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Topic 3.2: Properties of Solids

Worksheet · AP Chemistry

UNIT 3 · PROPERTIES OF SUBSTANCES AND MIXTURES

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How to Use This Worksheet

Work through the sections in order. Section A checks the ideas, Section B builds fluency with radii, densities, melting point data and identifications, and Section C mixes everything in exam style.

Use the same two questions for every substance in this worksheet. First, what are the particles: ions, atoms in a continuous network, whole molecules, or cations in an electron sea? Second, what holds them together, and what would melting, conducting or deforming do to that holding force? Settle those two, and each property follows.

Do not look at the answer key until you have attempted every question. The key gives full working, so compare your reasoning, not just your final answer.

Section A: Recall and Concepts

A1. (a) Name the four types of solid studied in this topic. (b) For each type, state the particles it is built from and what holds those particles together. (c) State which one is a single continuous structure with no individual molecules.

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A2. Sodium chloride is made entirely of charged particles, Na^+ and Cl^-. (a) Explain why solid sodium chloride does not conduct electricity. (b) State what changes when sodium chloride melts, and name the particles that carry the current in the melt. (c) A student says the melt conducts because electrons can finally flow through it. Correct the statement.

A3. (a) Define a crystalline solid and an amorphous solid, in terms of particle arrangement. (b) Give one example of each. (c) Explain why a crystalline solid melts sharply at one temperature, while an amorphous solid softens over a temperature range.

A4. Graphite and diamond are both pure carbon, and both are covalent network solids. (a) Describe the arrangement of carbon atoms in diamond and in graphite. (b) Explain why graphite conducts electricity but diamond does not. (c) Explain why graphite is used as a lubricant, while diamond tips are used on cutting tools.

A5. Brass is copper with zinc in its lattice; steel is iron with carbon in its lattice. (a) State which alloy is substitutional and which is interstitial. (b) State the size rule that decides which pattern an alloy follows. (c) Explain why both alloys are harder than the pure metals they are made from.

Section B: Core Practice

B1. Ionic radii: Mg^{2+} 72 pm, Ca^{2+} 100 pm, Na^+ 102 pm, O^{2-} 140 pm, Cl^- 181 pm. (a) Calculate the distance between neighbouring ion centres in MgO and in NaCl. (b) Take the attraction between neighbouring ions as proportional to (charge product) ÷ (separation)^2. Calculate the ratio of the attraction in MgO to the attraction in NaCl. (c) MgO melts at 2852 °C and NaCl at 801 °C. Calculate the difference between the melting points, and explain how your ratio in (b) accounts for MgO melting so much higher. (d) Use the same model on CaO: calculate its ion separation and attraction

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ratio to MgO, predict whether it melts above or below 2852 °C, and check against its actual melting point, 2572 °C.

B2. The density of liquid water is 1.00 g/cm³ and the density of ice is 0.917 g/cm³. (a) Calculate the volume occupied by 250 g of liquid water, and the volume of the ice it forms on freezing. (b) Calculate the percentage increase in volume when the water freezes. (c) Explain the increase in terms of the arrangement of water molecules in ice. (d) Using the two densities, state approximately what percentage of a floating iceberg's volume sits below the surface.

B3. Metallic radii: copper 128 pm, zinc 134 pm, silver 144 pm, iron 126 pm. The radius of a carbon atom is about 77 pm. As a rule of thumb, substitutional alloying needs the two radii to be within about 15% of each other. (a) Calculate the percentage difference between the zinc and copper radii, and between the silver and copper radii. (b) State which of zinc and silver can form a substitutional alloy with copper, justifying your answer with the percentages. (c) Calculate the percentage by which a carbon atom is smaller than an iron atom, and explain why carbon forms an interstitial alloy with iron instead. (d) Explain why brass, once formed, is harder than pure copper.

B4. Melting points: ice 0 °C, NaCl 801 °C, copper 1085 °C, quartz (SiO_2) 1713 °C, MgO 2852 °C. (a) Rank the five solids by melting point, lowest first, and name the type of each. (b) Quartz melts 1713 °C above ice, yet SiO_2 and H_2O are both covalent substances. Explain the difference. (c) A student claims that every ionic solid melts above every metallic solid, because ionic attractions are stronger than metallic ones. Use the data to evaluate the claim. (d) State what the ranking in (a) actually measures, if it is not a ranking of solid types.

B5. Four solids are tested. W: melts at 801 °C, does not conduct as a solid, conducts when molten, shatters under a hammer blow. X: shiny grey, conducts as a solid, bends without breaking, insoluble in water. Y: melts at 114 °C, conducts in no state, slowly sublimes at room temperature. Z:

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melts at 1713 °C, extremely hard, conducts in no state, insoluble in water. (a) Classify each solid, giving two pieces of evidence for each classification. (b) W and Y are stirred into separate beakers of water. State, with a reason, which beaker's water becomes able to conduct electricity. (c) State which solid's melting requires covalent bonds to break, and which solid's melting overcomes only intermolecular forces.

B6. A hammer blow knocks a layer of particles sideways by one particle spacing in two solids. (a) The first solid is ionic. Explain, in terms of charges, why it splits along the shifted plane instead of deforming. (b) The second solid is a metal. Explain why it bends instead, and state the electron sea's role. (c) The metal is then alloyed. Explain why the alloyed metal bends less easily under the same blow. (d) A student writes: "Metals bend easily because metallic bonds are weak." Iron melts at 1538 °C. Use that fact to explain what is wrong with the student's reason.

Section C: Exam Style

C1. Three white solids sit in unlabelled jars: sucrose, $C_{12}H_{22}O_{11}$, melting point 186 °C; sodium chloride, 801 °C; quartz, SiO_2, 1713 °C. (a) Classify each solid, and state what holds each one together. (b) Explain the order of the melting points in terms of what melting must overcome in each solid. (c) For each solid, state whether it conducts electricity as a solid, when molten, and dissolved in water (where it dissolves at all). Give a reason for molten sodium chloride and for a sucrose solution. (d) A student writes: "Sodium chloride conducts when molten because melting completely breaks its ionic bonds." Evaluate this statement.

C2. Copper wire bends easily; brass, a copper and zinc alloy, is noticeably harder; steel, iron with a little carbon, harder still. Metallic radii: copper 128 pm, zinc 134 pm, iron 126 pm; a carbon atom's radius is about 77 pm. (a) Explain why pure copper bends easily, in terms of its layers and its electron sea. (b) Calculate the percentage difference between the zinc and copper radii, state the

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alloy pattern brass follows, and explain why brass is harder than copper even though its atoms sit on the same lattice sites. (c) Calculate the percentage by which carbon is smaller than iron, state the alloy pattern steel follows, and explain why a small percentage of carbon hardens iron so much. (d) A student writes: "Brass is a compound of copper and zinc with a fixed formula." Identify the two errors.

C3. Graphite, diamond and glass are all network materials, but they behave very differently. (a) Graphite and diamond are both crystalline forms of carbon. Explain why graphite conducts electricity while diamond does not. (b) A graphite pencil leaves a dark line on paper, while a diamond tipped drill cuts through rock. Explain both facts from the bonding in each solid. (c) Window glass is mostly SiO_2, like quartz, but glass is amorphous. Explain why quartz melts sharply at 1713 °C while glass only softens over a wide temperature range. (d) A student groups the three as "all the same, because all are networks." Give two observations that show this grouping hides more than it reveals.

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Answer Key

A1. (a) Ionic, metallic, covalent network and molecular. (b) Ionic: alternating cations and anions, held by electrostatic attraction. Metallic: cations, held in a sea of delocalized electrons. Covalent network: atoms, held by covalent bonds running through the whole structure. Molecular: whole molecules, held by intermolecular forces. (c) The covalent network solid: its bonding never stops at a molecule boundary, so the whole crystal is one continuous structure.

A2. (a) Conduction needs charged particles that can move; in the solid the ions are locked in fixed lattice positions, so no charge travels. (b) Melting frees the ions; the mobile Na^+ and Cl^- ions carry the current. (c) No electrons flow in the melt: the ions move. Electron flow is the metallic mechanism; ionic conduction is charged particles moving.

A3. (a) Crystalline: particles in a regular, repeating, long range order. Amorphous: order only over short distances, no repeating long range lattice. (b) Crystalline: sodium chloride (also quartz, ice). Amorphous: glass (also many plastics). (c) In a crystal every particle sits in the same environment, held by the same forces, so one temperature defeats them all at once. In an amorphous solid the arrangements vary, so softening spreads over a range of temperatures.

A4. (a) Diamond: every carbon bonded tetrahedrally to four others, one continuous three dimensional network. Graphite: carbons bonded in flat layers, three bonds within each sheet. (b) Graphite's layer bonding leaves delocalized electrons free to move along the layers and carry a current; in diamond every valence electron is locked in a covalent bond, so no carrier can move. (c) Only weak dispersion forces hold graphite's layers together, so they slide and smear: slippery. Diamond's network runs at full strength in every direction, with no weak planes, making it extremely hard.

A5. (a) Brass is substitutional; steel is interstitial. (b) Guests near the host's radius take host sites; far smaller guests sit in the gaps. (c) The guests disturb the regular rows, so layers no longer slide smoothly and the metal resists deformation.

B1. (a) MgO: 72 + 140 = 212 pm. NaCl: 102 + 181 = 283 pm. (b) MgO: $(2 \times 2) \div 212^2 = 4 \div 44{,}944$. NaCl: $(1 \times 1) \div 283^2 = 1 \div 80{,}089$. Ratio = $4 \times 80{,}089 \div 44{,}944 \approx 7.1$: a neighbouring ion pair in MgO attracts about seven times as strongly. (c) 2852 - 801 = 2,051 °C. Both Coulomb factors favour MgO: double charges multiply the charge product by four, and smaller ions sit closer, growing the $1 \div \text{separation}^2$ term. A lattice held seven times as strongly per pair needs far more thermal energy to loosen. (d) CaO: 100 + 140 = 240 pm. Its charges match MgO's, so they cancel: attraction ratio, CaO to MgO = $(212 \div 240)^2 \approx 0.78$. CaO should melt below MgO, and it does: 2572 °C against 2852 °C. With charges tied, the bigger cation alone weakens the lattice.

B2. (a) Liquid: $250 \div 1.00 = 250$ cm³. Ice: $250 \div 0.917 = 273$ cm³ (272.6 cm³). (b) Increase 22.6 cm³; $22.6 \div 250 \times 100 = 9.1\%$. (c) In the liquid, molecules tumble and pack closely; in ice, each is locked

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by hydrogen bonds into an open hexagonal network at full bond length, taking more space. (d) The submerged fraction equals the density ratio: 0.917 ÷ 1.00 = 0.917, about 92% below the surface.

B3. (a) Zinc: (134 - 128) ÷ 128 × 100 = 4.7%. Silver: (144 - 128) ÷ 128 × 100 = 12.5%. (b) Both can: both percentages fall inside the 15% window, so either atom can take a copper site; zinc is the closer fit. (c) (126 - 77) ÷ 126 × 100 = 38.9% smaller, far outside the substitution window, so carbon occupies the gaps (interstices) between iron atoms. (d) Zinc atoms are slightly larger than the copper atoms they replace, distorting the neat rows; sliding a distorted row past its neighbours takes more force, so the alloy resists deformation.

B4. (a) Ice 0 °C (molecular), NaCl 801 °C (ionic), copper 1085 °C (metallic), quartz 1713 °C (covalent network), MgO 2852 °C (ionic). (b) Melting ice only overcomes the hydrogen bonds and other intermolecular forces between discrete H_2O molecules. Quartz has no SiO_2 molecules: one continuous covalent network, so melting must break covalent bonds, at far greater energy cost. (c) It fails: ionic NaCl melts at 801 °C, below metallic copper at 1085 °C. Type sets the mechanism, not a guaranteed strength: MgO's doubled charges top the list; copper's metallic bonding beats NaCl's lattice. (d) It measures how strongly each solid is held together: the attraction its melting must loosen.

B5. (a) W is ionic: it conducts only when molten, its ions then mobile, and it shatters because a shifted lattice aligns like charges. X is metallic: solid state conduction needs mobile electrons, and bending means layers slide rather than split. Y is molecular: it melts low and conducts in no state, having no charged particles; it is iodine. Z is a covalent network solid: extreme hardness and melting point, since melting breaks covalent bonds, and no conduction; it is quartz. (b) W's beaker: W dissolves into free moving ions, so its solution conducts. Y dissolves as intact neutral molecules, which cannot carry current. (c) Z breaks covalent bonds; Y overcomes only intermolecular forces.

B6. (a) Shifting a layer by one spacing brings cations face to face with cations, anions with anions, along the plane; the repulsion pushes the halves apart and the crystal cleaves. (b) Each cation is attracted to the electron sea as a whole, not to fixed neighbours. When the layer slides, the sea shifts with it and every cation is still attracted in its new position, so no repulsion plane forms: the metal changes shape instead. (c) Guests of a different size distort the rows or sit in the gaps, so a sliding layer catches and needs more force to move. (d) Melting point tests holding strength, so weak bonding would mean a low melting point; iron survives to 1538 °C, so its bonding is strong. Its malleability comes from the bonding being not directional: the attraction survives the sliding.

C1. (a) Sucrose: molecular, whole $C_{12}H_{22}O_{11}$ molecules held by intermolecular forces, hydrogen bonds among them. Sodium chloride: ionic, Na^+ and Cl^- in a lattice held by electrostatic attraction. Quartz: covalent network, silicon and oxygen held by covalent bonds in one continuous structure. (b) Sucrose melts by separating molecules, defeating only intermolecular forces: 186 °C. NaCl must loosen a lattice of full charges attracting in every direction: 801 °C. Quartz must break covalent

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bonds themselves: 1713 °C. The melting order is the order of what is defeated: forces between molecules, ionic attractions, covalent bonds. (c) Sucrose conducts in no state: neutral molecules throughout. NaCl does not conduct as a solid (ions locked), but does when molten and in solution (ions free to move), the freed ions carrying the charge themselves. Quartz conducts in neither state, and does not dissolve. A sucrose solution cannot conduct: dissolving separates neutral molecules and forms no ions, leaving nothing to carry a current. (d) Half right. Melting does destroy the lattice's fixed order, freeing the ions to move and conduct. But the attractions are not completely broken: the melt is still Na^+ and Cl^- pulling strongly on each other, which is why it stays a dense liquid, not a gas. Conduction needs mobile ions, not destroyed ones.

C2. (a) Copper's cations sit in a sea of mobile electrons and are attracted to the sea, not to fixed neighbours. When a layer slides, the sea shifts with it and the cations remain attracted in their new positions, so layers slide rather than the structure splitting. (b) (134 - 128) ÷ 128 × 100 = 4.7%. The radii are close, so zinc takes copper's lattice sites: substitutional. Each zinc is slightly larger than the copper it replaces, pushing its row out of line; sliding a crooked row takes more force than a straight one, so brass is harder. (c) (126 - 77) ÷ 126 × 100 = 38.9% smaller. Too small to take an iron site, carbon sits in the gaps: interstitial. Wedged there, carbon atoms distort the lattice and block layers from sliding in any direction, so a little carbon hardens iron a lot. (d) Brass is not a compound: no new substance forms, just one metal lattice with guest atoms in it. And it has no fixed formula: the copper to zinc ratio, and the properties, vary between samples.

C3. (a) In graphite each carbon bonds to three others in flat layers, leaving delocalized electrons free to move along the layers and carry current. In diamond each carbon bonds to four others in a three dimensional network, every valence electron held inside a bond, so no carrier can move. (b) Only weak dispersion forces hold graphite's layers together, so rubbing shears layers off onto the paper: the line is graphite. Diamond has no weak direction: bonds at full strength everywhere, harder than the rock, so the rock fails first. (c) Quartz is a regular repeating network, every silicon and oxygen in the same environment, so one temperature defeats the bonding throughout and melting is sharp. Glass has the same kinds of bonds in an irregular arrangement, a range of environments and strengths: the weakest regions loosen first, the rest follow gradually, so it softens over a range. (d) Conductivity: graphite conducts, diamond and glass do not, although all three are networks, because graphite's layered bonding frees electrons and theirs locks them into bonds. Melting: quartz and diamond melt sharply, while glass has no melting point and only softens, lacking a crystal's long range order. "Network" names a bonding pattern; its arrangement decides the properties.

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