# 2019-2020 Graduate Calendar

The information published in this Graduate Calendar outlines the rules, regulations, curricula, programs and fees for the 2019-2020 academic year, including the Summer Semester 2019, Fall Semester 2019 and the Winter Semester 2020.

For your convenience the Graduate Calendar is available in PDF format.

If you wish to link to the Graduate Calendar please refer to the Linking Guidelines.

The University is a full member of:

- Universities of Canada

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| May 1, 2019 | Initial Publication |
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# Disclaimer

The Office of Graduate and Postdoctoral Studies has attempted to ensure the accuracy of this on-line Graduate Calendar. However, the publication of information in this document does not bind the university to the provision of courses, programs, schedules of studies, fees, or facilities as listed herein.

## Limitations

The University of Guelph reserves the right to change without notice any information contained in this calendar, including any rule or regulation pertaining to the standards for admission to, the requirements for the continuation of study in, and the requirements for the granting of degrees or diplomas in any or all of its programs.

The university will not be liable for any interruption in, or cancellation of, any academic activities as set forth in this calendar and related information where such interruption is caused by fire, strike, lock-out, inability to procure materials or trades, restrictive laws or governmental regulations, actions taken by the faculty, staff or students of the university or by others, civil unrest or disobedience, Public Health Emergencies, or any other cause of any kind beyond the reasonable control of the university.

The University of Guelph reaffirms section 1 of the Ontario Human Rights Code, 1981, which prohibits discrimination on the grounds of race, ancestry, place of origin, colour, ethnic origin, citizenship, creed, sex, sexual orientation, handicap, age, marital status or family status.

The university encourages applications from women, aboriginal peoples, visible minorities, persons with disabilities, and members of other under-represented groups.

# Introduction

## Collection, Use and Disclosure of Personal Information

Personal information is collected under the authority of the University of Guelph Act (1964), and in accordance with Ontario's Freedom of Information and Protection of Privacy Act (FIPPA) http://www.e-laws.gov.on.ca/DBLaws/Statutes/English/90f31_e.htm. This information is used by University officials in order to carry out their authorized academic and administrative responsibilities and also to establish a relationship for alumni and development purposes. Certain personal information is disclosed to external agencies, including the Ontario Universities Application Centre, the Ministry of Advanced Education and Skills Development, and Statistics Canada, for statistical and planning purposes, and is disclosed to other individuals or organizations in accordance with the Office of Registrarial Services Departmental Policy on the Release of Student Information. For details on the use and disclosure of this information call the Office of Registrarial Services at the University at (519) 824-4120 or see https://www.uoguelph.ca/registrar/

## Statistics Canada - Notification of Disclosure

For further information, please see Statistics Canada's web site at http://www.statcan.gc.ca and Section XIV Statistics Canada.

## Address for University Communication

Depending on the nature and timing of the communication, the University may use one of these addresses to communicate with students. Students are, therefore, responsible for checking all of the following on a regular basis:

### Email Address

The University issued email address is considered an official means of communication with the student and will be used for correspondence from the University. Students are responsible for monitoring their University-issued email account regularly.

### Home Address

Students are responsible for maintaining a current mailing address with the University. Address changes can be made, in writing, through Registrarial Services.

## Name Changes

The University of Guelph is committed to the integrity of its student records, therefore, each student is required to provide either on application for admission or on personal data forms required for registration, their complete, legal name. Any requests to change a name, by means of alteration, deletion, substitution or addition, must be accompanied by appropriate supporting documentation.

## Student Confidentiality and Release of Student Information Policy Excerpt

The University undertakes to protect the privacy of each student and the confidentiality of their record. To this end the University shall refuse to disclose personal information to any person other than the individual to whom the information relates where disclosure would constitute an unjustified invasion of the personal privacy of that person or of any other individual. All members of the University community must respect the confidential nature of the student information which they acquire in the course of their work.

Complete policy at https://www.uoguelph.ca/secretariat/office-services/university-secretariat/university-policies .

# Learning Outcomes

## Graduate Degree Learning Outcomes

On May 27, 2013, the University of Guelph Senate approved the following five University-wide Learning Outcomes as the basis from which to guide the development of graduate degree programs, specializations and courses:

1. Critical and Creative Thinking
2. Literacy
3. Global Understanding
4. Communication
5. Professional and Ethical Behaviour

These learning outcomes are also intended to serve as a framework through which our educational expectations are clear to students and the broader public; and to inform the process of outcomes assessment through the quality assurance process (regular reviews) of programs and departments.

An on-line guide to the learning outcomes, links to the associated skills, and detailed rubrics designed to support the development and assessment of additional program and discipline-specific outcomes, are available for reference on the Learning Outcomes website

### Critical and Creative Thinking

Critical and creative thinking is a concept in which one applies logical principles, after much inquiry and analysis, to solve problems with a high degree of innovation, divergent thinking and risk taking. Those mastering this outcome show evidence of integrating knowledge and applying this knowledge across disciplinary boundaries. Depth and breadth of understanding of disciplines is essential to this outcome. At the graduate level, originality in the application of knowledge (master's) and undertaking of research (doctoral) is expected.

In addition, Critical and Creative Thinking includes, but is not limited to, the following outcomes: Independent Inquiry and Analysis; Problem Solving; Creativity; and Depth and Breadth of Understanding.

### Literacy

Literacy is the ability to extract information from a variety of resources, assess the quality and validity of the material, and use it to discover new knowledge. The comfort in using quantitative literacy also exists in this definition, as does using technology effectively and developing visual literacy.

In addition, Literacy includes, but is not limited to, the following outcomes: Information Literacy, Quantitative Literacy, Technological Literacy, and Visual Literacy.

### Global Understanding

Global understanding encompasses the knowledge of cultural similarities and differences, the context (historical, geographical, political and environmental) from which these arise, and how they are manifest in modern society. Global understanding is exercised as civic engagement, intercultural competence and the ability to understand an academic discipline outside of the domestic context.

In addition, Global Understanding includes, but is not limited to, the following outcomes: Global Understanding, Sense of Historical Development, Civic Knowledge and Engagement, and Intercultural Competence.

### Communication

Communication is the ability to interact effectively with a variety of individuals and groups, and convey information successfully in a variety of formats including oral and written communication. Communication also comprises attentiveness and listening, as well as reading comprehension. It includes the ability to communicate and synthesize information, arguments, and analyses accurately and reliably.

In addition, Communication includes, but is not limited to, the following outcomes: Oral Communication, Written Communication, Reading Comprehension, and Integrative Communication.

### Professional and Ethical Behaviour

Professional and ethical behaviour requires the ability to accomplish the tasks at hand with proficient skills in teamwork and leadership, while remembering ethical reasoning behind all decisions. The ability for organizational and time management skills is essential in bringing together all aspects of managing self and others. Academic integrity is central to mastery in this outcome. At the graduate level, intellectual independence is needed for professional and academic development and engagement.

In addition, Professional and Ethical Behaviour includes, but is not limited to, the following outcomes: Teamwork, Ethical Reasoning, Leadership, Personal Organization and Time Management, and Intellectual Independence.

# Table of Contents

# Physics

The Departments of Physics at the Universities of Guelph and Waterloo offer a joint program leading to MSc and PhD degrees in the following fields:

- Astrophysics and Gravitation
- Atomic, Molecular and Optical Physics
- Biophysics
- Chemical Physics
- Condensed Matter and Material Physics
- Industrial and Applied Physics
- Subatomic Physics
- Quantum Computing

The Guelph-Waterloo Physics Institute consists of members from both university departments and is administered by a joint co-ordinating committee. Students interested in graduate work in physics at either university should consult the application requirements and the on-line application procedures available from the web-site https://www.physics.uoguelph.ca/graduate-studies/graduate-studies-in-physics/how-to-apply. Students are ultimately registered at the university at which their advisor is located. A student comes under the general regulations of the university at which he or she is registered, and the degree is granted by that university.

## Administrative Staff

Graduate teaching and research in physics at the University of Guelph are operated through Graduate Studies in Physics, University of Guelph, University of Waterloo.

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**David Yevick**
AB Harvard, MA, PhD Princeton, Docuent Lund - Professor

## MSc Program

The MSc programs is offered in the following fields: 1) astrophysics and gravitation; 2) atomic, molecular and optical physics; 3) biophysics; 4) chemical physics; 5) condensed matter and material physics; 6) industrial and applied physics; 7) subatomic physics; and 8) quantum computing.

### Admission Requirements

Application for admission should be made as early as possible using on-line application methods described on the web-site https://www.physics.uoguelph.ca/graduate-studies/graduate-studies-in-physics/how-to-apply. Successful applicants are encouraged to start their graduate studies in May or September, but a January starting date is possible. Program offices should be consulted for admission deadlines.

The admission requirements are as follows:

- An honours BSc degree in physics (or equivalent) with at least a B standing (75%) from a recognized university.
- Three letters of reference, two of which normally are from academic sources.
- Proof of competency in English (for applicants whose prior education was in a language other than English). See the University regulations on English Language Proficiency Certification.
- GRE Physics Subject Test score for all applicants who have completed their post-secondary education outside of Canada.

Successful applicants are encouraged to start their graduate studies in May or September, but a January starting date is possible. Academic transcripts and other supporting documents should be forwarded as soon as they become available. Admission to the program cannot be granted until all requirements have been met and all documents submitted.

Applications are considered by the Admissions Committee. It should be noted that students will normally be admitted only if an advisor can be found to oversee their research. Since there are a limited number of openings each year, applicants are advised to state alternative areas of research on the preference form supplied (see web-site https://www.physics.uoguelph.ca/graduate-studies/graduate-studies-in-physics/how-to-apply).

### Program Requirements

Students enrol in one of two study options: 1) thesis, or 2) course work and major research project.

#### Thesis

Four one-term courses (at least 2.0 course credits) acceptable for graduate credit and a thesis based on original research are required. The subject of research must be approved by the candidate's advisory committee and the thesis must be read and approved by the advisory committee. One of the four courses may be an undergraduate course approved by the student's advisory committee and the Graduate Program Coordinator. If it is a physics course, it must be at the fourth-year level.

For all students one of the courses must include at least one of Quantum Mechanics 1 (PHYS*7010), Introduction to Quantum Field Theory (PHYS*7030), Statistical Physics 1 (PHYS*7040), Electromagnetic Theory (PHYS*7060), and Fundamentals of Astrophysics (PHYS*7810). An MSc student in this program who shows a particular aptitude for research and has a superior record in fourth-year undergraduate and three one-term graduate courses may be permitted, upon recommendation of the advisor and with the approval of the co-ordinating committee, to transfer into the PhD program without completing an MSc thesis.

An average of at least 70% must be obtained in the required courses. A minimum grade of 65% is required for a pass in each course. No more than two courses, of the first four taken, can have a grade of less than 70%. If a student does not meet these minimum grade requirements, or receives a failing grade in any course, they may be required to withdraw from the program.

### Course Work and Major Research Project (MRP)

Eight one-term courses (0.50 unit weight) acceptable for graduate credit, including a project course summarized in a report, are required. The project must be approved by the candidate's advisor and the report read and approved by the advisor and one other faculty member. [Exception: biophysics students taking the course-based MSc option are required to take only one of the core courses PHYS*7010, PHYS*7030, PHYS*7040, PHYS*7060, PHYS*7670, and PHYS*7810]. Two of the courses may be undergraduate courses approved by the advisor and the Graduate Advisory Committee. If they are Physics courses, they must be at the fourth year level. This program is recommended for those planning careers requiring a broad non-specialized knowledge of physics (for example, high school teaching).

## PhD Program

The PhD program is research-based and offered in the fields of: 1) astrophysics and gravitation; 2) atomic, molecular and optical physics; 3) biophysics; 4) chemical physics; 5) condensed matter and material physics; 6) industrial and applied physics; 7) subatomic physics; and 8) quantum computing.

## Admission Requirements

There are three pathways for admission to the PhD program:

1. An MSc degree in physics from an approved university or college with at least a B standing (75%) is normally required for entrance into the PhD program. Other requirements are the same as those described above for the MSc program (see web-site https://www.physics.uoguelph.ca/graduate-studies/graduate-studies-in-physics/how-to-apply).
2. Students with an undergraduate degree in Physics may apply for admission directly to the PhD program. Successful applicants will have an outstanding academic record, breadth of knowledge in physics, previous research experience, and strong letters of recommendation.
3. Students wishing to be considered for transfer to a PhD program prior to completion of the MSc program must request the transfer up to 3 full-time terms after initial registration and have an excellent academic record as well as a strong aptitude for research.

## Program Requirements

The core courses for the program are Quantum Mechanics 1 PHYS*7010, Introduction to Quantum Field Theory PHYS*7030, Statistical Physics 1 PHYS*7040, Electromagnetic Theory PHYS*7060, Introduction to Quantum Information Processing PHYS*7670, and Fundamentals of Astrophysics PHYS*7810. By the end of the first year of the program, three of the core courses, including one of Quantum Mechanics 1 PHYS*7010, Statistical Physics 1 PHYS*7040 and Electromagnetic Theory PHYS*7060 or their equivalent should be completed. This requirement may be satisfied, in full or in part, by courses taken during the M.Sc. (Exception: Biophysics students must have taken at least one of Quantum Mechanics 1 PHYS*7010, Statistical Physics 1 PHYS*7040, and Electromagnetic Theory PHYS*7060 by the completion of the first year of the PhD program.)

Two one-term courses not including any already taken for MSc credit are required; courses taken during the MSc program and in excess of those required will, however, be allowed for PhD credit. The extra courses must be identified prior to admission. One of the required courses may be an undergraduate course outside the student's main field of study and must be approved by the student's advisory committee and the Graduate Program Coordinator. No undergraduate course in physics may be taken for credit.

An average of at least 70% must be obtained in the required courses. A minimum grade of 65% is required for a pass in each course. No more than two courses, of the first four taken, can have a grade of less than 70%. If a student does not meet these minimum grade requirements, or receives a failing grade in any course, they may be required to withdraw from the program.

Students who transfer to the PhD, or who enter the PhD directly, will need to complete the course work requirements of both the MSc and PhD degrees, a total of six one-term graduate courses. Three of the core courses including one of Physics 7010, Physics 7040 or Physics 7060 will have been taken by the end of the first year of the PhD program.

## Interdepartmental Programs

## Biophysics Interdepartmental Group

The Department of Physics participates in the MSc/PhD programs in biophysics. Please consult the Biophysics listing for a detailed description of the graduate programs offered by the Biophysics Interdepartmental Group.

## Courses

* Courses offered annually. Other courses are offered on an alternate year basis and as requested.

## Perimeter Scholars' Institute Courses

**PHYS*6010 PSI Quantum Field Theory I U [0.50]**

Canonical quantization of fields, perturbation theory, derivation of Feynman diagrams, applications in particle and condensed matter theory, renormalization in phi^4.

*Department(s):* Department of Physics

**PHYS*6020 PSI Statistical Physics U [0.50]**

A brief review of ensembles and quantum gases, lsing model, landau theory of phase transitions, order parameters, topology, classical solutions.

*Department(s):* Department of Physics

**PHYS*6030 PSI Quantum Field Theory II U [0.50]**

Feynman Path Integral, abelian and nonabelian guage theories and their quantization, spontaneous symmetry breaking, nonperturbative techniques: lattice field theory, Wilsonian renormalization.

*Department(s):* Department of Physics

**PHYS*6040 PSI Relativity U [0.50]**

Special relativity, foundations of general relativity, Riemannain geometry, Einstein's equations, FRW and Schwarzschild geometries and their properties.

*Department(s):* Department of Physics

**PHYS*6050 PSI Quantum Theory U [0.50]**

Schrodinger equation: free particle, harmonic oscillator, simple time-dependent problems, Heisenberg picture and connection with classical physics. Entanglement and non-locality. Pure and mixed states, quantum correlators, measurement theory and interpretation.

*Department(s):* Department of Physics

**PHYS*6060 PSI Information and Data Analysis U [0.50]**

Probability, entropy, Bayesian inference and information theory. Maximum likelihood methods, common probability distributions, applications to real data including Monte Carlo methods.

*Department(s):* Department of Physics

**PHYS*6070 PSI Dynamical Systems U [0.50]**

Maps, flows, stability, fixed points, attractors, chaos, bifurcations, ergodicity, approach to chaos. Hamiltonian systems, Liouville, measure, Poincare theorem, integrable systems with examples.

*Department(s):* Department of Physics

**PHYS*6080 PSI Computation U [0.50]**

Common algorithms for ode and pde solving, with numerical analysis. Common tasks in linear algebra. Focus on how to write a good code, test it, and obtain a reliable result. Parallel programing.

*Department(s):* Department of Physics

**PHYS*6210 PSI Cosmology U [0.25]**

FRW metic, Hubble expansion, dark energy, dark matter, CMB, Thermodynamic history of early universe. Growth of perturbations, CDM model of structure formation and comparison to observations, cosmic microwave background anisopropies, inlation and observational tests.

*Department(s):* Department of Physics

**PHYS*6220 PSI Standard Model U [0.25]**

Application of Yan-Mills theory to particle physics, QCD and its tests in the perturbative regime, theory of weak interactions, precisions tests of electroweak theory, CKM matrix and flavour physics, open questions.

*Department(s):* Department of Physics

**PHYS*6230 PSI String Theory U [0.25]**

Superstring spectrum in 10d Minkowski, as well as simple toroidal and orbifold compactifications. T-duality, D-branes, tree amplitudes. Construct some simple unified models of particle physics. Motivate the 10- 11-dimensional supergravities. Simple supergravity solutions and use these to explore some aspects of adS/CFT duality.

*Department(s):* Department of Physics

**PHYS*6240 PSI Mathematical Physics Topics U [0.25]**

Differential forms, de Rham cohomology, differential topology and characteristic classes, monopoles and instantons, Kahler manifolds, Dirac equations, zero modes and index theorems.

*Department(s):* Department of Physics

**PHYS*6350 PSI Quantum Information Review U [0.25]**

Review of selected topics in Quantum Information.

*Department(s):* Department of Physics

**PHYS*6360 PSI Gravitational Physics Review U [0.25]**

Review of selected topics in Gravitational Physics.

*Department(s):* Department of Physics

**PHYS*6370 PSI Condensed Matter Theory U [0.25]**

Review of selected topics in Condensed Matter Theory.

*Department(s):* Department of Physics

**PHYS*6380 PSI Quantum Gravity U [0.25]**

Review of selected topics in Quantum Gravity.
*Department(s):* Department of Physics

**PHYS*6390 PSI Foundations of Quantum Theory U [0.25]**

Review of selected topics in Foundations of Quantum Theory.
*Department(s):* Department of Physics

**PHYS*6410 PSI Explorations in Quantum Information U [0.25]**

Review of selected topics in Quantum Information.
*Department(s):* Department of Physics

**PHYS*6420 PSI Explorations in Gravitational Physics U [0.25]**

Review of selected topics in Gravitational Physics.
*Department(s):* Department of Physics

**PHYS*6430 PSI Exploration in Condensed Matter Theory U [0.25]**

Review of selected topics in Condensed Matter Theory.
*Department(s):* Department of Physics

**PHYS*6440 PSI Exploration in Quantum Gravity U [0.25]**

Review of selected topics in Quantum Gravity.
*Department(s):* Department of Physics

**PHYS*6450 PSI Explorations in Foundations of Quantum Theory U [0.25]**

Review of selected topics in Foundations of Quantum Theory.
*Department(s):* Department of Physics

**PHYS*6460 PSI Explorations in Particle Physics U [0.25]**

Review of selected topics in Particle Physics.
*Department(s):* Department of Physics

**PHYS*6470 PSI Explorations in String Theory U [0.25]**

Review of selected topics in String Theory.
*Department(s):* Department of Physics

**PHYS*6480 PSI Explorations in Complex Systems U [0.25]**

Review of selected topics in Complex Systems.
*Department(s):* Department of Physics

**PHYS*6490 PSI Explorations in Cosmology U [0.25]**

Review of selected topics in Cosmology.
*Department(s):* Department of Physics

## Basic Group

**PHYS*7010 Quantum Mechanics I * U [0.50]**

Review of formalism of nonrelativistic quantum mechanics including symmetries and invariance. Approximation methods and scattering theory. Elementary quantum theory of radiation. Introduction to one-particle relativistic wave equations.
*Department(s):* Department of Physics

**PHYS*7020 Quantum Mechanics II U [0.50]**

Concepts of relativistic quantum mechanics, elementary quantum field theory, and Feynman diagrams. Application to many-particle systems.

*Prerequisite(s):* PHYS*7010 or equivalent
*Department(s):* Department of Physics

**PHYS*7040 Statistical Physics I* U [0.50]**

Statistical basis of thermodynamics; microcanonical, canonical and grand canonical ensembles; quantum statistical mechanics, theory of the density matrix; fluctuations, noise, irreversible thermodynamics; transport theory; application to gases, liquids, solids.
*Department(s):* Department of Physics

**PHYS*7050 Statistical Physics II U [0.50]**

Phase transitions. Fluctuation phenomena. Kubo's theory of time correlation functions for transport and spectral properties; applications selected from a variety of topics including linearized hydrodynamics of normal and superfluids, molecular liquids, liquid crystals, surface phenomena, theory of the dielectric constant, etc.

*Prerequisite(s):* PHYS*7040 or equivalent.
*Department(s):* Department of Physics

**PHYS*7060 Electromagnetic Theory * U [0.50]**

Solutions to Maxwell's equations; radiation theory, normal modes; multipole expansion; Kirchhoff's diffraction theory; radiating point charge; optical theorem. Special relativity; transformation laws for the electromagnetic field; line broadening. Dispersion; Kramers-Kronig relations. Magnetohydrodynamics and plasmas.
*Department(s):* Department of Physics

**PHYS*7080 Applications of Group Theory U [0.50]**

Introduction to group theory; symmetry, the group concept, representation theory, character theory. Applications to molecular vibrations, the solid state, quantum mechanics and crystal field theory.
*Department(s):* Department of Physics

**PHYS*7670 Introduction to Quantum Information Processing F [0.50]**

Quantum superposition, interference, and entanglement. Postulates of Quantum Mechanics. Quantum computational complexity. Quantum Algorithms. Quantum communication and cryptography. Quantum error correction. Implementations.
*Department(s):* Department of Physics

## Subatomic and Nuclear

**PHYS*7030 Quantum Field Theory U [0.50]**

Review of relativistic quantum mechanics and classical field theory. Quantization of free quantum fields (the particle interpretation of field quants). Canonical quantization of interacting fields (Feynman rules). Application of the formalism of interacting quantum fields to lowest-order quantum electrodynamic processes. Radiative corrections and renormalization.

*Prerequisite(s):* PHYS*7010 or equivalent.
*Department(s):* Department of Physics

**PHYS*7090 Green's Function Method U [0.50]**

Review of essential quantum field theory. Zero and finite temperature. Green's functions. Applications.
*Department(s):* Department of Physics

**PHYS*7150 Nuclear Physics U [0.50]**

Static properties of nuclei; alpha, beta, gamma decay; two-body systems; nuclear forces; nuclear reactions; single-particle models for spherical and deformed nuclei; shell, collective, interacting boson models.
*Department(s):* Department of Physics

**PHYS*7160 Special Topics in Subatomic and Nuclear Physics U [0.50]**

*Restriction(s):* Instructor consent required.
*Department(s):* Department of Physics

**PHYS*7170 Intermediate and High Energy Physics U [0.50]**

Strong, electromagnetic and weak interactions. Isospin, strangeness, conservation laws and symmetry principles. Leptons, hadrons, quarks and their classification, formation, interactions and decay.
*Department(s):* Department of Physics

**PHYS*7180 Special Topics in Subatomic and Nuclear Physics U [0.25]**

*Restriction(s):* Instructor consent required.
*Department(s):* Department of Physics

## Astronomy and Astrophysics

**PHYS*7810 Fundamentals of Astrophysics U [0.50]**

The fundamental astronomical data: techniques to obtain it and the shortcomings present. The classification systems. Wide- and narrow-band photometric systems. The intrinsic properties of stars: colours, luminosities, masses, radii, temperatures. Variable stars. Distance indicators. Interstellar reddening. Related topics.
*Department(s):* Department of Physics

**PHYS*7840 Advanced General Relativity W [0.50]**

Review of elementary general relativity. Timelike and null geodesic congruences. Hypersurfaces and junction conditions. Lagrangian and Hamiltonian formulations of general relativity. Mass and angular momentum of a gravitating body. The laws of black-hole mechanics.
*Department(s):* Department of Physics

**PHYS*7850 Quantum Field Theory for Cosmology U [0.50]**

Introduction to scalar field theory and its canonical quantization in flat and curved spacetimes. The flat space effects of Casimir and Unruh. Quantum fluctuations of scalar fields and of the metric on curved space-times and application to inflationary cosmology. Hawking radiation.

*Prerequisite(s):* PHYS*7010
*Department(s):* Department of Physics

**PHYS*7860 General Relativity for Cosmology U [0.50]**

Introduction to the differential geometry of Lorentzian manifolds. The principles of general relativity. Causal structure and cosmological singularities. Cosmological space-times with Killing vector fields. Friedmann-Lemaitre cosmologies, scalar vector and tensor perturbations in the linear and nonlinear regimes. De Sitter space-times and inflationary models.
*Department(s):* Department of Physics

**PHYS*7870 Cosmology U [0.50]**

Friedmann-Robertson-Walker metric and dynamics; big bang thermodynamics; nucelosynthesis; recombination; perturbation theory and structure formation; anisotropies in the Cosmic Microwave Background; statistics of cosmological density and velocity fields; galaxy formation; inflation.

*Department(s):* Department of Physics

**PHYS*7880 Special Topics in Astronomy U [0.50]**

Offered on demand

*Department(s):* Department of Physics

**PHYS*7890 Special Topics in Astrophysics U [0.25]**

Offered on demand

*Department(s):* Department of Physics

**PHYS*7900 Special Topics in Gravitation and Cosmology U [0.50]**

*Department(s):* Department of Physics

**PHYS*7910 Special Topics in Gravitation and Cosmology U [0.25]**

*Department(s):* Department of Physics

## Atomic and Molecular

**PHYS*7100 Atomic Physics U [0.50]**

Emphasis on atomic structure and spectroscopy. Review of angular momentum, rotations, Wigner-Eckart theorem, n-j symbols. Energy levels in complex atoms, Hartree-Fock theory, radiative-transitions and inner-shell processes. Further topics selected with class interest in mind, at least one of which is to be taken from current literature.

*Department(s):* Department of Physics

**PHYS*7130 Molecular Physics U [0.50]**

Angular momentum and the rotation of molecules; introduction to group theory with application to molecular vibrations; principles of molecular spectroscopy; spectra of isolated molecules; intermolecular interactions and their effects on molecular spectra; selected additional topics (e.g., electronic structure of molecules, experimental spectroscopic techniques, neutron scattering, correlation functions, collision induced absorption, extension of group theory to molecular crystals, normal co-ordinate analysis, etc.).

*Department(s):* Department of Physics

## Condensed Matter

**PHYS*7310 Solid State Physics I U [0.50]**

Phonons, electron states, electron-electron interaction, electron-ion interaction, static properties of solids.

*Department(s):* Department of Physics

**PHYS*7320 Solid State Physics II U [0.50]**

Transport properties; optical properties; magnetism; superconductivity; disordered systems.

*Department(s):* Department of Physics

**PHYS*7330 Special Topics in Theoretical Condensed Matter Physics U [0.50]**

*Department(s):* Department of Physics

**PHYS*7370 Special Topics in Surface Physics U [0.50]**

*Department(s):* Department of Physics

## Biophysics

**PHYS*7510 Clinical Applications of Physics in Medicine U [0.50]**

This course provides an overview of the application of physics to medicine. The physical concepts underlying the diagnosis and treatment of disease will be explored. Topics will include general imaging principles such as resolution, intensity, and contrast; x-ray imaging and computed tomography; radioisotopes and nuclear medicine, SPECT and PET; magnetic resonance imaging; ultrasound imaging and radiation therapy. Offered in conjunction with PHYS*4070. Extra work is required of graduate students.

*Restriction(s):* Credit may be obtained for only one of PHYS*4070 or PHYS*7510.
*Department(s):* Department of Physics

**PHYS*7520 Molecular Biophysics U [0.50]**

Physical methods of determining macromolecular structure: energetics, intramolecular and intermolecular forces, with application to lamellar structures, information storage, DNA and RNA, recognition and rejection of foreign molecules. Offered in conjunction with PHYS*4540. Extra work is required of graduate students.

*Restriction(s):* Credit may be obtained for only one of PHYS*4540 or PHYS*7520
*Department(s):* Department of Physics

**PHYS*7540 Special Topics in Biophysics U [0.50]**

Offered on demand

*Department(s):* Department of Physics

**PHYS*7570 Special Topics in Biophysics U [0.25]**

Offered on demand

*Department(s):* Department of Physics

## Applied Physics (including Technical Methods)

**PHYS*7140 Nonlinear Optics U [0.50]**

Classical and Quantum Mechanical descriptions of nonlinear susceptibility, nonlinear wave propogation, nonlinear effects such as Peckel's and Kerr effects, harmonic generation, phase conjugation and stimulated scattering processes.

*Department(s):* Department of Physics

**PHYS*7450 Special Topics in Experimental Physics * U [0.50]**

A modular course in which each module deals with an established technique of experimental physics. Four modules will be offered during the Winter and Spring semesters, but registration and credit will be in the spring semester. Typical topics are neutron diffraction, light scattering, acoustics, molecular beams, NMR, surface analysis, etc.

*Department(s):* Department of Physics

**PHYS*7470 Optical Electronics U [0.50]**

Optoelectronic component fabrication, light propogation in linear and nonlinear media, optical fiber properties, electro-optic and acousto-optic modulation, spontaneous and stimulated emission, semiconductor lasers and detectors, nose effects in fiber systems.

*Department(s):* Department of Physics

## Special Courses (offered on demand only)

**PHYS*7120 Special Topics in Theoretical Physics U [0.50]**

*Department(s):* Department of Physics

**PHYS*7710 Special Lecture and Reading Course U [0.50]**

*Department(s):* Department of Physics

**PHYS*7730 Special Topics in Physics U [0.50]**

*Department(s):* Department of Physics

**PHYS*7750 Interinstitution Exchange U [0.50]**

At the GWPI director's discretion, a PhD or MSc student may receive credit for a term of specialized studies at another institution. Formal evaluation is required.

*Restriction(s):* GWPI director approval required
*Department(s):* Department of Physics

**PHYS*7970 MSc Project U [1.00]**

Study of a selected topic in physics presented in the form of a written report. For students whose MSc program consists entirely of courses

*Department(s):* Department of Physics