Problem 1:

(a) Show how the β-ZnS and NaCl crystal structures are derived from the FCC by filling selected interstitial sites in the FCC unit cell.

(b) Many compound semiconductors have the β-ZnS structure, while the NaCl structure is common in ionic insulators. Explain in terms of the probable bond type.

(c) The plane of easiest cleavage for a material with the diamond cubic structure is usually {111}. Materials with the β-ZnS structure cleave most easily along {111} or {110}. Materials with the NaCl structure cleave on {100}. Why might you expect this?

(d) Elements that crystallize in the β-ZnS structure tend to have lower values of Poisson's ratio (ν), than those that crystallize in the NaCl structure. Why?

(e) The mineral calcium flourite has the stoichiometric formula CaF$_2$. The Ca$_2$ atoms form an FCC array and each F atom has exactly four Ca neighbors. Suggest a possible crystal structure for CaF$_2$.

Problem 2:

(a) Consider a binary system that contains two components, A and B. Component A has an FCC structure in its pure state while component B is BCC. The simplest possible binary phase diagram for the system is a eutectic diagram. Why? Sketch the phase diagram and label the phase fields.

(b) Given a temperature and composition (T,x) of the phase diagram in (a) it is possible to extract three pieces of information from the phase diagram: the phases present at (T,x), the compositions of the phases, and the fractions of the phases. Describe how.

(c) If a polygranular sample of the A-rich solution, α, is cooled into the two-phase, α+β, region the kinetics of precipitation of β are described by the kinetic diagram given below, where τ is the time required to initiate the transformation and ΔT is the undercooling below the temperature at which β precipitation becomes thermodynamically possible.

If the material is cooled as indicated by the upper arrow, the final microstructure contains nuclei of β almost exclusively in the grain boundaries of the α grains. Why might you expect this?
(d) If the material is cooled and then heated, as indicated by the lower path in the figure, the final microstructure consists of a dense distribution of $\beta$ precipitates in the interiors of the $\alpha$ grains. Why?

**Problem 3:**

Explain the following observations regarding the thermal conductivity of materials:

(a) The valence electrons in a metal are energetic particles that wander throughout the metal at high velocity. Nonetheless, they contribute very little to the heat capacity of the metal.

(b) While they contribute very little to the heat capacity of a metal, the valence electrons are almost completely responsible for its thermal conductivity. The thermal conductivity increases with the electrical conductivity.

(c) But the highest room temperature thermal conductivity is found in diamond, which is an insulator with almost no electrical conductivity.

(d) When diamond transforms to the more stable form of carbon, graphite, its electrical conductivity rises dramatically, but its thermal conductivity decreases.

(e) But other good insulators, such as silica glass, have such low values of the thermal conductivity at room temperature that they are used as thermal insulators.

**Problem 4:**

(a) Define the *Fermi energy*, $E_F$, of a material. Given its definition, show that a semiconductor behaves as an n-type extrinsic semiconductor if $E_F$ is significantly greater than the energy at the mid-point of the band gap, and as a p-type extrinsic semiconductor if $E_F$ is significantly below the mid-point of the band gap.

(b) Illustrate the behavior of the band structure at a junction between n-type and p-type semiconducting material and describe (briefly and qualitatively) how the band structure produces an asymmetry in the conduction characteristics of the junction.

(c) Some materials function as *photoconductors* in the sense that their normal conductivities are very low, but increase dramatically when they are illuminated with visible light. Explain how a semiconductor can behave as a photoconductor, and why a good photoconductor is opaque to visible light.

**Problem 5:**

(a) Materials that have exceptionally high values of the shear modulus, $G$, are invariably hard at ordinary temperatures. Why?

(b) Structural materials that are intended for service at very low temperature are often strengthened by adding interstitial solutes, for example, nitrogen in austenitic (FCC) steels. These alloys are relatively weak above room temperature, but exhibit a rapid increase in strength as the temperature is dropped to low values. Explain.

(c) Structural materials that are intended for service at very high temperatures are usually strengthened by precipitation hardening, using precipitates that involve substitutional solute species.
Examples include the Fe-based and Ni-based 'superalloys' used in jet engines, which are strengthened by precipitates of intermetallic compounds such as Ni3Ti. Why choose precipitation hardening? Why should the precipitates employ substitutional solutes?

**Problem 6:**

(a) A good, ductile metal fails in tension when the applied tensile stress exceeds a critical value called the ultimate tensile stress, $\sigma_u$, which is a reproducible material property. Describe the mechanism that produces the ultimate tensile stress. If you were assigned to improve the ultimate tensile stress, what material property would you attempt to change?

(b) Assume a small flaw in a ductile metal part that grows with time, for example, by fatigue. Describe and illustrate how the maximum tensile stress the part can withstand changes as the flaw grows. Suggest why it is often acceptable engineering practice to consider only the yield stress, $\sigma_Y$, and ultimate stress, $\sigma_U$, when designing a part.

(c) Assume a brittle fracture mode in a basically ductile metal. How would you approach the problem of improving the fracture toughness?

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**MSE 200A**

Survey of Materials Science

Fall, 2001

Final Exam

**Problem 1:**

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(e) The mineral calcium flourite has the stoichiometric formula CaF$_2$. The Ca atoms form an FCC array and each F atom has exactly four Ca neighbors. Suggest a possible crystal structure for CaF$_2$.

**Problem 2:**

(a) Suppose a one-component system has only three equilibrium phases: gas (g), liquid (l), and crystalline solid (s). At atmospheric pressure these phases are assumed in the sequence $s \rightarrow l \rightarrow g$ as the temperature is raised at low pressure. Explain this behavior in terms of the expected relative energies and entropies of the three phases (assume the pressure is low enough that the pv term in the Gibbs free energy can be neglected), and provide a simple illustrative sketch of the variation of free energy with temperature.
(b) The liquid phase can be cooled some distance below its melting point, $T_m$, before crystallizing to (s). Explain this behavior in terms of the nucleation-and-growth mechanism of a structural phase transformation. Why is there a thermodynamic barrier to the formation of a nucleus?

(c) A liquid phase will ordinarily solidify into a crystalline solid if cooled slowly, but may form a glass if cooled very rapidly. Explain this observation in terms of the relative kinetics of crystallization and glass formation.

(d) If a typical crystalline semiconductor is melted and then quenched into a glassy state its conductivity increases significantly (it may even become metallic). However, if a typical crystalline metal is melted and quenched into a glassy state, its conductivity decreases significantly. Interpret this phenomenon.

Problem 3:

Explain the following observations concerning oxidation and corrosion:

(a) While very fine particles of iron can burn spontaneously in air (for example, the sparks thrown off during the machining of steel), a bulk sample of iron oxidizes at a negligible rate unless the temperature is very high.

(b) If the same bulk sample of iron is immersed in damp soil, it oxidizes (rusts) fairly quickly.

(c) If a bulk sample of iron is immersed in damp soil very near a piece of zinc, the iron corrodes just as it would if the zinc were not there. But if the iron is connected to the zinc by a thin metal wire, the iron immediately stops corroding, and is protected from further corrosion until the zinc has corroded away.

(d) While Fe rusts easily in damp soil, Au does not; nuggets of pure gold last almost indefinitely in the earth.

(e) Fe, also, remains bright and uncorroded for long periods of time in moist air and some damp soils, if it is alloyed with more than 8% Cr.

Problem 4:

To turn a piece of single crystal silicon into a functional semiconducting device, such as an n-p-n bipolar transistor, it is necessary to achieve a high-purity silicon starting material, add chemically appropriate dopants in the proper places, and keep them there.

(a) The silicon crystal that is the starting material for an n-p-n junction that is to be used at room temperature has a band gap of moderate size (1.1 eV), and can be made so that it is chemically very pure. Why are these properties important?

(b) Suppose that the Si starting material has an unacceptably high level of impurities. A much purer Si can usually be made by re-melting the starting material and re-solidifying it under controlled conditions. Why and how does this method work?

(c) Si is made n-type by adding a donor, such as P, and is made p-type by an acceptor, such as B. Since boron is difficult to extract from Si, Si crystals often contain a moderate boron content as-received.
Assuming this makes them p-type, how can P be used to change the dominant carrier type in the regions that are to be n-type?

(d) Give a rough schematic drawing of the band structure of an n-p-n device, indicating the position of the Fermi level in each of the three regions when no external voltage is imposed. Explain.

(e) Explain how an n-p-n device can be made to function as a switch by controlling the voltage on the intermediate, p-type layer. Why is the p-type layer made thin?

**Problem 5:**

Visible light spans a range of wavelength between 0.4-1.0 μm, corresponding to a photon energy between $\approx 1.2$ eV and $\approx 3$ eV.

(a) An old practical test says that if you can see through a piece of material, it is almost certainly a good insulator. Why?

(b) Why the modifier "almost"? How can a transparent material fail to be a good insulator?

(c) On the other hand, there are many good insulators that you cannot see through, including both opaque ceramics and brightly colored plastics. Describe at least one possible microstructure that creates an opaque insulator.

(d) The “optical fibers” that are commonly used to transmit information in optical form are often opaque and metallic in appearance, as are most of the lasers (such as GaAs) that are used to create and process optical signals. Why isn’t this surprising?

**Problem 6:**

When I first came to Berkeley there was a major problem with bicycle theft on the campus (there probably still is, but I don’t hear as much about it). The bicycle locks that were readily available at that time were the product of a more innocent age, and were made of reasonably tough steel. Motivated bicycle thieves discovered that they could be easily and quickly cut with long-handed bolt cutters (tools that resemble snub-nosed scissors, with long handles for leverage).

(a) In designing a bolt cutter for efficient bicycle theft, it is important that the blades of the scissors be made to be much harder than the chains or lock-bolts that are to be cut. Why?

An obvious defense against the bolt cutter was the use of chains and lock bolts that were themselves hardened to very high strength. However, this proved a temporary solution. Sophisticated thieves quickly learned that hardened chains and lock-bolts can be broken with a hammer, particularly if they are first swathed with a bit of the liquid nitrogen that is widely available on campus.

(b) Why does hardening risk fracture? Why would liquid nitrogen help?

The current solution is metallurgically more sophisticated, and involves the use of "case-hardened" chains and bolts. These are made of relatively soft steel, but have a surface layer (the "case") that is hardened to very high strength to protect the softer steel "core".

(c) Discuss how a "case-hardened" chain can provide an effective defense against both hammers and bolt-cutters, and suggest how you might make such a material.
Problem 1:

A material has the composition $A_3B$, and, at room temperature, has the $Cu_3Au$ crystal structure. Provide brief explanations for the following observations.

(a) The material is a metallic conductor (show that it cannot be ionic or covalent in its bonding).

(b) Both its electrical and thermal conductivities decrease as temperature rises.

(c) The material is opaque to visible light. However, it is transparent to x-rays, unless the x-rays have energies very close to one of a few discrete values.

(d) At high temperature the structure becomes disordered; the material transforms into a random solid solution of $A$ and $B$ atoms on an FCC lattice.

(e) When the material disorders, its electrical resistance increases, its elastic modulus decreases, and its yield strength decreases.

Problem 2:

The phase diagram of the Pb-Sn binary system is shown above.

(a) As reflected in the phase diagram, Pb and Sn can form solutions at all compositions in the liquid state, but not in the solid state. Why?

(b) The solubility of Sn in the Pb-rich $\alpha$ phase increases with temperature (at least a low temperature). Why would you expect this?
(c) Suppose you are given a sample that has composition 20Sn-80Pb, but need a sample that has precisely the eutectic composition. How could you obtain it?

(d) If material of precisely eutectic composition is solidified, it forms the classic eutectic microstructure. Describe this microstructure and explain, briefly, why it forms.

(e) Suppose you have a sample of Pb-Sn that has the eutectic composition, and need it to have a microstructure that has equiaxed grains of the $\alpha$ and $\beta$ phases. How might you obtain it?

**Problem 3:**

![Diagram of MOSFET](image)

This figure shows a typical configuration of a metal-oxide-semiconductor field effect transistor (MOSFET). The drawing shows a positive voltage at the metal gate, which activates the inversion layer, or channel, in the underlying semiconductor.

(a) Using simple band diagrams, describe how a MOSFET works. In particular, explain why the current that flows between source and drain is negligible when the gate voltage is zero, but is significant when the gate voltage is large and positive.

(b) It is often desirable to have an oxide of exceptionally high dielectric constant in a MOSFET. Ferroelectric materials are good choices. Describe the mechanism of ferroelectricity and explain why it leads to a high dielectric constant.

(c) Suppose the semiconductor were a photoconductor, and the gate were replaced by a light source. Describe the behavior of the current from source to drain as the light is turned on and increased in intensity. What assumption must you make about the wavelength of the light?

**Problem 4:**

Simple ferromagnetic materials, like Fe, Ni and Co, are ferromagnetic at low temperature essentially because their atoms have net magnetic moments that align with one another.

(a) If a ferromagnetic material that has previously been magnetized is placed in a magnetic field, $H$, its magnetization, $M$, will trace out a "magnetic hysteresis loop" like that shown above as the field is cycled between large positive to large negative values. Explain the hysteresis in terms of the magnetic microstructure and its response to the magnetic field.
(b) How do the hysteresis curves of "hard" and "soft" magnetic materials differ? Identify a technological application for which one would want a "hard" magnet, and one for which one would want a "soft" magnet.

(c) How might you make a ferromagnetic material "harder"?

(d) Describe “antiferromagnetism”.

(e) Some antiferromagnetic materials (such as ferrites like lodestone) have net magnetic moments. How can this be?

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Problem 5:

(a) It is enormously difficult to make aluminum alloys that have strengths equal to even moderately high strength steel. In fact, when an Al alloy has a microstructure that is essentially identical to that of a steel, its yield strength will ordinarily be only about 1/3 as high. Why might you expect this?

(b) Structural materials that are intended for service at very low temperature are often strengthened by adding interstitial solutes, for example, nitrogen in austenitic (FCC) steels. These alloys are relatively weak above room temperature, but exhibit a rapid increase in strength as the temperature is dropped to low values. Explain.

(c) Structural materials that are intended for service at very high temperatures are usually strengthened by precipitation hardening, using precipitates that involve substitutional solute species. Examples include the Fe-based and Ni-based 'superalloys' used in jet engines, which are strengthened by precipitates of intermetallic compounds such as Ni₃Ti. Why choose precipitation hardening? Why should the precipitates employ substitutional solutes?

Problem 6:

Alvin Underfoot, a random undergraduate, supported himself, in part, from the modest profits of a small consulting business in which he applied what he had learned in E45 to solve the problems of the world. Since virtually no one had ever heard of him, his list of potential clients was not large. On the other hand, he was admirably qualified to offer complete confidentiality to those who made use of his services. For precisely this reason, Alvin's services were retained by a famous and accomplished superheroine with an unfortunate personal problem. She is, she tearfully confessed, an incurable exhibitionist. Even when flying on her many missions of mercy, she cannot bear to conceal herself from her admiring public, but insists on piloting transparent glass aircraft. These have an unfortunate proclivity to disintegrate in mid-air, a circumstance that has made her into an unusually proficient parachutist, but at considerable cost in bruises and broken bones. Since she is not, by training, a material girl, she needs a dedicated materialist to help her make her aircraft more reliable.

Her immediate problem concerned her available aircraft, made of the finest high-temperature glass, which were needed for immediate missions. How might they be made more resistant to fracture? In response, Alvin first explained why glass is brittle and, after thinking for some time, suggested that her planes might be improved by washing their surfaces with a certain acid that would chemically attack sharp surface cracks and blunt them into furrows. While she was doing that, he would consider more long-term solutions.

(a) Qualitatively, why is silica glass brittle, and why might Alvin's suggestion be of some help?

Alvin's client was pleased with his initial work, which increased the average lifetime of her aircraft from one flight to almost three, and returned for his suggestions for long-term solutions.

Alvin's first effort was to replace silica glass with a tough, transparent polymeric plastic. The resulting aircraft worked fine until his client accelerated to supersonic speeds, as was her practice, at which point aerodynamic heating caused the wings to droop like Dali's clocks, and caused our superheroine to practice skydiving.

(b) What difference in the basic mechanism of deformation makes it possible for transparent plastic (polymeric) to be tougher than transparent silica glass? Why might a tough plastic soften at high temperature?
Alvin's second effort was to build the aircraft of a fiber-reinforced plastic, in which fibers of transparent glass were used to strengthen a matrix of tough plastic. With some effort, he achieved a composite with very respectable mechanical properties at moderately high temperature. Unfortunately, the stuff was opaque.

(c) Why would a mixture of transparent materials be opaque?

Alvin's third effort was to return to a high-temperature glass, but to heat-treat it during forming so that the region near its surface had a high residual compressive stress. The resulting glass exhibited a high resistance to fracture, but, unfortunately, its fracture resistance disappeared when it was exposed to high temperature.

(d) Why would a compressive stress near the surface increase toughness? Why would the toughness disappear when the material was annealed at high temperature?

With this failure, Alvin conceded defeat. In desperation, he suggested that she steal an idea from Alaska Airlines, build her aircraft of aluminum, and paint a picture of herself on the outside. Our superheroine was last seen parachuting into the Caribbean, surrounded by fragments of glass.

Problem 1:

A material has the composition AB, and crystallizes in a structure which is based on fcc. In this structure successive (001) planes alternate, one with all A atoms, then one with all B atoms.

(a) Draw the crystal structure.

(b) Is it likely that the material is a metal? A semiconductor? An insulator?

(c) Do you expect this material to be transparent or opaque to visible light?

(d) Do you expect this material to be isotropic in its electrical conductivity?

(e) The crystal loses order at high temperature; A and B atoms become randomly distributed. Why might you expect this, and what is the resulting crystal structure?

Problem 2:

In its pure state a material made of component A has the fcc structure while a material made of B is bcc.

(a) The simplest phase diagram the AB system can possibly have is the simple eutectic phase diagram. Sketch the diagram and explain why it is the simplest possible.

(b) Let the composition of the solution lie on the A-rich side of the eutectic composition, and let the sample be cooled from the liquid state slowly enough that chemical equilibrium is maintained. Describe three different microstructures that might appear as the composition is made richer in B.
(c) An A-rich solution is solidified by cooling at a moderate rate. It is found to have an inhomogeneous composition, and a microstructure that consists of α(FCC) grains with a eutectic constituent in many of the grain boundaries. Why might you expect this?

(d) The material described in (c) has a composition such that, when it is homogenized, it forms a microstructure that is 100% α(FCC). The rate of homogenization increases with temperature, T. What is the highest temperature at which homogenization can ordinarily be done?

Problem 3:

Briefly interpret the following observation:

(a) A piece of iron is placed in seawater. It corrodes.

(b) A piece of gold is placed in seawater. It does not corrode.

(c) A piece of iron is plated with gold and placed in sea water. It does not corrode.

(d) A narrow hole is drilled through the coating in (c). The exposed iron corrodes much more rapidly that it did when the gold was not present, effectively drilling a hole into the body of iron.

(e) After the hole in (d) has reached a small, but noticeable depth, the gold plating is removed from the iron, which is then returned to the seawater. The corrosion continues to be concentrated at the hole, drilling it further into the body of iron.

Problem 4:

Simple ferromagnetic materials, like Fe, Ni and Co, are ferromagnetic at low temperature essentially because their atoms have net magnetic moments that align with one another.

(a) If a ferromagnetic material that has previously been magnetized is placed in a magnetic field, H, its magnetization, M, will trace out a "magnetic hysteresis loop" like that shown above as the field is cycled between large positive to large negative values. Explain the hysteresis in terms of the magnetic microstructure and its response to the magnetic field.
(b) How do the hysteresis curves of "hard" and "soft" magnetic materials differ? Identify a technological application for which one would want a "hard" magnet, and one for which one would want a "soft" magnet.

(g) How might you make a ferromagnetic material "harder"?

(h) Describe “antiferromagnetism”.

(e) Some antiferromagnetic oxides (such as ferrites like lodestone) have net magnetic moments. How can this be? Identify a situation which a “ferrimagnetic” oxide might be useful.

**Problem 5:**

Interpret the following observations:

(a) When a bit of phosphorous is added to pure Si the conductivity rises substantially. (Write an expression for the conductivity at low temperature, where the solutes dominate.)

(b) When a bit of boron is added to pure Si the conductivity rises substantially. (Write an expression for the conductivity at low temperature, where the solutes dominate.)

(c) When a bit of phosphorous is added to Si that contains a bit of boron, the conductivity decreases.

(d) A Si crystal that contains a bit of phosphorous is joined to a Si crystal that contains a bit of boron. It is found that current passes easily across the interface in one direction, but not the other. Which is the “easy” direction and why?

(e) When a Si crystal is strongly illuminated with light (particularly ultraviolet light of the proper frequency) its conductivity increases irrespective of its composition.

**Problem 6:**

(a) A material is tested in tension. It breaks in a brittle manner. The experimenters record the “ultimate tensile strength” as the highest stress reached in the tensile test. The data scatter widely. Why?

(b) A high-magnification study of the fracture surface shows that the brittle fracture mode in this material is transgranular cleavage. A knowledgeable metallurgist suggests that he can dramatically improve the toughness by processing the material. What microstructural change would he probably want, and how might he accomplish it?

(c) The approach taken in (b) appears to be successful. When tested in tension the material does not “crack”, but fractures after extensive local necking. Explain the change in the fracture appearance.

(d) A second metallurgist appears on the scene, and asserts that he can improve the toughness of the material even further. He processes and processes, but there is no obvious effect; the stress at which the sample breaks in tension remains exactly the same. Why might you expect this?
(e) A final test is done in which the same is tested in tension while immersed in seawater. Curiously, the result now depends on how fast the test is done. If the sample is loaded to failure fairly quickly, the ultimate tensile strength and the appearance of the fracture tensile stresses. Explain this result.
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The phase diagram of the Pb-Sn binary system is shown above.

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Alvin's client was pleased with his initial work, which increased the average lifetime of her aircraft from one flight to almost three, and returned for his suggestions for long-term solutions.

Alvin's first effort was to replace silica glass with a tough, transparent polymeric plastic. The resulting aircraft worked fine until his client accelerated to supersonic speeds, as was her practice, at which point aerodynamic heating caused the wings to droop like Dali's clocks, and caused our superheroine to practice skydiving.

(b) What difference in the basic mechanism of deformation makes it possible for transparent plastic (polymeric) to be tougher than transparent silica glass? Why might a tough plastic soften at high temperature?

Alvin's second effort was to build the aircraft of a fiber-reinforced plastic, in which fibers of transparent glass were used to strengthen a matrix of tough plastic. With some effort, he achieved a composite with very respectable mechanical properties at moderately high temperature. Unfortunately, the stuff was opaque.

(c) Why would a mixture of transparent materials be opaque?

Alvin's third effort was to return to a high-temperature glass, but to heat-treat it during forming so that the region near its surface had a high residual compressive stress. The resulting glass exhibited a high
resistance to fracture, but, unfortunately, its fracture resistance disappeared when it was exposed to high temperature.

(d) Why would a compressive stress near the surface increase toughness? Why would the toughness disappear when the material was annealed at high temperature?

With this failure, Alvin conceded defeat. In desperation, he suggested that she steal an idea from Alaska Airlines, build her aircraft of aluminum, and paint a picture of herself on the outside. Our superheroine was last seen parachuting into the Caribbean, surrounded by fragments of glass.
Problem 1:

A material has the composition AB, and crystallizes in a structure which is based on fcc. In this structure successive (001) planes alternate, one with all A atoms, then one with all B atoms.

(a) Draw the crystal structure.

(b) Is it likely that the material is a metal? A semiconductor? An insulator?

(c) Do you expect this material to be transparent or opaque to visible light?

(d) Do you expect this material to be isotropic in its electrical conductivity?.

(e) The crystal loses order at high temperature; A and B atoms become randomly distributed. Why might you expect this, and what is the resulting crystal structure?
Problem 2:

In its pure state a material made of component A has the fcc structure while a material made of B is bcc.

(a) The simplest phase diagram the AB system can possibly have is the simple eutectic phase diagram. Sketch the diagram and explain why it is the simplest possible.

(b) Let the composition of the solution lie on the A-rich side of the eutectic composition, and let the sample be cooled from the liquid state slowly enough that chemical equilibrium is maintained. Describe three different microstructures that might appear as the composition is made richer in B.

(c) An A-rich solution is solidified by cooling at a moderate rate. It is found to have an inhomogeneous composition, and a microstructure that consists of α(FCC) grains with a eutectic constituent in many of the grain boundaries. Why might you expect this?

(d) The material described in (c) has a composition such that, when it is homogenized, it forms a microstructure that is 100% α(FCC). The rate of homogenization increases with temperature, T. What is the highest temperature at which homogenization can ordinarily be done?
Problem 3:

Briefly interpret the following observation:

(f) A piece of iron is placed in seawater. It corrodes.

(g) A piece of gold is placed in seawater. It does not corrode.

(h) A piece of iron is plated with gold and placed in seawater. It does not corrode.

(i) A narrow hole is drilled through the coating in (c). The exposed iron corrodes much more rapidly that it did when the gold was not present, effectively drilling a hole into the body of iron.

(j) After the hole in (d) has reached a small, but noticeable depth, the gold plating is removed from the iron, which is then returned to the seawater. The corrosion continues to be concentrated at the hole, drilling it further into the body of iron.
Problem 4:

Simple ferromagnetic materials, like Fe, Ni and Co, are ferromagnetic at low temperature essentially because their atoms have net magnetic moments that align with one another.

(a) If a ferromagnetic material that has previously been magnetized is placed in a magnetic field, H, its magnetization, M, will trace out a "magnetic hysteresis loop" like that shown above as the field is cycled between large positive to large negative values. Explain the hysteresis in terms of the magnetic microstructure and its response to the magnetic field.

(b) How do the hysteresis curves of "hard" and "soft" magnetic materials differ? Identify a technological application for which one would want a "hard" magnet, and one for which one would want a "soft" magnet.

(m) How might you make a ferromagnetic material "harder"?

(n) Describe “antiferromagnetism”.

(e) Some antiferromagnetic oxides (such as ferrites like lodestone) have net magnetic moments. How can this be? Identify a situation which a “ferrimagnetic” oxide might be useful.
Problem 5:

Interpret the following observations:

(f) When a bit of phosphorous is added to pure Si the conductivity rises substantially. (Write an expression for the conductivity at low temperature, where the solutes dominate.)

(g) When a bit of boron is added to pure Si the conductivity rises substantially. (Write an expression for the conductivity at low temperature, where the solutes dominate.)

(h) When a bit of phosphorous is added to Si that contains a bit of boron, the conductivity decreases.

(i) A Si crystal that contains a bit of phosphorous is joined to a Si crystal that contains a bit of boron. It is found that current passes easily across the interface in one direction, but not the other. Which is the “easy” direction and why?

(j) When a Si crystal is strongly illuminated with light (particularly ultraviolet light of the proper frequency) its conductivity increases irrespective of its composition.
Problem 6:

(f) A material is tested in tension. It breaks in a brittle manner. The experimenters record the “ultimate tensile strength” as the highest stress reached in the tensile test. The data scatter widely. Why?

(g) A high-magnification study of the fracture surface shows that the brittle fracture mode in this material is transgranular cleavage. A knowledgeable metallurgist suggests that he can dramatically improve the toughness by processing the material. What microstructural change would he probably want, and how might he accomplish it?

(h) The approach taken in (b) appears to be successful. When tested in tension the material does not “crack”, but fractures after extensive local necking. Explain the change in the fracture appearance.

(i) A second metallurgist appears on the scene, and asserts that he can improve the toughness of the material even further. He processes and processes, but there is no obvious effect; the stress at which the sample breaks in tension remains exactly the same. Why might you expect this?

(j) A final test is done in which the same is tested in tension while immersed in seawater. Curiously, the result now depends on how fast the test is done. If the sample is loaded to failure fairly quickly, the ultimate tensile strength and the appearance of the fractutensile stresses. Explain this result.
Problem 1: (20 points)

A material has the composition AB, and crystallizes in a structure which is based on fcc. In this structure successive (111) planes alternate, one with all A atoms, then one with all B atoms (this is the CuPt structure). Provide brief explanations for the following observations.

(a) The material is a metallic conductor (show that it cannot be ionic or covalent in its bonding).

(b) Both its electrical and thermal conductivities decrease as temperature rises.

(c) The material is opaque to visible light. However, it is transparent to x-rays, unless the x-rays have energies very close to one of a few discrete values.

(d) At high temperature the structure becomes disordered; the material transforms into a random solid solution of A and B atoms on an FCC lattice.

(e) When the material disorders, its electrical resistance increases, its elastic modulus decreases, and its yield strength decreases.
Problem 2: (15 points)

(a) Consider a binary system that contains two components, A and B. Component A has an FCC structure in its pure state while component B is BCC. The simplest possible binary phase diagram for the system is a eutectic diagram. Why? Sketch the phase diagram and label the phase fields.

(b) Given a temperature and composition (T,x) of the phase diagram in (a) it is possible to extract three pieces of information from the phase diagram: the phases present at (T,x), the compositions of the phases, and the fractions of the phases. Describe how.

(c) If a polygranular sample of the A-rich solution, α, is cooled into the two-phase, α+β, region the kinetics of precipitation of β are described by the kinetic diagram given below, where τ is the time required to initiate the transformation and ΔT is the undercooling below the temperature at which β precipitation becomes thermodynamically possible. Give a brief, qualitative explanation for the shape of this kinetic curve.

(d) If the material is cooled as indicated by the upper arrow, the final microstructure contains nuclei of β almost exclusively in the grain boundaries of the α grains. Why might you expect this?
Problem 3: (15 points)

(a) Plot the expected variation of the diffusivity with temperature for a substitutional solute in a polygranular solid, and explain the shape of the graph.

(b) Let the diffusivity of a substitutional species be measured at temperature $T$, under two conditions: (1) the solid has uniform temperature, $T$; (2) the solid has a temperature gradient, and $T$ is an intermediate temperature. Would the two measurements differ? How and why?
Problem 4: (20 points)

(a) Define the Fermi energy, $E_F$, of a semiconductor. Given its definition, show that a semiconductor behaves as an n-type extrinsic semiconductor if $E_F$ is significantly greater than the energy at the midpoint of the band gap, and as a p-type extrinsic semiconductor if $E_F$ is significantly below the midpoint of the band gap.

(b) Sketch the band structure of an n-p-n bipolar transistor in the absence of any external potential. Indicate the position of the Fermi level.

(c) Give a brief explanation of how the bipolar transistor can be used as a switch by controlling the potentials applied at the emitter (n), base (p) and collector (n).

(d) Suppose that the semiconductor used is a photoconductor. Describe how you might use light instead of voltage to make the n-p-n junction function as a switch.
Problem 5: (15 points)

Interpret the following observations:

(k) Given examples of steel and aluminum alloys with essentially identical microstructures, the steel will be roughly three times as strong as the aluminum.

(l) Carbon is an effective solution strengthener in steel, but is relatively ineffective in aluminum.

(m) The ultimate tensile strength of a typical structural steel is a material property that shows only a small scatter from one test to another, while the ultimate tensile strength of a structural ceramic, like alumina or silica glass, is not a material property and may scatter widely from one test to the next.

(n) The elastic modulus of a structural material is almost insensitive to its microstructure.

(o) The elastic modulus of a fiber composite (high-modulus fiber in a relatively soft matrix) is highest when the fibers are continuous along the length of the piece in the direction of load, and is much less when the fibers are chopped into short lengths or the piece is tested perpendicular to the fiber axis.
Problem 6: (15 points)

(OK. I stole this from an old E45 exam. But it was fun.)

Given the financial success of the recent movie, the sinking of the Titanic has once again become a fashionable topic of conversation. I am always troubled when this happens since I am one of the few who know what really sent that good ship to the bottom of the sea, and I am sworn to secrecy. But nobody reads these exams anyway, so it shouldn't matter if I give a hint or two here.

The sinking of the Titanic was, in fact, one of the great crimes of the century, a vicious mass murder perpetrated by one Maples Pavilion, a metallurgist of enormous, though sadly perverted talent. The evil Dr. Pavilion coveted the fortune in jewels carried by the wealthy passengers on the Titanic's maiden voyage. While stealing the jewelry was child's play for a genius of the caliber of Pavilion, it was not enough. In order for him to fence the stones for maximum profit, no one must know they had been stolen. The jewels were to be filched and replaced with fake copies, which would be sent to the bottom of the sea along with their owners and anyone else who happened to be on board at the time. The sinking would, of course, be "accidental" and, given the time of year, would naturally be blamed on poor seamanship leading to collision with an iceberg.

Pavilion was, of course, blessed with insights into mechanical metallurgy that were decades ahead of his time. An examination of samples of the steel plate intended for the ship's hull revealed that it was thick plate made to a strength that was unusually high for the time, with a coarse-grained microstructure. Pavilion was, therefore, certain that the steel would fracture in a brittle manner in the cold waters of the North Atlantic.

(a) Each of the three factors, thick plate, high strength, coarse grain size, contributes to a high value of the ductile-brittle transition temperature. Why?

To verify this hypothesis, he invented fracture toughness testing, measured the fracture toughness ($K_t$) of the plate, and showed that it had a low value. He also measured the fatigue crack growth rate in the plate ($da/dn$) as a function of the cyclic stress intensity ($\Delta K$).

(b) Sketch the expected variation of $da/dn$ with $\Delta K$. Explain why the crack growth rate [$da/dn$] increases with crack length for a given cycle ($\Delta \sigma$) of the applied stress.

There followed in rapid succession the invention of an appropriate supercomputer, the development of suitable stress analysis codes and the construction of viable oceanographic models, all leading to the calculation of projected hull stresses as a function of time. Given hull stresses, fracture toughness and crack growth rates, Pavilion computed a set of crack lengths and locations that would virtually guarantee that, with no prior warning, the Titanic would crack like a raw egg at about the time the ship neared Newfoundland, and send it straight down before the first lifeboat could be launched.

(c) Given precise values of hull stress as a function of time, fatigue crack growth rates, fracture toughness and the mutual interaction of the cracks as they go unstable in a predictable sequence, describe how Pavilion would decide where and how big he should inscribe his hull cracks to ensure that the ship would split into pieces after a given time at sea.

To complete the crime, Pavilion and his associate, the iniquitous Prof. Treseder Union, booked passage under assumed names. On the first night out they purloined the jewels, planted the fakes, inscribed the cracks and escaped the ship by helicopter (another useful invention they brought on board disguised as a ceiling fan).
Still, the best-laid plans of mice and men oft go awry, and Pavilion spent anxious days at his satellite-linked video monitor watching the ship's progress, terrified that an unusually calm sea would permit the ship to reach harbor intact, or the crew would stumble onto his well-concealed hull cracks or some lucky soul might survive the looming tragedy to tell what really happened.

But as bitter experience has already taught you, life is not fair. The truly evil are protected by a curious inverse of Murphy's Law: for them, anything that can go wrong won't. And virtue was never at home in Maples Pavilion. He was, therefore, only mildly surprised when the captain of the Titanic actually did steer the ship smack into an iceberg. To be fair, it wasn't that much of a smack. The survivors were shocked that a collision they described as a "slight shudder" could produce a fatal rip. But by this time the poor Titanic didn't need much of a smack. Pavilion's cracks had grown almost to the point of instability under normal operating loads.

(d) Describe how and why the load required to propagate a crack to failure decreases with the length of the crack.

Maples Pavilion banked his ill-gotten gains and lived happily ever after. He was last sighted at a prestigious Junior University, where he had endowed a chair (in fact, quite a number of chairs along the very periphery of his eponymous round-ball court) and enjoyed the congenial company of kindred souls.
Problem 1: (15 points)

(a) Suppose you are given three materials, and are told that one is an insulator, one an intrinsic semiconductor, and one a metal. You send them out for x-ray diffraction, and find that one has the NaCl structure, one has the β-ZnS, and one has the fcc. Which is most likely to be the metal, which the semiconductor and which the insulator, and why?

(b) You look at them closely. One is transparent, two are not. Which is transparent, and why?

(c) One of the materials is noticeably colder to the touch. Which is it most likely to be, and why?

(d) You accidentally drop them on the floor. Two break, one does not. Which would you expect to survive, and why?

(e) You coat each with a strip of platinum and drop it in saltwater. After a few minutes, one shows visible corrosion, two do not. Which corrodes rapidly, and why?
Problem 2: (20 points)

(a) Describe the nucleation-and-growth mechanism of a structural phase transformation. Why is there a thermodynamic barrier to the formation of a nucleus? Derive an expression for the height of this barrier, assuming a spherical nucleus in the bulk.

(b) Let phase $\alpha$ transform to $\beta$ by nucleation and growth, where phase $\alpha$ is preferred at high temperature and $\beta$ at low temperature. It is often possible to suppress the transformation $\alpha \rightarrow \beta$ by cooling rapidly, but is almost never possible to suppress $\beta \rightarrow \alpha$ by heating rapidly. Why?

(c) A liquid phase will ordinarily solidify into a crystalline solid if cooled slowly, but may form a glass if cooled very rapidly. Explain this observation in terms of the relative kinetics of crystallization and glass formation. Include an appropriate temperature-transformation (TT) diagram that illustrates the kinetics of the nucleation-and-growth and glass transitions.

(d) If a typical crystalline semiconductor is melted and then quenched into a glassy state its conductivity increases significantly (it may even become metallic). However, if a typical crystalline metal is melted and quenched into a glassy state, its conductivity decreases significantly. Interpret this phenomenon.
Problem 3: (15 points)

Explain the following observations concerning oxidation and corrosion:

(a) While very fine particles of iron can burn spontaneously in air (for example, the sparks thrown off during the machining of steel), a bulk sample of iron oxidizes at a negligible rate unless the temperature is very high.

(b) If the same bulk sample of iron is immersed in damp soil, it oxidizes (rusts) fairly quickly.

(c) If a bulk sample of iron is immersed in damp soil very near a piece of zinc, the iron corrodes just as it would if the zinc were not there. But if the iron is connected to the zinc by a thin metal wire, the iron immediately stops corroding, and is protected from further corrosion until the zinc has corroded away.

(d) While Fe rusts easily in damp soil, Au does not; nuggets of pure gold last almost indefinitely in the earth.

(e) Fe, also, remains bright and uncorroded for long periods of time in moist air and some damp soils, if it is alloyed with more than 8% Cr.
Problem 4: (20 points)

(a) Draw a simple sketch of the band diagrams of an n-type and a p-type semiconductor. Indicate the position of the Fermi level relative to the center of the band gap in each material at moderate temperature.

(b) Roughly sketch the band structure of an n-p junction in which the two materials are joined and allowed to come to equilibrium.

(c) Explain qualitatively why the n-p junction conducts electricity much more easily in one direction than in the other.

(d) Give a brief explanation of how the bipolar transistor (basically, and n-p-n junction device) can be used as a switch by controlling the potentials applied at the emitter (n), base (p) and collector (n).
Problem 5: (15 points)

(a) Derive the “Considere criterion” for the plastic instability of a round tensile specimen. Show that the engineering stress-strain curve has a maximum at the “ultimate tensile stress” where the Considere criterion is satisfied.

(b) Derive an expression for the true stress-true strain relation of a material that would, in theory, undergo arbitrary large elongation without necking.

(c) Sketch the engineering stress-strain curve of the material of part (b).

(d) It is an “inconvenient truth” that processing a ductile material to ultrafine grain size ordinarily increases its strength, but at a severe, and eventually catastrophic loss of uniform elongation. Why?
Problem 6: (15 points)

(OK. I stole this from an old E45 exam, too. But it was fun.)

As most of you know, the small town of Wishful Thinking, Arkansas, has prospered greatly from the storage and sale of organic fertilizer, which is produced in literally unlimited quantities by a couple of its former residents. However, since you are not a member of the plaintiff's bar, you may not be aware of the morass the good citizens of that fine town had to wade through before their business was well established. The main problem concerned the construction of suitable tanks to store the vast mass of organic fertilizer.

Their first solution was a thin-walled steel tank placed on the only really suitable site, a hill above the town. Unfortunately, during its first filling the tank ruptured, sending a wall of organic fertilizer several feet thick cascading down the main street and flooding the mayor's house with goo so foul his wife threatened to leave forever to seek a new career in New York. The entire population of Wishful Thinking shoveled organic fertilizer for weeks to accomplish the clean-up.

To solve the problem, the city fathers consulted a local Guru. "I have consulted my introductory Materials Science texts," announced the Guru. "The tank fractured. The fracture of steel is governed by its fracture toughness. You, therefore, need to use steel with higher fracture toughness. You can increase the fracture toughness of the steel by slightly lowering its yield strength." The town fathers accepted his advice and reconstructed the tank of lower strength, higher toughness steel.

(a) It is often true that lowering the yield strength of a material raises its fracture toughness. Why?

Unfortunately, during its first filling the new tank ruptured, sending a wall of organic fertilizer several feet thick cascading down the main street and flooding the mayor's house with goo so foul his wife threatened to leave forever to seek a new career in New York City. The entire population of Wishful Thinking shoveled organic fertilizer for weeks to accomplish the clean-up. The city fathers sought a new Guru.

"Your consultant was an imbecile," said Guru Two. "I have examined both fractures. In both cases there is significant plastic deformation and pronounced thinning of the steel plate at the point of fracture. This kind of fracture isn't governed by fracture toughness, but by the strength of the steel. The solution is to build the tank with a much thicker plate, which will lower the stress it has to carry to a value below its strength." The town fathers accepted his advice and reconstructed the tank of thick steel plates.

(b) What does Guru Two mean by "the strength of the steel", and why does this "strength" govern the kind of fracture he found in the tank wall?

Unfortunately, during its first filling the new tank ruptured, sending a wall of organic fertilizer several feet thick cascading down the main street and flooding the mayor's house with goo so foul his wife threatened to leave forever to seek a new career in New York City. The entire population of Wishful Thinking shoveled organic fertilizer for weeks to accomplish the clean-up. The city fathers sought a new Guru.

"Guru Two was careless," asserted new Guru. "My analysis of this latest fracture shows that its surface is flat, with little plastic deformation. Thickening the plate lowered its fracture toughness with the result that it fractured from a small manufacturing flaw at a stress well below its strength. You need to build the tank out of steel that has a higher fracture toughness." "That's what Guru One told us," said the city fathers, "and his tank broke, almost drowning us in organic fertilizer." "He was wrong, but I am right,"

"Guru Two was careless," asserted new Guru. "My analysis of this latest fracture shows that its surface is flat, with little plastic deformation. Thickening the plate lowered its fracture toughness with the result that it fractured from a small manufacturing flaw at a stress well below its strength. You need to build the tank out of steel that has a higher fracture toughness." "That's what Guru One told us," said the city fathers, "and his tank broke, almost drowning us in organic fertilizer." "He was wrong, but I am right,"
quoth new Guru. The city fathers reluctantly accepted his advice, and rebuilt the tank with thick plates of a steel with exceptionally high fracture toughness. Sure enough, the tank could be filled without failing.

(c) If Guru One was wrong, how could it be that new Guru was right?

Unfortunately, it was a cold, cold winter in Wishful Thinking, Arkansas, that year. And it came to pass that on the coldest day of that cold, cold winter the new tank ruptured, sending a wall of organic fertilizer several feet thick cascading down the main street and flooding the mayor's house with goo so foul his wife threatened to leave forever to seek a new career in New York City. The entire population of Wishful Thinking shoveled organic fertilizer for weeks to accomplish the clean-up. In desperation, the city fathers sought yet a new Guru, and were drawn to consult with one Alvin Underfoot, a formerly random undergraduate who had received a solid, though cheap education in Materials Science in the public school system of the State of California.

"New Guru had the right idea," said Alvin, wisely, "he just lacked depth. A structural steel may be very tough at ambient temperature, but lose almost all of its toughness when the temperature drops a few degrees. The problem with your steel was its ductile-brittle transition temperature ($T_B$). The brittle transition temperature was too high. Rebuild the tank with an alloy whose brittle transition temperature is well below the coldest temperature on the coldest day of the coldest winter."

The city fathers took his advice, and the small town of Wishful Thinking, Arkansas, has, ever since, prospered mightily from the storage and sale of the organic fertilizer that is produced in literally unlimited quantities by a couple of its former residents.

(d) How is it that the fracture toughness of a nominally tough material can drop to a very low value when its temperature is lowered by only a few degrees? What sort of microstructure is conducive to a low value of $T_B$?