Personal, Background, and Future Goals Statement

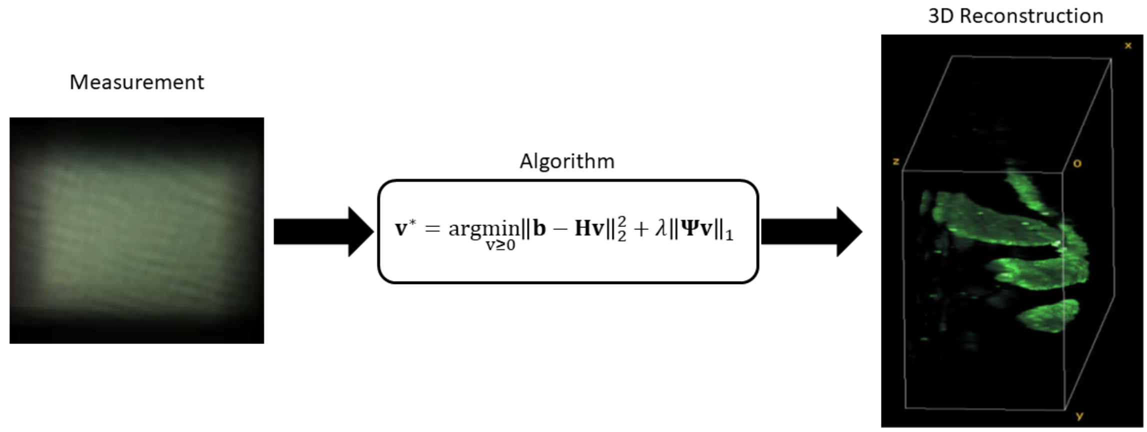


Figure 1: From measurement to reconstructed scene.
A flowchart outlining the decoding procedure for a diffuser-based computational camera. Here the mapping from scene to measurement is expressed as a linear forward model, while the inversion algorithm assumes a sparsity prior (LASSO regression). The complete 3D complexity of the scene is recovered from a single 2D measurement

At first glance, the figure above appears to vindicate the existence of magic. Computational cameras collect measurements that do not ordinarily bear any perceptual resemblance to the scene they are capturing. Instead, these measurements are prescribed encodings of the scene that often transcend our perceptual intuition. Computational imaging systems use algorithms to invert these encodings and recover the scene, often augmenting the information we would otherwise recover with traditional cameras. While far from magic, the functionalities born from this imaging paradigm often evoke a similar sense of astonishment.

My fascination for computational imaging emerged when I first encountered the figure above while studying physics and computer science as an undergraduate at UC Berkeley. How could it be that a single 2D sensor measurement could encode the 3D structure of a scene? The poster broke every intuition I had about how information is preserved under transformations. Moreover, it elegantly brought together my love for physics and computer science through the joint design of optics and algorithms.

Historically, unique encoding approaches have revolutionized how we extract different types of information about a scene such as depth, spectral content, and temporal evolution. My pursuit of a doctoral degree in optics is rooted in my fascination for these ingenious imaging modalities. **I plan to dedicate my future research towards developing the next generation of computational imaging systems.** Two primary motives drive my focus: 1) I find joy in the challenge of co-designing optical hardware with algorithms to create new imaging functionalities. 2) I believe that expanding humanity's capacity to "see the invisible" is an exciting and virtuous goal.

Intellectual Merit

Throughout my undergraduate studies, I have conducted research in fluid dynamics under Prof. Rajat Mittal at Johns Hopkins University [1]; magnetic levitation under Prof. George Whitesides at Harvard University [2]; and computational imaging under both Prof. Laura Waller at UC Berkeley [3] and David Theil at Lockheed Martin Space. The last of these experiences resulted in two novel imaging modalities: a lensless camera capable of synthesizing a large-format sensor, and a planar interferometer built on a photonic integrated circuit for space-based imaging.

Research in Lensless Imaging:
My undergraduate research in UC Berkeley's Computational Imaging Lab, led by Prof. Laura Waller sought to develop scalable lensless cameras. These cameras employ a phase or intensity mask in lieu of focusing optics to spatially multiplex light from the scene. In this research, we capitalized on the robustness of spatial multiplexing against pixel erasure to synthesize a large-format image sensor from a disjoint array of smaller cost-effective sensors. The specific functionality we sought to enhance using sensor arrays was single-shot 3D imaging on a diffuser-based lensless camera called DiffuserCam. My contributions to this project were **(a)** developing a mathematical forward model for spatially multiplexed measurements taken with a multi-sensor array, **(b)** implementing pipelines to simulate the physics of our camera and assess its capacity for reconstructing 3D scenes or wide-field scenes, and **(c)** developing a multi-sensor lensless prototype. In 2018, I was selected from a pool of more than 50 undergraduates to present this work and represent UC Berkeley at the NSF's Council of Undergraduate Research Fall symposium. Our prototype was proof-of-concept, demonstrating that disjoint sensor arrays are practical proxies for large detectors in lensless cameras. By extension, we showed that certain lensless cameras could successfully reconstruct 2D scenes with fewer than 10% of the pixels required for traditional cameras. The culmination of this work was a conference publication at COSI 2020 [3].

Research in Interferometric Imaging:
As a research intern at Lockheed Martin's Advanced Technology Center, I supported the development of an interferometric imager fashioned with a photonic integrated circuit (PIC). Unlike conventional imaging systems, our PIC-based imager is flat which provides a way of enhancing resolution without sacrificing the form factor of the optical system. Interferometric imagers measure interference patterns called 'fringes' that contain information about the spatial frequencies comprising a distant scene. As such, my contributions to this project were **(a)** implementing a signal processing pipeline that reconstructed the scene from fringe measurements**, (b)** exploring image reconstructions limitations under different radiometric conditions, and **(c)** designing the PIC architecture for a future iteration of our imager. A version of the reconstruction pipeline I wrote has since been used to test a prototype benchtop system.

Having accrued a strong understanding for the principles of interferometric imaging, I proposed an alternative PIC architecture that yielded theoretical improvements in the Fourier sampling density, resolution, and manufacturability of the imager. The original architecture performed pair-wise interference of input channels, whereas my proposed architecture interfered multiple channels from non-redundant baselines simultaneously to generate fringes with higher information density about constituent spatial frequencies. This proposed PIC architecture resulted in a patent [ii] and earned a dedicated initiative for its development within the company.

Research in Quantum Imaging:
Each of my past research experiences in computational imaging have been predicated on a classical description of light. That is, the imaging physics was modeled using ray/wave optics**. These experiences have since inspired my curiosity about imaging modalities that are predicated on a quantum description of light**. Recent methods like interaction-free imaging, single-photon imaging, and non-line-of-site imaging illustrate how leveraging quantum light promises to yield next-generation computational imaging tools. Most fascinating of all, these emerging imaging technologies offer a rare bridge between the mathematics of the quantum world and the human visual experience. As a doctoral student at the University of Arizona's College of Optical Science working under Professor Amit Ashok, I have begun developing an adaptive quantum imaging protocol that seeks to surpass classical resolution limits for incoherent distributed scenes.

Broader Impacts
Throughout my academic journey, I have been fortunate to work with mentors who uphold a high standard for teaching pedagogy. To reciprocate this fortune, I have been involved in supporting other

students at my graduate institution in their learning. Recently, I designed a module on super-resolution imaging for a graduate computational physics course which attempts to expose students to quantum information theory and quantum estimation theory by walking them through the so-called Two Point Source Problem. Here students explore how to estimate the separation of two closely spaced incoherent optical point sources beyond the Rayleigh limit by implementing quantum measurements numerically and computing information bounds. More wholistically, this module is designed to teach students how numerical methods can be used to solve problems in quantum mechanics that are otherwise analytically intractable.

As a member of the University of Arizona's 2022 CyVerse cohort, I was introduced to the Open Science research paradigm. Research communication today is no longer limited to journal publications. Instead, proper data management, documentation, version control, and cross-platform integration are becoming a necessary standard for ensuring scientific reproducibility and accessibility. In an attempt to expand open science best-practices within my institution, I have been developing a website and GitHub organization for our lab. Here our team has been able to host and collaborate on their project codebase, disseminate publications/preprints, provide project descriptions and documentation, and communicate weekly activity reports all in a centralized fashion.

Last year, I also started a department-wide journal club for undergraduate and graduate students. The purpose of this club is to review exciting new discoveries across a variety of active research areas in optics with the intent of inspiring future projects and refining scientific communication skills. Simultaneously, the club endeavors to cultivate a supportive and inclusive community of thinkers within the student body that promotes a growth mindset for learning. We have hosted voluntary presentations on non-linear optics, optical meta-materials, quantum optics, computational imaging, and topics outside of optics. Fundamentally, this club creates a space for the exchange of ideas, which in turn enriches the potential for new research directions.

In the remainder of my PhD, I intend to expand the value and reach of the journal club program beyond the College of Optical Sciences by creating an educational YouTube channel in which exciting technical research papers are decomposed into engaging bite-size summary videos. At a time of rising fake news and distrust of the scientific enterprise among the general public, I believe institutions of higher education have a moral obligation to populate the internet with accessible quality content. The YouTube channel I intend to create with my peers will nurture the curiosity of budding scientists and will rebuild people's trust in the epistemology of scientific research. The GRFP would provide me with the flexibility to realize each of these goals.

Publications [1] Palmer EH, Deshler N, Mittal R. (2017) "Aeromechanics of Long Jumps in Spider Crickets: Insights from Experiments and Modeling". *ASME International Mechanical Engineering Congress and Exposition*, Vol. 7: Fluids Engineering. [2] Shencheng Ge, Yunzhe Wang, Nicolas J. Deshler, Daniel J. Preston, and George M. Whitesides. (2018) "High-Throughput Density Measurement Using Magnetic Levitation". *Journal of the American Chemical Society.* [3] E. Zhao, N. Deshler, K. Monakhova, and L. Waller (2020) "Multi-sensor lensless imaging: synthetic large-format sensing with a disjoint sensor array". *Imaging and Applied Optics Congress*, OSA Technical Digest.

Patents [i] *"*Sample Analysis with Mirrors". PCT/US2019/032797 *(2019).* [ii]*"*N-Arm Interferometric Photonic Integrated Circuit Based Imaging and Communication System". PTO/US2021/11,159,235 B1 [iii] "Interactive Ultraviolet Decontamination System"..(patent pending).

Adaptive Bayesian Estimation for Compressive Quantum Super-Resolution Imaging

Traditional direct imaging systems are resolution-limited due to diffraction. The Rayleigh criterion has historically characterized this resolution limit for a given optical system with aperture diameter D, by setting a lower bound on the smallest resolvable feature size.

$$\theta_{min} \gtrsim \sigma = \frac{\lambda}{D} \tag{1}$$

Equation 1 is known as Rayleigh's Curse – to achieve higher resolution it appears one must create a larger optical system (increase D**)**. While the Rayleigh criterion was derived from a *classical* theory of electrodynamics, light is fundamentally a *quantum* phenomenon. Recently, [1] showed that **the Rayleigh Criterion does *not* constitute a fundamental resolution limit imposed by the laws of physics.** By formulating the optical field as a mixed quantum state $\hat{\rho}$, new information-theoretic bounds on the fundamental limits of image resolution have been uncovered and experimentally realized [2] for simple scenes. Quantum super-resolution imaging is a new thrust in image science dedicated to developing novel imaging modalities that beat the Rayleigh resolution limit for arbitrary scenes. In the quantum formalism, imaging tasks become a parameter estimation problem. In particular, one seeks to estimate the parameters $\vec{\theta} = [\theta_1, \dots, \theta_M]^T$ which characterize the quantum state of the optical field.

$$\hat{\rho}(\vec{\theta}) = \sum_{i=1}^{M} f(\theta_i)\, |\psi_i\rangle\langle\psi_i| \tag{2}$$

Any unbiased estimator of a field parameter θ_μ has a minimum achievable uncertainty (variance) set by the inverse of the Quantum Fisher Information (QFI) matrix **K**

$$\Sigma_{\mu\mu} \geq \frac{1}{N}[\mathbf{K}^{-1}]_{\mu\mu} \tag{3}$$

Equation 3 tells us that any single photon detection event has a maximum amount of information it can supply about a field parameter. In general, the uncertainty drops as the number of detected photons N grows. While we can write down the QFI matrix for a given parametrization of the optical field, quantum imaging still faces a critical challenge: **no general methods currently exist for finding optimal quantum measurements that saturate the QFI bounds in multi-parameter estimation problems.**

Intellectual Merit

Spatial Mode Demultiplexing (SPADE) is a general von Neumann projective measurement scheme [1]. It works by decomposing the optical field into a set of orthonormal transverse spatial modes and subsequently counting the number of photons detected in each mode. From a QFI perspective, the optimal set of spatial modes on which to apply SPADE measurements depends on the scene itself. Since the scene is initially unknown, my doctoral work seeks develop an adaptive measurement strategy that converges to the optimal SPADE basis for any incoherent scene. In particular, **I am developing a quantum super-resolution imaging system that employs adaptive Bayesian estimation to efficiently saturate Quantum Fisher Information bounds for sub-Rayleigh feature parameters.**

In the Bayesian setting, posterior probability distributions (beliefs) over the estimation parameters $\vec{\theta}$ are updated based on the result of a SPADE measurement $\vec{n}^{[k]}$.

$$p^{[k+1]}(\vec{\theta}) \leftarrow p(\vec{n}^{[k]}|\vec{\theta})\,p^{[k]}(\vec{\theta})/p(\vec{n}^{[k]}) \tag{4}$$

These updated beliefs subsequently inform the choice spatial modes on which to apply the next SPADE measurement so as to optimally reduce the joint uncertainty over the estimation parameters. In our protocol, we extend the single-parameter Bayesian quantum estimator derived in [3] to the multi-parameter case and define the measurement operator $\hat{B}$ implicitly through equation 5.1.

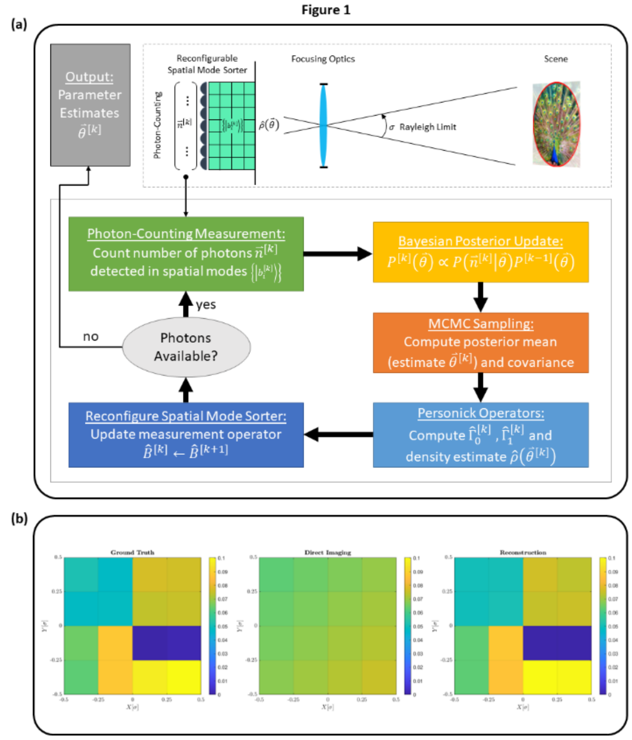
$$\hat{\Gamma}_1 = \hat{B}\hat{\Gamma}_0 + \hat{\Gamma}_0\hat{B} \tag{5.1}$$

$$\hat{\Gamma}_0 = \int \hat{\rho}(\vec{\theta})p(\vec{\theta})d\vec{\theta} \tag{5.2}$$

$$\hat{\Gamma}_1 = \int \hat{\rho}(\vec{\theta})p(\vec{\theta})(\vec{h}\cdot\vec{\theta})d\vec{\theta} \tag{5.3}$$

Importantly, the Bayesian framework allows us to enforce sparsity priors and thus leverage the compressibility of natural scenes for more efficient estimation. Figure 1a provides a schematic of the proposed adaptive measurement protocol. Simulated results shown in Figure 1b demonstrate the protocol's super-resolution capability: (left) a 4x4 sub-Rayleigh target scene, (middle) an estimate of the scene produced with conventional direct imaging methods, (right) an estimate of the scene produced by with our protocol. In this case, the estimation parameters were wavelet coefficients to a basis in which the target scene was ~25% sparse.

Figure 1



After further assessing the efficacy of this adaptive estimation protocol in simulation, I will develop a benchtop prototype of our super-resolution imaging system as proof-of-concept. Recently, the world's first reconfigurable spatial mode sorter was developed [4] at my graduate institution. The co-emergence of this adaptive algorithm with reconfigurable modal hardware presents unique opportunity to validate simulated performance with empirical testing. Furthermore, a prototype imager would allow us to characterize the robustness of this imaging system against real-world non-idealities including optical misalignment, modal cross-talk, and detector noise. The mathematical foundations of this adaptive protocol generalize to *any* multi-parameter quantum estimation problem. **It may therefore find future applications in spectroscopy, optical metrology, fluorescence microscopy, and astronomy.**

Broader Impacts

The adaptive quantum imaging approach presented here challenges conventional imaging paradigms and classical performance limits by casting imaging as a quantum estimation task. In doing so, it targets fundamental information bounds set by the laws of physics. As an emergent quantum technology this work may offer several societal benefits. First, by subverting Rayleigh's Curse we realize quantum-limited resolution without requiring large optical systems. In the same way that images from Hubble and the James Webb Space Telescopes captivated public imagination by allowing people to visually engage with the finest details of the cosmos, this technology could bring about a new wave of awe-inspiring images by advancing the next generation of deep-space imagers.

Second, the optical hardware required to implement our adaptive protocol is modular – it simply replaces the digital focal plane array on existing imagers. By augmenting existing imagers with a reconfigurable spatial mode sorter and photon detectors, this protocol immediately offers blanket resolution improvements to all conventional imaging systems without having to redesign them from scratch. From a commercial standpoint, such an advantage may inspire the birth of new industries.

References.

[1] Mankei Tsang, Ranjith Nair, and Xiao-Ming Lu. "Quantum Theory of Superresolution for Two Incoherent Optical Point Sources". Phys. Rev. X 6, 2016. [2] M. Paur et al. "Experimental demonstration of superresolution for two incoherent point sources using SPADE method". Imaging and Applied Optics 2016. Optica Publishing Group, 2016. [3] S Personick. "Application of quantum estimation theory to analog communication over quantum channels". IEEE Transactions on Information Theory 17.3, 1971. [4] Itay Ozer, Michael R. Grace, and Saikat Guha. "Reconfigurable Spatial-Mode Sorter for Super-Resolution Imaging". Conference on Lasers and Electro-Optics. Optica Publishing Group, 2022.

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

Nicolas is a student in the field of optics who has conducted research in fluid dynamics, magnetic levitation, and computational imaging. The author's contributions to their research have included developing a mathematical model for spatially multiplexed measurements taken with a multi-sensor array, implementing pipelines to simulate the physics of lensless cameras and assess their capacity for reconstructing 3D scenes, and developing a multi-sensor lensless prototype. The author also supported the development of an interferometric imager using a photonic integrated circuit and participated in the design of a quantum imaging system that utilizes the quantum properties of light to achieve super-resolution. The student has three published articles and three patents.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Excellent

Explanation to Applicant

The applicant has developed and taught a graduate computational physics course on using numerical methods to solve problems in quantum mechanics, and has designed a lab on super-resolution imaging to expose students to quantum information theory and quantum estimation theory. They have also been involved in promoting open science practices, including developing a website and GitHub page for their lab, starting a department-wide journal club for undergraduate and graduate students, and planning to create a YouTube channel to provide accessible summaries of technical research papers. The applicant is motivated to use their education and research experiences to promote scientific curiosity and understanding to a wider audience.

Summary Comments

In summary the applicant shows a bright future in their career with achievements in their PhD and more to come. I am thrilled to see what this student will achieve before graduation.

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

The applicant's interest in computational imaging is quite evident. The applicant has gained required skills to succeed in this field through strategic steps and experiences in their career so far. The applicant's experience will be highly valuable in designing and conducting future research. The applicant's writing style is impressive and the proposal is well written, making it understandable even for a non-expert.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Very Good

Explanation to Applicant

The applicant is driven to develop open-source applications and is aware of the broader impact their scientific work could have. The applicant contributed to the development of a computational physics course and starting a department-wide journal club which indicates their ability to take initiative.

Summary Comments

The applicant already has an impressive record as a researcher and shows promise for a future science leader. The applicant's broader impact is also notable.

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

The applicant shows outstanding potential for success as a graduate student. The application exudes enthusiasm for science and intellectual strength throughout, starting with the applicants discussion of his background. The large number of innovative ideas and discussions is remarkable. The applicant has significant publications already as well as two awarded patents. This is truly exceptional. This application indicates excellent potential to be a leader in science.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Excellent

Explanation to Applicant

The broader impacts are exceptionally well presented, including open science and software, the establishment of a journal club and plans for an educational YouTube channel.

Summary Comments

This is an excellent application in all respects, both in terms of the innovative proposed research that is exceptionally well discussed and the broader impacts.