Harvard PhD Program in Quantum Science & Engineering

QSE Graduate Open House

April 4-5, 2022

Welcome!

A New Program for the Quantum Future

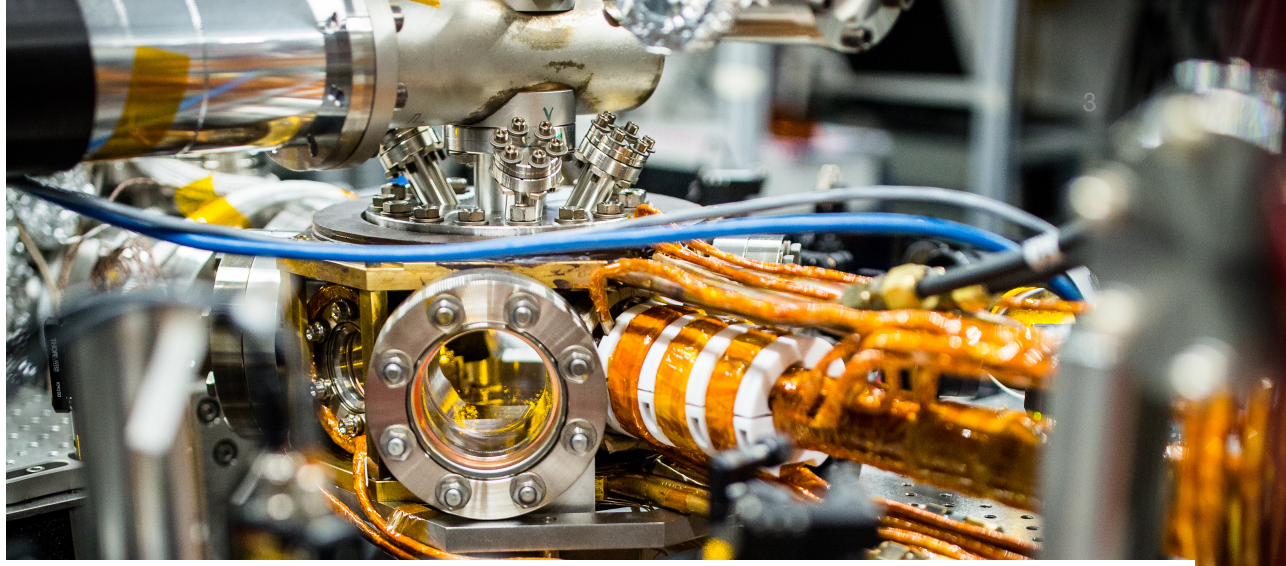
Apply yourself to the **Quantum Future.**

Harvard Quantum Science & Engineering PhD

Harvard Quantum Initiative
IN SCIENCE AND ENGINEERING

A NEW PROGRAM THAT

- SPANS the School of Engineering & Applied Sciences (SEAS), and departments in the Sciences (Physics, Chemistry).
- Recognizes the DIVERSITY of background expertise that is needed, creates A COMMON CORE CURRICULUM to rapidly bring students on-board, and yet provide flexibility of choice.
- Recognizes the importance of ADVISING at multiple levels.
- Recognizes the importance of PROFESSIONAL DEVELOPMENT and INTERNSHIPS.
- Emphasizes COMMUNICATIONS & COLLABORATIONS.



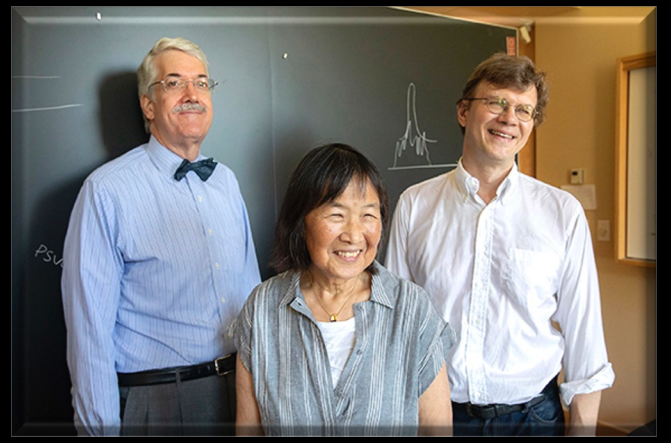
PhD in Quantum Science & Engineering

Training YOU: the future leaders in QSE

Harvard Quantum Initiative
IN SCIENCE AND ENGINEERING

THE PhD PROGRAM IN QSE BUILDS ON A COLLABORATIVE "QUANTUM COMMUNTY", coordinated by HQI

The HQI Mission: to provide the enabling infrastructure and opportunities to help scientists and engineers explore new ways to transform quantum ideas into useful systems and devices.



Harvard Quantum Initiative (HQI)

~ 45+ Members (PIs) from across SEAS, Physics, CCB, and Mathematics

16 current HQI Postdoctoral Fellows, 17 HQI Graduate Fellows

…. and growing

Harvard Quantum Initiative
IN SCIENCE AND ENGINEERING

Overview of the QSE Ph.D. Program

Coursework:

- 4 core foundational QSE courses
- 2 focus courses fundamental to sub-area (e.g. cryptography course for CS-focused student)
- 3 field courses (open, one course must be outside area of research)

2 lab rotations, one with a physics and/or chemistry emphasis and one with an engineering emphasis

Qualifying exam, thesis, teaching, and presence at annual research retreat

Opportunities for industry interaction, including internships cultivated by HQI

Foundational Course: Foundations of Quantum Mechanics

Term: Fall
Course Number(s): QSE-200, ENG-SCI-200, CHEM-200
Instructors: Federico Capasso and Kang-Kuen Ni

NEW, FOR THIS PROGRAM

Course Description:
This course is an introduction to the foundations of quantum mechanics, with specific focus on the basic principles involved in the control of quantum systems. Experimental foundations of quantum mechanics. Superposition principle, Schrödinger's equation, eigenvalue and time dependent problems, wave packets, coherent states; uncertainty principle. One dimensional problems: double well potentials, tunneling and resonant tunneling; WKB approximation. Hermitian operators and expectation values; time evolution and Hamiltonian, commutation rules, perturbation theory, transfer matrix and variational methods. Crystals, Bloch theorem, superlattices. Angular momentum, spin, Pauli matrices and Pauli equation. Coherent interaction of light with two-level systems. Quantization of the EM field, spontaneous and stimulated emission; elements of cavity QED; Qubits, entanglement, teleportation, Bell inequalities.

Preparation:
Should have a background in linear algebra, complex vectors and in quantum mechanics at an undergraduate level. Students entering without such a background are advised to take an undergraduate quantum mechanics course at the level of PHY143a or CHEM160, prior to taking Foundations of Quantum Mechanics.

Foundational Course: Foundations of Quantum Mechanics

Term: Fall
Course Number(s): QSE-200, ENG-SCI-200, CHEM-200
Instructors: Federico Capasso and Kang-Kuen Ni

NEW, FOR THIS PROGRAM

Course Description:

An introductory, GRADUATE LEVEL Quantum Mechanics course that is *not geared* to students with PHYSICS backgrounds alone.

Preparation:
Should have a background in linear algebra, complex vectors and in quantum mechanics at an undergraduate level. THERE ARE CHOICES OF UNDERGRADUATE QUANTUM MECHANICS COURSES for students who have never taken such a course previously.

Foundational Course: Introduction to Quantum Information Science I or II

Term: Spring
Course Number(s): QSE-210a, COMPSCI-210a, PHY-210a OR QSE-210b, COMPSCI-210b, PHY-210b
Instructor: Anurag Anshu OR Mikhail Lukin

NEW, FOR THIS PROGRAM

Course Description:
These courses will offer an introduction to some fundamental concepts in quantum information, quantum algorithms and quantum error correction. The focus will be to elucidate the nature of entanglement and its manipulation, framework for building quantum algorithms, methods for quantum error correction, the entropic view on various aspects of quantum information and various implementation models. The topics covered will be basics of quantum information (entanglement, quantum teleportation, Pauli operators), models of quantum computing (quantum circuits, quantum channels), fundamental quantum algorithms (Quantum fourier transform, Quantum phase estimation, Grover's search, Quantum walks), and quantum error correction (Stabilizer codes, fault tolerant quantum computing). Optional topics may include quantum entropies, experimental implementations and applications.

Preparation: One semester of quantum mechanics [QSE200, PHY143a, or PHY251A], or MATH 21b (or equivalent) and permission of the instructor.

Foundational Course: Introduction to Quantum Information Science I or II

Term: Spring
Course Number(s): QSE-210a, COMPSCI-210a, PHY-210a OR QSE-210b, COMPSCI-210b, PHY-210b
Instructor: Anurag Anshu OR Mikhail Lukin

NEW, FOR THIS PROGRAM

Course Description:

Introductory courses on the fundamentals of quantum information and its manipulation and control, including algorithms, error correction…

Preparation: Appropriate prior courses in Quantum Mechanics and linear algebra.

Foundational Course: Quantum Optics

Term: Fall
Next Academic Year Taught: 2023-24
Course Number(s): QSE-240, PHY-240 (formerly PHY-285b)
Instructor: Mikhail Lukin. Future instructors: Susanne Yelin, Norman Yao

Course Description:
Introduction to modern quantum optics and atomic physics. The basic concepts, theoretical tools and experimental methods will be introduced. Topics will include atomic coherence phenomena, non-classical states of light and matter, cavity quantum electrodynamics, mesoscopic quantum optics, atom cooling and trapping, and atom optics. Examples from current research areas in quantum information science will be discussed.

Preparation: A course in electromagnetic theory (PHY232a, PHY153 or equivalent); one half-course in intermediate or advanced quantum mechanics.

Foundational Course: Mesoscale and Low Dimensional Devices or Electromagnetic interaction with Matter

Mesoscale and Low Dimensional Devices
QSE-296, AP-296 Fall
Instructors: Donhee Ham and Philip Kim

Course Description:
Concepts of condensed matter physics are applied to the science and technology of beyond-CMOS devices, in particular, mesoscale, low-dimensional, and superconducting devices. Topics include: quantum dots/wires/wells and two-dimensional (2D) materials; optoelectronics with confined electrons; conductance quantization, Landauer-Buttiker formalism, and resonant tunneling; magneto oscillation; integer and fractional quantum Hall effects; Berry phase and topology in condensed matter physics; various Hall effects (anomalous, spin, valley, etc.); Weyl semimetal; topological insulator; spintronic devices and circuits; collective electron behaviors in low dimensions and applications; Cooper-pair boxes and superconducting quantum circuits.

Preparation: *Foundations of Quantum Mechanics (or equivalent), Physics 195 (undergraduate solid state physics)*

Foundational Course: Mesoscale and Low Dimensional Devices or Electromagnetic interaction with Matter

Electromagnetic Interaction with Matter
QSE-216, AP-216 Spring
Instructor: Donhee Ham

Course Description:
Applications of electric and magnetic interactions with quantized atoms in coherent (Rabi) and incoherent (Fermi or rate-equation) regimes. Topics include: Atom-field interactions in coherent v. incoherent regimes; T1 and T2 relaxations, spontaneous decay v. T1 relaxation, and homogeneous v. inhomogeneous broadening; applications of Rabi regime atom-field interaction (molecular beam maser, Ramsey spectroscopy, atomic clocks, nuclear magnetic resonance (NMR) spectroscopy, magnetic resonance imaging (MRI), Overhauser effect and dynamic spin polarization, pulse sequence techniques for coherent manipulation of atomic quantum states, Ernst operator algebra, and Janes-Cummings formalism applied to superconducting quantum circuits); applications of Fermi regime atom-field interaction (laser amplifier and oscillator, multi-mode lasing and mode locking, spatial and spectral hole burning, laser stabilization techniques; optical properties of quantum wells and quantum dots; optical spin injection).

Preparation: Quantum mechanics and electromagnetism, both at undergraduate level.

Field & Focus Courses

Focus courses: 2 courses fundamental to a student's subarea of research

Field courses: 3 elective courses, at least one of which must be outside the student's specialization

A full list of Field and Focus courses is available on the QSE website. Example courses include:

- Quantum Simulators: This class will introduce key concepts of quantum simulation, focusing on strongly correlated many-body systems and their implementation with cold atoms, quantum dot systems, ions, and photons.

- Cryptography: This course starts from the basics of private and public key cryptography and goes all the way up to advanced notions such as fully homomorphic encryption and indistinguishability obfuscation.

Additional Requirements (1)

Laboratory Rotation

Students will be expected to complete a minimum of two laboratory rotations, one in a laboratory with a strong engineering emphasis and another in a laboratory with a strong physics and/or chemistry emphasis.

Typical rotations would begin early in the G1 year and last from two months to one semester. Rotations will be of sufficient length to accomplish a substantial body of work (e.g. the development of some idea into a theory, construction of a device, etc.).

Additional Requirements (2)

Development and Presentation Skills

Students will be required to give a short talk about their research a least yearly, at one of the QSE or HQI gatherings

Retreat

Students will be required to attend the annual QSE retreat, which brings the entire QSE community together to learn about research progress in QSE both at Harvard and elsewhere. Advanced students will be required to present (orally or through a poster) their thesis research to date)

Teaching Requirement

Students will be required to serve as a TA for one course in a related unit (Physics, SEAS, Chemistry)

Additional Requirements (3)

Preliminary Qualifying Exam

The qualifying examination ensures that the student is prepared to undertake thesis research and is normally taken by the end of the fourth term of residence. This oral exam will emphasize general knowledge, reasoning, the ability to formulate a research plan, and ability to engage in high-level scientific discourse.

Example Student Pathway to QSE Degree

Quantum Science & Engineering Ph.D. Program Timeline for Model Student	
YEAR 1	
First Semester	• Foundations of Quantum Mechanics • Introduction to Quantum Information Science • Focus Course 1 • Research (Laboratory Rotation 1)
Second Semester	• Quantum Optics • Applied Quantum Systems • Focus Course 2 • Research (Laboratory Rotation 2)
Summer	• Possible internship with industrial partner or national lab
YEAR 2	
First Semester	• Field Course 1 • Service as TF
Second Semester	• Field Course 2 • Field Course 3 • Start of thesis project work
End of Year 2	• Preliminary Qualifying Exam
YEARS 3 -5	
• Focus on thesis research • Yearly retreat and communications opportunities • Yearly updates to Thesis Advisory Committee	

Creating an Environment Where Students Can Thrive

Advising and mentoring network

- Director of Education and Outreach serves as an information resource and "problem solver"
- Student Advisory Committee: oversees advising for all QSE students, responds to requests for change of advisor, organizes orientation activities, retreats and social activities
- 3-person Individual Advisory Committee for each student, even before identification of a Thesis Advisor: one member serves as student's Academic Advisor until a Thesis Advisor is identified
- A Student (Peer) Advisor will be designated for each entering QSE student

Creating an inclusive community

- Weekly "Pizza Talk" for/by QSE Graduate Students and Postdocs: focus on communications
- Yearly QSE retreat: research presentations, career discussions
- Incorporate programs like "Next-Gen Quantum Investigators": a program working with Postdocs on communications skills

Research Areas

- Quantum computing and quantum simulation
- Atomic-scale materials engineering
- Quantum communication and networking
- Quantum sensing and metrology
- Quantum information theory
- Quantum chemistry
- Quantum device engineering

A COMMON HOME FOR HQI AND ITS PROGRAMS

- Planned Program
  - New OFFICES, LABS, AND MEETING SPACES
  - A COMMON SPACE FOR QSE G1 STUDENTS
  - A SHARED, and FLEXIBLE INSTRUCTIONAL LAB (quantum maker space)
  - A “QUANTUM SHOP” (electronics, photonics)
  - Seminar and event spaces
  - SPACE FOR VISITORS

  A common space to talk and dream “quantum”
- Goal of occupancy by Spring 2024

Opportunity to tour the building on Tuesday, April 5 at 3:00pm

60 Oxford Street

A physical home for QSE at Harvard

YOUR WIDER COMMUNITY

Interfaculty and intra-Harvard

- **HQI postdoctoral fellowships:** roughly 1/3 current PDs co-advised
- **HQI Seed funds: 13** grants with an average award of **$101,000** for a one-year project.
  - **9** collaborative proposals
    - **5** interdepartmental projects
    - **3** interschool (FAS/SEAS)
    - **6** interdisciplinary
    - **3** collaborations between theorists and experimentalists

MIT & Other Universities

- Multiple successful collaborations between Harvard/MIT research groups
- Joint programs, workshops, and centers
- HQI is part of a broader Boston-area ecosystem including MIT, Boston University, and UMass

Industry Partnerships

- HQI seeks to build bridges to industry to advance QSE research, build shared instrumentation, create opportunities for novel research experiences for students, and to create new educational resources
- Current collaborations: IBM, QuERA Computing, AWS, Rakuten

Additional Slides on HQI Programs

Current HQI Programs

HQI Prize Postdoctoral Fellowship

- 6 postdoctoral fellows/year funded for two years
- 10 current postdocs with placements in Physics, Electrical Engineering, Computer Science, CCB. 25 postdocs funded since 2018.

HQI Undergrad Research Fellowships

Supports summer research opportunities for ~10 Harvard undergraduates with funding and community events

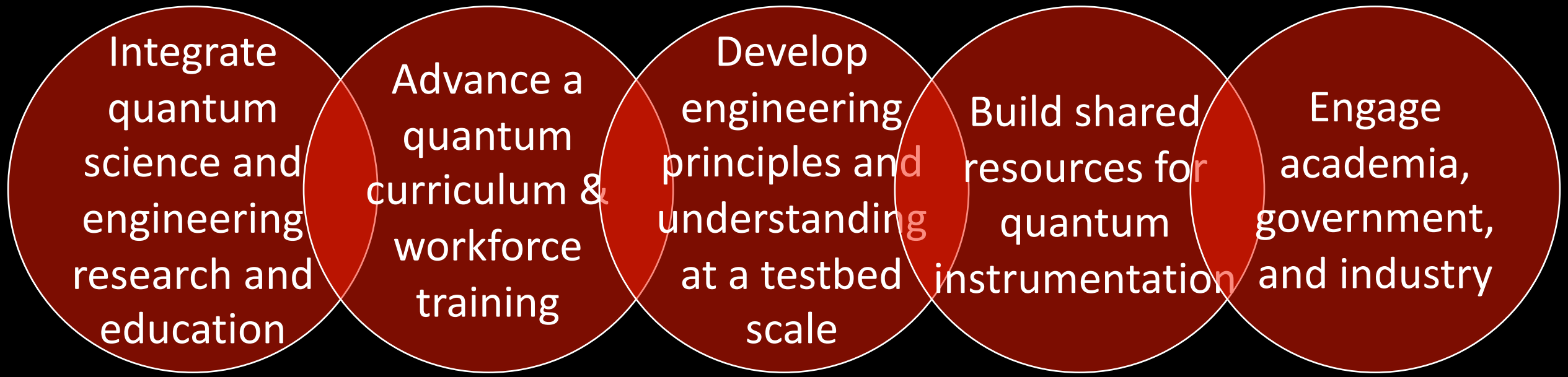
Events and Seminar Series

- Joint Quantum Seminar—invites field leaders to campus to give a colloquium talk and meet with students, postdocs, and faculty
- Job Talk Development Lab & Next-Gen Quantum Investigator Series—provides science communications training and faculty mentorship to prepare postdocs in the quantum community to go on the academic job market
- Annual research symposium that brings the HQI community together to present and discuss research

HQI Graduate Fellowships

- HQI fellowship that fund 6 students/yr who have home departments in SEAS, Physics, or CCB
- Selected for interest in QSE fields, particularly at the interface of multiple disciplines
- This program has been replaced by the QSE PhD program

HQI aims to build a quantum ecosystem in the Boston area



Harvard Quantum Initiative
IN SCIENCE AND ENGINEERING

Building a Trans-Disciplinary QSE Community

THEORY and QCS

- Algorithms
- Error Mitigation and QEC
- Small Codes
- Quantum Software
- Machine Learning

Anurag Anshu
Boaz Barak
Bert Halperin
Arthur Jaffe
Daniel Jafferis
Subir Sachdev
Madhu Sudan
Andrew Strominger
Clifford Taubes
Leslie Valiant
Ashvin Vishwanath
Norman Yao
Susanne Yelin

EXPERIMENTAL DEVICES, SENSORS & TESTBEDS

- Cold atoms
- Defect centers
- Superconducting
- Trapped ions
- Quantum optics
- Classical control
- Noise spectroscopy
- Dynamical error mitigation
- Calibration and qV&V
- Small codes
- SE and EM Modeling
- Molecules

Quantum Photonics
Federico Capasso
Lene Hau
Mikhail Lukin
Marko Loncar
Eric Mazur

2D Materials
Donhee Ham,
Philip Kim,
Hongkun Park
Suyang Xu
Amir Yacoby

Atoms, Molecules & Atom-like Systems
John Doyle
Markus Greiner
Evelyn Hu
Mikhail Lukin
Marko Loncar
Kang-Kuen Ni
Mikhail Lukin
Hongkun Park
Amir Yacoby

MATERIALS, MODELING, ANALYSIS & FABRICATION

- Surface & materials science
- Atomic Scale Imaging
- 3D integration
- Synthesis of Quantum Materials
- Modeling of Quantum Materials

Modeling of Quantum Materials
Rick Heller, Tim Kaxiras
Boris Kozinsky, Prineha Narang

Atomic Scale Imaging
Jenny Hoffman, Julia Mundy ,
Bob Westervelt

Synthesis of Quantum Materials
Philip Kim, Roy Gordon

Program Leadership

John Doyle

Henry F. Silsbee Professor of Physics
HQI Co-Director
Co-Director of Graduate Studies, QSE PhD

Evelyn Hu

Tarr-Coyne Professor of Applied Physics and of Electrical Engineering, SEAS
HQI Co-Director
Co-Director of Graduate Studies, QSE PhD

Standing Committee on Higher Degrees in Quantum Science and Engineering

John Doyle, Evelyn Hu, Boaz Barak, Kang-Kuen Ni, Marko Loncar