Economics 491: Bayesian Machine Learning

Professor:
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Course Times and Locations
ECON 491: Monday and Wednesday, 9:30AM-10:50AM, 123 David Kinley Hall

Office hours:
Wednesday 1:30-2:30, 102 David Kinley Hall. You can also make them by appointment. The best way to communicate with me is via email.

Course Website:
All course materials will be available to you on Canvas (`http://canvas.illinois.edu/`). I will post lecture slides and and homework assignments on Canvas. Homework assignments are submitted through Canvas.

Course Description:

This course is a junior/senior level undergrad class in Bayesian machine learning. The goal of the course to introduce students to Bayesian econometrics and statistics as well as frequentist methods that are common in economics, finance, marketing, and business applications. It aims to improve students quantitative skills. The course will make use of the `R` programming language.

The course will cover (i) fundamentals of Bayesian econmtrics statistics; (ii) beta-binomial model; (ii) Poisson count models; (iii) simple linear and multiple linear regression models with conjugate priors; (iv) Monte Carlo simulation techniques including Markov chain Monte Carlo; (v) Bayesian model averaging for linear regression (vi) Bayesian regression trees and forests (vii) Bayesian Lasso and horseshoe regression (vii) logistic and Probit regression (ix) fundamental time series models (x) Bayesian neural networks

Pre-requisites:

This course will assume you know the basics of mathematical probability, linear regression, and differential and integral calculus. We will also be using some basic results from matrix algebra (addition, substraction, multiplication of vectors and matrices as well as solving systems of linear equations). I also assume that you are willing to code in `R` and are familiar with `RStudio`. Throughout the course, I will review these topics in lectures.

Textbooks:

Unfortunately, there are not a lot of undergraduate books in Bayesian econometrics. The main book Johnson, Ott, and Dogucu (2022) is a book on Bayesian statistics, which covers most of the major models. It is accessible for undergrads. Importantly, I am using this book because it illustrates all the procedures using the `R` programming language. Moreover, it uses `rstan`, which is a powerful tool for estimating complex models.

Primary book(s):

- Both of these books are optional. Electronic copies are free on line.
- A. Johnson, M. Ott, and M. Dogucu. (2022), *Bayes Rules!*, CRC Press.
  - I call this book **JOD**
  - Introduction to Applied Bayesian Modeling.
  - Free online book
  - Book website: https://www.bayesrulesbook.com/
  - It has `R` code in the book.
  - It focuses on estimating complex models using `R`'s implementation of `stan`.
- G. James, D. Witten, T. Hastie, and R. Tibshirani (2023), *An Introduction to Statistical Learning*, Springer Press, Second Edition.
  - I call this book **ISLR**.
  - This book is the standard reference for statistics and machine learning.
  - It is frequentist...but it is still a good resource because it covers most of the same topics. And, the big picture ideas are the same.
  - There is a version of the book for `R` and one for `Python`.

Other text books:

- J. Albert (2009), *Bayesian Computation with R*, Springer Press.
- C. Robert and G. Casella (2009), *Introducing Monte Carlo Methods with R*, Springer Press.
  - This is a nice book but it does have some advanced material in it.
- J. M. Marin and C. Robert (2014), *Bayesian Essentials with R*, Springer Press.

Books for `R`:

- Hadley Wickham and Garrett Grolemund. (2017), *R for Data Science*, O'Reilly Press.
  - https://r4ds.had.co.nz

Course Outline (This is a rough outline and is subject to change.)

Topic 1: Probability and Bayes Rule

a. Class overview
b. Events, random variables, and probability distributions
c. Joint probabilities
d. Conditional probability
e. Bayes Rule
f. Probability models
g. Philosophy of probability
h. Monte Carlo simulation
i. Bias-variance tradeoff

References: Chapters 1 and 2 of JOD.

Topic 2: Binomial model with beta prior

a. Uniform and beta distributions
b. Binomial models
c. Maximum likelihood estimation for the binomial model
d. Posterior distribution
e. Conjugate, diffuse, and flat priors
f. Bias-variance tradeoff
g. Highest posterior density intervals
h. Posterior predictive distribution

References: Chapter 3 of JOD. Chapter 4 may also be useful.

Topic 3: Normal model with conjugate prior

a. Normal distribution and prior
b. Maximum likelihood estimation for the normal distribution
c. Posterior distribution of the model with unknown mean
d. Gamma and inverse gamma distributions
e. Posterior distribution of the model with unknown mean and variance
f. Diffuse priors
g. Bias-variance tradeoff
h. Highest posterior density intervals
i. Marginal likelihoods
j. Posterior predictive distribution

References: Chapter 5 of JOD.

Other options include:

- Chapters 3 and 4 of **Albert**.

Topic 4: Multivariate probability, vectors and matrices

a. Vectors and matrices
b. Basic operations with vectors and matrices
c. Covariance and correlation for a pair of random variables
d. Bivariate normal distribution
e. Covariance and correlation matrices
f. Multivariate normal distribution
g. Partial derivatives of a function

References: Class lecture slides.

Topic 5: Gibbs sampling, Markov chain Monte Carlo and R-stan

a. Gibbs sampling
b. Markov chain Monte Carlo
c. How to estimation Bayesian models using `rstan`

References: Class lecture slides and Chapters 9 & 10 of JOD.

Topic 6: Multiple linear regression with conjugate priors

a. Multiple linear regression
b. Maximum likelihood estimation of the model
c. Multivariate normal inverse gamma conjugate prior distribution
d. Posterior of the linear regression model
e. Ridge regression
f. Zellner's g prior
g. Highest posterior density intervals
h. Marginal likelihoods
i. Implementation in `rstan`

References: Chapter 11 of JOD and Chapter 3 of ISLR.

Topic 7: Bayesian hypothesis testing

a. Marginal likelihoods
b. Comparing two models
c. Comparing many models
d. Examples

References: Class lecture slides.

Topic 8: Bayesian model averaging for linear regression

a. Comparing two linear regression models
b. Comparing many linear regression models
c. Model averaging
d. Bayesian model averaging for linear regression

e. `R` package: BMS

References: Class lecture slides.

Topic 9: Bayesian Lasso, spike & slab, horseshoe priors

a. Lasso regression
b. Spike & slab priors
c. Regression with horseshoe priors
d. Implementation in `R`.

References: Class lecture slides and Chapter 6 of ISLR.

Topic 10: Non-linear regression

a. Basis functions
b. Splines
c. Non-linear regression with Bayesian model averaging
d. Non-linear regression with horseshoe

References: Class lecture slides and Chapter 7 of ISLR.

Topic 11: Bayesian regression trees (random forests)

a. Decision trees
b. Classification and regression trees (CART)
c. Frequentist random forest algorithms
d. Generalized additive models
e. Bayesian additive regression trees (BART)

References: Class lecture slides and Chapter 8 of ISLR.

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Additional topics if time permits
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Topic 12: Bayesian neural networks

a. Feedforward neural networks
b. Recursive neural networks
c. Variational inference

Topic 13: Time series models

a. Moving average models
b. Autoregressive models
c. ARMA models

d. Markov switching models

References: Chapter 12 of JOD.

Topic 14: Poisson and negative binomial regression (models for count data)

a. Poisson regression
b. Likelihood function
c. Priors
d. Posterior distribution
e. Negative binomial regression
f. Likelihood function
g. Implementation in `rstan`

References: Chapter 12 of JOD.

Topic: Fundamentals of Monte Carlo methods

a. Direct sampling
b. Accept-reject algorithms
c. Markov-chain Monte Carlo
d. Random walk metropolis
e. Metropolis-Hastings algorithm
f. What is `rstan` doing?

Evaluation:

Grade = 35% homework + 5% class participation + 30% midterm exam + 30% final exam
You will be given numerical scores for problem sets. I will curve the overall grade at the end of the semester and give a letter grade for the course.

Homework: There will be 8 problem sets assigned throughout the semester. You get to drop your lowest homework assignment (so 7 highest scores out of 8 count). The problem sets are graded on a check plus, check, check minus scale, where check plus is 100%, check is 85%, and check minus is 50%. Homework assignments more than 1 day late are subject to a penalty, e.g. minus 10%. However, the solutions will be posted 1 week after the deadline. Failure to turn something in before the solutions are posted results in a 0%.

Working with your other classmates is a great way to learn the material. However, you still have to put in the individual effort to figure things out on your own. Therefore, I will limit study groups to **three** individuals and **no more**. Each student must turn in their own assignments. Assignments are not to be submitted in groups. Finally, although I encourage you to collaborate to learn the material, you should not literally be copying one another's solutions to homework assignments. You won't learn anything that way.

Exams: There is one midterm and one final exam. The final exam is cumulative. You will need a calculator for the exams. And, you will be allowed to have a 1 page, hand-written, double sided cheat sheet of notes for formulas.

Class participation: Attendance and participation account for 5% of the grade. I will take attendance at "random" times by giving very simple quizzes.

Schedule:

1/21 W: first day of class
1/30 F: Problem Set 1 due
2/13 F: Problem Set 2 due
2/27 F: Problem Set 3 due
3/6 F: Problem Set 4 due
3/11 (W): **Midterm Exam**, in-class
3/14-3/22: Spring break = no classes.
3/27 F: Problem Set 5 due
4/10 F: Problem Set 6 due
4/24 F: Problem Set 7 due
5/1 F: Problem Set 8 due
5/6 W: last class meeting
5/8-5/14 **Final exam period**.

The final date, time, and room will be released mid-semester.

Academic Assistance:

Students are encouraged to utilize the many resources we have throughout campus to assist with academics. We recommend that you seek them out starting early in the semester, not just in times of academic need, in order to develop good study habits and submit work which represents your full academic potential. Many resources are found on the Economics Website including details about the Economics Tutoring Center, Academic Advising, and other academic support options:

https://economics.illinois.edu/academics/undergraduate-program/academic-student-support

Academic Integrity:

According to the Student Code, 'It is the responsibility of each student to refrain from infractions of academic integrity, from conduct that may lead to suspicion of such infractions, and from conduct that aids others in such infractions.' Please know that it is my responsibility as an instructor to uphold the academic integrity policy of the University, which can be found here:

https://studentcode.illinois.edu/article1/part4/1-401/

Academic dishonesty may result in a failing grade. Every student is expected to review and abide by the Academic Integrity Policies. It is your responsibility to read this policy to avoid any misunderstanding. Do not hesitate to ask the instructor(s) if you are ever in doubt about what constitutes

plagiarism, cheating, or any other breach of academic integrity. Read the full Student Code at

https://studentcode.illinois.edu/

Students with Disabilities:

To obtain disability-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and the Disability Resources and Educational Services (DRES) as soon as possible. To contact DRES you may visit 1207 S. Oak St., Champaign, call 333-4603 (V/TTY), or e-mail a message to disability@illinois.edu. DRES Website: www.disability.illinois.edu/

Community of Care:

As members of the Illinois community, we each have a responsibility to express care and concern for one another. If you come across a classmate whose behavior concerns you, whether in regards to their well-being or yours, we encourage you to refer this behavior to the Student Assistance Center (217-333-0050 or http://odos.illinois.edu/community-of-care/referral/). Based on your report, the staff in the Student Assistance Center reaches out to students to make sure they have the support they need to be healthy and safe. Further, we understand the impact that struggles with mental health can have on your experience at Illinois. Significant stress, strained relationships, anxiety, excessive worry, alcohol/drug problems, a loss of motivation, or problems with eating and/or sleeping can all interfere with optimal academic performance. We encourage all students to reach out to talk with someone, and we want to make sure you are aware that you can access mental health support at the Counseling Center (https://counselingcenter.illinois.edu/) or McKinley Health Center (https://mckinley.illinois.edu/). For mental health emergencies, you can call 911 or walk into the Counseling Center, no appointment needed.

Disruptive Behavior:

Behavior that persistently or grossly interferes with classroom activities is considered disruptive behavior and may be subject to disciplinary action. Such behavior inhibits other students' ability to learn and an instructor's ability to teach. A student responsible for disruptive behavior may be required to leave class pending discussion and resolution of the problem and may be reported to the Office for Student Conflict Resolution for disciplinary action.

Emergency Response Recommendations:

Emergency response recommendations can be found at the following website:

http://police.illinois.edu/emergency-preparedness/ .

I encourage you to review this website and the campus building floor plans website within the first 10 days of class. http://police.illinois.edu/emergency-preparedness/building-emergency-actionplans/ .

Religious Observances

The Religious Observance Accommodation Request form is available at

https://odos.illinois.edu/community-of-care/resources/students/religious-observances/.

Submit the form to the instructor and to the Office of the Dean of Students (helpdean@illinois.edu) as soon as possible.

Family Educational Rights and Privacy Act (FERPA)

Any student who has suppressed their directory information pursuant to Family Educational Rights and Privacy Act (FERPA) should self- identify to the instructor to ensure protection of the privacy of their attendance in this course. See http://registrar.illinois.edu/ferpa for more information on FERPA. Student information and records will not be released to anyone other than the student unless the student has provided written approval or as required by law.

Sexual Misconduct Reporting Obligation

The University of Illinois is committed to combating sexual misconduct. Faculty and staff members are required to report any instances of sexual misconduct to the University's Title IX and Disability Office. In turn, an individual with the Title IX and Disability Office will provide information about rights and options, including accommodations, support services, the campus disciplinary process, and law enforcement options. A list of the designated University employees who, as counselors, confidential advisors, and medical professionals, do not have this reporting responsibility and can maintain confidentiality, can be found here: http://www.wecare.illinois.edu/resources/students/#confidential. Other information about resources and reporting is available here: http://wecare.illinois.edu/.

Student Support

The Counseling Center is committed to providing a range of services intended to help students develop improved coping skills in order to address emotional, interpersonal, and academic concerns. Please visit their website to find valuable resources and services: https://counselingcenter.illinois.edu/.

Counseling Center Information: 217-333-3704 Location: Room 206, Student Services Building (610 East John Street, Champaign IL)

McKinley Mental Health Information: 217-333-2705 Location: 3rd Floor McKinley Health Center 1109 South Lincoln, Urbana, IL

Emergency Dean: The Emergency Dean may be reached at (217) 333-0050 and supports students who are experiencing an emergency situation after 5 pm, in which an immediate University response is needed and which cannot wait until the next business day. The Emergency Dean is not a substitute for trained emergency personnel such as 911, Police or Fire. If you are experiencing a life threatening emergency, call 911. Please review the Emergency Dean procedures: http://odos.illinois.edu/emergency/