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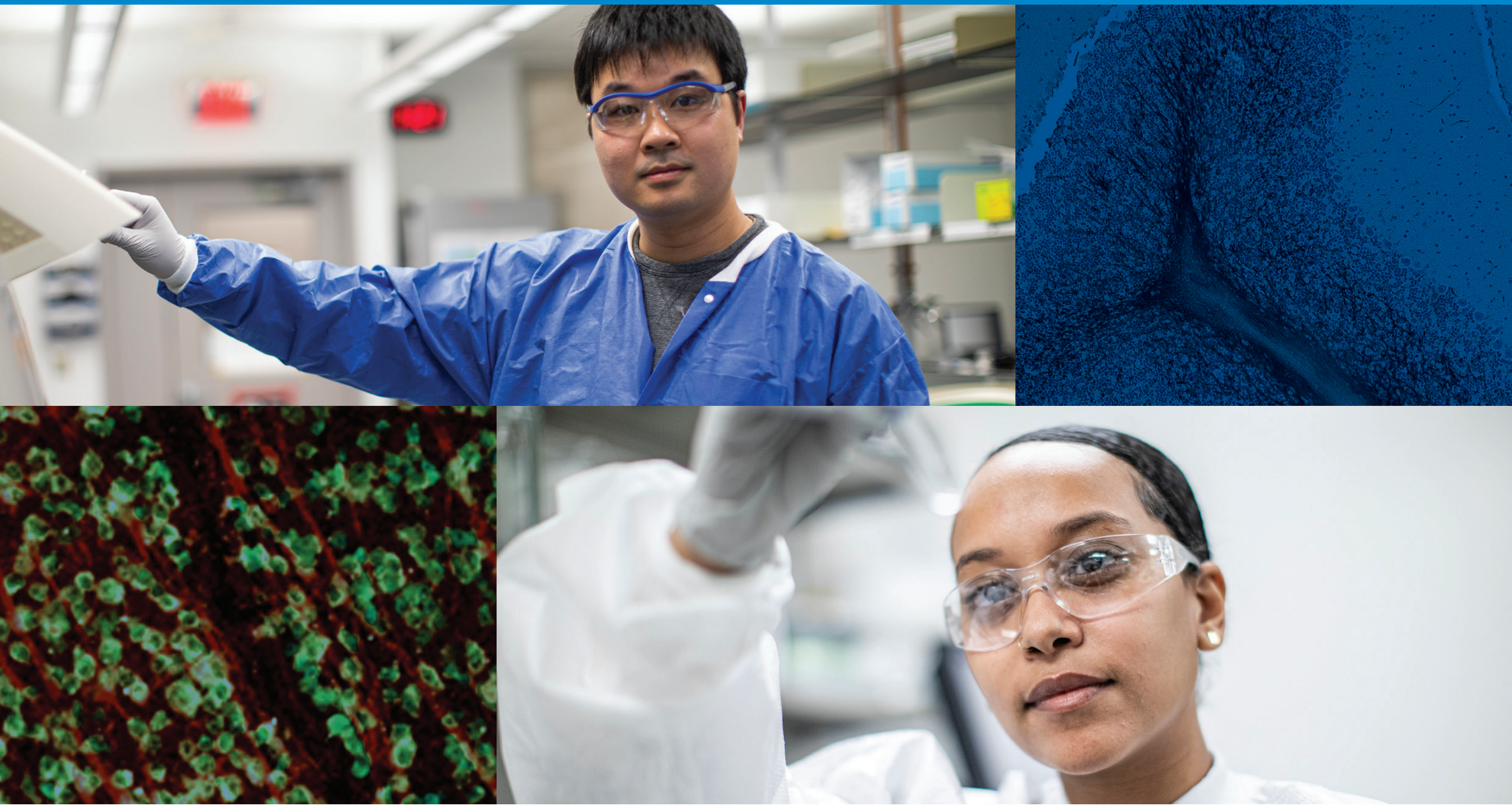

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Massachusetts Institute of Technology

December 2023

Dear MIT Community,

We are incredibly excited to share the 46th issue of the MIT Undergraduate Research Journal (MURJ). MURJ is a biannual, student-led publication featuring innovative undergraduate research at MIT. In this issue, we are proud to spotlight the research and contributions of students at MIT, which are the product of curiosity, resilience, and a commitment to contributing to their communities.

Research in this issue tackles problems across engineering, delving into the fields of plant biology and mechanical engineering. For instance, work on building an economical autonomous surface vehicle with applications in underwater exploration highlights students' creativity and drive to engineer accessible solutions. Investigation of proteins involved in seed development fuel knowledge in plant engineering. This work, with key applications to the sciences, is especially significant in the context of climate change.

We are also honored to showcase perspectives of faculty across the sciences, including nuclear science and physics. A dive of sustainability research at MIT reveals the diverse approaches researchers have taken in the energy and infrastructure space – creating fusion power as a reliable energy source and studying city resilience in response to natural disasters. As we look to the future, the importance of harnessing artificial intelligence, responsibly, is paramount. MIT Physics professors provide an assessment of the role of artificial intelligence in modern physics research. The investigations featured here, at the intersection of science and engineering, are indicative of a multidisciplinary space rich in innovative promise.

I would like to acknowledge the contributions of the authors and interviewees in this issue. The publication of MURJ would not have been possible without the effort of research, content, and layout staff. We hope our 46th issue and the work of its contributors is stimulating and inspiring.

Best wishes,

Anusha Puri
Editor-in-Chief

MURJ News

CANCER AND MOLECULAR ENGINEERING

Do bacteria hold the key to cancer therapy?

MIT researchers re-engineered a toxin-delivery system found in bacteria to kill human cancer cells with "efficiencies approaching 100%."

By Karie Shen

MIT researchers re-engineered a toxin-delivery system found in bacteria to kill human cancer cells with "efficiencies approaching 100%."

A cancer patient enters the chemotherapy room with both faith and fear. Chemotherapy drugs seep through the body, destroying not only cancer cells but also healthy cells that grow and divide quickly. So while the cancer is being treated, the patient will develop mouth sores, lose hair follicles, and suffer from bowel issues. Chemotherapy drugs are ruthless chemicals, lethal to both cancerous cells and healthy cells.

Researchers aim to create more targeted cancer treatments, in which toxic drugs are delivered only to cancer cells. This requires two things: (1) distinguishing healthy cells from cancer cells, and (2) effectively delivering toxins into the target cell. In work[1] published in March 2023, a team in MIT Professor Feng Zhang's laboratory reported that they had established a promising method to achieve this, using a syringe-like delivery system found in bacteria, known as the extracellular contractile injection system.

"The AI revolution is 'coming to the world of molecules.' 'We are in the middle of it right now."

The work was led by MIT graduate student Joseph Kreitz[2], who connected his background in these bacterial injection systems to Zhang's broad research interest in targeted delivery methods. The group focused on bacteria that depend on insects as host organisms, and use injection systems to deliver a variety of compounds to the insect's cells. The team wondered if they could re-engineer a type of bacterial injection system called PVCs (Photorhabdus virulence cassettes) to deliver compounds to human cells.

PVCs function like miniature syringes. They have long, tube-like bodies that carry compounds for delivery, and tail-like receptors that help the PVC to recognize and latch onto target cells. Then, PVCs drive a spike into the cell and inject their cargo. This provides a direct tunnel for compounds to get past the cell membrane, which ordinarily would not allow them into the cell.

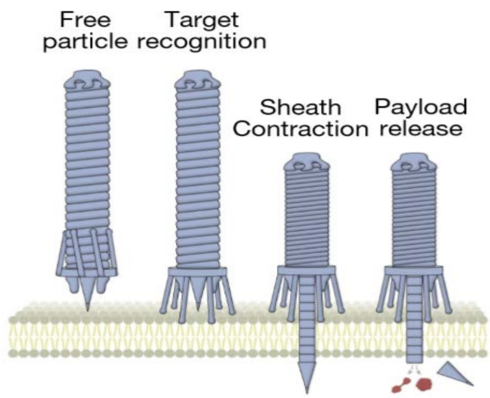

Figure 1b from the paper. PVCs recognize target cells using tail fibers and bind to the cells. They drive a spike through the cell membrane and deliver the protein payload into the cell.

According to Kreitz, when the team reprogrammed the receptors to target cancerous human cells in a dish, the PVCs left the healthy cells untouched, while almost 100% of the cancerous cells were killed. Kreitz emphasizes that "the absence of 'off-target' activity in a delivery system is very important in the treatment of many different diseases, particularly in the brain," where there is a diverse collection of different cell types. This specificity is one of the many superpowers of PVCs.

The research also marked an application of artificial intelligence to molecular design. The AI program AlphaFold predicts protein structures, and the team used it to study how the receptor tails of PVCs recognize their targets, as well as design new receptors for targeting cancerous human cells and mouse neurons. Without AlphaFold, this process would have taken many months, Kreitz explains, because the team would have needed to construct and test receptors empirically. But with the software, they could design candidates "almost in real-time," using AlphaFold to predict the 3D structures of natural PVCs that make initial contact with

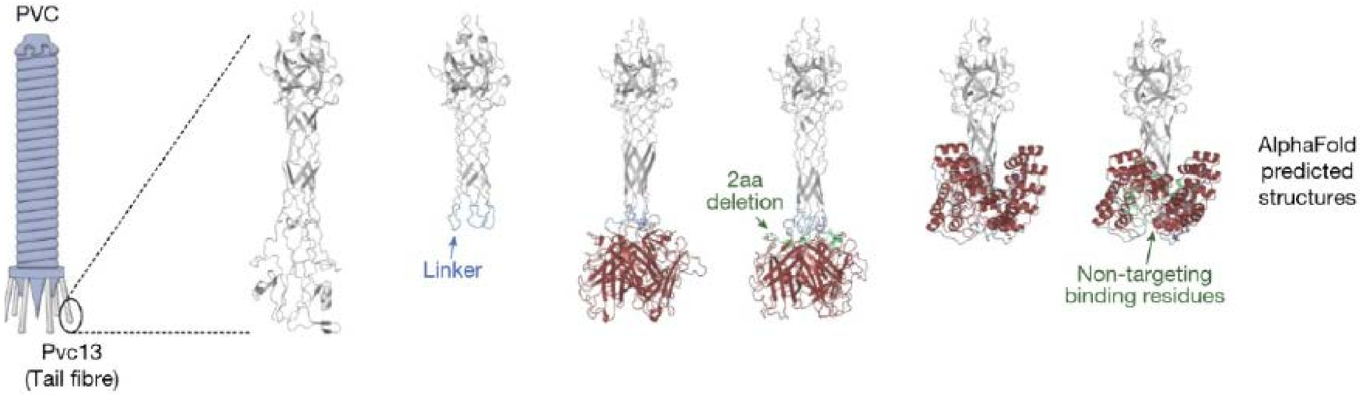

Figure 2a from the paper. AlphaFold predicted the 3D structures of the tail fiber proteins of natural PVCs as well as novel designs for human/mouse use.

target cells based on amino acid sequences, and engineering new binding structures. In an interview with MIT's Industrial Liaison Program, Professor Bradley L. Pentelute[3], who was not involved in the study, maintains that the AI revolution is "coming to the world of molecules." "We are in the middle of it right now," he says. "The future is really exciting."

Dr. Mirco Friedrich[4], a physician-scientist with a background in brain tumors, then joined the study to test whether PVCs could be used in a living organism, testing them in mouse brains. Cells in the brain are packed closely together, so chemotherapy causes substantial neuron death and even epileptic seizures. The PVCs were an effective solution – killing over 60% of the cells targeted. While this is not as effective as targeting cells in a dish, considering the mouse immune system working to clear foreign PVC particles and the sheer number of cells in the brain compared to the dosage administered, Friedrich says that this level of targeting is "something you can rarely reach with any delivery vehicle right now." He was excited "to achieve very specific targeting of only one cell type while sparing the others."

This experiment was only a proof of concept, as the team tested PVCs on healthy mice, specifically targeting neurons while avoiding other cell types such as microglia, the immune cells of the brain. A potential follow-up to the study would be targeting cancerous brain cells in a mouse while sparing healthy cells. This would be very powerful if successful, Friedrich asserted.

Another strength of PVCs is their ability to deliver proteins without involving DNA or RNA. Friedrich explains that certain DNA- and RNA-based therapies already in clinical trials are difficult to control. These therapies integrate viral DNA into human DNA, which is then used as the blueprint to create the desired proteins in the body. This process carries an "inherent risk" of causing harmful mutations, as the integration process is not well-controlled. PVCs, on the other hand, do not carry any DNA or RNA. The result is better control of dosage, side effects, and the length of time the drug remains in the body.

While Kreitz and the team aim to apply PVCs to the treatment of human disease in the future, he says the technology is in its infancy and will require extensive tests to ensure they are safe and effective in humans.

PVCs are an example of how a system found in nature – in this case, bacteria – can be repurposed for therapeutic use. Pentelute agrees in the interview, explaining that a large part of his research "has always been to look at nature." By understanding how nature accomplishes its tasks, researchers can engineer similar solutions for human goals. With the use of PVCs, cancer patients may not have to suffer the double-edged sword that is chemotherapy.

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Better Health, Brighter Future

Takeda is a global, R&D-driven biopharmaceutical company committed to discovering and delivering life-transforming treatments and vaccines that have a lasting impact on society.

Since our founding in 1781 in a market stall in Osaka, Japan, our values endure by putting patient needs first, building trust with society, strengthening our reputation, and developing the business - in that order.

BIOTECHNOLOGY

Biotech Company Spotlight: Kronos Bio

Kronos Bio is a small clinical stage biopharmaceutical company based in San Mateo, California, with research based in Cambridge, Massachusetts.

By Michael Samuel

Kronos Bio is a small clinical stage biopharmaceutical company based in San Mateo, California, with research based in Cambridge, Massachusetts. They specifically target transcription processes, "one of the main things that goes wrong in all of human disease," and especially so in cancer, which is caused by mistakes in the transcription of the genome, causing unregulated cell growth. Transcription is the process by which DNA is converted to RNA for translation, and it is regulated by proteins called transcription factors (TFs). TFs are the only proteins that can "directly bind to and recognize specific sequences on our DNA," and there are around 1500 in total.[1]

Gaining understanding of the functions and capabilities of TFs is crucial for future progress in this area of medicine. Compared to many proteins in the body, TFs are a little strange: they have no enzymatic activity, and they act in cooperation with external cues to control expression of genetic material. This makes attempts to isolate TFs for examination much less relevant to and informative of mechanisms of physiological function. On top of this, even AlphaFold, a deep learning application created by Google's parent company, Alphabet, currently has little success in correctly predicting the folded structure of TFs, Kronos Bio Senior Vice President and MIT Ph.D. Charles Lin pointed out. Because of these and other challenges, TFs are notorious in the pharmaceutical world for being difficult drug targets.

Part of the company's current work focuses on CD79, a molecule that encourages expression of certain oncogenes, or genes with potential to cause cancer. They are currently investigating KB-0742, which inhibits CD79 highly selectively, potentially decreasing expression of oncogenes. KB-0742 also has a long half-life, allowing for a low initial dose, allowing patients to avoid possible toxicity. Right now, the study is in the first stage ("escalation") of the safety testing, where they administer the drug to patients with cancer and observe efficacy and/or adverse effects, cautiously progressing to higher doses. When they pass this stage, they will move on to the second stage, where they enroll more participants who have the specific cancer(s) in which CD79 is thought to play a role. Preliminary trials suggest that the drug is safe, and the expected result was found in the few target participants in the trial. Further data is necessary to determine the efficacy and safety of KB-0742, but the few current results seem promising.

This research is motivated by the desire to use scientific findings to fulfill unmet need– in the words of Chief Scientific Officer Christopher Dinsmore, "If we don't know who we're trying to [help] and why it's going to work, it ends right there…" Deep knowledge of a field helps in generating more "relevant" hypotheses and being more uniquely poised to generate novel solutions from that field's vantage point. Dr. Lin stated that some of the focus of this research is by virtue of the size of the company and the field– biotech itself is a small field, and companies often need to focus on a pathway or problem solving approach. A good example of this is KB-0742: it "finds an intersection of high unmet need and transcription factor biology," creating a highly specific and important area to work in.

"If we don't know who we're trying to [help] and why it's going to work, it ends right there..."

For Kronos Bio, the best approach to complex problems such as cancer transcription factor activity is one of integrated systems biology, which requires a workforce with diverse skill sets and educational backgrounds. In Dr. Lin's words, "drug discovery is becoming a systems problem," which requires more and more interdisciplinary connections, from machine learning to medicinal chemistry. This type of research is aided by the general culture in biotech work, which Senior Scientist Emily Cohen, Ph.D., one of the panelists, described as "driven" and more "collaborative" than academic research.

Part of this is also due to increasing appreciation for interdisciplinary work– "This wouldn't have been possible 10 years ago," Dr. Lin said. This interdisciplinary aspect of biotech creates many avenues of entry into the field. Thus, interested undergraduates aren't required to major in biotechnology or course 20 and plan to go into biotech from their first year– in fact, some of the panelists didn't know they would be going into biotech until they were well into graduate school. The most important thing is passion about biology, physiology and pathology, and passion for the search for truth; with these, one has the opportunity to advance humanity's understanding of some of the most complex and critical systems.

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MURJ Features

Exploring the Role of Artificial Intelligence in Modern Physics Research

Featuring MIT Professors Andrew Vanderburg, Philip Harris, and Phiala Shanahan

By Charlotte Myers

Science and technology have always existed in a delicate symbiosis. While science is often understood as the fuel for technological advancements, the reverse is equally critical: improvements in technology are necessary to catalyze advancements in scientific research.

This dependence on technology is perhaps no more apparent than in physics research- a field which focuses on scales far beyond human perception, from the smallest subatomic particle to the vast expanse of the cosmos, making advanced technology indispensable in collecting and interpreting our observations. From digital cameras to computers to particle accelerators, the impact of technological advancements on physics research of the past is undeniable- but rarely do we have the chance to directly observe a profound technological shift in action.

The rise of artificial intelligence presents such an opportunity. As AI continues to spread across countless industries, physicists have also begun leveraging the power of AI to support their scientific work, a process which, though still in its infancy, has already shown immense potential to revolutionize the landscape of physics research.

One emerging use of artificial intelligence in physics research is to more efficiently process experimental data. A prime example of this application is the work of Dr. Andrew Vanderburg, Assistant Professor of Physics, who uses AI to search for exoplanets – planets beyond our local solar system. The process of identifying these exoplanets involves searching for dips in the brightness of stars over time, which could indicate the presence of a planet that temporarily blocks some of the light. But these dips in brightness could also arise from a number of other causes, from star spots to detector glitches to shielding from other stars. These sources must be separated from genuine exoplanet candidates - a process that has traditionally relied on tedious sorting by eye. But through the use of AI, Dr. Vanderburg's research group has been pushing to develop automated procedures that allow exoplanets to be identified much faster and much more efficiently.

Dr. Philip Harris, Associate Professor of Physics, is also using AI to propel new breakthroughs in experimental particle physics. In Dr. Harris' work at the Large Hadron Collider, he studies complex collisions that involve hundreds or even thousands of particles, with each collision producing an amount of data equal to 1000 times the size of the world wide web per year (Harris). This amount of information is beyond our ability to imagine – and certainly beyond our ability to store. To address this issue, Dr. Harris has pioneered the use of real-time processing: rather than saving and processing the data at a later time, the AI algorithms he has designed "can look at the event topologies and in 10 microseconds decide if it's interesting enough to store" (Harris). This technique has facilitated the study of more complex particle collisions, helping to build a more robust understanding of the structure of matter.

But AI is not restricted to the domain of the experimentalists- it also can be applied to fuel new advancements in theoretical physics, as highlighted by the work of Dr. Phiala Shanahan, Associate Professor of Physics and a Research Coordinator in the AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI). Dr. Shanahan's work is focused on understanding the fundamental structure and interactions of matter through the Standard Model - a model that, despite its apparently simple structure consisting of only 17 fundamental particles and interactions, is described by highly complex equations that are "intractably hard to solve with pen and paper" (Shanahan). Solving these equations is so computationally intensive that 10% of open science supercomputing in the US is dedicated to solving them- meaning advances in computational efficiency are inseparably tied to progress in this field (Shanahan). AI represents a profound advancement in this efficiency, which Dr. Shanahan leverages by using AI as "a computational tool to make solving these equations faster in a provably exact way." This is an entirely different realm from the experimental applications of AI. As Dr. Shanahan explains, there are "no biases, no systematic uncertainties, no black box, no training data; we have mathematical guarantees of exactness alongside faster algorithms."

"If a human makes a mistake, it's hard to know when that happens… but a machine learning program that does it very easily could. "

The diversity of applications of AI to physics is remarkable, but similar themes emerge in the benefit of these applications, most notably: speed. In Harris' work, he has seen "the same measurements being done with a quarter of the people" as compared to traditional methods, as "the use of deep learning algorithms can kind of replace what we were doing by hand fastidiously 10 years ago" - resulting in a remarkable acceleration of progress. In the experimental realm, this increase in speed is necessary to respond to the immense increase in the scale of data collected in modern research. "Digital cameras are getting so much bigger, and the amount of data is getting so much larger that we're going to have to use machine learning to even know what to look at, because there's just so much," as Dr. Vanderburg explains.

This increase in speed is especially revolutionary in theoretical physics- a realm where speed is inextricably connected with feasibility. The types of computations required for Dr. Shanahan's work could take tens of thousands of years on the world's largest supercomputers, making traditional methods not just inefficient, but functionally impossible. This positions AI not merely a tool to increase speed, but as an unprecedented opportunity to explore new frontiers in theoretical physics- frontiers that would otherwise be inaccessible.

Speed is often believed to have an inverse relationship with quality- but does this principle also apply to the effects of AI? As any user of ChatGPT can attest, AI may be just as prone to mistakes as the humans who design it- but there is a key difference between the mistakes of humans and AI: characterizability. As Dr. Vanderburg explains: "If a human makes a mistake, it's hard to know when that happens… but a machine learning program that does it very easily could. We can create a bunch of fake planets and show them to the machine learning program, and figure out the fraction of the time the machine learning program makes a mistake," allowing the results to be adjusted accordingly to account for these mistakes. So while AI is undeniably imperfect, its imperfections can be quantified and characterized in a way that could improve reliability.

As in all great symbioses, the benefits do not flow strictly one way. Rather, the application of physics to AI has revealed that physics can be a profound asset to AI itself. To power the real-time processing at the core of his research, Dr. Harris needed ultra fast AI algorithms, but a problem quickly emerged: algorithms of this kind were a largely unexplored realm in computer science. So rather than wait for computer science to catch up, Dr. Harris' team pioneered microsecond time scale AI algorithms, developing a toolkit which now has applications across a variety of fields. "I hope that the insight and the kind of problems that we're dealing with in physics can actually help to bring new ideas to head in the AI community to propel things further," as Dr. Harris remarks. The importance of this reciprocal relationship between physics and AI is also echoed by Dr. Shanhan, who has collaborated with Google DeepMind to develop new machine learning methods for a particular application in theoretical physics- a collaboration which helped propel both her research and industry applications of AI forward.

With every technological shift comes a unique set of challenges that must be adapted to, and AI is no exception to this rule. Many of the same issues that plague AI in other fields affect its application to physics research. For instance, Dr. Harris describes machine learning bias as a major problem in his research, as AI is "intrinsically biased based on the data you give it," meaning that the data used to train the AI will have a profound effect on the results that it generates. As Dr. Harris states: "When I started putting in some of the more advanced machine learning algorithms immediately, I found that it was just giving me these biased answers left and right, particularly if you're trying to do things like mass measurements or looking for resonances."

Dr. Vanderburg also faces the issue of machine learning bias in his research on exoplanets. "One of the challenges that we face is we're trying to answer questions with AI that we don't actually know the answers to all that well to begin with, so can we train this to detect planets better than a human can? I think the answer is no, because how can it learn to be better than a human if it's learning from us? If we're biased, it's going to learn our biases."

This issue is especially impactful in astronomy "because we very rarely have ground truths," as Dr. Vanderburg explains. "We cannot go to another planet at the moment and figure out what's actually going on. So that's a big challenge, figuring out: what actually should we feed into our program? What actually are the truth values?" In other words, the scope of AI is inherently restricted by the limitations of the humans who create it – an issue that may not have an ultimate solution, and will likely always be a "constant worry that we have when dealing with AI" (Harris).

Another major challenge with AI is explainability- a problem that emerges when AI is designed as a black box, shielding the internal processes and operations used to arrive at the results it generates. This is one area in which humans maintain the upper hand; as Dr. Vanderburg describes: "If I were to say, I think this is a planet, this dip in light, I could explain to you why, but it's really hard for AI algorithms to do that." The push towards greater explainability in AI will likely be a major step forward in its application to research, as with greater transparency comes higher confidence in results generated through AI.

But research does not exist in a vacuum; as important as the actual results of research is how these results are understood by the scientific community and the general public- a fact which also raises unique challenges in the application of AI to research. As Dr. Shanahan explains, one of the primary challenges she has faced in applying AI has been overcoming people's natural reaction of skepticism towards the results generated through the use of AI. Because her use of AI is so distinct from the typical applications in experimental physics- applications which are often plagued by biases and uncertainty- she has encountered frequent misunderstandings about the certainty of her results.

But in contrast to applications in data-driven areas, Dr. Shanahan emphasizes that the AI she deals with is "a rigorous mathematical construction that has been optimized in a precisely-defined way. There's nothing ill-defined about it, and no sources of error in our application." Understanding the diversity of the applications of AI to physics research, particularly the differences between experiment and theory, will be critical to breaking down misconceptions that act as obstacles to greater progress.

This same lack of trust also affects the application of AI to experimental physics. In dealing with the skeptics, Dr. Harris recommends that "we have to remind them that deep learning and the concepts that we're using in deep learning are really not new. They're all based on statistical tools that we've been developing over the last 100 years." But regardless of its track record, maintaining a healthy degree of public skepticism about the results generated through AI is critical. "I think it is really dangerous if we start, as a general public, believing that these things are accurate all the time," as Dr. Vanderburg warns. This skepticism is echoed by Dr. Harris: "there are a lot of people who are very quick to use it as a black box and they don't care what it's doing, so I think it's important to build in lots of checks." Maintaining this delicate balance between skepticism and trust will be essential to build a productive relationship with AI, one which supports the unprecedented potential that AI can yield without compromising the integrity that scientific progress relies on.

Regardless of its challenges, AI undeniably has the potential to transform the landscape of physics research. The question remains: what will be the role of the physicist in this new landscape? Is there truth to the growing moral panic over AI 'replacing' the role of humans? The answer, fortunately for us aspiring physicists, appears to be no. The foundation of experimental physics is data - data which AI can filter, process, and extrapolate from, but (at least for now), cannot collect. "AI is not going to learn the explanation for dark matter," as Dr. Harris explains. "It will be able to model everything given our knowledge of physics super precisely- more precisely than we can now. But it can't a priori simulate dark matter interactions unless you give it a model for how dark matter is interacting. So ultimately, we're never going to be able to replace actual, real world data."

In fact, rather than diminishing the role of humans in physics research, AI is re-centering the features that uniquely define us as humans, most notably: creativity. According to Dr. Vanderburg, AI is likely "not going to replace us, it's just going to mean that we spend less time doing the boring stuff and more time spending doing the hard stuff- the creative stuff that only humans can do." This sentiment is echoed by Dr. Harris, who emphasizes that "there's an infinite amount of research that you can do. And so what I've seen is that AI has just sped up the development of research- it hasn't really replaced people."

While many take an apocalyptic view of the future of AI, its integration into physics inspires an optimistic vision of the future of scientific research, one defined by increased speed and unprecedented possibilities. But like every technological shift, AI is ultimately limited; from bias to explainability to public distrust, the challenges of AI cannot be separated from the limitations of the humans who interact with it. But perhaps these limitations should be regarded with optimism as well. For it is

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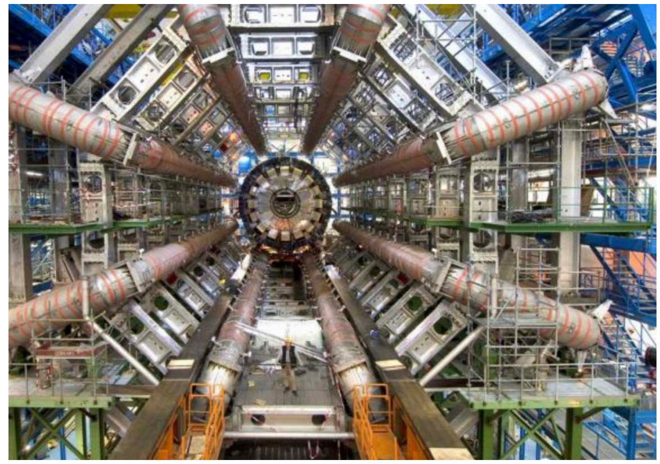

CERN: the source of many advancements in particle physics. CERN. https://timeline.web.cern.ch/worlds-largest-superconducting-magnet-switches

precisely what AI lacks - our human creativity and curiosity- that fuels our quest to understand the cosmos, suggesting our relationship with AI will remain not one of replacement, but collaboration.

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Musical Chronicles: **Preserving Music and Empowering People**

FEATURING DR. JOSEPH MAURER

By Emily Hu

Overture: The Prelude of the Story

Boom! reverberates the ~~timpani~~ *tamborita*, Pluck! rings the strums of the cello *guitar*, and in the background, couples ~~waltzing~~ *zapateando* to the beat of the music. Stomp……click…click…

Such an experience is bound to rival the excitement of any high-class theatrical production. But, as the final chords fade away and the dancers take their finishing bows, it becomes evident that this performance is no ordinary ballet, nor symphony, but an occurrence that if not for the waves of revivalist movements in past decades within both Mexico and the United States, had started to become more infrequent: a social gathering to celebrate the Mexican *Son*.

The Mexican *Son*, or the Mexican "Sound", is a class of folk music derived from both baroque classical music and traditional folk singing[4]. The styles of performance, including instrumentation and themes, vary from region to region, but all subgenres are united in their unique ability to evoke the themes of love and legends as well as impromptu gatherings known as *fandangos*[1].

Presently, we will not focus on the well-studied intricacies that underlie the *Son*'s theoretical background. Nor will the focus be on how the confluence of European musical traditions and folk traditions native to Mexico both birthed and continue to evolve the *Son* tradition. Rather, let us investigate an often under-credited engine driver behind the *Son* revivalism – the incidental involvement participants that are only fortuitously introduced.

They are the immigrant families who established enclaves for their culture outside of their homeland during large waves of immigration to the US, the parents of young children who sought cultural activities more closely aligned with their heritage, and the efforts of musical professionals who worked tirelessly to transform heritage music education into a reality[3].

Specifically, the following trifecta of questions are asked, both in terms of the Mexican *Son* and music revival in general. (1) How does the work of heritage music education seek to empower families and youth, and (2) How does the incidental involvement of families and children in these small-form education programs in turn evolve music and performance tradition? and (3) what are the larger societal implications, both present and future, of promoting heritage and folk music?

To this end, we will turn to a case study of a nonprofit Mexican *Son* Musical School, an organization founded by the performance group Sones de México in the neighborhoods of Chicago to *Son* education of children and their parents. Introducing us to the illustrative role of this education program is Dr. Joseph Maurer, who is a faculty member conducting research at MIT in ethnomusicology, which is the "the study of music in its social and cultural context"[6]. His research interests include heritage music, music revivalism, and nonprofit arts. He completed his dissertation at the University of Chicago studying heritage musical programs, including the Mexican *Son*, and currently instructs 21M.030, Introduction to World Music (which he highly recommends!).

In college, he majored in education policy and later worked as a college counselor for first-generation college-bound students, but through his progressively immersive experiences with folk music and frequent interactions with immigrant children, he realized that non-classical heritage music was not just “something on the side, but a whole world that you can research”[6].

Thus, let us allow ourselves to peel away the curtain of heritage music education and illuminate this world together.

Exposition: Community Empowerment through Music Education

It has been a long-accepted fact of the industry that communities, consisting of vibrant audiences and musical appreciation, hold a vital position in promoting music. The reverse, however, that music education confers direct empowerment to a community, is much less studied, and in truth, more difficultly quantifiable. Despite this elusive link between music education and community empowerment, however, anecdotes gathered by ethnomusicologists such as Dr. Maurer gives testimony to the fact that a connection does indeed exist.

In interviews in the Mexican *Son* Music School, for example, students’ parents expressed that heritage music education served as a gateway to transform “assimilationist attitude” of conforming with the larger Anglo-phone society, and instead allowed for both the parents, and later their families, to embrace their native culture[3]. The consequences here go beyond a personal level. For some parents in the program, such as Erica, the nonprofit model of the Mexican *Son* carried effects that transcended beyond the limits of family. Rather, the heritage education system represents her family’s motivation to actively relocate to ethnic enclaves, to establish inter-generational connections throughout the community, and to reclaim heritage from their homeland[3].

Even for families with a stronger artistic background, the nonprofit model still provided an unique cultural perspective to introduce children to their heritage. Mari Carmen, the mother of a boy involved in the program, noted that the *Son*’s attention to both a bilingual class model and the active engagement of parents within the classroom allow for a “building of the community,” and the participants to have “grown in a different way as well.” While the new heritage network is not a carbon copy of the former one, the new community is molded to embrace both the past and the present. In this case, something that is “so Chicago, and *Mexican Chicago*”[3].

Development: Evolution of Music Performance

From such anecdotal evidence, it becomes undeniable that music itself irreversibly molds the fabric of inter-generational families and multi-heritage communities. But what about the reverse direction – the community’s effect on music?

As becomes apparent, heritage education models often muddle the equilibrium of music performance, serving as part of a trend that seeks to both honor a pure approach of musical performance and irreversibly alter the landscape of music pedagogy and preservation.

To untangle this paradoxical phenomenon, it is important to put things in context of a larger revival, which can be understood here as a movement of a bottom-up approach in which common people, in place of governmental or state actors, seek to re-vitalize a belief or tradition[3,5].

In response to the commercialization of *Son* music, specifically the *Son Jarocho*, many musicians sought to revert to a more traditional way of performing the *Son*, as contrasted with the rising urban innovator trends[2]. It was from this revivalist trend of music preservation that heritage schools across the United States arose, including the previously mentioned Chicago Mexican Music School, were founded.

But here is where the paradox comes in.

As the *Son* in its traditional form is inherently an oral tradition, "when you document and write [the tradition] down and start teaching students out of books, you fundamentally change what the tradition is." Thus, in an effort to honor old traditions, heritage schools are compelled to in the same breadth modify those very same cultural fixtures. In short, "these processes of institutionalization always change the oral tradition into something else"[6].

"Thus, in an effort to honor old traditions, heritage schools are compelled to in the same breadth modify those very same cultural fixtures."

What results is a bidirectional flow of influence from the music to the community, and the community, back to its musical community. What the future holds for this intricate equilibrium, no one is capable of predicting accurately, but one thing is certain – that the involvement of key actors, of families and especially their youth, will forever be requisite.

Recapitulation: Youth Involvement and Lasting Effects

"It's so wonderful. Kids are learning about their culture. That's beautiful."

Such unadulterated praise for heritage education is what is often heralded from newspapers, interviews, and social media. But as Dr. Maurer warns, the picture, as it is often inevitable with any secondary education program, is more complex[3]. What we ought to consider then is the existence of three main categories of reactions from youth involvement in heritage.

First, as propagated by promotional articles, "some kids do get really passionate, and it, [the art form itself] becomes a very big part of their lives." On the counter, there are always youth who do not end up resonating with the activity. And lastly, there is a third reaction, which Dr. Maurer found in his research, whereby "there are kids who don't necessarily get deeply invested in the music as such, but nonetheless, the music program reaches them in a way that maybe other childhood activities don't. Even though they don't continue it, the program has really changed them as a person."[3]

In a sister study to the Mexican *Son* Music School, Dr. Maurer investigated a Korean drumming group located in Chicago, involving an art form that is difficult to engage in through post-secondary life due to the rarity of such groups in the United States. Despite the lack of continuity in pursuing the art form itself post-adolescence, many of the former students who were interviewed affirmed their passion for the activity and how heritage education had changed them. "Many had become more confident, more self-assured in speaking up assertively within groups of people, of not being afraid of other people's perception of them but being able to present themselves to the world".[6]

Thus, beyond the effects of empowering immigrant families and neighborhood enclaves, heritage music's education lasting influence on youth is beautiful – not beautiful in a one-dimensional monolithic way of solely ethnic self-identity, but fascinating in its way to "give many young people room to grow" in so many different ways.[6]

Coda: Future Implications

At the conclusion of our journey into the unfamiliar world of heritage music, two sentiments predominate: first, admiration for the work of our musical predecessors, and secondly, a realization.

A realization of the paramount importance these programs hold for communities.

A realization of the importance of continuing heritage music education for both immigrant and non-immigrant communities.

Even for the rest of us, who may not be actively involved in these programs, stories such as these allow us to realize that heritage music education is, as Dr. Maurer mentions, a "substantive way to engage in musical diversity". The impromptu *Sons* in the dim stage lighting of a ~~fandango~~ school gymnasium, the beats of Korean drums turned beats of passionate young hearts, and people everywhere – regardless of ethnicity or background – connecting to themselves and each other.

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Sustainability Research at MIT: **Looking Into Energy and Infrastructure**

By Gwyneth Tangog

At the Massachusetts Institute of Technology, sustainability is a central part of research and is a passion that many students have going into university. However, there are many projects on campus and labs to choose from, and students can easily be overwhelmed regardless of what year they are in college. To inform students about different labs and UROP opportunities available, we interviewed communications representatives from the MIT Plasma Fusion Science Center (Course 22 - Nuclear Science and Engineering) and the MIT Concrete Sustainability Hub (Course 1 - Civil and Environmental Engineering).

MIT Plasma Fusion Science Center (Course 22 - Nuclear Science and Engineering)

Interviewee: Julianna Mullen, Communications Director

What projects do you have in your lab? Who works on those projects?

220 people work at the MIT Plasma Fusion Science Center (PSFC). There are approximately 110 research projects spread over three main areas. Magnetic Fusion Energy is the main group with a lot of really cool research related to producing fusion energy. Then we also have Plasma Science, which is very important, as plasmas are where fusion reactions occur. Third is [the] Technology Development group, which is focused on developing all the components and tools to create the devices that produce fusion reactions.

What is the ultimate goal (i.e. vision) of the lab?

We are an education and research facility. We have 95 graduate students with us, 23 UROPs, and nine FUSARs (Fusion Undergraduate Research Scholars). As a part of MIT education is really important. We want to train the next generation of fusion scientists and plasma physicists. Many people don't realize just how much research we do. Of the 220 full time employees, about 120 are research scientists and postdocs, and around 40 are technicians. The rest are administrative staff. The ultimate goal is to increase our understanding and create technologies that are going to advance plasma physics and fusion science. The outcome people are really excited about is creating fusion power, which is the ability to not just maintain and sustain a fusion reaction, but to also take that and turn it into a commercial power plant that could, for example, take the place of a coal power plant on the electric grid. Everyone's been excited about fusion for the last 70 years and the joke has always been that it was 30 years away (which more recently had become10 years away). But now, it seems like it actually is 10 years away. There have been some cool breakthroughs recently, and the PSFC has been at the forefront of some really significant ones.

What aims do you have for the near future? What milestones are you looking forward to? Do you have any presentations upcoming or projects the lab is finishing up?

One of our largest private research partners is Commonwealth Fusion Systems which was spun out of the PSFC. The director of the PSFC, Dennis Whyte, is one of the co-founders along with three of his former students and an MIT postdoc. Now, 20% of the research in our portfolio is working with especially on a project called SPARC[1] which is a compact, high-field net energy device that's the proof-of-concept for ARC, a commercial fusion power plant that's scheduled to be done by the early 2030s.

In 2021, the PSFC tested a new kind of fusion magnet that has been in development since 2018. The concept for the magnet was actually first developed in Professor Whyte's fusion design class. The test showed it had a magnetic field of 20 tesla, which made it the world's most powerful fusion magnet. and Now the PSFC and CFS are trying to improve on that, [and] it will likely be a big deal.

One of the other really exciting technologies we're researching is called a "blanket" and it basically wraps around a plasma fusion reaction and catches the neutrons

1 For more information on SPARC, visit https://www.psfc.mit.edu/sparc

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that are being ejected from the reaction. The blanket is usually filled with some kind of molten salt, and the neutron bombardment makes the blanket incredibly hot. That heat can be used to produce steam, which can then be used to drive a turbine and generate electricity just like a regular power plant. So it's another way to derive power from a fusion reaction. We're planning to actually install a laboratory version of the blanket at the PSFC.

Up until 2016 we had a tokamak[2] called Alcator C-Mod at the PSFC (a fusion device). A tokamak looks like a donut that's ringed by many smaller donuts that are electromagnets, and fusion occurs in a plasma generated in the first donut. The electromagnet donuts squash the plasma inside the main donut and keep the plasma in place. C-Mod is being decommissioned right now so we can make room for other fun stuff but the data from C-Mod are still being used by us and a lot of other institutes. We're still learning a lot.

Right now we are also building something called PUFFIN (the PUlser For Fundamental [Plasma Physics] INvestigations)[3], which is a test-stand where researchers can study some of the ways plasmas behave and operate. They get some really cool images of plasma reactions. It's currently in progress and we have a couple of UROPs working on this project. We're hoping that the construction will be finished soon and we can share more details about the work.

We're also doing some really interesting stuff with AI and machine learning to advance fusion science. One of our research scientists, Cristina Rea, recently got a big award from the Department of Energy for this work. It's about applying machine learning to data from fusion reactions, but also about making all the data from these plasma physics and fusion science studies accessible. There are 54 public tokamaks operating all around the world. Many of these tokamaks are collecting data in different formats, some of which are easier to access than others, and so far one type of program can't access all of it. You have to reformat it, change all the metadata. This particular project is working to put it all in one specific kind of system so everyone can use it and have access to it. Some of these tokamaks are really old, but their data is still really valuable and it's still being analyzed because we keep developing stronger and stronger computers. Giving everyone access to the info is really important because the more scientists we have working on a problem, the faster we're going to solve it, right?

"The more scientists we have working on a problem, the faster we're going to solve it, right?"

Do you have UROP opportunities? What do you look for in UROPS? Do you accept first years?

We do accept first year UROPs, and we also have Fusion Undergraduate Research Scholars (FUSARs)[4]. FUSARs is a new program that is like a super UROP. Unlike a UROP, FUSars have a concrete commitment of 10 hours per week. There are more requirements and an extra class that goes along with it– it's "how to do science as a real human being" and it covers topics like "how to talk to people about your work", "how to maintain work-life balance", "how to interface with your advisor and your peers in a healthy way". Another big difference between ROPs and FUSARs is that FUSARs are currently the best paid undergraduate researchers on campus [$31/hour compared to the standard UROP pay of $15.50/hour]. The hope is that students don't have to choose between something that is academically advantageous and something that is going to pay the bills. We don't want students to have to choose.

In terms of qualities we look for in FUSARs and UROPs, the biggest things are consistency, which goes along with time management. I think it's incredible that people sign up for UROPs in their first year. You're just getting your feet under you and it's this massive addition. It's understandable that people burn out. But I think consistency matters, and it's something to think about. Also, if you do burn out, are you ready to talk to your advisor about it? You have to be honest about how you're doing. Other than that, it's just passion. If you're really interested in what you're doing, you can almost always do it. Everything else can be taught. What we're here for is to teach. Come with nothing, leave with something. Some projects do need specific backgrounds or at the very least it's helpful. But we do have first year UROPs and you can start from the floor and go from there. Some of this is about figuring out what you want. Figuring out what you don't want is just as important. I would tell people not to be afraid to try it and not like it as long as you can show up and keep your commitment. We understand that things happen and it can get overwhelming. If you talk to us, we can help fix it.

What is your advice for students who want to pursue research in the future?

I would say that you need to not be afraid to fail. I think you get to MIT and you're used to being the best

2 tokamak - a toroidal apparatus for producing controlled fusion reactions in hot plasma.

3 For more information on PUFFIN, visit https://puffin.mit.edu/

4 For more information on FUSARS, visit https://www.psfc.mit.edu/fusars

in everything, and it can feel devastating to not get the results you're expecting or for the results to be inconclusive which happens so much of the time and is so frustrating. You have to fail. You have to understand that it's not going to go perfectly every time and that's okay. Science is just controlled failure. We have to go through it. Things can be hard sometimes. The last few years have been especially hard. So, being kind to yourself is a big thing. Again, curiosity and passion and willingness to try something will get you so far in life. Just being willing to do something badly then learning to do it better is applicable to every single piece of your life, whether it's research or learning how to crochet. You just have to be okay with not being great at something at first.

The MIT Concrete Sustainability Hub (Course 1 - Civil and Environmental Engineering)

Interviewee: Andrew Laurent, Communications Director

While the MIT Concrete Sustainability Hub (CSHub) is under the department of Civil and Environmental Engineering, projects vary from experimental to literature and data-driven. The MIT CSHub has several categories of projects in their lab including but not limited to carbon neutrality, resilience, workforce, and infrastructure-type work.

What projects do you have in your lab? Who works on those projects?

1. City Resilience[5]

Starting with resilience, Bensu [Ipek Bensu Manav] and Katya [Katerina Boukin] are both PhD candidates and they work with Randy [Randolph Kirchain] and Hessam [Hessam AzariJafari] and CEE professor Franz-Josef Ulm. They are both deeply involved in resilience work and they've both been in the lab for a couple of years.

Bensu does a lot of work with city resilience, which really is a theme of the lab. She looks at Miami-Dade County, which has a lot of exposure to hurricanes and other natural disasters. She looks a lot at how the texture of the city affects the risk a structure has to be damaged. There's a lot of social vulnerability aspects; our lab has a very big social angle too.

Katya takes a similar approach to resilience, taking a look at the layout of the city, but with focus on the flooding angle. She has a bunch of cool simulations of the city of Cambridge and some other cool places we're still working on. She's modeled different severities of flood events and seen which areas get damaged, and which areas have long-term lasting impacts. What's cool with the two of them [Bensu and Katya] is that in terms of student engagement, they have a lot of autonomy and have really defined their own directions for themselves.

2. Fracture Mechanics

Ariel [Ariel Attias] and Athikom [Athikom Wanichkul] work on fracture mechanics of concrete structures. For example, if I have a concrete tower or a concrete slab, and I apply this certain kind of force to it, what happens and how do I learn to deal with that?

3. Carbonation

Marcin [Marcin Hajduczek] has invented a new method of artificial carbonation. What he does is that during the concrete-mixing process, he'll integrate sodium bicarbonate into the mix, sequestering it. There's a lot of potential there. He works with Franz and our newly-promoted research scientist, Damian Stefaniuk.

4. Flood Modeling

Danial [Danial Amini], kind of similar to Katya, he works on flood-modeling, but he's interested in making a scalable not-so-resource-intensive approach to flood-modeling, that way every given decision-maker can have access to these crazy tools. Something we prioritize in all our work is making things open-source, accessible, easy to use. Those are really important to us.[6]

What is the ultimate goal (i.e. vision) of the lab?

We want to help achieve a carbon-neutral concrete industry. The thing that makes it difficult and yet exciting at the same time is that concrete is the second most-consumed material in the world, after water. It's that essential. You might ask, 'What does resilience have to do with that?' or 'What does upgrading our infrastructure have to do with that?'

Concrete in certain applications and with certain tehnological improvements can be a good choice for a lot of scenarios. You might think, 'Concrete, when you build it, has more emissions than using materials like wood.' which is true, it's totally true. But from a resilience angle for example, concrete does a lot better than other materials. And with the way the climate's going, disasters are only

5 The ability of cities and structures to withstand natural disasters and general stresses (economic, environmental, social & institutional).

6 To learn more about the CSHub's current projects and members, visit https://cshub.mit.edu/

going to become more frequent. Aris Papadopoulos from Florida International University (FIU), the former CEO of Titan America, asked me a really good question when I interviewed him, 'It's true that concrete has more upfront emissions, but what is the carbon cost of disaster?'

Let me connect this to my own experience, and Bensu's experience. I grew up in South Florida, and there were so many hurricanes, flooded roads, and destroyed towns. For example, Fort Myers got totally leveled by a hurricane. It just makes sense to me because if you build with only low upfront environmental cost material, and they get destroyed, it's like you never had those things. And you have to keep rebuilding and rebuilding and then, eventually, you've emitted more carbon than you would have if you built sustainability in the first place. That's the driving purpose of the lab. Everything connects back to carbon emissions.

"Communication has always been a part of science."

What aims do you have for the near future? What milestones are you looking forward to? Do you have any presentations upcoming or projects the lab is finishing up?

Every semester, we invite all of our industry partners to campus and we call it the 'Advisory Meeting'. One of the purposes of this event is to get students to connect directly to people in the industry. We could just get feedback on our current work from industry, but that's not the whole story. Part of the Advisory Meeting is a poster session. We're going to have about 16 posters and about that many students coming to present them. Unlike in a research conference where your primary audience is other researchers, our students will be interacting with all industry stakeholders. The reason that that is cool is that they get to work on something else the lab is very interested in, which is communicating with non-technical audiences. That is a very big thing for us.

You may ask, 'Why does a lab have a communications guy?' and the answer is that something really important to research entities that they don't often consider— these crazy cool messages that we often work on, these things around topics like flood resilience— it can be hard to communicate that from a really high technical level to a lay audience. I recently did an article in MIT news about the importance of graphics in research communications. I talked to Miaomiao Zhang, and she told me something very interesting: 'Just doing the work of research, writing papers, getting results, performing different analyses is only half the story. The other half of research is communication.' When you go back to early science, when people were just sending letters around, that's really the foundation of what we're doing. Communication has always been a part of science.

Do you have UROP opportunities? What do you look for in UROPS? Do you accept first years?

"UROPs are super critical in terms of what we do beause they bring in all these skills and perspectives we don't possess. For me and for the CSHub in general, I don't think the college year matters as opposed to the skills you bring to the table.

For instance, my UROP student, Esther Song. I put up this really unconventional UROP opportunity: a Science Communications UROP which is so different from a typical UROP. What really stood out to me about her application was that she brought all these practical skills to the table. She has her own YouTube Channel and is a really strong video editor. She also had a bunch of experience doing literature reviews and things like that. As time goes on and technology advances, as you've seen with ChatGPT, what's not so important is that you have skills directly related to your position. She didn't have any experience in Concrete Science but to be honest with you, neither did I. What's important is her approach to things and the way she thinks about them.

Here at the CSHub, we choose UROPs because we're impressed by the way they think. We know that for undergrad and graduate students, it has to be a learning opportunity. That's what a UROP is by default, because otherwise, what's the point? Personally, I focus on having my UROP focus on learning new skills. For example, I'm having her learn a little bit of web administration, social media, and more. I try to provide experiences I would have liked as an undergrad so I can set her up long-term.

Specifically for the CSHub, a data science background often helps. I know a lot of our UROPs have experience in things like R, Python, signal processing, things like that. That's one technical skill that can definitely be an asset at the start but I won't say that it's a requirement.

What is your advice for students who want to pursue research in the future?

I was an English Major at NYU. You may ask, 'What is an English major doing at an MIT Lab? How did I get here?' The answer is not because I have all these skills or because

I'm super smart—I'm honestly just the opposite, but it was because I was open to unconventional opportunities. Instead of pursuing things like researching different trends in Victorian literature, I decided to do something different. [I thought:] I'm in college, I'm here to challenge myself. So, I ended up working a little bit for an economic risk lab. They introduced me to signal processing. My classes weren't gonna teach me anything like that.

So, my advice to students, especially undergrads, is to go after every single little thing you think you might even be a little interested in. So you might think, 'I'm in whatever program at MIT, and there's this UROP opportunity that looks super cool, but I'm not sure if I'm a good fit because they're looking for these skills and whatever.' Apply anyway. Think about how to sell yourself in your application and you will be just fine. I'm not saying you'll get that exact opportunity, but a good opportunity is going to emerge. Just think about it like that. Use it to expand your network. That's super important for post-college life. Seriously, that's one of the best things you can take away from college. Try to develop a good network. Other than that, just be open-minded. You never know what's going to happen.

Sustainability research is thriving at MIT in different departments and in a wide variety of projects. While the two labs interviewed are just a small look of what a student can get involved in sustainability research at MIT, we hope that this article gave valuable insight into sustainability research at MIT and how you can get involved in it yourself!


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MURJ

UROP Summaries

Elucidating Rapid-Alkalinization Factor (RALF) Peptide Receptors in Angiosperm Seeds[1]

Alysse Pusey[2], Caroline Anne Martin[3], Mary Gehring[4]

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Background

The investigation of seeds is valuable for numerous reasons, primarily due to relevance in agriculture and natural ecosystems. Seed development requires the coordination of three main tissue types: the endosperm, embryo, and seed coat. All signaling between the tissues must cross a cell membrane, and peptide signaling is likely an important medium for inter-tissue communication. In the model organism for studying plant biology Arabidopsis, there are about 500 genes for peptide ligands and receptors (Huang, 2015). We are interested in the uncharacterized seed-specific peptides that are secreted from the endosperm that may coordinate developmental processes to deepen our knowledge of how seeds develop.

The Gehring lab has generated a transcriptomic atlas of seed development using single nucleus RNA-sequencing to elucidate the timing and compartmentalization of transcripts that encode components of peptide signaling pathways. So far, we have captured days after pollination (DAP) 5 and 7, which represent intermediate and late developmental stages, respectively (Fig. 1). Using this dataset, we have identified two rapid-alkalinization factor (RALF) family peptides, RALF2 and RALF3, that appear to be secreted from the chalazal cyst at early to intermediate stages of development (Fig. 1). While the functions of RALF peptides in seeds are unknown, one known RALF receptor, FERONIA (FER), appears to control seed size (Yu, 2014). We hypothesize that RALF2 and RALF3 interact with the recognition receptor kinase FER in the seed. Our findings could expand our knowledge of the FER signaling pathway by further elucidating the way in which FER controls plant vegetative growth through RALF sensing.

Results

My current work aims to validate FER as a RALF2 and RALF3 receptor. I have generated a FER expression vector, a plasmid specifically designed for expressing FER in cells, and will perform protein pull-down using the vector-expressed FER and purified RALF2 and RALF3. Protein pull-down is an in vitro technique used to detect physical interactions between two or more proteins, and will indicate if there is a preferential interaction between FER and RALF2 or RALF3. I will use RALF7 as a positive control, as it is known to bind to FER. If a preferential interaction with FER is not found, I will repeat the experiment with other recombinant receptors, such as Hercules Receptor Kinase 1 (HERK1), THESEUS1, and ANJEA. HERK1 and ANJEA have been shown to associate with FER and may bind with RALFs, though evidence more strongly suggests that FER is the receptor of RALFs. THESEUS1 has been shown to bind to RALF34, and may bind to additional RALFs, though currently there is little evidence to support this.

The Gehring lab has generated CRISPR knockout Arabidopsis lines for RALF3, in which the RALF3 gene was silenced by the CRISPR Cas-9 system through cutting the DNA, and is in the process of generating CRISPR knockout lines for RALF2. I have performed the genotyping of RALF3 intermediate transgenic lines and validated the successful knockout of RALF3 from A. thaliana plants (Fig. 2). I will evaluate the phenotype of RALF2 and RALF3 knockout plants to probe the role of these peptides in seed and plant development.

Conclusion

This project serves to expand our knowledge of FER-RALF signaling in A. thaliana and investigate the role of RALF2 and RALF3 in seed development. Future steps will involve performing the seed size quantification experiments of RALF2 and RALF3 mutant seeds. If RALF2 and RALF3 are the ligands responsible for the FER seed size phenotype, then I expect the RALF2 and RALF3 double mutants to have larger seeds than wild type. These results will contribute to our growing knowledge of seed development, which may ultimately serve to inform future efforts to engineer seeds to enhance crop yield, drought resistance, or other desired traits.

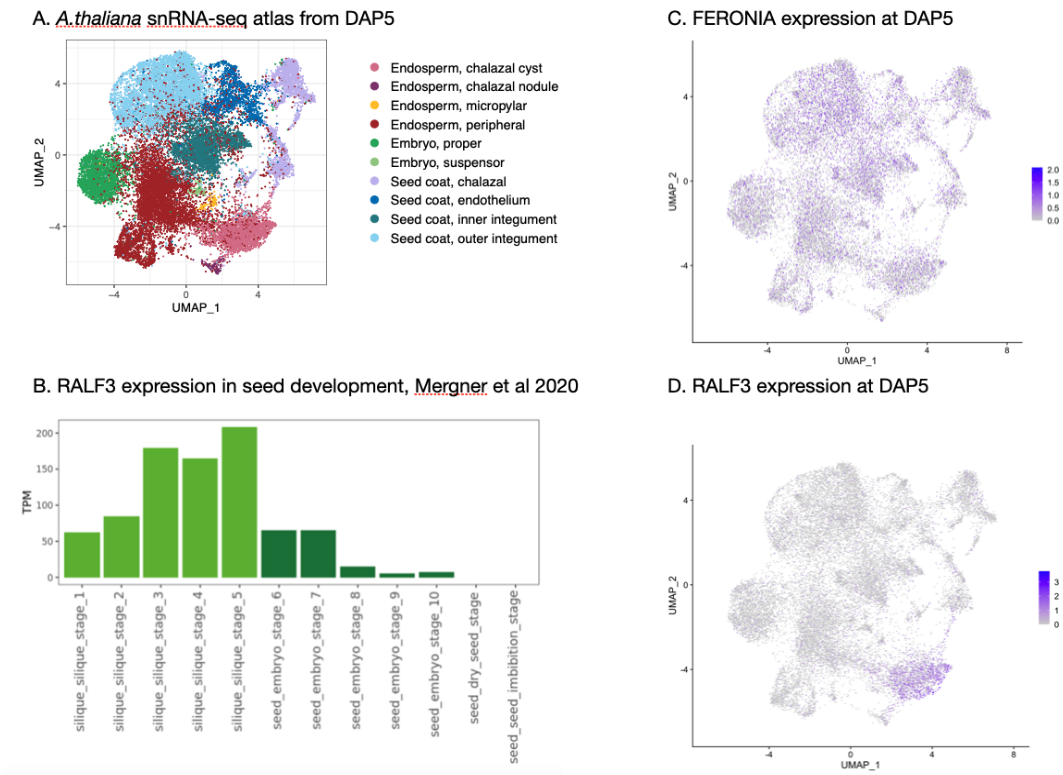

Fig. 1. a) Map of single nucleus RNA-sequencing results indicate the compartmentalization of genes that encode components of peptide signaling pathways at day after pollination 5 (DAP5) in A. thaliana. RALF2 and RALF3 appear to be secreted from the chalazal cyst which is shown in pink. **b)** Expression of RALF3 appears the highest in Stage 5 of seed development and drops quickly thereafter. **c)** Receptor FERONIA appears to be widely expressed throughout the seed at DAP5. **d)** Expression of RALF3 appears to be concentrated in the chalazal cyst at DAP5. permeability (filled) tested at a 60/40 CO_2/CH_4 composition.

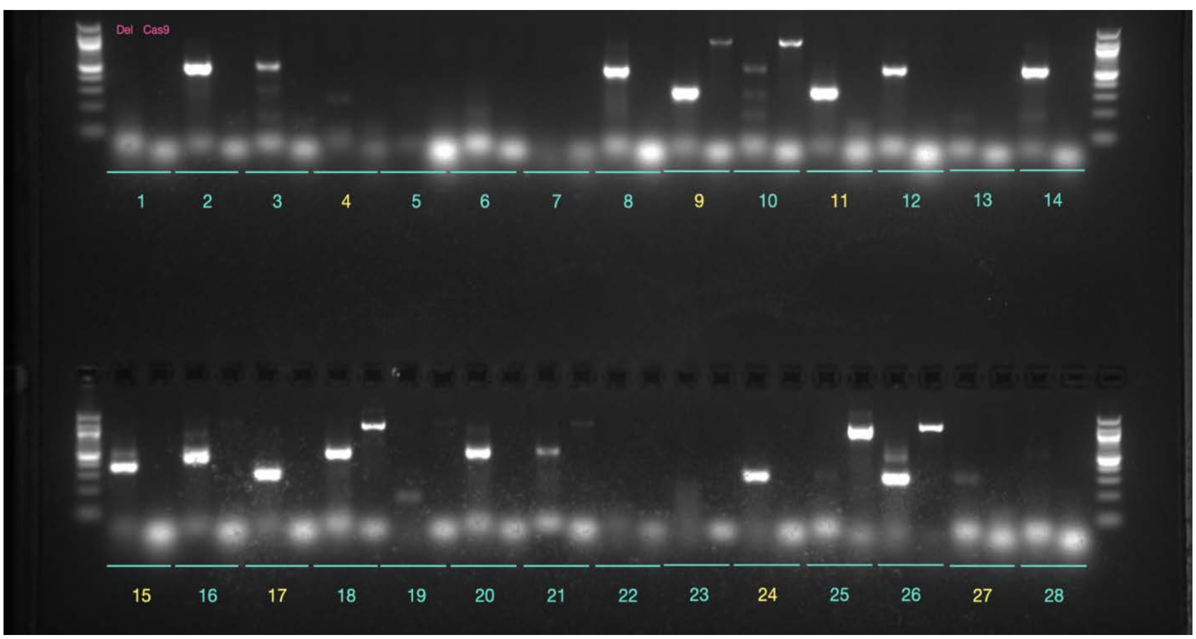

Fig. 2. Genotyping results for RALF3 T1 Arabidopsis plants suggest successful knockout of RALF3 gene in select plants. In each numbered pair, the first band represents RALF3 knockout sequencing and the second band indicates the presence of Cas9. Blue numbers correspond to bands of the size expected for WT plants that did not receive a RALF3 knockout. Yellow numbers indicate bands of the size expected for plants heterogenous for the RALF3 knockout.

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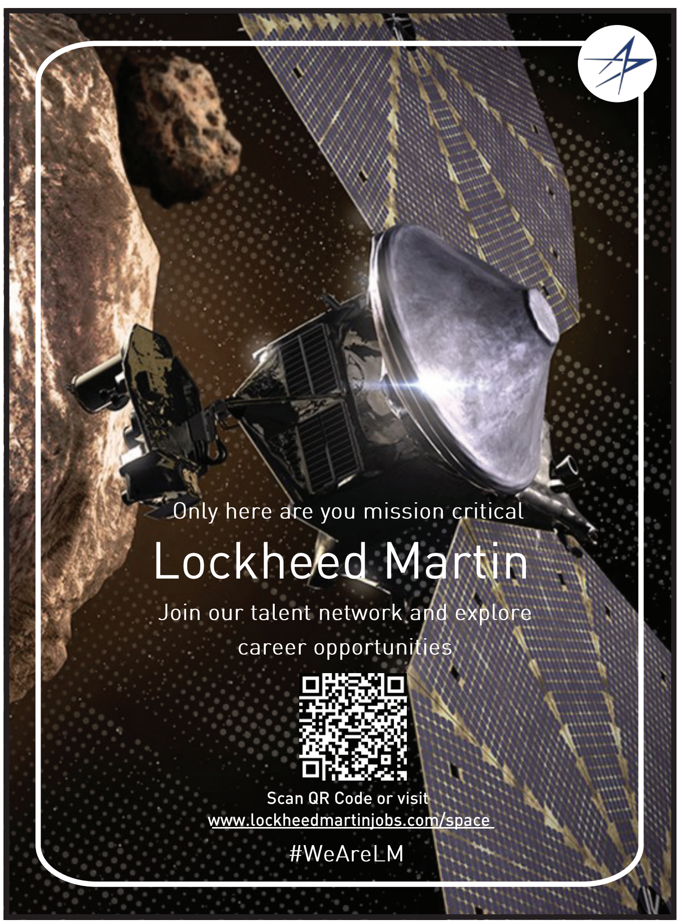

MURJ Reports

Ship Happens: A Multipurpose Autonomous Surface Vehicle Testing Platform

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Autonomous surface vehicles (ASVs) are robotic self-propelled vehicles that autonomously operate on the surface of the water. They are extremely useful for collecting data and automating tasks in an ocean environment. ASVs offer a more efficient and cost-effective solution to many traditional processes out on the water, with widespread applications in scanning, mapping, sampling, and aquafarming. To this end, we seek to lower the barrier to entry of building ASVs is lowered to further this technology's applications. This paper outlines the process of designing and manufacturing a low-cost ASV platform through a case study of MIT Arcturus' ASV, Ship Happens. Ship Happens was designed as a base platform that can be modified to perform a variety of tasks near the coast or in inland waters. The major considerations in our design were cost, ease of manufacturing, maneuverability, stability, and adaptability to different missions. This paper presents design principles and priorities in designing a similar surface vehicle so that the reader might adapt our design for their own uses.

As a flexible base platform, Ship Happens is a 5 3⁄4' catamaran capable of holding up to 300 pounds (136.078 kgs) of equipment. Overall, the entire base platform without sensors and electronics cost less than $500 in materials and can be manufactured and assembled by just one to two people. The design offers a more economical alternative to test on the water long-term.

For propulsion, Ship Happens uses two Blue Robotics T200 Thrusters at each hull's stern. To increase our maneuverability and prevent us from drifting into obstacles, we developed an optional low-cost azimuth thruster pod design that rotates in the yaw direction using servo motors, allowing us to engage our thrusters in any direction. The system is also mounted to a linear sliding mechanism to allow us to lift the thruster into the hull during transit and easily deploy the thrusters in the water.

In designing the system's power electronics, we aimed to cut down on costs without compromising the safety of the ASV. Therefore, we implemented many of the standard safety features one might expect of a mid-size electric development catamaran. However, when implementing overcurrent protection, fuses posed an issue: when the fuses blow and the vessel is out on the water, the vehicle is left adrift, and we must retrieve it. We thus designed an overcurrent protection circuit that will allow the ASV to retain power to communication systems and reactivate remotely should the protection circuit be triggered. Our overcurrent protection system prevents spikes in current from damaging sensitive, more expensive components using a combination of optoisolators, fuses, and current sensing. This system was also designed to be relatively inexpensive, costing less than $2K (before the cost of the computer) using off-the- shelf parts.

Ultimately, we hope that our design can be adapted for use by those interested in producing their own ASV prototyping platform for near-coast or inland waters. We hope that readers will take elements of our design that are useful to them and adapt to their uses, with the ultimate goal of furthering the application of this burgeoning technology.

Index Terms—autonomous surface vehicle, research platform, low-cost, autonomous boat, testing platform

1. Introduction

Autonomous surface vehicles (ASVs) have a wide number of applications across industries, including surveying and mapping, ocean data collection, marine life tracking, defen- sive operations, emergency response, transportation logistics, fishing, and aquaculture. ASVs are well-suited to monitor or work in large swaths of water for data collection, and the need for data collection will only become more relevant as typical data trends erode due to climate change. As a result, it's no wonder the global ASV market was valued at $520 million in 2020, with an expected 9.85% compound annual growth rate from 2021 to 2031 (ReportLinker, 2021).

Unfortunately, however, much of the potential for these applications remains untapped due to high cost. To better understand this, let's examine a case study. Let's say a local fish farmer was interested in learning more about how the runoff from a nearby industrial plant affects water quality and temperature over the course of a growing season. They want this to be done autonomously since they don't have experience using data collection instruments and don't want their workflow to be disrupted. The farmer's options are to either rent an autonomous boat at a steep $500 to $1000 per day, which will quickly add up over the course of the growing season, or purchase their own for $40 to $90K. Seeing as the annual salary of a fish farmer was around $30K in the US in 2022, this is simply too expensive (Salary & Compensation Data Platform, 2023).

Our design approach thus prioritized lowering costs and minimizing the number of manufacturing operations that would require sourcing large machinery. We also wanted the platform to be flexible so that it might be easily adapted to different uses. The ultimate goal is to democratize the creation of ASVs as platform technology.

2. Hull Design

At 5 3⁄4' (1.7526 m) long, Ship Happens (seen in Figures 1 and 2) is compact enough to fit inside of an SUV, but large enough to house necessary electronics and testing equipment one might need for a specialized mission. For stability, we selected a catamaran design. We used a 3' (0.9144 m) bridge made of marine plywood which spans nearly the entire length of the hulls to maximize the area of the deck and give more flexibility for component placement. The marine plywood deck is supported by carbon fiber beams, though we found that 80/20 aluminum worked just as well but weighed slightly more.

The hulls of Ship Happens were originally constructed as a platform for autonomous oysterbag flipping in 2021, but in the years since its conception, the hulls have been reused as a flexible platform for a variety of research applications (Kornberg et al., 2021). The hulls were then modified in 2023 to work with our low-cost azimuth thruster pods detailed in section III.

First, six layers of foam board were Computer Numerical Control (CNC) milled so that they create the general hull shape when stacked on top of one another, as seen in Figures 3 and 4. Because this milling process was done manually, users would thus be able to customize their hull profiles using this same process depending on their expected design requirements. Unlike inflatables, using foam design ensures the vehicle continues floating even if punctured.

Figure 1: *Ship Happens* in the Charles River in October 2022.

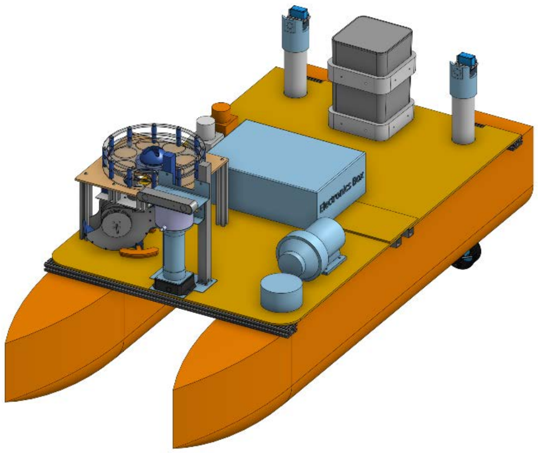

Figure 2: Computer-aided design of *Ship Happens*' full design.

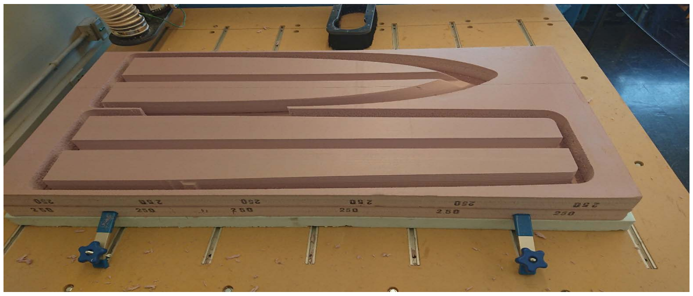

Figure 3: Foam board is milled out to shape.

The foam layers were glued together, with a single wooden beam running down the center line of each hull to hold the hulls up while the epoxy was applied along the exterior as seen in Figure 5. Lastly, a top layer of plywood was added to provide a mounting point for 3-inch steel studs to screw in and mount the deck.

After the foam layers were stacked, they had to be water-proofed. The foam was coated in layers of fiberglass soaked in epoxy. We estimated the amount of fiberglass necessary by calculating the surface area of your hull(s), multiplying by the

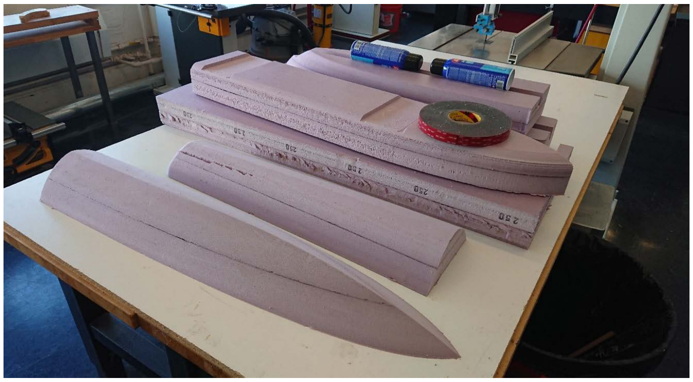

Figure 4: The foam board pieces are stacked together to create hull shape.

number of layers of fiberglass applied (typically around 5), and then adding 20-40% to allow for cutting errors and waste. (20% if it's a simple geometry and up to 40% for a complex shape.)

As necessary, excess fiberglass had to be cut off to prevent it from protruding off the surface. Furthermore, bubbles between layers were pushed out to ensure smooth adhesion. After each layer dried, the hulls were sanded so that the surface is smooth and followed the intended shape without sharp edges. Because epoxy and fiberglass can be irritating to your lungs and skin, we recommend wearing respirators, gloves, and aprons. This entire process can take days to weeks as each layer takes several hours to dry.

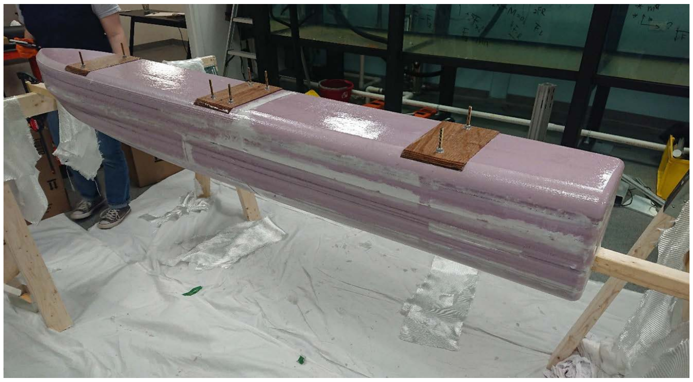

Figure 5: The completed hulls after drying.

Two years after the hulls' first iteration, we needed to adapt the design to accommodate our new thruster pods inside the hulls. We were able to accomplish this by drill pressing with a 2-1⁄2" (6.35 cm) Forstner bit on one side and a 5" (12.7 cm) hole saw on the other. We then ensured the hulls were watertight once again by resealing them using fiberglass strips soaked in epoxy resin, as seen in Figure 6. To ensure good contact with the walls of the hole while the epoxy dried, we used push pins through the strips and into the foam, as seen in Figure 7. To make placement of the strips easier, we would presoak the entire strip in epoxy, then use welding rods as chopsticks to move the sticky strips into place (Figure 8).

This process really highlighted the benefits of creating our own composites this way, as the hulls could be custom- designed, and then modifications could be made later on. Ultimately, we found this to be a very cost-effective way to produce custom hulls, costing less than $500 when similarly sized inflatables typically cost $2K to $5K. In total, our hulls and deck weigh 42.5 pounds (19.278 kgs) and can hold a maximum load upwards of 300 pounds (136.078 kgs).

Figure 6: Epoxy is painted onto the fiberglass strips for sections with simple geometry.

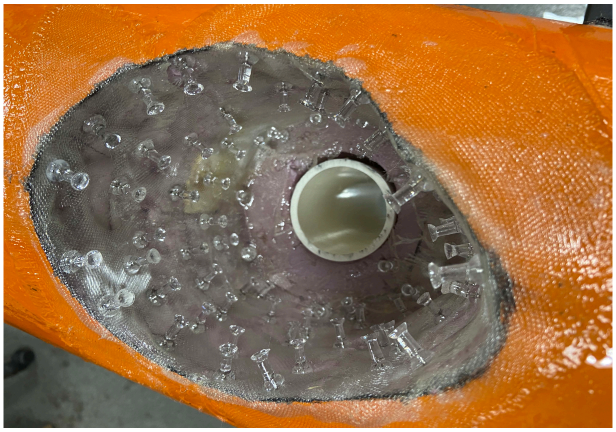

Figure 7: Push pins are used for the first layer to ensure good contact with the sides of the hole.

Figure 8: Difficult-to-access geometry required us to pre-soak the fiberglass strips and place them using welding rods.

On top of the deck is our sensor mast, a 3D-printed post elevated above the electronics boxes. This enables a wider and unobstructed field of view for our ZED 2i depth camera and Velodyne Puck lidar. Sensor selection is nonspecific and will vary depending on one's desired application; however, through the use of 3D-printed parts, sensors can easily be swapped out and new masts can be integrated. These 3D printers are becoming increasingly affordable, and open up many manufacturing possibilities for custom ASV parts.

3. Propulsion System

In order to get the most control out of our two Blue Robotics T200 Thrusters, we developed an azimuth thruster pod to rotate the thrusters in place. Each T200 thruster is attached to a servo motor through a PVC pipe, allowing us to reorient the thruster relative to the hull. The system is mounted inside a larger PVC pipe to create a telescoping mechanism, allowing us to lift the thruster into the hull during transport then move them down to deploy the thrusters in the water. By mounting the thruster this way, the force is redirected into the bearings, preventing shearing of the mount. The PVC extends up through the hull and above the deck to maximize the space between the thruster and the upper bearing, thus minimizing the force on the bearings caused by the cantilever. 3D-printed pieces mount the servo motor in place on top and connect the thruster to PVC. Figure 9 depicts the computer-aided design of the thruster assembly. In order to connect the thruster pod to our hulls, we created a composite of glass beads mixed with epoxy resin and cemented them into place. We found this was relatively easy to apply and provided a smooth finish.

Overall, the thruster pod layup seen in Figure 10 cost less than $85 (not including the thrusters themselves) and dra- matically improved our maneuverability versus skid steering. In the future, we hope to integrate a third thruster pod into our ASV to provide even more control and enable us to do stationkeeping (maintaining a position in the water despite external forces).

4. Electrical System

(a) (b) (c)

Figure 9: Azimuth thruster subsystem **(a)**, Cross-section of thruster assembly **(b)**, Thruster assembly integrated into the hulls **(c)**, Thruster assembly integrated into the vehicle.

To best support the onboard subsystems and their ease of use and robustness, we designed the layout of our hardware to promote a smooth testing and debugging process as shown in Appendix A. We also implemented several new features that would make Ship Happens further adaptable to different circumstances and applications. In order to provide overcurrent protection, we placed optocouplers at integral locations to isolate our propulsion power bus from some of our more sen- sitive electronics. Our Nvidia Jetson AGX Xavier processing unit is at the heart of our system, acting as the delta for all of our sensor data. Then, our Pixhawk and Arduino Mega microcontrollers are the intermediaries between the Xavier and all of the thrusters and task-specific motors on the vessel. There are also three buck converters to allow different power supply configurations to our components in order to optimize performance. This design choice is especially important for our computer (the Jetson Xavier), which requires certain specifi- cations for performance as well as our assortment of motors and their drivers. Note that although we used a Jetson Xavier, which costs about $2K, one would could also substitute in a Jetson Nano for $150 to reduce costs. Overall, our electronics system (minus our Jetson) cost around $2K.

Figure 10: Final assembly of thruster pod embedded within the hulls.

To enable quick access, our entire electronics system dis- connects from its water-resistant enclosure so that we can access every component for maintenance and development. We strategically designed an ideal, power-efficient electrical subsystem to ensure that as much of our battery capacity as possible went towards our external-facing systems like the mechanisms and the thrusters. As a result, we selected components like buck converters (due to their high efficiency) to step down our voltage sources.

Another important consideration in our design was the emergency power shut off system. This consists primarily of a battery management system (BMS) for our Lithium Polymer (LiPo) batteries, digitally controlled switches on our main power bus as well as the requisite signal interrupts to trigger said switches. We originally chose Solid State Relays to be used in place of Electro-Mechanical Relays to minimize power consumption and electromagnetic interference, but after field testing, we determined that while they are a solid, economical option, they are not reliable enough for continued use with large loads and current draw. Therefore we selected high- power (200A rated) DC contactors to serve as our main power switches. There are several manual emergency stop buttons around the vehicle which are wired into the contactor control circuit and thus will shut off power when depressed. Similarly, we have another signal interrupt that can be triggered remotely using a radio frequency controller to shut off power.

5. Auxiliary Systems

A. Thermal Management System

We developed a system that would allow us to supply cool air and exhaust warm air to the sealed electronic components in the box while minimizing the risk of water reaching them. The system consists of two different parts: the fan mounts, made up of a pair of circular acrylic mounting plates and a cast silicone gasket; and the fan casing, made up of a 3D- printed hollow cylinder meant to enclose the fan and funnel the air into a PVC pipe as seen in Figure 11.

The fan was selected based on the limits of the electrical power supply and the dimensions of the electronics box. Based on those two criteria, we decided to use a pair of Pano-Mounts QH8025IP2510 80 mm fans that operate at 12 V and 0.33 A. One fan would provide air at the inlet and the other would pull air from the exhaust of the electronics box. We used elbow joints to minimize the risk of water splashing into the fans at both the inlet and outlet.

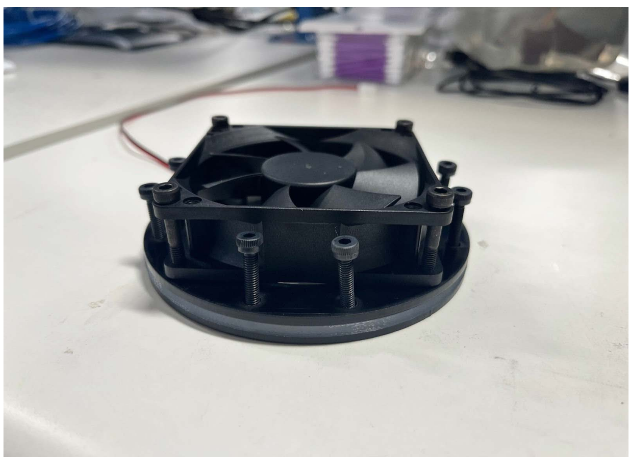

Figure 11: The fan is placed on the acrylic mounting plates with a silicone gasket in the middle. The wall of the electronics box sits between the silicone gasket and the bottom mounting plate.

We velcroed a thin sheet of aluminum on top of our electronics box to reflect incoming sunlight. We found attaching the sheet with velcro to be more effective than adhesive in cooling the box since it allows for convection between the battery box lid and the aluminum. The entire assembly can be seen in Figure 12.

To further diffuse heat away from our electronics, custom heat sinks were machined from aluminum for the electric speed controllers and relay switches to allow for more flex- ibility in component placement within the box. Though this ultimately was less expensive for us to machine since we had access to a mill, one could also purchase heat sinks for under $20 online. All other components were left with their original heatsinks where applicable.

B. Remote Visual Signaling

We included a remote visual signaling system in the form of an LED Tower. The purpose of the LED Tower is to visually communicate the status of the onboard systems from afar so as to be conducive to a more efficient debugging and tracking process while the ship is in the water. It has three different colored (red, green, and yellow) lights and a single pitch speaker, which together can signal up to 16 different statuses. To conserve space, instead of using electro-mechanical relays, we used MOSFETs as switches to turn the lights and sound on and off. They are further controlled by 5V digital signals from the Arduino Mega.

5. Conclusion

We hope that Ship Happens can serve as an example base vessel that might be adapted to any given marine need on the surface.

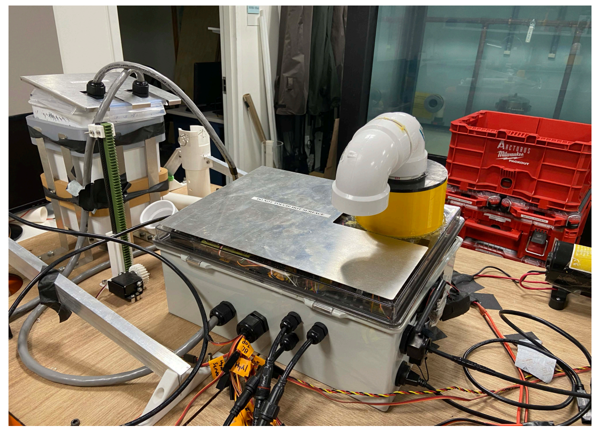

Figure 12: Fan assembly integrated into our electronics box.

Because the only specialized tool required for manufacture is a CNC mill for hull design, this enables the vast majority of the steps in construction to be done anywhere by only one to two people. And with an ultimate cost of just $500 for the hulls, $85 for the thruster pods (minus the thrusters themselves), and $2K for electronics (minus the computer), the platform remains an order of magnitude more affordable than existing alternatives for purchase. See the Table I below for a summary of the cost-comparison.

We hope our design process can enable anyone interested in building a small surface vehicle platform to do so at relatively low cost, allowing them to make use of and contribute to the surface vessel autonomy field.

Acknowlegement

We want to thank all of the sponsors whose generosity allowed us to not only build our boat but also foster a space

	Ship Happens	**Off-the-shelf**
Electronics	$1.5K	$6.5K-$10K
Hulls	$500	$2K-$5K

Table 1: Cost comparison between off-the-shelf alternatives for ASV components.

where students can learn and grow together.

1) MIT Departments of Mechanical Engineering, Mathematics, Aeronautics and Astronautics, and

2) Nuclear Science and Engineering

3) MIT Edgerton Center

4) RoboSys

5) ProjX

6) Coop Grant

7) Alex Soo

8) MIT Innovation Fund

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2) Toyota Research Institute: Lidar loan

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1) MIT Sea Grant

2) MIT Architecture and Design (MAD) Lab

3) MIT Laboratory for Manufacturing and Productivity

4) N51 Edgerton Center Team Shop

5) 4-409 Edgerton Student Project Laboratory

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4) Jim Bales: electrical system feedback

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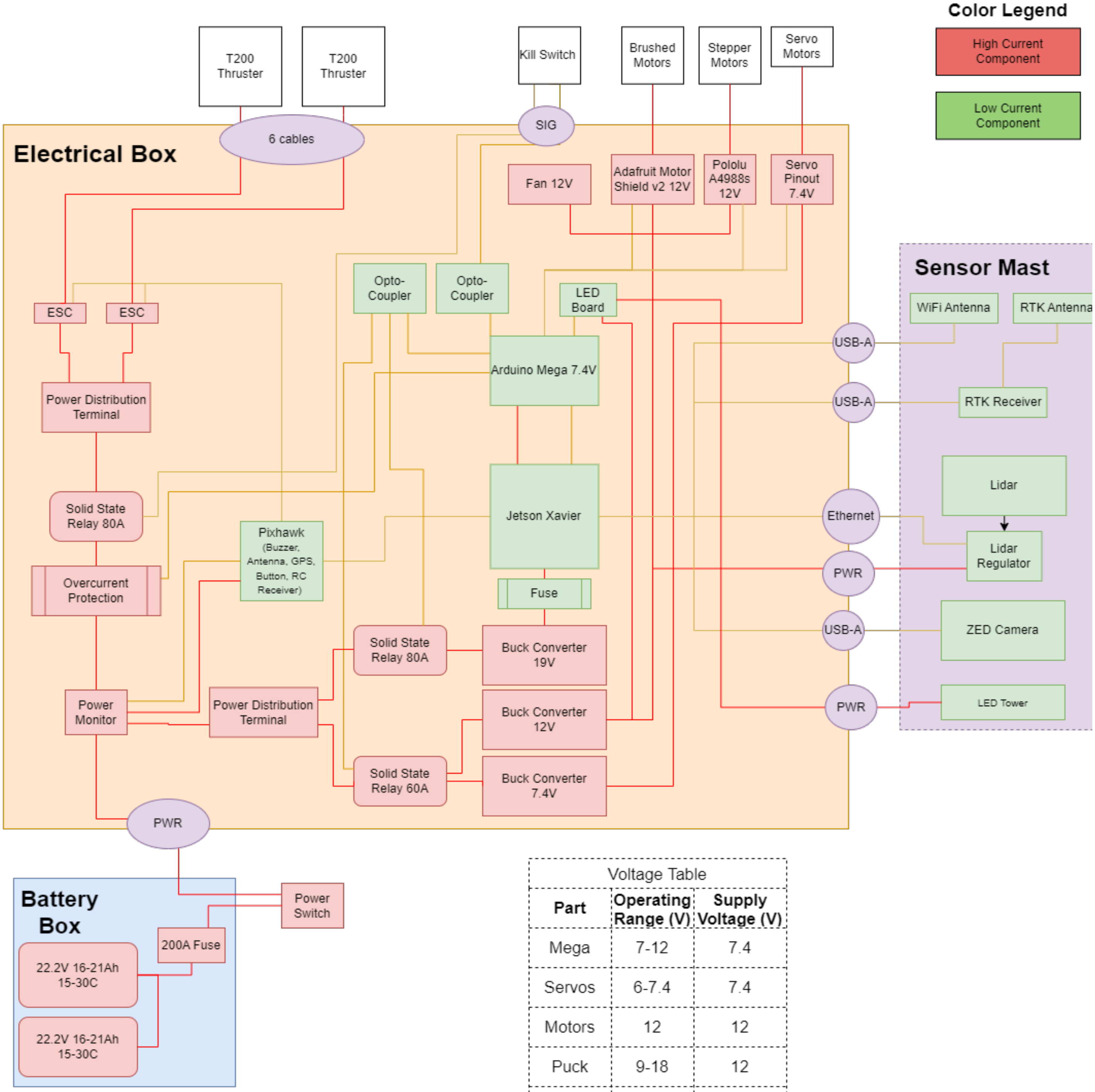
Appendix A



Voltage Table

Part	Operating Range (V)	Supply Voltage (V)
Mega	7-12	7.4
Servos	6-7.4	7.4
Motors	12	12
Puck	9-18	12
Xavier	9-20	19
Stepper	12	12
LED Tower	7-24	12

Electronics diagram providing an overview of the electrical system for the entire boat.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