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ECON 2070: A Computer Science Toolbox for Modern Economic Theory
CS 2370: Economic Analysis as a Frontier of Theoretical Computer Science
M/W 1:30–2:45, Fall 2024

SYLLABUS

Version 1.00

A. Course Overview

How can we use tools from machine learning theory to design better auctions? Can we use cryptography to better implement matching mechanisms? And how should we approach formally proving that welfare in Nash equilibria for many games is not "much worse" than in the social optimum? This course explores the application of diverse ideas, techniques, and solution aesthetics from theoretical computer science to derive meaningful new insights into classic economic problems. The three main themes are approximation theorems (including bounding the loss in revenue or welfare due to lack of information, to unpriced externalities, or to restricting the functional form of mechanisms); various notions of complexity (including computational complexity, communication complexity, and machine-learning sample complexity); and cryptographic tools (including cryptographic commitments, multiparty computation, and zero-knowledge proofs). Economic applications mostly include analysis of equilibria, pricing, and mechanism design.

Prerequisites
Economics students: Graduate-level economic theory at the level of MWG. No prior knowledge in computer science is required.
Computer science students: CS 136.

B. Before the Semester Starts

To petition to take the course, please BOTH petition on my.harvard AND fill out the petition questionnaire using the link posted on the course website on Canvas under "Announcements."

C. Course Website

Information and materials relevant to the class will be distributed on the course Canvas website (https://canvas.harvard.edu/courses/140838).

D. Office Hours

I encourage you to make office hours appointments with me to discuss paper ideas. To do so, please send me an email describing what you'd like to discuss (e.g., a paragraph- or page-long description of the project idea) and some blocks of time that are convenient and we can set up an appointment. Please feel free to reach out to me and make office hours appointments also regarding anything else.

We're very fortunate to have Jack Hirsch (he/him) as the TF for this course. The schedule of Jack's office hours will be determined by a poll of enrolled students to be sent out during the first week of class.

E. Writing Assignments

There are three main assignment types in this course: scribe notes, (nonregular) homework, and a final paper. The exact balance of these (and of participation) in the final grade will depend on what the amount of homework and the amount of scribe work will turn out to be (e.g., amount of scribe work will depend on the number of enrolled students).

E1. Homework

We will have infrequent homework assignments. Please submit the solution to each assignment in electronic form (PDF, typed in LaTeX) on Canvas by 11:59 pm ET on the due date. Three late days are allowed over the whole semester–send an email to Jack (jhirsch1@g.harvard.edu) when using one of these days. You are welcome to discuss the homework problems with others, but you must write up your solutions yourself and in your own words. Additionally, you must list the names of the students with whom you collaborated (if any). Copying someone else's solution, or just making trivial changes for the sake of not copying verbatim, is not acceptable.

E2. Scribe Notes

Each participant will be asked to take notes on at least one and no more than three lectures (depending on the number of students enrolled). Notes should be typed in LaTeX and submitted to Jack (jhirsch1@g.harvard.edu) within one week after each lecture. Notes will also be evaluated on clarity. Notes will be posted to the course website. Any of the three late days allowed for homework may also be used for scribe notes.

E3. Final Paper

The main assignment for this course is to write a final paper. The paper should set out a novel theoretical economic research question inspired by a computer-science perspective, argue the economic significance of this problem, and at least have a plan or conjectures for paths one might be able to take to get to an answer. No more than 10 pages. If less than 5 pages, then they should be of such high quality that it would be abundantly clear that more pages would be redundant. If (and only if) it is absolutely necessary, you may have an additional appendix for extra proofs that do not fit within the 10 pages, but the paper should be self-contained so that one can read the paper without needing to look at the appendix.

You are required to write a one-page proposal (of potentially multiple ideas) by Oct 20. The final project presentations are planned for the last few sessions of the class (likely 10- to 20-minute presentations, depending on the number of projects), and are a great opportunity to give and get feedback from fellow students. The final paper is due 11:59pm ET on Dec 10 (last day of reading period). This is a hard deadline imposed by the school, and cannot be extended.

You can also co-author your projects and work in pairs—in fact, you are encouraged to work in pairs of economist+computer scientist. Groups of more than two require permission, and the expectations will be adjusted accordingly.

F. Falling Behind

If you are starting to have difficulties in this course it is imperative that you come talk to us before you are so far behind that it is impossible to catch up. We want you to succeed in this course and are here to help you do so!

G. Student Wellbeing

Your physical and mental wellbeing is of utmost importance to us. As a PhD student, you may experience a range of challenges that can interfere with learning, such as increased anxiety, strained relationships, feeling down, difficulty concentrating and/or lack of motivation. I recognize that this environment is challenging, that all that is going on in the world right now can make this an especially difficult time, and that classes are not the only demanding part of your life.

You never owe me personal information about your (mental or physical) health, or anything else. However, feel free to talk to me about things that you are going through. If I can't help you, I may know somebody who can, and I will do my best to connect you to that person. If you need extra help, or you need to miss class, or need more time with something, just ask. I promise we will work with you.

There are also a number of resources available to you on campus to support your wellness, including Counseling and Mental Health Services (CAMHS), which can be reached at 617-495-2042, or you can visit their website https://camhs.huhs.harvard.edu/find-help-now. Please see "Support Resources" on the course site on Canvas for more resources. If you or anyone you know experiences any high levels of stress, difficult life events, or feelings like anxiety or depression, I strongly encourage you to seek support.

H. Diversity, Inclusion and Belonging

My goal is to create a learning environment that supports a diversity of thoughts, perspectives and experiences, and honors your identities (including race, gender, class, sexuality, socioeconomic status, religion, and ability). I (like many people) am still in the process of learning about diverse perspectives and identities. If something was said in class (by me or anyone else) that made you feel uncomfortable, please talk to me about it. If you feel like your performance in the class is being impacted by your experiences outside of class, please don't hesitate to come and talk with me. As a participant in offline and online course discussions, you should also strive to honor the diverse perspectives of your classmates and teaching staff.

I. Academic Integrity

Members of the Harvard University community commit themselves to producing academic work of integrity—that is, work that adheres to the scholarly and intellectual standards of accurate attribution of sources, appropriate collection and use of data, and transparent acknowledgement of the contribution of others to their ideas, discoveries, interpretations, and conclusions. Plagiarizing or misrepresenting the ideas or language of someone else as one's own, or any other instance of academic dishonesty violates the standards of our community, as well as the standards of the wider world of learning and affairs.

J. Use of Large Language Models (LLMs)

Tools based on Large Language Models, such as GPT and Bard, are here to stay. They encapsulate exciting possibilities, but also present challenges and potential pitfalls. The use of LLMs (subject to the above) is allowed in this course but must be disclosed as follows. If you use LLMs for any assignment, you are required to submit, with the assignment, a full transcript of each query to the LLMs together with the LLM's response. Regardless of whether or not you use LLMs, your work will be graded based on its content alone (i.e., the content would be graded as if written completely by you). In particular, the responsibility for the content of your submitted work lies solely with you, regardless of whether any LLM assisted you with its generation. This includes, but is not limited to, making sure that your academic work is of integrity as detailed in Section I above.

K. Class Schedule and Readings

Below is the list of dates at which lectures will be held. The list of topics below is tentative and subject to changes.
Papers below marked "read before class" are required reading before the relevant lecture, and many times introduce the computer-science tool (but not necessarily the economic application) discussed in the lecture.
Papers marked "read after class" are highly recommended reading after the relevant lecture. These are often the main topic of the lecture (the papers upon which the lecture was based) and go into details or generality not covered in the lectures. They sometimes reference computer-science terms or jargon that were introduced in class.
Papers marked "further reading" are optional reading materials that are natural next steps if you are particularly interested in the lecture topic.

<u>Overture</u>

Sep 4

- Bird's eye view: course intro and sampler.

<u>Part I: Is it an optimality theorem? Is it a uniqueness theorem? No! It's an approximation theorem!</u>

Sep 9

- Economic application: bounding loss in equilibrium due to unpriced externalities.
- Examples: routing/congestion games, simultaneous first-price auctions.
- Formal concept: the price of anarchy.
- Tool: smooth games, charging.

<u>Read after class</u>: Tim Roughgarden. *Twenty Lectures on Algorithmic Game Theory*, Chapter 14. Cambridge University Press, 2016, pages 187–201. DOI:https://doi.org/10.1017/CBO9781316779309.015
<u>Further reading</u>: Michal Feldman, Hu Fu, Nick Gravin, and Brendan Lucier. *Simultaneous auctions are (almost) efficient*. In Proceedings of the 45th Annual ACM Symposium on Theory of Computing (STOC 2013), 201–210. DOI:https://doi.org/10.1145/2488608.2488634
<u>Further reading</u>: Michal Feldman, Nicole Immorlica, Brendan Lucier, Tim Roughgarden, Vasilis Syrgkanis. *The price of anarchy in large games*. In Proceedings of the 48th Annual ACM Symposium on Theory of Computing (STOC 2016), 963–976. DOI:https://doi.org/10.1145/2897518.2897580

Sep 11

- Economic application: bounding loss due to lack of information.
- Examples: welfare/revenue maximization in sequential pricing with prior known distributions.
- Formal concept: competitive analysis / optimal stopping.
- Tool: prophet inequality.

<u>Optionally read before class:</u> though not necessary for following the lecture, those who have learned in the past about calculating the welfare of a mechanism using so-called "virtual values" (e.g., Equation 23.D.16 in MWG) may wish to brush up on the subject.
<u>Further reading</u>: Shuchi Chawla, Jason D. Hartline, David L. Malec, and Balasubramanian Sivan. *Multi-parameter mechanism design and sequential posted pricing*. In Proceedings of the 42nd ACM Symposium on Theory of Computing (STOC 2010), 311–320. DOI:https://dl.acm.org/doi/10.1145/1806689.1806733
<u>Further reading</u>: Robert Kleinberg and S. Matthew Weinberg. *Matroid prophet inequalities*. In Proceedings of the 44th Annual ACM Symposium on Theory of Computing (STOC 2012), 123–136. DOI:https://doi.org/10.1145/2213977.2213991
<u>Further reading</u>: Hossein Esfandiari, MohammadTaghi Hajiaghayi, Vahid Liaghat, and Morteza Monemizadeh. Prophet Secretary. SIAM Journal on Discrete Mathematics., 31, no. 3 (2017), 1685–1701. DOI:https://doi.org/10.1137/15M1029394

Sep 16

- Introduction to the multi-item monopolist's problem with a single buyer: mechanisms as menus, Rochet's Theorem: representing mechanisms via the corresponding buyer's utility, optimality of posted pricing for a single item, the "rabbit hole" of multiple items as motivation for restricting the functional form of mechanisms.

Sep 18, 23 (+part of Sep 25)

- Economic application: bounding revenue loss due to restricting the functional form of mechanisms.
- Example: multi-item auctions.
- Formal concept: bounding loss compared to an "unknown benchmark."
- Tool: weak duality via Lagrangian duality.

<u>Read before class (for Sep 18)</u>: Brush up on (or learn for the first time) Lagrangian duality by reading the first three pages here: https://www-cs.stanford.edu/people/davidknowles/lagrangian_duality.pdf

Read after class (Sep 18): Sections 1–4 in: Sergiu Hart and Noam Nisan. *Approximate revenue maximization with multiple items*. Journal of Economic Theory, 172 (2017), 313–347. DOI:https://doi.org/10.1016/j.jet.2017.09.001
Further reading (Sep 18): Sergiu Hart and Philip J. Reny. *The Better Half of Selling Separately*. ACM Transactions on Economics and Computation, 7, no. 4 (2019), , Article 18. DOI:https://doi.org/10.1145/3369927
Read after class (Sep 23): Yang Cai, Nikhil R. Devanur, and S. Matthew Weinberg. *A duality based unified approach to Bayesian mechanism design*. In Proceedings of the 48th Annual ACM Symposium on Theory of Computing (STOC 2016), 926–939. DOI:https://doi.org/10.1145/2897518.2897645
Further reading (Sep 23): Moshe Babaioff, Nicole Immorlica, Brendan Lucier, and S. Matthew Weinberg. *A Simple and Approximately Optimal Mechanism for an Additive Buyer*. Journal of the ACM (JACM) 67, no. 4 (2020), Article 24. DOI:https://doi.org/10.1145/3398745

Sep 25, 30
- Economic application: making up for loss by market augmentation, as an alternative approach to bounding loss.
- Examples: revenue in the single-item monopolist problem, welfare in a double auction market.
- Formal concept: market augmentation.
- Tool: coupling probability spaces.

Read before class: Bulow, Jeremy, and Paul Klemperer. *Auctions Versus Negotiations*. The American Economic Review 86, no. 1 (1996): 180–94. http://www.jstor.org/stable/2118262
Read after class: Moshe Babaioff, Kira Goldner, and Yannai A. Gonczarowski. *Bulow-klemperer-style results for welfare maximization in two-sided markets*. In Proceedings of the 31st Annual ACM-SIAM Symposium on Discrete Algorithms (SODA 2020), 2452–2471. DOI:https://doi.org/10.1137/1.9781611975994.150

Oct 2 — Rosh HaShanah Eve — class canceled

Part II: If I have seen further, it is by looking through the many lenses of complexity

Oct 7
- A high-level introduction to complexity as a coarse lens into how problems scale, via computational complexity.

Read after class: Sections 1–2 in: Tim Roughgarden. *Computing Equilibria: A Computational Complexity Perspective*. Economic Theory 42, (2010), 193–236. DOI:https://doi.org/10.1007/s00199-009-0448-y
Further reading: Sections 3–4 in: Tim Roughgarden. *Computing Equilibria: A Computational Complexity Perspective*. Economic Theory 42, (2010), 193–236. DOI:https://doi.org/10.1007/s00199-009-0448-y

Oct 9
- Economic application: conditions for existence of equilibrium prices.
- Tool: integrality gap of linear programming, reductions, P≠NP assumption.

Read before class: Brush up on linear programming duality by reading the following two blog posts: https://lucatrevisan.wordpress.com/2011/01/24/cs261-lecture-5-linear-programming/ ; https://lucatrevisan.wordpress.com/2011/01/24/cs261-lecture-6-duality-in-linear-programming/
Read before class: Liad Blumrosen and Noam Nisan. *Combinatorial Auctions*. Section 11.3 of Chapter 11 in Algorithmic Game Theory, edited by N. Nisan, T. Roughgarden, E. Tardos, V. Vazirani, Cambridge University Press, 2007, 275–279. Book PDF available at the publisher's site under "Resources."
Read after class: Tim Roughgarden and Inbal Talgam-Cohen. *Why Prices Need Algorithms*. In Proceedings of the 16th ACM Conference on Economics and Computation (EC 2015), 19–36. DOI:https://doi.org/10.1145/2764468.2764515

Oct 14 — Indigenous Peoples' Day — no classes

Oct 16

- Economic application: understanding how much a solution depends on the types of subsets of players.
- Examples: how much does the M-optimal stable matching depend on the preferences of the other side?
- Formal concept: communication complexity.
- Tool: reduction to disjointness.

Read before class: Brush up on Deferred Acceptance here: David Gale and Lloyd S. Shapley. *College Admissions and the Stability of Marriage*. The American Mathematical Monthly 69, no. 1 (1962), 9–15. DOI:https://doi.org/10.2307/2312726

Read before class: Read about measuring communication complexity here: Eyal Kushilevitz and Noam Nisan. *Communication Complexity*, Chapter 1. Cambridge University Press, 2009, pages 3–15. DOI:https://doi.org/10.1017/CBO9780511574948.002

Read after class: Yannai A. Gonczarowski, Noam Nisan, Rafail Ostrovsky, Will Rosenbaum. *A Stable Marriage Requires Communication*. Games and Economic Behavior 118 (2019), 626–647. DOI:https://doi.org/10.1016/j.geb.2018.10.013

Further reading: Itai Ashlagi, Mark Braverman, Yash Kanoria, and Peng Shi . *Clearing Matching Markets Efficiently: Informative Signals and Match Recommendations*. Management Science 66, no. 5 (2019), 2163–2193. DOI:https://doi.org/10.1287/mnsc.2018.3265

Oct 21, 23, 28

- Economic application: Bayesian analysis with prior from past data
- Example: multi-item auctions.
- Formal concept: sample complexity / PAC learning.
- Tools: parametric analysis via pseudo-dimension; non-parametric analysis based on input dimensionality.

Further reading (Oct 23): Jamie Morgenstern and Tim Roughgarden. *Learning Simple Auctions*. In 29th Annual Conference on Learning Theory (COLT 2016), 1298–1318. URL:http://proceedings.mlr.press/v49/morgenstern16.html

Read after class (Oct 28): Yannai A. Gonczarowski and S. Matthew Weinberg. *The Sample Complexity of Up-to-ε Multi-dimensional Revenue Maximization*. Journal of the ACM (JACM) 68, no. 3 (2021), Article 15. DOI:https://doi.org/10.1145/3439722

Further reading: Chenghao Guo, Zhiyi Huang, and Xinzhi Zhang. *Settling the sample complexity of single-parameter revenue maximization*. In Proceedings of the 51st Annual ACM SIGACT Symposium on Theory of Computing (STOC 2019), 662–673. DOI:https://doi.org/10.1145/3313276.3316325

Part III: Any sufficiently advanced cryptographic tool is indistinguishable from magic

Oct 30; Nov 4, 6

- Economic application: simulating simultaneous sealed-bid auctions from a distance. Cryptographic tool: nonmalleable cryptographic commitments.
- Material: defining secure encryption, impossibility of perfect hiding with perfect binding, cryptographic commitments as motivation for computational cryptographic guarantees.

Read after class: Chapter 1 in Boaz Barak's book, Section 8.12 of Boneh and Shoup's book.

Further reading: Matheus V. X. Ferreira and S. Matthew Weinberg. *Credible, Truthful, and Two-Round (Optimal) Auctions via Cryptographic Commitments*. In Proceedings of the 21st ACM Conference on Economics and Computation (EC 2020), 683–712. DOI:https://doi.org/10.1145/3391403.3399495

Nov 11

- Economic application: committing to a hidden mechanism while proving selected mechanism properties.
- Cryptographic tool: zero-knowledge proofs.
- Material: ZKP of hamiltonicity and hence any problem in NP, the simulation paradigm.

Read after class: Chapter 14 in Boaz Barak's book.
Read after class: Ran Canetti, Amos Fiat, Yannai A. Gonczarowski, *Zero-Knowledge Mechanisms*. https://arxiv.org/abs/2302.05590

Nov 13

- Economic application: implement correlated equilibrium as cheap talk + Nash equilibrium; participant-privacy-preserving deferred acceptance and auctions.
- Cryptographic tool: secure multiparty computation (via a high-level brief introduction).

Read after class: Yevgeniy Dodis and Tal Rabin. *Cryptography and Game Theory*. Chapter 8 in Algorithmic Game Theory, edited by N. Nisan, T. Roughgarden, E. Tardos, V. Vazirani, Cambridge University Press, 2007, 181–205. Book PDF available at the publisher's site under "Resources."
Further reading: Izmalkov, Sergei, Matt Lepinski, and Silvio Micali. *Perfect Implementation*. Games and Economic Behavior, 71, no. 1 (2011), pages 121-140.
DOI:https://doi.org/10.1016/j.geb.2010.05.003

Coda: All good things…

Nov 18

- New Horizons: short guest lectures presenting vignettes of cutting-edge related research.

Nov 20, 25; Dec 2, 4

- Student presentations of final projects.