Department of Physics Guidelines for the PhD Candidacy Exam

This document is intended to provide guidance about preparing for the candidacy exam. For full details see the relevant information in the University Calendar and the Physics Graduate Student Handbook (link here). Briefly, the student prepares a short thesis proposal document and then takes an oral examination, as described below.

Purpose of the Candidacy Exam -- The U of Alberta Calendar states; "Students must demonstrate to the satisfaction of the examining committee that they possess: 1) an adequate knowledge of the discipline and of the subject matter relevant to the thesis; 2) the ability to pursue and complete original research at an advanced level; 3) the ability to meet any other requirements found in the department's published policy on candidacy examinations."

In the broadest sense, a PhD candidacy exam is meant to examine the ability of a student to complete independent research. To this end, the student will be examined on three facets of a successful researcher: their level of foundational knowledge, their ability to solve problems, and their ability to plan their research.

Timing -- The candidacy exam must be completed after the student has finished most of their required coursework for the PhD, within the three years since the start of the PhD, and at least six months before the final thesis defense. While this sets the formal boundaries for the timing of the exam, the department expects the supervisor to arrange for the exam to be completed before the end of the second year of study (third year of study for students who transfer to the PhD program without completing a MSc; these students must complete the exam within four years of starting the MSc program).

People -- The candidacy exam takes place between the PhD student and the candidacy examination committee (the Committee). The candidacy exam committee consists of the PhD supervisory committee ex-officio members (supervisor and two other members) and either one university examiner or one specialized knowledge examiner. When deemed necessary by the supervisor, one additional university examiner or specialized knowledge examiner may be appointed to the examining committee. In such cases, the examining committee consists of the ex-officio examiners and either two university examiners or one university examiner and one specialized knowledge examiner.

The Physics Department will appoint another faculty member as the Chair of the committee. The Chair administers the exam, making sure that the procedures are followed and that the exam questions remain in-scope. However, the Chair does not participate in asking questions. During the scheduling of the exam, the supervisor will discuss the composition of the exam committee with the student, and the student should raise any concerns about committee composition at that time.

Thesis Proposal -- This is a document (10-20 pages, plus references) prepared by the student that addresses the following:

- a summary of the status of the field in which the student plans to do research
- an outline of the anticipated PhD project, including a statement of the main scientific objectives
- a broad description of the methodology to be used
- milestones and a timeline for completing the research project

The student must distribute the thesis proposal as a single PDF file to the entire examining committee at least one week prior to the oral exam.

Format of the Oral Exam -- The candidacy exam is an oral examination administered by the Committee defined above. The oral exam consists of four phases:

1. Oral presentation by the student of their research status: This presentation summarizes progress toward thesis to date (nominal duration 20 minutes). The oral presentation updates the Committee on progress but the research subjects presented are generally not a major focus of questioning during the exam. In preparing for the exam, the student should think of the presentation as defining the topics on which more fundamental questions will be asked instead of the presentation being the actual subject of the examination.
2. Review of student's academic record and status of fulfilment of degree requirements. This is conducted by the examination Committee only; the student waits outside the exam room. (nominal duration: 5 minutes)
3. Questioning: each Committee member asks the student a series of questions. Typically, the questioning happens in two rounds with each Committee member having the lead for 10 to 15 minutes. Questioning is free form and other Committee members will often ask follow-up or clarification questions. The Committee Chair ensures that the questioning remains balanced and focused on the examination topics. A second round of questioning will usually follow though it will frequently not be as long as the first round. (Nominal duration 60 to 120 minutes)
4. Deliberation: The exam Committee discusses performance on the exam and reaches a consensus about the result of the exam. For more information on the result of the exam, see Decision of the Candidacy Committee in the University Calendar.
5. The Chair of the Committee (not the supervisor) informs the student of the results of the exam.

Expectations of the Student -- A student is expected to have a basic understanding of a wide range of topics of physics, and a rich understanding of those fields supporting their research. A student may have already developed a deep understanding of their thesis research, but this is not the primary area of focus for the candidacy exam.

Expectations of the Examination Committee -- The examination committee is expected to maintain its focus on evaluating a student's preparation in the research fields required for executing their proposed thesis. The committee will ask questions that test the student's underlying knowledge of their research area rather than any preliminary research presented in the thesis proposal. Lines of questions should be directed at the student and the committee members will refrain from asking questions of each other.

Oral Exam Preparation and Requirements -- Formally, any topics even loosely connected to the field of research are considered to be in scope for the exam. In practice, the candidacy exam focuses on a narrower set of knowledge learned in coursework and through review articles in the student's field of study. The student should consult with their research supervisor about an optimal plan of study. In general, though, the best preparation is to prepare a strong conceptual understanding of relevant areas of physics. This can include the supporting textbooks at the undergraduate level and, to a lesser degree, graduate level, as well as major review articles. The student must be able to outline the supporting research for their focus area.

Ideally, this preparation takes place in the course of a student's PhD studies (and earlier), thus requiring minimal preparation at the time of the candidacy. In practice, most students will want to review some of this material just before the candidacy. In particular, they should prepare a conceptual understanding that will allow them to address the following:

- What is the physics framework in which my research is taking place?
- What are the major open questions in my field of research?
- What are the other methods that are used to answer research questions like my own?
- What are the relative strengths and weaknesses of other research approaches?

Oral Exam Questions -- Examiners typically ask questions in a series around a theme, sometimes called the stem question. The line of questioning can then branch out substantially from the original line of questioning. This typically happens because the student raises a particularly interesting point or makes a statement that suggests a conceptual misunderstanding.

Through the preparation and the actual examination, a student should be guided by the nature of the exam: each Committee member is encouraged to use 10-15 minutes to complete their lines of questioning per round. This timing implies that the depth of the responses cannot be extensive and focuses on conceptual questions and simple quantitative estimates. Long derivations or proofs are generally out of scope during the candidacy but the student may be asked to summarize lines of reasoning or justify particular steps in longer, well-known proofs. It is particularly important to be able to develop plausible answers to hypothetical questions. As such, one particular area of skill that students should develop is the ability to answer Fermi problems and to complete estimates of quantities relevant to the proposed thesis research, often using the whiteboard. It is important to know (at the one-significant-digit level, and with appropriate units) relevant physical constants and relevant scales (energies, masses, etc.) of physical processes. This allows the student to routinely check if their answers make sense.

If the student is in doubt about the scope of the question asked, they should feel free to ask their committee members for clarification. In general, student answers should be as simple and direct as possible. Straightforward answers are an ideal starting point since that is usually what the examiners are looking for. The oral exam format means that the student can interact with the examiners, and the examiners will then ask for a more in-depth discussion if they desire.

Best Practices -- During the preparation and the exam, several strategies can help lead to a successful outcome. Students are recommended to:

- Consult with their supervisor about good resources for preparation and material that should be included in the thesis proposal. The supervisor may also suggest consulting with other members of the committee.
- Practice speaking and working simple estimate problems at the board including mental mathematical estimates.
- Arrange a practice exam with post-candidacy graduate students in physics. This should include those not exclusively from the student's research group. Often the most difficult questions on oral exams are simple questions asked by "outsiders".

Sample Questions -- Below, some sample qualifying exam questions are listed, based on those that were asked during previous examinations. They are broadly grouped by research area; note that Geophysics does not list specific questions but gives guidance in topics (see below). These are intended to give a general sense of the level of questions that are expected to be answered but **should not be regarded as a study guidance on a particular exam, nor do they constrain the types of questions that can be asked.**

Astrophysics

1. Explain the physics behind degeneracy pressure and describe how it specifically manifests in compact objects.
2. What is the mass-radius relationship for a white dwarf? What physical scalings lead to this result?
3. What sets the upper/lower mass limit of main sequence stars? What is the upper/lower mass limit?
4. List common assumptions that underlie the study of stellar structure. Why are these well justified?
5. What is the Chandrasekhar mass limit? Why is there such a mass limit?
6. Sketch the curve of the binding energy per nucleon for various nuclei. What implications does the peak have for stellar evolution? How does the shape of the curve determine the length of the various stages of stellar evolution?
7. Sketch the evolution of a 1 solar mass star in the HR Diagram. Describe its internal structure in each stage of its evolution.
8. Estimate the mean free path of a star in a galactic collision.
9. What is “Faraday rotation”? How is it used in astronomy?
10. What is the MHD approximation? What are the MHD equations for continuity, momentum conservation and energy conservation?
11. What is meant by “free-free” absorption? How is this different from electron scattering?
12. Write down the basic equations of the p-p chain that provides the Sun’s nuclear power.
13. What was the approximate flux in neutrinos on Earth due to SN1987A? If nineteen SN1987A neutrinos were detected by manmade experiments, what was the total cross-section of all those experiments to ~10 MeV neutrinos?
14. If a typical interstellar dust grain is 0.2 microns in size, and starlight suffers an extinction of 1 magnitude per kpc, estimate the space density of dust grains.
15. Why is the gas in the interstellar medium largely transparent at visible wavelengths?
16. Sketch a typical cooling function $\Lambda(T)$ for diffuse interstellar gas and identify its prominent features. Overplot a hypothetical heating curve and show how to identify points of thermal equilibrium and their stability.
17. Name five molecules found in the interstellar medium and comment on how they are detected.
18. What is an HII region? Estimate how the Strömgren radius scales with the luminosity of the ionizing source and with the ambient density.
19. X-ray emission from a nearby supernova remnant is observed to peak at ~0.5 keV. Estimate the velocity with which the blast wave is propagating through the interstellar medium.
20. What is the “fundamental plane” for elliptical galaxies?
21. What is the Schechter luminosity function? What is the luminosity of a typical bright galaxy?
22. Why are core-collapse supernovae observed primarily in star-forming galaxies?
23. Explain why the explosion energy of Type Ia supernovae is typically ~1051 ergs.
24. Explain the difference between explicit vs implicit time integration, and the associated advantages and disadvantages of using each scheme.
25. Why is there a maximum mass for neutron stars?
26. Explain the difference between cosmological, gravitational, and Doppler redshift.
27. How many wave families are there in ideal MHD? At what speed do each of them propagate?
28. Explain how finite-volume methods for astrophysical fluid dynamics work.

29. Explain the difference between strong and weak scaling in parallel computing. What is the most common reason why perfect scaling breaks down?
30. Explain the difference between shared and distributed memory compute clusters.
31. Point to the Triangulum Galaxy right now (the Local Sidereal Time is 14:35:00).

Biophysics

Specific questions/topics:

1. Primary, secondary, tertiary, and quaternary protein structures. What does “native structure” mean in terms of energy and entropy? What is a transition state in this context?
2. How do proteins fold on biologically relevant timescales? Levinthal’s Paradox. Protein folding landscape.
3. Forces that hold biopolymers (DNA, RNA, proteins, etc.) together.
4. Write down the general expression for the free energy for a polymer.
5. H-P model of protein folding. Derive the probability of a six-mer “PHPPHP” being in the folded state using Boltzmann/Gibbs factors and the partition function.
6. How does genetic information flow inside the cell? Draw the reaction network and write the corresponding ordinary differential equation model of transcription and translation.
7. Statistical mechanical model of oxygen binding to dimoglobin. What is the partition function for this system? What is the probability of finding one oxygen molecule bound and/or the average occupancy as a function of ligand potential energy?
8. Is Stokes’ drag relevant for optical tweezer experiments?
9. Give an example of where stochasticity is important in biology. How is this fundamentally related to random walks and diffusion? How would you quantitatively model this phenomenon or measure it experimentally?
10. Temperature effects on biological systems (e.g., enzymes). Does the Arrhenius equation apply to living systems?
11. Give three examples of molecular motors, how they work, and what energy source they use.
12. What is the Luria-Delbruck fluctuation test? How would you design an experiment using this test to measure the rate of mutation in bacteria?

Biophysics Candidacy report and thesis research related questions/topics:

1. Questions related to i) literature review, ii) feasibility of research plan, and iii) research results.
2. What are the physical principles behind the theoretical or experimental techniques that you are using in your research? What other techniques could you be using, what are the pros and cons of each of these methods, and why are you not using them?
3. Details on the steps required complete your thesis research, including experiments, data analyses, publication plans, and timeline.

Biophysics General questions:

1. What are the three most important discoveries in biophysics?
2. What are the major outstanding questions in your field of research?
3. Why should your thesis research be funded/published?

Condensed Matter Physics

1. (optics focus area) With respect to light-matter interactions, what are “selection rules” and how do they affect these interactions?
2. (optics focus area) In a two-level system, what are Rabi oscillations, and what physical parameters determine the amplitude and frequency of these oscillations?
3. (optics focus area) Describe the operation of a laser.
4. (optics focus area) Explain how a reflection grating works.
5. How does lock-in detection work?
6. What are the Bravais lattices? Describe / draw simple Bravais lattices (e.g. cubic, fcc, hcp).
7. What is Bragg reflection? How does it apply to high energy X-rays, high energy electrons (> 10 keV) and to low energy electrons (few eV) in a crystal?
8. What methods can provide you with structure of a solid? Describe the concept of a few (2 - 3) methods and what information you can obtain. E.g. electron diffraction, X-ray diffraction, LEED, neutron diffraction, etc.
9. Describe the temperature dependence of the specific heat for both the phonon and electron contributions in a solid. What differences are produced from quantum effects?
10. What is the temperature dependence of the resistivity for a metal? For an insulator? Semiconductor? What happens in a superconductor?
11. What is the Fermi energy? Why does this concept arise in the theory of metals? (Depending on the student’s background this line of questioning could continue with Kronig-Penney model, density of states, nesting, etc.)
12. What is the Fermi surface?
13. What is the reciprocal lattice?
14. Describe the Drude model of conduction in metals.
15. When is a metal opaque/transparent?
16. Explain the difference between direct/indirect band gap semiconductors, intrinsic/extrinsic semiconductors.
17. Describe the different types of bonding in solids.

Geophysics

Geophysics students are expected to answer questions in topics from two thematic pools:

Pool 1: General geophysics knowledge. This includes an understanding of the structure and dynamics of the Earth’s interior, the principles of plate tectonics, and the basics of geophysical exploration methods. This material is covered in GEOPH 521. Students should complement the GEOPH 521 course notes with the general geophysics textbooks listed on the GEOPH 521
syllabus. These include:

- The Solid Earth: An Introduction to Global Geophysics (second edition), C.M.R. Fowler, Cambridge University Press, 2005.
- Fundamentals of Geophysics (second edition), W. Lowrie, Cambridge University Press, 2007. Available online through the UofA library: http://app.knovel.com/web/toc.v/cid:kpFGE00004
- Physics of the Earth (fourth edition), F.D. Stacey and and P.M. Davis, Cambridge University Press, 2008.

Pool 2: Topics related to Ph.D. research. The supervisor and supervisory committee will provide additional topics for study, as well as recommended readings. These topics are associated with the particular subfield of Geophysics in which the student is working (Inverse Problems, Paleomagnetism, Rock Physics, Seismology, Geodynamics, etc.).

Gravitation and Cosmology

Mathematical tools

1. Metric. Christoffel symbols.
2. Covariant derivatives.
3. Diffeomorphisms, Lie derivatives
4. Spacetime symmetries. Killing equations.
5. Riemann curvature. Ricci curvature and Ricci scalar.
6. Bianchi identities.
7. Particle and light motion in the gravitational field.
8. Geodesic congruences, expansion, shear, vorticity, Raychaudhuri equation
9. Non-coordinate bases and tetrads
10. Fermi and Riemann normal coordinates and their construction

General Relativity

1. Electromagnetic field. Maxwell equations in an external gravitational field.
2. Einstein-Hilbert action. Boundary terms.
3. Matter Lagrangian. Stress-energy tensor. Covariant conservation law.
4. Energy conditions
5. Einstein equations.
6. Kepler's laws (in the nonrelativistic approximation of GR)
7. Linearized gravity. Gravitational waves.
8. Gravitational wave production and propagation
9. Quadrupole approximation
10. Brief understanding of Hamiltonian GR

Black holes

1. Spherically symmetric metrics. Schwarzschild solution.
2. Gravitational collapse.
3. Black hole in astrophysics: Masses and observational evidences.
4. Particle motion in the Schwarzschild spacetime. Circular orbits. ISCO.
5. Light motion in the Schwarzschild spacetime.
6. Weak field approximation. GR and Newton’s light deflection by a heavy body.
7. Rotating black holes. Kerr metric.
8. Conformal transformation, Penrose diagrams and the asymptotic structure of spacetime
9. Quasi-local conserved quantities: mass, charge, spin of black holes
10. Penrose process.
11. Black hole thermodynamics. Temperature and entropy of a rotating black hole.

Cosmology

1. Homogeneous and isotropic metric. FRW solution.
2. Early time evolution of matter and radiating cosmologies.
3. Inflation.
4. Cosmological perturbations.
5. Cosmological micro-wave background.

Additional material

- Approximate values in SI units for G, c, hbar, Planck mass, Planck length, Planck time, length of the year, elementary charge, proton mass, electron mass, solar mass, astronomical unit, age of the universe, radius of the observable universe, and the fine structure constant, the earth orbital velocity in units of the speed of light, and the Schwarzschild radius of a black hole in terms of the mass in units of a solar mass.

References

Main sources:
Carroll, Sean M (2004). *Spacetime and Geometry: An Introduction to General Relativity*. Addison Wesley.

C. W. Misner, K. S. Thorne, J.A Wheeler, (1973), *Gravitation*, W. H. Freeman Princeton University Press.

James B. Hartle, (2002*), Gravity: An Introduction to Einstein's General Relativity*, Publisher: Pearson.

Additional material on black holes:
Valeri P. Frolov, Andrei Zelnikov (2011). *Introduction to Black Hole Physics*, Oxford University Press.

Additional material on cosmology:
M. P. Hobson, G. Efstathiou and A.N. Lasenby (2006), *General Relativity*, Cambridge University Press.

Particle Physics

1. Does the mass of a particle travelling at close to the speed of light change compared to its mass at rest? Explain.
2. Why are muons far more penetrating than electrons?
3. Draw the tree-level Feynman diagram with vertex factors labelled for $RELEVANT_PROCESS [This is typically a process which is either common or related to your area of research e.g. neutrino CC interaction with a nucleus, a Higgs decaying to two photons, single-top quark production in a collider, a B meson decay etc.]
4. What is observed in $YOUR_EXPERIMENT when a $PARTICLE is produced? [This will usually be a particle likely to be produced in your experiment, sometimes the question may use a simple detector model instead of your experiment].
5. If you had (almost) unlimited money how would you improve $YOUR_EXPERIMENT or $FEATURE of $YOUR_EXPERIMENT to make it function better for your intended research?
6. Explain the reasoning behind a particular design choice for $YOUR_EXPERIMENT. e.g. why does IceCube use ice instead of sea water? Why does ATLAS use a liquid argon calorimeter instead of a scintillating crystal calorimeter? Why does DEAP use argon instead of xenon etc.
7. How does a photomultiplier work?
8. Why is the hadronic interaction length for materials longer than the radiation length despite the fact that the strong interaction coupling is larger than the EM interaction?
9. Both the EM and strong interactions are transmitted by massless, spin-1 bosons so why is the EM interaction so different from the strong?
10. What limits the energy of the LHC?

11. Why is the next electron-positron collider likely to be a linear collider instead of a circular one?
12. “You can never observe a free quark.” Why is this statement often made and is it actually true?
13. Explain how the Higgs mechanism gives fundamental particles mass.
14. What types of interaction are we certain the Dark Matter undergoes?
15. What is the evidence for the existence of Dark Matter? Why can it not be explained by an existing SM particle?
16. If Dark Matter was produced in a collider and did not interact with the detector, how can we know it was produced?
17. Why does a charged pion decay into a muon rather than an electron despite the electron decay having a much larger mass difference and hence phase space?
18. Would you expect there to be roughly equal numbers of neutrinos and anti-neutrinos in a cosmic ray shower? Explain.
19. At low energies neutrinos can penetrate light-year thicknesses of ordinary matter. Is this true at high (>100 TeV) energies? Explain.
20. What problem with the Standard Model was Supersymmetry invented to solve and how does it solve it?
21. What are C, P and T symmetries. Which individual and combined symmetries are violated and provide examples.
22. What is the evidence for there only being three generations of leptons?
23. What is the evidence for there only being three generations of quarks?
24. What phenomena/non would the Standard Model be completely unable to explain with less than three generations of quarks and leptons?
25. What was the November revolution in particle physics?
26. How do we know that gluons exist?
27. How do we know that neutrinos oscillate between flavours?
28. What is the MSW effect?
29. What is the difference between a majorana neutrino and a dirac neutrino? Why do we only discuss this for neutrinos and not charged leptons?
30. Using only known and experimentally confirmed physics, can a muon decay into just an electron and a photon?
31. How would you go about measuring the absolute mass of a neutrino?
32. What is a sterile neutrino?
33. “Large Extra Dimensions”: what is the common feature of these theories, what problem with the Standard Model do they hope to address, and what would their experimental signature be?

Space and Plasma Physics

1. What assumptions are made in the Parker solar wind model?
2. What is the Parker spiral?
3. Explain the “frozen-in” approximation in ideal MHD. Outline a mathematical derivation.
4. Give a phenomenological explanation of ExB and grad-B drifts of charged particles in a magnetised plasma. Illustrate on the board.
5. Given a linear mirror machine with B_{max} at the ends and a constant and uniform magnetic field B_{min} between, derive an expression for the loss cone angle.
6. In question 5 above, what happens to confined particles as the two ends of the mirror (where $B = B_{max}$) are slowly brought closer together?
7. In 6 above, what happens if the two ends are brought closer together ‘very abruptly’?

8. What is the strength of Earth's magnetic field in this room, and what is its approximate direction?
9. Name a few indices used to parametrise magnetospheric activity, and explain how they are measured.
10. Why is the plasmasphere approximately corotating with Earth?
11. What is a typical electron density electron temperature and ion temperature in the solar wind at one AU?
12. Other than H+, what are approximate concentrations of other ions in the solar wind?
13. What is the IRI? What can it be used for and how is it constructed?
14. What is the main ion species present in mid-latitude ionosphere?
15. Explain in physical terms, the Hall and Pedersen conductivities.
16. Describe and explain the equatorial electrojet.
17. What are Birkeland currents. Explain phenomenologically how they are generated.
18. What is the "Terella"?
19. How strong can ionospheric winds be (in m/s)?
20. What is the Carrington event?
21. What causes magnetospheric storms? What are their effects on and near Earth?
22. What is Fermi acceleration of type 1, and 2?
23. Under what space-physical conditions can particles be affected by Fermi acceleration?
24. Derive an expression for the ratio between the electric energy density, the magnetic energy density, and the kinetic energy density in:
    a. an electron plasma wave in an unmagnetised plasma
    b. an ion acoustic wave in an unmagnetised plasma
    c. a shear Alfvén wave in a plasma with a uniform magnetic field
25. Explain particle collisions to someone with very limited knowledge of physics.
26. In a fully ionised non degenerate plasma, which between small angle collisions or large angle collisions dominate?
27. With pure Coulomb collisions (no neutrals), explain how collisions can affect particle and energy diffusion. Which between the two (particle and energy diffusion) is the strongest, and why?
28. What are the conditions (what approximations are needed) for particle and energy transport to be well accounted for with diffusion equations?
29. Describe Landau damping and explain it in physical terms.
30. What is the "echo" phenomenon in the context of Landau damping?
31. What is the "equatorial fountain"? Who discovered it, in what year, and how?
32. Name a few ground-based space physics programs based in Canada, or that Canada participates in, and briefly describe their research focus.
33. What is the difference between a wave phase velocity and its group velocity? How are these derived mathematically?