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FRE 6991: SPECIAL TOPICS IN FINANCIAL ENGINEERING

MARKETS AND INFORMATION THEORY

Edward D. Weinberger, Ph.D., F.R.M
Adjunct Professor
Dept. of Finance and Risk Engineering
edw2026@nyu.edu
Office Hours by appointment
(6 46) 436-6174 (cell)

The word "information" is often bandied about in discussions of financial markets: profiting from "non-public information", otherwise known as insider trading is a no-no, the claim that "security prices reflect all available information" (the famous efficient market hypothesis), etc. Yet there is relatively little contact between financial theory and the well-developed theory of information, familiar to electrical engineers and computer scientists. This course is intended to identify (and possibly expand on!) some of the contacts that do exist between these two fields.

Course Overview and Goals:

The purpose of this project-based course is to explore some of the applications of information theory to financial markets and, not incidentally, to

- expose students to the basic quantities in information theory, such as
    - Shannon entropy,
    - mutual information,
    - Kullbach-Leibler divergence
    - channel capacity

  and demonstrate their utility in understanding financial markets
- give students the opportunity to manipulate and analyze financial data by attempting to measure the above quantities and draw conclusions from the results
- give students the opportunity to work in a group to practice the oral and written communication of quantitative subjects.

Because this is not a Ph.D. level course, there is no expectation that student projects will constitute original research. However, there will be some discussion of my existing research, and some suggestions for research to be undertaken in the future.

Prerequisites

FRE6083 (Quantitative Methods) or equivalent and graduate standing. If you have these, you will have an understanding of multivariate calculus and probability. Facility with Bloomberg, quantitative tools, such as MatLab and R, and/or programming languages such as Python. More important than any of these, however, is that elusive facility known as "mathematical maturity".

Grading and Assessment

The course is graded entirely on two mini-projects, weighted as indicated below. Ideally, each project will be done as part of a 3 person team, designed to replicate the collaborative nature of the financial industry . The assessment for each project is multi-faceted, combining a 20 minute (or so) oral presentation, a written

report containing the same information[1] , and a peer review component, with each member of the team taking responsibility for one of these facets (So the student responsible for the written report could, in principle, get a different grade from the student responsible for oral report, and yet a different grade could be given to the student managing the peer reviews). This framework mirrors the professional skills required in the field. (See detailed grading rubric below.)

- Mini-Project 1: Attempts to measure the entropy of a price process - 45%
  - Written Report: 20%
  - Oral Presentation: 15%
  - Peer Review of other groups' work: 10%

  This project will involve the estimate of the entropy of a single security's price increments over various time periods and various methods. Students will begin by assessing the stationarity of the relevant time series. The estimation methods to be used could include binning the per-period returns, weighting these returns by trading volume over the period, fitting the observed price increments to an analytical distribution, various compression techniques (Why is the latter included?) and/or using a variant of the technique to be presented in the second class. How do the results compare? How do the results compare between high frequency and daily data? What do these results have to say about market efficiency and/or anything else that is relevant?

  As part of the presentation, explain why you chose the dataset that you did.

- Mini-Project 2: Information-Theoretic Portfolio Optimization - 55%
  - Written Report: 25%
  - Oral Presentation: 20%
  - Peer Review of other groups' work: 10%

  This project leverages the techniques developed previously to estimate the Kullbach-Leibler divergence and/or the mutual information of pairs of financially relevant data series and draw conclusions therefrom. Part of the reason why this project is weighted more heavily than the other is because there is more opportunity to draw financially interesting conclusions here, and part of your grade will be determined by your ability to draw such conclusions. Here are some ideas:
  - The paper to be discussed in the second class studied the entropy of the ETF price fluctuations over 1, 5, and 10 minute intervals. In most cases, the entropy over the 1 minute intervals was lower than that over 5 minute intervals, suggesting that the famous "random walk" of securities prices isn't so random over short times. Confirm that by looking at the mutual information between the return over one interval and the return over the next. Compare that to an estimate of the autocorrelation. Try to make some statement about statistical significance.
  - Compute the autocorrelation matrix of fluctuations in the spot exchange rates of the major world currencies (GBP, EUR, CAD, AUD, CHF, and JPY) against the US Dollar. Do the same with the *normalized* mutual information for each pair of currencies. If $H(S_1)$ is the entropy of an exchange rate S_1, and $I(S_1, S_2)$ is the mutual information, the normalized mutual information is the quotient

    $$I(S_1, S_2)/ H(S_1) = 1 - H(S_1| S_2) / H(S_1) \leq 1.$$

    How do the autocorrelation and mutual information matrices compare? Try to make some statement about statistical significance in each case.

[1] The requirement that the written report contain only the same information as the oral presentation is intended to make manageable the scope of the former

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- (Hard) Create a tracking portfolio for an illiquid security (CoPilot suggested the Macy's Inc. 6.65% corporate bond, due April 2026, CUSIP 55616XAE2) using a few, more liquid securities. (CoPilot suggests portfolio consisting of a US Treasury security of similar duration, and a retail sector ETF, and a CDS index for the consumer discretionary sector.) This challenging task involves finding the weights for each of the securities in the tracking portfolio such that mutual information between the returns for the illiquid security and the tracking portfolio is minimized. The distribution of the tracking portfolio returns can be estimated via kernel density estimation (See the Wikipedia article with that title.). How does the portfolio perform out of sample, especially during a time of market stress? How do the results depend on choice of kernel?

Required text

Elements of Information Theory by Thomas M. Cover and Joy A. Thomas, 2nd Ed., Wiley Series on Telecommunications and Signal Processing, 2006, ISBN-10: 0471241954.

Classic text

Shannon, Claude and Weaver, Warren. *The Mathematical Theory of Communication*, University of Illinois Press, 1962.

Papers to Be Referenced in Class (to be put on course site)

"Entropy and Efficiency of the ETF Market". Lucio Maria Calcagnile, Fulvio Corsi, Stefano Marmi, *Computational Economics*, (2020) **55**:143–184.

"Towards a Theory of Pragmatic Information", Edward D. Weinberger, preprint available on the web at https://arxiv.org/abs/2403.12324

"An Information-Theoretic Framework for Information Diffusion in Financial Markets: From Informed Traders to Noise Traders via a Noisy Channel", prepared by resea.ai

Additional Reading

Biais, B., Glosten, L., & Spatt, C. (2005). Microstructure: A survey of microfoundations, empirical results, and policy implications. Journal of Financial Markets, 8(2), 217-264.

Buchen, P. W., & Kelly, M. (1996). The maximum entropy distribution of an asset inferred from option prices. Journal of Financial and Quantitative Analysis, 31(1), 143-159.

Darbellay, G. A., & Wuertz, D. (2000). The entropy as a tool for analysing statistical dependences in financial time series. Physica A, 287(3-4), 429-439.

Gulko, L. (1998). The entropy theory of stock option pricing. International Journal of Theoretical and Applied Finance, 1(3), 293-327.

Gu, G.-F., & Zhou, W.-X. (2009). Emergence of long memory in stock volatility from a modified Mike–Farmer model. EPL, 86(4), 48002.

Jizba, P., Kleinert, H., & Shefaat, M. (2012). Rényi entropy and improved option pricing. Physica A, 391(10), 2971-2989.

Kantelhardt, J. W., Zschiegner, S. A., et al. (2002). Multifractal detrended fluctuation analysis of non-

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stationary time series. Physica A, 316(1-4), 87-114.

Kristoufek, L., & Vosvrda, M. (2013). Measuring capital market efficiency: Global and local correlations structure. Physica A, 392(1), 184-193.

Kwon, O., & Yang, J.-S. (2008). Information flow between stock indices. The European Physical Journal B, 55(4), 271-278.

Lombardi, M. J., & Van Stralen, B. (2015). The non-linear predictability of exchange rates: A commodity currency perspective. International Journal of Forecasting, 31(1), 94-108.

Mantegna, R. N., & Stanley, H. E. (1999). Introduction to Econophysics: Correlations and Complexity in Finance. Cambridge University Press.

Marschinski, R., & Kantz, H. (2002). Analysing the information flow between financial time series: An improved estimator for transfer entropy. The European Physical Journal B, 30(2), 275-281.

Maasoumi, E., & Racine, J. (2002). Entropy and predictability of stock market returns. Journal of Econometrics, 107(1-2), 291-312.

Neri, F., & Schneider, P. (2019). Improving risk-neutral density estimation via maximum entropy. Journal of Econometrics, 209(2), 206-230.

Ortega, G. J., & Klein, R. W. (2016). Information-theory approach to the microstructure of financial markets. International Review of Financial Analysis, 47, 247-258.

Philippatos, G. C., & Wilson, C. J. (1972). Entropy, market risk and the selection of efficient portfolios. Applied Economics, 4(3), 209-220.

Pincus, S. M., & Kalman, R. E. (2004). Irregularity, volatility, risk, and financial market time series. Proceedings of the National Academy of Sciences, 101(38), 13709-13714.

Sandoval, L., & Franca, I. D. P. (2012). Correlation of financial markets in times of crisis. Physica A, 391(1-2), 187-208.

Schreiber, T. (2000). Measuring information transfer. Physical Review Letters, 85(2), 461-464.

Stutzer, M. (1996). A simple nonparametric approach to derivative-security valuation. Journal of Finance, 51(5), 1633-1652.

Tóth, B., Lempérière, Y., Deremble, C., et al. (2015). Liquidity, market impact, and the informational content of order flow. Market Microstructure & Liquidity, 1(1), 1550002.

Wang, G.-J., Xie, C., Chen, S., & Chen, Y. (2014). Statistical properties of the foreign exchange network at different time scales: Evidence from detrended cross-correlation coefficient and minimum spanning tree. Entropy, 16(2), 895-912.

Zunino, L., Tabak, B. M., Pérez, D. G., Garavaglia, M., & Rosso, O. A. (2009). Forecasting market movements: An information theory approach. Physica A, 388(14), 2854-2864.

Outline of Lectures

<u>Lecture 1</u>: Introduction and Basic Definitions

1) Review of course mechanics
2) The Efficient Market Hypothesis is stated in terms of information

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3) Mathematical Preliminaries
   a) Review of covariance and correlation – and their limitations
   b) Stationarity and ergodicity
   c) Types of stochastic convergence
4) Entropy formula with motivation
   a) Motivation and intuitions
   b) From entropy of discrete random variable to entropy of continuous random variable
   c) Basic properties, including uniqueness
   d) Joint and conditional entropy
   e) The chain rule
   f) Shannon-McMillan-Breiman Theorem (noiseless coding theorem)
   g) Basic ideas of data compression (the beginning of Shannon's part of Shannon and Weaver)
5) Basics of market microstructure and why it's hard to compute entropy
6) Description of first project

Lecture 2: Explication of "Entropy and Efficiency in the ETF Market"

1) Reminder of difficulties of computing entropy
2) Their approach
   a) Their model of market microstructure
   b) Binary vs trinary discretization
   c) Grassberger correction of entropy estimate
3) Their conclusions

Lecture 3: Student Presentations for First Project and Measures of Relationship

1) Student presentations
2) Covariance, correlation, and linear regression – The good, the bad, and the ugly
   a) The Gauss-Markov Theorem
   b) Great for
      i) Statistical hedging and tracking portfolios
      ii) (Auto) Regression
      iii) VaR
   c) Not so great in times of stress!
3) Kullbach-Leibler divergence and mutual information
   a) Non-negativity, chain rule, and other basic properties
   b) Data Processing Inequality
   c) Mutual Information is function of correlation for normal random variables!
4) Description of second project

Lecture 4: Information Theory and Gambling

1) The Kelley criterion
2) The horse race and optimal betting
3) Mutual information is increase in doubling rate
4) Some computer science preliminaries
   a) Kolmogorov complexity of sequences
   b) The Chomsky Hierarchy of languages and automata
5) Gamblers
6) Optimal betting in the stock market: mutual information upper bound on effect of side information on doubling rate

Lecture 5: The Noisy Coding Theorem and Information Asymmetry

1) The classical noisy coding theorem
   a) Setup

   b) Statement
   c) Intuitive picture of proof
2) Fundamental question of information asymmetry
   a) Noise vs informed traders:
   b) Does everybody become informed?
   c) Can paradigm of noisy coding theorem help?
3) The resea.ai framework: a critical review of an attempt to map information asymmetry onto noisy coding paradigm

Lecture 6: Student presentations and pragmatic information

1) Student presentations for second project
2) Pragmatic information as the "available information" in the EMH
   a) Basic definitions and properties
   b) Pragmatically useful information
   c) Limitations imposed by receiver's location in Chomsky Hierarchy
   d) Pragmatic channel capacity
   e) Approach to market efficiency via pragmatically useful information

Lecture 7: What Information Theory Has to Say About Financial Bubbles and Crashes: A Good Excuse for A Review. Final Thoughts

1) How behavioral finance quirks might affect the system and other increases in noise; informational avalanches as triggers of crashes
2) Review of a market as a noisy communication system
3) Thoughts on future research, in particular applying network information theory

Detailed Grading Rubrics

Rubrics are an indispensable tool for providing transparent, objective, and consistent evaluation.[20] The following rubrics will be used to assess the written reports, oral presentations, and peer reviews for the mini-projects. These rubrics are provided to students at the beginning of the course to ensure clear expectations and to guide their work throughout the class.

Table 1: Technical Report Rubric

Criterion	Exemplary (5/5)	Proficient (4/5)	Developing (3/5)	Needs Improvement (2/5)
Content and Analysis	The report presents a compelling, in-	The report provides reasonable	The analysis is basic or generalized. The	The analysis is vague or not evident. The

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	depth analysis that shows a thoughtful, original interpretation of the topic. It synthesizes complex ideas and provides important, data-driven insights. [15]	support for its arguments and demonstrates a basic understanding of the topic, with some noteworthy analysis. The reader gains some insights.	report sometimes supports its claims, but the central argument is not consistently clear. The reader gains few insights.	central purpose or argument is generally unclear, leaving the reader confused or misinformed. [15]
Methodology	The methodology is technically rigorous and flawlessly executed. It demonstrates a sophisticated understanding of information-theoretic principles and their appropriate application to financial data. All assumptions and limitations are clearly stated.	The methodology is sound and provides a reasonable approach to the problem. The student correctly applies most of the relevant concepts, with minor technical flaws or omissions.	The methodology contains notable errors in its application of information-theoretic principles. The approach is generally sound but lacks rigor or attention to detail.	The methodology is fundamentally flawed. The student fails to apply core concepts correctly, and the analysis is unreliable.
Organization and Structure	The ideas are arranged logically to support the central argument, flowing smoothly from one section to another. The	The ideas are generally arranged logically and are clearly linked. For the most part, the reader can follow the line of reasoning. [15]	The organization is generally logical, but some ideas fail to make sense together or digress from the central argument. The reader is fairly	The writing is not logically organized. The ideas are disconnected, making the report difficult to follow and the central purpose unclear.

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	structure is clear, and the narrative is easy to follow and compelling.		clear about the intended purpose.	[15]
Writing Mechanics	The report is free or almost free of errors in grammar, spelling, and punctuation. The tone is consistently professional and academic, with precise, effective, and sophisticated word choice. All sources are cited correctly. [15]	The writing contains occasional errors that do not majorly distract the reader. Word choice is generally good, and the tone is mostly professional and appropriate for a technical paper. [15]	The writing contains frequent errors in grammar or mechanics that are a major distraction to the reader. Word choice is adequate but generic, and the tone is inconsistent. [15]	The writing has many errors, making it unprofessional and difficult to read. Many words are used inappropriately, confusing the reader. Citation is missing or incorrect. [15]

Table 2: Oral Presentation Rubric

Criterion	Outstanding (5/5)	Proficient (4/5)	Acceptable (3/5)	Needs Significant Improvement (2/5)
Content and Clarity	The presentation is organized in a logical and compelling way. The main purpose is readily apparent, and	The presentation is well-structured and organized, and the main purpose is generally clear. The presenter	The presentation is somewhat organized, but the flow is not consistently logical. The presenter's	The presentation lacks a logical structure, and the main purpose is unclear. The presenter does

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	the presenter clearly demonstrates a full command of the subject matter. Complex findings are explained with exceptional clarity. [16]	understands the content well, and the findings are communicated effectively.	understanding of the content is basic, and some findings are difficult to follow.	not demonstrate an understanding of the content.
Delivery and Physical Presence	The presenter(s) speak clearly, articulately, and with appropriate voice projection. Eye contact is consistently maintained with the audience. Body language is professional and confident. [16]	The presenter(s) speak clearly and are audible. Eye contact is generally maintained. Body language is appropriate and professional for the most part.	The presenter(s) occasionally speak too quickly or quietly. Eye contact is limited. Body language appears nervous or unprofessional, distracting the audience.	The presenter(s) are inaudible or unintelligible. No eye contact is made with the audience. Body language is unprofessional and undermines the presentation.
Visual Aids	Visual aids (e.g., slides, charts) are professional, well-designed, and effectively enhance the presentation's narrative. They are not distracting and clearly support the presented materials. [16]	Visual aids are professional and generally effective at supporting the presentation. They are well-integrate d into the content.	Visual aids are minimally supportive and may contain too much text or unorganized content. They do not significantly enhance the presentation.	Visual aids are unprofessional, unhelpful, or absent. They detract from the presentation.
Q&A Session	The presenter(s) answer all questions effectively, confidently, and	The presenter(s) answer questions effectively and are able to	The presenter(s) struggle to answer some questions or their responses	The presenter(s) are unable to answer questions effectively, or

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	with great clarity. Responses are consistent with the presented information and provide additional context or insights that enhance the material. [16]	provide context or clarity. Their responses are consistent with the presented information.	are not always clear. Their answers are generally consistent with the presentation.	their responses are inconsistent or confusing. [16]

Table 3: Peer Review Rubric

Criterion	Excellent	Satisfactory	Incomplete
Technical Rigor	The review accurately identifies both major and subtle technical strengths and weaknesses in the project's methodology, data analysis, and model implementation. It provides specific, actionable suggestions for improvement.	The review identifies major technical issues but may overlook more subtle flaws. The suggestions are generally helpful but may lack specificity.	The review focuses only on minor technical details or fails to identify significant technical flaws. The suggestions are unhelpful or misguided.
Analytical Depth	The review demonstrates a deep understanding of the project's core objectives and findings. It goes beyond a simple summary to evaluate the validity of the	The review correctly summarizes the project's objectives and findings. It provides a basic evaluation of the conclusions but does not delve into a deeper analysis of	The review provides a superficial summary of the project. It fails to grasp the central analytical questions or misinterprets the findings.

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	conclusions and the significance of the results.	their implications.	
Clarity and Professionalism	The feedback is constructive, specific, and professionally worded. It avoids personal or vague language and provides a clear rationale for every comment.	The feedback is generally constructive and professional. Comments are mostly clear, but some may lack the specificity required to be fully actionable.	The feedback is vague, unhelpful, or unprofessional. It does not provide sufficient detail for the authors to understand the critique.

Course Materials and Resources

- **Access your course materials**: https://brightspace.nyu.edu/d2l/home/208906
- **Databases, journal articles, and more**: Bern Dibner Library (library.nyu.edu) NYU Virtual Business Library (guides.nyu.edu/vbl)
- **Obtain 24/7 technology assistance:** Tandon IT Help Desk (soehelpdesk@nyu.edu, 646.997.3123)
  NYU IT Service Desk (AskIT@nyu.edu, 212-998-3333)

Departmental/School-Wide Policies (Comments specific to the projects **in bold**, below)

Academic Misconduct

A. Introduction: The School of Engineering encourages academic excellence in an environment that promotes honesty, integrity, and fairness, and students at the School of Engineering are expected to exhibit those qualities in their academic work. It is through the process of submitting their own work and receiving honest feedback on that work that students may progress academically. Any act of academic dishonesty is seen as an attack upon the School and will not be tolerated. Furthermore, those who breach the School's rules on academic integrity will be sanctioned under this Policy. Students are responsible for familiarizing themselves with the School's Policy on Academic Misconduct.

B. Definition: Academic dishonesty may include misrepresentation, deception, dishonesty, or any act of falsification committed by a student to influence a grade or other academic evaluation. Academic dishonesty also includes intentionally damaging the academic work of others or assisting other students in acts of dishonesty. Common examples of academically dishonest behavior include, but are not limited to, the following:

   1. Cheating: intentionally using or attempting to use unauthorized notes, books, electronic media, or electronic communications in an exam; talking with fellow students or looking

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at another person's work during an exam; submitting work prepared in advance for an in-class examination; having someone take an exam for you or taking an exam for someone else; violating other rules governing the administration of examinations.

2. Fabrication: including but not limited to, falsifying experimental data and/or citations.
3. Plagiarism: Intentionally or knowingly representing the words or ideas of another as one's own in any academic exercise; failure to attribute direct quotations, paraphrases, or borrowed facts or information.
4. Duplicating work: presenting for grading the same work for more than one project or in more than one class, unless express and prior permission have been received from the course instructor(s) or research adviser involved.
5. Forgery: altering any academic document, including, but not limited to, academic records, admissions materials, or medical excuses.

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Disability Disclosure Statement

Academic accommodations are available for students with disabilities. Please contact the **Moses Center for Students with Disabilities** (212-998-4980 or mosescsd@nyu.edu) for further information. Students who are requesting academic accommodations are advised to reach out to the Moses Center as early as possible in the semester for assistance.

Inclusion Statement

The NYU Tandon School values an inclusive and equitable environment for all our students. I hope to foster a sense of community in this class and consider it a place where individuals of all backgrounds, beliefs, ethnicities, national origins, gender identities, sexual orientations, religious and political affiliations, and abilities will be treated with respect. It is my intent that all students' learning needs be addressed both in and out of class, and that the diversity that students bring to this class be viewed resource, strength and benefit. If this standard is not being upheld, please feel free to speak with me.

One of the ways that I try to maintain an equitable environment is by devising grading standards that are fair to all students. I therefore cannot arbitrarily raise a student's grade simply because failure to do so will "spoil their GPA" or cause them to lose a scholarship.