Physics 95. Topics in Current Research

Prof. Aravi Samuel, Department of Physics.

This tutorial is based on the Tuesday Night Seminars. Each Tuesday night, one or two Harvard faculty members introduce their research to interested students, including undergraduates enrolled in the course, as well as graduate students who would like to learn about the topics investigated. The talks illustrate how research is done, and provide research examples of projects graduate students might study if they join the group. Before each seminar, the enrolled students read examples of previous work, and in the Monday class, they present and discuss the concepts. Students learn how to express scientific concepts verbally, and in writing for their final report. The course is aimed at juniors and seniors who are familiar with the basics in classical mechanics, electricity and magnetism, and quantum mechanics.

Aravi Samuel received his BA in physics and PhD in biophysics from Harvard. He studies brain and behavior in small organisms like fruit flies, nematodes, and bacteria. Email: samuel@physics.harvard.edu

Armaan Shaikh graduated with a BA in Physics from Cambridge University, UK. This year, he is a research fellow with Suyang Xu in Chemistry, working on 2D materials. . Email: armaanshaikh@fas.harvard.edu

Monday Meeting (Monday 3-4:15 PM in Lyman 330 – except 10/21 and 11/18 in Northwest 243). We will meet experimental groups in our department, tour labs, and learn about ongoing experiments.

Tuesday Meeting (Tuesday 7:30-8:45 PM in Jefferson 356). Faculty from the Physics Department will give seminars about ongoing work in theory and experiment.

Office Hours held by Aravi and Armaan by appointment.

Course Materials will be distributed as this main PDF course packet, containing hyperlinks to directly download all required and recommended reading material.

Grades will be based on Response papers (60%); Final presentation (20%); Class participation (20%). Students are expected to write three 'response papers' over the semester. For each paper, you will respond to the research that you encounter. As you listen and read about the work of each research group, think about an issue that particularly interests you. Discuss with Aravi, Armaan, and/or the relevant faculty member. Respond to the issue with a short essay. At the end of the semester, one essay will be selected on which you will deliver one oral presentation.

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The Harvard Physics Department

Front: Jacob Barandes, Susanne Yelin, Anna Klales, Jenny Hoffman, Mara Prentiss, Masahiro Morii, Paul Horowitz, Norman Yao
Middle: Andrew Strominger, Sonia Paban, Peter Galison, Isaac Silvera, Subir Sachdev, Cumrun Vafa, Cora Dvorkin, Matthew Reece, Arthur Jaffe, Aravinthan Samuel, Matthew Schwartz.
Rear: David Nelson, Tim Kaxiras, Carlos Argüelles-Delgado, David Morin, John Doyle, Matteo Mitrano, Eslam Khalaf.
Not pictured: Michael Brenner (SEAS), Adam Cohen (Chemistry), Jordan Cotler, Michael Desai (OEB), Douglas Finkbeiner (CFA), Melissa Franklin, Howard Georgi, Markus Greiner, Lene Hau, Eric Heller, John Huth, Daniel Jafferis, Philip Kim, John Kovac, Mikhail Lukin, L. Mahadevan (SEAS), Vinothan Manoharan, Eric Mazur, Julia Mundy, Kang-Kuen Ni (Chemistry), Hongkun Park (Chemistry), Mara Prentiss, Lisa Randall, Sunghan Ro, Haim Sompolinsky, Christopher Stubbs, Ashvin Vishwanath, David Weitz, Robert Westervelt, Suyang Xu (Chemistry), Amir Yacoby, Susanne Yelin, Xi Yin, Xiaowei Zhuang (Chemistry).

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Contents

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Dramatis Personae

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Class Meeting	Topic	Presenter
Sep 3	Introduction to Course (Slides)	Prof. Aravinthan Samuel
Sep 9	Tour of Argüelles-Delgado Lab	Dr. Will Thompson
Sep 10	Exploring neutrinos at IceCube (Slides)	Prof. Carlos Argüelles Delgado
Sep 16	Tour of Mitrano Lab	Dr. Filippo Glerean
Sep 17	Exploring quantum materials with ultrafast spectroscopy (Slides)	Prof. Matteo Mitrano
Sep 23	Tour of Hoffman Lab	Ben November
Sep 24	Designing Quantum Materials at Atomic-Scale	Prof. Julia Mundy
Sep 30	Tour of Doyle Lab	Prof. John Doyle
Oct 1	Fundamental Physics Using Precision Measurement	Prof. Xing Fan
Oct 7	Tour of Kim Lab	Isabelle Phinney
Oct 8	Condensed Matter Theory	Prof. Eslam Khalaf
Oct 14	Tour of Yacoby Lab	Marie Wesson
Oct 15	Quantum Information, Computation, and Spacetime	Prof. Jordan Cotler
Oct 21	Tour of the Greiner Lab	Martin Lebrat, Perrin Segura, Michal Szurek
Oct 22	Quantum Many-Body Physics	Prof. Norm Yao
Oct 28	Tour of Lukin Lab	Sophie Li, Andrei Ruskuc, Aziza Suleymanzade
Oct 29	Theoretical Quantum Optics and Information	Prof. Susanne Yelin
Nov 4	Tour of the Cohen Lab	TBD
Nov 5	All-optical neurophysiology	Prof. Adam Cohen
Nov 11	Tour of the Lichtman Lab	Dr. Daniel Berger
Nov 12	Computational neuroscience	Prof. Haim Sompolinsky
Nov 18	Tour of Needleman Lab	Yash Rana
Nov 19	Active matter and biophysics	Prof. Sunghan Ro
Nov 25	Practice presentations	(Group 1)
Nov 26	Practice presentations	(Groups 2,3)
Dec 2	Practice presentations	(Group 4)
Dec 3	Final presentations	(Groups 1,2)
Dec 10	Final presentations	(Groups 3,4)

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Assignments

Essay One, Due September 30

In the first weeks of Physics 95, you were introduced to the Samuel, Argüelles-Delgado, Mitrano, Hoffman, and Mundy labs. Write a short essay (1000-1500 words) that demonstrates your ability to probe interesting research issues from **one** group that interested you.

In your essay, *describe the background work* that was presented (either on lab tour or Tuesday night presentation), *how particular issues* piqued your curiosity, *how you were inspired to ask one or more questions* that probed more deeply into what was presented, and finally *how your questions might be answered.* You are learning about cutting-edge research, so your questions might *not* have answers. If so, discussing *possible* answers is fine. You might gather insights about your questions from each week's reading or conversations with faculty. You can also contact faculty by email, and put their insights about your questions *in your own words.*

Essays are graded based on (i) the *clarity* of your summary of faculty research, (ii) your demonstrated *curiosity* in asking probing questions, and (iii) the *coherence* of your discussion of answers to your questions. Our goal is for you to dig more deeply into the material that was presented, and demonstrate an ability to learn more by asking and answering new questions.

If you're unsure about good topical questions for your essays, contact Aravi or Armaan for ideas. Armaan will host Office Hours based on each week's presentations. At these optional office hours, you can sign up to meet and chat more about the work of a specific lab.

Essay Two, Due October 21

See above for the ground rules of this Essay (and the next ones). You can write about any topic that we cover until October 21. including any topic from the first three weeks of class.

Essay Three, Due November 18

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Oral Presentations

Each student will present a 10 minute oral presentation with 2 minutes Q&A about one research topic.

Step 1) Topic assignment. Nov 20. To avoid too many people talking about the same thing, I'll make a first pass at assigning the topic of each student's oral presentation based on your Essays. I'll distribute assignments on November 20, after receiving your last Essay (if you don't like your assignment, just let me know).
N.B. This time-line makes it difficult for anyone to write or talk about the Needleman, Ro, Lichtman, or Sompolinsky labs. We would give credit to anyone bold enough to volunteer to give an oral presentation on these topics, even if they didn't write about it.

Step 2) Group practice sessions. Nov 25-Dec 2. We'll split the class into four groups for Practice Presentations. Each student is only expected to attend their assigned Group Session with 4 or 5 other students. Each group is expected to listen to, critique, and improve one another's presentations.

Nov 25	3-4:30 PM	Lyman 330	Group 1
Nov 26*	6-9 PM	Lyman 330	Groups 2,3
Dec 2	3-4:30 PM	Lyman 330	Group 4

*Dinner provided

Step 3) Final presentations. Dec 3, 10. All groups are expected to attend both Final Presentation sessions.

Dec 3*	6-9 PM	Jefferson 356	Groups 1,2
Dec 10*	6-9 PM	Jefferson 356	Groups 3,4

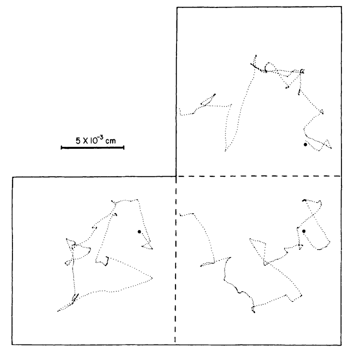
*Dinner provided

Additional Notes. To avoid wasting time with A/V and Mac/PC compatibility, *send all presentations to Armaan beforehand*. You can use any platform (e.g., PowerPoint, Keynote) to prepare each presentations, *but send the final copy as landscape PDF.* We will collect all presentations on one computer.

Week Zero: Samuel Lab

Tuesday, September 3, 7:30 PM, Talk from Prof. Samuel

ARAVI SAMUEL studied with Howard Berg as a graduate student. Howard was the famed inventor of the tracking microscope that discovered the biased random walk of bacterial chemotaxis. Aravi's lab continues to study navigational behaviors in other animals including *C. elegans* and *Drosophila* larva. But when Howard died two years ago, he adopted Howard's 'orphans' and we continue to study bacterial chemotaxis.



WE HAVE MADE TWO MAJOR DISCOVERIES. First, we developed a new form of 'optogenetic biochemistry' that allows us to measure the 'impulse response' of individual flagellar motors to the signaling molecule (CheY) that triggers CW rotation. Second, we have shown that the torque-generating units that cause bacterial flagellar rotation are *themselves* spinning motors. The rotation of the bacterial flagellar motor is driven by a set of even smaller motors that encircle it!

Reading

- **A class review of bacterial chemotaxis by Howard Berg**
  H C Berg. A physicist looks at bacterial chemotaxis. *Cold Spring Harbor Symposia on Quantitative Biology*, 53 Pt 1:1–9, 1988. ISSN 0091-7451 Download PDF
- **A recent review of bacterial chemotaxis, updated by structural information from cryo-EM**
  Shuaiqi Guo and Jun Liu. The bacterial flagellar motor: Insights into torque generation, rotational switching, and mechanosensing. *Frontiers in Microbiology*, 13:911114–911114, 2022. ISSN 1664-302X Download PDF
- **The ultra-sensitivity of the flagellar motorEM**
  Philippe Cluzel, Michael Surette, and Stanislas Leibler. An ultrasensitive bacterial motor revealed by monitoring signaling proteins in single cells. *Science*, 287(5458):1652–1655, 2000. ISSN 0036-8075 Download PDF
- **The classic impulse response measurement of the bacterial flagellar motor**
  Steven M. Block, Jeffrey E. Segall, and Howard C. Berg. Impulse responses in bacterial chemotaxis. *Cell*, 31(1):215–226, 1982. ISSN 0092-8674 Download PDF

Week One: Argüelles-Delgado Lab

Monday, September 9, 3 PM, Tour with Dr. William Thompson
Tuesday, September 10, 7:30 PM, Talk from Prof. Argüelles-Delgado

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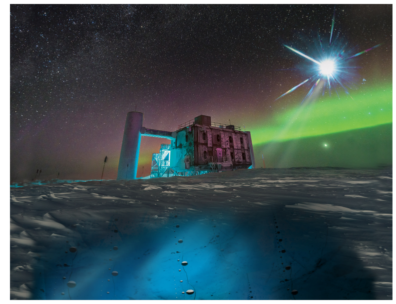

IceCube Observatory and Aurora

Carlos and Will participate in the IceCube Neutrino Observatory, You can learn more about IceCube from its website. You can also read about IceCube in *Physics Today*:

- Observation of the Milky Way with neutrinos
- First observation of the Glashow resonance
- Looking for astrophysical tau neutrinos

Note that the 'Glashow' of Glashow resonance is Sheldon Glashow, Professor Emeritus at Harvard and long-time member of our department.

On the tour, Will Thompson will show you the IceCube digital optical modules (DOMs), the light sensors that form IceCube, a muon tagger we are working on building to deploy in the IceCube Upgrade, how we are trying to use the DOMs to do glaciology, and some work we are doing to build detectors for a different experiment named TAMBO.

Reading

- **Using ML to enhance resolution of neutrino telescopes.**
  Felix J. Yu, Nicholas Kamp, and Carlos A. Argüelles. Enhancing events in neutrino telescopes through deep learning-driven super-resolution, 2024 Download PDF
- **Searching for new physics using supernova timing.**
  Jeff Lazar, Ying-Ying Li, Carlos A. Argüelles, and Vedran Brdar. Supernovae time profiles as a probe of new physics at neutrino telescopes, 2024 Download PDF

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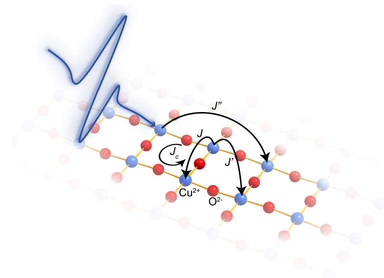
Week Two: Mitrano Lab

Monday, September 16, 3 PM, Tour of the Mitrano Lab with Dr. Filippo Glerean
Tuesday, September 17, 7:30 PM, Talk from Prof. Mitrano



Matteo and Filippo will give us our first introduction to "quantum materials", systems that have surprising properties owing to quantum-mechanical effects over wide scales. The particular expertise of the Mitrano Lab is applying ultrafast optics to manipulate and measure quantum materials.

On Monday, Filippo will show us the lab to see ultrafast laser systems used to interrogate photoexcited quantum materials at different energy scales. We will see optical parametric amplifiers generating tunable light at near infrared frequencies, as well as setups based on nonlinear crystals to emit intense terahertz pulses. These pulses are then used within in-vacuum THz spectrometers with cryogenic capabilities to probe material properties at ultralow temperatures.

On Tuesday, Matteo will talk about the use of ultrafast laser systems to induce metastable electronic phases in low-dimensional materials. Metastable phases are nonequilibrium states of matter which evade decay towards equilibrium due to some physical constraints, thus representing an appealing platform for functional devices. Matteo will show how ultrafast optical and x-ray spectroscopy can be used to identify a rare symmetry-protected form of electronic metastability.

A general background to ultrafast spectroscopy appeared in *Physics Today*: Download PDF

Reading

- Jacqueline Bloch, Andrea Cavalleri, Victor Galitski, Mohammad Hafezi, and Angel Rubio. Strongly correlated electron-photon systems. *Nature*, 606(7912):41–48, 2022. ISSN 0028-0836 Download PDF
- Alberto de la Torre, Dante M. Kennes, Martin Claassen, Simon Gerber, James W. McIver, and Michael A. Sentef. Colloquium:nonthermal pathways to ultrafast control in quantum materials. *Reviews of Modern Physics*, 93(4), 2021. ISSN 0034-6861 Download PDF
- Ankit S. Disa, Tobia F. Nova, and Andrea Cavalleri. Engineering crystal structures with light. *Nature physics*, 17(10):1087–1092, 2021. ISSN 1745-2473 Download PDF
- M Mitrano, Johnston S, Y-J Kim, and MPM Dean. Exploring quantum materials with resonant inelastic x-ray scattering. *PRX*, 2022 Download PDF

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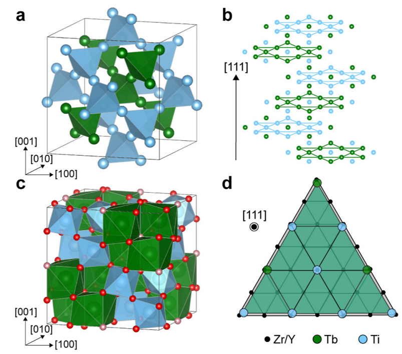
Week Three: Hoffman and Mundy Labs

Monday, September 23, 3 PM, Tour of Prof. Jenny Hoffman's Lab
Tuesday, September 24, 7:30 PM, Talk from Prof. Julia Mundy



The Hoffman Lab focuses on uncovering new physics and applications by combining atomic layer-by-layer growth with atomic resolution imaging. They employ advanced techniques such as Scanning Tunneling Microscopy (STM) and Magnetic Force Microscopy (MFM) to study phenomena at interfaces and on small scales. The lab's research addresses fundamental questions in condensed matter physics, including the mechanisms of electron pairing and vortex pinning in high-temperature superconductors, as well as the control of insulator-to-metal transitions at the nanoscale. On Monday, Ben November will lead a tour of the Hoffman lab.

The Mundy Lab focuses on the design and synthesis of quantum materials, particularly emergent phenomena in oxide thin films. Prof. Julia Mundy's research is at the cutting edge of atomic-scale engineering, where small perturbations can induce significant changes in material properties, unlocking new states of matter. Her lab specializes in using thin film epitaxy to create materials with strong spin frustration, exotic magnetic properties, and novel superconductors.

Reading

- B Voigtlander. *Scanning Probe Microscopy: Atomic Force Microscopy and Scanning Tunneling Microscopy*. Nanoscience and Technology. Springer Nature, Netherlands, 2015. ISBN 9783662452400 Download PDF
- Minhal Gardezi. *A Tight-Binding Approach to Creating van der Waals Metamaterials*. PhD thesis, Wellesley College and Harvard University, 2020 Download PDF
- Qi Song, Spencer Doyle, Grace A. Pan, Ismail El Baggari, Dan Ferenc Segedin, Denisse Cordova Carrizales, Johanna Nordlander, Christian Tzschaschel, James R. Ehrets, Zubia Hasan, Hesham El-Sherif, Jyoti Krishna, Chase Hanson, Harrison LaBollita, Aaron Bostwick, Chris Jozwiak, Eli Rotenberg, Su-Yang Xu, Alessandra Lanzara, Alpha T. N'Diaye, Colin A. Heikes, Yaohua Liu, Hanjong Paik, Charles M. Brooks, Betuel Pamuk, John T. Heron, Padraic Shafer, William D. Ratcliff, Antia S. Botana, Luca Moreschini, and Julia A. Mundy. Antiferromagnetic metal phase in an electron-doped rare-earth nickelate. *Nature Physics*, 19(4):522–528, 2023. ISSN 1745-2473 Download PDF
- Grace A. Pan, Dan Ferenc Segedin, Harrison LaBollita, Qi Song, Emilian M. Nica, Berit H. Goodge, Andrew T. Pierce, Spencer Doyle, Steve Novakov, Denisse Cordova Carrizales, Alpha T. N'Diaye, Padraic Shafer, Hanjong Paik, John T. Heron, Jarad A. Mason, Amir Yacoby, Lena F. Kourkoutis, Onur Erten, Charles M. Brooks, Antia S. Botana, and Julia A. Mundy. Superconductivity in a quintuple-layer square-planar nickelate. *Nature Materials*, 21(2):160–164, 2022. ISSN 1476-1122 Download PDF

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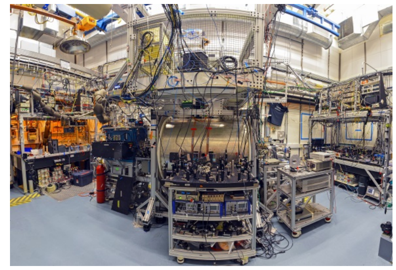
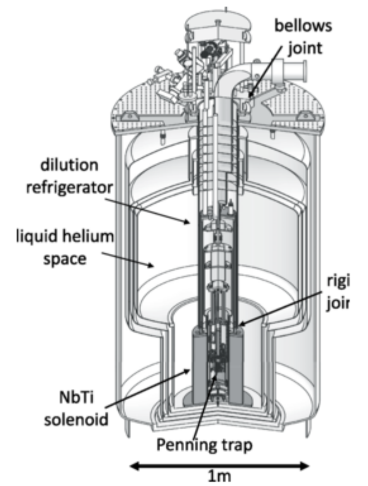
Week Four: Doyle and Fan Labs

Monday, September 30, 3 PM, Tour of Prof. John Doyle's Lab
Tuesday, October 1, 7:30 PM, Talk from Prof. Xing Fan

The Doyle Lab makes precision measurements in particle physics. A major focus is the ACME experiment (see panoramic view), which has set the most stringent limits on the **electron's electric dipole moment (EDM)**, a fundamental probe of new physics beyond the Standard Model. Their approach to exploring quantum science and chemistry is trapping and cooling molecules to ultracold temperatures using buffer-gas cooling. The upper limit to the electron's electric dipole moment is now:



$$|d_e| < 1.1 \times 10^{-29} e\,\mathrm{cm}$$



The Fan Lab also searches for new physics using precision measurement. Prof. Fan contributed to the most precise measurements to date of the **electron magnetic moment**, another rigorous test of the Standard Model and its limits using quantum cyclotron techniques. The electron magnetic moment μ_s is measured in the unit of the Bohr magneton μ_B as

$$\mu_s = -\frac{g}{2}\left(\frac{e\hbar}{2m}\right) = -\frac{g}{2}\mu_B$$

His measurements with a single isolated electron in a Penning trap (see schematic) yields a new measurement of the electron magnetic moment:

$$g/2 = 1.001\ 159\ 652\ 180\ 59\ (13)$$

Combined with the Standard Model calculation, this yields an independent determination of the fine structure constant:

$$\alpha^{-1} = 137.035\ 999\ 166\ (16)$$

You can read about Fan's in *Wired Magazine* and APS News

Reading

- X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse. Measurement of the electron magnetic moment. *Physical Review Letters*, 130(7):071801–071801, 2023. ISSN 0031-9007 Download PDF
- V. Andreev, D. G. Ang, D. DeMille, J. M. Doyle, G. Gabrielse, J. Haefner, N. R. Hutzler, Z. Lasner, C. Meisenhelder, B. R. O'Leary, C. D. Panda, A. D. West, E. P. West, and X. Wu. Improved limit on the electric dipole moment of the electron. *Nature*, 562(7727):355–360, 2018. ISSN 0028-0836 Download PDF

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Week Five: Kim and Khalaf Labs

Monday, October 7, 3 PM, Tour of Prof. Philip Kim's Lab
Tuesday, October 8, 7:30 PM, Talk from Prof. Eslam Khalaf

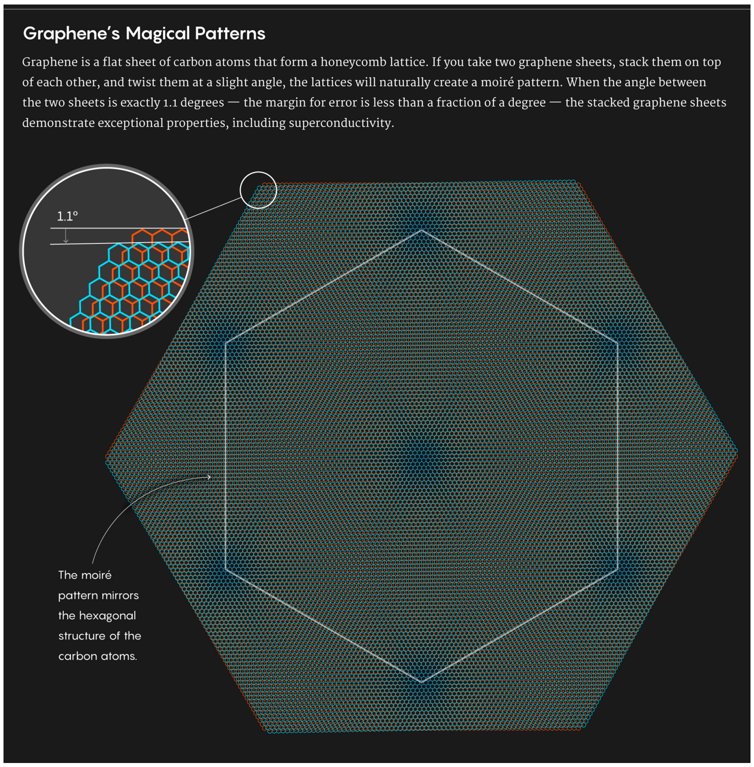

Figure 1: You can read about this new field in *Quanta Magazine*: How twisted graphene became the big thing in physics — Whats the magic behind graphenes magic angle — A new twist reveals superconductivitys secrets .

Philip Kim's lab is a leader in the field of bilayer graphene. In 2018, Pablo Jarillo-Herrero, a former postdoc in the Kim lab, made the extraordinary discovery that twisted bilayer graphene at specific magic angles becomes superconducting (see figure from *Quanta Magazine*! This discovery was soon replicated and extended in the labs of Cory Dean (another former postdoc in the Kim group) and the Kim lab itself. A new field of *twistronics* has emerged. Isabelle Phinney, a graduate student in the Kim lab, will give us a tour of the experimental setups for fabricating and studying these twisted nanostructures.

Eslam Khalaf will describe new theoretical approaches to understanding topological superconductivity in these deceptively simple structures that have become goldmines for new physics.

Reading

- "Physics in Low-Dimensional Materials" by Philip Kim. Harvard Physics Department Newsletter, 2015. Download PDF

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- Patrick J. Ledwith, Eslam Khalaf, and Ashvin Vishwanath. Strong coupling theory of magic-angle graphene: A pedagogical introduction. *Annals of Physics*, 435:168646, 2021. ISSN 0003-4916 Download PDF

Week Six: Yacoby and Cotler Labs

Monday, October 14, 3 PM, Tour of Prof. Amir Yacoby's Lab
Tuesday, October 15, 7:30 PM, Talk from Prof. Jordan Cotler

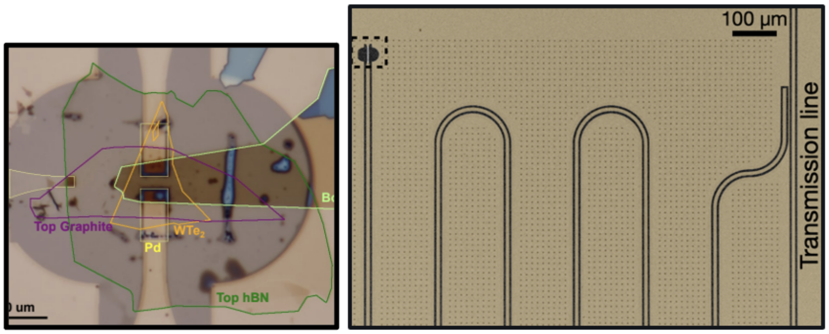


Figure 1: Monolayer WTe2 embedded in a superconducting microwave quantum circuit.

Amir Yacoby and his lab work at the intersection of quantum materials and the development of new quantum probes. The lab's focus on developing innovative experimental techniques allows for precise study of quantum effects that manifest in low-dimensional, low-temperature systems, where traditional methods often fall short. Among the many techniques we have developed and use to study quantum materials are scanning NV center magnetometry, scanning single electron transistor electrometry, and microwave spectroscopy of 2D materials with circuit QED.

Marie Wesson, a graduate student in the Yacoby lab, will lead our Monday tour. Her research focuses on the design and application of superconducting microwave devices, aimed at investigating properties such as kinetic inductance of unconventional superconductors and time reversal symmetry breaking in quantum materials.

Jordan Cotler will describe new theoretical approaches in quantum computation in his Tuesday Seminar. Quantum computers are expected to exceed the capabilities of traditional supercomputers in performing certain algorithms. Quantum computing can also advance our understanding of the natural world, enabling access to physics beyond the reach of conventional experimental approaches. For example, coupling quantum computers to experimental systems can facilitate novel methods for learning properties of quantum many-body states and quantum many-body dynamics which are otherwise inaccessible. Empirical evidence supporting theoretical findings will be presented. We will discuss the role of quantum information in explaining physical phenomena with examples in condensed matter physics and quantum gravity.

Reading

- Dorit Aharonov, Jordan Cotler, and Xiao-Liang Qi. Quantum algorithmic measurement. *Nature Communications*, 13(1):887–887, 2022. ISSN 2041-1723 Download PDF

Updated: October 24, 2024

- Jordan Cotler, Soonwon Choi, Alexander Lukin, Hrant Gharibyan, Tarun Grover, M. Eric Tai, Matthew Rispoli, Robert Schittko, Philipp M. Preiss, Adam M. Kaufman, Markus Greiner, Hannes Pichler, and Patrick Hayden. Quantum virtual cooling. *Physical review. X*, 9(3):031013, 2019. ISSN 2160-3308 Download PDF
- C. G. L. Bottcher, N. R. Poniatowski, A. Grankin, M. E. Wesson, Z. Yan, U. Vool, V. M. Galitski, and A. Yacoby. Circuit quantum electrodynamics detection of induced two-fold anisotropic pairing in a hybrid superconductor-ferromagnet bilayer. *Nature Physics*, 2024. ISSN 1745-2473 Download PDF
- Francesco Casola, Toeno van der Sar, and Amir Yacoby. Probing condensed matter physics with magnetometry based on nitrogen-vacancy centres in diamond. *Nature reviews. Materials*, 3(1):17088, 2018. ISSN 2058-8437 Download PDF
- A Yacoby, H.F Hess, T.A Fulton, L.N Pfeiffer, and K.W West. Electrical imaging of the quantum hall state. *Solid State Communications*, 111(1):1–13, 1999. ISSN 0038-1098 Download PDF

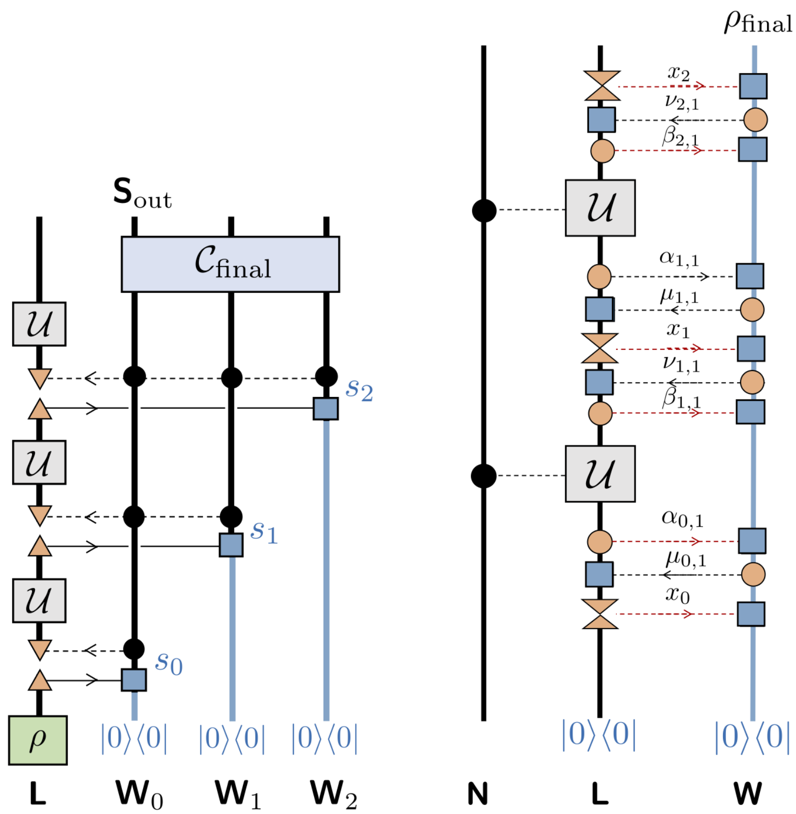
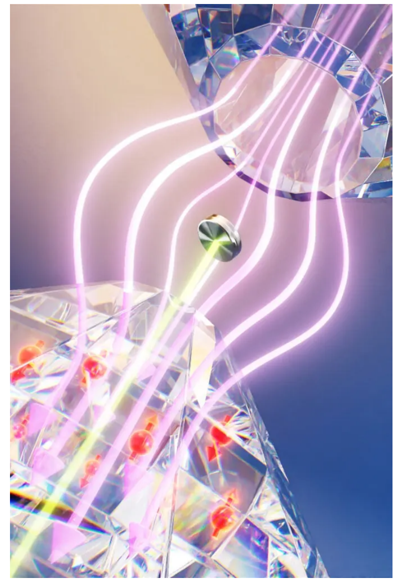


Figure 2: Circuit for quantum algorithmic measurement.

Week Seven: Greiner and Yao Labs

Monday, October 21, 3 PM, Tour of Prof. Markus Greiner's Lab
Tuesday, October 22, 7:30 PM, Talk from Prof. Norman Yao



Norm Yao and his lab work at the intersection of quantum science and engineering. A recent breakthrough was the development of a quantum sensor using naturally-occurring nitrogen vacancy centers in diamond. The strength of diamond makes it ideal for high-pressure physics, like the superconducting transition in cerium hydride at a million atmospheres of pressure. The repulsion of the magnetic field at the superconducting transition (the Meissner effect) can be measured using the NV-centers in a diamond anvil cell containing cerium hydride. You can read about this achievement in Physics Today.

The Greiner lab uses ultracold quantum gases on optical lattices to simulate models from condensed matter physics. Their microscopy allows them to manipulate individual atoms with precise control and accuracy. Recent examples include quantum simulations of the Hubbard model to better understand models for fractional quantum Hall physics, ferromagnetism, and quantum matter with long-range interactions.

Martin Lebrat, a postdoc in the Greiner lab, will lead our Monday tour of their so-called Lithium Lab. Two graduate students, Perrin Segura and Michal Szurek, will lead tours of the Rubidium and Erbium labs respectively.

Reading

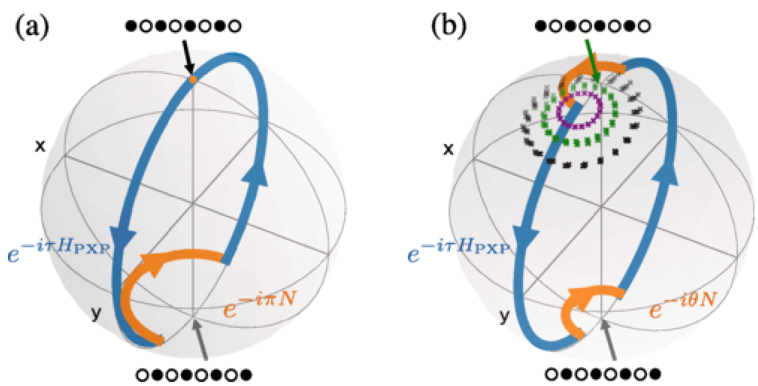
- P. Bhattacharyya, W. Chen, X. Huang, S. Chatterjee, B. Huang, B. Kobrin, Y. Lyu, T. J. Smart, M. Block, E. Wang, Z. Wang, W. Wu, S. Hsieh, H. Ma, S. Mandyam, B. Chen, E. Davis, Z. M. Geballe, C. Zu, V. Struzhkin, R. Jeanloz, J. E. Moore, T. Cui, G. Galli, B. I. Halperin, C. R. Laumann, and N. Y. Yao. Imaging the meissner effect in hydride superconductors using quantum sensors. *Nature*, 627(8002):73–79, 2024 Download PDF
- Martin Lebrat, Muqing Xu, Lev Haldar Kendrick, Anant Kale, Youqi Gang, Pranav Seetharaman, Ivan Morera, Ehsan Khatami, Eugene Demler, and Markus Greiner. Observation of Nagaoka polarons in a Fermi-Hubbard quantum simulator. *Nature*, 629(8011):317–322, 2024 Download PDF
- Julian Leonard, Sooshin Kim, Joyce Kwan, Perrin Segura, Fabian Grusdt, Cecile Repellin, Nathan Goldman, and Markus Greiner. Realization of a fractional quantum Hall state with ultracold atoms. *Nature*, 619(7970):495–499, 2023 Download PDF

Updated: October 24, 2024

- Lin Su, Alexander Douglas, Michal Szurek, Robin Groth, S. Furkan Ozturk, Aaron Krahn, Anne H. Hebert, Gregory A. Phelps, Sepehr Ebadi, Susannah Dickerson, Francesca Ferlaino, Ognjen Markovic, and Markus Greiner. Dipolar quantum solids emerging in a Hubbard quantum simulator. *Nature*, 622 (7984):724–729, 2023 Download PDF

Week Eight: Lukin and Yelin Labs

Monday, October 28, 3 PM, Tour of Prof. Mikhail Lukin's Lab
Tuesday, October 29, 7:30 PM, Talk from Prof. Susanne Yelin



Mikhail Lukin's lab works in quantum optics and quantum information science. On the Monday tour, Dr. Andrei Ruskuc, Dr. Aziza Suleymanzade, and Sophie Li will give tours of three experiments.

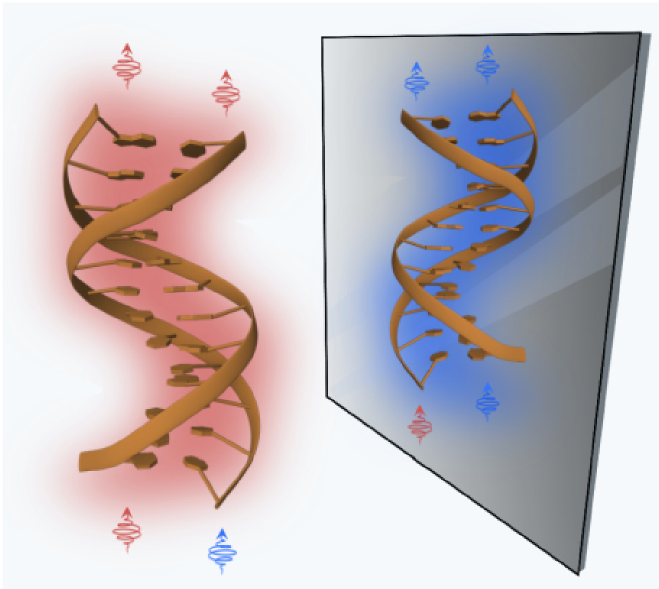
Silicon vacancy defects in diamond nanocavities are a promising platform for quantum networking, with optical and spin properties ideal for scalable quantum communication systems. The *electron spin* of these color centers can be communication qubits with strong coupling to the cavity mode. The *nuclear spin* can be used as memory qubits with >2s coherence times (made longer by cooling).. Nanofabricated diamond devices with embedded SiV defects can achieve strong coupling between single photons and single matter qubits, leading to efficient spin-photon entanglement. This system is a robust and versatile architecture for creating entangled photon states, critical for quantum repeaters and quantum communication. You will see an entanglement distribution between two labs (B16 and G12), nuclear spin entanglement over 35 km using deployed fiber across Boston, and blind distributed computation using our quantum network.

Quantum computing and simulation using 87Rb atom arrays. We trap individual atoms in vacuum in an optical tweezer, enabling real-time spatial control. When these atoms are pumped into ground electronic states, interactions are introduced using lasers to excite Rydberg states. This system allows us to explore many-body 2D phase transitions, hardware-efficient encoding of classical optimization problems, and the detection of a topological spin liquid state.

Quantum processor architecture based on reconfigurable atom arrays. This architecture features high-fidelity entangling gates, local qubit control, mid-circuit readout, and any-to-any connectivity for hundreds of atomic qubits. By grouping atomic qubits together to form error-corrected logical qubits, we are exploring fault-tolerant quantum computation with dozens of logical qubits and hundreds of logical entangling gates.

Quantum Networking with Neutral Atoms Coupled to Optical Cavities. For practical quantum computation, the number of atoms in these systems must scale significantly without compromising qubit properties or gate fidelities. This can be achieved with modular quantum computation; whereby remote processors are linked with photons that distribute entangled states. To achieve this, atoms must be coupled to cavities with high cooperativity, enabling spin-photon entanglement and efficient quantum information transfer via optical fibers. These cavities also enable high fidelity, fast qubit readout and multi-qubit gates. You will see a quantum network prototype based on 87Rb atoms coupled to Fabry-Perot cavities.

- M. K. Bhaskar, R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park, D. Englund, M. Loncar, D. D. Sukachev, and M. D. Lukin. Experimental demonstration of memory-enhanced quantum communication. *Nature*, 580(7801):60–64, 2020 Download PDF
- C M Knaut, A Suleymanzade, Y-C Wei, D R Assumpcao, P-J Stas, Y Q Huan, B Machielse, E N Knall, M Sutula, G Baranes, N Sinclair, C De-Eknamkul, D S Levonian, M K Bhaskar, H Park, M Loncar, and M D Lukin. Entanglement of nanophotonic quantum memory nodes in a telecom network. *Nature*, 629 (8012):573–578, 2024 Download PDF
- Jacob P. Covey, Harald Weinfurter, and Hannes Bernien. Quantum networks with neutral atom processing nodes. *npj quantum information*, 9(1):90–12, 2023 Download PDF
- Tamara Dordevic, Polnop Samutpraphoot, Paloma L. Ocola, Hannes Bernien, Brandon Grinkemeyer, Ivana Dimitrova, Vladan Vuletic, and Mikhail D. Lukin. Entanglement transport and a nanophotonic interface for atoms in optical tweezers. *Science*, 373(6562):1511–1514, 2021 Download PDF



SUSANNE YELIN'S LAB delves into theoretical quantum optics. Her groupâĂŹs research centers on the quantum scale interaction of light with atoms, molecules, and solid-state systems. In particular, Prof. Yelin will discuss cooperative light scattering and superradiance, with a specific application to the connection of light polarization and chirality. This relates to fundamental questions of the homochirality of life.

READING

- B Gohler, V Hamelbeck, T.Z Markus, M Kettner, G.F Hanne, Z Vager, R Naaman, and H Zacharias. Spin Selectivity in Electron Transmission Through Self-Assembled Monolayers of Double-Stranded DNA. *Science*, 331(6019):894–897, 2011 Download PDF
- S. Furkan Ozturk and Dimitar D. Sasselov. On the origins of life's homochirality: Inducing enantiomeric excess with spin-polarized electrons. *Proceedings of the National Academy of Sciences*, 119(28): 1–e2204765119, 2022 Download PDF
- Jonah S. Peter, Stefan Ostermann, and Susanne F. Yelin. Chirality dependent photon transport and helical superradiance. *Physical Review Research*, 6(2):023200, 2024a Download PDF
- Jonah S. Peter, Stefan Ostermann, and Susanne F. Yelin. Chirality-induced emergent spin-orbit coupling in topological atomic lattices. *Physical Review. A*, 109(4), 2024b Download PDF

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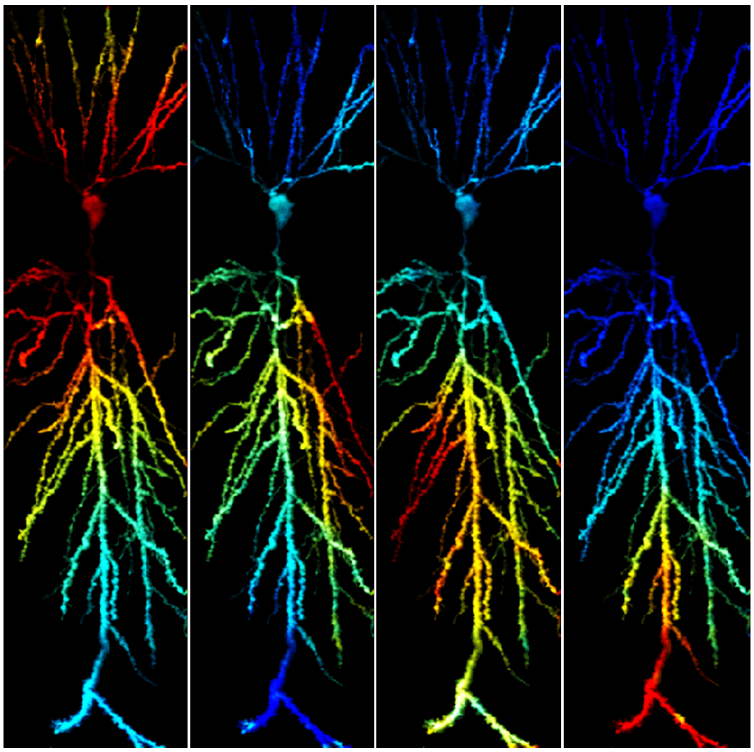
Week Nine: Cohen Lab

Monday, November 4, 3 PM, Tour of Prof. Adam Cohen'sLab
Tuesday, November 5, 7:30 PM, Talk from Prof. Adam Cohen



Adam Cohen. How does the brain compute? The brain is made of neurons and other cell types, which are themselves made from lipid membranes, ion channels, transporters, and a variety of other molecular machines. How do the computational properties of the brain emerge from these wet, squishy components? We are developing tools to record brain dynamics across scales of space and time, from the fastest electrical flickers of individual neuronal branches ("dendrites"), to large-scale patterns of whole-brain activity. I will give an overview of the measurement tools and of some of the things we have learned about the biophysics of brain computations.

Reading

- Adam E. Cohen. Optogenetics: Turning the Microscope on Its Head. *Biophysical Journal*, 110(5):997–1003, 2016 Download PDF
- Valentina Emiliani, Adam E. Cohen, Karl Deisseroth, and Michael Haeusser. All-Optical Interrogation of Neural Circuits. *The Journal of Neuroscience*, 35(41):13917–13926, 2015 Download PDF
- Bill Z. Jia, Yitong Qi, J. David Wong-Campos, Sean G. Megason, and Adam E. Cohen. A bioelectrical phase transition patterns the first vertebrate heartbeats. *Nature*, 622(7981), 2023 Download PDF

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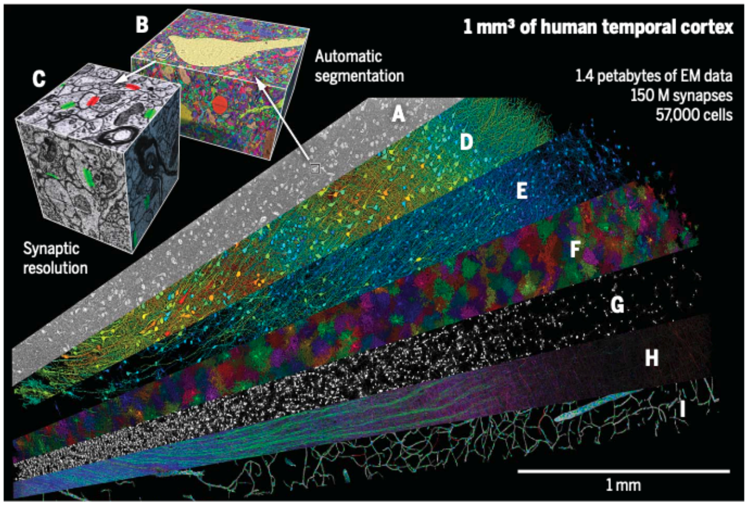
Week Ten: Lichtman and Sompolinsky Labs

Monday, November 11, 3 PM, Tour of Prof. Jeff Lichtman's Lab, **N.B. Class starts in Northwest 243 *not Lyman 330***
Tuesday, November 12, 7:30 PM, Talk from Prof. Haim Sompolinsky



Jeff Lichtman's research focuses on the study of neural connectivity and how it changes as animals develop to accommodate information that is acquired by experience. With his colleagues he has developed a number of tools that permit synaptic level analysis of neural connections, like the Brainbow technique, which can be used to label neurons in individual colors for light microscopy. More recently he has helped develop automated electron microscopy approaches for large scale neural circuit reconstruction (see reconstructed piece of mouse cortex above) as well as combined light-and electron microscopic techniques (CLEM). CLEM can for example be used to augment EM data with tags for certain proteins to identify cell types. Connectomic methods seek to make it routine to acquire neural circuit data in any nervous system. Much of Jeff's earlier work has centered on the mammalian peripheral nervous system which undergoes profound activity-dependent circuit reorganizations in early life. These alterations allow axons to prune most of their branches while strengthening a small subset of synapses in a competitive process called synapse elimination. Recent work in the Lichtman lab has shifted more towards studies of the central nervous system in a multitude of animals, ranging from hydra, *C. elegans*, zebrafish and mouse to the human cortex.

Dr. Daniel Berger and Dr. Nagaraju Dhanyasi will give us a tour of the Lichtman lab.

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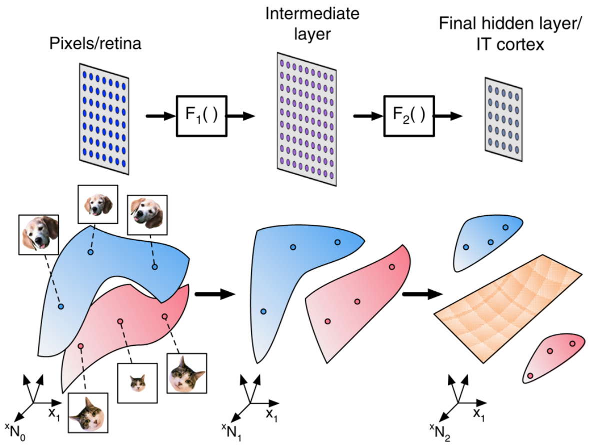

HAIM SOMPOLINSKY's Lab focuses on theoretical neuroscience and is dedicated to uncovering the fundamental principles of brain organization, dynamics, and function across multiple scalesâĂŤfrom molecules and cells to neural circuits. By applying concepts from statistical physics and dynamical systems to these problems, he has developed new theoretical frameworks that bridge physics and neuroscience. Building on his earlier statistical work on critical phenomena and chaos, his research areas cover theoretical and computational investigations of cortical dynamics, sensory processing, motor control, neuronal population coding, learning, and memory. His groundbreaking work has advanced our understanding of local cortical circuits, associative memory, chaos and excitation-inhibition balance in neural networks, and principles of neural coding.

In his Tuesday night seminar, Haim will discuss how neural networks develop the ability to represent and discriminate between different objects and concepts. He will explore the geometry and separability of object manifolds in deep neural networks, shedding light on the functional principles underlying learning and memory in both artificial and biological systems.

READING

- Alexander Shapson-Coe, Michal Januszewski, Daniel R. Berger, Art Pope, Yuelong Wu, Tim Blakely, Richard L. Schalek, Peter H. Li, Shuohong Wang, Jeremy Maitin-Shepard, Neha Karlupia, Sven Dorkenwald, Evelina Sjostedt, Laramie Leavitt, Dongil Lee, Jakob Troidl, Forrest Collman, Luke Bailey, Angerica Fitzmaurice, Rohin Kar, Benjamin Field, Hank Wu, Julian Wagner-Carena, David Aley, Joanna Lau, Zudi Lin, Donglai Wei, Hanspeter Pfister, Adi Peleg, Viren Jain, and Jeff W. Lichtman. A petavoxel fragment of human cerebral cortex reconstructed at nanoscale resolution. *Science*, 384(6696):eadk4858, 2024 Download PDF
- Uri Cohen, SueYeon Chung, Daniel D. Lee, and Haim Sompolinsky. Separability and geometry of object manifolds in deep neural networks. *Nature Communications*, 11(1):746–746, 2020 Download PDF
- Ben Sorscher, Surya Ganguli, and Haim Sompolinsky. Neural representational geometry underlies few-shot concept learning. *Proceedings of the National Academy of Sciences*, 119(43):1–e2200800119, 2022 Download PDF

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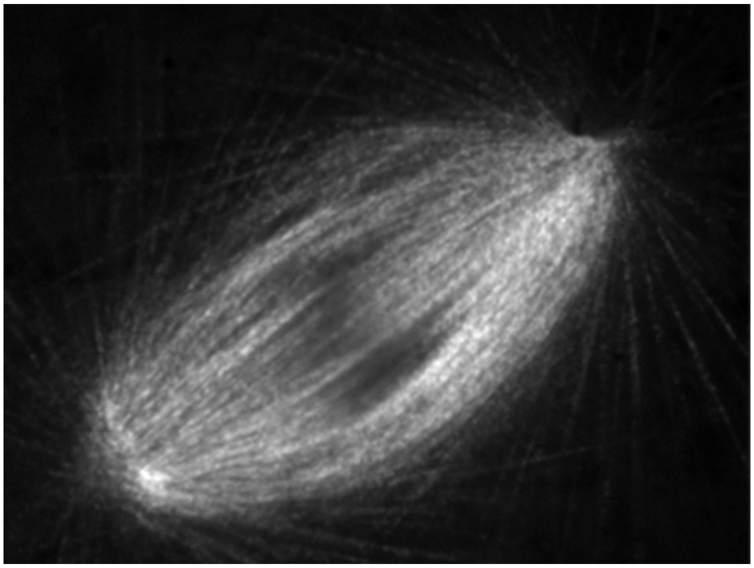
Week Eleven: Needleman and Ro Labs

Monday, November 18, 3 PM, Tour of Prof. Dan Needleman's Lab
Tuesday, November 19, 7:30 PM, Talk from Prof. Sunghan Ro



Sunghan Ro's research area is the statistical physics of soft and living matter, in and out of equilibrium. Recently, he has focused on studying collective phenomena in active matter, which consists of units driven out of equilibrium at the individual level. Examples of active matter include natural systems such as bacteria and animals, as well as artificial systems like colloids and robots. Due to the driving forces, active matter exhibits collective behaviors not seen in equilibrium systems, such as phase separation without attraction or polar order with a steady-state current that breaks time-reversal symmetry at a macroscopic scale.

The Needleman lab aims to understand biological self-organization by performing research on four interconnected themes: the spindle (see above), the nucleus, preimplantation embryo development, and cellular energetics. We perform quantitative experiments, which we attempt to interpret with the aid of theory and simulations, and we engage in extensive technique development.

Reading

- Jung Hoon Han, Ethan Lake, and Sunghan Ro. Scaling and Localization in Multipole-Conserving Diffusion. *Physical Review Letters*, 132(13):137102–137102, 2024 Download PDF
- Daniel Needleman and Zvonimir Dogic. Active matter at the interface between materials science and cell biology. *Nature Reviews Materials*, 2(9):17048, 2017 Download PDF
- Colm P Kelleher, Yash P Rana, and Daniel J Needleman. Long-range repulsion between chromosomes in mammalian oocyte spindles. *Science Advances*, 10(39):eadq7540, 2024 Download PDF

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