

PHYSICS

PHY

Department of Physics
and Astronomy
College of Natural Science

101 Concepts in Physics

Fall. 1(1-0)

Conceptual foundations of physics emphasizing key experiments.

102 Physics Computations I

Spring. 1(0-3) P: (PHY 183 or concurrently) or (PHY 183B or concurrently) or (PHY 193H or concurrently) or (PHY 181B or concurrently) RB: CSE 101 or CSE 231

Use of Mathematica to solve, analyze and graph equations and data from mechanics.

170 Investigations in Physics

Fall. 3(0-6) R: Open to freshmen in the Department of Physics and Astronomy. Approval of department.

Experiments in optics, electronics, sound and mechanics; analysis of data using computers, library research and oral presentations.

183 Physics for Scientists and Engineers I

Fall, Spring. 4(5-0) P: MTH 132 or MTH 152H or LB 118 Not open to students with credit in LB 271 or PHY 193H or PHY 231 or PHY 231C.

Mechanics, Newton's laws, momentum, energy conservation laws, rotational motion, oscillation, gravity, and waves.

183B Physics for Scientists and Engineers I

Fall, Spring, Summer. 4 credits. P: MTH 132 or MTH 152H or LB 118 Not open to students with credit in PHY 183 or PHY 193H or PHY 231 or PHY 231C or LB 271.

Mechanics, Newton's laws, momentum, energy conservation laws, rotational motion, oscillation, gravity, waves.

184 Physics for Scientists and Engineers II

Fall, Spring. 4(5-0) P: (PHY 183 or PHY 183B or PHY 193H or PHY 233B or LB 271) and (MTH 133 or MTH 153H or LB 119) Not open to students with credit in LB 272 or PHY 184B or PHY 232 or PHY 234B or PHY 294H or PHY 232C.

Electricity and magnetism, electromagnetic waves, light and optics, interference and diffraction.

184B Physics for Scientists and Engineers II

Fall, Spring, Summer. 4 credits. P: (PHY 183 or PHY 183B or PHY 193H) or (PHY 231 and PHY 233B) or (PHY 231C and PHY 233B) or (LB 271 and PHY 233B) RB: MTH 133 or MTH 153H or LB 119 Not open to students with credit in LB 272 or PHY 184 or PHY 232 or PHY 232C or PHY 294H.

Electricity and magnetism, electromagnetic waves, light and optics, interference and diffraction.

191 Physics Laboratory for Scientists, I

Fall. 1(0-3) P: (PHY 183 or concurrently) or (PHY 183B or concurrently) or (PHY 193H or concurrently) or (PHY 231 or concurrently) or (LB 271 or concurrently) or (PHY 181B or concurrently) Not open to students with credit in LB 271L or PHY 251.

Error analysis, exercises in motion, forces, conservation laws and some electricity and magnetism studies.

192 Physics Laboratory for Scientists, II

Spring. 1(0-3) P: PHY 191 and ((PHY 184 or concurrently) or (LB 272 or concurrently) or (PHY 184B or concurrently) or (PHY 294H or concurrently) or (PHY 232 or concurrently) or (PHY 232C or concurrently)) Not open to students with credit in LB 272L or PHY 252.

Electric and magnetic fields, circuits, wave optics, modern physics.

193H Honors Physics I-Mechanics

Spring. 3(4-0) P: (MTH 133 or concurrently) or (MTH 153H or concurrently) or (LB 119 or concurrently) Not open to students with credit in LB 271 or PHY 183 or PHY 231 or PHY 231C.

Mechanics and waves.

201 Physics Computations II

Fall. 1(0-3) P: (PHY 184 or concurrently) or (PHY 184B or concurrently) or (PHY 294H or concurrently) RB: MTH 133 and PHY 102

Computer methods to analyze and visualize physics problems. Tools used will include programming languages (Fortran) and mathematical software (Mathematica, etc).

205 Directed Studies

Fall, Spring, Summer. 1 to 3 credits. A student may earn a maximum of 3 credits in all enrollments for this course. R: Approval of department.

Guided individualized study in an area of physics.

213H Navigating the Universe

Spring. 3(3-0) Interdepartmental with Integrative Studies in Physical Science. Administered by Integrative Studies in Physical Science. P: (MTH 103 or MTH 110 or MTH 116 or (LB 118 or concurrently) or (MTH 112 or concurrently) or (MTH 124 or concurrently) or (MTH 132 or concurrently) or (MTH 201 or concurrently) or (STT 200 or concurrently) or (STT 201 or concurrently)) or designated score on Mathematics Placement test RB: High school physics, high school algebra, and high school trigonometry

Philosophical and biographical history of physics. Comparing physics of fields, relativity, quantum mechanics, elementary particle physics, and cosmology to art as an alternate way of understanding and representing the world.

215 Thermodynamics and Modern Physics

Fall, Spring. 3(4-0) P: ((PHY 184 or concurrently) or (PHY 184B or concurrently) or (PHY 294H or concurrently) or (LB 272 or concurrently) or (PHY 234B or concurrently) and ((MTH 234 or concurrently) or (MTH 254H or concurrently) or (LB 220 or concurrently)) Not open to students with credit in PHY 215B.

Thermodynamics, atomic physics, quantized systems, nuclear physics, solids, elementary particles.

215B Thermodynamics and Modern Physics

Fall, Spring, Summer. 3 credits. P: ((PHY 184 or concurrently) or (PHY 184B or concurrently) or (LB 272 or concurrently) or (PHY 294H or concurrently) or (PHY 234B or concurrently) and (MTH 234 or MTH 254H or LB 220) Not open to students with credit in PHY 215.

Thermodynamics, atomic physics, quantized systems, nuclear physics, solids, elementary particles. This course is given in the competency based instruction format.

231 Introductory Physics I

Fall, Spring. 3(4-0) P: MTH 103 or MTH 116 or LB 118 or MTH 124 or (MTH 132 or concurrently) Not open to students with credit in LB 271 or PHY 183 or PHY 183B or PHY 193H or PHY 231C.

Mechanics, Newton's Laws, momentum, energy, conservation laws, thermodynamics, waves, sound.

231C Introductory Physics I

Fall, Spring. 3 credits. P: MTH 103 or MTH 116 or MTH 124 or (MTH 132 or concurrently) or LB 118 RB: MTH 116 Not open to students with credit in LB 271 or PHY 183 or PHY 183B or PHY 193H or PHY 231.

Mechanics, Newton's Laws, momentum, energy, conservation laws, thermodynamics, waves, sound. This course is an internet based course.

232 Introductory Physics II

Fall, Spring. 3(4-0) P: PHY 231 or PHY 231C or PHY 183 or PHY 183B or PHY 193H or LB 271 Not open to students with credit in LB 272 or PHY 184 or PHY 184B or PHY 232C.

Electricity and magnetism; optics; atomic, nuclear, and subnuclear physics.

232C Introductory Physics II

Fall, Spring. 3 credits. P: PHY 231 or PHY 231C or PHY 193H or LB 271 Not open to students with credit in LB 272 or PHY 184 or PHY 184B or PHY 232 or PHY 294H.

Electricity and magnetism; optics; atomic, nuclear, and subnuclear physics. This course is an internet based course.

233B Calculus Concepts in Physics I

Fall, Spring, Summer. 2 credits. P: (PHY 231 or PHY 231C) and (MTH 132 or MTH 152H or LB 118) Not open to students with credit in PHY 183 or PHY 193H.

Kinematics, dynamics, applications of Newton's laws. PHY 231B plus PHY 233B is equivalent to PHY 183B. This course is given in the competency based instruction format.

234B Calculus Concepts in Physics II

Fall, Spring, Summer. 2 credits. P: (PHY 232 or PHY 232C) and ((MTH 133 or concurrently) or (MTH 153H or concurrently) or (LB 119 or concurrently))

Electricity and magnetism. PHY 232 (or PHY 232C) plus PHY 234B equals PHY 184. This course is given in the competency based instruction format.

251 Introductory Physics Laboratory I

Fall, Spring, Summer. 1(0-2) P: (PHY 231 or concurrently) or (PHY 231B or concurrently) or (LBS 271 or concurrently) or (PHY 183 or concurrently) or (PHY 183B or concurrently) or (PHY 231C or concurrently) or (PHY 193H or concurrently) RB: MTH 103 Not open to students with credit in LBS 271L or PHY 191.

Laboratory exercises involving simple mechanical systems.

252 Introductory Physics Laboratory II

Fall, Spring, Summer. 1(0-2) P: (PHY 251 or PHY 191 or LB 271L) and ((PHY 232 or concurrently) or (PHY 232C or concurrently) or (PHY 184 or concurrently) or (PHY 184B or concurrently) or (PHY 294H or concurrently) or (LB 272 or concurrently)) Not open to students with credit in LB 272L or PHY 192.

Laboratory exercises involving simple electromagnetic and optical systems.

Physics—PHY

- 294H Honors Physics II-Electromagnetism**
Fall. 3(4-0) P: PHY 193H and ((MTH 234 or concurrently) or (MTH 254H or concurrently) or (LB 220 or concurrently)) Not open to students with credit in LB 271 or PHY 184 or PHY 184B or PHY 232 or PHY 232C.
Electricity and magnetism, electromagnetic waves and optics.
- 305 Directed Studies**
Fall, Spring, Summer. 1 to 3 credits. A student may earn a maximum of 3 credits in all enrollments for this course. P: PHY 184 or PHY 184B or PHY 232 or PHY 232B or PHY 232C or PHY 294H or LBS 272 R: Approval of department.
Guided individualized study in an area of physics.
- 321 Classical Mechanics I**
Spring, Summer. 3(3-0) P: (PHY 184 or PHY 184B or PHY 294H or LB 272) and ((PHY 215 or concurrently) or (PHY 215B or concurrently)) and ((MTH 234 or concurrently) or (MTH 254H or concurrently) or (LB 220 or concurrently))
Newtonian point particles. Oscillations. One-particle chaos. Central-force motion. Systems of particles.
- 357B Topics in Contemporary Physics**
Fall, Spring, Summer. 3 credits. P: PHY 215 or PHY 215B RB: PHY 184 or PHY 184B or PHY 294H or PHY 234B or LBS 272 R: Not open to students in the Department of Physics and Astronomy.
Atoms and nuclei, weak decay interaction, weak bosons, strong interaction, conservation laws, quarks and gluons. This course is given in the competency based instruction format.
- 390 Physics Journal Seminar**
Spring. 1(3-0) P: Completion of Tier I writing requirement. R: Open only to juniors or seniors in the Department of Physics and Astronomy or Lyman Briggs School.
Written and oral reports on selected articles in the current literature. Critique of presentations by peers.
- 405 Directed Studies**
Fall, Spring, Summer. 1 to 3 credits. A student may earn a maximum of 5 credits in all enrollments for this course. P: PHY 184 or PHY 184B or PHY 232 or PHY 232B or PHY 232C or PHY 294H or LBS 272 R: Approval of department.
Guided independent study of special topics.
- 410 Thermal and Statistical Physics**
Spring. 3(3-0) P: PHY 471
Equilibrium statistical mechanics and thermodynamics, kinetic theory, phase transformations.
- 415 Methods of Theoretical Physics**
Spring of odd years. 4(4-0) Interdepartmental with Lyman Briggs. Administered by Lyman Briggs. P: ((MTH 234 or concurrently) or (LB 220 or concurrently) or (MTH 254H or concurrently)) and (LB 271 or PHY 183 or PHY 193H) and (LB 272 or PHY 184 or PHY 294H) RB: (MTH 235 or concurrently) or (MTH 255H or concurrently) or (MTH 340 or concurrently) R: Open to students in the College of Engineering or in the Lyman Briggs College or in the Department of Mathematics or in the Department of Physics and Astronomy. SA: LBS 415
Mathematical methods applied to physical problems in mechanics, electromagnetism, and thermodynamics. Multiple integration, vector calculus, Fourier series, ordinary and partial differential equations, eigenvector problems, coordinate transformations, and complex analysis. Newtonian mechanics, rigid body dynamics, heat flow, electrostatics, harmonic motion, and waves.
- 422 Classical Mechanics II**
Fall. 3(3-0) P: PHY 321
Hamiltonian and Lagrangian mechanics. Non-inertial frames. Coupled oscillations. Continuous systems.
- 423B Special Relativity**
Summer. 3 credits. P: PHY 321 RB: Some understanding about electric and magnetic fields.
Concepts of special relativity applied to coordinate transformations, mechanics, and electrodynamics. This course is given in the competency based instruction format.
- 431 Optics I**
Fall. 3(2-3) P: ((PHY 192 or LB 272L) and completion of Tier I writing requirement) and (PHY 184 or PHY 184B or PHY 234B or PHY 294H or LB 272) and (PHY 215 or PHY 215B)
Lenses, aberrations, apertures, and stops. Diffraction, interferometry, spectroscopy, fiber optics.
- 440 Electronics**
Spring. 4(3-3) P: (PHY 192 or LB 272L) and ((MTH 235 or concurrently) or (MTH 255H or concurrently) or (LB 220 or concurrently)) and ((PHY 184 or concurrently) or (PHY 184B or concurrently) or (PHY 294H or concurrently) or (LB 272 or concurrently))
Concepts of electronics used in investigating physical phenomena. Circuits, amplifiers, diodes, LEDs, transistors.
- 451 Advanced Laboratory**
Fall. 3(1-6) P: (PHY 440) and completion of Tier I writing requirement
General research techniques, design of experiments, and the analysis of results based on some historical experiments in modern physics.
- 471 Quantum Physics I**
Fall. 3(3-0) P: (PHY 215 or PHY 215B) and (PHY 321 or concurrently) and (MTH 235 or MTH 255H or LB 220)
Schrödinger equation, hydrogen atom, harmonic oscillator, and other one-dimensional systems.
- 472 Quantum Physics II**
Spring. 3(3-0) P: PHY 471 RB: A Mathematics course on Boundary-Value Problems
Matrix formulation of quantum mechanics, perturbation theory, scattering.
- 480 Computational Physics**
Spring of even years. 3(3-0) RB: CSE 131 or CSE 230
Applications of scientific computational techniques to solutions of differential equations, matrix methods, and Monte Carlo methods used in physics.
- 481 Electricity and Magnetism I**
Fall. 3(3-0) P: MTH 234 or MTH 254H or LB 220 R: Open to juniors or seniors or graduate students.
Electrostatics, dielectrics, magnetic fields of steady state currents, Faraday law of induction.
- 482 Electricity and Magnetism II**
Spring. 3(3-0) P: PHY 481 RB: A Mathematics course on Boundary-Value Problems. R: Open to juniors or seniors or graduate students.
Maxwell's equations, scalar and vector potentials, electromagnetic plane waves.
- 490 Senior Thesis**
Fall, Spring, Summer. 1 to 4 credits. A student may earn a maximum of 5 credits in all enrollments for this course. P: (PHY 390) and completion of Tier I writing requirement R: Open to seniors in the Department of Physics and Astronomy or in the Chemical Physics major or in the Bachelor of Arts in Physics or in the Bachelor of Science in Physics or in the Physics and Geophysics major. Approval of department.
Design, carry out, and analyze an original experiment or computation. A written and oral report is required.
- 491 Atomic, Molecular, and Condensed Matter Physics**
Fall. 3(3-0) P: (PHY 471 and PHY 410) and completion of Tier I writing requirement
Many-electron atoms. Molecules, crystal structure, lattice dynamics. Band models of metals and semiconductors. Transport properties.
- 492 Nuclear and Elementary Particle Physics**
Spring. 3(3-0) P: (PHY 471) and completion of Tier I writing requirement RB: PHY 472
Properties of nuclei, nuclear models, nuclear reactions. High-energy accelerators. Weak, electromagnetic and strong interactions. Symmetries and conservation laws. Elementary particle spectrum, quarks, gluons.
- 800 Research Methods**
Fall, Spring, Summer. 3(3-0) A student may earn a maximum of 6 credits in all enrollments for this course.
Design and setup of experiments in various faculty research areas. Data collection and analysis. Study and practice of theoretical methods.
- 810 Methods of Theoretical Physics**
Fall. 3(3-0)
Theoretical methods used in classical mechanics, quantum mechanics, electrodynamics, and statistical mechanics.
- 820 Classical Mechanics**
Fall. 3(3-0)
Two-body central force problem, Hamilton's principle, Lagrangian and Hamiltonian equations of motion, variational methods, small oscillations, classical fields.
- 831 Statistical Mechanics**
Spring. 3(3-0)
Equilibrium statistical mechanics and thermodynamics. Boltzmann transport equations and hydrodynamics. Brownian and Langevin motion.

- 832 Special Topics in Statistical Mechanics**
Fall, Spring. 3(3-0) A student may earn a maximum of 12 credits in all enrollments for this course. RB: PHY 831 and PHY 841 and PHY 852
Topics vary and may include superfluidity and superconductivity, magnetism, non-linear dynamics and chaos, phase transitions and critical phenomena, transport theory, disordered systems, and computational physics.
- 841 Classical Electrodynamics I**
Spring. 3(3-0) RB: PHY 810
Electrostatics, magnetostatics, time-varying fields and Maxwell's equations. Gauge transformations. Poynting's theorem and conservation laws.
- 842 Classical Electrodynamics II**
Fall. 3(3-0) RB: PHY 841 and (PHY 810 or concurrently)
Plane electromagnetic waves, polarization states, reflection, refraction. Wave guides and resonant cavities. Radiating systems, dipole fields, radiated power. Special theory of relativity.
- 850 Electrodynamics of Plasmas**
Spring of odd years. 3(3-0) Interdepartmental with Astronomy and Astrophysics and Electrical and Computer Engineering. Administered by Electrical and Computer Engineering. RB: ECE 835 or PHY 488 SA: EE 850
Plasma kinetic and macroscopic plasma transport theory. Electromagnetic wave propagation and charged particle diffusion processes in plasma. Electromagnetic energy absorption via elastic and inelastic collisions. Dc, rf, and microwave discharges.
- 851 Quantum Mechanics I**
Fall. 3(3-0) R: Open only to graduate students in the College of Engineering or College of Natural Science.
Axioms of quantum and wave mechanics, applications to spherically symmetric potentials. Hydrogen atom, harmonic oscillator, matrix mechanics, angular momentum theory, rotations.
- 852 Quantum Mechanics II**
Spring. 3(3-0) RB: PHY 851
Approximation methods, perturbation theory, atomic physics applications, scattering theory, identical particles, Pauli principle, Bose and Einstein statistics, Hartree-Fock approximation, collisions of identical particles, radiation.
- 853 Advanced Quantum Mechanics**
Fall. 3(3-0) RB: PHY 852
Quantum description of relativistic particles and fields. Dirac equation, interpretation of negative energy states, Lagrangian field theory, quantization of free fields, interactions, perturbation theory, S-matrix, and Feynman rules.
- 854 Quantum Electrodynamics**
Spring of odd years. 3(3-0) RB: PHY 853
Application of quantum field theory to the interaction of electrons and photons: pair annihilation, Compton scattering. Bound states, renormalization theory.
- 861 Beam Physics**
Spring of odd years. 3(3-0) RB: PHY 820 and PHY 841
Particle accelerator theory and design.
- 891 Elementary Particle Physics**
Spring. 3(3-0) RB: PHY 853
Nonabelian gauge theory, spontaneously broken gauge theory, electroweak interaction, QCD, W and Z boson coupling to quarks and leptons, charm, top and bottom quarks, particle generations.
- 899 Master's Thesis Research**
Fall, Spring, Summer. 1 to 6 credits. A student may earn a maximum of 36 credits in all enrollments for this course. R: Open only to graduate students in the Physics major.
Master's thesis research.
- 901 Frontiers in Physics and Astronomy**
Spring. 1(1-0)
Seminar and discussions in physics. Attendance at weekly colloquium.
- 905 Special Problems**
Fall, Spring. 1 to 4 credits. A student may earn a maximum of 9 credits in all enrollments for this course. R: Open only to graduate students in the Department of Physics and Astronomy.
In-depth study of a topic in physics or in astrophysics and astronomy.
- 911 Group Theory and Symmetry in Physics**
Fall of odd years. 2(2-0) P: PHY 810 and PHY 851 or approval of department
Group representation theory as the general framework to formulate fundamental symmetries in physics. Irreducible states and tensors, projection operator techniques, rotation and translation, Lie groups, Lorentz and Poincare groups. Offered first half of semester.
- 912 Modern Nonlinear Dynamics**
Spring of even years. 2(2-0) P: PHY 820 or approval of department
Nonlinear dynamics of Hamiltonian and dissipative systems; method of averaging; adiabatic invariants; KAM theorem; invariant manifolds; bifurcation theory; dynamical chaos. Offered first half of semester.
- 913 Foundations of Nanoscience and Nanotechnology**
Fall of odd years. 2(2-0) P: PHY 851 or approval of department RB: PHY 971
The self-assembly process and unusual phenomena occurring in nanostructures of carbon. Magnetic aggregates in different size ranges. Finite size and low-dimension effects. Fractional conductance quantization. Response in nanostructures to mechanical stress, high temperature, and electric fields. Offered first half of semester.
- 916 Quantum Transport and Quantum Optics**
Spring of odd years. 2(2-0) P: PHY 831 and PHY 852 or approval of department
Photon counting statistics. Atom-photon interaction. Electron scattering in metals and semiconductors. Low-dimensional systems. Anderson localization. Weak localization.
- 917 Introduction to Elementary Particle Physics**
Spring of odd years. 2(2-0) P: PHY 851 or approval of department RB: PHY 853
The phenomenology of elementary particle physics, emphasizing the experimental evidence for the Standard Model. Role of elementary particle physics in the development of the early universe.
- 961 Non-Linear Beam Dynamics**
Fall, Spring. 3(3-0) A student may earn a maximum of 6 credits in all enrollments for this course. RB: PHY 861
Dynamics of particle beams.
- 962 Particle Accelerators**
Fall, Spring, Summer. 3(3-0) A student may earn a maximum of 6 credits in all enrollments for this course. RB: PHY 861
Theory of particle accelerator design.
- 963 U.S. Particle Accelerator School**
Fall, Spring. 3(3-0) A student may earn a maximum of 12 credits in all enrollments for this course. RB: PHY 861 SA: PHY 962C
Participation in suitable courses offered by the U.S. Particle Accelerator School.
- 964 Seminar in Beam Physics Research**
Fall, Spring. 3(3-0) A student may earn a maximum of 12 credits in all enrollments for this course. RB: PHY 861 SA: PHY 962D
Presentation of current research topics in beam physics or accelerator design.
- 971 Atomic and Electronic Structure of Matter**
Spring. 3(3-0) RB: PHY 491 and PHY 852 and PHY 841 and PHY 831 SA: PHY 871
Atomic structure, bravais lattices, x-ray scattering. Vibrations, phonons, neutron scattering. Electron in solids, electron gas. Bloch's theorem. Metals, semiconductors and insulators. Introduction to cooperative phenomena.
- 972 Transport and Dynamics in Bulk and Mesoscopic Systems**
Fall. 3(3-0) RB: PHY 971 and PHY 831 and PHY 841 and PHY 852
Transport theory. Weak and strong localization. Quantum effects in small structures. Quantum hall effects and Wigner crystal. Superconductivity and other cooperative phenomena.
- 973 Special Topics in Condensed Matter Physics**
Fall, Spring. 3(3-0) A student may earn a maximum of 12 credits in all enrollments for this course. RB: PHY 971 and PHY 972
Topics vary and may include quantum optics, scattering methods and Green's functions.
- 980 Advanced Reading in Physics**
Fall, Spring, Summer. 1 to 3 credits. A student may earn a maximum of 4 credits in all enrollments for this course. R: Approval of department.
- 981 Nuclear Structure**
Fall, Spring. 3(3-0) RB: PHY 492 and PHY 831 and PHY 841 and PHY 852
Nuclear forces, nuclear matter, nuclear-structure models, few-nucleon systems, electromagnetic and weak transitions.
- 982 Nuclear Dynamics**
Spring. 3(3-0) RB: PHY 492 and PHY 831 and PHY 841 and PHY 852
Scattering theory, resonance reactions, compound nuclear decay and fission, direct and breakup reactions, time-dependent Hartree-Fock, Vlasov equation, nuclear transport equations, particle production, nuclear liquid-gas phase transition, quark-gluon plasma.

Physics—PHY

983 Nuclear Astrophysics

Fall, Spring. 3(3-0) RB: PHY 410 and PHY 472 and PHY 482

Low energy reaction theory, survey of astrophysics, physics of nuclei and reaction relevant to astrophysics, nuclear reaction rates in stellar environments, stellar evolution, solar neutrinos, big bang nucleosynthesis, dark matter, supernova explosions, r-process, hot CNO and rp-process, cosmochronology

999 Doctoral Dissertation Research

Fall, Spring, Summer. 1 to 24 credits. A student may earn a maximum of 120 credits in all enrollments for this course. R: Open only to graduate students in the Physics major.

Doctoral dissertation research.