**Volume 36** Fall 2018

# MURJ

## Massachusetts Institute of Technology Undergraduate Research Journal

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**MURJ Staff**
**MIT Undergraduate Research Journal**

**Massachusetts Institute of Technology**

December 2018

Dear MIT community,

We are delighted to present the 36th issue of the MIT Undergraduate Research Journal, a biannual student-run publication that showcases undergraduate research on campus. The pages within contain student work on modeling quasars, harnessing compressed sensing to collect genetic data, and developing advanced near-infrared photodetectors.

In addition to student work, this semester's issue highlights ongoing MIT research compiled by our News editors and staff. Our News writers take a look at such diverse topics as wearable technology, a food security program in Indonesia, transformable materials, and algorithmic bias.

This issue also features an interview with Dava Newman, an MIT professor in the Department of Aeronautics and Astronautics and former Deputy Administrator of NASA. Newman recently testified before the Senate Subcommittee on Space, Science, and Competitiveness, advocating human space flight to Mars. Also included is an interview with Pinar Yanardag, a former MIT Media Lab Postdoctoral Associate and current CEO of AI Fiction. Yanardag discusses her project to unite artificial intelligence and human creativity to generate music, pizza recipes, perfumes, and more.

Biannual publication of this journal is a collaborative undertaking by an extraordinary team of dedicated students. We would like to thank our editorial board and contributors for their time and hard work this semester. In addition, we would like to thank all the undergraduates who shared their research with us and the

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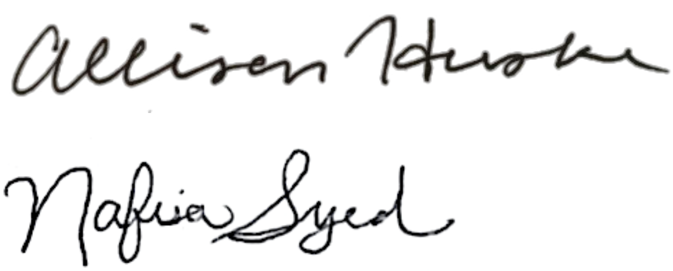
greater MIT community.

For previous issues of the MIT Undergraduate Research Journal, please visit our website at murj.mit.edu. If you are interested in contributing to future issues of the MIT Undergraduate Research Journal, we invite you to join our team of authors and editors or submit your research for our Spring 2019 issue. Please contact murj-officers@mit.edu if you have any questions or comments.

Best,

Allison Huske
Nafisa Syed





Massachusetts Institute of Technology

**UNDERGRADUATE RESEARCH JOURNAL**
**Volume 36, Fall 2018**

RIGHTS AND THE GOVERNMENT

# Fixing Raskin

***How can you make sure those entitled to support actually receive it? Two MIT economics professors fix pitfalls in the Indonesia support program, Raskin, by putting information in the hands of the people.***


*Indonesian rice vendor (Photo: Wiki Commons)*

**Raskin, or Rice for the** Poor, is Indonesia's largest support network for families in need. Established in the 1990s after the Asian financial crisis, the program has endured despite less than half the rice actually reaching those people in need. The government would ship hundreds of kilos of rice to distribution points where a local official would then take over and distribute the rice to the poor, charging these families a fraction of the current market price. Issues arose with these local officials. Some would give rice to people they thought were in need rather than those the government identified, or the truly corrupt would set the price at what they wanted, depriving Indonesia's poorest citizens of a staple food.

The Indonesian government recognized that continuing the program without addressing the issues would not help the intended recipients. Around this time, two MIT professors in economics became involved. Instead of radically changing the structure of the program or tightening the rules, Professor Abhijit Banerjee and Professor Ben Olken suggested an easier solution: letting those recipients know exactly what they were entitled to. Eligibility cards were sent to 66% of the villages in the study, detailing to each recipient how much rice they were allotted each month and exactly how much they needed to pay. This improvement increased the amount of aid beneficiaries received by 25%.

What was the important factor in this method? "I think the key point is that transparency of benefits is really important— giving people tangible information so that they know their rights can be empowering," says Olken. Employing the idea of common knowledge in Raskin, where both the beneficiaries and the aid officials know the policy, prevents officials from obscuring the program details or completely ignoring them. Now they could be held accountable because of the dissemination of information.

The result? The Indonesian government decided to implement "Social Protection Cards", identification cards for the nation's poorest that allowed them access to social programs like Raskin as well as a school subsidy program and temporary cash transfer program. These cards not only inform their beneficiaries what they are entitled to but they also prevent local officials from deviating from the government's price or intended recipients.

— Leah Yost

WEARABLE DEVICES

# Combining Fabrics and Electronics

***Novel incorporation of diodes into fabrics opens up new possibilities for wearable medical devices and other functional fabrics.***

**Fabric might seem like one** of the most mundane technologies, but materials scientists are finding ways to make fabrics capable of much more. A research group led by Professor Yoel Fink from the Department of Materials Science and Engineering has developed a novel method for incorporating diodes into fabric. The work, recently published in *Nature*, is a step towards functional fabrics capable of tasks such as medical sensing and communication.

Semiconductor diodes are one of the basic building blocks of modern electronics. However, limitations in typical fiber-drawing processes have made incorporating diodes into fabric fibers difficult. In these processes, metals are embedded into a polymer preform and drawn out, along with the polymer, into fibers. However, this technique is limited to low-melting-temperature metals, and the results are low quality compared to other forms of electronics. Fink's group uses a new technique in which high-melting-temperature metals are embedded in a fiber as it is drawn rather than before.

*"a step towards functional fabrics capable of tasks such as medical sensing and communication"*

First, semiconductor materials are embedded in an initial polymer base. When the base gets thermally drawn into thin fibers, it holds the electronics in place. During the drawing process, tungsten or copper wires are embedded into the fibers for electrical connections. Using this procedure, the researchers were able to get 95% of light-emitting diodes (LEDs) embedded in the fibers to function.

The group demonstrated a potential system for using their fabrics to measure a wearer's heart rate. For this, they embedded an LED and a diode-based photodetecting device in a sock. When the user places their fingers on the device, the photodetector measures small changes in light intensity due to constrictions in blood vessels, allowing for a measurement of heart rate.

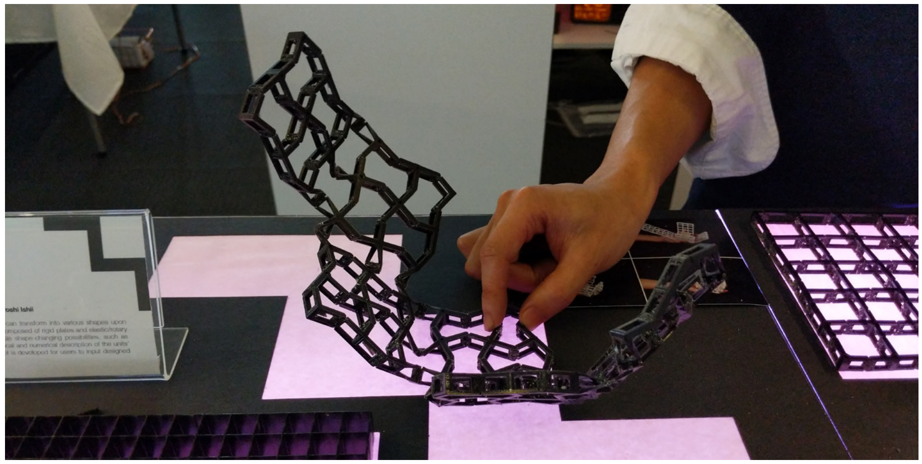
Beyond physiological monitoring, the researchers mention automated medicine release systems as a possible next step for fabric-integrated electronics. This new technique for integrating materials into fibers opens up a new pathway to create more complex fabric-based devices, making fabrics exciting and innovative.

— Jordan Hines


*Fabrics on display at a store. (Photo: Wikimedia Commons)*

MATERIALS

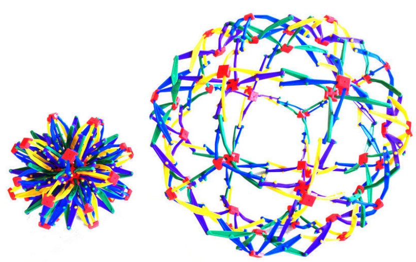
# Expanding the world of transformable materials



*Net of kinetiX bending unit cells folds into a box when one cell is compressed (Photo: Jocelyn Ting)*

**Do you remember the globe** you played with as a child? It was multicolored and multi-hinged, encouraging one to stick perhaps a head inside before giving the sides a slight push, causing it to contract into a ball a fraction of its original size. This toy, the Hoberman sphere, is one large scale example of an auxetic material. Scientist are currently very interested in auxetic materials due to the unusual ways they move when compressed, stretched, or rotated.

When stretched, the sides of an

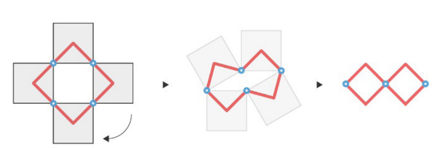


*Hoberman sphere (Photo: Instructables)*

auxetic material will thicken widthwise, while a normal material would thin in this direction. During impact, auxetic materials will contract towards the direction of the impact whereas non-auxetic materials would flow away. In sports technology, scientists have created shoulder pads using auxetic foams that thicken when compressed, requiring less material and providing more protection and comfort. In biomedicine, scientists are using the auxetic geometry of rotating squares to create a new type of coronary stent. These stents are composed of lattices of squares connected by hinges at their corners, and expand as the hinges rotate. Their auxetic properties lead to better mechanical adhesion, avoiding the common problem of stent migration.

MIT Media Lab's Tangible Media Group was inspired by the potential of auxetics as a material for programmable movement. They envision the future of human computer interaction as a connection of the digital tangible worlds, and have done many high profile projects such as TRANSFORM and aeroMorph. In a recent paper published in *Computer and Graphics*, they detail their most recent creation, kinetiX.

The group started with the lattice of rotating squares and simplified its motion to a square unit cell of 4 bars and 4 hinges. The genius of kinetiX is that a cell's compression response can be changed by simply shifting the hinges in relation to the plates. The group found that lateral shifts resulted in scaling and shearing effects. Even more revolutionary, they produced out-of-plane effects when they angled the hinges within the plates or angled the plates themselves outwards. The former resulted in a twisting motion while the latter gave a bending motion. This is novel, because most of auxetics research just involves stacking 2D auxetic structures in 3D space. kinetiX extends this research by creating auxetic cells that move in 3D (twisting and bending) and can also be stacked and chained together. By conceiving this material as a unit cell, the group has essentially created spatially deformable Legos. Like manipulating impurities in a crystal, or stacking elements together, one could create a multitude of geometries and responses. As a final step, they 3D-printed the cells along with sheets of tesselated cells, confirming the motions predicted by their simulation. Here the group demonstrated many applications, in encoded displays (using the scale units to encode letters that appear when the sheet is compressed), easy packaging (2D net that becomes a box when squeezed), and conformable helmet (using their simulation to iterate sheets that conform to heads). kinetiX continues research in auxetics and motion control. It's an open-ended invitation to materials scientists and all disciplines that play with motion to reimagine the possibility of auxetic inspired structures.



*Simplifying rotating squares to a basic kinetiX unit cell (Photo: J. Ou et al. / Computers & Graphics 75)*

— Jocelyn Ting

ETHICS IN TECHNOLOGY

# Eliminating Bias from Computer Programs

*"Without working to ensure fairness, we can create a future that works for the few who can afford it, rather than for everyone."*

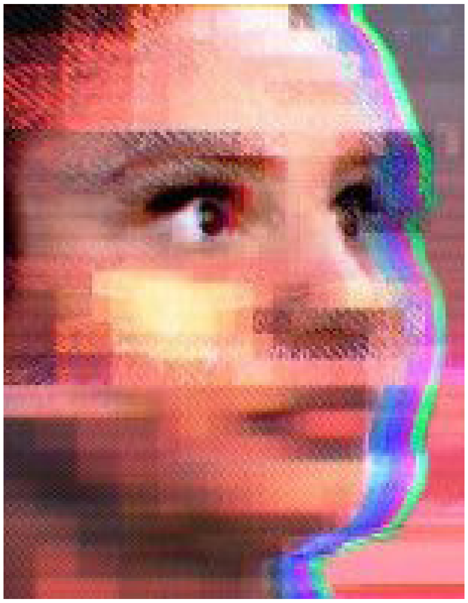
**Five years ago, researchers from** the University of Maryland discovered that prosecutors in Harris County, Texas were up to four times more likely to seek the death penalty for minorities when compared to white people who faced the same charges. Some tech companies took this as a call to action. Rather than using a human prosecutor who may have ingrained biases, why not use a computer program, which we can create to be impartial?

These types of programs are called automated decision-making systems (ADMs). Over the past few years, these systems have been created for fields such as medicine and education, with widely varying results. To analyze the behavior of these programs, a team led by researchers Alejandro Noriega-Campero and Michiel Bakker from the MIT Media Lab studied the problems with the automated systems that are already in place, and proposed approaches for evaluating and ensuring their fairness.

The group is working to solve a problem known as "algorithmic bias," the idea that computers can become prone to discriminating against the poor and oppressed. To counter this, the group proposed a novel method they call "active fairness," which can be used to ensure that ADMs treat everyone as equals. This means that computer programs designed to do everything from delivering verdicts in courtrooms to determining creditworthiness must not discriminate based on a person's race, background, or ability. As automation has become more common, instances of algorithmic bias have become more common, highlighting the need for ADMs to be assessed for fairness.

Active fairness essentially limits the amount of information that computer programs are allowed to use to make decisions. For example, a program guiding a judge's decision in a courtroom will calculate the defendant's risk of recidivism. In making this risk calculation, an algorithm using active fairness should be able to pick out which variables are discriminatory. Race is an obvious example of one, however there is a need to do better than the obvious solution. Other demographic variables can often be correlated with a higher risk of recidivism, but making judgments on these would be discriminatory as well.

Most existing machine learning models are very opaque; understanding the decisions made by artificial intelligence is an area of active research. LSI-R is an example of an ADM that is already in use in American courtrooms, and understanding the reasons behind its verdicts is nearly impossible. It takes in as much data as it can about a defendant's upbringing and environment, and makes decisions based on all of the information it has. Models using active fairness would instead use as few variables as it needs to, and only ask for more information when it is not confident in its decision based on the data it already has. This not only creates a model that is more fair, but also one that is more transparent. If we're able to know which variables were used to reach a decision by an algorithm, then we're able to evaluate the model more easily.



*Tay, the infamous chatbot from Microsoft that learned to write inflammatory tweets, is an example of an algorithm that was susceptible to bias. (Photo: Microsoft)*

Many envision that in the future, computers will automate every aspect of our lives. As computers begin to take on roles in areas such as recruiting, banking, and law, eliminating algorithmic bias will pave the path toward a more equal society. Without working to ensure fairness, we will create a future that works for the few who can afford it, rather than for everyone.

— Jack Cook

# MURJ Features

MIT Department of Aeronautics and Astronautics

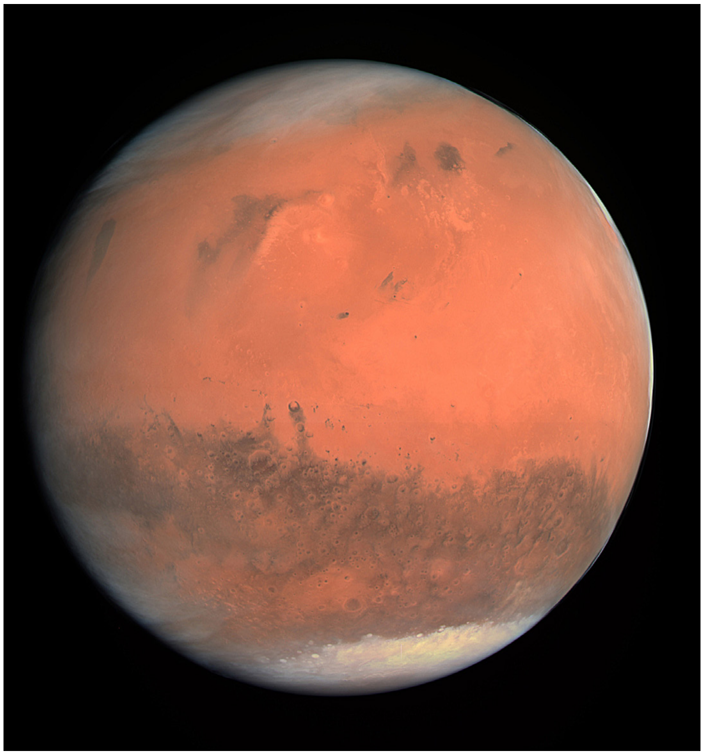
# MURJ Spotlight: Dava Newman

This issue's spotlight features Apollo Professor Dava Newman, a professor in the Department of Aeronautics And Astronautics

By Leah Yost

## INTRODUCTION

Professor Dava Newman, an Apollo Professor of Aeronautics and Astronautics, testified before the Senate Subcommittee on Space, Science, and Competitiveness on putting Americans on Mars in July 2018. Considered an expert in her field, Newman works as a professor in the Department of Aeronautics and Astronautics as well as doing extensive research in the Human Systems Laboratory. She also has a history at NASA, where she was the Deputy Administrator from 2015 to 2017. Enthusiastic and optimistic about the future of space travel, Newman hopes that further exploration will not only reveal more about the universe, but also cause us to reflect back here on Earth.



**The red planet:** the next step in human space exploration. (Photo source: Wikipedia)

## INTERVIEW

**How did you become interested in space exploration?**

I was very influenced by Apollo 11, the landing on the moon. I was five years old, and just watching it with my family. I still remember that it's my first space memory, and it taught me some important lessons, and first and foremost was that anything was possible. A benefit of growing up in Montana is you can see the stars every night, and humanity was going to the Moon, let alone US and NASA, and so it just opened things up.

**What was it like giving a testimony before the Senate Subcommittee on Space, Science, and Competitiveness?**

It's interesting. You have to definitely do your homework. First how it works. I'll tell you the process a little bit. First you're invited to be a witness, and so in this case my last testimony on human space flight to Mars. I was invited by Senator Markey. And when you get a call like that, of course my first answer is yes. I have to say it was a great experience, and it was not partisan at all. It was four witnesses there, but the other three were close friends of mine. So there's no nonsense. Across the four of us there were all different backgrounds and hopefully all different perspectives

**Professor Dava Newman** testifying before a Senate subcommitte about puttining Americans on Mars.
(Photo Credit: NASA/D)

on what's it going to take to get humans to Mars.

It's an interesting process. I think maybe we [MIT students and professors] should do more practice. I'm an engineer. I love being an aerospace engineer. But at the end of the day, it's probably not about my technology or inventions. It's about what can I do with my science and technology to get them implemented, to impact and to make a difference, especially when it comes to policy. We can have the best technology in the world, but if we can't communicate it and share it, we're not going to have the impact for society that we necessarily want to have.

**What was the goal of this testimony?**

I think first and foremost the goal was to get it [space exploration] on the agenda. You're to be an expert and you're supposed to give them the give them justifications and reasons. My goals were to articulate that but also to articulate all the good work that's going on across the sectors, to stay focused and keep focused, and have the right budgets so that we can really achieve this. Absolutely my last sentence was asking for good budget raise for NASA. So kind of any opportunity, especially in the public forum like that, you definitely have to make sure that we have the appropriate, good, robust budgets for all of NASA. I think, as scientists and engineers, we have to take every opportunity to testify and try to explain to people the importance of the investments in science, technology, education, and research.

**How do you envision different countries working together to put humans on Mars?**

So we have had the International Space Station for the last 18 years, which is almost your entire life! It's, say, five main partners, but I think even more important is that a hundred nations have participated, meaning maybe fly an experiment, or get something up in space. So boy, you know, it's not all nations but a hundred nations I think is a great model for international cooperation. So, to me, that is a great model, and we can just improve upon it for when we do lunar exploration and when we do Mars. I think it just brings out the best in humanity. My whole career has been dedicated to global exploration. As far as I see exploration is not just for one nation and definitely when I was a student I knew I wanted to dedicate my career to peaceful space exploration not so much the militarization of space and things like that. I hope every chance and leadership opportunity I get, I emphasize that global exploration for humanity is for all the girls and boys out there. I think we're better when we can work together and celebrate that next step of exploration, especially when it comes to reaching other planets.

**What are the biggest technology or scientific obstacles right now in travelling or living on Mars?**

We're doing fantastic research here at MIT. Now we're going to use probably conventional chemical propulsion because we want to get humans to Mars in eight months and it takes about two years round trip. So we're hopefully safe and healthy getting there, then we're going to explore for 500 days on the surface of Mars. So on the International Space Station, we're really working on what's called bio regenerative life support. We're actually growing plants in space like lettuce, cabbage, and a few other things that astronauts are eating. Which is great because anything living in that harsh, isolated, and confined environment is wonderful.

Our number one challenge, because we're going

**Although we've been exploring Mars** with probes and flybys, the next step is feet on the ground.
(Photo Source: NASA)

into deep space, is radiation. We're still studying radiation, and we don't how we are going to do radiation protection. Also, on the space station we study weakened muscles and bones, and then the human factors, meaning the psychology of people. You know, four people being locked in something in a smaller than my office for four year mission, right? So those are really all the top astronaut performance issues that are potential showstoppers that research works on. To make the Mars mission work, there's a whole bunch of things you can work on in terms of astronaut performance and physiology, but those are my top list of research questions we are still working on. That's why we are on the space station and getting some answers to longer duration flight.

**What advice would you give students who are interested in space travel?**

I would just say definitely if students are passionate about space travel to follow your passion because there's no better time. I was fortunate to grow up, see, and experience some of Apollo, but now is a great time if you're interested in space and space travel because I think almost any MIT student, who's a student today, is going to have the opportunity to actually travel in space. How cool is that? You know, we had 18,000 applicants and 12 people selected [for NASA astronauts]. In the future it's going to be that thousands of people can actually fly, you know, not just the 12 lucky ones that get looked at as NASA astronauts. So students are really fortunate today because they are going to have lots of opportunities.

**How might you convince someone of the importance of space travel?**

I look at a couple important messages about space travel, really exploration. I always say there's three fundamental questions we have in exploration. My questions are: Are we alone in the universe? Are there other habitable planets? When will we find life elsewhere besides Earth? I think they guide all of exploration. I think we will probably find other habitable planets. Then I think perhaps in the next decade we will find the evidence of life. It might be past life but it might be some living. I think the evidence is mounting. I think we'll definitely find life elsewhere. And why is that important? For me, the exploration was important, but really all of our exploring into the solar system is just to reflect back here on Earth. It's to reflect back on this wonderful planet that we live on and life here on Earth. So it just gives me that perspective.

There's something actually called the overview effect. The idea is all astronauts see Earth differently because they've gone into space and looking down on Earth, and it's just beautiful. It really is transformative. Having that little overview effect of Earth, most people are transformed to think about Earth differently. They say we're all in this together. So in all my talks and speeches I tell everybody we are all astronauts. We're living on spaceship Earth. So we kind of have to figure out how to live together, how to get along, and how to use our resources. So I think we really do have to first educate people and then see how we can change behavior to live in balance with the Earth. I always say Earth doesn't really need us. We need the Earth. So we need our planet and it doesn't really care if we are for here or not, right? ▪

# MIT Media Lab: Pinar Yanardag

BY RACHEL ROCK

## INTRODUCTION

This MURJ interview features Pinar Yanardag, a recent Postdoctoral graduate of MIT Media Lab and now the CEO of AI Fiction, a creative studio specializing in AI. Pinar's latest project, How to Generate (Almost) Anything, sees her and her team pushing the boundaries of creative interaction between humans and AI. This novel framework-using AI to collaborate, and not compete with, human creativity is paving the way for a promising future where humans and smart machines work together to create beautiful things.

## INTERVIEW

**There's this fear that the robots are coming to take our jobs. A 2017 Gallup survey of over 3,000 US adults reported that 73% of those asked predicted that AI will eliminate more jobs than it creates and 63% predicted that technological innovation and smart machines will widen the gap between the rich and the poor. Other surveys show similar findings. Why do you think this is?**

People fear things that they are not familiar with. So when I talk about AI and robots, the public fears this because many lack backgrounds in technology. On top of this, people keep hearing from intellectuals like Stephen Hawking regarding the subject. Then, they start to become scared that AI that it is going to take over. It is entirely understandable for the public to fear from AI, which is actually a part of the reason we started this project. We wanted to show people that you don't have to be scared of AI; we can actually work with AI and create beautiful things.

**Tell me more.**

So, if you are a musician, or you are a fashion designer, or a graffiti artist, AI can help you to inspire you


**AI-Generated Pizzas** made into reality by Crash Pizza. Apparently, the shrimp, jam, and sausage recipe was so delicious head chef and owner Tony Naser was contemplating adding it to the menu! (Photo Source: Rachel Rock) to create beautiful things through collaboration. We need to embrace AI and we have to work with it, and here we wanted to playfully show that in creative markets you can use AI to create things you wouldn't have been able to create otherwise. For example, for the dress project, we have designs generated by the AI, some of them really weird, but what I discovered with the AI as a human you think I cannot add this type of shoulder or this type of skirt, but then you see it with the AI and it makes you think, "Wow! This is really interesting," and you're inspired.

The thing with AI is that AI is very good at analyzing from millions of data points, so this would take years for a human to look at thousands of fashion designs and then use these features...to create something new. So AI is really good at analyzing millions of data points and you train a neural network it largely consists of-it is like a neural network in our brains, but it is analyzing millions of parameters and it is connecting different features together in order for us to analyze the data. There is really this power. Whatever data you feed to it. AI is looking at every piece and analyzing millions of features and bringing those together to create new pieces on its own. It is dreaming these things up based on what it learns. This power is something we can harness. Whether it is graffiti, whether it is dresses, whether it is pizza, you can generate almost anything with the AI by giving it the data, collectively generated by humans over the last even hundreds of years. With this power of AI, you can use it to produce something good.

**So, every week you've been working to do that: uniting both human creativity and the power of AI to create beautiful and interesting things. Do you think you could do a week-by-week of the project so far?**

For the first project, we did a musical collaboration. Marvin Minsky was the founder of Media Lab and the artificial intelligence laboratory CSAIL. He was really a pioneer in the field and is often referred to as the father of artificial intelligence. So, for the first piece, we wanted to do something with music to commemorate him and help him create beyond the grave (Minsky passed recently-around two years ago). Marvin Minsky was a really good musician as well with a penchant for improvisation. He has many improvisations on YouTube, so I took one of his improvisations and I commissioned a musician to transcribe one of his improvisations because, again, I'm not a musician, so I couldn't transcribe it. A musician that I commissioned transcribed his music piece. This was the first part of the project.

The second part of the project was training an AI to generate music. So, for all of the projects, we need enough data to feed to the algorithm. In this case, you can feed the algorithm classical music, or you can feed the algorithm rock music, so basically anything you want with all these media files. In my case, I wanted to use arcade music-game songs. I had already culled about 20,000 arcade songs from the 80s and 90s.

So we took the first minute of Marvin's song and how it works is that the AI is able to complete what you feed to it, so the AI can make songs starting from a random point, or you can give the AI this. AI completed the song! In all of our projects, we aim to bring these creations to life. So we don't just want to make the pizza recipes, but to actually cook it, we don't want to just make the perfume recipe but smell the perfume, so for the music piece we have a piano in the basement at MIT Media Lab and I wanted to really hear the song played on this piano. We found a great musician who used to play on. He was very excited to collaborate, and studied the piece and he played the song that Marvin and AI collaborated on on the piano. We actually didn't know the history of the piano, but it turns out after we launched the project a professor from the Media Lab told us that this piano actually belonged to Marvin, so it was Marvin's piano, which is really cool! That was the first week. The next was a piece of pizza.

***Laughs* Pizza?**

Yes! For the pizza piece we culled around 600 pizza recipes, but these are artisan pizza recipes, so this is not like Papa John's Pizza. It's more like Otto Pizza in Boston, so recipes like cranberry and butternut squash pizza. so we culled artisan pizza recipes that have this nice ingredients, and then we trained AI to make new recipes and some of them *laughs* were really weird like shrimp and jam pizza and like there is one with sweet potato and beans and brie cheese so, yeah, seem really weird. But we actually wanted to cook these pizzas and see what they tasted like.

So we contacted Crash Pizza in Boston, an artisan pizza place that uses hundreds of ingredients. We explained and we just wanted to ask and see if we could bring some of the ingredients on our own like the shrimp ingredient and just add it to the pizza while they're making it and they said "no."

Then, I was really upset, and I don't know how I thought of it, but then I find the owner of the pizza place from Facebook and I explained our project to him, and he told us that we don't even have to bring the ingredients. He's going to do all of the ingredients to help us. When we came, he had prepared everything and he was waiting for us. He also invited us to the kitchen where we got to make these pizzas as well and we did this really nice Italian wood-fire oven pizza. It was a really nice experience doing the pizza itself. This oven is like 900 degrees and it is able to cook a pizza in 90 seconds. We thought it was a really nice experience.

To be honest, I hate shrimp, and I don't like bacon, but the best one was shrimp and jam pizza. I was really shocked that I liked it. And everybody else liked it as well. The chef actually was considering adding it to his menu as a special. The most disappointing one, I think was the blueberry, spinach, and feta pizza because the blueberry was just mashed up and we couldn't really taste the blueberry much. So that was the pizza piece.

**Third?**

This was the dress piece. We trained the AI on thousands of magazine covers vintage sewing magazines that had these patterns of dresses in the 1930s and 40s and 50s and 60s, and we used the sewing shop at the MIT Media lab. The Media lab is really like a playground for this sort of creativity. We found someone- Agnes- with a long history of making dresses (she was doing dresses for operas, theater…). She knew how to bring this into reality by making the dresses. I think her dress or jumper was really nice. Mine was weird *laughs* not something you would wear outside, but hers was actually really good.

I also designed my own fashion collection right based on the AI-generated image, but we didn't have time to actually make them. I call it the electric fur collection. *laughs* I think the point is that I don't have any experience in fashion design- I never did fashion design before, but with the AI's inspiration, I designed some interesting pieces. I mean I wouldn't wear most of them


**AI-inspired graffiti** adding a new splash of color to Graffiti Alley, Cambridge. Human designer IMAGINE left an especially meaningful artist statement: No Human Being is Illegal. (Photo Source: Rachel Rock)

**AI-Collaborated Fashion** designed by Agnes Cammeron (human professional) and Garak (fashion designer AI). In the future, AI may help designers push the envelop for avant-garde designs.
(Photo Source: Rachel Rock)

*laughs* but regarding the jumper with the red color, I would consider it. I was able to design things I wouldn't have been able to without the AI's inspiration. And Agnes definitely was able to augment her skills to design something cool as well.

**Fourth?**

This was the perfume piece, which I think was the most fun one for me. We collected at least 30,000 perfume recipes from the websites that listing all of the new perfumes and their notes. So, what's a note? A perfume consists of three notes: top note, heart note, and base note. For example, top note might be Bergamont, lemon, for heart note, lily, jasmine, rose, and in base you can use vanilla, sandalwood, or different oils. Basically, once you have this information, you can create a new perfume by mixing different essential oils together. So the idea was to collect all this information from the commercial perfume recipes and then train the AI to make new ones. We check these formulas against the data set to make sure AI was not just repeating the same thing that it saw from the data set, because sometimes it will do that. So, all of the data recipes that we tried are novel-brand new recipes, meaning they are scents or at least perfumes that nobody has ever smelled before because we have pretty much all the perfumes in the world created and from this, the AI has generated something new. So we went to several perfume shops to gather the ingredients, and then we mixed it in the Koch Institute. After this, we did a smell test with some other people from the lab. The first one that we tried smelled like a nice bathroom, or luxury shampoo, so it was pleasant in that sense whereas the second one was more feminine with notes of lily, jasmine, and rose essential oils. People said they would buy it for girlfriends, wives, and whatnot, so people really liked the smell.

**Fifth?**

Then, we did the graffiti piece, which was really interesting. As you've seen so far, for all the projects, we are generating some media, whether it be text, notes, images or whatnot. In this case, we collected these graffiti pictures from all over the world and trained AI to generate new images. AI learns strategies from the various images that we show it. For example, in most pieces, the graffiti is in the middle, and so the AI learns to positions the its pieces centrally. AI is learning these kinds of features and creating new designs, and we wanted to bring AI's dreamed-up creations into reality: for graffiti artists to create them, or be inspired by them. So, we found two artists who were really excited to work with us.

I don't know if you've ever visited graffiti alley in Cambridge. It's in front of Target on Main Street. It's one of the famous art streets in Boston. We wanted to collaborate with some artists and bring some of these collaborated graffiti pieces to alley and found two artists who were really excited to work with us. For the first piece, the artist looked at the AI generated design, and she really liked the background gradient from yellow to dark red. She took inspiration from AI regarding coloring, but since she's an artist, she has her own experience and thoughts of what she wants to write in the graffiti piece. She made the statement, "No human being is illegal." She's from Nepal, and I'm from Turkey, and we were both dealing with some immigration problems, so the work was really imbued with a deeper sense of meaning through this.

For the second piece, we collaborated with a graffiti artist called SOBEK. He wanted to completely bring AI's design into reality. So, you can see the AI. He wanted to hide art in his design, though. It's not easy to see but there are graffiti artists, especially in Europe, whose style is exactly like this. So then we did the chocolate truffle project.

**Chocolate. Truffles. Enough said. Tell me more!**

Similar to the pizza piece, we collected these artisan truffle recipes, and the AI generated recipes that didn't exist in the data set and we collaborated with MIT Laboratory of Chocolate Science. I don't know if you've heard of it. So, it's not an actual scientific lab, but they still call themselves chocolate scientists, as they really know how to do chocolate. And truffles. So we collaborated with them and actually threw a party in one of the Chocolate Officer's houses.

> *"We collected these artisan truffle recipes and the AI generated recipes that didn't exist in the data set."*

In total, we made four truffles. The first one was pumpkin and matcha truffle which was matcha, pumpkin puree, walnuts, and vanilla. The second one was white chocolate, peppermint, vanilla, honey and rosemary, and this was actually the best one! You wouldn't expect the flavors to blend well, or that rosemary would even taste good in a chocolate truffle, it was delicious. Everybody liked it. It was a very nice and different taste. Oh and just a quick note here, AI's just making stuff up, so for this one, it was suggesting 1 cup of honey, which would have been an excessive amount of honey. And a whole cup of fresh Rosemary, which was also a crazy amount. And for the third chocolate truffle recipe, it actually wanted 1,116 Chai tea bags. So that's, I think, why we also want the human collaboration because even just a human, and in more nuanced cases, an experienced chocolate maker can look at the recipes and tell what goes well together or what to edit in the recipe.

So that was the rosemary and peppermint truffle and the third one that we made was a beet and cranberry truffle, so it has dried cranberry, beets, lemons, pecans, and chocolate. But for the fourth one, there was something about it that was kind of disgusting for many people which was a ginger snap and meat truffle, so it has meat in it. It was suggesting that we use ginger snap cookies, cream cheese, chocolate, dates, and one cup of meat. Some people found it disgusting and did not even want to be involved in the making of it, but others among us saw it as a challenge. So, they took the gingersnap cookies, crumbled them, and mixed them with the meat--along with hot pepper. It was pretty disgusting. Some people thought that if we cooked the recipe a bit more, so it was crispy like bacon, then it could be better.

After we did the tasting, we took the leftovers (but not the meat one, because we didn't want to poison people) and we went to the Stata building and asked people to taste them and guess which recipe it came from. So we gave them the recipes and they tasted the truffles that they wanted and to guess which recipe it belongs to. Most of the time they tried to guess, they couldn't guess which recipe went with each truffle. I think it is interesting to see people's reactions when I say, "Oh, this is actually a pumpkin matcha truffle that they made," and they're like, "Oh no, I hate pumpkin b-"

**But I love the truffle!**

Exactly!

**So those are the projects you've done so far. What next?**

We have some other materials, but

the videos are not edited. There are things in the works, too. Poetry, choreography, board games, viruses…

**This concept is really exciting for professionals who have expertise in an area. Can you see graphic designers, chefs, and other professionals working with this technology to augment their abilities in the future?**

Definitely, I think that it's going to become mainstream where human professionals collaborate with AI. The artists who are able to collaborate with the AI are seen as pioneers in their areas, these artists who use AI and machine learning in their work. This shows that we are in the early step of this human-AI creative collaboration. There are only a few people who are doing this… So many people see AI as a black box that they don't know about, and they only think that researchers at MIT or these large companies are able to use AI to do cool stuff. But we really want to show in this project that you can create almost anything with out-of-the-box algorithms. We share those designs on our website, and you might want to try those designs out. I really hope people see these designs and see that they can get inspired by AI and they don't have to fear from AI, but they can actually work with AI to create beautiful things.

**Because there's a value in human creativity.**

Yes. We don't want someone to just take these pizza recipes and perfectly follow each detail. I don't think it's interesting to just eat a pizza that's completely AI-generated, but for example, as with what happened for our Pizza piece, the chef saw the recipe and he thought, "Hmm...this white sauce might go better with these ingredients, so I'm going to use the white sauce," or after we made the pizza, he remarked, "Oh, arugula might really go well in this recipe," and after he added arugula, the pizza was MUCH tastier. So we want humans to work with the AI to work with what the AI has generated and get inspiration from AI to create new things. There's actually...there's definitely a larger value of human creativity, where AI is acting as an inspiration for humans to create.

**So, my final question is how can people get involved if they're really excited about your project? Or if they're not some creative professional?**

If you are an artist in an area that we haven't tried yet, and you're interested in collaborating, you get in contact with us and you can suggest an idea. Since we want to generate diverse projects, we'd be happy to train an AI and collaborate with the person to generate a new episode.

Regarding the general public, my goal is actually to create a platform to allow non-practitioners and people with no experience with AI to just come to the website and create things. Whatever they want to create, they will have access to those algorithms, and they can use the datasets or upload their own data. I want to democratize this creative usage of AI. However, this is a very large project. It's not easy to do, but this is the larger goal I am ultimately pursuing.

Currently, at the conclusion of every project, we share designs that we haven't tried out yet, so you could try them out. We post them on HowtoGenerateAlmostAnything.com, our website. We also have a SoundCloud page through which you can listen to all of the music that we create, and we post YouTube videos for all the projects, where we are documenting what we are doing. So you could get involved in those ways. And in the future, there will only be more opportunities. ▪

# MURJ Reports

# Using Compressed Sensing To Improve the Efficiency of Gene Expression Data Collection

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## 1. Introduction

In the context of experimental biology, time is the scarcest and most desirable of resources. From generating gene expression profiles for tissue samples to sequencing genomes, the most formidable obstacle that hinders rapid hypothesis testing is the latency required to conduct experiments and process the resultant high-dimensional biological data. One way to increase throughput is multiplexing, which allows a biologist to obtain several measurements in one experimental batch. However, current multiplexing methods can never scale to the sheer amount of data produced during genome-scale profiling experiments.

A more data-centric approach to the problem is compressed sensing. Unlike multiplexing, compressed sensing takes advantage of the latent structure inherent in gene coexpression patterns and shared biological pathways to reduce the ratio of measurements required per data point; indeed, compressed sensing can be utilized in parallel with multiplexing to further reduce the number of required measurements. The application of compressed sensing to the process of collecting experimental data is known as compressive biology, a nascent field with the primary goal of designing data collection pipelines that prescribe how to measure biological data in a compressed format, use computational methods to decompress the data, and interpret the results.

Compressive biology is still in its formative stages. My collaborators and I are working towards a multi-part milestone that demonstrates its applicability to spatial profiling of gene expression, which involves (i) collecting compressed data during an experiment, (ii) establishing the appropriate image preprocessing pipelines for such data (Figure 1), (iii) using learned representations of gene expression patterns and compressed sensing algorithms to decompress the data, and (iv) establish ing methods for validating the output given ground truth, gene-specific spatial profiles. My role is twofold: first, to accomplish (ii) so that these pipelines can be easily applied to compressed data from future experiments; second, as our ability to iterate upon these compressed experiments improves, to explore alternative, more effective compressed sensing algorithms for (iii) so that we can better approximate the ground truth gene expression profiles.

## 2. Preliminary Results and Evaluation

To evaluate the output of the compressed sensing pipeline, we must have baselines of gene expression data that we can use as standards of comparison. To accommodate this, these baselines feature as control data that are collected during these prototypical compressed sensing experiments, i.e. for each composite measurement that represents the combined gene expression signal of some set of

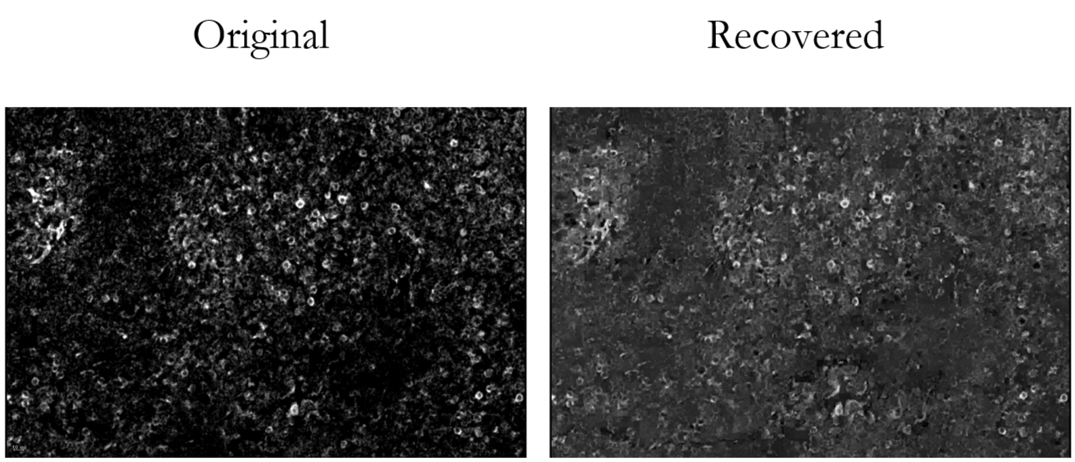


Figure 1: Results of applying compressed sensing to spatial gene expression data. The image on the left is a baseline that results from measuring a single gene, while the image on the right is the output of applying compressed sensing to composite measurements.

genes, the corresponding measurement for each of those genes is also obtained. We can use these to directly evaluate the output of our pipeline - for example, we can compute a pixel-by-pixel loss function that quantifies the quality of our reconstruction. Indeed, we have already calculated this loss for an initial dataset without conducting any image preprocessing (Figure 1), and the results indicate that even with this constraint, compressed sensing is able to recover gene-specific measurements to an appreciable degree.

## 3. Conclusion

In summary, the goal of this project is to both establish the potential of compressed sensing as a solution to the problem of obtaining large amounts of gene expression data and to produce an example procedure for applying this technique to a particular data type. The aim is to publish this result for spatial gene expression profiling as an example of the efficacy of compressed sensing in the context of biological experimentation, with the eventual hope that such an approach can become ubiquitous in the field.

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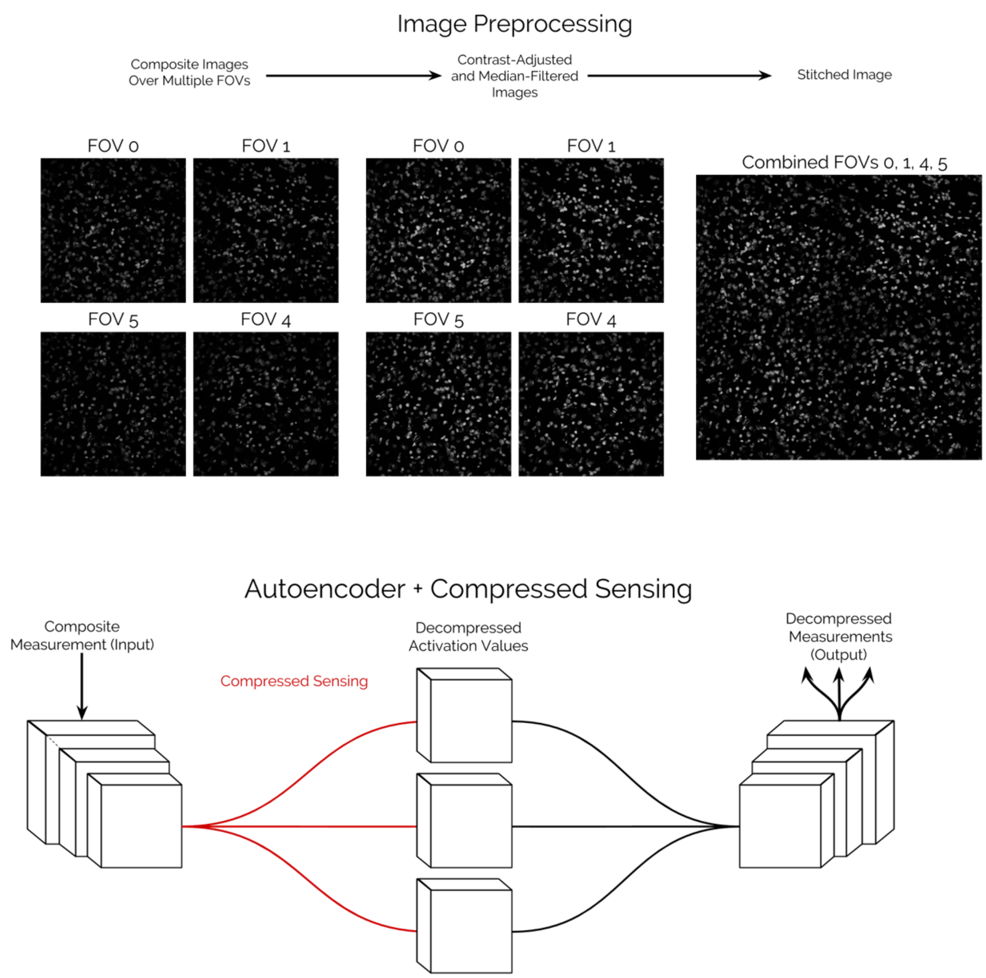


Figure 2: A pipeline for applying compressed sensing to spatial gene expression data. Compressed sensing (red) is a key step that is the main focus of the project; however, the refinement of other steps is also vital to produce an accurate output.

# NIR Silicon Photodetector Enhancement Using Photonic Crystal Cavity Resonators

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**The growing demand on efficient sensors for light ranging, thermal-cameras, and soon, free-space optical communications has yet to be answered. In this study, we use polycrystalline silicon in conjunction with a photonic crystal cavity (PhCC) to enhance light absorption for efficient sensing. We present a more cost-effective alternative to the current III-V detectors. By adding a 2D-PhC resonator layer, surface-illuminated light can be confined within a 5µm diameter region with great intensity, leading to a higher effective path-length and improved detector responsivity. More than 1000 variants of this detector are designed and implemented in a 65nm CMOS process. Using a bi-sectional method, we find the most optimized designs. We validate experimental findings by simulating mode behavior of the PhCC structures using FDTD models. We report polysilicon PhCC-enhanced sensors with Q-factors of 6500 resulting in responsivities at 1300nm up to 0.13mA/W – a 25x improvement over non-resonant surface-illuminated silicon detectors.**

## 1. INTRODUCTION

The vision of the research presented is to enable the advancements of near-infrared (NIR) technologies. The increase in demand on efficient sensors for light ranging, thermal-cameras, and soon, free-space optical communications is resulting in a gap between the commercial needs and the state-of-the-art. Basic research that aims to examine material and physical limitations is essential for addressing this demand. Silicon is becoming the most widely used material in fiber-based communication for its integratable with the electronics world (Jalali, Fathpour, 2006). Leveraging this advanced complementary metal-oxide-semiconductor (CMOS) technology to the free-space world is the focus of this research. Using the NIR range to send and receive information between objects in a short-ranged environment, while maintaining eye-level safe emissions, is one of the biggest challenges for free-space applications.

The indirect bandgap of crystalline silicon poses some optical limitations. This forces the crystal to undergo momentum exchanges every time a photon is absorbed or emitted. In addition, it requires for a photon to have enough energy for a band-to-band transition to occur. NIR (1.1-1.4µm) photons have lower energy than the bandgap of silicon, hence they have a significantly lower chance of generating current. There are a few phenomena that could be harnessed to enable sub-bandgap absorption. Surface-state-assisted and virtual-state-assisted absorption allow for more than one photon to add its energy and overcome the gap.

The combined aforementioned effects result in an absorption depth of silicon around the order of 104 cm at 1300 nm and orders of magnitudes higher at longer wavelengths (Green, 2008). This sets a research challenge which is currently being tackled from different directions. An early method to enhance low-absorbing silicon is to expose it to high levels of deuteron and neutron radiation. The damages radiation causes to the crystal create mid-bandgap states that ultimately lower the weak-absorption effects (Casalino et al., 2010). A different method utilizes the Schottky diode effect where a metal layer is placed near the semiconductor junction. The electrons generated near the metal surface carry kinetic energy, which allows it to overcome the energy gap (Amirmazlaghani et al., 2013). This method, however, requires applying an external reverse voltage to provide electrons with a high enough energy. Moreover, a common method found in the literature uses light confining structures to increase the effective path-length of light in the material. Resonance-enhanced devices add a Fabry-Perot cavity, creating an enhancement factor proportional to the Q/V where Q is the quality factor of the resonator and V is the mode volume (Casalino et al, 2012; Vahala, 2003). This work focuses on a type of light-confining structure known as photonic crystals cavities.

The purpose of using silicon is to utilize the platform's well-established technology. However, previous enhancement techniques modify the devices beyond what is permitted by current CMOS standards (Casalino et al., 2010). Hence, a CMOS-compatible enhancement mechanism called photonic crystal microcavities has been proposed as an alternative method. Photonic crystals (PhC) have proven to be efficient structures to control light. By engineering a periodic dielectric structure, it is possible to create transverse light-confining structures that are compatible with the silicon CMOS environment (Joannopoulos et al., 1997; Bravo-Abad et al., 2009). Experimental works in waveguide-based and thermophotovoltaic devices have demonstrated an increase in photocurrent generation through the use of PhC microcavities (Tanabe et al., 2010; Shemeya, Vandervelde, 2012).

High Q/V silicon-based PhC structures have been already demonstrated and now used as passive coupling enhancers (Akahane et al., 2003). In III-V quantum cascade detectors, a PhC is used as a coupling mechanism to direct incident light into a traverse surface. It is also shown to increase its photocurrent absorption at resonance (λ ~ 9μm) and lower detector noise (Reininger et al., 2013). Such advances have also been demonstrated in quantum-well infrared detectors. Normal incident light on a PhC layer on the surface of detector created sharp peaks in photocurrent generation at long IR wavelengths (λ = 7.6μm) (Kalchmair et al., 2011).

## 2. Methods

The outline of this research will be to characterize and model a surface-illuminated NIR PhC detector that unites polysilicon and 2D-PhC. This will be accomplished by first testing on a semiconductor parameter analyzer (Agilent 4155c) to measure resonance characteristics as well as the efficiency of the photodetectors; then, second, building a device model in a semiconductor industry-standard software that will allow for interpreting the data measured in the lab. Since, these devices involve both an optical resonant structure and a diode structure, there will be a need to model both physical effects. The electromagnetic modeling of the resonant structure will be done in a Finite-Difference Time-Domain (FDTD) solver, Lumerical Solutions. By calibrating the models to the measurement data, this work will help in designing the next generation of resonance-enhanced NIR photodetectors with high efficiency in silicon technology.

The chip layout consists of 1088 devices that are designed and fabricated to test the quality of Junction/PhCCs arrangement. Each device consists of a unique set of 7 parameters that control the bandgap of the PhC, coupling efficiency, and cavity resonance wavelength. The parameters are shown in Table 2. The challenge in this section is finding the most optimized device. Each device is 12μm wide (diameter) and 220 nm thick. A picture of a device is shown in Figure 1.

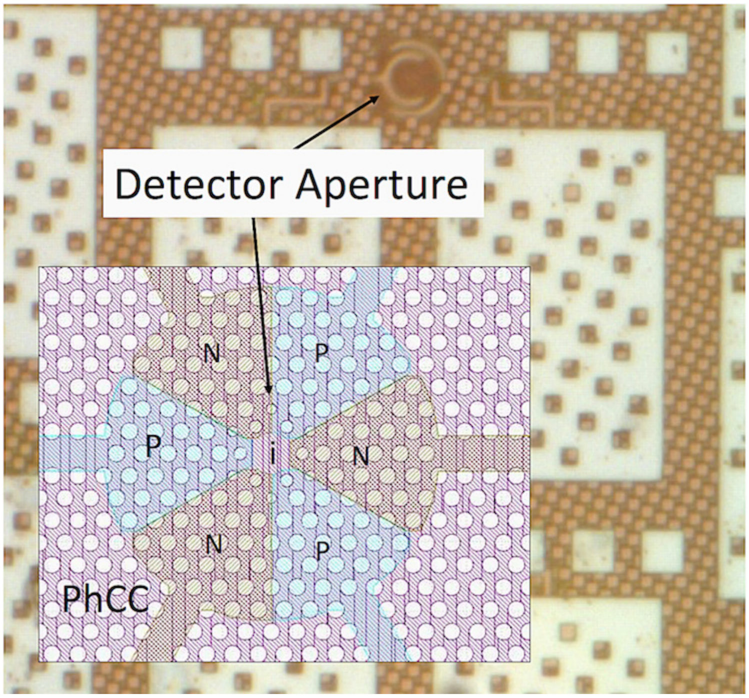


Figure 1. An optical microscope photograph of the device. Overlaid is the layout of the given PhC cavity of the corresponding device.

The setup consists of a tunable laser that ranges from 1260 nm to 1650 nm (Santec TSL-250F). The laser is connected by a single mode fiber to the probe station where the rest of the optics lie. The infrared beam is collimated using a $f$ = 25mm ThorLabs lens followed by a polarizing beam splitter (PBS) cube that directs it through the microscope objective and eventually onto the chip. The polarization is controlled using a three-paddle in-fiber polarization controller. After focusing the beam on the chip, the light reflects

| Reference | Type Device | Material | Responsivity | Dark current | Wavelength |
|---|---|---|---|---|---|
| Casalino et al. (2012) | F–P microcavity | Silicon, 100μm depth | 0.063 mA/W | 3.5 x $10^9$ pA (-0.1V) | 1550nm |
| Amirmazlaghani et al. (2013) | – | Graphene-Silicon Schottky junction | 9.9 mA/W (-16V) | 2.4 x$10^6$ pA (-16V) | 1550nm |
| Desiatov et al. (2015) | Silicon Pyramids (apex ~50μm$^2$) | Al–Silicon Schottky junction | 12 mA/W | 8 x $10^4$ pA (-0.1V) | 1300nm |
| Alloatti, Ram (2016) | Lateral PN, 45nm CMOS | SiGe, 10μm x 10μm | 0.032 mA/W | < 10 pA (-2V) | 1080nm |
| Casalino et al. (2017) | F–P microcavity | Graphene–Silicon Schottky junction | 20 mA/W (-10V) | 0.15x$10^9$ pA (-10V) | 1550nm |

Table 1. A comparison between silicon surface-illuminated devices optimized for NIR. We can see that devices made using a Schottky junction have a superior conversion efficiency; they also have a higher operating bias and a higher dark count rate.

| | | | |
|---|---|---|---|
| Unit Cell | 0.37 - 0.4µm | $R_d$/Cell | 0.1 - 0.2 |
| $R_1$/Cell | 0.17 - 0.35 | Defect Shift/Cell | 0.1 - 0.25µm |
| $R_2$/Cell | 0.17 - 0.35 | Defect Layers | 1 - 3 |
| Intrinsic Spacing (d) | 0.0 / 0.4µm | | |

Table 2. The 7 design parameters for the photonic crystal and their respective values. Values are swept to create 1088 different variants of detector design. A visual representation of the parameters are shown in Figure 2.

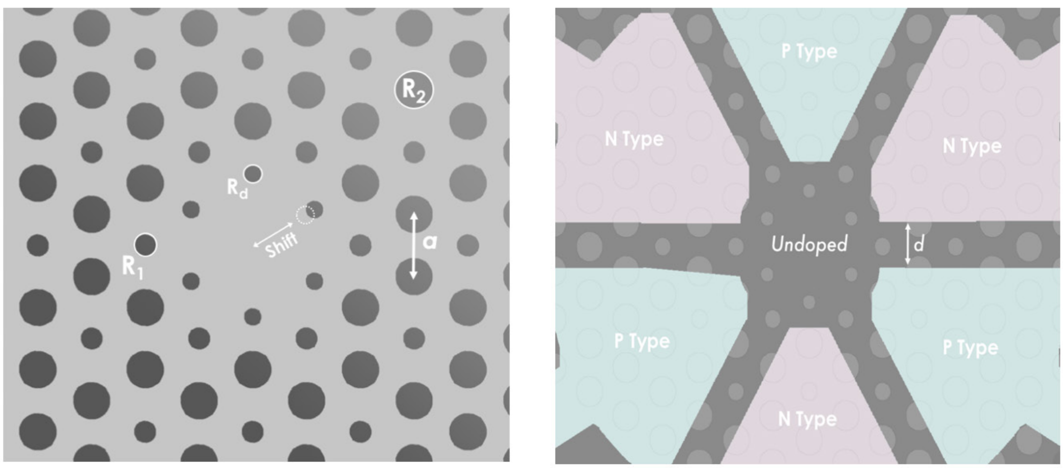


Figure 2. PhCC bi-atomic layout parameters (r) Detector junction layout with intrinsic region spacing of 0.4µm.

back through the objective/PBS where an infrared camera is set up. The infrared camera is used for beam alignment and spot size estimation.

We verified the detector's photoresponse under white-light illumination to find its diode characteristic behavior. This is done by probing the device using a semiconductor parameter analyzer (SPA). An IV characteristic of a randomly selected diode is shown in Figure. 3. The clear turn-on and breakdown voltages and the photoresponse to white light suggest the diode is indeed operating. However, only a fraction of the devices had a clear turn-on. Out of the 30 measured, only 6 devices did not experience premature breakdowns around -6V. This feature of the IV characteristic is only seen with devices with 0µm intrinsic region spacing. We speculate this is due to carrier tunneling through the narrow n-p spacing and causing an avalanche cascade. For the rest of this report, we will focus on the subset of devices that do not experience premature breakdowns and that have non-zero d. FDTD simulations in Lumerical Solutions are done in conjunction with the experimental testing. The simulation will help evaluate the performance of different devices. p-Si and SO2 were selected to reconstruct the PhC microcavities. Sources were defined as planar waves with wavelengths ranging between 1.2 and 1.6µm to best mimic the

| Device | $R_1$/a | $R_2$/a | Shift per cell | $R_d$/a | Layers |
|---|---|---|---|---|---|
| C23R14 | 0.31 | 0.31 | 0.2 | 0.1 | 3 |
| C22R29 | 0.297 | 0.33 | 0.2 | 0.1 | 3 |
| C24R18 | 0.33 | 0.33 | 0.2 | 0.1 | 3 |

Table 3. PhCC parameters of the three highest performing devices (shown in Figure 5). Table 3 presents the parameter values of the three devices with the highest Q/V values. A reverse bias plot of the highest device is shown in Figure 7.

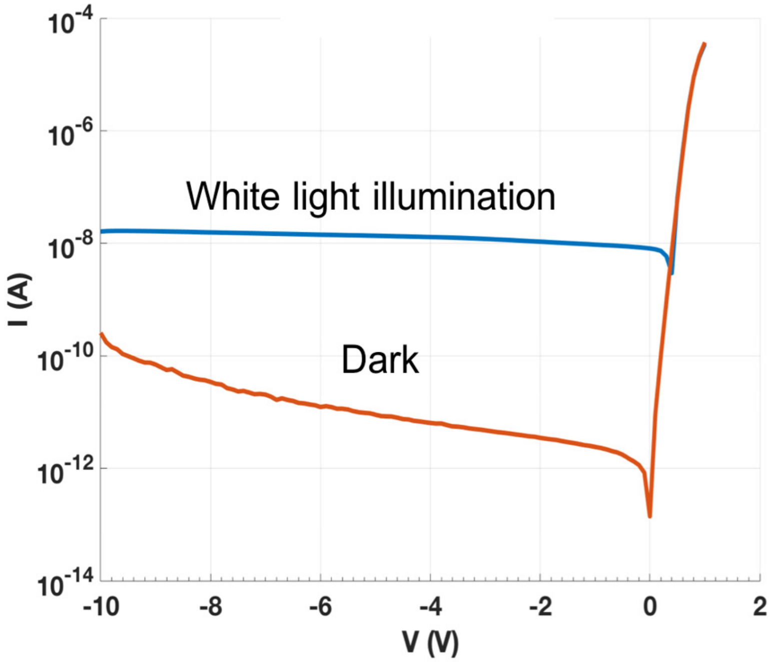


Figure 3. IV curve of a device under dark and white light conditions. Intrinsic region spacing d=0.4μm

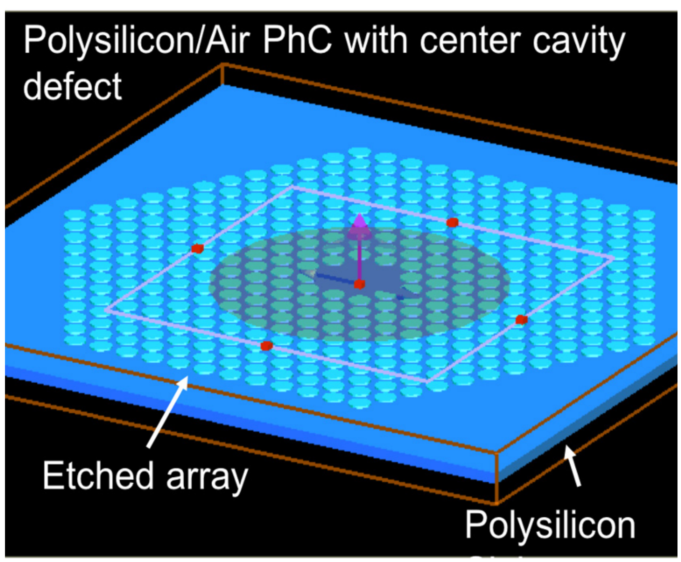


Figure 4. Photonic crystal microcavity structure made in Lumerical. Materials chosen are p-Si and SO2 with indices 3.5 and 1 respectively.

tunable laser. This allows us to identify the resonance modes found in the tested devices. A diagram of the one of the devices constructed in Lumerical is shown in Figure 4.

The spectral response of the device is found using the SPA. This spectrum is used to find the resonances of the PhC and measure the detector performance, as well as to estimate the device's Q.

## 3. Results

The main evaluation metric for PhC cavities is Q/V, which directly correlates to the efficiency of the light confining structures. However, this value is implicit and generally difficult to estimate. Experimentally, we rely on comparing the ratio between on and off-resonance enhancement in the PhC detectors. Figure 5 shows three devices with high confinement and photocurrent generation. On the other hand, for the simulated cavities, we directly use the quality factor and mode volume to compare different designs. The result for the simulation is shown in Figure 6. Finally, combining the two optimizations (physical and simulated) allows us to find the highest performing design for a surface-illuminated PhC detector.

## 4. Discussion

Optimized PhCC structures have been presented with Q-factors up-to 6500 and high extinction peaks due to Q/V of the order 10^16 cm^(-3). The purpose of using PhCC structures is to provide the missing link for surfaces-illumined detectors by efficiently coupling incident beams into transverse layers giving a CMOS-compatible design. Although responsivities are below commercial III-V detectors (0.9W/A), the high signal-to-noise ratio at zero-bias and integration into microelectronic processes opens countless possibilities for the future of PhCC detectors. A notable possibility is an array of packaged PhCC detectors with a cascaded high-gain Trans-Impedance Amplifier (TIA) to create a multidirectional, narrowband, NIR sensor die. This work demonstrates that through using a resonance layer it is possible to enhance the sub-bandgap responsivity of polycrystalline silicon to an order of 0.1mA/W.

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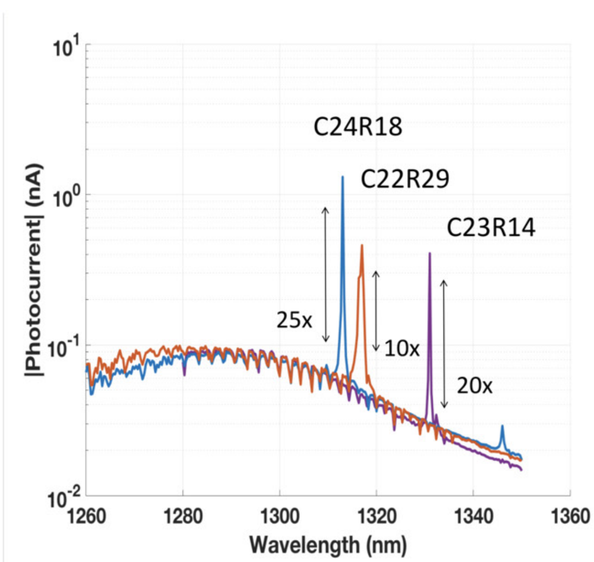


Figure 5. Spectral responses of devices C24R18, C22R29, and C23R14 and their respective enhancements.

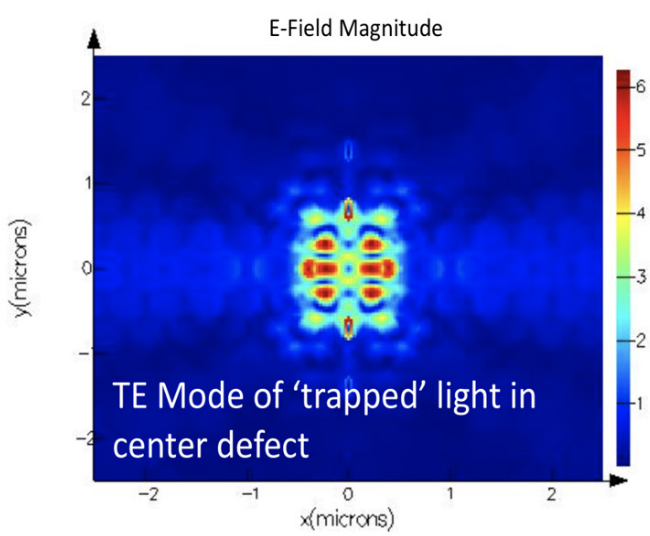


Figure 6. Simulated PhC cavity in Lumerical. Colorbar showing the intensity of E/E_Normalized.

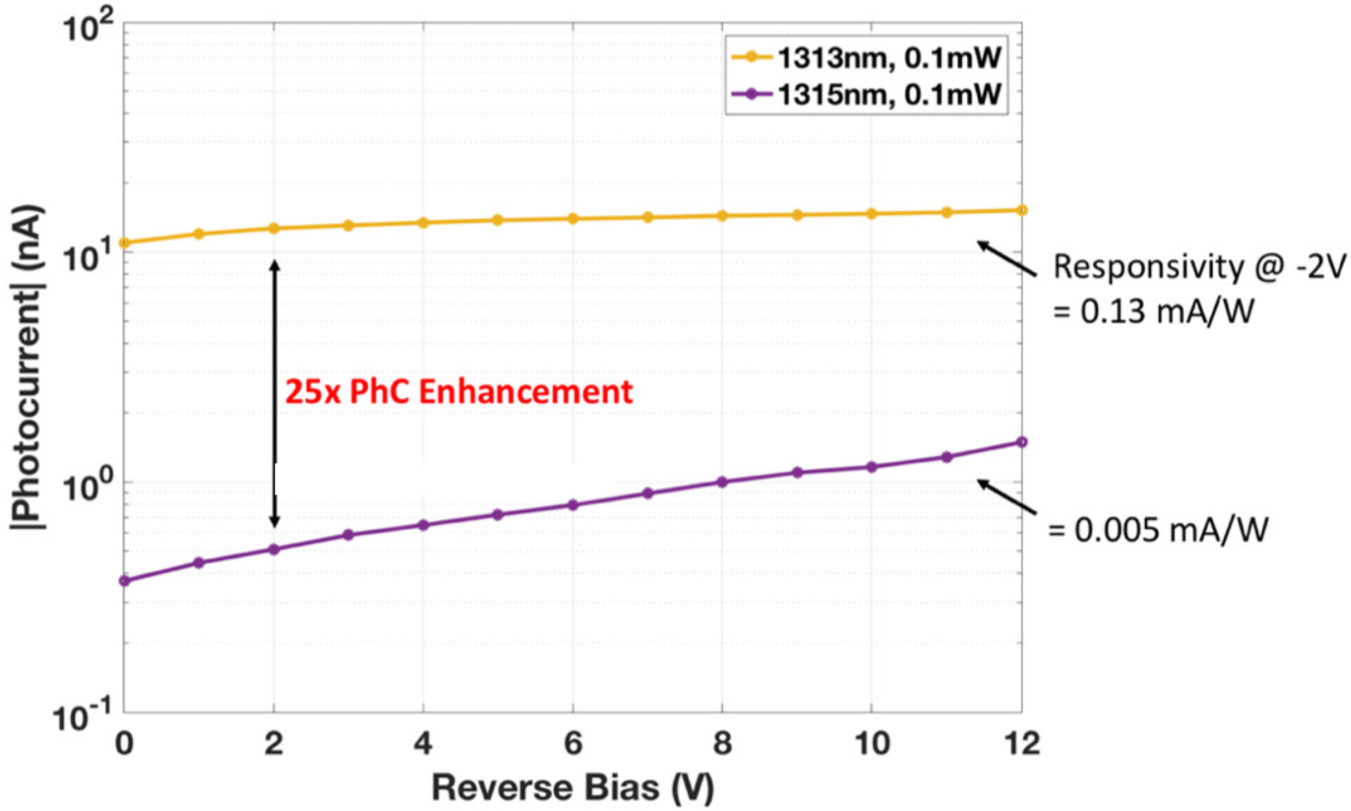


Figure 7. IV curve of C24R18 on and off-resonance in reverse bias.


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# Robust modeling of quadruply lensed quasars (and random quartets) using Witt's hyperbola

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**We develop a robust method to model quadruply lensed quasars, relying heavily on the work of (Witt, 1996), which showed that for elliptical potentials, the four image positions, the source, and the lensing galaxy lie on a right hyperbola. For the singular isothermal elliptical potential, there exists a complementary ellipse centered on the source which also maps through the four images, with the same axis ratio as the potential but perpendicular to it. We first solve for Witt's hyperbola, reducing the allowable space of models to three dimensions. We then obtain the best fitting complementary ellipse. The simplest models of quadruple lenses require seven parameters to reproduce the observed image configurations, while the four positions give eight constraints. This leaves us one degree of freedom to use as a figure of merit. We applied our model to 30 known lenses, and include their figures of merit. We then modeled 100 random quartets. A selection criterion that sacrifices 20% of the known lenses can exclude 98% of the random quartets.**

## 1 Introduction

Astronomers with experience studying quadruple lenses can reliably determine, by examination of relative positions and fluxes, whether a quartet of point sources is lensed. They have trained a neural network, located between their ears, to identify such systems. With the advent of the Gaia probe, quadruple lenses are being discovered at an astonishing rate (Lemon et al., 2018), and as evidenced by (Delchambre et al., 2018), there is a clear necessity for robust methods to model these systems.

It is widely thought that the gravitational equipotentials that produce most quadruply lensed quasars can be reasonably approximated by concentric ellipses (Kassiola and Kovner, 1993). The simplest models for isothermal elliptical potentials include seven parameters, and a quartet of image positions gives eight constraints (Keeton, 2001). While that leaves one degree of freedom for use as a figure of merit, it can be difficult to find the best fitting model in that seven dimensional space.

In what follows, we lean heavily on the work of (Witt, 1996), who finds that for elliptical potentials, the positions for all four images, the center of the lens, and the projected (but unobservable) position of the quasar all lie on an hyperbola whose asymptotes align with the potential's major and minor axes. The hyperbola gives us the position angle and restricts the positions of the lens and the source to a one dimensional locus. It reduces the dimensionality of the space to be searched from 7 to 3.

We also show that for the specific case of the singular isothermal elliptical potential, there exists an ellipse mapping through all 4 image positions, whose minor axis is aligned with the major axis of the potential, has an axis ratio inverse to the axis ratio of the potential, and is centered on the source.

We then search along Witt's hyperbola for the source position and axis ratio that minimize the scatter in the lensing strengths determined by the positions of the four quasar images. We use this scatter as our figure of merit.

In Section 2, we briefly explain gravitational lensing,

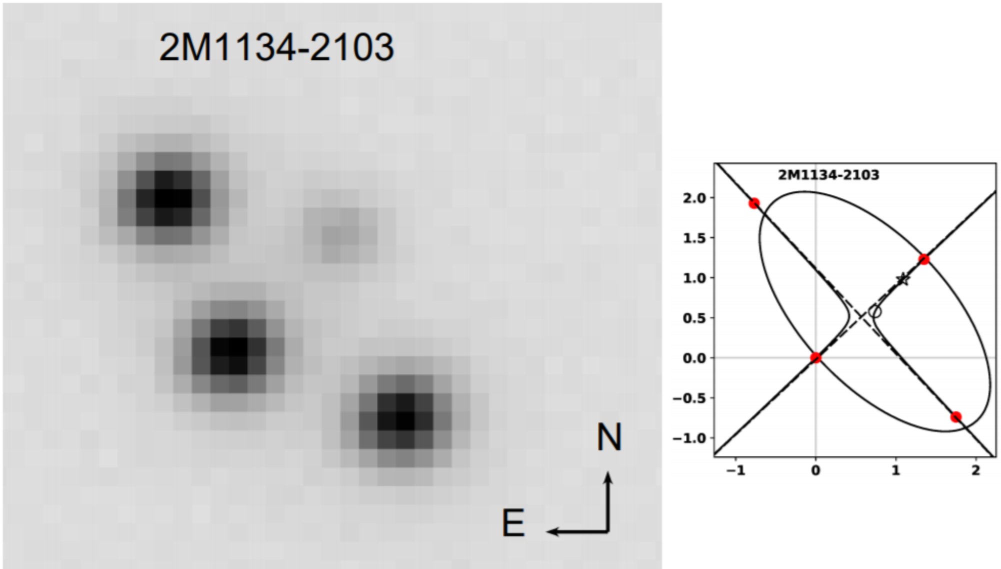


**Figure 1:** *Quadruple lens system 2M1134-2103, with both images at the same scale. On the left is a Sloan i filter image taken from the ATLAS survey, and the scale of this figure is $0.''21$ per pixel. On the right is the plot our model produces for 2M1134-2103. The red dots are the image positions, the circle is the source position, and the star is the galaxy position. The parameter values are* $b = 0.''92, q = 0.491, \theta = 133.1^\circ$ *with* $\sigma_{\ln b} = 0.071$.

and discuss the importance of quadruple lenses. In Section 3, we give background into the geometry associated with the quadruple systems, and explain our method of solving for the source position and axis ratio by minimizing the scatter in the lens strength. In Section 4, we compute our proposed figure of merit with a sample of spectroscopically confirmed quadruply lensed quasars. In Section 5, we analyze random quartets, and compare them to the known figures of merit. In Section 6, we discuss the results of the previous sections, and how they might be used to accept or reject the lensing hypothesis.

# 2 Background

## 2.1 Gravitational Lensing

Albert Einstein's theory of General Relativity represents gravity as the warping of space-time. Light propagates along paths called geodesics, which are a generalization of the notion of straight lines to curved spaces. When gravitational fields are not strong, one can treat the propagation of light as if there were an index of refraction proportional to the gravitational potential (Narayan and Bartelmann, 1996).

From Fermat's principle, it is known that light follows a path that is stationary in time. For everyday situations, this is the single path that takes the least amount of time for light to travel (Blandford and Narayan, 1986). However, on the astronomical scale, a massive body such as a galaxy can warp space to the degree that multiple paths satisfy this stationary criteria, and multiple images of one source object appear. In this way, the galaxy acts as a lens," although the French have a better name for the phenomenon: *mirage gravitationnel* (Surdej and Surdej, 2001).

In gravitational lensing, there are three important phenomena and their corresponding equations: time delay, deflection, and distortion. The first deals with the difference in travel time between different paths, the second with the degree to which light gets bent towards the observer, and the final with how the images are magnified and distorted. In this paper, we will only be dealing with deflection, and the associated lens equation,

$$(\vec{u} - \vec{u}_s) = \vec{\nabla}\psi, \tag{1}$$

where $\vec{u}_s$ is the position at which the source would be in the absence of lensing, and $\psi$ is the projected, two-dimensional gravitational potential obtained by integrating the three-dimensional potential along the line of sight. The solutions of the lens equation, $\vec{u}_i$, give the positions of the images of the source. The $\vec{u} - \vec{u}_s$ term is also known as the deflection, since it is the difference between the observed position and the position the source would have had sans lensing. Therefore, the stronger the gradient in the potential, the greater the deflection (Blandford and Narayan, 1986).

## 2.2 Quadruple Lenses

Configurations with four images, known as quadruple lenses, are of particular interest. For example, they permit measurements of time delays (Treu and Marshall, 2016), put constraints on cosmological parameters such as the Hubble constant (Suyu et al., 2013), allow study of the structure of quasars (Bate et al., 2008), offer research on

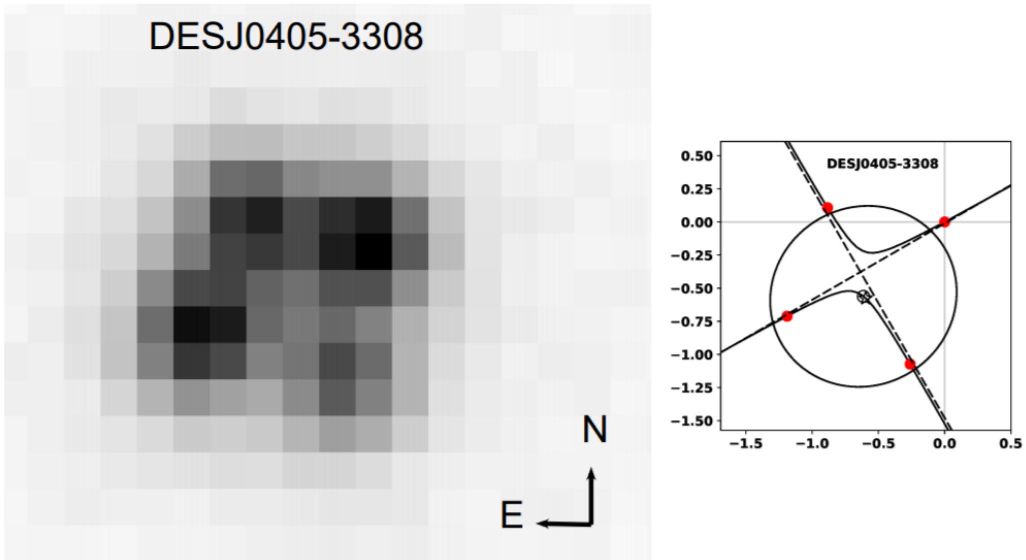


**Figure 2:** *Quadruple lens system DESJ0405-3308, with both images at the same scale. On the left is a Sloan i filter image taken from the DES survey, and the scale of this figure is 0.″26 per pixel. On the right is the plot our model produces for DESJ0405-3308. The red dots are the image positions, the circle is the source position, and the star is the galaxy position. The parameter values are* $b = 0.''67, q = 0.944, \theta = -120.6^\circ$ *with* $\sigma_{\ln b} = 0.130$.

the stellar content of the lensing galaxy through microlensing (Schechter and Wambsganss, 2004), and can be used as a probe for gas clouds along the line of sight (Zahedy et al., 2017).

Nearly four dozen quadruply lensed quasars have been discovered since PG1115+080 (Weymann et al., 1980), many in recent years. Gaia, whose mission is to create a detailed three-dimensional map of the Milky Way, offers a way to detect these systems (Prusti, 2018); it is expected to discover approximately 2900 quasars, with around 80 having two or more images (Finet and Surdej, 2016).

All of the many applications of quadruply lensed quasars require a model for the gravitational potential. In the gravitational lensing literature, a frequently used model is the elliptical potential. Witt argues that equation (4) applies equally well to a singular isothermal sphere with external shear $\gamma$, substituting $1+\gamma/1-\gamma$ for $1/q^2$ in equation (4). This is true for the special case in which the shear term in the potential is centered on the source (Witt and Mao, 1997). When the shear term is centered on the galaxy the hyperbola is offset. One way or the other, one might model a singular isothermal sphere with shear following the approach developed below for the singular isothermal elliptical potential.

## 3 Method

### 3.1 Witt's Hyperbola

In Witt's paper, he assumes an elliptical potential of the form $\psi = f(r)$, where $r = x^2 + y^2/q^2$ is the equation of an ellipse with semi-major axis aligned with the x-axis of the coordinate system, and where $f$ is an arbitrary function that describes the variation in spacing of the elliptical equipotentials. For the purposes of this paper, we will use the singular isothermal elliptical potential

$$\psi = b\sqrt{(x-x_g)^2 + (y-y_g)^2/q^2} = bt \tag{2}$$

where $b$ is the lens strength, $(x_g, y_g)$ is the position of the lensing galaxy, $q(<1)$ is the axis ratio of the potential, and $t = \sqrt{r}$. Note that $t$ plays the role of a distance from the galaxy. The singular isothermal elliptical potential, hereafter SIEP, is a good approximation to the actual potentials produced by the lensing galaxy (Kassiola and Kovner, 1993).

The lens equation for this potential is the following,

$$\vec{u} - \vec{u}_s = \frac{1}{t}\frac{d\psi}{dt}\left[(x - x_g)\hat{x} + \frac{(y-y_g)}{q^2}\hat{y}\right], \tag{3}$$

where $(x_s, y_s)$ is the (unobservable) position of the source. Witt uses only the direction of this equation, taking the ratio of the y component of the displacement vector to the x component of the displacement vector to get

$$\frac{(y-y_s)}{(x-x_s)} = q^{-2}\frac{(y-y_g)}{(x-x_g)} \tag{4}$$

Cross multiplication of (4) gives an equation of the form

$$xy + Ax + By = C, \tag{5}$$

(the coefficients being determined by the galaxy and source positions and the axis ratio), which happens to be a right

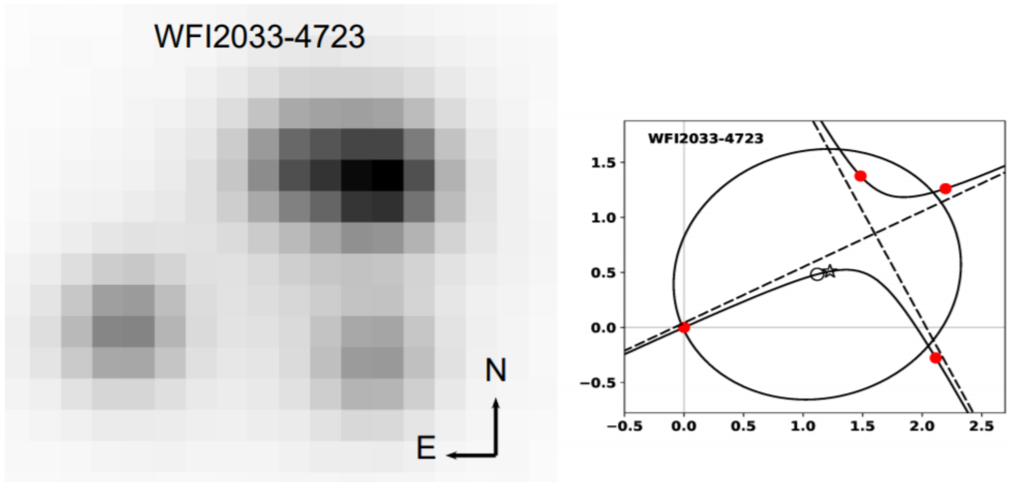


**Figure 3:** *Quadruple lens system WFI2033-4723, with both images at the same scale. On the left is a Sloan i filter image taken from the DES survey, and the scale of this figure is* $0\overset{\prime\prime}{.}26$ *per pixel. On the right is the plot our model produces for WFI2033-4723. The red dots are the image positions, the circle is the source position, and the star is the galaxy position. The parameter values are* $b = 1\overset{\prime\prime}{.}12, q = 0.906, \theta = -63.1^\circ$ *with* $\sigma_{\ln b} = 0.118$.

hyperbola with asymptotes aligned with the x and y axes. It is clear that, along with the four images, the galaxy and source must lie on this curve, since they satisfy the equation above.

We can with no loss of generality take our coordinate system to be one in which the asymptotes of the hyperbola are not merely aligned with the axes but coincident with them, in which case:

$$xy = W^2, \tag{6}$$

where W is a constant with units of length.

One must apply an arbitrary rotation and translation to Witt's hyperbola to give it the form that it takes in the observed coordinate system. If one shifts the images in the observed system system such that one image is at the origin, the equation for the hyperbola takes a simpler form, and is as follows:

$$c_1 x'^2 + c_2 x'y' - c_1 y'^2 + c_3 x' + c_4 y' = 0. \tag{7}$$

We observe only the four images. The position of the source is unknown, the position of the lensing galaxy is often unknown, and even when the position of the lensing galaxy is known, the equipotentials will not have the same shape since the galaxy may not have the same orientation. The image positions are measured in a coordinate system that is rotated and translated by unknown amounts from the coordinate system in which Witt's hyperbola takes its simplest form.

Gravitational lensing requires seven parameters to model a system: the orientation $\theta$, the two galaxy coordinates $(x_g, y_g)$, the two source coordinates $(x_s, y_s)$, the lens strength $b$, and the axis ratio $q$. Witt's hyperbola has immense power in modeling systems. It not only gives the orientation, but also describes the position of the galaxy and source by one coordinate, not two. Therefore, Witt's hyperbola reduces the dimensionality of the space to be searched from 7 to 3.

Four observed image positions suffice to determine the four unknown coefficients, $c_1 - c_4$, that uniquely describe the hyperbola. If the lensing potential is *not* elliptical the four images will still give a hyperbola, but we would not expect the source or the galaxy to lie on it. Indeed any four points will produce a right hyperbola, so the hyperbola, by itself, does not tell us if four images are in fact lensed or whether the potential producing them is elliptical.

## 3.2 A Complementary Ellipse

So far, we have only used the direction of the lens equation. Taking the magnitude squared of each side of (3) and a little algebra gives the equation

$$(x - x_s)^2 + q^2 (y - y_s)^2 = b^2 \tag{8}$$

This equation is important in that for the SIEP, the images appear at the intersection of Witt's hyperbola and an ellipse centered on the unlensed source position, with minor axis aligned with the major axis of the potential.

The four image positions are enough to determine the four parameter values of equation (8). But as in the case of the hyperbola, *any* four points will produce an ellipse once we specify the orientation of the axes. However, unless the images are precisely those of a singular isothermal elliptical potential, the hyperbola determined by equation (7) and the ellipse determined by equation (8) are not consistent with each other. The source position, as determined from the ellipse, will not, in general, lie on the hyperbola.

### 3.3 Modeling the Singular Isothermal Elliptical Potential

As we wish to construct a self-consistent model, we chose one that is consistent with the hyperbola determined from the four images. We then find an ellipse of the form of equation (8), with the source on our hyperbola, that comes close to passing through the four images.

It is evident from equation (8) that for variable sourceH position and axis ratio, each image will have an associated lens strength $b_i$. For perfect source position and axis ratio, the $b_i$ will be equal, since the configuration is the result of one lensing strength. Therefore, minimizing the standard deviation of the logarithm of the lens strength,

$$\sigma_{\ln b(x_s,q)} = \sqrt{\left\langle (\ln b_i - \langle \ln b \rangle)^2 \right\rangle}, \quad (9)$$

where $\langle \ln b \rangle = \frac{1}{4}\sum_{i=1}^{4} \ln b_i$, will give the source position and axis ratio that is in this sense the best fit. In the coincident coordinate system, this is a simple, 2-dimensional minimization problem, since the y-coordinate is given by $\frac{W^2}{x}$. As we show in Appendix A, once the source position and axis ratio are known, the galaxy position is immediately determined. In Appendix B, we show how to determine which branch of the hyperbola the source and galaxy lie on.

Considering the singular isothermal elliptical potential is only a model, albeit a very useful one, the minimum of the scatter will not be at zero. However, this is good; we can use this minimum value as a figure of merit. It can be used to determine how closely a system resembles the singular isothermal elliptical potential, offering insight as to whether a system is a lens or not.

## 4 Known Lenses

To test our method, we examined thirty known quadruple lenses and recorded their figures of merit. The average value for the figure of merit was $\langle \sigma_{\ln b} \rangle = 0.0531$, and the standard deviation was $\sigma_{\sigma_{\ln b}} = 0.0468$.

We also include three spectroscopically determined quadruply-lensed quasars, and their plots determined by our program. As seen in the plot, the hyperbola goes through all four image positions, along with the source and galaxy positions. In minimizing the scatter, you determine a source position and axis ratio, which in turn determines the ellipse. For the specific case of the singular isothermal elliptical potential, this ellipse will map through the four points; however, since the potential is only a model, this ellipse will not go perfectly through all four images for real systems, but the deviation from the image positions and the ellipse gives a visual for the scatter.

Two systems above caused trouble for our program: HE0230-2130 and PS0630-1201; the former having the largest scatter, and the latter having a galaxy position that lies outside the ellipse. Both of these systems have two lensing galaxies, so their potentials deviate from the elliptical model more so than systems with one lensing galaxy, which might explain their issues.

| System | Figure of Merit: $\sigma_{\ln b}$ | Axis Ratio |
|---|---|---|
| GRAL1131-4419 | 0.002 | 0.901 |
| SDSSJ1138+0314 | 0.004 | 0.818 |
| ATLAS0259-1635 | 0.009 | 0.892 |
| HE0435-1223 | 0.010 | 0.861 |
| HE1113-06412 | 0.015 | 0.924 |
| PSJ0147+4630 | 0.015 | 0.711 |
| RXJ1131-1231 | 0.016 | 0.746 |
| HS0810+2554 | 0.018 | 0.896 |
| WGD2100-4452 | 0.019 | 0.853 |
| Q2237+030 | 0.020 | 0.876 |
| SDSSJ1251+2935 | 0.027 | 0.769 |
| WGD2038-4008 | 0.033 | 0.771 |
| WFI2026-4536 | 0.036 | 0.765 |
| MG0414+0534* | 0.038 | 0.658 |
| DESJ0408-5354* | 0.041 | 0.818 |
| DESJ0924+0219 | 0.044 | 0.910 |
| RXJ0911+0551* | 0.045 | 0.563 |
| B0712+472 | 0.049 | 0.883 |
| 2M1310-1714 | 0.051 | 0.953 |
| WG0214-2105 | 0.052 | 0.782 |
| PG1115+080 | 0.053 | 0.769 |
| WISE2344-3056 | 0.070 | 0.862 |
| 2M1134-2103 | 0.071 | 0.491 |
| PS0630-1201* | 0.082 | 0.401 |
| SDSSJ1330+1810 | 0.091 | 0.991 |
| SDSSJ1330-0148 | 0.091 | 0.991 |
| WFI2033-4723* | 0.118 | 0.906 |
| H1413+117 | 0.123 | 0.801 |
| DESJ0405-385 | 0.130 | 0.944 |
| HE0230-2130* | 0.220 | 0.707 |

**Table 1:** *List of thirty known quadruples, with their associated figures of merit and axis ratios. * denotes a two-lens system.*

There is a natural physical limit q > 0.5 to the singular isothermal elliptical potential as an edge-on infinitely flat galaxy with a flat rotation curve produces equipotentials with q = 0.5 (Monet, Schechter, and Richstone, 1981). Thus the models for systems with $q \leq 0.5$ are very suspect. The axis ratio q = 0.49 derived for 2M1134-2103 argues against our model. (Lucey et al., 2018) find that the system is better modeled as a singular isothermal sphere with external shear $\gamma = 0.34$, among the highest known for quadruply lensed quasars.

As Witt mentioned, there is ambiguity in determining the orientation of the system. The correct orientation has the asymptotes of the hyperbola aligned with the axes, but there are two unique orientations with that property. In Appendix C, we sort out this issue.

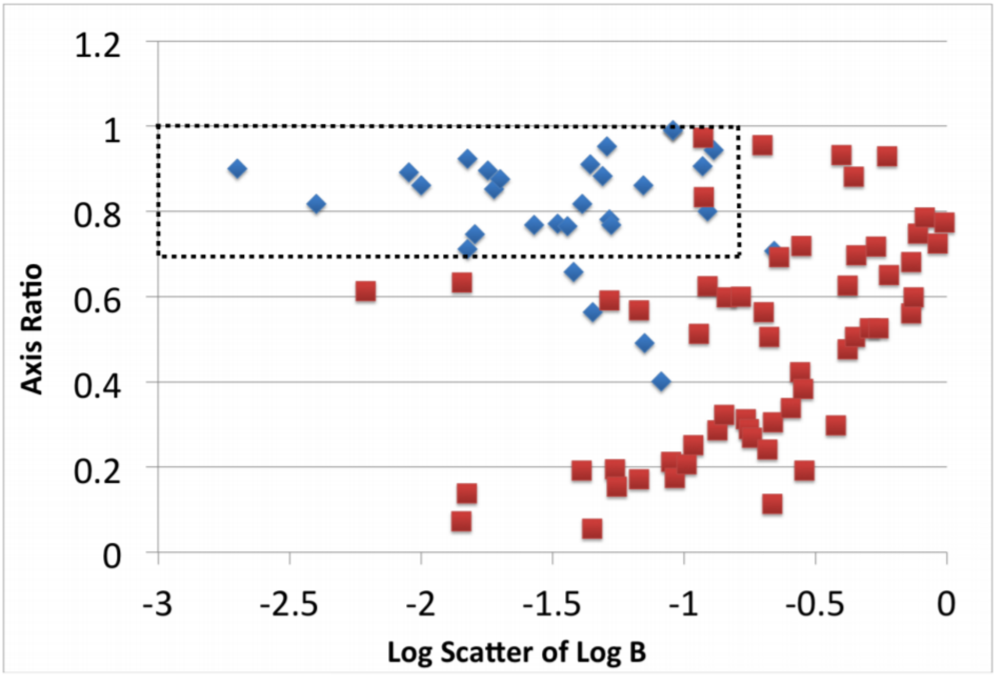


**Figure 4:** *Scatter plot of the logarithm of the figure of merit vs the axis ratio. Thirty known lenses are in blue, and fifty-six random quartets are in red. The dashed box catches 25 of the 30 known lenses, as well as 2 of the random quartets.*

## 5 Random Quartets

To see how well our figure of merit discriminated between genuine lenses and random quartets, we generated 100 random quartets within the unit circle and applied our program to them. We rejected the cases that had three or more images on one branch of the hyperbola.

In Figure 4, we plot the logarithm of the scatter versus the axis ratio for our known system and random quartets that passed our criteria above. We hoped for more separation between the real and random quartets, but every model has it's downsides. The dashed box catches 25 of the 30 known lenses, as well as 2 of the 100 random quartets. So roughly, our model has a 2% false positive rate. Two percent of 80,000, which is roughly the number of quartets identified by (Delchambre et al., 2018), is 1,600; in other words, a lot of eyeballing is still required.

The systems that lie below the box include RXJ0911+0551 and 2M1134-2103 for which external shear rather than the ellipticity of the lens is thought to dominate the quadrupole term in the potential. MG0414+0534 and PS0630-1201, also below the box, are systems for which a second lensing galaxy contributes significantly to the potential. HE0230-2130, another double lens, lies to the right of the box. While it's a shame to lose these systems, they are all pretty different from our adopted model.

It is clear from the comparison of our lensed systems and our random quartets that positions alone do not permit perfect discrimination between the two. If this discrimination does not suffice for some particular task, there is additional information that might be brought to bear on improving it – the relative fluxes of the four images.

In the absence of micro-lensing, the relative fluxes that our model parameters predict for the four images can be obtained from the distortion equation. These cannot be used directly, because micro-lensing is expected to be universal in quadruply lensed quasars (Witt, Mao, and Schechter, 1995). (Yahalomi, Schechter, and Wambsganss, 2017) have shown how one might take micro-lensing into account in assessing the likelihood that observed flux ratios are consistent with the lens model and microlensing. One would then still need to decide how to combine the present astrometric discrimination and the photometric figure of merit.

## 6 Conclusion

We discussed the basics of gravitational lensing, and the phenomenon of quadruple lenses. We then developed a method for modeling quadruply lensed quasars through the use of Witt's hyperbola and the complementary ellipse, as well as assigning a figure of merit to potential systems. We applied this method to 30 known quadruply lensed systems and 100 random quartets, and included their figures of merit. For future systems, this figure of merit can help astronomers determine if a newly discovered system is the product of gravitational lensing, or merely a random configuration.

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## Appendix A

In this appendix, we show how to determine the galaxy position from the source position and axis ratio. Using the direction of the lens equation, Witt derived equation (4). This equation gives us a right hyperbola mapping through the four images, the source, and the galaxy positions. Essentially, this hyperbola gives us the possible locations for image positions given the configuration of the system. For simplification, moving the y-terms to the left and x-terms to the right, one recovers

$$\frac{(y-y_s)}{(y-y_g)} = q^{-2}\frac{(x-x_s)}{(x-x_g)} \tag{10}$$

In the coincident coordinate system, the y-coordinate is given by $W^2/x$, so as x goes to zero, the left hand side approaches unity while the right hand side approaches $q^{-2}\frac{x_s}{x_g}$. Therefore, for perfect source position and axis ratio, the x-coordinate of the galaxy position is given by

$$x_g = \frac{x_s}{q^2}, \tag{11}$$

and since the galaxy also lies on the hyperbola, the y-coordinate is immediately determined.

## Appendix B

In the coincident coordinate system, the branches of the hyperbola are separated by the x and y axes. The question arises as to which branch the galaxy and source will lie on. To determine this, we minimize the scatter, subject to the constraint that the source lies within the image configuration, on both branches of the hyperbola. The branch that the source which minimizes the scatter lies on is determined to be the correct branch.

## Appendix C

The hyperbola gives us two unique orientations for the system. However, the ellipse determines which of these systems is correct. Looking at equation (8), it is easy to see that coefficient for $y^2$ is simply $q^2$. Thus, determining the equation for the ellipse using the four image positions determines the axis ratio. Therefore, if q>1, you know you are in the wrong orientation. If you happen to be in the orientation where q>1, rotating by $\frac{\pi}{2}$ gets you into the correct orientation.

However, since the ellipse determined by the image positions is only accurate for near-perfect systems, it might not give the orientation which minimizes scatter. Therefore, we use our method for four possible orientations: observed, rotated by +/- $\frac{\pi}{2}$, and rotated by $\pi$. The orientation which gives the smallest scatter is determined to be the correct orientation. We then rotate the found source and galaxy positions back into the observed frame, if need be.


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