# TCS-UY.4504 Advanced Seminar: Entropy

## Department of Technology, Culture and Society | NYU-Tandon

Prof: Jonathan Bain
jon.bain@nyu.edu
https://research.engineering.nyu.edu/~jbain

Off. Hr: Zoom, Tues 12:30-1:30pm remote
Office: 2Metrotech, 9th Fl., Rm929

2 MetroTech, 8th Fl., Rm827
M/W 10:00-11:50am
Spring 2024

**I. Instructional Format**: Instruction will be conducted in-class, unless circumstances require otherwise. Please be aware of the NYU policy on face masks at nyu.edu/life/safety-health-wellness/coronavirus-information/covid-related-guidance/protective-equipment.html. Masks are not required but welcome. As a reminder, if you are ill or are exhibiting symptoms of illness (coughing, sneezing, runny nose, etc.), you should stay home until you feel better and your symptoms are gone. It's ok to miss one or two lectures in this class: these can be easily made up by discussing any missed content with me. On the other hand, if you find yourself in a situation in which you will have to miss more than a week of lectures, please see Section VII.3.ii below. I will periodically remind the class of these policies over the course of the semester.

**II. Description:** What happens when you throw a cup of coffee into a black hole? Can a "very observant and neat-fingered being" defeat the 2nd Law of Thermodynamics? Can quantum entanglement weirdness be quantified? In this seminar we will attempt to answer these and similar questions by using techniques from the field of history and philosophy of science to explore the many roles that the concept of entropy plays in physics: from its origin in 1865 in the emerging field of thermodynamics, to its application a decade later to statistical mechanics, and then onward in the 20th century to its appearances in classical information theory and quantum mechanics, its extension in the 1970s to the physics of black holes (by NYU-Tandon alumnus Jacob Bekenstein), and finally current applications of it to solve the infamous black hole information loss paradox. We will be concerned throughout with the extent to which these different roles entail different notions of entropy: Is thermodynamic (TD) entropy the same as statistical mechanical (SM) entropy? Is information-theoretic entropy the same as TD and/or SM entropy? Is quantum mechanical entropy the same as TD, SM, and/or information-theoretic entropy? What sort of entropy is black hole entropy? We will also be concerned with critically evaluating popularized accounts of entropy (as a measure of "disorder", "randomness", and/or "uncertainty"): Are such accounts justified by the way entropy is actually used in physics? By the end of the seminar we should better appreciate the historical contingency of theoretical terms in physics, and how a single theoretical term can live many diverse non-overlapping lives.

This is a 4-credit course that meets over a 15 week semester. You should thus expect to devote 6.6 hours per week of supplemental time for this course. Supplemental time is time outside of classroom instruction that involves reading assignments, writing, exam preparation, homework assignments, and study time. For additional information on NYU policies related to this, please see: www.nyu.edu/academics/accreditation-authorization-assessment/resources-faqs/required-weekly-minutes.html

## III. Objectives

*HuSS (Humanities and Social Sciences) General Education Objectives*

Think critically, creatively and independently; demonstrate information literacy; demonstrate skills in inquiry and analysis; demonstrate effective oral communication skills; demonstrate effective writing skills; bring the perspectives of HuSS to bear on technical discourse; demonstrate ethical reasoning.

*STS (Science, Technology and Society) Cluster Objectives*

- Demonstrate a basic understanding of the following:
  - How sci & tech shape society (in historical, philosophical, sociological, cultural, and technical ways).
  - How social processes frame sci and tech enterprises, including theory construction, invention, and innovation.
  - The relation between the content of sci/tech knowledge, and the social context in which it is created.
- Demonstrate technical proficiency in a field in the natural sciences or engineering.
- Demonstrate ability to critically analyze and communicate issues involving interactions among sci, tech, & society.

## IV. Reading

### A. Online via Bobst:

1. [RF17] Rex, A. & C.B.P. Finn (2017) *Finn's Thermal Physics*, Taylor & Francis (excerpts).
2. [Lem13] Lemons, D. (2013) *A Student's Guide to Entropy*, Cambridge Univ. Press, (excerpts).
3. [RP11] Rieffel, E. & W. Polak (2011) *Quantum Computing: A Gentle Introduction*, MIT Press, (excerpts).

### B. Online at course website:

1. [An22] Ananthaswamy, A. (2022) "Is Our Universe a Hologram?", *Scientific American* scientificamerican.com/article/is-our-universe-a-hologram-physicists-debate-famous-idea-on-its-25th-anniversary
2. [Ben87] Bennett, C. (1987) "Demons, Engines and the Second Law", *Sci Am*, 108-116.
3. [Bub01] Bub, J. (2001) "Maxwell's Demon and the Thermodynamics of Computation", *Studies in History and Philosophy of Modern Physics 32*, 569-79.
4. [EN99] Earman, J. and J. Norton (1999) "Exorcist XIV: The Wrath of Maxwell's Demon. Part II. From Szilard to Landauer and Beyond", *Stud Hist Phil Mod Phys 30*, 1-40.
5. [EN98] Earman, J. and J. Norton (1998) "Exocist XIV: The Wrath of Maxwell's Demon. Part I. From Maxwell to Szilard", *Stud Hist Phil Mod Phys 29*, 435-71.
6. [FW11] Frigg, R. & C. Werndl (2011) "Entropy: A Guide for the Perplexed", in C. Beisbart & S. Hartmann (eds.) *Probabilities in Physics*, Oxford Univ. Press, 115-42.
7. [FW19] Frigg, R. & C. Werndl (2019) "Statistical Mechanics: A Tale of Two Theories", *The Monist 102*, 424-438.
8. [Gol01] Goldsein, S. (2001) "Boltzmann's Approach to Statistical Mechanics", in J. Bricmont *et al*. (eds.) *Chance in Physics, Lecture Notes in Physics 574*, Springer, 39-54.
9. [Mus20] Musser, G. (2020) "The Most Famous Paradox in Physics Nears Its End", *Quanta Magazine*, quantamagazine.org/the-most-famous-paradox-in-physics-nears-its-end-20201029/.
10. [Pru20] Prunkl, C. (2020) 'On the Equivalence of von Neumann and Thermodynamic Entropy', *Philosophy of Science 87*, 262-280.
11. [PT19] Prunkl, C. and C. Timpson (2019) 'Black Hole Entropy is Thermodynamic Entropy', https://arxiv.org/abs/1903.06276.
12. [Wal20] Wallace, D. (2020) "Why Black Hole Information Loss is Paradoxical", in N. Huggett, *et al.* (eds.) *Beyond Spacetime*, Cambridge University Press, 209-236.
13. [Wal18] Wallace, D. (2018) "The Case for Black Hole Thermodynamics Part I: Phenomenological Thermodynamics", *Stud Hist Phil Mod Phys 64*, 52-67.
14. [Wol21] Wolchover, N. (2021) "This Physicist Discovered an Escape from Hawking's Black Hole Paradox", *Quanta Magazine*, quantamagazine.org/netta-engelhardt-has-escaped-hawkings-black-hole-paradox-20210823.

**V. Requirements**: This course has two websites: A Brightspace website, brightspace.nyu.edu, accessible only to enrolled students, and a public website, https://research.engineering.nyu.edu/~jbain/tcs_seminar.

1. **Seven homework assignments**. These are posted in the Contents section in Brightspace. Please submit them by their due dates to links in the Brightspace Assignments folder. One optional extra credit assignment may also be submitted and will count towards your final homework grade.
   *Submission format*: The preferred file type is .pdf. Please label the file you submit using the following format:
   <assignment number>.<last name>_<first initial>.<file type>
   *Example*: Jon Bain's .pdf submission for homework #7 should be labeled:
   07.Bain_J.pdf
2. **One research paper** of no less than 15 pages and no more than 20 pages (typed, 12-point, double-spaced, spell-checked!). Suggested themes are posted in the Contents section in Brightspace. It will be your responsibility to pick a theme and then, in consultation with me, develop it into a research topic for your paper. Your paper should conform to guidelines that are posted in the Contents section of Brightspace and that will be discussed in class. The grade for your paper will be based on two parts:
   (a) An *initial draft*.
   (b) A *revised draft* that addresses comments on the initial draft.
   Due dates for research topic, initial draft, and revision are in the Schedule of Topics below.
3. **One midterm** and **one final**. Each exam will consist of 8 short answer questions, of which you will be asked to pick 6; and 3 short essay questions, of which you will be asked to pick 2. A response to a short answer question should be no more than 1 paragraph (~3-4 sentences), and a response to a short essay question should be no more than 1 page (~3-4 paragraphs). Both the midterm and the final will be open-book, open-notes, take-home exams and should be submitted by their due-dates to the relevant link in the Brightspace Assignments folder. For the policy on makeup exams, please see Section VII.3.ii below.

## VI. Grade Distribution

Homework: 10% total  Midterm: 15%  Initial Draft: 30%  Revision: 30%  Final: 15%

## VII. Reminders on University Policies

1. **Inclusion Statement.** NYU values an inclusive and equitable environment for all 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 learning needs be addressed both in and out of class, and that the diversity that students bring to this class be viewed as a resource, strength and benefit. If this standard is not being upheld, please feel free to speak with me.

2. **Moses Statement.** If you would like to request accommodations, please contact the Moses Center for Students with Disabilities (CSD) at 212-998-4980, mosescsd@nyu.edu, nyu.edu/csd, 726 Broadway, 2nd Flr. You must be registered with CSD to receive accommodations.

3. **Standards and Procedures**. The NYU-Tandon Office of Student Affairs maintains a Community Standards and Procedures website at engineering.nyu.edu/life/student-affairs/community-standards-procedures. It contains information relevant to:

   (i) ***Incompletes***. It is NYU-Tandon policy that incompletes can be given only in extenuating circumstances (medical emergencies, accidents, *etc*.). An incomplete cannot be given

because of a heavy course load, job commitments, or because you've simply fallen behind. For this reason, you should attend every lecture and make sure you're aware of assignment deadlines and exam dates. If you find yourself falling behind during the semester, do not hesitate to contact me. If you think you qualify for an incomplete grade at the end of the semester, see the procedure in (ii) below.

(ii) ***Excuses due to illness or circumstances***. If you are experiencing an illness or any other situation, emotional or physical, that might affect your academic performance in a class (for instance, if you have to miss more than a week of lectures, or you think you qualify for an incomplete grade at the end of the semester), please email or schedule a visit with Deanna Rayment, Coordinator of Student Advocacy, Compliance and Student Affairs, Dibner Hall Room LC 240C, eng.studentadvocate@nyu.edu. Deanna is your official advocate at NYU-Tandon. (No other NYU school offers a similar service to its students!) She can reach out to your professor on your behalf when warranted. She can also advise you on all issues related to Health and Wellness. For legal and privacy reasons, you should not directly contact your professor with requests and concerns of this nature.

(iii) ***University Honor System***. Please be aware of the university policy on cheating and plagiarism in the Student Code of Conduct. Cheating on an exam, or plagiarizing on an essay assignment, are sufficient reasons for receiving an F in the course. The Code of Conduct can be downloaded from the Office of Student Affairs website listed above.

4. **Grading Policy.** The following is NYU-Tandon's grading policy for undergrad classes:

| | | | |
|---|---|---|---|
| A | Excellent (4.000) | S | Satisfactory |
| A- | Excellent (3.667) | U | Unsatisfactory Progress |
| B+ | Good (3.333) | W | Withdrew Officially |
| B | Good (3.000) | I | Incomplete (converts to F after 180 days) |
| B- | Good (2.667) | AUD | Auditor Status |
| C+ | Satisfactory (2.333) | NR | No record |
| C | Satisfactory (2.000) | P | Passing |
| C- | Satisfactory (1.667) | | |
| D+ | Minimum Passing Grade (1.333) | | |
| D | Minimum Passing Grade (1.000) | | |
| F | Failure (0.000) | | |

**VIII. Class Schedule**: Readings serve as background and sources for a given lecture topic, and should be completed by the date on which they appear. For multiple readings on a given day, try to read through at least one. This schedule may need to be modified over the course of the semester.

| | | |
|---|---|---|
| 1 | **Mon 1/22.** *Heat Engines and the 2nd Law*<br>Background: [RF17] Chap 3 | **Weds 1/24.** *Heat Engines and 2nd Law, cont.*<br>[Lem13] pp 1-7; [RF17] Chap 4 |
| 2 | **1/29.** *Thermodynamic Entropy*<br>[Lem13] pp. 7-19; [RF17] Chap 5 | **1/31.** *Thermodynamic Entropy, cont.*<br>**Sample research topics**; **hw1 due** |
| 3 | **2/5.** *Maxwell's Demon*<br>[EN98] pp. 435-464 | **2/7.** *Maxwell's Demon, cont.*<br>**Sources for history & philosophy of physics** |
| 4 | **2/12.** *Statistical Mechanics: Boltzmann Entropy*. [Lem13] Chap 2; [Gol01] | **2/14.** *Stat Mech: Gibbs Entropy.* [Lem13] Chap 5; [FW19]. **Paper guidelines**; **hw2 due** |
| 5 | **2/19. No Class (Presidents' Day)** | **2/21.** *Gibbs Entropy, cont.*<br>**How to construct an abstract and outline** |
| 6 | **2/26.** *Classical Info Theory: Shannon Entropy*. [Timp04]; [Lem13] Chap 8 | **2/28.** *Shannon Entropy, cont.*<br>**Citation methods**; **hw3 due** |
| 7 | **3/4.** *Information and Maxwell's Demon*<br>[EN99] pp. 1-20. **Research topic due** | **3/6.** *Info and Maxwell's Demon, cont.*<br>[Bub01]; [Ben87]. **Midterm handed out** |
| 8 | **3/11.** *Quantum Mechanics: Basics*<br>[RP11] pp. 1-16. **Midterm due** | **3/13.** *Quantum Mechanics: Basics, cont.*<br>**hw4 due** |
| 9 | **3/18. Spring Break** | **3/20. Spring Break** |
| 10 | **4/1.** *Density Operators and Mixed States*<br>[RP11] pp. 205-214. | **4/3.** *Quantum Entanglement*<br>[RP11] pp. 31-41. **First draft due** |
| 11 | **4/8.** *Entanglement Correlations* | **4/10.** *Von Neumann Entropy*<br>[RP11] pp. 216-217. **hw5 due** |
| 12 | **4/15.** *Von Neumann Entropy as TD Entropy.* [Pru20] | **4/17.** *Black Hole Thermodynamics*<br>[Wal18]. |
| 13 | **4/22.** *Black Hole Entropy as TD Entropy*<br>[PT19]. | **4/24.** *Black Hole Entropy as Entanglement Entropy.* [An22]**. hw6 due; Revision due** |
| 14 | **4/29.** *The Black Hole Information Loss Paradox.* [Wal20]. | **5/1.** *The Black Hole Information Loss Paradox, cont.* |
| 15 | **5/6.** *Overflow/Review*<br>**hw7 due; Final handed out (due 5/10)** | |