cm, beyond the 12.0 cm front. A spot cannot travel further than the solvent carrying

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it, so the report is wrong. (d) The 9.6 cm spot, R_f = 0.80: it travelled 80% as far as the solvent, so it spent the largest share of the run in the mobile phase.

B2. (a) P: 1.5 ÷ 7.5 = 0.20. Q: 4.5 ÷ 7.5 = 0.60. R: 6.0 ÷ 7.5 = 0.80. (b) 1.5 ÷ 7.5 = 0.20 and 4.5 ÷ 7.5 = 0.60. (c) The mixture appears to contain P and Q, matching at 0.20 and 0.60. R is absent: no spot at 6.0 cm, where 0.80 would appear. (d) A match in one solvent is evidence only, because a different dye could share the value by coincidence. Repeating in a different solvent and checking the matches hold strengthens the identification.

B3. (a) 4.2 ÷ 6.0 = 0.70. (b) R_f is unchanged under identical conditions, so predicted distance = 0.70 × 10.0 = 7.0 cm. (c) 5.0 ÷ 10.0 = 0.50. (d) The dye travelled a smaller fraction of the front distance, so in the new solvent it is less well carried and spends more time held. R_f depends on the solvent, so values from different solvents cannot be matched.

B4. (a) Less polar solvent: P = 2.0 ÷ 8.0 = 0.25, Q = 6.4 ÷ 8.0 = 0.80. More polar solvent: P = 6.0 ÷ 8.0 = 0.75, Q = 6.8 ÷ 8.0 = 0.85. (b) P changes by 0.75 − 0.25 = 0.50; Q by 0.85 − 0.80 = 0.05. P changes more. (c) P is more polar: held strongly on polar paper in the less polar solvent, it was released by a more polar solvent, which dissolves and competes for a polar dye far better. Q was already carried well and barely changed. (d) The less polar solvent: its gap is 0.80 − 0.25 = 0.55, against 0.85 − 0.75 = 0.10. A larger gap means a cleaner separation.

B5. (a) X first, then Y, then Z; Z is left last. (b) X to Y: 78 − 69 = 9 °C. Y to Z: 126 − 78 = 48 °C. (c) Y and Z, gap 48 °C, separate well by simple distillation. X and Y, only 9 °C apart, would vaporise together and need a fractionating column. (d) Strongest to weakest forces: Z, then Y, then X, following the boiling points. X has the highest vapour pressure.

B6. (a) Evaporation, or distilling the water off. Filtration fails because dissolved ions pass through filter paper with the water. (b) Filtration: water passes through, insoluble sand stays on the paper. (c) Paper chromatography: each dye has a different balance of attraction to the stationary phase and solubility in the mobile phase, so they travel different distances. (d) Distillation, simple distillation being enough for a 50 °C gap. The lower boiling liquid is collected first. No covalent bonds are broken: only intermolecular forces are overcome.

C1. (a) Food colouring: 2.1 ÷ 8.4 = 0.25 and 6.3 ÷ 8.4 = 0.75. Known colourings: 0.25, 4.2 ÷ 8.4 = 0.50 and 0.75. (b) It appears to contain the first and third colourings, matching at 0.25 and 0.75. It does not contain the second: no spot appears at 4.2 cm. (c) Strongest attraction first: first (0.25), then second (0.50), then third (0.75). Least travel means most time held. (d) The claim overstates the evidence: matching values in one solvent are a likely match, not proof, since a different colouring could share a value. A run in a different solvent, checking that both matches hold, tests it. (e) The colourings dissolve off the baseline into the solvent pool. No spots climb or separate, and with no spot distances, no R_f values can be obtained.

C2. (a) A: 1.8 ÷ 9.0 = 0.20. B: 7.2 ÷ 9.0 = 0.80. C: 4.5 ÷ 9.0 = 0.50. (b) Most polar first: A, then C, then B. Polar silica holds the most polar compound most strongly, so A, travelling least, is most polar,

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and B is least polar. (c) B first, then C, then A. (d) A compound held for most of a plate run travels a short distance. In the column that compound is carried out slowest, so the distance ranking reverses into a time ranking. (e) A, held most strongly. The more polar solvent dissolves it better and competes with the silica, so its elution time falls most.

C3. (a) CH_4 first, then C_2H_6, then C_3H_8. (b) CH_4 to C_2H_6: $-89 - (-162) = 73$ °C. C_2H_6 to C_3H_8: $-42 - (-89) = 47$ °C. (c) All three are nonpolar, so only London dispersion forces act. CH_4 is smallest, with the fewest electrons and the least polarizable electron cloud, so its forces are weakest and it boils lowest. Forces strengthen as molecules grow, so boiling points rise from CH_4 to C_3H_8. (d) C_3H_8 has the strongest forces: it needs the most energy to vaporise and boils last. CH_4 has the highest vapour pressure, because its weak forces let molecules escape most readily. (e) The column gives a large surface where vapour condenses and vaporises again many times. Each cycle enriches the vapour in CH_4 and returns less volatile material downwards, so the vapour reaching the condenser is far purer than one vaporisation would give.

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