NC STATE UNIVERSITY

College of Engineering
Department of Nuclear Engineering

https://www.ne.ncsu.edu/

Campus Box 7909
Burlington Engineering Labs
2500 Stinson Drive
Raleigh, NC 27695-7909

NE 491/591 Special Topics In Nuclear Engineering
Monte Carlo Methods and Applications

Fall 2022, 3 Credit Hours

1 Course Information

- **Schedule**:
  - *Time:* Mondays and Wednesdays, 10:15 AM - 11:30 AM
  - *Location:* Room 327, 111 Lampe Drive
  - *Course website:* **Moodle** is used to post lecture notes, homework and other materials.
  - *Lecture recordings:* **Panopto** is used to host the lecture recordings.
  - *TA:* Farah Alsafadi, fralsafa@ncsu.edu
- **On-Campus Instructor**:
  - *Instructor:* Dr. Xu Wu, Assistant Professor of Nuclear Engineering
  - *Office:* Burlington Laboratory 2110
  - *Office Hours:* Monday, 1:00 - 3:00 PM, in-person, or Zoom (by appointment)
  - *Phone:* 919-515-6570
  - *Email:* xwu27@ncsu.edu
  - *Website:* https://www.ne.ncsu.edu/people/xwu27
- **Off-Campus Instructor**:
  - *Instructor:* Dr. John Zino, Associate Teaching Professor of Nuclear Engineering
  - *Phone:* (910) 398-2832
  - *Email:* jfzino@ncsu.edu, John.Zino@ge.com
  - *Website:* https://www.ne.ncsu.edu/people/jfzino
- **Course evaluations**:
  - Online class evaluations will be available for students to complete during the last 2 weeks of the semester. It will become unavailable at 8am on the first day of finals.
  - Students will receive an email directing them to a website where they can login using their Unity ID and complete evaluations.
  - All evaluations are **confidential**; instructors will **not** know how any one student responded to any question, and students will not know the ratings for any instructors.
  - Results of the evaluation is revealed to the instructor **after** the grades are posted.
  - Evaluation website: http://go.ncsu.edu/cesurvey

2 Description and Objectives

- This course provides a detailed discussion over the fundamental concepts and issues associated with the Monte Carlo method. Students will be able to learn the fundamental and advanced topics on the application of Monte Carlo techniques to solve radiation transport problems in nuclear engineering.
- The course will cover foundational concepts of probability theory and stochastic methods for discrete and continuous distribution functions. Additionally, applications of generalized Monte Carlo techniques to solve neutron, photon, and electron radiation transport problems typically encountered in reactor physics, shielding, criticality safety, and radiation dosimetry will be addressed.

3 Prerequisites

- NE 301, or basic understanding of nuclear reactor physics.
- Background in Probability and Statistics, equivalent to ST 311 and ST 371.
- Programming experience (e.g., Python, MATLAB) is highly recommended.

4 Outline of Topics

Part 1: Monte Carlo Theory

1. Random Variables and Sampling
   - Discrete and Continuous Random Variables
   - Random Numbers
   - Fundamental Formulation of Monte Carlo (FFMC)
   - Sampling Procedures for One-dimensional and Multi-dimensional Density Functions
2. Random Number Generator (RNG)
   - Random Number Generation Approaches
   - Pseudo-Random Number Generators (PRNGs)
   - Randomness Testing
3. Fundamentals of Probability and Statistics
   - Statistical Moments
   - Sample Statistics
   - Common Discrete and Continuous Distribution Functions
   - Limit Theorems
   - Relative Uncertainty and Confidence Levels
   - Normality Tests

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4. Monte Carlo Integrals and Variance Reduction Techniques
   - Numerical Integrals with Monte Carlo
   - Variance Reduction Techniques
     - Importance sampling
     - Control variates
     - Stratied sampling
     - Combined sampling
5. Fixed-Source Monte Carlo Particle Transport
   - The Linear Boltzmann Equation (LBE)
   - MC for Simplified Particle Transport
   - Perturbation via Correlated Sampling
   - Statistical Reliability of MC Results
   - Variance Reduction for Fixed-Source Particle Transport
     - PDF biasing with Russian roulette
     - Particle splitting with Russian roulette
     - Weight-window technique
     - Integral biasing
     - Hybrid method (CADIS and FW-CADIS)

Part 2: Monte Carlo Applications

6. Geometry Modeling and Particle Tracking
   - Generalized Geometry
   - Surfaces
   - Repeated structures geometry
   - Particle Tracking
7. Physics & Data in MCNP
   - Source definition
   - Materials/Physics Input
   - Cross-sections
   - Scattering tables $S(\alpha, \beta)$
8. Scoring/Tallying
   - Major Physical Quantities in Particle Transport
     - Flux (surface, volume), current, track-length, dose, energy deposition, pulse height, point detector, reaction rates
   - Tallying in Steady-state System

- Tallying in Time-dependent System
- Variance reduction techniques in MCNP

9. Eigenvalue (Criticality) Monte Carlo Method
   - Power Iteration for Eigenvalue Problems
   - Eigenvalue Calculation with MC
   - Derivation and Formulation of the Fission-Matrix (FM) Methodology
   - Application of the FM Method

5 Assignments and Grading Policy

(1) **Homework problems (30%)**, see Table 1.

- Homework will be assigned periodically throughout the semester. The last homework assignment may be due during the last week of classes.
- Homework will be submitted via Moodle.
- *Late submission*: Unless stated otherwise, assignments are due at the beginning of class on the designated due date. Assignments turned in within 24 hours of this time are considered LATE and will be assessed a 25% penalty. Assignments turned in after 24 hours will be marked and returned to the student, but no credit will be assigned.
- To allow for unforeseen circumstances, students are granted a one-time exemption. Exceptions to this policy may be granted for documented medical or family emergencies. But the students need to contact the course instructor before the deadline.

Table 1: Homework

Homework	Weights	Topics
1	5%	Random variables, random numbers, FFMC and sampling
2	5%	RNG/PRNG and randomness testing
3	5%	Statistical moments, limit theorems, confidence level, normality testing
4	5%	MC integrals and variance reduction
5	10%	Fixed-source MC partice transport and its variance reduction

(2) **Mid-term exam (25%)**

(3) **Computational projects (45%)**, see Table 2.

- Project 6 is only for students taking NE 591. For undergraduates taking NE 491, the weights (10%) will be evenly distributed to CP1 - CP5.
- Computational project reports are short (4-5 pages) technical summary describing the details of an engineering analysis. These are not full technical reports but rather abbreviated technical notes which summarizes the key aspects of a study and provide enough detail that a knowledgeable person could re-create the results of the study given the same input and description.

- The basic elements of a computational project report include:
  - Introduction: problem background, definition, and objective statement
  - Input: document all input assumptions, sources, describe MCNP calculation model
  - Analysis: describe calculations performed, show geometry plot
  - Results: present results, show graphs, tables, comparison to measurement, etc.
  - Conclusions: provide a summary of findings.

Table 2: Projects

Project	Weights	Topics
1	5%	Godiva Neutron Leakage benchmark problem: *Modeling of Godiva bare spherical reactor and comparison of measured and calculated neutron energy leakage spectra*
2	5%	Photon Build-up Calculations: *Use MCNP to model unit photon shielding problem and generate gamma-ray buildup factors. Then use BU factors to compare point-kernel results to MCNP*
3	7%	Lead/Poly Shielding Optimization Problem: *Model Cf-252 spontaneous fission source (n,p) and calculate optimum Pb/Poly thicknesses to minimize total neutron and gamma-ray dose rate on other side of shield*
4	8%	Photon-Electron Dosimetry Problem: *Model a series of photon-electron internal dosimetry calculations simulating absorbed fractions for different photon energies and compare results to ICRP-23.*
5	10%	Valduc Critical Benchmark Experiments: *Model a series of pin-lattice critical experiments using* UO_2 *(4.7%) fuel rods in water for different fuel pin-lattice configurations.*
6	10%	Deep penetration streaming problem: *Cs-137 calibration well deep penetration streaming benchmark problem and comparison to measured data*

6 Computational Code - MCNP v6.2

- The MCNP v6.2 computer code will be used to perform all analyses for the computational projects. The MCNP executable (or source code if necessary) and data library can be requested (free of charge for students) at the RSICC website:
  https://rsicc.ornl.gov/Default.aspx
- The RDFMG cluster will be available for the computer projects. Training will be provided on accessing the cluster and running MCNP.
  https://www.ne.ncsu.edu/rdfmg/rdfmg-guide/

7 Recommended Texts

1. **Required textbook**

- **Haghighat, A. (2020). Monte Carlo methods for particle transport. Second Edition, ISBN 9780367188054, CRC Press.**

2. Reactor physics books for reference

- Prinja, A. K., & Larsen, E. W. (2010). General principles of neutron transport. In Handbook of nuclear engineering.
- Lewis, E. E., & Miller, W. F. (1984). Computational methods of neutron transport. ISBN: 978-0-89448-452-01993, 1st Edition
- Carter, L. L., & Cashwell, E. D. (1975). Particle-transport simulation with the Monte Carlo method (No. TID-26607). Los Alamos Scientific Lab., N. Mex.(USA).
- Schaeffer, N. M. (1973). Reactor shielding for nuclear engineers (No. TID-25951). Radiation Research Associates, Inc., Fort Worth, Tex.(USA).

3. Statistical books for reference

- Casella, G., & Berger, R. L. (2002). Statistical inference. Pacific Grove, CA: Duxbury.
- Liu, J. S. (2008). Monte Carlo strategies in scientific computing. Springer Science & Business Media.

4. Further readings

- Turner, J. E., Wright, H. A., & Hamm, R. N. (1985). A Monte Carlo primer for health physicists. Health physics, 48(6), 717-733.
- Werner, C. J. (2017). MCNP Users Manual-Code Version 6.2. Los Alamos National Laboratory, LA-UR-17-29981.
- Zino, J. F. (1992). The need of coupled differential and integral spectral radiation measurements (No. WSRC-MS-92-408; CONF-930907-4). Westinghouse Savannah River Co., Aiken, SC (United States).
- Peterson, R. E., & Newby, G. A. (1956). An unreflected U-235 critical assembly. Nuclear Science and Engineering, 1(2), 112-125.
- Zino, J. F. (1995). Exposure rate response analysis of criticality accident dectector at Savannah River Site (No. WSRC-MS–94-0544). Westinghouse Savannah River Co.

8 Others

(1) **Attendance**

- Required; Active class participation is strongly encouraged.
- University policy on definition of excused absences: https://policies.ncsu.edu/regulation/reg-02-20-03-attendance-regulations/

(2) **Captured Lectures**

- This on campus course will be captured and distributed via the Internet and/or electronic media as part of the Engineering Online (EOL) program for the distance students.

- These video recordings may contain an image of you entering the classroom, asking a question or being a part of the studio class.
- Please notify Dr. Linda Krute, Director of EOL, at ldkrute@ncsu.edu if you DO NOT want your image to be included in the lecture presentation. If EOL does not hear from you after the first week of the class, we will assume that you are in agreement with this procedure.

(3) **Academic Integrity**

- University policy on academic integrity: POL 11.35.01 – Code of Student Conduct `https://policies.ncsu.edu/policy/pol-11-35-01/`
- By signing your name on either test or homework for this course every student implies the following statement: "I have neither given nor received unauthorized aid on this test or assignment".
- Absolutely no collaboration is permitted during closed-book tests.
- Collaboration on homework assignments is allowed, but the submitted work must be your own individual work. Homework assignments must not be treated as group assignments. Zero grade will be assigned for particular homework for the first offense. Second offense will be reported to the Office of Student Conduct.

(4) **Supporting Fellow Students in Distress**

- As members of the NC State Wolfpack community, we each share a personal responsibility to express concern for one another and to ensure that this classroom and the campus as a whole remains a healthy and safe environment for learning.
- Occasionally, you may come across a fellow classmate whose personal behavior concerns or worries you, either for the classmate's well-being or yours. When this is the case, I would encourage you to report this behavior to the NC State's Students of Concern website: `http://go.ncsu.edu/NCSUcares`.
- Although you can report anonymously, it is preferred that you share your contact information so they can follow-up with you personally.

(5) **Students with Disabilities**

- Reasonable accommodations will be made for students with verifiable disabilities. In order to take advantage of available accommodations, students must register with Disability Services for Students at 1900 Student Health Center, Campus Box 7509, 515-7653.
- For more information on NC State's policy on working with students with disabilities, please see the "REG 02.20.01 – Academic Accommodations for Students with Disabilities" at `https://policies.ncsu.edu/regulation/reg-02-20-01/`.

(6) **Use of Electronic Devices in Class**

- Cell phones are to be turned OFF prior to entering the classroom/lab. No exceptions.
- Use of laptops/other electronic devices during class is permitted only for the purpose of following the posted lecture materials/taking electronic notes.