Undergraduate Journal of Scientific Research

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CHARLES EDISON FUND

Letter from Dean Galvin

Undergraduates who conduct research during their time at the University of Notre Dame are well prepared for future careers, as well as for admission into graduate or medical schools. *Scientia*, a student-run journal, not only grants students the opportunity to have their research published, but also demonstrates how science progresses from the laboratory to the pages of a journal.

Support from our generous donors has allowed many of our students to complete research during the summer. It is a time away from the books, assignments, and daily grind of college, so students can delve into one project about which they're passionate. Working either on or off campus, students participating in summer research learn alongside scientists and other laboratory professionals. Many students also assist researchers throughout the year on a range of projects, sometimes dovetailing off previous discoveries they made over the summer or during previous years.

By publishing their research methods and results in *Scientia*, students also learn the art of communicating about science. The research articles themselves allow students to practice how to speak the language of science. The news articles, by contrast, afford students the opportunity to write about research in accessible ways for the educated public—those who may have experience in other fields within or apart from science.

This year's issue marks the 10-year anniversary of *Scientia*, and one of growth for the publication. Attendance at monthly "Talk Science" lectures is unprecedented, thanks to the support of several faculty members who assist with these talks on a variety of scientific topics. And the four accepted submissions in this issue reflect the diversity of high-caliber research in the fields of physics, biology, and mathematics.

Science is a continual process of discovery. I am honored to support *Scientia* and the research advanced by the undergraduate students in Notre Dame's College of Science.

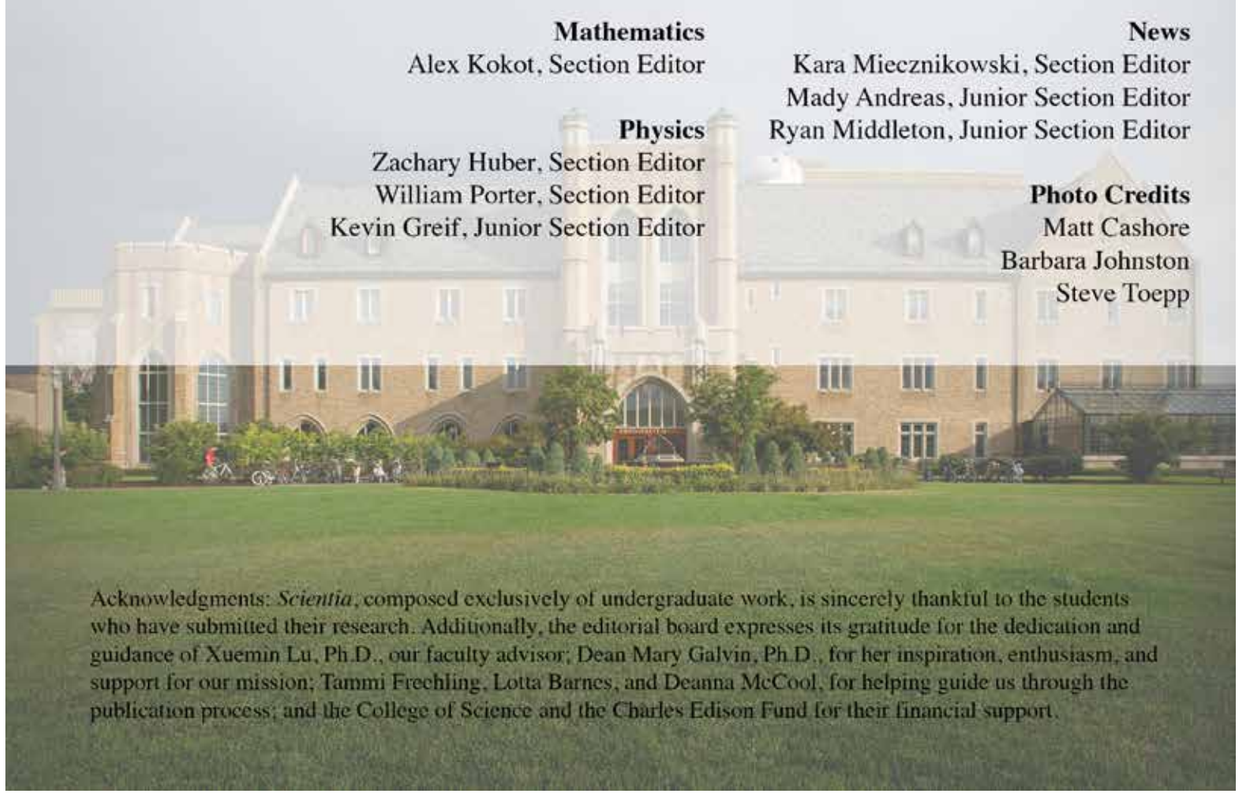
Sincerely,

Mary E. Galvin

Mary E. Galvin, Ph.D.

William K. Warren Foundation Dean of the College of Science
Professor of Chemistry

Editorial Board 2018–2019



Acknowledgments: *Scientia*, composed exclusively of undergraduate work, is sincerely thankful to the students who have submitted their research. Additionally, the editorial board expresses its gratitude for the dedication and guidance of Xuemin Lu, Ph.D., our faculty advisor; Dean Mary Galvin, Ph.D., for her inspiration, enthusiasm, and support for our mission; Tammi Frechling, Lotta Barnes, and Deanna McCool, for helping guide us through the publication process; and the College of Science and the Charles Edison Fund for their financial support.

Letter from the Editors

Scientia, Latin for knowledge, has always been a student-run publication of high-quality undergraduate research in the College of Science. Founded in 2009 with the goals of celebrating and encouraging research, we are proud to say that *Scientia* has now been contributing to the scientific community of Notre Dame for a decade.

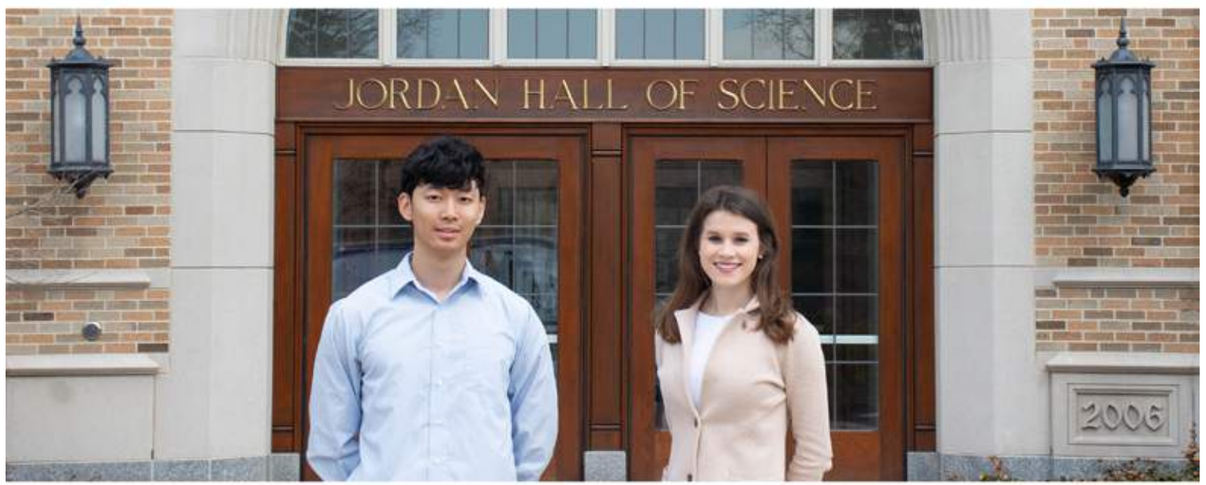
The 2018–2019 academic year has been one of great growth for *Scientia*. The "Talk Science" seminar series has garnered greater attendance this year than ever before, featuring presentations by students and faculty from a diverse array of departments. Included in this edition of the journal is a new section—the Student Spotlight—showcasing individual undergraduates who have had their research published in other journals in the hopes of spreading awareness and encouraging other students to follow in their footsteps. Strides have been made in updating *Scientia*'s image, from our first-ever T-shirt design competition to the debut of our new 10th-edition cover. It truly has been a wonderful year, and we are grateful to have been a part of it.

The publication of this journal would not have been possible without the dedication of more than a few people here at Notre Dame. We would like to thank all of our editors and reviewers for their tireless effort in putting this journal together, and the undergraduates and their advisors who contributed their work to *Scientia*. We so appreciate our advisor, Dr. Xuemin Lu, for her advocacy, vision, and mentorship. We wish to formally acknowledge Dean Galvin and the College of Science for the continued support we have received over the years, with special thanks to Ms. Tammi Freehling, Ms. Lotta Barnes, Ms. Deanna McCool, and Ms. Elise Brady.

Looking to the future, we are honored to pass the torch on to Rosie Crisman and Vaishali Nayak as Co-Editors in Chief. We have full confidence that they will take *Scientia* to new heights in the 2019–2020 year.

In Notre Dame,

Ruby Hollinger & Eric Sah
Editors in Chief



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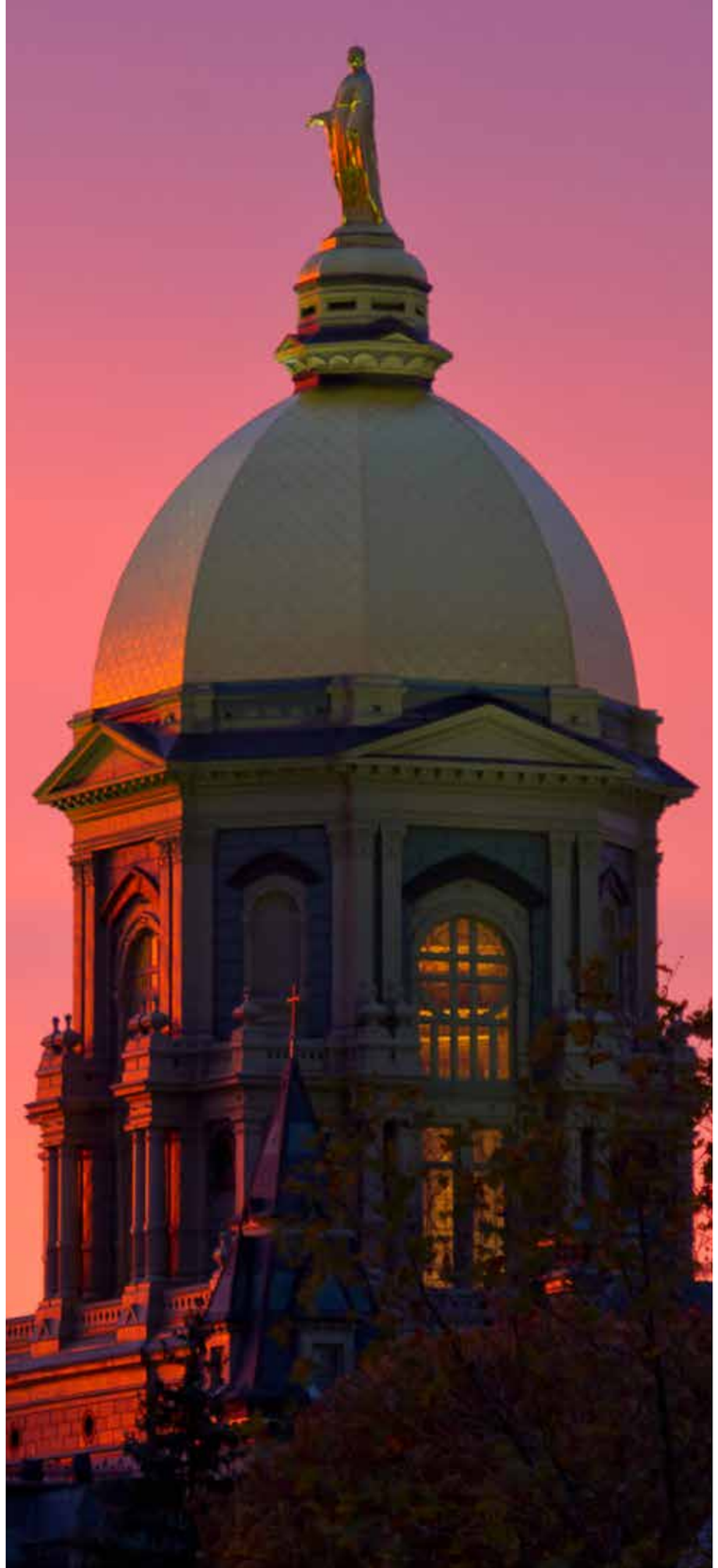
ON THE FRONT AND BACK COVERS
A Notre Dame student group on campus used MakerBot 3D printers at Fitzpatrick Hall to create a prosthetic hand. Orthodontic rubber bands connect the finger joints. The gauntlet allows the user to control the hand while the fishing wires make the fingers curl.

THE UNIVERSITY OF
NOTRE DAME

The 1,250-acre campus of the University of Notre Dame is located on the north side of South Bend, Indiana, just 90 miles from Chicago. Founded in 1842 by Rev. Edward F. Sorin, a French Holy Cross priest, Notre Dame had very humble beginnings. Now, it is the preeminent Catholic educational institution in the United States, with an annual enrollment of 8,530 undergraduate students, and more than 1,300 professors, who together hold advanced degrees from major universities around the world. Notre Dame's endowment is the 11th largest in the country, and research in science attracts more than $40 million in federal research funds each year.



College of Science New Faculty Spotlight

ABIGAIL ABIKOYE, LAUREN CONNELLY, NICOLE LEE, MEGAN MCCABE, KRISTIN MEHLMANN

Badih Assaf, Ph.D., Frank M. Freimann Physics Assistant Professor in the Department of Physics, received his B.S. in physics at the American University of Beirut in 2009, where he also earned a minor in mathematics. He went on to receive his M.S. in physics at Northeastern University (Boston) in 2011 before receiving his Ph.D. in physics at Northeastern University in 2014. At Northeastern, Assaf completed his thesis titled "Magnetotransport in Thin Films and Heterostructures of Topological Matter." Assaf completed a postdoctoral fellowship at the École Normale Supérieure in the Département de Physique in Paris between the years of 2014-2018, where he instructed and researched. At Notre Dame, Assaf currently researches the synthesis, optical, and transport properties of quantum materials. One current project is to prepare lab setups for electrical and infrared optical measurements at high magnetic fields. Assaf is also planning and teaching a course about topology and Dirac fermions in condensed matter. He has general scientific expertise in topics such as magneto-optics, DC and RF transport, chemical vapor deposition, and device fabrication (optical and electronic lithography). In his free time, Assaf enjoys performances at DPAC, cooking, soccer, and exploring race car technology.

Maria Alexandrova, Ph.D., assistant professor of the practice, joined Notre Dame in 2018. She received her M.D. from Yaroslav-the-Wise Novgorod State University in Russia in 2002 and her M.S in community health from Minnesota State University Mankato in 2008, where she was both the founder and the first president of the Global Health Club. Most recently, she received her Ph.D. in health education from Southern Illinois University Carbondale in 2012. Before coming to Notre Dame, Alexandrova was an obstetrician-gynecologist in Russia, performed research in women's health, and worked on several ecological projects as an intern at the United Nations Headquarters in New York City. Her primary interests are centered on the prevention of maternal and infant mortality, the use of modern technology platforms for community outreach, and the prevention of cancers associated with human papilloma virus (HPV). Currently, she is in the Master of Science in Global Health Program, where her role encompasses the maternal and child health sector of teaching and research.

Ana Lidia Flores-Mireles, Ph.D., Hawk Assistant Professor of Biological Sciences, earned her Ph.D. in microbiology from Cornell University. She served as a postdoctoral researcher at the Washington University School of Medicine in St. Louis before coming to Notre Dame in June 2018. Her primary research interest is the bacterial pathogenicity in catheter-associated infections. Catheter-associated urinary tract infections (CAUTIs) make up 40% of all healthcare-associated infections and have the potential to lead to secondary infections that may be fatal. Flores-Mireles works to understand how inflammation resulting from urinary catheterization leads to an increased risk of contracting a microbial infection. She hopes to eventually be able to work on developing innovative, targeted treatments and already holds a patent for treating pilus-related diseases in a clinical setting. She has a great passion for teaching and translational research and Notre Dame provides opportunities for both of these.

David Hansen, Ph.D., assistant professor in the Department of Mathematics, received his B.A. in mathematics from Brown University in 2010 before receiving his Ph.D. from Boston College in 2013. He worked as a postdoctoral researcher at Institut de Mathématiques de Jussieu from 2013 to 2014 and immediately afterward became a J.F. Ritt assistant professor at Columbia University. Over the past six years, he has been invited to speak at numerous seminars, conferences, and colloquia that have taken place in universities and cities in and outside of the United States. Hansen is now an assistant professor in the Department of Mathematics here at Notre Dame, having joined in the fall of 2018. He focuses on algebra and number theory, particularly p-adic Hodge theory and p-adic aspects of the Langlands program. Recently, Hansen has been working to find applications of new tools and ideas that have been discovered by Fargues, Fontaine, and Scholze, as well as on foundational questions around adic spaces and perfectoid spaces.

Tyvette Hilliard, Ph.D., research assistant professor, earned Bachelor of Science degrees in both chemistry and biology from Chicago State University in 2007. She received her Ph.D. in medicinal chemistry from the University of Illinois–Chicago in 2012. She was a postdoctoral fellow at the University of Hawaii Cancer Center from 2012 to 2015 and became a postdoctoral fellow at the University of Notre Dame in 2015. She worked in this capacity for three years prior to joining the Notre Dame faculty in 2018. Hilliard knew she wanted to be an obstetrician-gynecologist at a very young age and, coming from a violent neighborhood, she worked hard not to follow its standard. She overcame many adversities to be where she is today, and although she didn't expect to go to graduate school, she has become a promising investigator, studying women's health. The objective of her current research is to use preclinical mouse models to determine the influence of host factors, including maternal obesity, on the metastatic success of ovarian cancer, the deadliest gynecological cancer among U.S. women. She investigates the influence of maternal obesity on the metastatic success of ovarian cancer in next generation offspring and uses pre-clinical mouse models to investigate the mechanistic link between maternal obesity and ovarian cancer metastasis in offspring.

Cristian Koepfli, Ph.D., assistant professor in the Department of Biological Sciences, received his Ph.D. at the Swiss Tropical and Public Health Institute in Switzerland before becoming a postdoctoral fellow at the Walter and Eliza Hall Institute for Medical Research in Australia. In addition to being in Notre Dame's Department of Biological Sciences, he is affiliated with the Eck Institute for Global Health, a partnership between the University and IU South Bend Medical School. His current research focuses on how infectious diseases, such as malaria, are transmitted and diagnosed. Koepfli uses genotyping methods to better understand stages of transmission and infectious stages of parasites. He and his team focus on understanding the current molecular diagnosis system, specifically with determining the number of infections missed by clinicians. At Notre Dame, he enjoys the broad range of perspectives on infectious disease research, including genome sequencing of microbes and the mosquitos that transmit them, mathematical modeling, and how ecology and climate change impact disease transmission. Koepfli has a special interest in infections not associated with fever, specifically how this lack of fever relates to the diagnosis process and how clinicians determine when individuals are infectious without the presence of fever. Eventually, Koepfli hopes to discover new strategies for infectious disease control. In his spare time, he loves being outdoors and with his family. Coming from Switzerland, he thinks the only thing Notre Dame is missing is some proper mountains nearby.

Choon Kim, Ph.D., research assistant professor in the Department of Chemistry and Biochemistry, received his B.S. in genetic engineering and his M.S. in biology at the Chonnam National University (Korea). In 2006, he received his Ph.D. in biochemistry from Notre Dame. Afterward, he conducted research at Rockefeller University in New York City before returning to Notre Dame as a research scientist in 2015. Now, Kim focuses on the study of MRSA bacteria, which have a structural gene called BlaZ that encodes a class A β-lactamase, which is a resistant determinant for β-lactam antibiotics. He recently discovered that the staphylococcal BlaZ exists in two forms: phosphorylated and dephosphorylated. Kim ultimately hopes to explain various pathways that inhibit the phosphorylation of BlaZ. This would cause the MRSA bacteria to lose its virulence through the release from the S. aureus surface. One of his most recent papers explored the potentiation of activity of β-lactam antibiotics by farnesol and derivatives. Kim enjoys playing squash and bowling at his leisure.

John Koren III, Ph.D., research assistant professor in the Department of Chemistry and Biochemistry, earned his B.S. in microbiology and B.A. in chemistry from the University of South Florida. He then went on to receive his M.S. in pharmacology and his Ph.D. in neuroscience from the University of South Florida. Koren worked as a postdoctoral scholar at the Memorial Sloan-Kettering Cancer Center in New York City before returning to the University of South Florida as an assistant research professor. Koren came to Notre Dame in April 2018. His lab focuses on multiple biomedical research projects. His multidisciplinary lab's current projects include an investigation into treatments for Alzheimer's disease focusing on accumulated tau proteins, profiling mechanisms of survival in individual cancer cells, and using the molecular chaperone Grp94 to treat glaucoma. Koren is also the director of the Warren Center for Drug Discovery's Biology and Screening facility: a for-service facility dedicated to assisting internal and external scientists in their biology and drug discovery projects.

Evgenii Kovrigin, Ph.D., research associate professor and director of the Magnetic Resonance Research Center at the University of Notre Dame, graduated from Krasnoyarsk State University in Russia in 1993 with a B.S. in chemistry and completed his M.S. in molecular biology at Moscow State University in 1995. He went on to earn his Ph.D. in chemistry at Russia's Engelhardt Institute of Molecular Biology in 1999, before becoming a postdoctoral scientist at the country's Institute of Protein Research. Moving to the United States in 2001, Kovrigin became a postdoctoral fellow, first at UT Southwestern Medical Center–Dallas and then at Yale University, where he was awarded the Anderson Postdoctoral Fellowship. Before coming to Notre Dame, Kovrigin was an assistant professor of biochemistry at the Medical College of Wisconsin and, most recently, an assistant professor of chemistry at Marquette University, Wisconsin. Kovrigin's other notable accolades include the MicroCal Young Scientist Award, which was presented to him at the second International Conference on Applications of Biocalorimetry in 1999 in Halle/Saale, Germany, for his doctoral studies on protein thermodynamics in mixed solvents. His research is mainly focused on understanding the fundamental relationships between protein structure, dynamics, and interactions with ligands. In particular, he utilizes Nuclear Magnetic Resonance (NMR) spectroscopy as his main method of investigation, combined with a range of other biophysical and biochemical methods. At Notre Dame, the major direction of Kovrigin's research is theoretical development of NMR line shape analysis and software to enable broad application of this method by the research community.

Christian Melander, Ph.D., George and Winifred Clark Professor of Chemistry and Biochemistry, received his B.S. in chemistry from the University of California-Davis in 1994, followed by his M.A. and M.Phil. in chemistry, both from Columbia University in 1995 and 1998, respectively. Melander then earned his Ph.D. in chemistry, also from Columbia University in 1998, before working as a postdoctoral scholar at the California Institute of Technology, and then as a research associate at the Scripps Research Institute. He then moved to North Carolina State University, where he investigated bacterial infections and resistance for 14 years before joining the faculty of Notre Dame in the fall of 2018. Melander's interests lie in developing unique molecules to combat bacterial infections and the problems arising from failed antibiotic therapies. More specifically, he hopes to address bacterial biofilms, which frequently lead to chronic infections, and bacterial resistance to multiple antibiotics, which frequently lead to acute infections. Melander's lab utilizes the structural motifs found in natural marine products to inhibit and disperse biofilms of different makeups. To fight multidrug-resistant bacteria, his lab investigates narrow spectrum antibiotic profiles that are less damaging to innocuous bacteria, along with small molecules that reduce bacterial resistance.

Patrick O'Malley, Ph.D., research assistant professor in the Department of Physics, earned his B.S. in physics from Tennessee Technological University in 2006. He then went on to receive his doctoral degree in physics and astronomy from Rutgers University in 2012. Now at Notre Dame, O'Malley conducts research that attempts to answer two simple yet difficult questions: How do elements and their isotopes form? How can we predict their abundances? We believe that the majority of elements and isotopes are produced in stars, yet the exact beginnings of every type of nucleus remain undiscovered. An astronomer might be able to determine the composition of elements and isotopes on the surfaces of such stars, but O'Malley is interested in the processes that generated those abundances in the first place. More specifically, he studies the structures of nuclei and measures their properties in an attempt to unravel these mechanisms. This, he hopes, will contribute to the existing body of work produced by the nuclear science and astrophysics community, with the end goal of creating models that accurately describe how stellar processes create some of the thousands of isotopes known to man.

Roberta Melander, Ph.D., research associate professor in the Department of Chemistry and Biochemistry, received her M.Chem. in medicinal chemistry from the University of Manchester Institute of Science and Technology in 2004 and her Ph.D. in biological chemistry from the University of Manchester in 2008. Before coming to the University of Notre Dame, Melander worked as a postdoctoral research associate at University College London from 2008 to 2009 and at North Carolina State University from 2009 to 2011. She became an editor for the *Chemical Biology and Drug Design* journal in 2011, a position she currently holds while conducting research here at Notre Dame. Her work uses small molecules to study and control bacterial behaviors. Melander aims to develop small molecules that mediate antibiotic resistance and tolerance, the evolution of resistance to antimicrobial agents, and virulence: These would all create potential novel therapeutic options for treating bacterial infections.

Eric Riedl, Ph.D., is an assistant professor in the Department of Mathematics at the University of Notre Dame. One of the University's own, Riedl graduated summa cum laude in 2010 with a B.S. in mathematics and piano performance from the University of Notre Dame. He then went on to earn his Ph.D. from Harvard University in 2015. From there, Riedl accepted a position at the University of Illinois at Chicago as a research assistant professor, a position he held for three years prior to his return to Notre Dame. Riedl is also the recipient of the National Science Foundation Graduate Fellowship, as well as the American Mathematical Society Simons Travel Grant. As an algebraic geometer, Riedl is interested in birational geometry, rational curves, hypersurfaces, and rationality problems. More specifically, he focuses on the geometry of hypersurfaces in projective space by studying the rational curves lying upon them. Outside of math, Riedl likes to run and swim, and can occasionally be found playing the piano for fun and playing French horn in church. He enjoys how supportive the department is, and appreciates the multitude of resources and friendly senior faculty members present in the Department of Mathematics.

Felipe H. Santiago-Tirado, Ph.D., assistant professor in the Department of Biological Sciences, received his Ph.D. in molecular and cellular biology from Cornell University in 2011. He then worked as a postdoctoral researcher at both Cornell University and Washington University School of Medicine. After completing advanced coursework in molecular mycology at the Marine Biological Laboratory in Woods Hole, Massachusetts, he became a staff research scientist in the Molecular Microbiology Department at the Washington University School of Medicine before assuming his current position as an assistant professor at the University of Notre Dame. More than 300 million people worldwide suffer from severe fungal infections, and 1.6 million of them die every year because not enough is known about such infections. Santiago-Tirado endeavors to bring this underappreciated global health problem into the spotlight by studying *Cryptococcus neoformans*, a widespread environmental fungus, which took approximately 200,000 lives in 2016. By understanding this organism and its unique survival and dissemination strategies within host immune cells, he hopes to uncover broadly applicable biological mechanisms and lay the foundation for development of novel therapeutics.

Jason Rohr, Ph.D. Ludmilla F., Stephen J., and Robert T. Galla College Professor in the Department of Biological Sciences, received his B.A. in biology and environmental sciences from Binghamton University in 1996, where he also completed his M.A. in teaching biology in 1997 and his Ph.D. in ecology and behavior in 2002. Prior to his arrival at Notre Dame, he spent 12 years at the University of South Florida, where his most recent roles included associate chair at the Department of Integrative Biology, director of the Center for Infectious Disease Ecology Research (CIDER), and courtesy professor in the Department of Global Health. Rohr has also been an affiliate of the Florida Climate Institute since 2015. His research interests encompass both ecology and public health, with a special interest in how anthropogenic changes affect wildlife populations, species interactions, and the spread of both wildlife and human diseases. In particular, his current research interests in ecology include ecotoxicology, conservation biology, and community, population, behavioral, climate change, and disease ecology. With regards to public health, Rohr is currently focused on investigating the drivers of human schistosomiasis and how to sustainably feed the projected world population of 11 billion. Additionally, he is also researching the impacts of climate change on vector-borne and other zoonotic diseases, as well as the effects of biodiversity on disease risk, and microbiome-infectious disease interactions. Outside the lab and classroom, Rohr loves spending time with his family.

Hyungsuk Tak, Ph.D., assistant professor in the ACMS Department, received his B.A. in statistics from Korea University in 2009 and his A.M. in statistics from Harvard University in 2012. Continuing his studies at Harvard, he wrote his thesis, *Topics in Bayesian Hierarchical Modeling and its Monte Carlo Computations*, and received his Ph.D. in statistics in 2016. Before coming to Notre Dame in August 2018, he was a postdoctoral fellow at SAMSI ASTRO/UNC STOR. His main research interest is in astro-statistics. He also studies time delay cosmography for inferring the Hubble constant, as well as robust statistics, Bayesian hierarchical modeling and computation, Bayesian-frequentist unification, and statistical computation, including Markov chain Monte Carlo. Tak is preparing for the era of the Large Synoptic Survey Telescope (LSST) and is working to develop practically motivated data analysis tools with astronomers and astrophysicists here at Notre Dame.

Thomas Totten, Ph.D., visiting assistant professional specialist in the Department of Applied and Computational Mathematics and Statistics, received his B.S. in mathematics from the University of Notre Dame before earning his M.A. in actuarial science at Ball State University. He earned his Ph.D. in business administration at Oklahoma State University. Totten, a fellow of the Society of Actuaries, created a startup company called Votaire that uses actuarial sciences to help clients more successfully build retirement plans. Totten honed his actuarial skills during tenures with the international firm Hewitt Associates and United Actuarial Services, where he was the chief health care actuary. Totten is a retired CEO and current chairman of the board of Nyhart and has acquired 10 firms for the company, which has grown into a well-known, national firm. Nyhart has now partnered with Notre Dame to create a new course for undergraduates who aspire to a career in actuarial science. The research-based course consists of using actuarial science to solve major problems facing the retirement industry. As a Notre Dame alumnus, he had always hoped to return to the University in some way. In Totten's free time, he races his Orbea bicycle and spends time with his family.

Katharine White, Ph.D., Clare Boothe Luce Assistant Professor in the Department of Chemistry and Biochemistry, joined the University of Notre Dame in early 2019. White started her professional education by earning her B.S. in chemistry from Saint Mary's College in 2007, where she was also granted the American Chemical Society Outstanding Undergraduate Research Award that same year. She then went on to receive her Ph.D. in chemistry from the Massachusetts Institute of Technology in 2012. After her Ph.D., White completed a Ruth L. Kirschstein National Research Service Award Postdoctoral Fellowship at the University of California–San Francisco. White's research is concerned with the temporary increases in intracellular pH that are required for healthy cellular processes and that, when dysregulated, are associated with diseases like cancer. By understanding protonation events and their impact across different biological scales, such as effects on cellular proteins, cell-to-cell communication, and the mutational landscapes of human cancers, White hopes to expand what we know about the molecular mechanisms of cancer. The long-term goal of her research is to exploit these mechanisms for safer and more effective cancer treatments and to identify the cancer subtypes and specific patients who would benefit most from such therapies.

Rebecca Whelan, Ph.D., is an associate professor in the Department of Chemistry and Biochemistry at the University of Notre Dame. Whelan completed her B.A. in chemistry and English at Lawrence University in Wisconsin in 1996, after which she earned her Ph.D. in chemistry from Stanford University in 2003. Shortly after, she worked as a postdoctoral researcher at the University of Michigan, before becoming an assistant professor, associate professor and then chair of the Chemistry and Biochemistry Department at Oberlin College, where she spent the last 14 years prior to her arrival at Notre Dame. The Whelan Lab is motivated by the need to detect and treat ovarian cancer in its early stages, when therapeutic intervention is most effective. Current projects include identifying and validating DNA aptamers for ovarian cancer biomarkers and proteomics analyses of those biomarkers. Whelan is the recipient of the W.M. Keck Foundation Fellowship, the Gordon Research Conference in Bioanalytical Sensors Chair's Award, and the Henry Dreyfus Teacher-Scholar Award; she is also a Stanford University Distinguished Alumni Scholar. When not thinking about DNA aptamers, bioinformatics, or mass analyzers, Whelan can be found exploring the streets of South Bend, practicing taiko drumming, posting her radio shows on Mixcloud, or trying to bake the perfect apple pie.

Victoria Woodard, Ph.D., assistant teaching professor in the Department of Applied and Computational Mathematics and Statistics, earned her B.S. in actuarial science and first M.S. in mathematics from Ohio University. Woodard went on to earn her second M.S. in statistics from North Carolina State University, where she eventually continued on to receive her Ph.D. in mathematics and statistics education. Before coming to Notre Dame in July 2018, she taught calculus, statistics, and statistical computing at Meredith College in Raleigh, North Carolina. Woodard is focused on statistics education, especially on incorporating advanced teaching and learning technology into the classroom. She enjoys applying her research findings in her classes and seeing her students learn and succeed as a result. Her favorite things about Notre Dame are the dedicated students and supportive colleagues, along with having the ability to conduct independent pedagogy and apply her own research to her classroom. She feels that she has a say in the way she teaches her classes and appreciates having her voice heard.

Bridging the Divide Between Science and Policy

RYAN SHEEHY

With the recent polar vortex in the northern Midwest, hurricanes bringing record flooding to the Carolinas and Texas, and severe drought in southern California, weather greatly impacts our lives today more than it ever has. The importance of studying not only weather but how climate may change in the near future is clear; however, another essential investigation lies in how prepared major cities are to cope with these changes.

The University of Notre Dame is making great strides in this research, endeavoring to make this information more readily accessible to both policymakers and the public. Patrick Regan, associate director of the Notre Dame Environmental Change Initiative, has been a part of this bridging between science and policy with the Urban Adaptation Assessment (UAA). UAA is a free, open-source program funded by the Kresge Foundation that provides a practical model for the future impact of climate change on urban areas. "The Notre Dame Global Adaptation Initiative (ND-GAIN) had an index that ranks different countries in their readiness to confront global changes brought about by overcrowding, resource constraints and climate disruption. The UAA is a downscaled version of this rating that looks at cities within the United States to assess the different regions of the country."

The UAA is an interactive database that uses intermediate rates of National Oceanic and Atmospheric Administration (NOAA) weather and climate change estimates to predict the effects of sea-level rise, drought, and the probability of other climate hazards, projecting until 2040. "NOAA has the environmental data out there. All we did was aggregate them and put them in a way that the local mayor could visualize it," said Regan. Combining the U.S. Coast and Geodetic Survey, the Weather Bureau, and the U.S. Commission of Fish and Fisheries into one agency under the Department of Commerce, NOAA studies the Earth and environmental changes and manages environmental resources to promote a healthy global environment.

The UAA provides climate vulnerability data for more than 270 U.S. cities and calculates projected costs based on location and current infrastructure for each city according to varying rates of environmental change. "[The UAA] shows where the projected sea level rise will be as well as what areas will be impacted," said Regan. He hopes that this program will incentivize cities to "start to adapt to the pressures of the coming climate change." For example, assuming an intermediate rate of climate change, there will be a 1.3-foot sea level rise in New York City by 2040, which would cost New York about $2 billion. The program's projections should grab the attention of lawmakers and governmental officials and lead them to consider allocating funds to prepare for this situation.

More than just presenting the scientific data and potential costs, the UAA aims to make local officials aware of sub-city regions that may be affected more greatly by climate change. The UAA shows demographics of these regions, such as median household income, race and ethnicity percent, percent of single mothers, and more, so that policymakers can better visualize the vulnerability of different areas and allocate funds accordingly. "These data do not tell them where to put the sea walls; it's not advice, but it makes the town council think about various things with regard to how taxpayer money could be most efficiently spent," said Regan.

UAA takes different cohorts of data and makes this data easily accessible and understandable for city officials and the general public; this is an essential stepping stone that is often overlooked, letting beneficial scientific research go unapplied to real world issues. The free program is being marketed to city officials across the nation so that it can be used to help prepare cities for inevitable climate change. Regan and Notre Dame communications have written op-eds and attended conferences to bring exposure to the UAA tool. Regan is even teaching a one-credit course this semester: "[The course] teaches students how to use the UAA tool, pays for their plane ticket home, and prepares them to talk to their mayor or local sustainability officer about the interface," said Regan. These efforts spread awareness of the UAA and help bridge the divide between scientific knowledge and policy decisions, allowing local officials and the general public to have a greater understanding of scientific and social impacts of climate change in the near and far future.

The Urban Adaptation Assessment provides a practical model for the future impact of climate change on urban areas

Center for Research Computing Participates in NSF Cyberinfrastructure Center of Excellence Program

AIDAN CROWLEY

As technology rapidly advances and scientists develop new methods to gather increasing amounts of data about the natural world around us, critical questions emerge. How do we securely archive and share the immense quantity of data we collect? How can data scientists process this information efficiently? In what ways can data sharing be streamlined to facilitate collaboration and progress among scientists around the world?

Researchers from the Center for Research Computing (CRC) at the University of Notre Dame are working on a $3 million pilot project funded and supported by the National Science Foundation (NSF) to explore how NSF can more efficiently help large-scale research facilities address these and other common needs. Dr. Jarek Nabrzyski, Dr. Jane Wyngaard, and Dr. Charles Vardeman are three of the lead CRC researchers tasked with creating a model and strategic plan for a Cyberinfrastructure Center of Excellence. The goal of the CRC is to use computational tools and services to solve large-scale problems in the community, and even internationally, by translating technologies into solutions to scientific challenges. "Scientists come to us with their challenges, and our goal is to help solve these with computer and data technological solutions," said Wyngaard, CRC data science technologist. The results of this pilot project will be used to benefit large research and data-collecting facilities of the NSF.

"The NSF currently supports nearly 20 research facilities that operate in a number of scientific fields and are intended to collect and analyze an immense amount of data," said Nabrzyski, director of the CRC and concurrent professor of computer science and engineering. "In order to handle all that data and computation, a state-of-the-art cyberinfrastructure, as well as adequate tools, are necessary to serve each facility." Collaborating with the University of Southern California, Indiana University, the Renaissance Computing Institute, and the University of Utah, CRC researchers are developing a program that will analyze data management and data processing systems to aid data storage and sharing among NSF research facilities. The NSF funds several multimillion-dollar research and data-collecting facilities, such as the IceCube Neutrino Observatory in Antarctica and the National Ecological Observation Network (NEON). Each of these facilities faces a similar set of problems—how to preserve immense amounts of data, deliver them to scientists, and analyze them—all the while ensuring that their research and data-collecting methods advance in parallel with the advancement of technology. The pilot cyberinfrastructure project will help large-scale facilities like these to collect data in a streamlined manner and make data more available to researchers, especially moving into the future as technology and data-collecting methods rapidly advance. "Our goal is to use this project to develop new data strategies and understand how cyberinfrastructure models can be reproducible and relevant even 10, 20, 30 years into the future," said Nabrzyski. Specific focuses of the project lie in best methods to curate and preserve exceedingly large stores of data collected at NSF research facilities. By addressing areas such as data management, reproducibility, and reuse, this cyberinfrastructure pilot project aims to ensure that the data-mining technologies these facilities use today can be translated into the future.

The pilot project is split up into various areas: simplifying data, data collection pipelines, data security, data sharing, and data preservation. The vision for the project in the future is to determine the best way for centers like the CRC to help large-scale research facilities like those of the NSF. The long-term goal is to establish a Cyberinfrastructure Center for Excellence to support these research facilities. The researchers are currently in the conceptualization phase of their two-year pilot program, working to understand challenges that scientists encounter in running these facilities and what expertise they need from the outside, as researchers at these facilities often do not have the time or experience to manage these large amounts of data on their own. The program will be reevaluated in September 2020 after the initial two pilot years have passed.

When asked about the biggest challenges of the project, Wyngaard mentioned, "It can sometimes be difficult engaging with a large research facility, as it requires finding the right people to talk to amongst many and building trusted relationships with them." Nabrzyski expanded on Wyngaard's comment, adding, "It takes time to learn their history and culture—these organizations have decades of existence and momentum already. It is up to us to take the time to understand how they currently operate and what they see as feasible moving forward, and this takes time and investment on their part as well."

Despite any challenges, Notre Dame researchers have found the project engaging and exciting. When asked about the most enjoyable aspect of the project, Wyngaard said, "It is very encouraging to see large-scale facilities running on open-source tools, highlighting the maturity of these technologies and the ability of researchers to collaborate and share data across disciplines using non-proprietary tool stacks." Nabrzyski emphasized the larger-scale effects of the project, saying, "It is impressive to consider the impact that we can make—the advice that we give day to day can impact these facilities for the next 30 years. We have to be cautious about what ideas we suggest and implement, as the data acquired by the facilities is used by researchers worldwide and will continue to do so for years to come."

In discussing the future of the project, Nabrzyski emphasized, "We are preparing now for even bigger challenges. We are currently focused on single large-scale facilities, but

new questions arise when it comes to integrating these data." Wyngaard added, "With the growing multidisciplinary nature of the key questions in science, these facilities that are already very large by themselves are beginning to come together and share their data. Understanding the challenges that each of these facilities faces individually will prepare us for embracing challenges that need to be faced when they all come together."

Notre Dame Club Lends a Hand to Children in Need

KARA MIECZNIKOWSKI

Prosthetics are widely used by people with missing limbs and can generally make life much easier for someone missing a hand or leg. Unfortunately, prosthetics are often viewed as impractical for children with limb differences, being cited as too expensive and quickly outgrown. This makes access to a prosthetic less than ideal for many children and their families. Notre Dame's e-NABLE group aims to counter this problem by 3D printing free models of prosthetic hands for children in need.

e-NABLE is a global foundation that was created in 2011 by Ivan Owen, an artist, and Richard Van As, a South African carpenter who had lost his fingers in a woodworking accident. Notre Dame's chapter of e-NABLE, which includes students from both the College of Science and College of Engineering, is relatively new and only became an official club earlier this year. Michael Skinner, an undergraduate student and member of ND's e-NABLE club, elaborated on the type of prosthetics they create. "Prosthetics range; it's such a broad field. Instead of running off of robotics or batteries…[a 3D-printed model] runs off a certain flexion of your wrist," said Skinner. "So when you move your wrist a certain way, it closes the hand." The club uses the 3D printers in the Stinson-Remick Hall of Engineering on campus, and prints each prosthetic with a thermoplastic called polylactic acid (PLA). Skinner likens the process to using a glue gun. "It's like molding [plastic] with heat and then letting it cool off."

Each prosthetic hand is specific to the child receiving it. There are a variety of different models, and each prosthetic is sized and created according to the need of the child. For example, "One girl we worked with…, she was missing all of the fingers on her hand except for her pinky [finger]. So for her we had to do a different type of hand...to make sure that she fit in it comfortably," said Skinner.

Recipients of prosthetics are discovered in a variety of different ways. The club reaches out to local hospitals and acquaintances, but sometimes their discovery is less intentional. Skinner reflected on such an occasion, which involved a coincidental conversation with a late-night Uber driver. Last year, Skinner and his family were taking an Uber and started talking with the driver, who mentioned that he had a child who was missing four fingers on each hand. "I immediately thought of the work we do at e-NABLE," said Skinner. He is also aware, however, that not every child missing a limb wants or need a prosthetic: "Prosthetics aren't for everyone. Some people work very well without prosthetics; it's really just preference," said Skinner. He told the driver about the club's work and provided his contact information; shortly after, e-NABLE ND was able to build a custom 3D prosthetic hand for the child.

e-NABLE Notre Dame has served children outside of South Bend—from Michigan to Chicago—and the chapter is growing at a quick rate. Patrick Cunniff, a biochemistry major, joined the club because of his interest in bioengineering and prosthetics. "e-NABLE has provided me and many others the chance to apply some of the things we have learned in biology and engineering classes to help those who need it," Cunniff said. "Joining e-Nable has been one of the most influential and best decisions that I have made at Notre Dame, and I have loved the experiences it has provided: meeting students from different areas of study and working together to make a difference for our community as a whole."

Community Partners in Health

MATTHEW GUGGENBILLER

"What would you fight for?" This question is often asked during Notre Dame football games, both on the stadium's video screen and on TV screens across the country. This phrase is not only a question but a prerogative for all those affiliated with the University of Notre Dame to champion causes in their chosen fields globally. In response, Notre Dame and the Indiana Biosciences Research Institute (IBRI) have partnered to fight healthcare challenges both close to home and across the country.

IBRI is a state-run facility that operates to "catalyze scientific discovery and applications" resulting in "improved health outcomes for patients." Its new partnership with Notre Dame will allow for greater collaboration between the two organizations via a new IBRI office located in Notre Dame's Innovation Park. The journey began when Nitesh Chawla, Ph.D., a faculty member and data analyst at the University of Notre Dame, was named to the IBRI as a visiting fellow; in 2008, Chawla was promoted to the directorship of the Interdisciplinary Center for Network Science and Applications (iCeNSA), at Notre Dame. He has continued to conduct research in data analytics in the Department of Computer Science in the College of Engineering and remains a crucial link between the two institutes.

Through the partnership, individuals at both institutions now have access to the wealth of unique resources each organization provides, and Notre Dame particularly benefits through the vast corporate partnerships IBRI has established. This allows students, faculty, and staff to network with industry leaders and collaborate between multiple fields of study. From their partnership, IBRI gains cutting-edge technologies from the University, such as advanced electron microscopy, microCT scanning machines, and a top-notch Mass Spectrometry and Proteomics facility to aid in greater commercialization of their own academic innovations. Progress is already being made in the fields of microfluidics, Type II diabetes, and cardio-metabolic diseases. Many professors are already taking advantage of this unique partnership to work on breakthroughs that cross disciplines.

Michael Puglia, Ph.D., a researcher affiliated with the University and with IBRI, is working across all three of these disciplines to develop new diagnostic tests for Type II diabetes. Puglia has obtained samples from the Fairbanks Institute Tissue Core to aid in his research. With these new tissue samples, Puglia hopes to develop more accurate tests for acute inflammation, insulin resistance, and autoimmunity risk factors in patients with Type II diabetes. In addition to his bioengineering work with Type II diabetes, Puglia's research extends into cardiovascular disease. He is hopeful that the future partnership across all three organizations will result in a simple blood test that will accurately predict the likelihood of cardiovascular disease via analysis of the presence of a certain antibody in the blood. Promisingly, $50 million of grant funding for this project has been pledged by the state of Indiana, Lilly Endowment, Eli Lilly and Company, Roche Diagnostics, Dow AgroSciences, Indiana University, and the Indiana University School of Medicine. In the future, the researchers hope to aid patients and clinicians in differential diagnosis and treatment options.

The future of healthcare is growing in complexity and will require a multidisciplinary approach in solving its multifaceted challenges. Research relies on resources, and unfortunately many research projects are scrapped or discarded because they lack the funding necessary to pursue their innovative ideas. Interdisciplinary partnerships, such as the one between IBRI and Notre Dame, will pave the way for researchers to continue their innovative work and improve the lives of millions across the country.

Enhancing Cancer Immunotherapy Using Reactive Nitrogen Species (RNS)

CESAR MORENO

Cancer is one of the most pervasive health issues society faces today. Aside from requiring unique, case-by-case analysis, its hijacking of an individual's own cells makes it especially difficult to treat. Over time, cancer becomes resistant to all forms of treatment, mutating and evolving to survive. As we learn more about cancer, we search for new forms of treatment to combat that evolution. An exciting new type of therapy, immunotherapy, utilizes a patient's own immune cells to treat the malignancy. These immune treatments are often plagued, however, by myeloid-derived suppressor cell (MDSC) secretion of extremely reactive molecules known as reactive nitrogen species (RNS), which prevent the activation of immune cells. However, a study by assistant professor Dr. Xin Lu's laboratory in Notre Dame's Department of Biological Sciences has identified a method of neutralizing this effect and improving immunotherapy efficacy.

Immunotherapy aims to program the body's own T lymphocytes to attack the cancer cells present. T cells are activated by the presentation of pathogenic compounds on a compromised somatic cell to a T cell receptor, which activates the lymphocytes to kill the infected cells that present those compounds. MDSCs, however, prevent this seemingly ingenious process from taking hold. These cells affect the body's immune response by inhibiting T cells from multiplying in response to a disease; the key to preventing this suppression lies in understanding how and why it occurs in the first place.

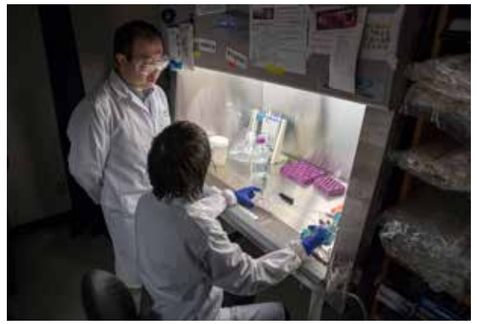
According to Lu, "MDSCs produce free radicals called reactive nitrogen species to modify amino acid tyrosine in proteins of cells around, including T cells… which alters and prevents normal T cell responses." This immune limiting response is extremely important, because it prevents the T cells from over-responding and causing an autoimmune disease (attacking of healthy somatic cells). By functional definition MDSCs can then prevent needed immune responses. There is thus a delicate balance between suppressing and activating the immune system. In some solid tumors, MDSCs are the most abundant immune cells present in cancer microenvironment, an important mechanism these cancers employ to evade the immune system. While Lu concedes that the particular mechanism that MDSCs utilize is poorly understood, "there have been several references to the importance of inhibiting reactive nitrogen species secretion from MDSCs." Nitration (by RNS) of lymphocyte-specific protein tyrosine kinases (LCKs) is implicated in the reduced production of interleukin 2 (IL-2), an important cytokine (the immune system's chemical communication language) involved in T cell activation. The Lu Lab postulated that the inhibition of these RNS might lead to better T cell activation. In their paper, myeloid-derived suppressor cells inhibit T cell activation through nitrating LCK in mouse cancers, the group investigated RNS neutralization in the treatment of prostate cancer and lung cancer in mice.

After confirming the involvement of LCK nitration in the suppression of T cells, Lu's laboratory sought to inhibit the RNS by using uric acid (UA). According to Lu, UA is a very potent peroxynitrite neutralizer that can help negate the RNS from MDSCs. In their experiment, the researchers compared the number of T cells present following immune checkpoint blockade (ICB, the specific form of immunotherapy attempted in this study), a co-culture containing UA, and a combination of the two.

Lu found significantly higher numbers of activated cytotoxic T cells when the immunotherapy and uric acid were combined together in the tumor-bearing mice. While UA alone showed no statistical difference in its effects compared to the control, its combination with ICB showed a nearly three-fold number of cytotoxic T cells (T cells involved in killing

compromised cells) and a decrease in T regulatory cells (cells that inhibit immune responses). After three weeks of treatment, mice showed tumor volumes approximately five times smaller than that of mice treated with just ICB or UA, and 10 times smaller than those with no treatment at all.

Lu believes that the findings have broader implications and can likely be applied to solid tumors in future clinical cancer diagnosis and treatment. For him, the question is now: "How do we develop antibodies that can identify specific MDSCs?" This area is the topic of his current research, and his newer projects are working to develop monoclonal antibodies that can quickly and specifically detect activated MDSCs. The identification of MDSCs, the Lu Lab believes, would go a long way in helping to create individualized treatments for each patient.



Dr. Xin Lu and his laboratory are working toward improving immunotherapy efficacy with the use of reactive nitrogen species

Notre Dame Unveils Largest Hypersonic Quiet Wind Tunnel in the United States

MADDIE COLE

In November 2018, history was made at Notre Dame with the grand opening of the United States' first Mach 6 wind tunnel. The $5.4 million project was funded with grants from the University of Notre Dame and the Department of Defense. With a nozzle exit diameter of 60 centimeters—2.5 times larger than any other hypersonic tunnels in the United States—the tunnel's innovative design will allow for the conduct of experiments not previously possible. Thomas Juliano, professor in the Department of Aerospace and Mechanical Engineering and principal investigator on this project, commented that although the Department of Aerospace and Mechanical Engineering at Notre Dame "is known for larger scale experimental fluids projects...no one has ever completed something like this before."

Juliano completed his master's and Ph.D. work at Purdue University, where he focused on the design and creation of test facilities. After his work at Purdue, he conducted research at the Air Force Research Lab in Dayton, Ohio, where he contributed to hypersonic flight-test programs. Upon his arrival to Notre Dame in August 2014, he began work on proposals and plans for the Mach 6 quiet wind tunnel.

The Mach 6 tunnel is unlike any other, Juliano notes, due to its "combination of high speed, large size, and quiet performance," and is specifically designed to minimize acoustic disturbances that have been a problem in other hypersonic wind tunnels. The label refers to the speed at which the tunnel operates: at six times the speed of sound. In an amazing feat of engineering, the tunnel contains a special research feature that "allows researchers to more accurately predict aspects of flight through the atmosphere," Juliano said.

In addition to this most recent addition to the Notre Dame Aerospace and Mechanical Engineering Department, only two other hypersonic quiet tunnels exist in the United States: one at Purdue University and the other at Texas A&M University, (previously at NASA Langley). However, the tunnel built by Juliano and his team is much larger than its predecessors and allows researchers to conduct more and larger experiments. In collaboration with Purdue University, two successor facilities will be built in the next three to five years; a Mach 8 tunnel at Purdue, followed by a Mach 10 tunnel at Notre Dame.

As the principal investigator, Juliano said that a team of people ultimately made the project come together: technical staff at the White Field Laboratory, machinists in the engineering machine shop of Hessert, and other technical support organizations on campus offered expertise necessary to bring the project to completion. Graduate and undergraduate students also contributed to parts of the design.

Ultimately, Juliano believes that the tunnel has the potential to aid in the design of future high-performance hypersonic vehicles. Relevant experiments have been slated to occur in the near future, the first of which will measure the flow quality of the tunnel itself.

The PAD Project: Fighting for Better Illicit Drug Detection

NOEL VINCENT

Over a century of innovation and regulation within the U.S. pharmaceutical industry continues to bring confidence to household decisions regarding medications. Internationally renowned, the stringent and uncompromising drug review process of the U.S. Food and Drug Administration (FDA) is considered to be the "gold standard" of pharmaceutical regulation. From drug development to postmarketing oversight, spanning years of trials and inspection, the FDA serves as a watchdog on behalf of the American people.

Unfortunately, millions of people around the world find themselves without such regulatory protection. In certain developing countries, those suffering from illnesses have the additional burden of potentially falling victim to ineffective and even dangerous counterfeit medications. Such products are a result of the illicit drug supply chain networks that have sprung up in the absence of adequate regulation. In the Department of Chemistry and Biochemistry at the University of Notre Dame, the Lieberman Lab is addressing this issue by bringing the fight to the network's doorstep.

In a recent study, the World Health Organization (WHO) found that "about 10% of the medicines that people use in the developing world [...] are either falsified or substandard," said Dr. Marya Lieberman, a professor of analytical chemistry and head of the Lieberman Lab. In addition to being ineffective, falsified drugs can contain fillers that cause complications in patients, and substandard medications allow the survival of pathogens that are "differentially resistant" to the drug, further complicating the patient's condition. Ultimately, poor-quality drugs contribute to the growing issue of worldwide antibiotic resistance in addition to increasing unnecessary human suffering.

The detection of poor quality medications has always been a slow and expensive process. Samples need to be sent to labs where methods like High Performance Liquid Chromatography (HPLC) are used to delineate sample components. "The problem right now is that it takes at least a year from the time you find a bad-quality medicine for a report or publication to go out saying that it was bad," says Sarah Bliese, a graduate student in the Lieberman Lab. "By that point the drug isn't even on the market anymore, so it's not benefiting anyone." This is where the Lieberman Lab has chosen to innovate. By developing a new technology called the Paper Analytical Device (PAD), the Lieberman Lab is able to track fake medications in real time. The PAD is a essentially a miniature laboratory that can be used quickly and efficiently by field researchers. With just a simple swipe of a medication across the center of a PAD, reactants placed along the 12 lanes of the PAD change colors with respect to characteristic functional groups on the medications, allowing for instantaneous assessment of whether the drug is fake.

The project is a recipient of the National Science Foundation's Early-Concept Grant for Exploratory Research (EAGER). Government partners in Kenya, Malawi, Tanzania, Uganda, and Ethiopia have begun to use the PADs to screen drugs in ways they have been unable to before. These partners also send back samples to the Lieberman Lab for confirmatory analysis using more quantitative instrumentation. In addition to their collaboration with international partners, the lab also works with colleagues closer to home. Dr. Christopher Sweet and his team at Notre Dame's Center for Research Computing are involved in automating the analysis of the test results so that the color barcode produced by PADs can be quickly read by computers, ensuring an accurate read of the data. In addition to barcoding—to address the problems of keeping track of medications—the lab is also exploring blockchain techniques to enter data into shared notebooks. (Blockchain is the same technology used by cryptocurrencies like Bitcoin). This new, secure way to share data would allow for more citizen scientists to join the efforts out in the field.

Dr. Marya Lieberman's laboratory has developed the PAD device to address illicit drug supply chain networks

The falsification of drugs is not a novel crime. Illicit medication can be traced back to ancient Greek apothecaries, which resorted to using cheap production methods, and even early Latin manuscripts have been found to report many false painkillers. This plague of illicit drugs has followed humanity into the modern age. When the first herbal antimalarials were shipped out of South America, "people were complaining about fake Peruvian bark," said Lieberman. "It's just people. People sometimes act for their own self-interest and they may try to make some money, selling a product that everybody seems to want."

There is still much more to be done to combat falsified and substandard drugs. Transparency issues are prevalent among nations that would rather not admit to the international community that there are poor-quality drugs in their markets. Lieberman mentioned that the airline industry went through the same conversation regarding reporting safety concerns. Ever since a system that encouraged transparency was enacted, the airline industry as a whole has been much safer. A similar attitude among regulatory agencies could incentivize the reporting of instances of illicit drugs. Alongside combating illegitimate drugs, rewarding companies that make the proper investments of time and money to produce drugs properly would encour-

age integrity within the pharmaceutical supply chain. Making track records of different manufacturers available to the public would allow governmental bodies, which make multibillion dollar healthcare decisions, to make more educated choices.

"What really draws me to this research is that you know instantly why this work matters," said Blise, alluding to her time abroad working on the PAD Project. "You get to use [the PAD] in the way that you always hope it would get to be used." If the project continues to succeed, the lab plans to enter the fight against the opioid crisis in the United States, partnering with law enforcement to detect different types of opioids out in the field.

Re-Personalizing Medicine: The Pathos Project

BRYAN MIN

When Ruth Hillebrand received a call late one night, she was not expecting a physician she had just met to abruptly deliver a terminal cancer diagnosis over the phone. Unfortunately, her experience is all too common. As medicine has become more and more standardized and ruled by insurance claims, patients have become increasingly depersonalized. Depersonalization in one of the most personal professions arose as a means of convenience for both physicians and the health system as a whole; though depersonalization does allow for greater quantitative patient care and seemingly higher efficiency, it has also perpetuated and exacerbated a lack of compassion between physicians and their patients. Fortunately, physicians, healthcare professionals, and patients have recognized the gaps in physician education and have begun to advocate for changes to the system. Notre Dame has led the way in the push for greater compassion in medicine.

Enter Dr. Dominic Vachon and the Ruth Hillebrand Center for Compassionate Care in Medicine. Opened in 2011, the Hillebrand Center is one of two included in Ruth Hillebrand's will dedicated to training future physicians in truly compassionate care. Another center exists at the University of Toledo Medical School, handling patient communication training. But even before future physicians enter their graduate training, they must begin to focus on the importance of compassion in their intended career. Consequently, the Hillebrand Center at Notre Dame is becoming known for teaching future healthcare professionals the importance and principles of compassionate care in medicine. Vachon, a medical psychologist, currently serves as the director of Notre Dame's Hillebrand Center. When describing the formulation of the center and its focus on the undergraduate level (unique to many physician training programs), Vachon described its founding: "...the argument was made," said Vachon, "[to] start earlier with this [training] since this is not going well." Beginning training at the undergraduate level is accomplished through the Compassionate Care in Medicine Club and Vachon's one-and-a-half credit course, "Introduction to Personalism in Medicine: the Pathos Project."

The Pathos Project is one of many classes offered by the Hillebrand Center and is focused on instilling the spirit of compassionate care in the context of a system that discourages any kind of personalization. The class meets once a week and emphasizes hands-on learning and student discussion. The traditional component of the course consists of a workshop teaching the skill of "being-with," a foundational skill for the course and for compassionate care in medicine. The course also attracts eight visiting physicians who share their stories of maintaining a person-centered mindset in their practice. The second, unique part of the course requires students to actively engage in the community and with vulnerable populations. This volunteer work involves the skills learned in the classroom: active listening, experiencing the nature of suffering, exploring the physician-patient relationship, and understanding biomedical reductionism. With these two components in hand, Vachon said, "You have the Pathos Project."

So why has one of the most personal and helpful of the "helping professions" become so depersonalized? Depersonalization in medicine is often cited as necessary for the protection of a clinician's mental health in the context of an extremely stressful and emotionally taxing job. Becoming too involved with the patients has been viewed as weakness, as it leaves the physician vulnerable to experiencing great patient suffering. However, according to Vachon, "When we are connected to our patients, our patients benefit, but so do we. It's this mysterious dynamic." The benefits of the patient-physician relationship based on empathy and mutual respect are still being studied. Unfortunately, new advances in medical technology can remove the humanism from medicine as patients start to be seen as simply organs and bodies; the holistic approach to medicine has declined in favor of a new, more "scientific" medicine. Thankfully, there is a new wave of scientific study of compassion, powered by clinicians and scientists that share concerns for both sides of the healthcare field: physician burnout is occurring at an alarming rate, patient satisfaction is at an all-time low, and there are widespread accounts of experiences very similar to that of Ruth Hillebrand's. "Patients aren't happy, clinicians aren't happy, no one's happy," said Vachon, who is among the many who believe compassion is one the major factors in fixing these problems. "It was thought—it still is thought—that compassionate caring is a nice thing to add to your medical practice, but it's not essential," Vachon said. As is seen in the state of healthcare, this is absolutely not the case. "If compassion is not infused in what you do, your patients will suffer but so will you." In this sense, there is a shift in the perception of compassion, from one of sentimental or virtuous importance to one of inherent and biological necessity — humans are designed as compassionate beings.

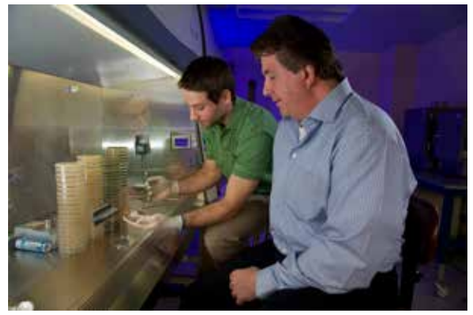
As it turns out, compassionate care is beneficial not only for doctors and patients, but for clinics as a whole. Compassion leads to better health outcomes, which is all around beneficial for every party involved. "Your patients are happier, they're more likely to come back, and their health outcomes are better if they feel a connection with you," said Vachon. The Cleveland Clinic and the Mayo Clinic are two examples of such clinics that enjoy high patient satisfaction and subsequent success due to a change in culture to one of compassion. When clinics choose to treat people well, business is more successful and clinicians are happier.

The roots of the Pathos Project were with two Notre Dame graduates (Dr. Yuri Maracich and Dr. Keri Oxley) who were troubled by the depersonalization they experienced in medical school both of patients and the medical students themselves. Piloted at Notre Dame nine years ago under the direction of Fr. James Foster, C.S.C., M.D., this course continues to attract students who want to prepare for the challenges of working in healthcare. As big of a problem as it is, Vachon is optimistic in the efforts being made. "In the middle of crisis is danger, but also opportunity," Vachon said, and though the problem is extensive throughout the medical profession, the Pathos Project and the Hillebrand Center offer new hope for the future.

Warren Family Research Center Engages in Collaborative Projects Worldwide

ZHEFAN "LAURE" ZHANG

In August 2018, Notre Dame's Warren Family Research Center for Drug Discovery and Development announced its collaboration with Perlara, a rare disease drug discovery platform company, on a project that aims to develop more effective treatments for a variety of glycogen storage disorders (GSD). This strategic move immediately gathered the interests of the scientific community and industries worldwide. Followers of the Warren Family Research Center are not surprised by this recent development, as the collaboration is simply the most recent iteration of the center's rich drug discovery portfolio. Dedicated to creating new collaborative opportunities, the center has enabled its faculty researchers to connect with expertise outside of their own research areas.



Richard Taylor has led several collaborations with international teams to develop treatments for rare diseases

Collaborations with companies such as Perlara are "a representation of our strength," said Richard Taylor, the interim director of the Warren Family Research Center from 2014 to 2017. "Most Warren Center researchers have collaborations with external academic and industrial partners. The projects are never limited to this University or to the United States." In the past years as interim director, Taylor has led several collaborations with international teams to develop treatments for rare diseases. One highlight is a cooperation with the Grace Science Foundation and the biopharmaceutical company, Retrophin, on the study of NGLY1 deficiency, a complex neurological syndrome that results in a variety of enervating symptoms. The research work currently involves more than 30 researchers from around the world. After hearing about Taylor's work on NGLY1 deficiency, a family with a loved one suffering from Cori disease (GSDIII) asked for the help of his research team. Taylor decided to work on GSDIII following this conversation, and recruited Perlara researchers as partners in this continuing conversation with the family.

GSDIII is caused by the mutation of a protein essential to the metabolism of glycogen. This mutation may lead to low blood sugar and an enlarged liver along with weakness and stiffness of muscles. Researchers from the Warren Center have been engaged in the study of Cori disease since 2018. The Notre Dame-led project aims to develop simple organism models that can be used to screen and identify compounds for improving symptoms related to Cori disease. "By working with simple organisms like worms and flies, it's less expensive to treat the use with a large number of compounds, so you can determine which parts of a large set of compounds are potentially beneficial," Taylor explained. The platform can help researchers to identify the small group of compounds that actually show beneficial functions on the simple organism models. Eventually, discoveries from the platform will be used to develop drugs used in human trials.

This is not the first time the Warren Family Research Center has reached out to other teams for collaboration on the treatment of Cori disease. Taylor previously initiated an effort to work together with researchers at Indiana University School of Medicine who concentrate on Lafora disease, an autosomal recessive genetic disorder. According to recent findings, scientists have found that particular approaches to Lafora disease can be applied to treat Cori disease. The two teams have collaborated to establish a new, ongoing mouse model to test their hypothesis, and are looking forward to the potential results revealed by this experiment.

In the near future, Taylor anticipates more teamwork between Notre Dame scholars and outside partners. He believes that it is important for researchers to realize the importance of bringing individuals with different areas of expertise together,

particularly in the field of rare disease. To effectively impact the multitude of diseases under the "rare disease" umbrella, the Warren Family Research Center will continue to strive to discover treatments for rare diseases through partnerships.

"The Notre Dame community plays an essential role in this process and is extremely supportive to research projects that are well aligned with our Catholic mission," Taylor added. "It's very important for undergraduate and graduate-level students to realize that they can participate in the research on rare diseases as well. Their capabilities go far beyond the simple education system—we are not merely providing training exercise in the lab, but actually trying to solve problems, and students can be a major part of that."

Notre Dame Fosters Growth and Leadership Through Summer Biology REU

RYAN MIDDLETON

Each summer, the University of Notre Dame invites 12–14 undergraduate students from around the country to engage in the University's Biological Sciences Research Experience for Undergraduates (REU), funded by the National Science Foundation (NSF). The purpose of the 10-week program is to provide research opportunities to students from universities with smaller amounts of research funding. This year, Notre Dame hosted students from various states and U.S. territories, from Oklahoma to Puerto Rico. The REU also partnered with Notre Dame's Naughton Fellowship and hosted two international students from Ireland. Each student in the program is placed in a research laboratory on campus: research projects for the biology REU are quite diverse, ranging from the investigation of cancer and cell death mechanisms to the study of tuberculosis virulence.

One of the students involved in this year's REU was Floyd Nichols, a senior undergraduate student at St. Vincent College in Latrobe, Pennsylvania. His research project was completed in Dr. Melissa Berke's lab and examined microbial population composition of permafrost samples from different altitudes across Alaska in order to determine differential levels of soil nutrients and fungi/bacteria ratios. Nichols shared his thoughts on the program, which, compared to his past research experiences, he believes to be the most rigorous he's encountered. "The REU program provided me the opportunity to do research that I didn't really have experience with before. I go to a small school, St. Vincent College, and we don't really have resources like that," said Nichols. "Now [the field of my REU research] is what I'm going to be pursuing [in graduate school]: biogeochemistry/earth sciences."

As an added bonus, Notre Dame's REU provides enriching experiences outside of the lab and focuses on fostering relationships between students. Nichols explained that he felt ND's REU allowed him to create lasting relationships with other scientists with whom he is still in contact and will likely remain close throughout his career. "Every once in awhile, [my advisor Melissa Berke would] send me an email and say, 'this person is looking for a Ph.D. student next year, you might be interested in the work she does.' She would always keep an eye out for astrobiologists or microbiologists [for me to get in contact with]." Aside from his mentor, Nichols continues to maintain friendships with other rising Ph.D. students who completed the program—relationships that could one day be the basis of professional collaborations among research laboratories around the nation.

REU students engaged in many activities outside of the lab over the course of the summer. On two occasions, the group traveled to Chicago—once the first weekend as a bonding experience and a second time later in the summer to tour, network with, and learn about Northwestern University. The students also volunteered with a local summer camp, teaching the children about science and hopefully igniting young passions for a field that is always in desperate need of strong and enthusiastic minds. The goal of these activities is not only to expose the participants to different environments and facilitate group bonding, but also to encourage peer leadership. Each activity is organized by one of the students themselves so as to cultivate leadership skills. The program director holds weekly meetings with the REU students to discuss the planning of these experiences as well as to check in on project progress and bring in guest speakers from Notre Dame's Department of Biology.

Nichols is very grateful for his experience with the Notre Dame Biological Sciences REU: "I'd never been to Chicago before, didn't know much about Northwestern, didn't know anything about biogeochemistry," said Nichols. "Now that is where I'm going [for my Ph.D.]: to Chicago to [study] biogeochemistry at Northwestern."

Examining Native and Invasive Flower Preferences in Wild Bee Populations

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Abstract

This experiment set out to determine if introduced and invasive flowers are less appealing to native pollinators, potentially contributing to the effects of habitat loss on these vulnerable insect populations. Invasive plants pose threats to native ecosystems by crowding out native plants and displacing native species. Wild bee populations face threats from habitat loss and fragmentation. To determine non-native flowers' effects on wild bees, I observed plots of either native or introduced wildflowers and counted the number of visits made by different genera of bees. I found no significant preference for native or introduced flowers in five of the six genera observed. One genus, Lasioglossum sp. showed a significant preference for introduced flowers.

Introduction

Insect pollinators face a wide variety of threats, from habitat loss and fragmentation to pesticides to disease. The federal Pollinator Research Action Plan (1) describes the threats facing pollinators and calls for increased research to protect these integral species. Native bees, the most effective pollinators of many native plants, are a vital part of their ecosystems. Determining specific land management strategies aimed at protecting both the native plants and the insects that feed on them can facilitate healthier ecosystems.

An important aspect of land management is controlling invasive species. Invasive plants threaten native plant populations by crowding and outcompeting native plants for limited resources. In efforts to help bolster failing populations of native pollinators, providing land for wildflowers to colonize may not be sufficient: successional native plants may be required. As insect pollinators depend on plants for their food supply, any disturbance to the plant community has the potential to disturb the insect pollinator community. Some native bees, particularly Apidae genera *Xenoglossa sp*, *Peponapis sp*, and some Andreninae genera are highly specialized, visiting only one genus or species of plant (1). While these bees are an extreme example, many bees prefer specific plants, and may be unable or unwilling to feed on introduced species. Wild bees will have co-evolved with the species native to their ranges, and may or may not be willing to feed on new species. In this study, I would like to learn how invasive and introduced plant species affect the native pollinator populations.

Previous literature gives conflicting information on this topic. In a review of relevant literature, Litt et al. (2) found that pollinator prevalence decreases as invasive plant abundances increase. However, Lopezaraiza-Mikel et al. (3) found that in plots with invasive plants, more pollinators were found. Yet another study found that in reclaimed farmland, pollinators showed a preference for native plants (4). This topic is little studied, and more research is needed to determine the general effect of invasive and introduced plant species on native bee communities. In determining the potential effects these plants have on the pollinator community, land managers and others concerned with pollinator conservation can better understand how to save the vital parts of ecosystems.

The Upper Peninsula of Michigan contains unique ecosystems. A majority of this part of the state is covered in hardwood forest and forested swamp, with little urban or agricultural land (5). Wildflowers are contained to roadsides and occasional meadows. Bee diversity in the Upper Peninsula is lower than in many parts of the Lower Peninsula (6), though this could be due in part to sampling bias.

Methods and Materials

Study Site

All research was conducted at the University of Notre Dame Environmental Science Center on the border of Wisconsin and the Upper Peninsula of Michigan. The Center sits on 7500 acres containing hardwood forests, lakes, streams, bogs, and meadows. The plots used in this experiment were largely found in meadows, with some placed along roadways (Figure 1). To determine the food preferences of wild bees, I found 33 plots containing primarily one type of wildflower. Flower species can be found in Table 1. Plot size was not standard due to differing densities of flowers. I attempted to standardize flower density, prioritizing that metric over raw plot size. All plots were roughly one meter square, with none larger than 2 m^2 or smaller than 1 m^2.

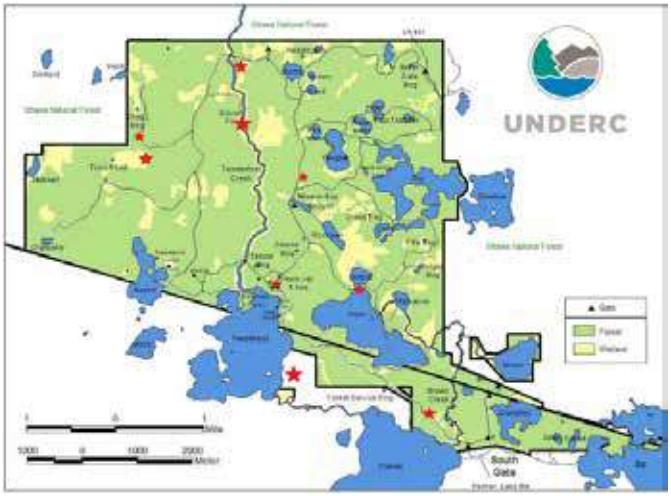

Figure 1. Site map of the UNDERC property. Plot locations marked with red stars. Several meadows contained multiple plots. Map from https://underc.nd.edu/

Flower Name	Plant Status	Description
Ranunculus acris	Introduced	Tall buttercup. Small, five-petaled yellow flowers on top of a 1' – 3' plant.
Hieracium aurantiacum	Introduced	Devil's paintbrush. Small orange flowers, many petals, on a short fuzzy plant.
Trifolium repens	Introduced	White clover. Very small: plants, clusters of three leaves, single round white flower on top. Common in lawns.
Trifolium pretense	Introduced	Red clover. Clusters of three leaves, plant terminating in a purple globular flower.
Chrysanthemum leucanthemum	Introduced	Common daisy. Yellow center surrounded by white petals. Single flower on a stalk 1' – 3' tall.
Potentilla recta	Introduced	Sulfur or rough-fruited cinquefoil. 5 petaled yellow flower, reminiscent of a simple rose. Flowers in clusters on a plant 3'' tall. Stems hairy at the top.
Lamium purpureum	Introduced	Purple Dead Nettle. Sprawling plant with a square stem. Uppermost leaves tinged with purple. Spike of small purple flowers.
Linaria vulgaris	Introduced	Yellow toadflax, butter and eggs. Small plant with narrow leaves and yellow flowers in a raceme.
Melilotus alba	Introduced	White sweetclover. Clusters of three leaves, racemes of tiny white flowers. Plants from 3' – 8' tall.
Lotus corniculatus	Introduced	Bird's foot trefoil, butter-and-eggs. Low, sprawling plants. Yellow flowers, leaves in clusters of five, though three are more prominent than the last two.
Iris versicolor	Native	Blue flag iris. Large, showy, dark purple flowers with a yellow patch at the base of the petal. Single flower on a stalk 4'' – 31'' tall. Leaved flat, oval, nearly as tall as the flower stalk. Grows in dense clumps.
Asclepias syriaca	Native	Common milkweed. Plant grows 2' – 6' tall. Large clump of white or pale pink flowers with 5 reflexed petals and an elevated central crown. Leaves very broad, opposite or whorled around the stem. Sap very thick, sticky, and white.
Asclepias incarnata	Native	Swamp milkweed. Plant grows 4' – 5' tall. Large clump of deep pink flowers with 5 reflexed petals and an elevated central crown. Leaves long and narrow. Very thick white sap emerges upon breaking leaves.
Rubus allegheniensis	Native	Blackberry. Somewhat sprawling plant, were upright than related plants. Older stems woody, all covered in sharp prickles. 5 petaled white flowers, reminiscent of simple roses.
Stellaria sp.	Native	Chickweed. Very small white flowers. 5 petals, deeply lobed so as to appear as 10 petals. Low growing plants.
Hieracium maximum	Native	Cow parsnip. Plant can grow 3' – 8' tall. Small white flowers in a large umbel, 8'' across. Leaves very large and deeply lobed.
Rudbeckia hirta	Native	Black eyed Susan. Plants 2' – 3' tall. Single flower on each stem. Yellow petals around a dark black center. Narrow, hairy leaves.
Erigeron sp.	Native	Fleabane. Small flower bunch, yellow centers with many narrow white petals around. 1' – 3' tall.
Hypericum punctatum	Native	Spotted St. John's Wort. Clusters of 5 petaled yellow flowers at the top of a plant growing 1' – 3' tall. Leaves simple with a blunt point.
Achillea millefolium	Native	Yarrow. Clusters of small white ray and disk flowers on the top of a branching stem. 0.5' – 3.5'. Leaves almost feathery, arranged spirally on the stem.

Table 1. All species of flowers observed in my experiment. In two cases, species could not be determined due to the similarity of the species in the genus (14, 9).

Observational Methods

I observed each plot for 30 min at varying points during the day. 10am was the earliest start time, as bees are less active before then, and 5pm was the latest I began observations. All observations were made during days on which it was not raining. During each 30 min period, I recorded the number of visits made by wild bees, noting the genus for each visit. For some plots with a very high number of visits, it is probable that my counts were too low due to the abundance of visiting bees and the impossibility of counting every visit. I made an effort to visit each type of flower twice, to minimize any environmental effects. For example, several plots were along roads, and I found the same plant growing in a meadow to minimize any effect the road may have on pollinator visits. Such replication was not possible in every case due to scarcity of certain plants and time constraints. Of the 33 plots, 19 were comprised primarily of introduced plants and 14 were comprise primarily of native wildflowers. Of the 19 introduced, four are on an invasive species list for Wisconsin (WI DNR); *Melilotus alba*, *Linaria vulgaris, Leucanthemum vulgare*, *Lotus corniculata*. The rest are considered non-native, but not necessarily invasive. Because I wanted to determine the effect of non-native species on wild bees, I decided that both invasive and introduced species might reveal this, as neither would have the co-evolution of native species. There are several non-native bees in Michigan; the European honey bee, as well as a few others. I found no honey bees. It is likely that all the bees written about in this study are native to the area, though there is one non-native *Lasioglossum* (*L. zonulus*) found in Gogebic county that may have been observed.

Plants were identified to species with Newcomb's Wildflower Guide (7). I assigned each flower a status of "Native" or "Introduced." Since only a few of the introduced species were technically invasive, I merged the two categories for the sake of statistics. Bees were identified to genus on the wing, in the field. Identifying bees to species requires a specimen, and in some cases requires dissection, neither of which I wanted to attempt. I hypothesized that generic identification was enough to find statistical significance. In a few cases, I took photos and compared these photos to pictures taken by the USGS Bee Inventory and Monitoring Lab (8), which provides high quality macrophotographs of bees. Two genera were not included in my data analyses as they were only spotted at two plots, and therefore did not have enough data associated with them to reveal meaningful statistical results.

To analyze my data, I performed ANOVA tests to determine whether there was a significant difference in bee visits between native and introduced flower species. Both the bee counts as an overall count and each genus independently were tested for significant differences. All statistical tests were done using R (8).

Results

I found six genera of bees over the duration of my project. (Table 2) Two in the family Apidae (*Bombus, Svastra*), two in the Halictidae family (*Halictus, Lasioglossum*), and two in the Megachilidae family (*Megachile, Osmia*). Bombus species were the most abundant. These large, extremely fuzzy bees are eusocial, living in large hives underground. According to Gibbs et al. 2017, there are nine species of bumble bees in Gogebic County. These bees are generalist feeders, showing no loyalty to any specific type of flower. The one *Svastra sp*. found, *Svastra obliqua*, was found at three plots. This species has a scattered range in MI, and is not confirmed to be present in this county. However, I am reasonably confident in my identification, and believe that based on its scattered presence throughout the state that it is reasonable for it to occur here. *S. obliqua* live in loose aggregations of females, nesting underground. These bees are pollen specialists, feeding only on pollen from flowers in the Asteracea family, though adults may also feed on nectar from other flowers. The genus *Halictus* has one species in this county; *H. rubicundus* (7). This species displays a range of social behaviors, with some individuals nesting in weakly social aggregations and other showing solitary nesting behavior. *H. rubicundus* is a generalist species, without specificity in feeding. *Lasioglossum* species were the second most commonly observed bees. There are nine species of *Lasioglossum* in Gogebic county, one of which is an exotic species. Without identifying the bees observed to species, I do not know whether this exotic species was observed or not. *Lasioglossum* is a large genus of small sweat bees. These bees are generalists for the most part, although some exceptions exist. They are extremely abundant in the United States and are important pollinators of many wildflowers (1). The genus includes solitary, primitively eusocial, semisocial, and parasitic species. Most nest in the ground, with some nesting in rotting wood. At least one nest site was observed in my project. The family Megachilidae can be identified by the unique positioning of their pollen collecting hairs.

While other bees have these hairs on their metathoracic legs, Megachilids have their pollen collecting hairs on the undersides of their abdomens. Two genera in this family were observed in this project. *Megachile* is large genus with species that display a large range of foraging behaviors. Species are most often generalists, with only a few showing specialist feeding. All species are solitary, nesting in a variety of environments. *Megachile* usually line their nests with leaves or flower petals. Five species of *Megachile* live in Gogebic county. Finally, I observed the one species of Osmia found in Gogebic county. *Osmia lignaria,* the blue orchard bee, is a solitary bee that nests in preexisting structures like beetle burrows or dead twigs. These bees are a dark metallic blue. While generalist feeders, *O. lignaria* prefer pollinating fruit trees and vines. County records all from Gibbs et al. 2017.

Bee Family	Bee Genus	Description
Apidae	*Bombus sp.*	Large, densely hairy bees. Bright yellow and black striped bees, occasionally with orange on the abdomen. Eusocial, generalist feeders.
	Svastra obliqua	Large, fuzzy golden bees. Males with extremely long antennae. Solitary, pollen specialists on Asteraceae, though adults will eat nectar from other flowers.
Halictidae	*Halictus rubicundus*	Small, dark bee. Prominent white stripes on the abdomen. Pollen pockets on metathoracic legs. Generalist feeders. Variable sociality.
	Lasioglossum sp.	Large genus, generally small, dark bees. With or without striped abdomens. Wing venation weakens near margin. Variable sociality, generalist feeders.
Megachilidae	*Megachile*	Large genus, medium to large bees. Pollen carried on the underside of the abdomen as opposed to on the metathoracic legs. Individuals observed in this experiment superficially resembled *Bombus*.
	Osmia lignaria	Small, dark metallic bees. Solitary. Generalist feeders although they prefer fruit trees.

Table 2. The families and genera of the bees observed in this experiment. Three genera were monospecific for Gogebic county, and are identified to species in the table (7).

Overall, there was no significant difference in number of visits by wild bees to native and introduced flowers (Kruskal-Wallis chi-squared = 0.062407, df = 1, p-value = 0.8027). Examining each genus of bee separately, I found that *Bombus, Svastra, Halictus*, and *Megachile* showed no preference for native or introduced flowers (p=0.814, p=0.134, p=0.2336, p=0.803). The p value for the *Svastra* genus is approaching significance, and could potentially be significant with a larger sample size. One genus, *Lasioglossum* showed a significant preference for introduced flowers (p= 0.0281).

Discussion

The data analysis did not support my hypothesis that wild bees would prefer native wildflowers over introduced species. (Figure 2) There was no significant difference in bee preferences except in one genus, which showed a preference for introduced flowers; the opposite of what I expected. (Figure 3) These results suggest that generalist feeding strategies extend to non-native flowers. The introduced flowers could be closely related to native flowers so as to be appealing to bees, or could fulfill some other criteria bees use to choose their food. Of the 10 introduced flower species I examined, four genera do not have native species, and five genera do have native representatives in MI and WI. (One genus observed had two invasive species included in this project. Bumble bees have been shown to have color biases towards certain colors of flowers (10, 11), and this innate choosing of flower color, shape, size, or some other criteria could matter more than evolutionary familiarity.

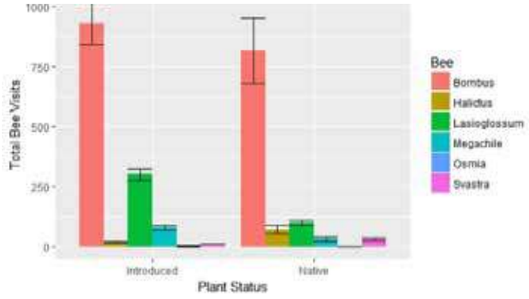

Figure 2. Comparing bee visits by genus to introduced and native flowers. Bars show the total number of visits summed across all flowers, separated into native and introduced flowers. Error bars are standard deviation, calculated with R (10). Five of the six genera showed no preference for either native or introduced flowers. Lasioglossum sp. showed a preference for introduced flowers, with non-overlapping error bars. Plots made with ggplot2 (13).

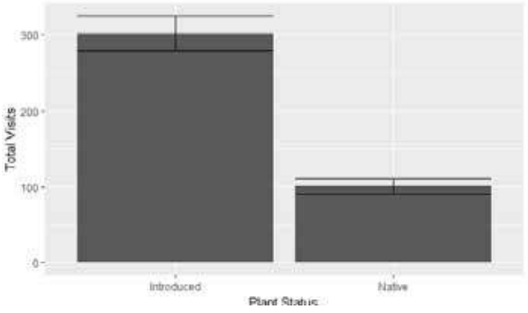

Figure 3. Lasioglossum sp. visits to introduced and native flowers. Bars show the total number of visits summed over all flowers observed, split into introduced and native bees. These bees showed a significant preference for introduced species. (p=0.0281.) Plots made with ggplot2 (13).

A future study could do well to extend this research. Very little is known about bee preference or avoidance of invasive plants, and while this project began that research, more could be done. This project was limited in size and time, as I was taking classes in addition to collecting data. This meant that I was held to bloom times that aligned with research weeks and did not have the chance to collect data on all the wildflowers found here. Further, this project was conducted in an area

relatively lacking in bee diversity. Fewer than 50 species of bee are found in this county, and far fewer were found in this experiment. Extending the research throughout the summer would give a more complete picture of the floral and bee diversity. Repeating this experiment in an area with higher bee diversity could reveal if these patterns extend across more genera, especially specialist feeders.

These findings have implications for land management and pollinator conservation. Land set aside for pollinators, be it roadsides, abandoned farmland, or empty lots are all capable of supporting at least some wild bee diversity. Ensuring that plants in these areas be native is ideal, though non-native flowers will not necessarily detract from overall species composition and pollinator recovery. As native bees face threats from habitat loss, this research shows that habitat containing any flowers, not just native flowers, can help recover declining bee populations. More research is needed to determine whether all bee genera show this lack of necessity, but these preliminary results suggest that flowers, regardless of their native or invasive status are capable of supporting wild bee populations. Invasive flowers pose different threats, and should be managed appropriately, but they do not necessarily pose a threat to wild bees.

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About the Author

Eileen Reeves is a senior environmental sciences major. She works and conducts research in the Museum of Biodiversity at Notre Dame in the herbarium and insect collections. Last summer she completed a summer-long project at the University of Notre Dame Environmental Research Center in northern Michigan. She will be conducting more research this summer at UNDERC's Montana field station. Her primary research focus is insects, especially bees. She plans to pursue a graduate degree in forestry at Michigan Technological University.

What does the LANCE of St. George Do? Analyzing Data from a Nuclear Accelerator

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Abstract

A detailed analysis of the cross sections of nuclear fusion reactions is important for understanding numerous other properties of stars, including isotope formation, energy generation, and stellar lifetimes. One specific type of nuclear reaction, called an alpha-gamma (α,γ) reaction, is frequent in intermediate-mass stars in their helium burning phase. 12C(α,γ)16O is one such reaction, and will serve as an example. This work focuses on resolving some of the difficulties involved in studying these cross sections by modeling aspects of them in a laboratory setting. This is done by sending a beam through the Sta. Ana accelerator, having it impinge on a helium target, and by feeding the resultant beam through St. George (1) in Notre Dame's Nuclear Science Lab (NSL). A primary difficulty in calculating the (α,γ) nuclear reaction cross section is knowing the charge state fraction of the resultant selected ions. Knowing the charge state of the beam and recoil products after they have traveled through the target is also difficult, since the incoming beam has a statistical probability of gaining or losing electrons due to interactions with particles in the target. To resolve some of these issues, a program, ETACHA (2), that models these processes is used. This work outlines the development and preliminary usage of a Python interface, LANCE, which was designed to run ETACHA and process its output data.

Introduction & Theory

Nuclear astrophysics is a subfield of nuclear physics, whose specific goals are to understand and describe the nuclear processes in stars. In galaxies throughout the universe, clouds of dust, primarily hydrogen, clump together due to the gravitational force each particle exerts on every other. As the cloud collapses, the pressure in the center becomes very high, and the core of the protostar becomes very hot. As these hydrogen nuclei accumulate kinetic energy, they eventually gain enough for the quantum tunneling effect to allow the positively charged nuclei to fuse and form helium through a succession of reactions. This chain of reactions releases energy in the form of electromagnetic radiation, which exerts positive pressure on the surrounding atoms, counterbalancing the negative gravitational pressure and thus stabilizing the star. This is precisely the reaction chain powering the Sun. Generally speaking, the various reaction chains converting four hydrogen nuclei into helium are known as the hydrogen burning phase in the life of a star. A star in its hydrogen burning phase finds its helium concentrated near its center, with its hydrogen surrounding it, due to the helium's greater mass. If a star is massive enough, then at the end of its hydrogen burning phase, the gravitational pressure will produce enough energy for the helium nuclei to fuse together, and the star enters the helium burning phase. In extremely massive stars, there is enough energy to fuse even heavier nuclei, producing all the elements up to iron. Fusion stops there, since the binding energy of fusion reactions (with a couple interesting exceptions) increases from isotopic hydrogen to iron, and then decreases nearly monotonically to uranium. In these very massive stars, after each phase of burning, there is a residual layer surrounding the core, with the lightest element, hydrogen, being the farthest out. Thus, a cross section of a star right before exploding as a supernova looks a bit like the layers of an onion (Fig. 1).

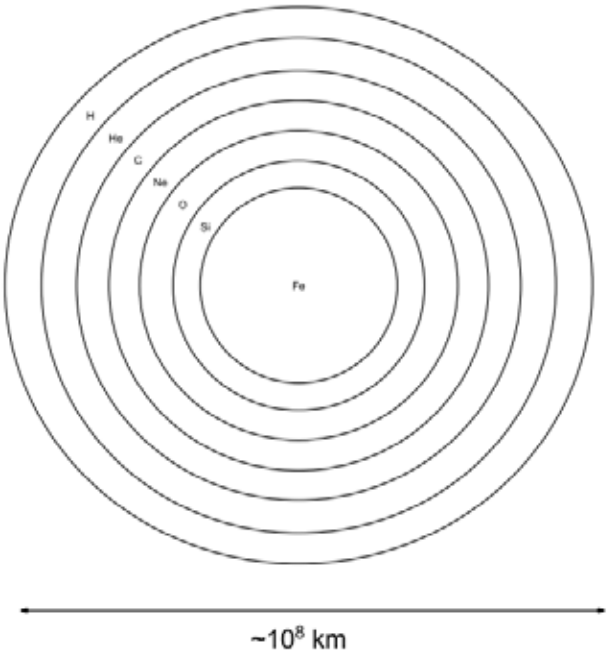

Figure 1. Layers of a Star. A cross section of a supermassive star just before undergoing a supernova.

The reaction that occurs when an atom fuses with a helium nucleus (alpha particle) and releases nothing but gamma rays, is known as an alpha radiative capture or an alpha-gamma (α,γ) reaction. These gamma rays, after experiencing lots of scattering, eventually escape the center of the star and propagate away, carrying energy with them. These reactions are important to the understanding of stellar lifetimes (by studying their reaction rates and energy outputs) and the formation of the elements since many other elements also fuse with helium in stars. One interesting (α,γ) reaction which is quite difficult to study in the lab at stellar energies, yet interesting to model and analyze, is 12C (α,γ), which forms 16O. This equation can be written as

$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma.$$

When analyzing this reaction in the lab, it is important to know how much of the carbon beam reacts with helium nuclei, and how much of it merely interacts with the electrons in the helium target. ETACHA models this interaction, providing more details on the incoming beam's charge state distribution, and thus allowing for a better understanding of when the reaction does occur. In this paper, an exposition on the experimental methods used to study radiative capture with the St. George recoil separator will be presented. The need for an estimate of the charge state fraction of ions passing through or produced in the target will be discussed, and an interface to ETACHA providing that calculation will be introduced and described.

Laboratory Method

In the Notre Dame Nuclear Science Laboratory, the study of this reaction is performed using the Stable ion Accelerator for Nuclear Astrophysics (Sta. ANA accelerator) via a process known as inverse kinematics, in which the heavier isotope (carbon in this case) is accelerated into the target filled with the lighter element (here, helium). The resultant beam and the few nuclear reaction products are then sent through the Strong Gradient Electromagnetic Online Recoil separator for capture of Gamma-ray Experiments (St. George) (1). St. George uses dipole magnets to steer the desired beam particles and select a single charge state, quadrupole magnets to focus them, and a Wien Filter to select only the recoils (reaction products) with a desired velocity as a result of their charge-to-mass ratios.

Dipole magnets are two coils of wire above and below the beam to ensure as uniform of a magnetic field as possible. The necessary current for a specific isotope to be sent through can be calculated from the Lorentz Force and the Biot-Savart Law for current in a loop:

$$\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B}), \qquad B = \frac{CI}{2r}$$

where C is dependent on the region through which the magnetic field lines point. Knowing that v×B =vB since the two are perpendicular, setting the Lorentz Force equal to the centripetal force, rearranging, multiplying B by N turns of the loop, and setting the two equal gives

$$\frac{mv^2}{r} = qvB \Rightarrow B = \frac{mv}{qr} = \frac{CNI}{2r} \Rightarrow I = \frac{2mv}{CNq}.$$

Quadrupole magnets operate under the same principle but are usually lined up with two or three next to each other since each one "sandwiches" the beam, i.e., compressing it along the x-axis but elongating it along the y-axis, for example. Having multiple quadrupole magnets next to each other with alternating focusing planes provides a way to compress the beam in both transverse axes. The Wien Filter operates in a similar way to a dipole magnet but with an added complexity: a perpendicular electric field and no change of direction. With the same Lorentz Force from the magnetic field, but also a Lorentz Force from the electric field, we can select a specific velocity from the beam by balancing the two forces:

$$qvB = qE \Rightarrow v = \frac{E}{B}.$$

All other beam particles will be deflected to the side. Each of these electromagnetic apparatuses is intended to guide the ions that emerge from the helium target in such a way so as to transmit as high of a percentage of the desired recoil ions as possible to the detector system at the end of St. George. The equation governing the number of particles counted by the detector at the end of St. George is

$$N_{recoils} = N_{projectiles} \times n_{target} \times \sigma \times T_{St.G} \times p_q,$$

where σ is the cross section of the reaction, and p_q is the charge state fraction, i.e., the probability of finding the isotope of interest in the desired charge state. When running the experiment, the number of projectiles and the amount of target are known, and fortunately the transmission of St. George is nearly 100%, so the charge state fraction (i.e. the ratio of the number of particles in a specific charge state to the number of total particles) is a critical quantity to measure an accurate reaction cross section.

ETACHA is a program that models the charge state distribution of the ions as they travel through a target, resulting in the distribution of p_q. The evolution of the charge state distribution is important for understanding properties of this reaction and the incident ion's affinity for electrons as a function of energy, depth, initial charge, and other parameters. The Laborsaving Algorithm for Navigating the Code ETACHA (LANCE) is written to process the data file with the progression of the beam charge state, which ETACHA outputs. It is used to simulate the charge state of the beam and of the products of reaction through the target.

Implementation & Results

Part of the motivation for LANCE to be written is to provide and interface for ETACHA. ETACHA gives the user the option to enter parameters into the program after starting it, and to change values if they have better ones than the program itself proposes. LANCE makes it possible for the user to specify all of their input parameters beforehand, so that they can simply hit start, and the program would run from start to finish. As with any program, there are multiple versions of ETACHA, four to be exact (3). The earliest versions were designed for lighter elements in the beam, and as ETACHA was updated, it was built to include heavier isotopes (higher proton number, Z, and higher quantum number, n), including properties that some heavy metals have that lighter ones either lack or only have to a very minute degree. In the later versions, some assumptions were made, such as excitation to higher n, to calculate the charge state evolution at higher Z, which introduce error when used to analyze lighter nuclei, compelling us to use earlier versions when studying a beam of carbon, for example. To make a comparison of the outputs of each version of ETACHA a little easier, LANCE takes a command line argument that specifies which version of ETACHA to use and extracts the final data from that specific output file. This makes comparing experimental data from St. George with the model much simpler since it's all in the same place. The output file

from ETACHA are data files with all of the input parameters labeled and in a table, but this is not very convenient since it doesn't give a visual image of how the charge state distribution of the incident beam actually evolves as the beam moves through the target. Furthermore, the data from the experiments are organized in a way that enables the progression of the charge state distribution to be clearly seen along the x-axis (depth). For this reason, LANCE takes only the data from the table in the output file, sorts it, and plots it with thickness along the x-axis, and fraction of the beam in a given charge state on the y-axis, with a legend for each charge state, as can be seen in (Fig. 2).

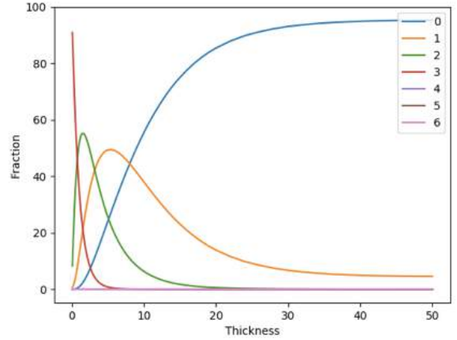

Figure 2. Charge State Evolution. A sample plot of the data file produced by LANCE. The legend indicates the number of electrons on the atom passing through a target of 50μm. The incoming beam has 3 electrons, but as the beam travels through the target, most of the atoms are stripped of their electrons, leaving most of the beam with no electrons. Other plots are similar.

LANCE is also split up into modules for the purpose of debugging and upgrading, allowing the author to update it with much more convenience. A schematic of the current working version can be seen in (Fig. 3). The 12C (α,γ) reaction was modeled on all four versions of ETACHA at a typical beam energy and on a Helium target of a typical depth for this type of reaction, and their outputs can be seen in Fig. 4-7.

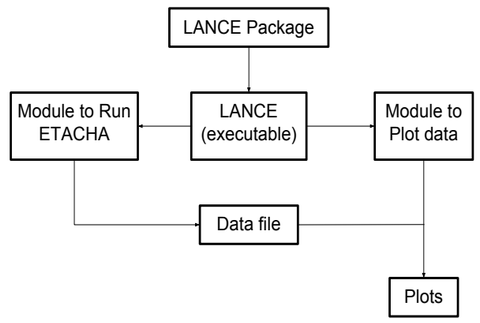

Figure 3. Schematic of LANCE. The structure of package in which LANCE resides and how it functions.

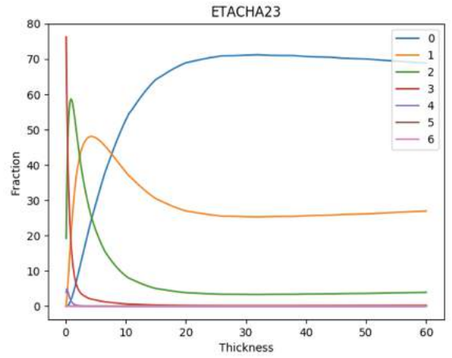

Figure 4. Plots of LANCE. 12C3+ on He at 10.5 MeV. The output of ETACHA23 plotted by LANCE. The units of Thickness are micrometers (μm).

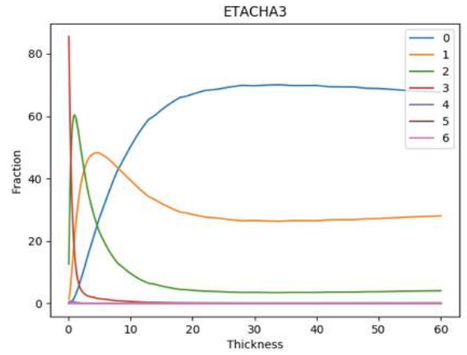

Figure 5. Plots of LANCE. 12C3+ on He at 10.5 MeV. The output of ETACHA3 plotted by LANCE. The units of Thickness are micrometers (μm)

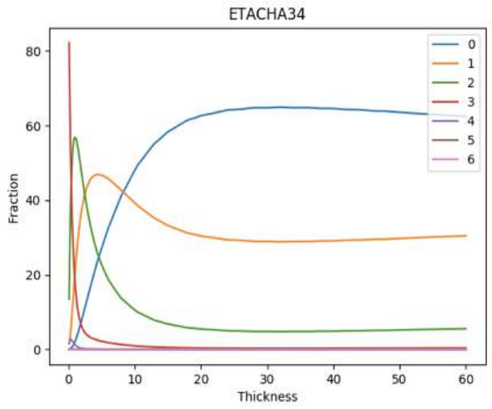

Figure 6. Plots of LANCE. 12C3+ on He at 10.5 MeV. The output of ETACHA34 plotted by LANCE. The units of Thickness are micrometers (μm).

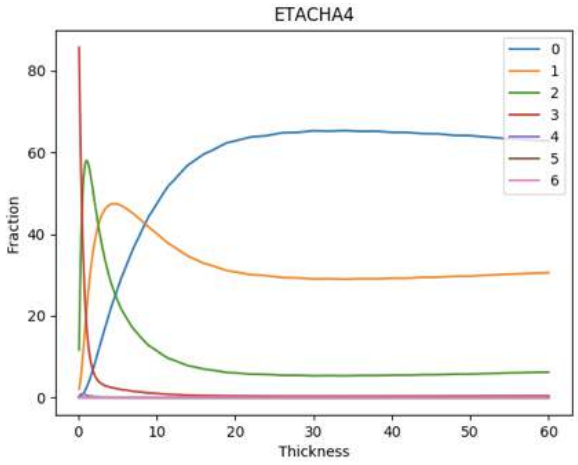

Figure 7. Plots of LANCE. 12C3+ on He at 10.5 MeV. The output of ETACHA4 plotted by LANCE. The units of Thickness are micrometers (μm).

Conclusion & Future Work

There are a number of steps to be taken with LANCE, some of the most exciting being the ability to stitch together the output files for charge states larger than 6 (for versions 23, 3, and 34) or 9 (for version 4) and the availability of a more idealized input parameter system. With the parameter upgrade, there will most likely be a new module for retrieving and storing the data and potentially the creation of a new data file with information that is easier to access as well. In addition, the simulation of the evolution of the charge state of reaction products will be enabled. This will involve the calculation of all possible charge state fractions of the beam prior to the reaction, and then follow all of the reaction products to the end of the target. For this purpose, there will be the addition of new input parameters, specifying the desired energies at which to run, and a loop over those parameters, feeding a new input parameter every time it is required. With this, the plots could take on multiple extra dimensions, including energy, depth, initial charge state, version of ETACHA, etc. Then the user will have yet another visual indication as to how each of these variables influences the evolution of the charge state distribution. In summary, LANCE, written as an interface to ETACHA, a program that calculates the charge state fractions of ions passing through some material, is currently used to compare experimental work with the predictions of ETACHA. Once validated, it will be used to predict the expected charge state fraction of the ions involved in radiative capture measurements with St. George.

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About the Author

Michael Kurkowski is a junior physics and math major from the Chicago suburbs, living in Knott Hall. He is also a Sorin Scholar and the president of the Notre Dame Liturgical Choir. He conducts research with Professor Manoel Couder in computational nuclear astrophysics. He focuses on charge state calculations specific to stellar nuclear reactions. These experiments are conducted using the Sta. Ana accelerator and the St. George recoil separator in the Nuclear Science Lab in the basement of Nieuwland Science Hall.

Simulation of the ND Cube Active-Target Time Projection Chamber

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Abstract

Studies of detectors are necessary for major advances in nuclear physics techniques. To make such advances, detectors with high efficiency are needed to study reactions with radioactive beams. These radioactive beams are used to study nuclei that are important for advancing nuclear theory, but these beams have low intensities. One way to address this problem is to use an Active Target Time Projection Chamber (TPC). Active Target TPCs are a kind of the next generation detectors that improve efficiency by using a thick gas target with track imaging. At the University of Notre Dame, we are developing an Active-Target TPC called the ND Cube. Upon completion, the ND Cube will be able to track reaction trajectories and provide good resolution for reactions. Before using the ND Cube, it is necessary to understand its behavior through simulation to optimize its efficiency. I simulated the electric field and the behavior of electron drift lines inside the ND Cube using the finite element analysis software COMSOL and CERN's Garfield++ toolkit. Based on the simulation, the resolution and the expected transport of the electrons in the detector can be determined. We found a standard deviation of $\sigma = \pm 0.85$ *cm for each electron drifting in 55 cm of air at 1 atm, which determines the resolution of our imaged tracks. In the future, the simulation results will be used to compare and analyze the experimental data. Finally, I simulated Micromegas of a similar Active Target TPC detector to resolve possible systematic errors due to non-uniform electric fields..*

Introduction

The Active Target Time Projection Chamber is a detector that opens a wide range of possibilities for nuclear physics studies. The concept of the Time Projection Chamber (TPC) was first proposed in the early 1970s (1). In the half century since its development, the Active Target TPC has become one of the latest and most advanced nuclear reaction detectors. In 2016, the Prototype Active Target TPC was used to study the Beryllium and Carbon nucleus and test the prediction of a molecular dynamics' calculation (2), which proves that the Active Target TPC can be useful for nuclear physics if developed further. The radioactive beams used in the accelerator allow us to study nuclei that are difficult to access, but these beams have low intensities. The lower the intensity, the less data can be collected. To make up for the low intensities, detectors like the Active Target TPC with high efficiency are needed to study reactions using radioactive beams.

The Active Target Time Projection Chamber (TPC) is called the ND Cube (Fig. 1) is built to solve this problem. The Active Target TPC is a kind of the next generation detectors that improves efficiency by using a thick gas target with track imaging. When the radioactive beams hit the gas inside the chamber, electrons are emitted along the trajectory of the reaction. The electrons then drift downward through the chamber and are collected by the Micromegas. The Micromegas is an electron collector that amplifies the drifting electrons and converts them into electronic signals. Ideally, the electrons drift downward in straight-lines in a uniform electric field. However, due to the non-uniformity of the electric field inside the Active Target TPC, the electron will follow these non-uniform field lines and thus the drift lines will not be straight. Therefore, simulation is necessary to understand the drift lines' behavior and to figure out the resolution of the Active Target TPC.

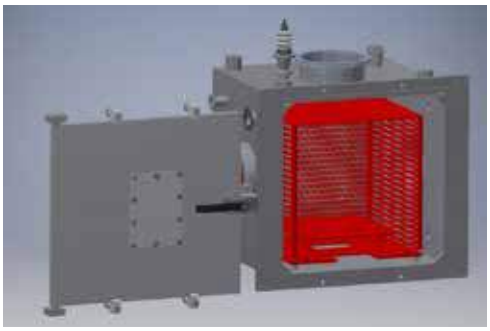

Figure 1. On-Building Active Target Time Projection Chamber

The field cage shown in red in Fig. 1 is the part that the electrons drift through under the influence of a strong electric field. In this simulation, COMSOL, a commercial Finite Element Analysis (FEA) software, is used to simulate the electric field inside the chamber. Finite Element Analysis is a numerical approach to the solution of boundary-value problems in physics and engineering (3). Using computer simulation, I efficiently and economically calculated the deviation caused by the non-uniformity of the field. Next, I imported the simulated electric field data into the Garfield++ toolkit to calculate electron drift lines. Garfield++ is a package based on C++ developed by The European Organization for Nuclear Research (CERN). Garfield++ is designed for the detailed simulation of particle detectors that use gas as a sensitive medium like the Active Target TPC (4). Garfield++ provided positions of the starting points and the end points of the electrons drifting in the detector. These data of starting points and end points were collected and analyzed. Finally, I used COMSOL to simulate the electric field of a developing Micromegas.

Simulation of Electron Drift

Electrons drift through the gas in the field cage under the influence of a strong electric field. Ideally, the electric field is uniform, so the electrons drift through the chamber as a straight line. However, the electric field is not uniform. The electrons follow the electric field lines and produce a tilted drift line. In addition, electrons may deviate from their ideal endpoint due to collision with gas molecules which is called straggling. Both cases will be studied in this paper.

Simulation of the Electric Field

The first step of this simulation is to analyze the uniformity of the electric field inside the chamber using COMSOL. In this simulation step, the Active-Target TPC is simplified as two parallel plates with a voltage difference of 120 V. In the simplified model (Fig. 2), the two plates have radius 0.5 m and of thickness 0.1 m. Theses plates are separated by 0.9 m and are surrounded by air.

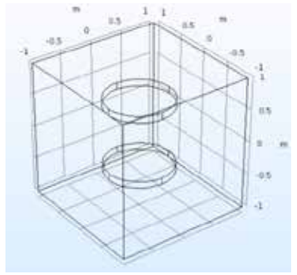

Figure 2. 3D configuration of the simplified ND Cube.

Fig. 3 shows the simulated result for a cross-section of the electric field of the Active Target TPC. The electric field is uniform at the center of the plates, but not near the edges. This non-uniformity will cause the electron drift lines to be tilted.

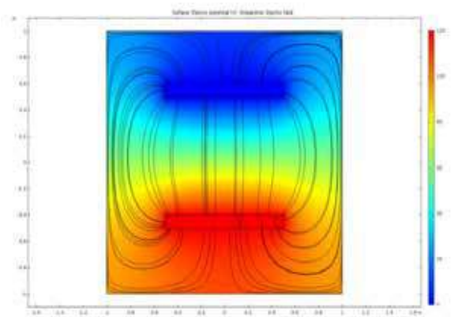

Figure 3. x-z cross-section of the electric field inside the Cube.

Simulation of Straggling

Next, the simulation result of the electric field is imported into the Garfield++ toolkit. Using the electric field data, the Garfield++ toolkit simulates the behavior of an electron drifting through the chamber. It automatically tracks the trajectory of the electron and the endpoints of the drift lines. The electron starts drifting in the z-direction from +25 cm to -30 cm with x, y coordinates both set to zero. Since the x-direction is symmetric to the y-direction, only the deviation in the x is recorded. Fig. 4 shows an electron drift line in detail.

To study the effect of straggling, I used Garfield++ to determine the deviation of each individual electron drifting from the same initial location. In the simulation, Garfield++ ran one thousand times, calculating one thousand drift lines starting from the same initial location. The deviation was calculated based on the endpoints of these one thousand drift lines.

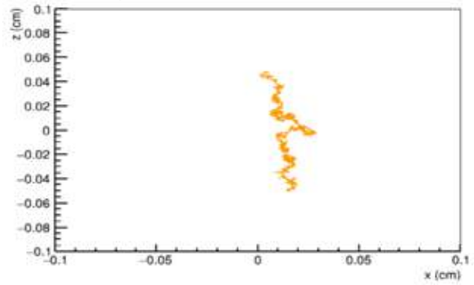

Figure 4. An electron drift line of one electron, simulated by COMSOL and Garfield++ toolkit

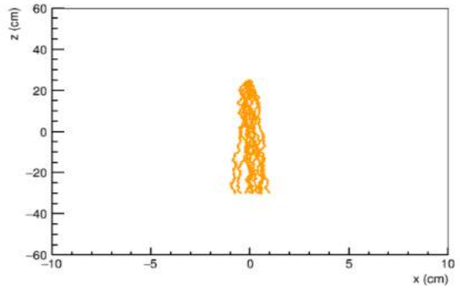

Figure 5. Simulation result of the distribution of electron drift lines starting from the same position; ten drift lines are shown in this figure

One thousand electron drift lines all start from the same initial location but stop at different endpoints. The 1000 endpoints are retrieved and drawn as a histogram in Fig. 6. The standard deviation of the endpoints is $\sigma = \pm 0.85$ cm. This value represents the spread in the position of the detected electrons due to collisions, which is called straggling. This value can be compared to measured values. It indicates the precision with which we can measure electron's position.

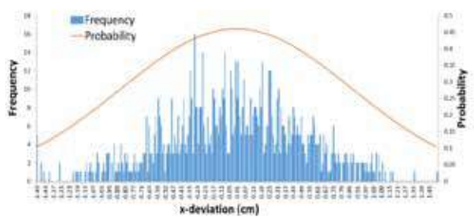

Figure 6. Histogram of 1000 electron drift endpoints; x-coordinates are the deviation from the ideal endpoint, which is an x-deviation of zero

Electron Drift Lines in a Non-Uniform Electric Field

To study how electron drift lines, behave in a non-uniform electric field, I calculated how the drift lines deviate according to the different initial locations inside the chamber because the electric field varies with position. Thus, the deviation and behavior of electron drift lines are also different. In this simulation, 50 separate trials were performed from the center of the chamber at the location x = 0 cm to the edge of the chamber at x = - 45 cm. For each trial, 100 simulations are done at the same initial location, and an average endpoint is calculated based on these simulations. The endpoints are compared with the starting points to calculate the deviation. Fig. 7 demonstrates how a straight drift line slightly tilts to the left as a result of the non-uniform electric field.

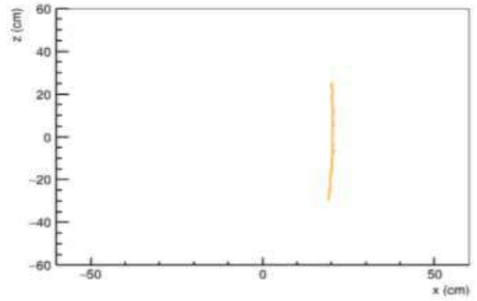

Figure 7. Simulation of the electron drift line from a different location in the electric field; in this figure, the electron drift line starts from (20, 0, 25); the line is not straight but tilted due to the non-uniformity of the electric field

Analyzing the simulation result in Fig. 8, I found that the electron drift lines deviate the most near the edge of the plates because of the non-uniformity of the electric field as shown in Fig. 3. Based on the data from Fig. 8, the deviation caused by the non-uniformity of the electric field can be accounted for when solving for the initial position of the detected electrons.

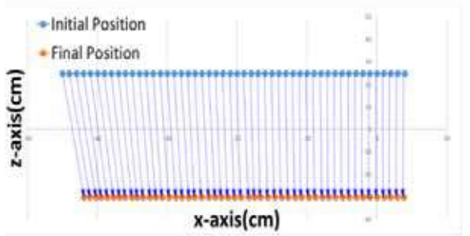

Figure 8. Mapping of electron drift lines' initial and final positions

Electric Field Simulation of a New Micromegas

Micromegas is the part of the Active Target TPC that detects the drifting electrons. It has two plates that contain strong electric fields inside. The uniformity of the electric field will determine the accuracy of the electrons' positions. The developing new Micromegas has a big hole in the middle of the plates because a beam will pass through the hole in our new setup. Thus, understanding how the electric field distortion caused by the hole will provide crucial information to the design of the new Micromegas. My simulation helped determine the magnitude of the distortion area and analyze impact on the electron position's precision.

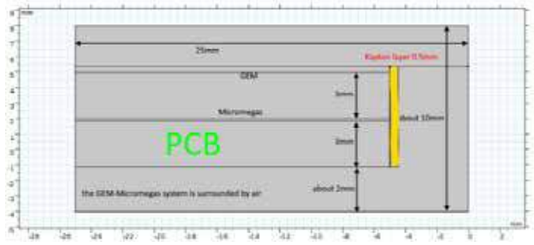

Figure 9. 2D configuration of the Micromegas; the hole is on the right of the Kapton layer (yellow part)

I used COMSOL to perform the simulation. The geometry is set up as shown in Fig. 9. The top plate of the GEM is set to -550 V and the bottom layer of the Micromegas is grounded (at 0 V). The simulation is done with an extra fine auto mesh configuration using COMSOL. According to Fig. 10, the distortion of the electric field is within 2 mm which is as the same magnitude of the distance between the GEM's plate and Micromegas' plate. This distortion area is significantly smaller than the diameter of the plate (30 mm). Thus, the distortion of the electric field is within the acceptable range of the experiment because it will not negatively influence data collection in the Micromegas.

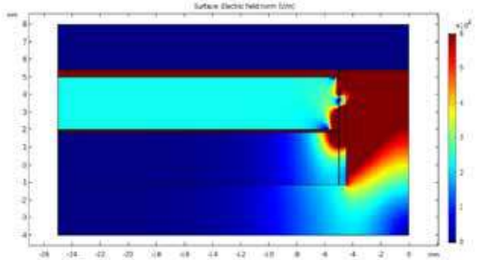

Figure 10. Simulation result of the Micromegas; the distortion covers less than 2 mm inside the Micromegas

Conclusion

The precision of the position of charged-particle tracks in detectors can be determined by simulations that combine the spread in detected positions due to collisions (straggling) and the deviation due to the non-uniformity of the electric field. In this experiment, the standard deviation caused by straggling in the ND Cube is $\sigma = \pm 0.85$ cm. Ideally, a mapping can be drawn from every starting point to the corresponding endpoint up to the precision limited by straggling. Therefore, the corresponding starting points can be obtained via a reverse calculation using this mapping. We can then calculate the trajectory of the reaction with a known calculated accuracy. Thus, Active Target TPC or the ND Cube will be an efficient tool for studying reactions of radioactive beams.

In this simulation, the Active Target TPC is simplified as two parallel plates. The next step of this research is to redo the simulation with the actual 3D CAD model. The gas surrounding the detector chamber in the simulation will be

the same composition as the gas used in the actual experiment. Therefore, the accuracy of the simulation can be further improved.

The method used in my simulation can be applied to analyze other similar detectors as well. COMSOL can calculate electric and magnetic fields even with detectors of irregular shapes. The rest of the simulation will be the same. This method also can analyze the behavior of ions and positrons in the detector chamber to prevent possible sparks and distortion of the electric field inside the chamber. By improving our simulation, we can rigorously ensure that our final detector will be as efficient as possible for measuring rare nuclear reactions using radioactive beams.

Acknowledgement

Prof. Tan Ahn in Notre Dame's physics department gave me many advice and guidance on this work. Notre Dame's graduate Student Samuel Henderson and undergraduate Zach Serikow both helped me a lot in finishing this. This work was funded by the University of Notre Dame's Eagan Summer Fellowship.

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About the Author

Lihao Yan is a sophomore at Notre Dame from Beijing, China. He is a double major in physics and philosophy and lives in Zahm house. Lihao is a member of the executive board of Notre Dame's Chinese Culture Society and a member of the Student Government. As a researcher, he works with Professor Tan Ahn's research group on developing nuclear physics detectors. He is working in Notre Dame Nuclear Science Laboratory (NSL) on simulating and developing the next-generation nuclear detector. After graduation, Lihao is hoping to go to graduate school to pursue a Ph.D. degree in theoretical physics.

Class Number Formulae

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Abstract
In this paper, we are going to follow a text written by Jarvis to explore the concept of class numbers and class groups; moreover, we are going to find ways to calculate the class number over number fields by deriving a class number formula through Analytic Number Theory with Dirichlet Unit Theorem. We will first explain some geometric techniques in order to prove the finiteness of class numbers and Dirichlet Unit Theorem, and then we will use Analytic Number Theory to derive the formula. This formula is very useful in computing the class number of a specific number field and deciding if the number field is a unique factorization domain by analyzing the class group of the number field.

Preliminaries

Definition 1. An *ideal I* in a commutative ring R is defined with the following properties:
(i) $0_R \in I$
(ii) if i and $j \in I$, then $i - j \in I$
(iii) if $i \in I$, $c \in \mathbb{R}$, then $ci \in I$.
An ideal with only one generator is called a *principal ideal*.

Definition 2. A field K is a *number field* if it is a finite extension of $\mathbb{Q}$.

Definition 3. Let K be a number field, then $\mathbb{Z}_K$ is the *ring of integers* of K, with $\mathbb{Z}_K = \{\alpha \in K | \alpha \text{ is an algebraic integer}\}$

Definition 4. A *fractional ideal* of $\mathbb{Z}_K$ is a subset of K with the form $\frac{1}{\gamma}\mathfrak{c}$, with $\mathfrak{c}$ an ideal in $\mathbb{Z}_K$ and γ a non-zero element of $\mathbb{Z}_K$. The fractional ideal is principal if $\mathfrak{c}$ is principal.

Definition 5. Let R be an integral domain, then R is a *principal ideal domain* if every ideal is principal.

Definition 6. Let R be in a ring, and $u \in R$. If there exists $v \in R$ such that $uv = 1$, then u is a unit in R

Definition 7. Let $p \in R$. Then p is *irreducible* if
(i) p is not a unit.
(ii) whenever $p = ab$, then either a or b is a unit.

Definition 8. A ring R is a *unique factorization domain* if it is an integral domain in which every element $a \in R$ can be written as $a = up_1 \dots p_n$, where u is a unit and each p_i irreducible.

Fact 9. *Let $\phi : R \to S$ be a ring homomorphism. Then there is an isomorphism*

$$R/ker\phi \cong im\phi$$

Definition 10. An *nth roots of unity* is a number $\zeta \in \mathbb{C}$ such that $\zeta^n = 1$.

Definition 11. After choosing a basis for K a number field, represent $a \in K$ as a matrix. Thus, we define *norm* as the determinant of a, denoted by $N_{K/\mathbb{Q}}(a)$.

What is a Class Group and Class Number In order to explain what a class group is and how it works, we need several facts. [Thm. 4.31, 5.30, 5.32]{**Jar14**}

Fact 12. *A principal ideal domain (PID) is a unique factorization domain (UFD). If we do a contrapositive, we will see this fact as: If a domain doesn't have unique factorization, then there are some ideals that are not principal.*

Fact 13. *Ideals in a ring of integers of number field can be uniquely factorized into prime ideals. This implies that we could use fractional ideals to represent ideals in the ring of integers.*

Fact 14. *Fractional ideals and principal fractional ideals form an Abelian group.*

Definition 15. Let K be a number field, $\mathfrak{F}_K$ be the group of fractional ideals, and $\mathfrak{PF}_K$ be the group of principal fractional ideals. Then we define the quotient group $C_K = \frac{\mathfrak{F}_K}{\mathfrak{PF}_K}$ to be a *class group* of K. And we call the number of elements in this group, h_K, the *class number*.

Remark 16. From the definition, we observe that when $h_K = 1$, the class group C_K is trivial, meaning that the domain is a unique factorization domain; otherwise, it will not be a unique factorization domain.

Finiteness of Class Number and Dirichlet's Unit Theorem

In this section, we will need some geometrical techniques. This will be introduced in the following sections.

Finiteness of Class Number

Definition 17. Let V be an n-dimensional real vector space. A *lattice* in V is a subgroup in the form

$$\Gamma = \mathbb{Z}v_1 + \dots + \mathbb{Z}v_m$$

where $\{v_1 \dots v_m\}$ are linearly independent vectors in V. The lattice is *complete* if $m = n$

Definition 18. The *fundamental mesh or fundamental region* associated to Γ, Φ_Γ, is defined as

$$\Phi_\Gamma = \{\alpha_1 v_1 + \dots + \alpha_m v_m | 0 \le \alpha_i < 1\}$$

Definition 19. $\Gamma \subset \mathbb{R}^n$ is discrete if for any radius $r \ge 0$, Γ contains only finitely many points within a disc of radius r centered at 0.

Definition 20. A region $X \subset V$ is *centrally symmetric* if $x \in X$ implies $-x \in X$

Definition 21. A region $X \subset V$ is *convex* if $x, y \in X$, and $t \in [0,1]$ then the line $\{(1-t)x + ty\} \subset X$

Now, we recognize three basic fact, to which I will not provide a proof in order to introduce a theorem faster.

Fact 22. *A subgroup $\Gamma \subset V$ is a lattice iff it is discrete*

Fact 23. *A subgroup $\Gamma \subset V$ is complete iff $\exists$ a bounded $B_V \in V$ such that $\bigcup_{\gamma \in \Gamma}(B_V + \gamma) = V$.*

Fact 24. *Assume Γ is a lattice in $\mathbb{R}^n$. If $v_i = (a_{i1}, ..., a_{in})$, then the volume $vol(\Gamma) = |\det(a_{ij})|$*

Theorem 25. *(Minkowski) Assume Γ is a complete lattice in V. Let X be a centrally symmetric convex subset of V. Suppose $vol(X) > 2^n vol(\Gamma)$, then X contains at least one non-zero lattice point.*

Proof. We prove this by contradiction. Assume there are no non-zero lattice points. Then it is clear that $(\frac{1}{2}X + \gamma_1) \cap (\frac{1}{2}X + \gamma_2) = \emptyset$, where γ_1 and γ_2 are distinct lattices (if not, then we can find $x_1, x_2 \in X$ such that $\gamma_1 - \gamma_2 = \frac{1}{2}x_2 - \frac{1}{2}x_1$). Then, we know that $\{\Phi_\Gamma \cap \frac{1}{2}X + \gamma\}_{\gamma\in\Gamma} = \emptyset$. But this is a subset of Φ_Γ. Thus $vol(\Gamma) \geq vol(\Phi_\Gamma \cap \{\frac{1}{2}X + \gamma\}_{\gamma\in\Gamma}) = vol(\frac{1}{2}X) = \frac{1}{2^n}vol(X)$, which is a contradiction. □

Definition 26. If σ: $K \hookrightarrow \mathbb{C}$, and $\sigma(K) \subset \mathbb{R}$, then σ is called a *real embedding*. Otherwise it is called a *complex embedding*. Its conjugate denoted by $\bar{\sigma}$ is defined as $\bar{\sigma}(k) = \overline{\sigma(k)}$.

Proposition 27. *Let $K_\mathbb{R} = \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$ (Since $\mathbb{C} \cong \mathbb{R}^2$, we could understand this space as a real space with $(r_1 + 2r_2)$-dimensional space). And i be a mapping from $K \hookrightarrow K_\mathbb{R}$. $\Gamma = i(\mathbb{Z}_K)$ is a complete lattice in $K_\mathbb{R}$ and $vol(\Gamma) = |D_K|^{1/2}$.*

Proof. Assume $\Gamma = \mathbb{Z}i\omega_1 + ... + \mathbb{Z}i\omega_n \subset K_\mathbb{R}$. Let M be the matrix $(\tau_i\omega_j)$. Then, by definition, we know that $D_K = \triangle\{\omega_1, ..., \omega_n\} = \det(M)^2$. Then, by the reasoning in proposition 3.8, we know that $vol(\Gamma) = |det(\tau_i\omega_j)| = det(M) = |D_K|^{1/2}$ □

Definition 28. The *discriminant of ideal* $\mathfrak{a}$, if $\mathfrak{a} = \alpha_1\mathbb{Z} + ... + \alpha_n\mathbb{Z}$, is $D(\mathfrak{a}) = \triangle\{\alpha_1, ..., \alpha_n\} = \det(\tau_i\alpha_j)^2$, where τ are all embeddings of K into $\mathbb{C}$.

Corollary 29. *If $\mathfrak{a}$ is a non-zero ideal of $\mathbb{Z}_K$, then $\Gamma = i(\mathfrak{a})$ is a complete lattice in $K_\mathbb{R}$, with $D(\mathfrak{a}) = N_{K/\mathbb{Q}}(\mathfrak{a})^2 D_K$, and Φ_r has volume $N_{K/\mathbb{Q}}(\mathfrak{a})|D_K|^{1/2}$*

Proposition 30. *Let Γ be a lattice in $K_\mathbb{R}$, and let $c_1, ..., c_{r_1}, C_1, ..., C_{r_2} \in \mathbb{R}_{>0}$ satisfy $c_1...c_{r_1}(C_1...C_{r_2})^2 > \left(\frac{2}{\pi}\right)^{r_2} vol(\Gamma)$. Then there exists a non-zero $v = (x_1, ..., x_{r_1}, z_1, ..., z_{r_2}) \in \Gamma$ such that $|x_j| < c_j$ for all $j = 1, ..., r_1$, and $|z_k| < C_k$ for all $k = 1, ..., r_2$.*

Proof. In this proof, we want to invoke Minkowski's theorem. Let X be the set of all elements with $|x_j| < c_j$ for all $j = 1, ..., r_1$, and $|z_k| < C_k$ for all $k = 1, ..., r_2$. Then it is clear that X is centrally symmetric and convex. Then we have $vol_\mathbb{R}(X) > (2c_1)...(2c_{r_1})(\pi C_1^2)...(\pi C_{r_n}^2)$. Thus, we know that $vol(X) = 2^{r_2} vol_\mathbb{R}(X) > 2^{r_2}(2c_1)...(2c_{r_1})(\pi C_1^2)...(\pi C_{r_n}^2) > 2^{r_1+r_2}\pi^{r_2}\left(\frac{2}{\pi}\right)^{r_2} vol(\Gamma)$. Therefore, we finally get $vol(X) > 2^n vol(\Gamma)$. Thus we know v exists. □

Proposition 31. *Let $\mathfrak{a}$ be a non-zero integral ideal of $\mathbb{Z}_K$. Then there exists a non-zero $\alpha \in \mathfrak{a}$ such that $|N_{K/\mathbb{Q}}(\alpha)| \leq \left(\frac{2}{\pi}\right)^{r_2} N_{K/\mathbb{Q}}(\mathfrak{a})|D_K|^{1/2}$*

Proof. By Corollary 3.13, we take M, where $M > \left(\frac{2}{\pi}\right)^{r_2} N_{K/\mathbb{Q}}(\mathfrak{a})|D_K|^{1/2} = \left(\frac{2}{\pi}\right)^{r_2} vol(\alpha)$

Therefore, by proposition 3.14, we could choose $c_1...c_{r_1}(C_1...C_{r_2})^2 = M$. Therefore, there is a non-zero element $\alpha \in \mathfrak{a}$, such that each of its coordinates is smaller than the embeddings. Therefore, we know that $N_{K/\mathbb{Q}}(\alpha) < M$. Since M can be infinitely close to the value, we know that we get the equation required. □

Theorem 32. *The class group $C(K)$ is finite.*

Proof. We take $\mathfrak{b} \in [\mathfrak{a}^{-1}]$, where $[\mathfrak{a}^{-1}]$ denotes the ideal class of $\mathfrak{a}^{-1}$, WLOG, we assume $\mathfrak{b} \in \mathbb{Z}_K$. Then by proposition 3.15 we have $\exists\beta$ such that $|N_{K/\mathbb{Q}}(\beta)| \leq \left(\frac{2}{\pi}\right)^{r_2} N_{K/\mathbb{Q}}(\mathfrak{b})|D_K|^{1/2}$.

Then let $\mathfrak{c} = \langle\beta\rangle\mathfrak{b}^{-1} \in [\mathfrak{a}]$. Therefore, we have $N_{K/\mathbb{Q}}(\mathfrak{c}) = |N_{K/\mathbb{Q}}(\beta)|N_{K/\mathbb{Q}}(\mathfrak{b})^{-1} \leq \left(\frac{2}{\pi}\right)^{r_2}|D_K|^{1/2} = M$.

Therefore, we know there are finitely ideals whose norm is within a bound. Thus there are only finitely many ideal classes □

Now, let's find a better bound.

Lemma 33. *Let $X \subset \mathbb{R}$*

$X_t = \{(x_1, .., x_{r_1}, z_1, .., z_{r_2}) | |x_1| + .. + |x_{r_1}| + 2|z_1| + .. + 2|z_{r_2}| < t\}$

Then $vol(X_t) = 2^{r_1}\pi^{r_2}\frac{t^n}{n!}$

Proof. Since $\mathbb{C} \cong \mathbb{R}^2$, we could see each z_i as u_i, v_i. And by a former proposition, $vol(X) = 2^{r_2} vol_\mathbb{R}(X)$, we only need to calculate $vol_\mathbb{R}(X)$ by changing variables (u_i, v_i) to $(\frac{R_i}{2}\cos\theta_i, \frac{R_i}{2}\sin\theta_i)$, thus

$$\begin{aligned} vol_\mathbb{R}(X) &= \int_{X_t} 1 dx_1...dx_{r_1}du_1dv_1...du_{r_2}dv_{r_2} \\ &= 2^{r_1}4^{-r_2}(2\pi)^{r_2}\int_{Y_t} R_1..R_{r_2}dx_1...dx_{r_1}dR_1...dR_{r_2} \\ &= 2^{r_1}4^{-r_2}(2\pi)^{r_2}\frac{t^n}{n!} \end{aligned}$$

Therefore, we have $vol(X_t) = 2^{r_1}\pi^{r_2}\frac{t^n}{n!}$ □

Theorem 34. *(Minkowski bound) Every ideal class of K contains an integral ideal $\mathfrak{c}$ of norm at most $\frac{n!}{n^n}\left(\frac{4}{\pi}\right)^{r_2}|D_K|^{1/2}$*

Proof. Assume $\mathfrak{b} \in [\mathfrak{a}^{-1}]$, with $\mathfrak{a}$ an ideal class. We want to invoke Minkowski's theorem, so we choose a t, such that $2^{r_1}\pi^{r_2}\frac{t^n}{n!} > 2^n vol(\mathfrak{b})$. Since $n = r_1 + 2r_2$, by a proposition proved before, we pick

$$t^n > n!\left(\frac{4}{\pi}\right)^{r_2}|D_K|^{1/2}N_{K/\mathbb{Q}}(\mathfrak{b})$$

Then we know there exists a non-zero $\beta \in \mathfrak{b}$ with $i(\beta) \in X_t$. Moreover, we have Arithmetic Mean-Geometric Mean inequality giving

$$\left(\prod_\tau |\tau(\beta)|\right)^{\frac{1}{n}} \leq \frac{1}{n}\left(\sum_\tau |\tau(\beta)|\right)$$

$$|N_{K/\mathbb{Q}}(\beta)| \leq \left(\frac{t}{n}\right)^n$$

$$|N_{K/\mathbb{Q}}(\beta)| < \frac{n!}{n^n}\left(\frac{4}{\pi}\right)^{r_2} N_{K/\mathbb{Q}}(\mathfrak{b})|D_K|^{1/2}$$

Therefore, if $\mathfrak{c} = \langle\beta\rangle\mathfrak{b}^{-1} \in [\mathfrak{a}]$, then plug in our previous result into $N_{K/\mathbb{Q}}(\mathfrak{c}) = |N_{K/\mathbb{Q}}(\beta)|N_{K/\mathbb{Q}}(\mathfrak{b})^{-1}$, we get our result. □

Dirichlet's Unit Theorem

Remark 35. We are going to introduce several mappings for future use: $l : (x_1, ..., x_{r_1}, z_1, ..., z_{r_2}) \mapsto (\log|x_1|, ..., \log|x_{r_1}|, \log|z_1|, ..., \log|z_{r_2}|)$ and

$$\mathbb{Z}_K^\times = \{\varepsilon \in \mathbb{Z}_K | N_{K/\mathbb{Q}}(\varepsilon) = \pm 1\}$$

$$S = \{y \in K_\mathbb{R}^\times | N(y) = \pm 1\}$$

and we have

$$H = \{x \in \mathbb{R}^{r_1+r_2} | tr(x) = 0\}$$

Also,

$$\lambda : \mathbb{Z}_K^\times \xrightarrow{i} S \xrightarrow{l} H$$

And let $\Gamma = \lambda(\mathbb{Z}_K^\times)$.

Proposition 36. *The kernel of λ is $\mu(K)$, group of roots of unity in K.*

Proof. $\eta(K) \subseteq ker(\lambda)$ is clear. The embeddings clearly map the roots of unity to 0.
Now we prove the other direction. If $\varepsilon \in ker(\lambda)$, then $|i(\varepsilon)| = 1$. Therefore, it is a bounded region. And it is a lattice, thus it is discrete, thus it is finite. And since the kernel is closed under multiplication, we know every element has finite order. Thus it is a root of unity. □

Corollary 37. *Γ is a subgroup of H.*

Proposition 38. *Γ is a lattice in H.*

Proof. It suffices to prove that Γ is discrete. Thus, we want to show if $B(r,h) \subset H$, then $\Gamma \cap B(r,h)$ is finite. Consider $l^{-1}(\Gamma \cap B) = l^{-1}(\Gamma) \cap l^{-1}(B)$. Since $l^{-1}(\Gamma) = i(\mathbb{Z}_K^\times)$. We know $i(\mathbb{Z}_K^\times)$ is finite, $i(\mathbb{Z}_K^\times) \cap l^{-1}(B)$ is finite. And $l^{-1}(B)$ is bounded. Thus Γ is discrete. □

Proposition 39. *There is a bounded region $B_S \subset S$ such that*

$$S = \bigcup_{\varepsilon\in\mathbb{Z}_K^\times} i(\varepsilon)B_S$$

Proof. Consider the lattice $i(\mathbb{Z}_K^\times) \in K_\mathbb{R}$ of volume $|D_K|^{1/2}$. Then if we move the lattice by y, we have $yi(\mathbb{Z}_K^\times)$ also have volume $|D_K|^{1/2}$, because $N(y) = \pm 1$. Then we can appeal to proposition Prop. 3.14 to set up a X contains a non-zero point $x \in yi(\mathbb{Z}_K^\times)$, and thus we have $N(x) = N_{K/\mathbb{Q}}(\alpha)$, with $\alpha \in \mathbb{Z}_K^\times$. Therefore, we know that $N_{K/\mathbb{Q}}(\alpha)$ is bounded by an M from 3.14. Thus, there are only finitely many α, thus we construct a set $\{\alpha_1, ..., \alpha_N\}$. Thus, $\alpha = \varepsilon^{-1}\alpha_k$. Therefore, we know that $y = xi(\alpha)^{-1} = xi(\alpha_k)^{-1}i(\varepsilon)$. Therefore, we could take $B_S = \{s \in S | s \in Xi(\alpha_k)^{-1}\}$. □

Corollary 40. *Γ is a complete lattice in H.*

Proof. By last proposition, $S = \bigcup_{\varepsilon\in\mathbb{Z}_K^\times} i(\varepsilon)B_S$, take $B_H = l(B_S)$. We know that B_S is a translate of X. And $N(x) = \pm 1$, thus all the coordinates are bounded away from 0. Thus the logarithm is not a problem. Thus, B_H is bounded. Thus, we let $H = \bigcup_{\varepsilon\in\mathbb{Z}_K^\times}(\lambda(\varepsilon) + B_H) = \bigcup_{\gamma\in\Gamma}(\gamma + B_H)$. Therefore, by proposition 3.7, we know that Γ is complete. □

Theorem 41. *(Dirichlet) $\exists\varepsilon_1, ..., \varepsilon_r$ such that all $\varepsilon \in \mathbb{Z}_K^\times$ can be written uniquely in the form*

$$\varepsilon = \zeta\varepsilon_1^{v_1}...\varepsilon_r^{v_r}$$

with $\zeta \in \mu(K)$, $v_i \in \mathbb{Z}$, and $r = r_1 + r_2 - 1$ ($\mathbb{Z}_K^\times \cong \mu(K) \times \mathbb{Z}^r$).

Proof. Consider the map: $\lambda : K^\times \to \mathbb{R}^{r_1+r_2}$ restrict to $\lambda : \mathbb{Z}_K^\times \to H$. Then the kernel is $\mu(K)$, image is Γ, and Γ is complete lattice in r-dimensional vector space. Therefore, $\Gamma \cong \mathbb{Z}^r$. □

Definition 42. We define $\varepsilon_1, ..., \varepsilon_r$ as the*fundamental units*.

Calculate Class Number through Analysis

Riemann Zeta Function

Definition 43. We define the *Riemann Zeta Function* as following:

$$\zeta(s) = \sum_{n=1}^\infty \frac{1}{n^s}$$

Definition 44. We define the *Gamma function* as following:

$$\Gamma(z) = \int_0^\infty e^{-t}t^z\frac{dt}{t}$$

Definition 45. We define the *functional equation* as following:

$$\xi(s) = \pi^{-s/2}\Gamma(s/2)\zeta(s)$$

Definition 46. We define the *Dedekind zeta function* as following:

$$\zeta_K(s) = \sum_\mathfrak{a} \frac{1}{N_{K/\mathbb{Q}}(\mathfrak{a})^s}$$

where $\mathfrak{a}$ is an integral ideal in number field K.

Fact 47. *We can write the Riemann Zeta Function as*

$$\zeta(s) = 2^s\pi^{s-1}sin(\frac{\pi s}{2})\Gamma(1-s)\zeta(1-s)$$

Fact 48. *$\zeta(s), s \in \mathbb{R}$, converges absolutely for all $s > 1$, and diverges for $s \leq 1$.*

Fact 49. *If $Re(s) > 1$, then*

$$\zeta(s) = \sum_{n=1}^\infty \frac{1}{n^s} = \prod_p (1 - \frac{1}{p^s})^{-1}$$

The same applies to Dedekind zeta function: If $Re(s) > 1$, then

$$\zeta(s) = \prod_{\mathfrak{p}} \frac{1}{1 - N_{K/\mathbb{Q}}(\mathfrak{p})^{-s}}$$

In this section, we want to know a bit about the functional equation. Thus, we will begin proving a result:

Lemma 50. *Set $\theta(t) = \sum_{n\in\mathbb{Z}} e^{-\pi t^2 n^2}$. Then if $t \neq 0$, $\theta(1/t) = t\theta(t)$.*

Proof. Fix $t > 0$, and let $f(x) = e^{-\pi t^2 x^2}$. And define $F(x) = \sum_{n\in\mathbb{Z}} f(x+n)$. Thus $F(x) = \sum_{n\in\mathbb{Z}} e^{-\pi t^2 (x+n)^2}$. We know that $F(0) = \theta(t)$. It is periodic with $F(x) = F(x+1)$. We take its Fourier series. $F(x) = \sum_{m\in\mathbb{Z}} a_m e^{2\pi i m x}$. Thus, we compute a_m:

$$\begin{aligned} a_m &= \int_0^1 F(x) e^{-2\pi i m x} dx = \sum_{n\in\mathbb{Z}} \int_0^1 f(x+n) e^{-2\pi i m(x+n)} dx \\ &= \int_{-\infty}^{\infty} f(x) e^{-2\pi i m x} dx = \int_{-\infty}^{\infty} e^{-\pi t^2 x^2 - 2\pi i m x} dx \\ &= e^{-\pi m^2/t^2} \int_{-\infty}^{\infty} e^{-\pi(tx + im/t)^2} dx = t^{-1} e^{-\pi m^2/t^2} \end{aligned}$$

Therefore,

$$\theta(t) = F(0) = \sum_{m\in\mathbb{Z}} a_m = \sum_{m\in\mathbb{Z}} t^{-1} e^{-\pi m^2/t^2} = t^{-1}\theta(1/t)$$

□

Proposition 51. *For $Re(s) > 1$, we have*

$$\int_0^{\infty} (\theta(t) - 1) t^{s-1} dt = \pi^{-s/2} \Gamma(s/2) \zeta(s)$$

Proof. We evaluate the integral by changing variable $u = nt$ and $v = \pi u^2$

$$\begin{aligned} &2 \int_0^{\infty} \sum_{n\geq 1} e^{-\pi t^2 n^2} t^{s-1} dx = 2 \sum_{n=1}^{\infty} \frac{1}{n^s} \int_0^{\infty} e^{-\pi u^2} u^{s-1} du \\ &= 2\zeta(s) \int_0^{\infty} e^{-v} (v/\pi)^{s/2 - 1} (2\pi)^{-1} dv = \pi^{-s/2} \Gamma(s/2) \zeta(s) \end{aligned}$$

□

Theorem 52. *For $Re(s) > 1$, $\xi(s) = \xi(1-s)$*

Proof. We evaluate $\xi(s)$ by changing variable $u = 1/t$, and by Lemma 4.8 and proposition 4.9, we have

$$\begin{aligned} \xi(s) &= \int_1^{\infty} (\theta(t) - 1) t^{s-1} dt + \int_0^1 (\theta(t) - 1) t^{s-1} dt \\ &= \int_1^{\infty} (\theta(t) - 1) t^{s-1} dt + \int_1^{\infty} (u\theta(u) - 1) u^{-s-1} du \\ &= \int_1^{\infty} (\theta(t) - 1) t^{s-1} dt + \int_1^{\infty} u^{-s} (\theta(u) - 1) + u^{-s} - u^{-s-1} du \\ &= \int_1^{\infty} (\theta(t) - 1) t^{s-1} dt + \int_1^{\infty} u^{-s} (\theta(u) - 1) du - \frac{1}{s} - \frac{1}{1-s} \end{aligned}$$

Therefore, we get

$$\int_1^{\infty} (\theta(t) - 1)(t^{s-1} + t^{-s}) dt - \frac{1}{s} - \frac{1}{1-s}$$

Which clearly satisfies $\xi(s) = \xi(1-s)$. □

Class Number Formula

Remark 53. In this section, we are going to derive the *Analytic Class Number Formula*:

$$\lim_{s\to 1} (s-1)\zeta_K(s) = \frac{2^{r_1 + r_2} \pi^{r_2} R_K h_K}{m |D_K|^{1/2}}$$

Where R_K is the regulator of K, h_K is the class number of K, and m is the number of roots of unity in K

Definition 54. Let $\varepsilon_1, \ldots, \varepsilon_r$ be a set of fundamental units, $r = r_1 + r_2 - 1$. $\lambda : K \to \mathbb{R}^{r_1 + r_2}$ be the logarithm mapping. The *regulator*, R_K is the absolute value of the determinant of any $r \times r$ minor in the $(r+1) \times r$-matrix with entries $\lambda_i(\varepsilon_j)$.

Definition 55. A *cone* in $\mathbb{R}^n$ is a subset $X \subset \mathbb{R}^n$ such that if $x \in X$ and $\lambda \in \mathbb{R}_{>0}$, then $\lambda x \in X$

Proposition 56. *Let X be a cone in $\mathbb{R}^n$, $F : X \to \mathbb{R}_{>0}$, be a function satisfies: $F(\xi x) = \xi^n F(x)$, with $x \in X, \xi \in \mathbb{R}_{>0}$. Let $T = \{x \in X | F(x) \leq 1\}$ be bounded, with non-zero volume $v = vol(T)$. Let Γ be a lattice in $\mathbb{R}^n$, with $\Delta = vol(\Gamma)$. Then $Z(s) = \sum_{\Gamma \cap X} \frac{1}{F(x)^s}$ converges for $Re(s) > 1$ and $\lim_{s\to 1}(s-1)Z(s) = \frac{v}{\Delta}$*

Proof. First, we notice $vol(\frac{1}{r}\Gamma) = \frac{\Delta}{r^n}$. Let $N(r)$ be the number of points in $\frac{1}{r}\Gamma \cap T$, then $N(r)$ is also the number of points in $\{x \in \Gamma \cap X | F(x) \leq r^n\}$. Then $v = vol(T) = \lim_{r\to\infty} N(r) \frac{\Delta}{r^n}$. Now we arrange $0 < F(x_1) \leq F(x_2) \leq \ldots$, and let $r_k = F(x_k)^{1/n}$. Then $N(r_k - \varepsilon) < k \leq N(r_k)$. Therefore, $\frac{k}{r_k^n} \leq \frac{N(r_k)}{r_k^n}$. This gives $\lim_{r_k\to\infty} \frac{k}{r_k^n} = \lim_{k\to\infty} \frac{k}{F(x_k)} = \frac{v}{\Delta}$. Thus, $\forall \varepsilon > 0$, $\exists k_0$, such that $\forall k \geq k_0$, we have $(\frac{v}{\Delta} - \varepsilon)\frac{1}{k} < \frac{1}{F(x_k)} < (\frac{v}{\Delta} + \varepsilon)\frac{1}{k}$. Thus,

$$(\frac{v}{\Delta} - \varepsilon)^s \sum_{k=k_0}^{\infty} \frac{1}{k^s} < \sum_{k=k_0}^{\infty} \frac{1}{F(x_k)^s} < (\frac{v}{\Delta} + \varepsilon)^s \sum_{k=k_0}^{\infty} \frac{1}{k^s}$$

Therefore, we know it converges when $Re(s) > 1$. And if we multiply $\lim_{s\to 1}(s-1)$ on both sides, since the pole of $\zeta(s)$ is at $s = 1$. We will get the equation we want. □

Definition 57. The cone $X \subset K_{\mathbb{R}}$ is defined with the following property ($x \in X$):
(i) $N(x) \neq 0$
(ii) The coefficients ξ_i of $l(x)$ satisfy $0 \leq \xi_i < 1$
(iii) $0 \leq arg(x_1) < \frac{2\pi}{m}$, where x_1 is the first component of x

Lemma 58. *If $y \in \mathbb{R}^n$, with $N(y) \neq 0$. Then y is uniquely of the form $xi(\varepsilon)$, where $x \in X$ and $\varepsilon \in \mathbb{Z}_K^{\times}$.*

Proof. Let $l(y) = \gamma\lambda + \gamma_1\lambda(\varepsilon_1) + \ldots + \gamma_r\lambda(\varepsilon_r)$. Let's write $\gamma_i = k_i + \xi_i$, with $k \in \mathbb{Z}, \xi \in [0,1)$. And let $\eta = \varepsilon_1^{k_1} \ldots \varepsilon_r^{k_r}$. Let $z = yi(\eta)$. We know that $0 \leq arg(z_1) - \frac{2k\pi}{m} < \frac{2\pi}{m}$ for some k. Choose $\zeta \in \mu(K)$ such that $\tau_1(\zeta) = e^{2\pi i/m}$, then $x = yi(\eta^{-1}\zeta^{-k}) \in X$, thus $y = xi(\eta\zeta)$. □

Remark 59. Let connect what we have proved before with class numbers. By Dedekind zeta function: $\zeta_K = \sum_{C\in C_K} f_C(s)$, summing all the ideal classes. And $f_C(s) = \sum_{\mathfrak{a}\in C} \frac{1}{N_{K/\mathbb{Q}}(\mathfrak{a})^s}$.

But if we take $\mathfrak{b} \in C^{-1}$, then $\mathfrak{a}\mathfrak{b}$ is principal, say $\langle\alpha\rangle$. Thus, $\mathfrak{a}$ and $\langle\alpha\rangle$ are bijective, and $\alpha \in \mathfrak{b}$. Thus,
$f_C(s) = N_{K/\mathbb{Q}}(\mathfrak{b})^s \sum_{\mathfrak{b}|\langle\alpha\rangle} \frac{1}{N_{K/\mathbb{Q}}(\alpha)^s}$. Let $\Gamma = i(\mathfrak{b})$,
$\Theta = \{x \in K_{\mathbb{R}} | x = i(\alpha), \alpha \in \mathfrak{B}\}$, where $\mathfrak{B}$ is a complete set of non-associate members of $\mathfrak{b}$, then
$f_C(s) = N_{K/\mathbb{Q}}(\mathfrak{b})^s \sum_{x\in\Theta} \frac{1}{N(x)^s}$

Proposition 60.

$$vol(T) = \frac{2^{r_1 + r_2} \pi^{r_2} R_K}{m}$$

Proof. Let $\varepsilon \in \mathbb{Z}_K^{\times}$. Then it preserves volume. And also by the last lemma, we let $\tilde{T} = \bigcup_{k=0}^{m-1} Ti(\zeta^k)$, and this has $vol(\tilde{T}) = m \cdot vol(T)$. Now, we let
$\overline{T} = \{x \in \tilde{T} | x_i > 0, \forall i = 1, \ldots, r_1\}$. Then $vol(T) = \frac{2^{r_1}}{m} vol(\overline{T})$.
Now we compute $vol(\overline{T})$ by change of variables first.
$(x_1, \ldots, x_{r_1}, z_1, \ldots, z_{r_2}) \mapsto (x_1, \ldots, x_{r_1}, R_1, \phi_1, \ldots, R_{r_2}, \phi_{r_2})$Where $z_k = R_k e^{i\phi_k}$. And the Jacobian of this change is $R_1 \ldots R_{r_2}$. Now, since $l(x) = \xi\lambda + \xi_1\lambda(\varepsilon_1) + \ldots + \xi_r\lambda(\varepsilon_r)$, and
$l(x_1, \ldots, x_{r_1}, z_1, \ldots, z_{r_2}) \mapsto$
$(\log(x_1), \ldots, \log(x_{r_1}), 2\log(R_1), \ldots, 2\log(R_{r_2}))$. We could do another change of variable with
$\log(x_i) = \frac{1}{n}\log\xi + \sum_{k=1}^{r} \xi_k \lambda_i(\varepsilon_k)$ and

$\log(R_i) = \frac{2}{n}\log\xi + \sum_{k=1}^{r} \xi_k \lambda_{r_1+i}(\varepsilon_k)$. And the Jacobian is computed to be $|J| = \frac{R_K}{2^{r_2} R_1 \ldots R_{r_2}}$. Therefore,

$$\begin{aligned} vol(\overline{T}) &= 2^{r_2} vol_{\mathbb{R}}(\overline{T}) \\ &= 2^{r_2} \int_{\overline{T}} dx_1 \ldots dx_{r_1} dy_{r_1+1} dz_{r_1+1} \ldots dy_{r_1+r_2} dz_{r_1+r_2} \\ &= 2^{r_2} \int_{\overline{T}} R_1 \ldots R_{r_2} dx_1 \ldots dx_{r_1} dR_1 d\phi_1 \ldots dR_{r_2} d\phi_{r_2} \\ &= 2^{r_2} (2\pi)^{r_2} \int_{\overline{T}} |J| R_1 \ldots R_{r_2} d\xi_1 \ldots d\xi_r = 2^{r_2} \pi^{r_2} R_K \end{aligned}$$

Thus, we plug this back into our equation. We will then get what we want. □

Let's make a conclusion with our remark.

Remark 61.

$$\begin{aligned} \lim_{s\to 1}(s-1) f_C(s) &= N_{K/\mathbb{Q}}(\mathfrak{b}) \frac{v}{\Delta} \\ &= \frac{N_{K/\mathbb{Q}}(\mathfrak{b}) 2^{r_1 + r_2} \pi^{r_2} R_K}{N_{K/\mathbb{Q}}(\mathfrak{b}) m |D|^{1/2}} = \frac{2^{r_1 + r_2} \pi^{r_2} R_K}{m |D|^{1/2}} \end{aligned}$$

Therefore, we could use the relation between $\zeta(s)$ and $f_C(s)$ to get:

$$\lim_{s\to 1}(s-1)\zeta_K(s) = \frac{2^{r_1 + r_2} \pi^{r_2} R_K h_K}{m |D_K|^{1/2}}$$

References
1. Jarvis, Frazer *Algebraic Number Theory* New York, NY: Springer, 2014.

About the Author

Ting Gong is a first-year honors math and philosophy major at Notre Dame. He is from China, and he went to high school in Kansas City. Besides doing math, he devotes his time to practicing instruments: violin and piano. He is very interested in number theory and algebra, and after college, he wants to be a mathematician and devote his time to research about the fields he loves.

New to the Journal: Student Spotlight

Several Notre Dame students publish their research in renowned peer-reviewed journals every year. The Student Spotlight section is a new addition to the journal to celebrate and learn from some of these students.

We interviewed senior physics and honors mathematics major Maciej Olszewski and sophomore science-business major Jon Klein for insight on their research and publication experiences.

How did you get involved in research?

Maciej: Fall semester of freshman year, I went around to various professors in the physics department asking for research positions. In the course of three weeks, I met with about 10 professors both in the physics and chemistry departments. What really intrigued me about Professor Morten R Eskildsen's proposed project was that it was an independent project, which he described as "high risk, high reward." For that reason, I decided to take on the project and spent the next six months trying to figure out what the project was about. After I started getting some preliminary results, I was hooked and have continued working on the project ever since.

Jon: I was attempting to brainstorm an idea for my high school science fair project. Around that time, the "ALS Ice Bucket Challenge" was making a lot of headlines on local TV channels and social media. I became curious and started reading more about ALS with the hopes of trying to understand the disease in an attempt to help people afflicted by it someday. I became really fascinated by the complexity of motor neuron disorders. One article by Dr. Avindra Nath, the clinical director at the National Institutes of Health, caught my interest; his article described the terrible case of a man with HIV and ALS-like symptoms, but after taking anti-retroviral HIV medication, surprisingly, his ALS symptoms also improved. I thought to myself: Could a treatment for ALS already exist in the form of an anti-retroviral medication? Are these two diseases somehow related? So, I decided to focus my project on searching for a biological link between HIV and ALS. Ultimately, my involvement in research stemmed from my random curiosity and a desire to help others.

What kind of research have you done, with what professor/lab?

Maciej: I have worked with Professor Morten Eskildsen in the physics department. His group conducts various types of experiments to quantify the motion and structure of how magnetic flux penetrates type-II superconductors in "magnetic tornadoes", called vortices. My project was based around a molecular dynamics code, which modeled the interactions between stable vortices and simulated the motion of the vortex lattice that they form. In my work, I took an existing simulation and implemented anisotropic interactions, which drove the lattice to form different structures. These structures corresponded to experimentally observed lattice structures by Professor Eskildsen's group. The bulk of my work is focused on figuring out new ways to classify these structures and find measures that best summarize my results and make them easy to compare to experimental results.

Jon: With the guidance and help of my research mentor, Dr. Nathan Staff at the Mayo Clinic, I have learned how to extract relevant information from protein databases and previously published literature. Data compiling is very time consuming but an essential step towards completing any bioinformatics-based research. Figuring out the most appropriate tool to conduct analysis is also critical for the success of any project, and it took me a lot of trial and error until I eventually found a very powerful protein network analysis tool called Cytoscape. The software is open-source and supported by community users, mostly protein bioinformaticians. Over the course of a few years, I compiled data and learned how to effectively use protein network analysis tools to obtain some encouraging information on potential network links and drug targets for ALS in connection to retroviral diseases such as HIV. In addition to my own research, I've worked in a microscopy lab, imaging mitochondria in neurons.

To what journal have you submitted/will you submit your work?

Maciej: I have been published twice:
"Structural transitions in vortex systems with anisotropic interactions"—M W Olszewski, M Eskildsen, C Reichhardt and C J O Reichhardt 2018 *New J. Phys*. 20 023005

"Skyrmions in Anisotropic Magnetic Fields: Strain and Defect Driven Dynamics"—R Brearton, M W Olszewski, S Zhang, M R Eskildsen, C Reichhardt, C J O Reichhardt, G van der Laan, and T Hesjedal. *MRS Advances*, n.d. 1–8. doi:10.1557/adv.2019.43.

I also have another manuscript in preparation to be submitted to *Physical Review B*, should be submitted by end of March:

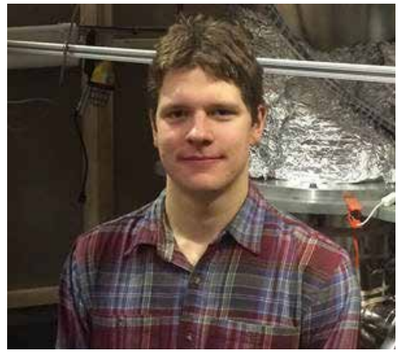
"Rotational transition, dislocations and domain formation in vortex systems with combined six- and 12-fold anisotropic interactions"—M W Olszewski, M Eskildsen, C Reichhardt and C J O Reichhardt, n.d.

Jon: I have submitted "Amyotrophic Lateral Sclerosis and Frontotemporal Degeneration" to *BMC Bionformatics*, and my paper was accepted.

What helped you to get published, and what advice would you give to other ND students?

Maciej: My main advice is for students to try and engage as much as possible in research and try to find new opportunities to take advantage of. There are many ways to excel at research, but in order to do so you need to create opportunities and work hard to achieve your goals. I had the amazing opportunity of spending three and a half months working at Los Alamos National Laboratory with two of my collaborators, which led to my first paper. I also had a chance to study abroad at Oxford, where I found a research group that was interested in my work, to whom I proposed a possible collaboration, which ended up leading to another publication. The opportunities for you to do good research are around you, you just need to be able to find them and capitalize on them.

Jon: The paper is currently under review; I am waiting to hear back. It's a stressful but also exciting process! Personally, I've learned that perseverance is absolutely essential for scientific research, and a big component of research is learning from failures. You should not get frustrated if your research doesn't yield the results you are hoping for, because at the end of the day, you've probably grown for the better and you'll be able to help others do the same.



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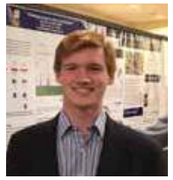

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