MSML610: Advanced Machine Learning

MSML610 Class Mechanics

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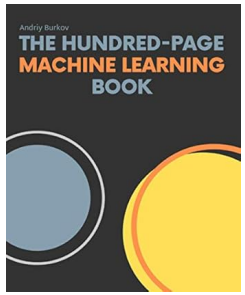
- ***MSML610***
- Class Map

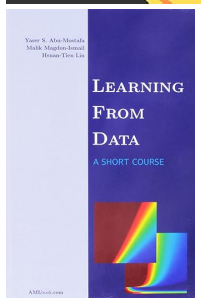
Invariants of a Class Lecture

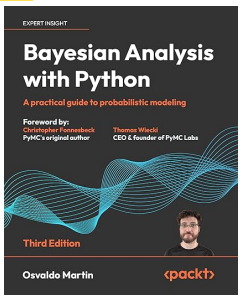
- **Invariants**
  - Focus on intuition over math (unless necessary)
  - Emphasize realistic assumptions and numerical methods
    - Analytical solutions are so 1800s
  - Interactive Jupyter notebook tutorials for hands-on approach
    - Tutorials are mainly done at home
    - Videos of each tutorial will be added over time
- **Class flow**
  - Lessons alternate between slides, whiteboard, tutorials
  - 2:45 hours per class lessons
    - 50 mins
    - 10 break
    - 50 mins
    - 10 mins
    - 45 slides (Topic refresher!)

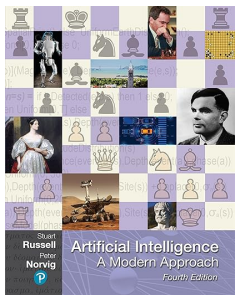
Books of the Class

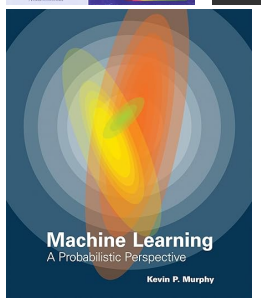
- **Goal**: make the slides self-sufficient from recommended books
  - **Simple**
    - Burkov: *"Machine Learning Engineering"* (2020)
    - Burkov: *"The Hundred-Page Machine Learning Book"* (2019)
  - **Medium**
    - Abu-Mostafa et al.: *"Learning From Data"* (2012)
    - Martin: *"Bayesian Analysis with Python"* (2nd ed, 2021)
    - Russell et al.: *"Artificial Intelligence: A Modern Approach"* (4th ed, 2020)
  - **Hardcore**
    - Hastie et al.: *"The Elements of Statistical Learning"* (2nd ed, 2009)
    - Koller et al.: *"Probabilistic Graphical Models: Principles and Techniques"* (2009)
    - Murphy: Machine Learning: *"A Probabilistic Perspective"* (2012)
    - Sutton et al.: *"Reinforcement Learning: An Introduction"* (2nd ed, 2018)

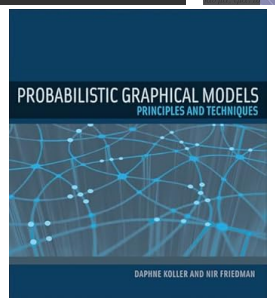


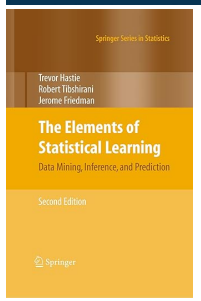


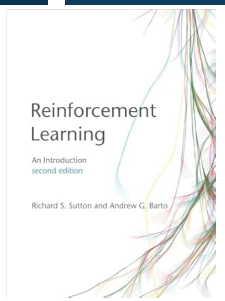












Grading

- **Quizzes** (40%)
  - Multi-choice quizzes on previous 2 lessons
  - 4-5 quizzes to make you study during the semester and don't cram
- **Final Project** (60%)
  - A comprehensive application of course concepts
  - Python project selected from a list of topics

Class Projects

- The project is *"Build X with Y"*, where X is a "use case" and Y is a "technology"
  - Study and describe technology Y
  - Implement a use case X using the technology Y
  - Create Jupyter notebooks to demo your project
  - Commit code to GitHub and contribute to open-source repo
  - Write a blog entry
  - Present your project in a video
- There is a list of X and Y you can pick from, e.g.,
  - Statistical learning
  - Big data
  - LLMs
  - Deep learning
  - ...
- Each project:
  - Is individual or group ($n < 4$)
  - Has different levels of difficulty

Links

- ELMS
- Syllabus
  - Schedule
  - GitHub project
  - Class FAQs
- Project specs

Yours Truly

- **GP Saggese**
  - 2001-2006, PhD / Postdoc at the University of Illinois at Urbana-Champaign
  - LinkedIn
  - gsaggese@umd.edu
- **University of Maryland**:
  - 2023-, Lecturer for UMD DATA605: Big Data Systems
  - 2025-, Lecturer for UMD MSML610: Advanced Machine Learning
- **In the real-world**
  - Research scientist at NVIDIA, Synopys, Teza, Engineers' Gate
  - 3x AI and fin-tech startup founder (ZeroSoft, June, Causify AI)
  - 20+ academic papers, 2 US patents

- MSML610
- ***Class Map***

1. Intro

- A Map of Machine Learning
- What Is Artificial Intelligence
  - AI
  - Machine Learning
  - AI vs ML vs Deep-Learning
  - The Foundation of AI
  - Brief History of AI
  - AI State of the Art
  - Risks and Benefits of AI

2. Machine Learning Techniques

- Paradigms
- Techniques
  - Machine Learning in Practice
  - How to Do Research
    - Simple Is Better
    - Research Methodology
  - Pipeline Organization
  - Input Processing
  - Learning Algorithms
    - Gradient Descent
    - Stochastic Gradient Descent
  - Performance Metrics
    - Precision and Recall
  - Model Selection
  - Aggregation
    - Bagging
    - Boosting
    - Stacking

3. Knowledge Representation

- Knowledge Representation
  - Basics of Knowledge Representation
  - Examples of Logic
  - Logical Agents
  - Ontologies
  - Reasoning in Ontologies
- Propositional logic
- First-order Logic
- Non-classical Logics
- Description Logics
  - Semantic Web

4. Machine Learning Models

- Models
  - Naive Bayes
  - Decision trees
  - Random forests
  - Linear models
  - Perceptron
  - Logistic regression
  - LDA, QDA
  - Kernel methods
  - Support vector machines
  - Similarity-based models
  - Clustering
  - Anomaly detection

5. Machine Learning Theories

- Is machine learning possible?
- Growth function
- The VC dimension
- Overfitting
- Bias Variance Analysis
- Learning curves
- Learn-validation approach
  - Train / test
  - Cross-validation

6. Bayesian Statistics

- Logic-Based AI Under Uncertainty
- Probabilistic Reasoning
  - Conditional Independence
  - Bayesian Networks
  - Semantics of Bayesian Networks
  - Constructing a Bayesian Network
  - Exact Inference in Bayesian Networks
  - Approximate Inference in Bayesian Networks
    - Direct sampling methods

7. Probabilistic Programming

- Concepts
- Coin Example
  - Analytical Approach
  - Communicating a Bayesian Analysis
  - Probabilistic Programming
- Posterior-Based Decisions
  - Chemical Shift: Example
  - Posterior Predictive Checks
    - Robust Inference
- Groups Comparison
- Hierarchical Models
- Simple Linear Model
  - Logistic Regression
- Multiple linear regression
- Comparing Models
  - Posterior Predictive Checks
  - The Balance Between Simplicity and Accuracy
  - Measures of Predictive Accuracy
    - Information Criteria
    - Cross-Validation
    - Bayes Factors and Information Criteria
- Regularizing priors

8. Reasoning Over Time

- Reasoning over time
- HMMs
- Markov random fields
- Markov logic network
- State space models and Kalman filter
  - G-h filter
  - Discrete Bayes filter
- Dynamic Bayesian networks
- State space model
- Variational Inference
  - Expectation-Maximization (EM) Algorithm

9. Causal Inference

- Causal AI
  - Why Causal AI?
  - Concepts in Causal AI
  - Variables
  - Paths
  - The Ladder of Causation
  - Correlation vs causation models
- Business processes around data modeling
  - Modeling processes
  - Roles

10. Timeseries Forecasting

- Time Series
  - Basic definition
  - Time series operators
  - Time series decomposition
- Classical Methods
  - Simple models for stochastic process
  - Autoregressive models
  - Moving average models
  - ARMA(p, q) process
  - ARIMA model
  - ARCH model

11. Probabilistic Deep Learning

- Neural networks
  - Biological inspiration
  - Neural networks
- Advanced Neural Network Architectures
  - Convolutional networks
  - Recurrent Neural Networks (RNNs)
  - Deep learning learning algorithms
  - Deep learning architectures
- Fundamentals of Deep Learning
- Training Deep Neural Networks
- Interpretability and Explainability
- Deep Generative Models
- Bayesian Deep Learning
- Deep Probabilistic Models
- Uncertainty Quantification
- Probabilistic Programming and Inference
- Modern Research Frontiers
- Bonus Topics

12. Reinforcement Learning

- Sequential decision problems
  - Utilities over time
  - Algorithms for MDPs
- Reinforcement learning
  - Passive reinforcement learning
  - Active reinforcement learning
  - Generalization in reinforcement learning
  - Policy search
- Fundamentals
- Classical Methods
- Exploration Strategies
- Policy Gradient Methods
- Value Function Approximation
- Deep Reinforcement Learning
- Model-Based Reinforcement Learning
- Advanced Topics
- Applications

Refresher: Probability

- Probability
  - Probability definition
  - Probability measure
  - Independent events
  - Conditional probability
  - Law of total probability
  - Bayes theorem
- Random variables
  - Random variables
  - CDF, PMF, PDF of Random Variables
  - Joint distributions
  - Marginal distributions
  - Independent RVs
  - Conditional PDF RVs
- Mathematical expectation of RVs
  - Mean
  - Variance and covariance
  - Statistics of RVs
- Probability inequalities
- Statistical Inference
  - Definitions

Refresher Probability Distributions

- Interesting RVs
  - Bernoulli
  - Binomial
  - Gaussian
  - Log-Normal
  - Poisson
  - Chi-square
  - Student's t-distribution
- Probability inequalities

Refresher Linear Algebra

- Linear algebra
  - Vector and vector spaces
  - Affine spaces
  - Vectors and matrices
  - Linear functions
  - Connections between Machine Learning and Linear Algebra

Refresher Information Theory

- Information theory
  - Entropy
    - Kullback-Leibler divergence
  - Connections between Information Theory and ML

Refresher Game Theory

- Game theory
  - Connections between Machine Learning and Game Theory

Refresher: Numerical Optimization

- Optimization / numerical methods

Refresher: Stochastic Processes

- Stochastic processes