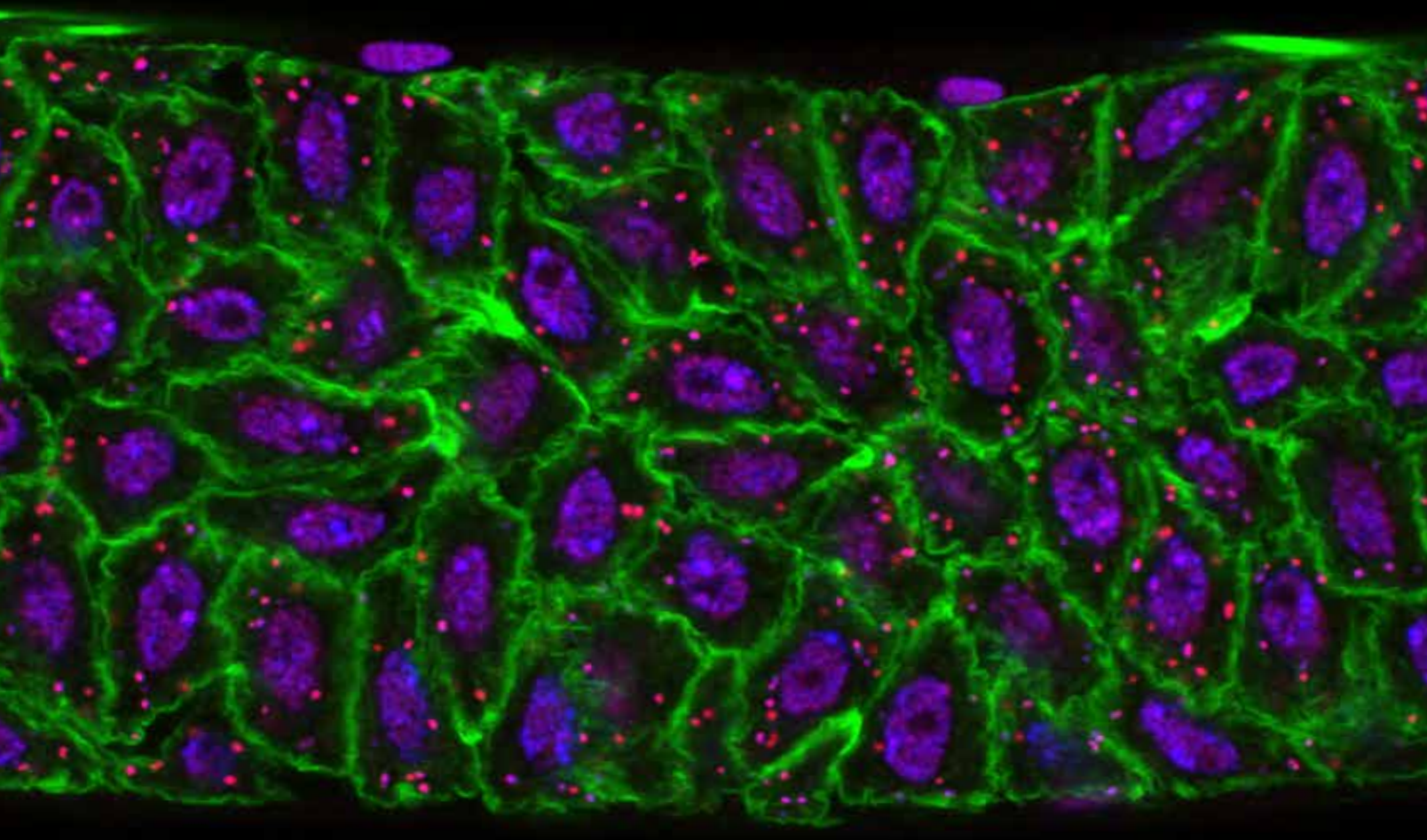
# inquiry@ UC SANTA CRUZ RESEARCH MAGAZINE

2020–21

## Nature's master manipulator



RIVER OF LIFE | A DANGEROUS ELEMENT | LOCAL GOES GLOBAL

UC SANTA CRUZ

# The spirit of **inquiry@**UC Santa Cruz

Welcome to the 6th edition of *inquiry@UC Santa Cruz*, our annual showcase of the exceptional research being performed at UC Santa Cruz across its five academic divisions.

As in previous years, the stories in these pages were crafted by alumni of the world-renowned UC Santa Cruz Science Communication Master's Program (see INQUIRING**minds**, p. 59). Their writing this year invites you to: view an artist's work that asks us to contemplate history from a modern perspective; mind your manners when interacting with robots; plunge into the politics of multi-city coalitions and their fight against climate change; open your mind to how the expansion of gender identities is changing the world; embrace the uncertainty of a mathematical quest; dive into aquaculture and a mission to provide a more sustainable approach for satisfying the world's growing appetite for farm-raised fish; track mercury's hazardous journey through our habitats, including the college cafeteria; travel the Nile via a historical exploration of how its changing course has impacted human health; and, in our cover story, admire a ubiquitous bacterium whose wily ways are unexpectedly providing valuable insights into the complexities of cell biology and solutions to age-old scourges.

Credit: Kurtz Photographics.

In addition, in PEN**&**INQ (p. 58) you'll find selected books authored by our faculty; likewise, you'll find recent inventions highlighted in **inquiries&**INNOVATIONS (p. 13).

Importantly, this year we celebrate our new chancellor—professor of chemistry Cynthia Larive, a highly accomplished researcher and educator—as well as our new membership in the Association of American Universities (AAU), a prestigious and influential group composed of America's 65 leading research universities (see BRIEF **inquiries**, p. 4). The outstanding breadth, depth, and creativity of the UC Santa Cruz research enterprise provides a wealth of intellectual adventures to share with you. We hope you enjoy this sampling!

Want to know even more? Access this issue and past issues of *inquiry@UC Santa Cruz* — enhanced with hyperlinks, additional artwork, and references for "**Further Inquiry**"—online at *inquiry.ucsc.edu.*

**Scott A. Brandt**
Vice Chancellor for Research
and Professor of Computer Science



# inquiry@ UC SANTA CRUZ RESEARCH MAGAZINE

2020–21


BRIEF **inquiries** page **4**

**inquiries&**INNOVATIONS page **13**

FEATURES

**Nature's master manipulator**
*Exposing the secrets of a successful symbiont*
*By Robert Pollie* page **14**

**Living history**
*New media art connects past to present with archival material*
*By K. M. Watson* page **22**

**What are your pronouns?**
*As choices for gander and sexual identities expand, the world slowly changes*
*By Aylin Woodward* page **27**

**River of life**
*Modern history ties the altered Nile to disease*
*By Cameron Walker* page **30**

**Robotic etiquette**
*Engineering improved human-robot interaction*
*By Ramin Skibba* page **37**

**A dangerous element**
*Tracking the elusive biogeochemistry of mercury*
*By Ula Chrobak* page **40**

**Fungi and fuel rise to the top**
*Grad student research stars in Grad Slam competition*
*By Emma Hiolski* page **45**

**Local goes global**
*As national governments waver, cities take up the climate fight*
*By Lindzi Wessel* page **46**

**Fish for all**
*Seeking sustainable aquaculture via fish-free feeds*
*By Bethany Augliere* page **49**

**Superior simulations**
*Mathematical quest seeks to embrace uncertainty*
*By Dana Mackenzie* page **56**

PEN**&**INQ page **58**

INQUIRING**minds** page **59**


*About the cover:* ***Wolbachia*** (red specks) colonize the developing egg cells of the nematode *Brugia malayi* (the larger purplish ovals are the nuclei of the eggs), one of several parasitic worms that cause the neglected tropical disease lymphatic filariasis, better known as elephantiasis. By infiltrating the eggs of these nematodes and many other invertebrates, the bacterium is able to spread from one generation of hosts to the next. That and many other canny survival strategies have made *Wolbachia* one of the world's most ubiquitous organisms and an object of increasing fascination to biologists. Credit: Laura Chappell, with permission.

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2020–21

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6/20 (1920-245/2.5M) IM2021



# BRIEF **inquiries**

ALL DIVISIONS

## Highest regards

Cynthia K. Larive was confirmed as the eleventh chancellor of University of California, Santa Cruz, by the UC Board of Regents on May 16, 2019. She began her tenure on July 1, 2019. Credit: C. Lagattuta.

When **Cynthia Larive** began her tenure at UC Santa Cruz in July 2019 as the new chancellor, she already knew she was joining a university with a commitment to impactful research. But a few months into the job, she got a reminder of just how highly the university is regarded. In November, the Association of American Universities (AAU), an exclusive group of universities at the forefront of research and academics, named UCSC as one of its newest members.

"AAU membership is such a great recognition of the ongoing contributions of our faculty, students, and staff," said Larive.

The AAU includes only 65 member universities, chosen based on factors including faculty citations and awards, research funding, and commitment to undergraduate and graduate education. Together, AAU members work to shape educational policy at both institutional and national levels.

UCSC is one of the youngest schools invited to join the AAU, and one of only 15 without a medical school. "To be a university that does not have a medical school and be admitted to the AAU is really something to be proud of," said Larive. The university's strong focus on interdisciplinary research, undergraduate student success, and diversity and inclusion all help it stand out, she said.

Larive is no stranger to what it takes to run a successful research enterprise. At UC Riverside, Larive was both a professor of chemistry and served as provost and executive vice chancellor. Her research involved developing improved tools for chemical analysis used to study everything from human biology to food—one project had her characterizing the compounds in pomegranate juice.

"I've been involved in many collaborative research projects and worked with people who weren't chemists to tackle important and complex problems," said Larive, "And this informs the way I think about things." This big picture perspective that she's such a fan of is already prevalent at UCSC, she said, and AAU membership is a prestigious, very public confirmation of this. In recent years UCSC researchers have come together to launch large-scale, cutting-edge initiatives in genomics, global climate change, coastal policy, and agroecology, to name just a few.

Moving forward, Larive plans to fully support UCSC faculty in their hands-on approach to shaping the university's research program—they're the ones who can spot areas ripe for new research and collaborations, she said. "We're on a great trajectory already."

*—Sarah C. P. Williams*

PSYCHOLOGY

## You are welcome

Associate professor of psychology **Rebecca Covarrubias** spent nine long years in Tucson studying at the University of Arizona. While she often visited home, her family visited the university to drop her off for her freshman year, and once again when she graduated with her doctorate. The university was so unfamiliar to them as to be "almost unwelcoming," she said. "Home was only a two-hour drive away, but it felt like worlds apart."

It was initially unfamiliar and hard for Covarrubias, too. She now aims to make this cultural mashup—a challenge for many "first-gen" college students like herself—more visible and less stressful.

While universities value independence and intellectual exploration, first-gen college students from racial/ethnic minority backgrounds are often balancing—and are strengthened by—family obligations. They care for siblings, translate at medical appointments, or offer financial support. "A university

At East Los Angeles College, families of first-gen college students attend a Regional Family Conference, a free, bilingual event for low-income, first-gen families to meet parents of graduated students with similar backgrounds. Credit: Regional Family Conferences, courtesy of Rebecca Covarrubias.

BIOMOLECULAR ENGINEERING

## From volcanic puddles

A prevalent theory posits that simple organic molecules initiated a primitive version of metabolism in hydrothermal vents deep in the ocean, leading four billion years ago to the origin of life. Professor of biomolecular engineering **David Deamer** thinks otherwise.

"There are layers of difficulty trying to get reactions to work in underwater vents," Deamer said. As explained in his book *Assembling Life* (January 2019), Deamer's alternative theory suggests that these critical molecular transformations occurred under more favorable conditions: in hot springs associated with volcanoes.

Small pools fed by hot springs would have contained mixtures of nucleotides—the building blocks of DNA and RNA—mixed with lipids, the primary component of cell membranes. When the pools evaporated, concentrated films of nucleotides and lipids would form on mineral surfaces. Under these conditions the nucleotides spontaneously link into DNA and RNA, a reaction demonstrated in Deamer's lab, which, incidentally, led to a patent. Ongoing wet-dry cycles selected for chemically stable, lipid-encapsulated nucleic acid chains, creating the molecular seeds for the emergence of living organisms.

Deamer and research associate **Bruce Damer** tested the idea by adding nucleotides to water samples from natural hot springs in volcanic sites around the world. Analysis of the mixtures cycled through wet-dry phases revealed microscopic vesicles containing polymers. Although not alive, these "protocells" are an essential first step toward molecular systems that can initiate Darwinian evolution, Deamer said.

Professor David Deamer (left) and research associate Bruce Damer at Mt. Lassen in Northern California, one of multiple volcanic sites around the world (including also New Zealand and Yellowstone National Park in Wyoming) where they carried out experiments that offer clues about the chemical beginnings of life. Credit: Courtesy of David Deamer.

*—Mike Wooldridge*

DIGITAL ARTS AND NEW MEDIA

## Kanye? Or Not?

Imagine a tabletop game where cards illustrated with faces stand in racks before you and your opponent. You're ready to take turns asking yes-or-no questions to guess each other's unseen cards. Wait…what's this? All the faces depict black men, and half are Kanye West.

This is *'ye or nay?*, a game/artwork created by assistant professor of digital arts and new media and critical race and ethnic studies **A. M. Darke**, a conceptual artist and activist who designs tools for social intervention. A work in progress with illustrator Tajae Keith, *'ye or nay?* is Darke's satirical reimagining of *Guess Who?*, the classic game in which the first question commonly asks: male? (or, female?). Darke replaces this question in *'ye or nay?* with one based on a "far less ridiculous binary": Kanye West? (or, not Kanye West?).


*'ye or nay?*, a game created by Assistant Professor A. M. Darke, a conceptual artist and activist, reimagines the classic game *Guess Who?* All the game's cards depict black men, and half of them are Kanye West. Credit: A. M. Darke, with permission.

By requiring players to describe and differentiate among black men, *'ye or nay?* provides opportunities for them to reflect on their perceptions and biases in an engaging way, Darke said. But the main goal of depicting black faces is so black people can see themselves represented in a broader way than in mainstream, white-dominated culture, they said. "*'ye or nay?* is just as much about celebrating black male beauty as it is about examining the language we build around blackness."

*—Erika K. Carlson*

ELECTRICAL AND COMPUTER ENGINEERING

## Better biosensors

Efforts to improve sensors that can measure biological substances in or on the body—for monitoring glucose in diabetics, for example—face the challenge of working at the pH (hydrogen ion) levels found in living organisms. Human blood, sweat, and tears typically have a pH of around 7. "Unfortunately, many metals that are good at measuring substances like glucose are only effective at pH 11," said professor of electrical engineering **Marco Rolandi.**

Rolandi and his team have now overcome the pH challenge. Their research leading to the patent-pending invention was published in July 2019 in the *Nature* journal *Scientific Reports*. By boosting the immediately surrounding pH, their millimeter-sized, metal-based biosensor can measure glucose levels in a solution that mimics body fluids.

The group created the biosensor by depositing small amounts of different metals on glass using a process called photolithography. Palladium metal increases the nearby pH by drawing hydrogen ions out of solution. The higher pH levels allow cobalt-oxide contacts next to the palladium to react with glucose and change oxidation state; the device measures the resulting current to determine the glucose concentration. The metal-based biosensor could offer advantages over current glucose monitors for diabetics, which typically last only months as the enzymes on which they rely eventually degrade. In addition, such a device implanted in the body may be less tissue-reactive, Rolandi said.

*—Mike Wooldridge*

Professor of electrical engineering Marco Rolandi and his group invented a metal-based biosensor for measuring glucose in pH-neutral fluids like those found in the human body. Here, Rolandi points to an enlarged image of the device in his laboratory while (left to right) doctoral students **Harika Dechiraju, Manping Jia**, and **John Selberg** look on. Credit: C. Lagattuta.

ECOLOGY AND EVOLUTIONARY BIOLOGY

## Bat cave blues

White-nose syndrome has killed millions of bats, cutting a deadly path across North America. Originally confined to the eastern United States, the disease is now affecting bats in Washington, Oregon, and California.

Caused by the fungus *Pseudogymnoascus destructans,* the disease attacks bats when they are hibernating, said Professor **Marm Kilpatrick**. The disease appears as a white powder on the bats' skin, hence its name.

Kilpatrick, a disease ecologist, was interested in how the fungus spread between and among different bat species never observed in social groups or in contact with each other. To study this, Kilpatrick and **Joseph Hoyt**, then a doctoral student (and now an assistant professor at Virginia Tech), daubed a UV fluorescent powder, which mimics the fungus, on individual bats. Tracking the dust's spread in the caves and to other bats showed how "cryptic" connections—shared contact with part of the cave or very brief contact with other bats—play a key role in transmission of the fungal pathogen. The mechanism is similar to how contact between strangers coming together in planes or subway cars, or in stores or cafes, might spread human pathogens, like the coronavirus in the Covid-19 pandemic, Kilpatrick said.

The overall prognosis for bat species in North America is dire, said Kilpatrick, who is also researching potential treatments. The northern long-eared bat, for example, has suffered population declines of more than 99 percent; three other species have also been heavily affected but will likely persist. "The disease has caused massive, enormous declines," Kilpatrick said.

*—Thomas Garlinghouse*

Little brown bats in hibernation show early growth of white-nose syndrome. The disease—a focus of research for professor and disease ecologist Marm Kilpatrick—has devastated bat populations across North America. Credit: Larisa Bishop-Boros, Wikimedia Commons (CC BY-SA 3.0).

culture of independence and separation largely renders these connections invisible," said Covarrubias, whose research focuses on issues of identity, culture, health, and educational quality/access for underrepresented and diverse individuals.

To help bridge the divide, Covarrubias works with the Hispanic-Serving Institutions initiative's Sense of Belonging team to organize a free, bilingual, half-day conference for low-income, first-gen families to meet parents of graduated students with similar backgrounds. Institutions must also change, said Covarrubias, who serves as faculty director of the Student Success Equity Research Center. "We can give students tools to navigate academia, but we also need to create a culture that reflects students' varied backgrounds and ways of being."

*—Jyoti Madhusoodanan*

HISTORY

## Transformed by occupation

Okinawa, a tiny speck in the vast Pacific Ocean, plays an outsized role in American history. For 75 years, since the end of World War II, the United States has occupied this smallest of the five main islands of Japan with a string of strategically significant military bases.

The consequences of this occupation are the focus of the Okinawa Memories Initiative, a sprawling oral history project led by associate professor of history **Alan Christy**. The work aims to document and understand the dramatic social changes that occurred as Okinawan society rapidly transformed from very traditional to very modern.

The research chronicles, for example, the impact of a surge in high-tech entertainment and media services. Based on this business focus, Naha, the island's main city, is poised to become a major driver of the Japanese economy over the next decades, Christy said. "The media environment is incredible for a place its size," he said.

Left: Children experienced a much-changed world from the traditional one of their elders on Okinawa, which rapidly modernized following the island's 1945 occupation by the U.S. military that continues to this day. This photograph of likely grandmother and granddaughter (names unknown) is a favorite of **Geri Gail**, a former UCSC staff member who donated the collection of her father's snapshots of Okinawa in the early 1950s to UCSC in 2013. Credit: The Gail Project ©Geri Gail, with permission.

The project, which began with the donation of a cache of photographs taken by Charles Eugene Gail, an American military officer stationed on Okinawa in the early 1950s, has since broadened its scope to encompass the entire occupation, from 1945 to the present. To uncover the personal stories of Okinawans during this time of major transformation, Christy and collaborators use interviews, photographs, and archival records found in both Okinawa and Washington, DC. "The changes that happened here are historically significant, and well worth understanding," Christy said.

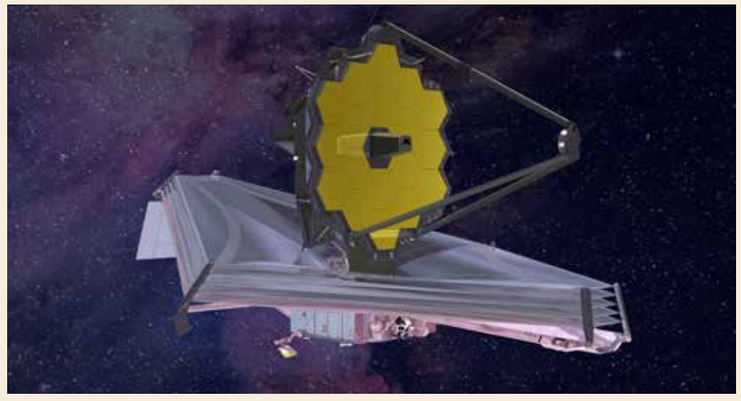
*—Thomas Garlinghouse*

ASTRONOMY AND ASTROPHYSICS

## Space sanctuaries

**Natalie Batalha** thinks there's life on other planets and she's made it her mission to find it. Before joining the Department of Astronomy and Astrophysics in 2018, Batalha helped lead NASA's Kepler Mission, which surveyed a section of the Milky Way Galaxy and discovered more than 2,600 new planets. Many were dubbed "Goldilocks planets"—planets roughly the same size and temperature as Earth, making them ideal places to search for liquid water and life.

Now, Batalha wants to characterize the atmospheres of some of those planets. She believes scientists will be able to detect unique biosignatures in the atmospheres surrounding planets that host life by learning what's typical when it comes to planetary atmospheres. "I think living worlds will stand out like a sore thumb," Batalha said.



Professor of astronomy and astrophysics Natalie Batalha will be collecting data from the James Webb Space Telescope, shown here in an artist's impression, as part of her search for extraterrestrial life. The new space telescope is scheduled for launch in 2021. Credit: Northrop Grumman/NASA (CC BY 2.0).

Batalha will collaborate with researchers from around the world to collect this atmospheric data using the James Webb Space Telescope, scheduled to launch in 2021 and orbit in space for five to ten years. In anticipation of that launch, Batalha is busy analyzing data on new planets being observed through a telescope at the Keck Observatory in Hawaii. The basic information collected there helps her choose which planets to focus on with the Webb mission.

Searching for extraterrestrial life is not only driven by pure curiosity, Batalha said, but also questions about what it takes for planets—including Earth—to sustain life. "We need to make sure our own planet continues to be a habitable sanctuary for humanity," she said.

*—Sarah C. P. Williams*

ENVIRONMENTAL STUDIES

## Not just plants

Walking across the UC Santa Cruz campus, the towering pines and wildflowers are easy to spot. Less obvious? The fungi that call these plants home. But those fungi play key roles in the campus ecosystem. Just as a human body teems with microorganisms, all plants host fungi that can help them thrive, cause disease, or anything in between, according to professor of environmental studies **Gregory Gilbert**. "Fungi really shape everything plants do," he said.

Gilbert, along with professor of ecology and evolutionary biology **Ingrid Parker**, has collected thousands of plant samples from around UCSC and extracted their DNA to study what fungi they're infected with. Their goal is to understand which species of fungi infect which plants, and how those infections spread over time. Santa Cruz is an ideal place to study these interactions because of the range of climate conditions and plant diversity, Gilbert said. "We have this amazing living laboratory campus."

Ubiquitous plant-fungus relationships on the UC Santa Cruz campus, most not as obvious as this one between a wild raspberry and a rust fungus, are one focus of ongoing research by professor of environmental studies Gregory Gilbert. Credit: Gregory Gilbert, with permission.

When a new disease-causing fungus invades an ecosystem, there is often sparse science to inform—and frequently little time to determine—what might be done to limit its spread and impact. Gilbert hopes his research, besides illuminating the less obvious, will help inform such actions by improving our understanding of the biology through which plants and fungi interact.

*—Sarah C. P. Williams*

MUSIC

## Discordant compositions

Poets consider music to be humankind's universal language. But deep divides of race and income at times split its makers—at least those who were members of the American Federation of Musicians (AFM)—in the early 20th century. **Leta Miller**, professor emerita of music, discovered a piece of this troubled past in San Francisco's history, where black and white musicians formed separate, competing union local chapters.

The conflict in San Francisco came to a head in 1934 when the black Local 648 sued their white counterpart, Local 6, for attempting to control all gigs. State laws eventually forced the two to merge in 1960. But Miller found that similarly segregated union locals were commonplace across dozens of U.S. cities—and some even persisted into the early 1970s. "I was quite astonished at how many there were," Miller said.

Supported by a 2019–20 Dickson Emeriti professorship, Miller is now working on a book

Clubs in San Francisco's Fillmore district (shown in white) provided work to black musicians during the 1950s, following earlier territorial scuffles between the black and white musicians' unions. Professor emerita of music Leta Miller uncovered the details of this history through her research into the widespread segregation in the unions that persisted into the 1970s in some U.S. cities. Credit: Courtesy of Leta Miller.

EARTH AND PLANETARY SCIENCES

## Making the Earth move

Professor Emily Brodsky and the UC Santa Cruz seismology group study how injecting water underground, such as occurs with wastewater during fossil fuel production, can trigger earthquakes. Here, graduate student **Travis Alongi** deploys an instrument for measuring subterranean fluid pressure. Credit: Courtesy of Emily Brodsky.

Modern methods of extracting fossil fuel from the ground also bring up vast amounts of highly contaminated water. The safest way to dispose of that toxic wastewater is to pump it back underground, but that can disturb faults and trigger earthquakes. "People make earthquakes by shoving water into the ground or by pulling water out," said professor of Earth and planetary sciences and induced seismology expert **Emily Brodsky**, who has made it her mission to understand this phenomenon.

To more closely investigate how wastewater injection triggers earthquakes, Brodsky and then–researcher and lecturer **Thomas Goebel** (now an assistant professor at the University of Memphis), analyzed data from 18 drill sites around the world. Their findings, published in *Science* (August 2018), overturned conventional wisdom about the safest place to inject wastewater. Oil companies typically avoid injecting into deeper, harder basement rock that contains most seismic faults, opting instead for shallower, softer sedimentary rock. Brodsky and Goebel's evaluation of injection depths and affected rock types revealed that the sedimentary strategy triggered more earthquakes and ones of higher magnitude. "Sedimentary injections are more dangerous than basement injections, the opposite of what everyone thought," Brodsky said.

Sedimentary injections can transmit pressure up to 10 kilometers away, increasing the chances of disturbing faults. Oil companies are better off injecting into basement rock, especially if they can pinpoint areas free of major faults, Brodsky said.

*—Mike Wooldridge*

about segregation in musicians' unions across the nation. While the separation was no doubt rooted in racism, black musicians in many cases actually chose to form their own locals. Miller found that, apart from promoting identity and community, doing so allowed them to set their own rates—sometimes undercutting the white competition. Each local also garnered a seat at the AFM national convention, so "having their own local ensured that black musicians were guaranteed a voice at the meeting," Miller said. "That was probably very important."

*—Jyoti Madhusoodanan*

BIOMOLECULAR ENGINEERING

## Boosting blood cells

Approved in 1998, the drug sildenafil citrate—better known as Viagra—offered men with erectile dysfunction a welcome alternative to the invasive solutions then available for their non–life-threatening but life-altering condition. As urban legend has it, Viagra's developers initially tested it as a drug to lower blood pressure and were surprised by its notable side effect. The rest is history.

Now, researchers led by professor of biomolecular engineering **Camilla Forsberg** have found another potential use for the infamous "little blue pill." Recently published in *Stem Cell Reports* (October 2019), their work showed that the drug enhanced the effect of the immunostimulant plerixafor, boosting the blood stem cell mobilization (movement from bone marrow to bloodstream) critical to the high-risk transplants used to treat—and potentially cure—patients with blood-based cancers and other immune-based disorders. Extracted from donors or patients themselves, the mobilized stem cells are "transplanted" into the patient to reconstitute their blood after a course of high-dose chemotherapy and/or radiation kills off both normal and malignant cells.

Research specialist **Stephanie Smith-Berdan**, first author of a report describing a new method for collecting blood stem cells needed to treat patients with blood cancers, performs benchwork in the laboratory of professor of biomolecular engineering Camilla Forsberg. Credit: C. Lagattuta.

The results suggest that the new combination may provide a more rapid and effective means of collecting stem cells than older, often unsuccessful methods needing multiple injections over several days. "We try to provide paradigms for clinicians to work with," said Forsberg, whose wide-ranging research focuses on the molecular biology of hematopoietic stem cells. "The lab is where we can do new and crazy things and make discoveries."

*—Thomas Garlinghouse*

ENVIRONMENTAL STUDIES

## Urban farming

Even in a city, a wildlife haven might be just around the corner. In urban gardens throughout Santa Cruz, the Monterey Bay Area, and Santa Clara County, **Stacy Philpott**, professor and director of the Center for Agroecology & Sustainable Food Systems, has cataloged a wealth of species, at least 60 types of bees, 25 of spiders, 18 of ladybugs, and about 60 of birds.

Philpott and her research group study how differences in urban gardens, like their "messiness" and the number and types of nearby trees and shrubs, affect their biodiversity. In general, the group finds that what's good for biodiversity is good for human gardeners too. Their experiments suggest that gardens

WRITING PROGRAM

## Success before tragedy

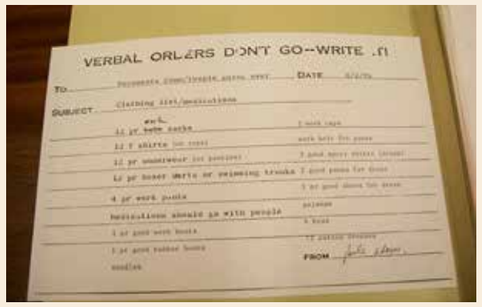
To create the Peoples Temple in 1955, its founders merged religious ideology with a vision of a world that transcended race and social class. Twenty-four years later, more than 900 of the group's members lay dead, their bodies decomposing in the Guyanese jungle heat.

The group's written records both reflect and—importantly—shaped its tragic path, said teaching professor of writing **Heather Shearer**. Shearer began researching the group's documents expecting to find evidence of "brainwashed cult members," she said. "But I saw a really different picture."

Ninety-six boxes of letters, pledges, and checklists—some on memo pads printed with the header "Verbal orders don't go—write it!"—bear witness to the group's meticulous planning and utopian achievements: a racially integrated church in 1950s Indiana, communal housing developed in Northern California, and members' excitement as they built Jonestown. "They're known for dying, but let's not forget what they accomplished," Shearer said. "It's impressive how organized they were, and how the writing helped them organize."

Dismissing them as a cult denies what we learn from their written communications, Shearer said. "They had noble aspirations. The documents show how much they wanted to build a better society and how hard they worked for it."

*—Jyoti Madhusoodanan*




A memo headed by "Verbal orders don't go—write it!" lists items to be packed for the fateful move to Jonestown. Teaching professor of writing Heather Shearer's study of records from the Peoples Temple reveals how such written communications were key to the group's impressive success that preceded its tragic failure. Credit: Heather Shearer, with permission.

ECONOMICS

## Fertilizing development

In the Mamba market in Tanzania, Associate Professor Jonathan Robinson and collaborators that included Associate Professor **Alan Spearot**, chair of the Economics Department, current doctoral student **D. J. Jeong**, former doctoral student **Brian Giera**, now an economist at Amazon, and former doctoral student **Shilpa Aggarwal**, now an assistant professor at the Indian School of Business in Hyderabad, India, recorded food prices and surveyed buyers and sellers to quantify travel costs and times from various villages. Credit: David Roughgarden, courtesy of Jonathan Robinson.

In the fight against global poverty, rigorous field research can provide important insights. This conclusion determined the 2019 Nobel Prize in Economic Sciences, awarded to three researchers—Abhijit Banerjee, Esther Duflo, and Michael Kremer—for their pioneering efforts in applying this approach to the study of economics in developing countries. This rigorous, quantitative methodology also drives the work of associate professor and development economist **Jonathan Robinson.**

Robinson's collaborative research with Duflo and Kremer, among others, focuses on understanding why potentially life-changing agricultural practices remain little used in many impoverished areas. For example, while the use of fertilizer has increased dramatically in countries like India, smallholder farmers in sub-Saharan Africa haven't followed suit. The weak uptake there may be due to different environments and crops grown, or inadequate education, but another barrier could be the high cost of access related to poor infrastructure.

In a recent study, Robinson and collaborators quantified how poor roads and distance from a fertilizer retailer correlate with decreased fertilizer usage and individual farmer productivity in Tanzania. Their results directly connect the increased costs of obtaining fertilizer for farmers in more remote villages with reduced earnings from what they grow. "Farmers ultimately choose to adopt inputs like fertilizer based on profitability," Robinson said. "Even if fertilizer increases yields, farmers may reject it because the costs of access are too high."

*—Erika K. Carlson*

with more biodiversity have more effective pollination and natural pest control.

It's also clear that urban gardens can be invaluable to the people who use them. Surveys of community members who work these gardens show that many garden as a way to spend time outdoors, relieve stress, and hang out with their families. For some, having access to a space to grow produce provides a vital way to put food on the table. A substantial number of lower-income gardeners surveyed experience some food insecurity, Philpott said. "There's a lot of demand for space in cities and many interests competing for its use," Philpott said. "Our research shows that gardens are important spaces."

*—Erika K. Carlson*

While studying the biodiversity of urban gardens in and near Santa Cruz, Professor Stacy Philpott and her group have cataloged more than 60 species of bees, like this bumblebee—*Bombus vosnesenskii*—visiting a lavender plant in a Salinas community garden. Credit: Stacy Philpott, with permission.



# inquiries&INNOVATIONS

By Marcus Woo

## Inhibiting inflammatory enzymes

Enzymes called lipoxygenases help control the body's inflammatory responses. "We're realizing their role in human disease is quite significant," said professor of biochemistry **Ted Holman**, part of a group awarded two related patents for inhibitors of the lipoxygenases 12-LOX and 15-LOX-1.

Inhibiting 12-LOX could prevent a dangerous condition that afflicts some surgery patients, potentially saving lives in rare cases where heparin, a drug commonly used to prevent blood clots during surgery, instead induces platelets to aggregate excessively, triggering stroke and bleeding. And inhibiting 15-LOX-1 could help stroke patients. After an ischemic stroke, blood returns to the brain as the patient recovers. But the oxygen in the returning blood can also be harmful, and blocking 15-LOX-1 may limit the damage this can cause.

*Maloney D, Luci D, Jadhav A, Holman T, Nadler J, Holinstat M, Taylor-Fishwick D, Simeonov A, Yasgar A, McKenzie S. 4-((2-hydroxy-3-methoxybenyzl)amino) benzenesulfonamide derivatives as potent and selective inhibitors of 12-lipoxygenase. U.S. Patent 10,266,488, filed October 10, 2014, issued April 23, 2019; and Van Leyen K, Holman T, Maloney D, Jadhav A, Simeonov A, Rai G. Inhibitors of human 12/15-lipoxygenase. U.S. Patent 10,287,279, filed February 19, 2016, issued May 14, 2019.*

## Cancer treatment maps

A cancer cell is a cell that has run amok. Exactly how this happens depends on an immense set of possible cancer-causing errors that occur with great variability among cancer types and individual patients. But identifying the specific errors could help doctors choose the best treatments—to "personalize" therapy for each patient.

To accomplish this, the patented algorithm developed by professor of biomolecular engineering **Josh Stuart** and collaborators compares the genomic blueprints of tumor and healthy cells. The resulting dynamic pathway map pinpoints the errors that led to the cancer—and thus possible targets for therapy. "The invention takes very complex data and focuses attention on likely treatment alternatives for patients," Stuart said.

*Vaske C, Benz S, Stuart J, Haussler D. Method of generating a dynamic pathway map. U.S. Patent 10,192,641, filed October 26, 2011, issued January 29, 2019.*

## More efficient networks

In internet networks, databases called routing tables tell each node where to route data. When the network is large and dynamic, efficiently updating the routing tables becomes critical. "The goal is to reduce the amount of time and to reduce the amount of messages that have to be exchanged," said **J. J. Garcia-Luna-Aceves**, professor of computer science and engineering.

His patented method organizes nodes into hierarchical groups, so that not every node has to store and send every message about how to update the tables. The approach would be especially useful for special-purpose wireless networks that are constantly changing, such as ones used for disaster relief or on the battlefield.

*Garcia-Luna-Aceves J, Li Q. Method for distance-vector routing using adaptive publish-subscribe mechanisms. U.S. Patent 10,091,094, filed October 16, 2014, issued October 2, 2018.*

## Finding gut leaks

The sugar substitute sucralose can't be digested, so it usually exits the body via the bowel. But finding it in urine or blood could signal a leak in the gut, due to inflammation from Crohn's disease or another gastrointestinal disorder. Doctors typically perform colonoscopy to evaluate such leaks. But measuring sucralose could be simpler, quicker, and cheaper—perhaps as an initial screening.

To readily detect and measure sucralose in urine or blood, professor of organic chemistry **Baktham Singaram** and collaborators invented a chemical process that causes a sample to glow with a brightness proportional to the sucralose concentration. In addition, the time between sucralose ingestion and its appearance in urine or blood reveals the leak's location. "Using our procedure, we can say globally where the leak is," Singaram said.

*Singaram B, Resendez A, Webb D. Fluorescence method for sensing chlorinated disaccharides. U.S. Patent 10,274,483, filed June 5, 2015, issued April 30, 2019.*

## RNA-targeted therapy

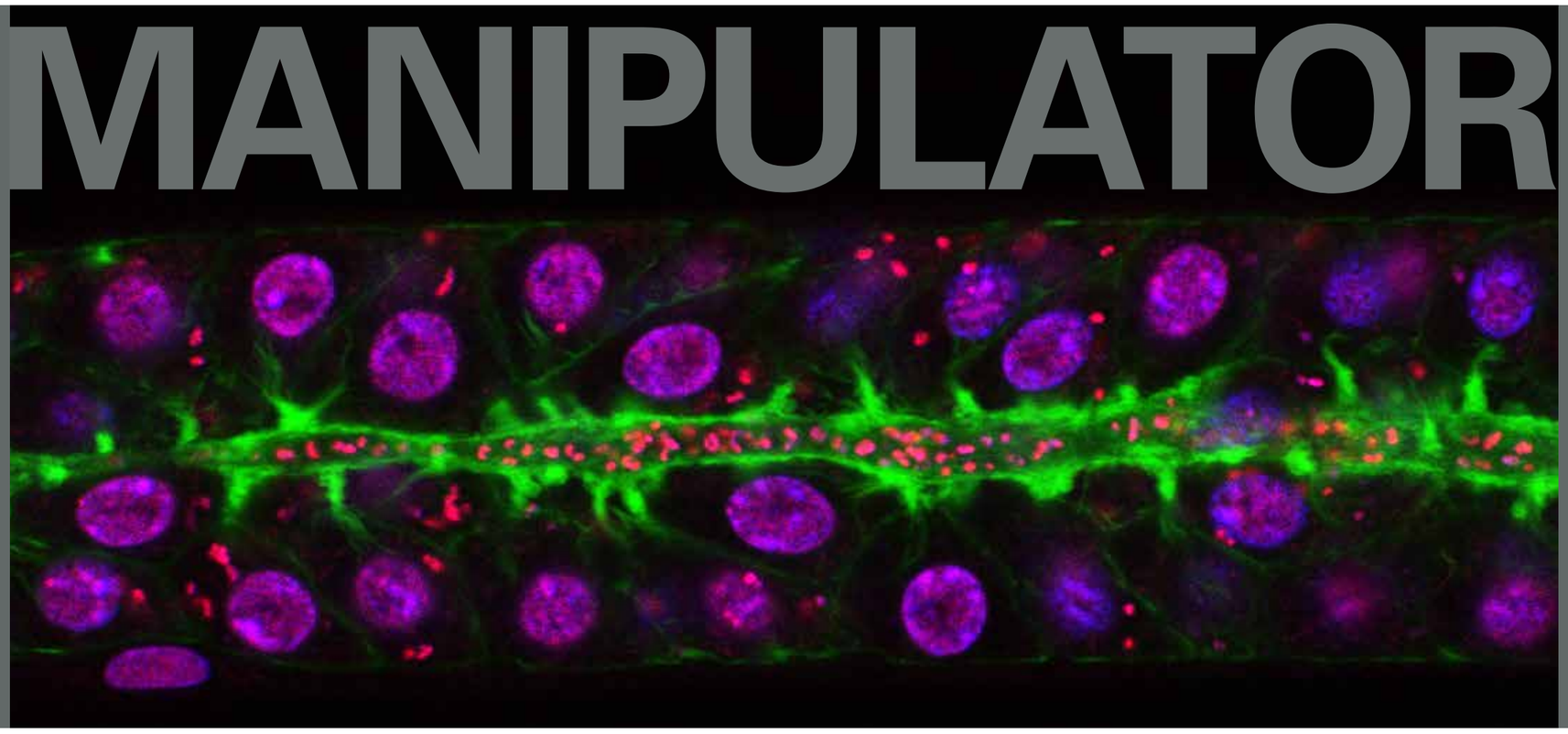
A cancer cell or virus can be inhibited by severing its RNA, the coiled molecule that transmits its genetic material. But to prevent toxic side effects and the development of resistance, the RNA has to be cut in specific places along its sequence. Such precise slicing can be done with ribozymes, a type of RNA that acts like an enzyme.

To get the right ribozymes, **William Scott**, professor of chemistry, and **Sara O'Rourke**, project scientist, invented a way to engineer simplified "hammerhead" ribozymes. "It really increases our flexibility to design a potent inhibitor for pretty much any RNA molecule you could want to target," Scott said. The researchers are applying their technique to develop drugs for chronic myelogenous leukemia and RNA-based viruses, like the Covid-19 coronavirus.

*O'Rourke S, Scott W. Catalytic strands of minimal hammerhead ribozymes and methods of using the same. U.S. Patent 10,301,626, filed March 1, 2016, issued May 28, 2019.*

By Robert Pollie

# Nature's master MANIPULATOR



## Exposing the secrets of a successful symbiont

Left: *Wolbachia* (red specks) in the developing egg cells of the nematode *Brugia malayi* (the larger purplish ovals are the nuclei of the eggs), one of several parasitic worms that cause the neglected tropical disease lymphatic filariasis, better known as elephantiasis. In these filarial nematodes, *Wolbachia* is an "obligate mutualistic endosymbiont," a symbiotic sidekick the worms can't live without. Credit: Laura Chappell, with permission.

Below: A common fruit fly, Drosophila melanogaster, seen here feeding on a banana, frequently shows up as an unwanted guest in kitchens, gardens, orchards, and vineyards worldwide. It also continues to serve as a widely-used model organism for biological research, including *Wolbachia* studies in the laboratory of UCSC distinguished professor of molecular, cell, and developmental biology Bill Sullivan. Credit: Sanjay Acharya, Wikimedia Commons (CC BY-SA 4.0).

Calling a lowly microbe intelligent may seem over the top, but you can forgive a little hyperbole when **Bill Sullivan** describes the bacterium *Wolbachia* as "really smart." Sullivan, UC Santa Cruz distinguished professor of molecular, cell, and developmental biology, is explaining how the intracellular parasite sneaks its way through the embryos of certain fruit flies and into their nascent eggs, allowing it to pass from one generation of flies to the next. *Wolbachia* appears to do this by hitching rides on the fly's motor proteins, which carry supplies to the egg-producing region of the embryo. The proteins march along a system of microtubules, like porters lugging cargo up the gangways of ships.

Partway through the proceedings, the embryo does a 180, flipping the polarity of the microtubules. Motor proteins that had been trooping toward the egg-zone do an about-face and start heading away. Getting to the mothership now requires hopping aboard a different type of motor protein, designed to seek the "plus" end of the microtubule instead of the "minus" end. And—here's the really smart part—that's exactly what *Wolbachia* does, deftly rejiggering binding sites on its surface to make the switch. If, as Sullivan suspects, the embryo's microtubular reversal is meant to deflect invading parasites, *Wolbachia* does an end-around and keeps on coming.

### The great pandemic

That maneuver, discovered by Sullivan and colleagues, is just one of many exploits that have made *Wolbachia* one of the most successful parasites on Earth. It's believed to infect roughly half the world's several million insect species. Stick a butterfly or beetle, wasp or fly, ant or bedbug under a sufficiently powerful microscope, and there's a decent chance you'll find *Wolbachia* in some of its cells, tucked into the cytoplasm like tapioca pearls in pudding. *Wolbachia* shacks up in other invertebrates, too, including mites, ticks, spiders, and some nematode worms. Its sheer ubiquity has led some scientists to dub the contagion "one of the great pandemics in the history of Life."

*Wolbachia* doesn't directly infect humans, but it has a way of getting into the heads of biologists captivated by its machinations, its global conquests, and increasingly, its potential as a weapon against some of humanity's greatest scourges. "It's an amazing organism," said **Laura Serbus**, a former postdoc of Sullivan's who now studies *Wolbachia* in her own lab as assistant professor of biological sciences at Florida International University. "It's teaching us so much about how infections and cells themselves work."

Sullivan's own relationship with *Wolbachia* started casually enough. He was teaching an undergraduate genetics course and looking to liven things up with field trips. When he read that a bacterium, *Wolbachia*, was sweeping northward through California's fruit fly population, he hatched a plan: he and his students would hit up local wineries

and apple orchards, collect the swarming flies and analyze them to see if the infection had reached Santa Cruz County (it had).

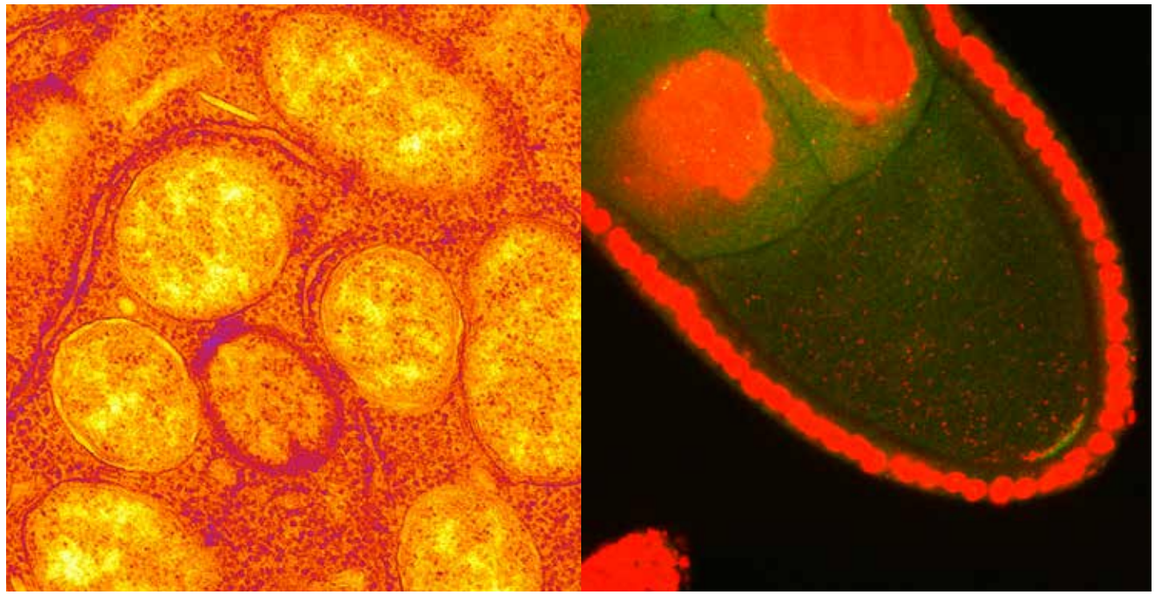
That was 20 years ago, and what began as a fling has become a lasting passion. Today, Sullivan is recognized as a leading expert on *Wolbachia*, at a time when worldwide interest in the bacterium is exploding. "The field has gotten so much more crowded and competitive than it used to be," said population biologist Michael Turelli, distinguished professor of genetics at UC Davis, who's been researching *Wolbachia* since the late 1990s. "But at the big international meetings, people still look to Bill when it comes to the cell biology of *Wolbachia*."

## Microscopic moviemaking

In retrospect it was a natural fit. Sullivan was schooled in the genetics of *Drosophila melanogaster*, the classic laboratory fruit fly (online he's been known to use the screen name "Count Drosophila"). And he was adept at methods used to probe the innermost workings of cells. As a postdoc in the 1980s, he'd cut his teeth in live fluorescent microscopy, tagging proteins with dyes that light up under the microscope, then watching, and filming, cellular events as they played out in real time. Sullivan refers to it as "making movies," and his lab has produced thousands of short films over the years (example titles: *Syncytial Divisions*, and the sequel, *Syncytial Divisions II)*.

The first *Wolbachia*-related problem he applied those skills to is something called cytoplasmic incompatibility (CI), one of the ploys *Wolbachia* uses to spread among insects. *Wolbachia* is transmitted hereditarily via insects' eggs, so the more *Wolbachia*-infected females there are, the more the bacteria propagate. *Wolbachia* helps things along by turning infected males into a form of selective birth control. When these males mate with uninfected females, the pairing is sterile. Infected females, on the other hand, can reproduce successfully with any male, infected or not. With this big advantage in the mating game, *Wolbachia*-carrying females outbreed their competition and can quickly take over populations.

But exactly how CI scuppers the infected male/uninfected female crosses wasn't known. Using their moviemaking chops, Sullivan and then-postdoc **Uyen Tram** (now a research associate at the Ohio State University), traced the problem to a timing glitch at the very beginning of embryogenesis, just after the egg is fertilized by sperm and starts dividing. When



*Wolbachia* is an endosymbiont, a symbiotic organism that only lives inside the cells of its hosts. Here, *Wolbachia* (large ovals) crowd the cytoplasm of a fruit fly cell. Credit: Alain Debec, Institute of Ecology and Environmental Sciences, Sorbonne University, with permission.

things are working properly, paternal chromosomes from the sperm and maternal chromosomes from the egg are in lockstep as they replicate and line up together in the middle of the cell. At that point the egg begins cleaving, ultimately creating two new cells with identical sets of mom and pop chromosomes. But in the case of CI, the father's chromosomes are late to the party. They're slow to replicate and fail to line up in time for cleavage. This leaves the daughter cells with only half the chromosomes they need. The embryo is DOA.

Sullivan and Tram submitted their findings to the journal *Science* in 2002. The paper was quickly greenlighted without further revision—a rare feat in the persnickety world of top-tier science publications. After that auspicious beginning, Sullivan and team went on to work out a more detailed model that's a leading theory of how CI works. It explains not only why normal females can't breed with infected males, but why infected females can: *Wolbachia* seems to delay the maternal chromosomes to match the late-arriving paternal ones, ensuring that all pieces are in place before division occurs.



Polar express: *Wolbachia* (tiny red specks) are seen here flocking to the posterior pole (lower right) of a fertilized *Drosophila* egg, putting themselves in position to get incorporated into the next generation of eggs. Credit: Laura Serbus, with permission.

## Evolutionary ingenuity

That was the first of many *Wolbachia*n mysteries explored by Sullivan and his collaborators. In 2004, along with postdocs Laura Serbus and **Shelbi Russell** and then-Ph.D. student **Patrick Ferree** (now an associate professor of biology at Claremont McKenna College), he began tackling another puzzle: how *Wolbachia* gets into the germ line, the cells that give rise to eggs and sperm. It's a trek the microbes have to make in each new generation of insects they infect. They start out scattered throughout the egg cell inherited from the infected mother, but soon after fertilization, the bacteria begin migrating to the posterior end of the egg, the part that will become the germ tissue of the embryonic fly.

Using the tools of knockout genetics (see sidebar, p. 18) on *Drosophila melanogaster*, Sullivan and team were able to piece together the molecular mechanics described in the opening paragraphs above: how *Wolbachia* infiltrates cellular supply lines, latches onto motor proteins, and changes horses in mid-stream to get to the rear of the egg.

It's a bravura display of evolutionary ingenuity, and not least because *Wolbachia* strikes such a delicate balance. While it binds to some of the available motor proteins, it also leaves plenty of slots open for the embryo's own supplies. "As Shelbi Russell has shown, *Wolbachia* seems to have evolved as a weak competitor for the attachment sites, so it doesn't impair the embryo's development," Sullivan said. Playing nice with hosts is good parasite policy. If they thrive, so does *Wolbachia*.

Sullivan and his team weren't just uncovering the secrets of *Wolbachia*; they were developing new tools and techniques for *Wolbachia* research. Since *Wolbachia* can't live outside of cells, studying it had previously meant working with whole infected insects: breeding them, subjecting them to various treatments, dissecting out the tissues of interest, and eyeballing the samples under the microscope to see the effects on *Wolbachia*. It was laborious and complicated. With the help of the cell biologist Alain Debec of the Institute of Ecology and Environmental Sciences at the Sorbonne University in Paris, Sullivan's group radically simplified matters by developing the first *Wolbachia*-infected *Drosophila* cell line: cells containing *Wolbachia* that could be raised in vitro. "You can grow them indefinitely, freeze them, thaw them out whenever you need them, and do all sorts of neat things," Sullivan said.

One of the neat things Sullivan did was to apply new "high throughput" lab technology—implemented by UC Santa Cruz professor of chemistry **Scott Lokey**—to streamline testing and assays. Instead of wrangling flies, manually manipulating them and inspecting specimens one by one, he and his team could process hundreds of cell samples in batches using robotic handling systems. Mechanized microscopes could scan the samples and analyze the results. This automated approach made procedures like knockout genetics hundreds of times faster. "We could accomplish in weeks what would have taken years," Sullivan said.

## The worm turns

In the mid-2000s, Sullivan's research took another turn when he learned that *Wolbachia* had been implicated in two major human maladies: onchocerciasis and lymphatic filariasis, better known, respectively, as river blindness and elephantiasis. The two diseases, which afflict more than 150 million people in tropical regions, are caused by parasitic filarial nematodes transmitted by blood-feeding insects. Once in humans, the threadlike adult worms

pump out larvae that circulate through the body and can get stuck in tissues, causing grievous damage: permanent vision loss in river blindness and horrific swelling of the limbs and genitals in elephantiasis.

Now researchers were reporting that *Wolbachia* living in the worms was at least partly to blame. The bacteria, leaking from the nematodes, seemed to trigger a hyper-immune reaction and severe inflammation responsible for some of the worst symptoms. What's more, the worms depended on *Wolbachia* for their very survival. In filarial nematodes, *Wolbachia* is an "obligate mutualistic endosymbiont," a symbiotic sidekick the worms can't live without.

The corollary was clear: kill the germ, and you could kill the worm. This was a potential game-changer. No drug existed that could safely rid sufferers of the adult nematodes. Instead, the standard treatment consists of killing the larvae with "microfilaricide" medications. Since the adult worms continue to churn out new larvae and can live in humans for a decade or more, keeping symptoms in check means patients have to take microfilaricides for years. But what if you could kill the adult worms after all, by dispatching the *Wolbachia* inside them using anti-bacterial meds? Then a real cure might finally be at hand.

Initial tests were encouraging. One study found that a six-week course of the antibiotic doxycycline could sharply reduce filarial nematodes in elephantiasis patients. That was a major step forward, but still not the magic bullet researchers were hoping for. Doxycycline isn't safe for children and pregnant women, and six weeks of drug therapy isn't practical for the kind of mass administration programs needed to reach millions of people in underdeveloped areas. The hunt was on for new compounds that offered speedier, simpler treatment. The effort got a big boost from the Bill & Melinda Gates Foundation, which was pouring hundreds of millions of dollars into the fight against river blindness, elephantiasis, and other neglected tropical diseases that affect the world's poorest people.

Sullivan was no expert on tropical medicine, or nematode worms for that matter (he is a fly guy), but he knew a lot about *Wolbachia* and thought he might have something to contribute. Attending a conference on tropical diseases in 2007, he met scientists from the Anti-*Wolbachia* Consortium (A•WOL), which had begun drug discovery with Gates Foundation backing. "The problem was that they were using older, slower assay methods," said Sullivan. "I told them we had a better way." As luck would have it, the cell line and high-throughput automated assay system used by Sullivan's team were tailor-made for testing potential anti-*Wolbachia* drugs.

## Learning by breaking

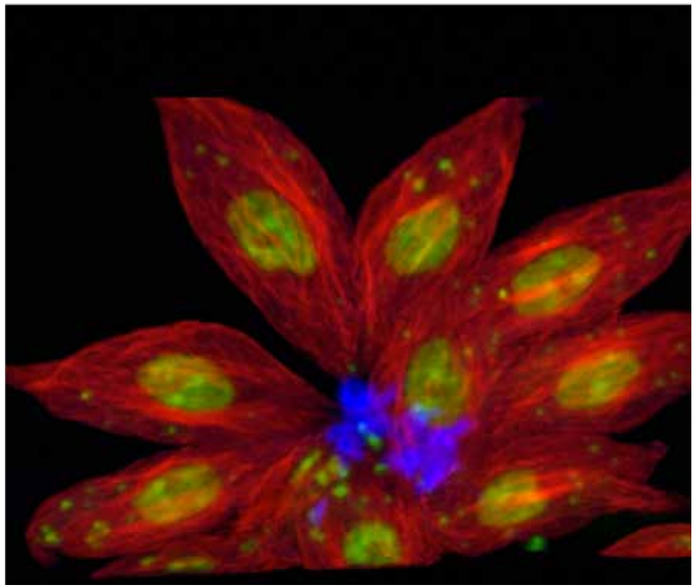
It's one of the oldest tactics in the genetics research playbook: to understand a biological process, knock out the genes that control it (usually in fruit flies or mice) and watch what goes wrong. In the past, scientists did this in scattershot fashion using DNA-damaging chemicals. These days they use more exacting tools like RNA interference and CRISPR to selectively block the expression of specific genes.

Bill Sullivan isn't just a seasoned practitioner of the craft; he's written a famous description of it, a parable called *The Salvation of Doug*. It tells the story of a geneticist (a stand-in for Sullivan) and a biochemist (the titular Doug, based on Sullivan's friend **Doug Kellogg**, professor of molecular, cell, and developmental biology at UC Santa Cruz) applying the tools of their respective trades to figure out how cars work. The biochemist grinds up cars and analyzes their chemical composition, learning a lot about their makeup but nothing of their function. The geneticist takes the knockout approach, hogtying autoworkers on their way to the car factory and noting the defects in vehicles rolling off the assembly line. For example, tying up one worker results in cars that lack steering wheels and swerve uncontrollably. By a process of subtraction, the geneticist is able to suss out how cars are built and what their parts do.

Originally published in a genetics newsletter in 1993, the story took on a life of its own—downloaded thousands of times, assigned in college classes, and translated into multiple languages. You'd think any author would be jazzed to see their prose go viral, but Sullivan is over it. "I'd rather be known for my research," he said, "but I'm still introduced at speaking engagements as the guy who wrote *The Salvation of Doug*."



Two months later, with support from A•WOL and funding by the Gates Foundation, Sullivan had his own drug-screening operation up and running on Lokey's high-throughput equipment. Over the next few years, Sullivan and his team checked almost 5,000 substances, looking for compounds that could kill *Wolbachia* without harming the host *Drosophila* cells. They found one, albendazole, that showed promise. Subsequent studies by A•WOL-affiliated researchers demonstrated that in combination with doxycycline, albendazole was able to shorten treatment times from six weeks to one. Larger clinical trials are underway.



A nematode oocyte (egg-producing structure) shows *Wolbachia* (green specks) in the developing eggs. Credit: Frederic Landmann, with permission.

After that initial success, it was time to scale up. The Lokey lab was at capacity, so Sullivan reached out to the California Institute for Biomedical Research (Calibr), a nonprofit that develops next-generation medicines, and set them up with the cell line and assay system. Together, Calibr and Sullivan's lab have now identified several promising drug candidates while screening more than 300,000 compounds.

## The dark side of symbiosis

While Calibr and other organizations continue to search for new drugs, Sullivan has gone back to more fundamental questions. The nature of the worm-germ symbiosis, for example: it's obvious what *Wolbachia* gets out of the deal—room and board—but what does it bring to the table? To answer the question, Sullivan and postdoc **Frederic Landmann** (now an assistant professor at the Montpellier Cell Biology Research Center in southern France) treated filarial nematodes with antibiotics, wiping out the *Wolbachia* inside them. With the bacteria purged, development of young worms was scrambled, the embryos fatally deformed. In adult worms, apoptosis—a type of programmed cell death that organisms use to cull unwanted cells—went wild, leading to the mass suicide of normal cells.

No wonder the worms need *Wolbachia* to live; it seems to play a role in regulating several essential processes. But for Sullivan, that left a nagging question. Why do the nematodes rely on a bacterium to do things that other species, including the worms' own evolutionary forebearers, could handle quite well on their own? Sullivan believes that something less benign is at work than the win-win partnership implied by "mutualistic symbiosis." Instead of providing a service to nematodes in need, *Wolbachia* may have muscled its way into machinery that was already working just fine, shoving aside existing components and making itself indispensable for its own selfish ends.

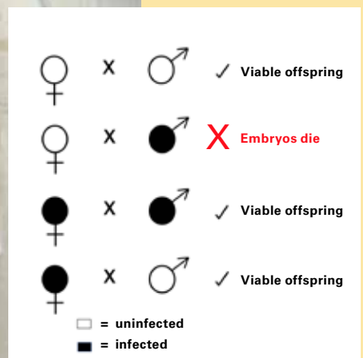
Sullivan calls this "addictive symbiosis" (a phrase he borrowed from the book *The Symbiotic Habit*, by entomologist Angela E. Douglas), and he thinks it may be far more common in nature than assumed by conventional biological thinking, with its "comforting mutualistic kumbaya view." He writes, "I would argue that many obligate endosymbiotic relationships are more akin to a big-box store locating in a town: much outcry and displacement, but ultimately a dependence on its presence. Simply by its presence, the box store created a need where none previously existed. Both in society

## Weaponizing *Wolbachia*

The viral diseases dengue fever, zika, and chikungunya have been spreading at alarming rates in recent years—in part, it's thought, because global warming is extending the range of the *Aedes aegypti* mosquitoes that transmit the viruses to humans. Now medical researchers are fighting back with a new weapon: *Wolbachia*.

For reasons still unclear, mosquitoes infected with *Wolbachia* make lousy hosts for RNA viruses such as dengue, zika, and chikungunya, and hence don't pass them to humans. *Wolbachia* naturally infects many mosquito species, but not *A. aegypti.* Organizations such as the World Mosquito Program are working to change that. They're raising *Wolbachia*-infected female *A. aegypti* and releasing them into the wild. The infected females breed with wild males, and, assisted by cytoplasmic incompatibility (see figure below), spread *Wolbachia* throughout the local *A. aegypti* population. Remarkably, it seems to be working. In pilot studies in Southeast Asia and Australia, the program has seen dramatic drops in dengue transmission.

While that approach aims to tamp down the viruses in mosquitoes, another method exploits the flipside of cytoplasmic incompatibility to suppress the mosquitoes themselves. Public health organizations around the world are raising and releasing *Wolbachia*-infected *A. aegypti* males, which act like flying contraceptives, mating with wild uninfected females and ensuring that their eggs don't hatch. Bill Sullivan witnessed this strategy in action on a 2018 visit to the Sun Yat-sen University–Michigan State University Joint Center of Vector Control for Tropical Diseases in Guangzhou, China. "It was incredible," he said. "They were breeding and releasing 10 million infected males a week. They'd load them into little drone airplanes, which zipped around, spitting out a million mosquitoes at a time."




In many insect species, *Wolbachia* uses a mechanism called cytoplasmic incompatibility to tilt the reproductive playing field in favor of its female hosts, promoting its spread through the population. Whereas *Wolbachia*-infected females can breed with any male—infected or not—uninfected females can only produce viable offspring with uninfected males. Credit: Bill Sullivan, with permission.

Above: Automated screening of anti-*Wolbachia* drugs at UC Santa Cruz was performed using the high-throughput facility shown here, implemented with the help of professor of chemistry Scott Lokey. Credit: Roger Linington, with permission.

Opposite page, far left: *Wolbachia*-carrying mosquitoes are bred at the Sun Yat-sen University–Michigan State University Joint Center of Vector Control for Tropical Diseases in Guangzhou, China. Each rack contains nearly a million infected mosquito larvae. When released, the infected adult males mate with wild, uninfected females, rendering them infertile. Credit Guangzhou Wolbaki Biotech, with permission.

and in biology, addictive symbiosis may be the rule rather than the exception."

Whether it's a cozy alliance or hostile takeover, worm and germ may be headed for a full-blown merger. Sullivan and others speculate that *Wolbachia* might someday become an intrinsic feature of its nematode hosts, like the ancient bacteria that long ago invaded our single-celled ancestors and became mitochondria—the intracellular "power houses" that all higher life forms depend on.

That example points out just how fluid and negotiable roles like parasite, pathogen, and mutualist can be. *Wolbachia* blurs the bright lines between those categories, and between organisms themselves. It tends to fuzz the boundaries between scientific domains, too. "The work that Bill's done has given us new insight into how *Wolbachia* does its thing, and in the long run my bet is that it's going to help us understand how symbionts in general do their thing," said Barton Slatko, a molecular parasitologist at New England Biolabs who studies *Wolbachia* in nematodes. "It goes beyond cell biology and has implications for population biology, ecology, and evolution."

Exploring those implications is the goal of Sullivan's next big *Wolbachia* venture, a collaboration with population biologists Michael Turelli at UC Davis and Brandon Cooper, an assistant professor of biological sciences at the University of Montana. Their goal is what Turelli calls a "grand synthesis" connecting *Wolbachia*'s microscopic meddling to its large-scale effects on species and ecosystems.

For Sullivan it's just one more twist in a mostly accidental journey. "I was fascinated by what *Wolbachia* does to cells and had no idea our work would have biomedical and ecological relevance," he said. "It's really a story of where curiosity can take you." Curiosity, and, Sullivan admits, maybe a little something else: "It could be a case of addictive symbiosis."

By K. M. Watson

# Living history

## New media art connects past to present with archival material

The 19th-century visionary and orator Frederick Douglass established his place in history by chronicling his life as a series of revealing events: enslaved childhood, self-education, escape, and an unending fight for justice and equality. Douglass's remarkable life provides a powerful canvas for the multifaceted, archive-based art of UC Santa Cruz distinguished professor of the arts **Isaac Julien**. Using innovative new and emerging media techniques and technologies that bring his historical subjects to life, Julien aims for others to see them—now including the lifelong activist Douglass—as he does, through a lens of 21st-century sensibility and perspective.

"I'm very interested in how we can look at these past figures and contemporize them for a whole new audience," said the moving-image artist, known globally for his path-breaking work in films and video installation. To do this in the recently exhibited *Lessons of the Hour—Frederick Douglass*, Julien included disparate elements, sometimes all simultaneously: visualizations of the famous abolitionist in some of his most poignant moments, broadcasts of his oratory that resonate with today's issues, and displays of movement surrounding Douglass that can be soothing, intriguing, and even jarring. The intent, Julien said, is to utilize new media and cinema technologies, along with new archival research and understandings, "to create an active relationship between past and present, as a way of commenting on the moment that we inhabit."

The result is a compelling mesh of past and present that provokes the audience to consider possible connections between the two. This type of engagement is one of the hallmarks of Julien's work, which spans decades and covers widely varying social and cultural subjects, including the Harlem Renaissance poet Langston Hughes in the film *Looking for Langston* (1989) and the crisis of migration into Europe in his work *Western Union Small Boats* (2007). "Isaac has a way of synthesizing our understanding of the past that brings its relevance into the present and helps us to understand how we all connect in the context of history," said Jonathan Binstock, director of the University of Rochester's Memorial Art Gallery, during a public talk about the Douglass exhibition.

Above: The 10-screen film installation *Lessons of the Hour* was commissioned by the Memorial Art Gallery in Rochester, NY, to build its moving images collection. Shot by UCSC distinguished professor of the arts Isaac Julien in multiple locations using various technologies and incorporating different types of sound, the project is the product of extensive research and use of archival materials. Credit: Courtesy of the artist (Isaac Julien) and Memorial Art Gallery, University of Rochester.

Left: Julien describes creating his art as involvement in poetry. "My work is very much a poetic quest for a language to express experiences which are part of the everyday experience of people like myself," he once told the Tate. "Dance, theater, music, sculpture, painting—all of these different modes of art-making are encapsulated into my practice, which is why I chose film as a medium for making my work." Credit: Jonathan Binstock, courtesy of Memorial Art Gallery, University of Rochester.

*Lessons of the Hour* project curator John Hanhardt described Julien's work as a type of "philosophical cinema" that brings ideas, issues of representation and understanding, and knowledge as a kind of fluid movement between memory and direct experience. "This is not a linear narrative projected on a single screen. It's 10 screens—different positions, sizes—where you follow the action and are shaped by the action, just as you are shaped by the visual experiences you have in your daily life."

Born in London to parents from Saint Lucia in the Caribbean, Julien previously had limited exposure to Douglass, except for what he had discovered while on a teaching appointment (1998–2002) at Harvard University. To begin the project, commissioned in 2017 by the Memorial Art Gallery as part of an initiative to build its collection of moving images and also supported by UCSC, Julien explored Rochester—Douglass's longtime home in New York—and dove into the university's archives. He and his assistants scoured old books, papers, magazines, drawings, and photographs, searching for clues to a deeper understanding of Douglass and his time. Julien found "there was this inner Douglass world that was fascinating." He also uncovered a "symbiotic relationship" with Douglass while reading the activist's "Lecture on Pictures." Called the most photographed American of the 19th century, Douglass, like Julien, was fascinated by photography and its power to influence others.


While making *Lessons of the Hour*, Julien worked with experts in the history of photography at the Eastman Museum to research and recreate authentic imagery. Actors portraying Douglass and Anna Murray-Douglass (who encouraged Douglass to escape from slavery and later married him) were filmed in a set built to show traveling by railroad, a symbol for both the Underground Railroad and Douglass's extensive travels. Pictured here: *The North Star,* 2019, framed photograph on gloss inkjet paper mounted on aluminum, 160 × 213.29 cm. Credit: Courtesy of the artist (Isaac Julien); Jessica Silverman Gallery, San Francisco; Metro Pictures Gallery, New York; and Victoria Miro Gallery, London/Venice.

## Shaking the dust off

The process that Julien uses for his work is the basis for a new lab he and longtime collaborator and partner **Mark Nash**, professor of film and digital media, have established on campus. The Isaac Julien Lab (IJ Lab), modeled in part after Julien's London studio, prizes the use of archival material as an intrinsic part of the creative method. It also intentionally addresses the university's three academic priorities: Justice in a Changing World, Digital Interventions, and Earth Futures. Its first crop of students in a Master of Fine Arts program, to begin in fall of 2020, will be asked to propose a project that involves one or more of these themes. For Julien's work in particular, issues of social justice are a common thread.

With its history of inventive thinking in its Humanities and Arts Divisions, UCSC makes sense as a place for a new media lab that prides itself on developing ideas and artistic innovations that will "shake the dust off" traditional ways of creating and viewing art, said Julien. In addition, its proximity to the San Francisco Bay Area's technological innovations and world-class art collections, such as the Kramlich Collection of media art and the Joyner/Giuffrida Collection of abstract art, provides vital pools of creativity. This wealth of resources, Julien said, can stimulate younger people who want to become artists, as well as those interested in the business aspects of art, helping to shape a "type of entrepreneurial creator who is able to navigate the art world as it's constituted today."

In a good example of the practical experience students can expect to gain, those enrolled in one of Julien's spring classes were slated, before the Covid-19 shutdown, to help launch a new installation of *Lessons of the Hour* at the McEvoy Foundation for the Arts in San Francisco (see *www.mcevoy.arts*). The collaboration was intended to expose students to various aspects of producing an exhibition, such as helping to organize and set up the gallery space, and tackling the intricacies of a complex installation that involves many complicated digital technologies. UCSC students had a similar engagement with the Douglass project in 2019, said Nash, when "production of the single-screen version of the work introduced some students to a specialized editing and sound process, and gave them access to Julien's expert collaborators." That version of *Lessons of the Hour* was exhibited at Art Basel in Miami Beach in December 2019.

## Past is present

Combining gallery pieces and film on multiple screens, the original Douglass exhibition provides a vivid illustration of the complex work that goes into creating these media projects. Julien and his team not only researched Douglass and influential people in his life using archival materials, they consulted with Douglass scholar Celeste-Marie Bernier, and investigated historical photographic processes, and settings

A sense of place resonates throughout *Lessons of the Hour* with vivid imagery and sounds. Pictured here is part of a re-enactment of Douglass during his self-imposed exile overseas as a fugitive slave, reflecting on the beauty of America in contrast to the ugliness of its slaveholding. *Rapture 1846*, 2019, photograph on matte structured paper mounted on aluminum, 150 × 210 cm. Credit: Courtesy of the artist (Isaac Julien); Jessica Silverman Gallery, San Francisco; Metro Pictures Gallery, New York; and Victoria Miro Gallery, London/Venice.

## Words to fuel action

From the wide porch of his Victorian house on a hill in Washington, Frederick Douglass, you might say, could see his past, present, and future: in the distance was Maryland, where he grew up enslaved; surrounding him was his stately home and grounds; and close by across the river stood the country's capital, with its numerous political engagements and appointments. What Douglass couldn't see was how far-reaching his legacy, especially his words, would be.

In classrooms and auditoriums across the country, debate leagues and thousands of students cultivate the ancient art of using words and their power to arouse and agitate for change, just as Douglass did in his early teens when he embraced *The Columbian Orator* as a guide for his self-education. Other young activists draw from their personal experiences and passions, like Douglass, to make their cases for change.

Here is a sampling of what these emerging leaders have to say:

Mei-Ling Ho-Shing, 19, survivor, Marjory Stoneman Douglas High School shooting: "At the end of the day, a black boy from Chicago and a white girl from Parkland need to be able to sit at a decision-making table and bounce back ideas on how to end this nationwide crisis in our country. Gun violence is capable of affecting everyone, so the movement needs to look like everyone."

Xiuhtezcatl Martinez, 20, youth director for Earth Guardians: "In the light of a collapsing world—what better time to be born than now? Because this generation gets to rewrite history, gets to leave our mark on this Earth, we will be known as 'The Generation,' as the people on the planet that brought forth a healthy, just, sustainable world for every generation to come."

Jacob Lemay, 9, LGBTQ rights activist: "My name is Jacob, and I'm a 9-year-old transgender American. My question is: what will you do in your first week as president to make sure that kids like me feel safer in schools? And what do you think schools need to do better to make sure that I don't have to worry about anything but my homework?"

Greta Thunberg, 17, climate activist: "I want you to act as if the house is on fire, because it is."

Malala Yousafzai, 22, education advocate for girls: "So, let us wage a glorious struggle against illiteracy, poverty and terrorism, let us pick up our books and our pens, they are the most powerful weapons. One child, one teacher, one book and one pen can change the world."

and sounds of the past. To learn more about how photographs were made at the time, for instance, they turned to experts at the George Eastman Museum, located on the photography and motion picture film pioneer's Rochester estate. Tintype specialists guided them in the creation of authentic photographs similar to those of the Douglass era. Royal Shakespeare Company actor Ray Fearon, who portrayed Douglass, took lessons so he would speak with the correct accent as he gave life to sections of Douglass's autobiography and excerpts from three of his hundreds of lectures delivered across the country and in the United Kingdom: "Lessons of the Hour," "What to the Slave Is the 4th of July?," and "Lecture on Pictures." A combination of environmental sounds, such as the sharp lashing of a whip, and original scoring inspired by music of the time fill the space around Douglass's words. For backdrops, Julien and his team created sets based on their research and traveled to key shooting locations such as Scotland, where Douglass had exiled himself from 1845–47 until supporters raised $711.66 to buy his freedom.

Photographs filled the house in Washington, DC, where Frederick Douglass spent his final years. Intrigued by the emerging technology and called the most photographed American of the 19th century, Douglass talked about his fascination with photography in his "Lecture on Pictures." During his research into Douglass, Julien discovered their mutual interest in picture-making and its power to influence human relations. Credit: K. M. Watson.

Julien's work reminds his audiences that issues and struggles of the past, such as the fight for equality and social justice, continue to play out. One example is when the actor Fearon, as Douglass, addresses an audience seated in a Royal Academy of Arts lecture hall. Members dressed in both contemporary and 19th-century clothing listen intently as Douglass delivers passages from "What to the Slave Is the 4th of July?" At the same time on other screens around the room, aerial drone shots emerge of modern-day Baltimore, the site of the 2015 Freddie Gray protests and riots that fueled the Black Lives Matter movement against violence and systemic racism.

Striking the right tone and making Douglass come alive for today's audiences was a demanding undertaking, said Julien, in part because of Douglass's formidable historic stature. "The biggest challenge was to make a work that would be convincing. He's a very tall order." In his time, Douglass proved to be a powerful and indefatigable man of influence in the fight against slavery and for equality and justice, and his legacy continues more than 200 years after he was born. "There is a strong connection between the kind of quest that Douglass was demanding and striving for and, if you like, the unfinished business of these issues in the 21st century," Julien said.

Douglass's great-great-great grandson Kenneth B. Morris, Jr., saw this connection as well when he cofounded the Atlanta-based nonprofit Frederick Douglass Family Initiatives. The organization's efforts focus on modern-day slavery and the global problem of human trafficking. "When you look at slavery today there are many parallels to historic slavery," Morris has said. "It's about profit. It's about exploiting the most vulnerable among us." Morris now leads the fight for freedom in the same way as his famous distant relative, through education. Julien said that meeting Morris and hearing his reaction to *Lessons of the Hour*—he told Julien he was "extremely moved"—made him feel like he had been successful in making Douglass come to life in a meaningful way. "As an artist, you have a responsibility for how you are going to translate feelings, words, and actions, and do them justice."




By Aylin Woodward

# What are your pronouns?

## As choices for gender and sexual identities expand, the world slowly changes

Unlike computers that only deal with "0" or "1", humans can imagine the often murky grey that exists between viewpoints. When it comes to gender identity, however, this ability to think beyond a rigid duality remains unexercised, indeed often culturally taboo, for many people. You are either man or woman, "she" or "he," and your genetic makeup biologically forbids you from being anything but one of two genders.

But the world is changing. Increasingly, individuals—especially from younger generations—are bucking the gender binary. Their self-identification as either nonbinary or genderqueer and use of pronouns including "they" and "ze," means they experience their gender identity as falling outside the categories of man and woman. The same goes for sexual identity—an individual's orientation can be more than just the dyad of heterosexual or homosexual preferences. Accordingly, many have begun to verbalize their attractions to people regardless of gender.

Closely observing these changes is **Phillip Hammack**, UC Santa Cruz professor and chair of psychology. Hammack, who also directs the Sexual and Gender Diversity Lab, has devoted his career

Members of Gendered Intelligence, a United Kingdom–based nonprofit aimed at increasing public understanding of gender identity, and other nonbinary people march in the London Pride parade on June 27, 2016. UCSC professor of psychology Phillip Hammack's research reveals that, in the age of the internet, it's easier for individuals of nonbinary gender and sexual identities to find one another and share their experiences. Credit: Katy Blackwood (CC BY-SA 4.0).

to understanding the diversity of sexual and gender identities. His more recent research explores what nonbinary thinking and the proliferation of identities mean for intimate relationships.

Despite major victories like marriage equality, Hammack and his collaborators have discovered that bias and discrimination remain a problem for lesbian, gay, and bisexual (LGB) individuals, with many continuing to experience mental and physical stress due to their minority status. "After 2015, a lot of people thought, 'Well isn't the fight done now?'" said Stephen Russell, professor of child development at the University of Texas at Austin. "Yet there are these vexing disparities of well-being for sexual minority people: these kids don't fare as well as straight kids."


According to Hammack, the gender binary of "male" and "female" is a thing of the past, as documented by this sign outside an all-gender restroom at the San Diego airport in California. Hammack studies the increasing fluidity and diversity of gender identities among U.S. youth. Credit: Wikimedia Commons (CC BY-SA 3.0).

Russell, who focuses on the experiences of sexual minority youth, worked with Hammack on a five-year study of LGB adults in America who came of age in different historical contexts. As part of this research, Hammack delved deeply into the life histories of LGB community members. "What Phil designed was this beautiful means of drawing out their lifelines," said Russell. "He helped them narrate their lives' high and low points and tell us what they meant."

We spoke with Hammack at UC Santa Cruz's Stevenson College to discuss the gender and sexual diversity movement, and what his research reveals about it.

**What's behind the emerging embrace of gender and sexual diversity?** I think the real, decisive change we see is related to information—how people access and control it. In the 20th century, we looked to science, doctors, and medicine as sources of expertise on these topics. And because we were limited to that basis of how knowledge was constructed and disseminated, it was hard to challenge the stigma associated with that framework.

But then came the internet, and eventually social media. The latter was pivotal to the creation of nonbinary thinking. It has allowed people to find one another. You can now educate yourself using Wikipedia, of all things, about what you feel your identities are. We're no longer limited to being monogamous heterosexual or homosexual people. We have words like pansexual, meaning someone who's attracted to others regardless of their sex or gender identity, and polyamory, the practice of having intimate relationships with more than one partner. These terms have been introduced into the popular lexicon. The source of authority on what is possible for gender and sexual identity is no longer top-down, but instead bottom-up, which is why we've seen this huge explosion of language.

**How does this "explosion of language" help?** I call it a time of radical authenticity. You can really embody what feels true and right in a way you couldn't in the 20th century. It used to be you had the way you felt but didn't know what you should call this identity. Now, you can communicate so much about yourself using this language. People ask, "Why do we need all these terms?" It's because individuals' experiences are much more diverse than the language historically used to describe them. We are now slowly accumulating the language necessary to capture the range of our experiences.

**So, is using the LGBTQ+ moniker still okay?** I intentionally avoid the acronym LGBTQIA because it's identity based—each letter is an identity—and it's always going to exclude someone's experience.

Viewing sexual and gender diversity as a spectrum rather than composed of separate categories invites a broader range of people into the "sexual minority" community. And part of that spectrum includes people who experience intimacy differently. The paradigm of only hetero and homo couples is gone. Relationships now include transgender and nonbinary partners, multiple, consensual partners, or asexual people who don't experience sexual attraction at all.

**Gender and sexual identity diversity seems to be largely a youth movement. Are there intergenerational differences among members of the community?** Ilan Meyer, a scholar for public policy at the Williams Institute at UCLA School of Law, Stephen Russell, myself, and four other investigators have worked on the first long-term study of health and well-being across three generations of LGB people.

This Generations study, which started in 2015, is funded by a $3.4 million federal grant from the Eunice Kennedy Shriver National Institute of Child Health and Human Development.

Our team not only completed the first random, national sample of sexual minority Americans, but we did 191 life-history interviews with ethnically and gender diverse LGB people in the 18–25, 34–41, and 52–59 age brackets. We aimed to explore gender identity in a historical context. What did it mean if you grew up recently with marriage equality versus 30 years ago in the throes of the AIDS epidemic? The impact of growing up in one era compared to the other should have ramifications for the rest of your life.

**What did you observe?** There's a relationship between prejudice and health. People who experienced stigma had more of what we call minority stress, and due to this they experienced more mental and physical health problems.

Unsurprisingly, we found that the middle group—of which I am a part—who grew up during the height of AIDS internalized more stigma around having sex. They experienced a rhetoric that characterized gay men as disease carriers who were inevitably going to die, whereas the older and younger generations shared an openness around sex because that rhetoric was absent.

A man waves a Pride flag outside the United States Supreme Court in Washington, DC, during deliberations on the Obergefell vs. Hodges case for same-sex marriage on April 28, 2015. Two months later, the Supreme Court ruled to end marriage discrimination. According to a five-year study conducted by Hammack and colleagues, marriage equality in the U.S. hasn't eliminated discrimination against LGB community members. Credit: Ted Eytan (CC BY-SA 2.0).

**Why are things still difficult for LGB youth?** Ilan believed that the younger cohort would have had less minority stress than the older generation, but we observed that the way stigma works in people's lives has just been rearranged. There's now more opportunity to be out, but that comes with more opportunity for discrimination. Certainly, the older generation reported experiencing more internalized homophobia than LGB youth, and the younger cohort have experienced the expanding diversity of identities.

But stories about bullying and coming out to parents among LGB youth sound exactly like those from the older generation. The idea that we can say "Everything's better!" doesn't account for the fact that it's "better" in the context of having your worth debated publicly. The Generations study showed that marriage equality and social progress haven't made as big a difference in people's day-to-day lives as one might think—at least not yet.

**If you could say one thing to people struggling with their own gender and/or sexual identities and/or that of others?** Falling outside of what has been typically considered normal is a privilege, not a curse. In my own life, it has expanded my consciousness and range of experience in deeply meaningful ways. The stories we hear of success for those who are diverse in their gender or sexual identities are typically stories of embracing one's diversity—reframing the problem away from oneself and toward a stigmatizing society. Thankfully, that society is changing rapidly, and those who embrace their diversity are leading the revolution in how we think about gender and sexuality, opening up space for a broader range of possibilities in gender, sexuality, and relationships. Not only are they happier and healthier, they are also directly changing society for the better by being radically authentic.

By Cameron Walker

# River of life

## Modern history ties the altered Nile to disease

Every August, the flood came. The river spilled and filled into the basins Egyptian farmers had carved out to hold the water that made crops thrive. When the floodwaters receded in October, farmers planted the winter crops of wheat and barley. Spring was for harvesting. By summer, the river sank to its lowest levels. Smaller plots of sugarcane, cotton, fruits, and vegetables grew on riverbanks. And when the flood came again, it cleansed the soil for the next season while nurturing flood crops like maize, rice, and sorghum, staple foods for local farming communities.

The lives of the people along the Nile, too, swayed to this seasonal rhythm. Villagers tended to the flow of the river when it rose; they planted crops when it fell. They feasted after the spring harvest, then suffered through the windy, dry summer. These people and their river made Egypt one of the richest lands in the world. As a province of the Ottoman Empire, Egypt supplied wheat to the Ottoman capital of Constantinople, and to Muslim pilgrims on their way to Mecca. (The Republic of Turkey was founded in 1923, the capital was moved to Ankara, and Constantinople was renamed Istanbul in 1930.)

But by the turn of the 20th century, life along the Nile danced to a different and more demanding beat. In the 1820s, increased interest in cash crops like cotton drove construction of deep irrigation canals to extend the growing season. Then came the first big dam. Built by British engineers and more than 10,000 laborers about 1,000 kilometers upstream from Cairo, the Khazan Aswan (or Aswan Low) Dam was completed in 1902, four years after construction started in 1898. The resulting changes in the Nile shifted farming along the river from the ebb and flow of flood, winter, spring, and summer to a year-round calendar of crops. And in addition to transforming the river, the now ever-present water turned the bodies of Egyptians, particularly the men who worked the land, into new colonies of constant, debilitating disease.

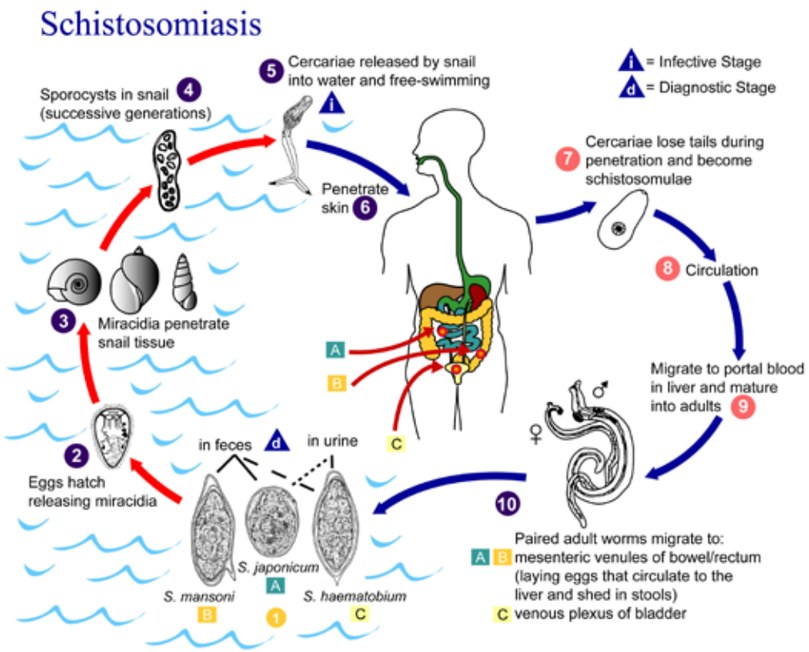
The research of UC Santa Cruz associate professor of history **Jennifer Derr** focuses on this period of transformation, tying together colonial politics, the altered Nile, and the changing health of the people who had for centuries flourished on the river's flood plain. In her recently published (July 2019) book, *The Lived Nile: Environment, Disease, and Material Colonial Economy in Egypt*, Derr writes about how changes in the Nile triggered new plagues that afflicted many Egyptians until the late 20th century. In her book and continuing research, Derr searches for connections between people and the world around them. "Human health does not exist separate and apart from environmental health," she said, whether along the Nile River more than a century ago or elsewhere in the world today. "This is one of the primary lenses through which I try to understand the effects of climate change and our experiences of the planet."

### The backstory

Derr found her research focus while traveling a winding academic path. As an undergraduate at Stanford University, she studied biology and worked as an oncology researcher, thinking she would go into medicine. Then she traveled to Egypt on a study abroad program and began learning Arabic. Derr loved studying the language, and "what it meant to live in a place and work to understand it deeply." After completing a master's degree in Arab studies at Georgetown University, she circled back to Stanford for her doctorate in history. Here, she dove into the history of the modern Middle East, writing her dissertation on agriculture, irrigation, and colonial politics in the southern part of Egypt in the late 1800s and early 1900s. Modern history drew her attention because it aligns with how she attempts

The Nile and the people who depended on its seasonal flooding made Egypt one of the richest lands in the world. This idyllic scene near the city of Aswan in southern Egypt showcases the river's beauty. Credit: Wikimedia Commons (CC BY-SA 4.0).

The green ribbon of the Nile River, seen from orbit, flows northward to the Mediterranean Sea. More than 95 percent of Egyptians live within a few miles of the river, which has made the surrounding land fertile and prosperous for thousands of years. Credit: Jeff Schmaltz, NASA Visible Earth (public domain).




## Breaking the cycle

Started in 1997, Egypt's National Schistosomiasis Control Program offered the medication praziquantel to all school children in the Nile Delta. By 2010, the infection rate had dropped from more than 30 percent in many rural villages to less than 3.5 percent. But schistosomiasis remains a public health concern, both in Egypt and elsewhere, with an estimated 140 million people infected worldwide. "It is true that incidence of infection has decreased," said Sanaa Antonios, professor of parasitology at Tanta University in Egypt. "However, in some spots in the country it is still present, which is alarming." Infections are especially common in children, who swim in the canals in the summer and don't know the danger of schistosomiasis, she said. Women are also at increased risk, as they are now much more likely to work in and around the water with men.

And changing waterways are still a problem in Africa. In neighboring Ethiopia, a transformation in agriculture is underway, with new efforts to cultivate the lowland areas of the country to grow sugar, cotton, and other cash crops, said parasitologist Bayissa Chala at the Adama Science and Technology University in Ethiopia. "Resurgence or even outbreak of urogenital schistosomiasis in endemic areas where the snail hosts thrive is possible," he said.

In 2012, the World Health Organization launched an effort to eliminate schistosomiasis as a public health issue by 2025, primarily by targeting school-age children and other at-risk groups for preventive treatment with praziquantel. But a recent status update indicates that many countries have failed to meet interim goals. "Although praziquantel is effective, it does not prevent re-infection," said Laura Braun, an engineer and researcher at Imperial College London. "Anyone going back in the lake or river is likely to get infected again." A multi-pronged approach that also includes water treatment and educational campaigns might be more effective than simply providing praziquantel, Braun said, "because it prevents people from getting infected in the first place."

Figure at left: Parasitic flatworms of the genus *Schistosoma* cause the disease known as schistosomiasis. Two main species infect humans in sub-Saharan Africa: *S. haematobium*, which affects the urinary tract and *S. mansoni*, which affects the liver. The parasite's life cycle begins in freshwater snails, which release free-swimming "cercariae" that bore through human skin. Once inside a human host, the parasites grow into mature worms that pump out eggs. The eggs work their way through the tissues, over time resulting in chronic, progressive damage to the bladder or liver. Infected people pass along the eggs by urinating or defecating into water, where the eggs hatch into "miracidia" that infect the snails, starting the cycle anew. Credit: Centers for Disease Control and Prevention (public domain).

Derr, who came to UCSC in 2012, spent years sifting through government archives and records held by research institutions to learn about the history of the Nile River, its changing political, economic, and environmental landscapes, and the lives of the people who worked in and around its waters. "Jennifer's work sheds light on the historical intersections of disease, water management, and social policy in modern Egypt," said assistant professor of history **Alma Heckman**, who studies modern Jewish history in North Africa and the Middle East.

to understand the world: "When I encounter something, I always want to know the backstory. History is central to how I understand politics and the dynamics of our contemporary world."

One of the major backstories Derr explores in her book concerns schistosomiasis, a disease caused by parasitic flatworms with a complex life cycle involving freshwater snail and human hosts. Two species of the parasite, *Schistosoma haematobium* and *S. mansoni*, cause the disease in Egypt. More debilitating than deadly, schistosomiasis nonetheless remains a substantial problem in the developing world. Massive public health campaigns against schistosomiasis, also called bilharzia, have been undertaken in Egypt, including a recent $10 million eradication effort supported by the World Health Organization.

Paired adult schistosome worms, each about a centimeter in length, live in the veins of their human host. This scanning electron micrograph shows the oral and ventral suckers of the larger male (top). The enveloped female (smaller, below, in groove), continuously produces as many as 300 eggs each day, equivalent in total to its body weight. Credit: Bruce Wetzel, National Cancer Institute (public domain).

The changes in the Nile substantially exacerbated the impact of schistosomiasis. Studies in the Nile Delta and Valley in the 1930s found that about 60 percent of people in areas with year-round irrigation were infected with one or both species of *Schistosoma*. In contrast, the average infection rate was only 5 percent in areas of southern Egypt where people still followed traditional basin agriculture practices. The disease wasn't new—*Schistosoma* eggs, thousands of years old, have been found preserved in mummies. But the rates of infection, where they occurred, and the symptoms that people suffered were transformed beginning in the 19th century. The changing geography and prevalence of infection, "strongly links it to the spread of perennial irrigation," Derr said.

In records found in the Egyptian National Library and Archives in Cairo, state archives in the United Kingdom and France, and a variety of smaller collections including those of the Institution of Civil Engineers in London and the Rockefeller Foundation, Derr traced the changing Nile, starting in the early 1800s, when Egyptian viceroy Mehmed Ali began to corral more water to grow cotton to sell on the world markets. The British occupation of Egypt in 1882 brought more ambitious ideas of large-scale engineering and profits that shaped and rapidly changed Egypt in the decades to come.

## Greater contact

Even before the first large dam tamed the Nile, the new focus on summer irrigation put Egyptian laborers into greater contact with the water, standing knee-deep as they operated the manual irrigation tools that lifted water to their crops. More time in the water meant more exposure to the *Schistosoma cercariae*—the infectious form of the parasite. Workers with higher worm loads in their systems suffered more painful manifestations of disease. In addition to the tell-tale bloody urine and, ultimately for many, bladder cancer, those most severely afflicted might develop debilitating large growths in sensitive areas of their bodies. The constant irrigation promoted other diseases as well, including hookworm, associated with moist soil, and pellagra, a nutritional deficiency linked to changing food staples. By connecting the altered Nile to the emergence of disease, Derr's work shows "just how deeply and viscerally humans are connected

to their environment," said Alan Mikhail, professor and chair of the Department of History at Yale University. "What is in the water of the Nile courses through the human body," said Mikhail, an expert on Egypt during the time of the Ottoman Empire.

Today, we know that rivers large and small carry contaminants and bacteria through their channels and surrounding environments. We also know the channels of the human body through which water-borne toxins and pathogens can flow to cause disease. But these channels were yet to be discovered at the time the Nile began taking its modern shape. "People didn't understand disease through the model of infection and contagion," Derr said. In Egypt and elsewhere, people believed disease resulted from "imbalances in humors" within the body wrought, in part, by outside influences, such as the season or the alignment of planets. Illness was also associated with native peoples and the places they lived, with schistosomiasis known as a disease of warm weather.

As the Nile changed and schistosomiasis became more widespread, the views and attention of scientists also shifted. European scientists studied the disease during the colonial period, but their interest waned with the fading of that era, and schistosomiasis became just one of many "neglected tropical diseases." One facet of Derr's research endeavors to uncover the work of Egyptian scientists who continued to study the disease. In the 1920s, Egyptian physician Muhammad Khalil led the Bilharzia Research Section of the Egyptian Public Health Department. Khalil and colleagues mapped infections with the two species of schistosomes to geographic areas within Egypt, set up treatment programs for schistosomiasis and other diseases, and conducted public health campaigns to prevent infection. As Egypt's battle with the disease persisted, Egyptian physicians and scientists stood at the forefront of research and treatment, Derr said.

## A larger narrative

Schistosomiasis also provides a backstory for a larger narrative Derr plans to tell about the history of Egypt through the bodies of its people. As the Nile continued to change in the 20th century, the disease did too. Infections with *S. mansoni*, the species that can damage the liver, were previously seen in limited areas on the Nile. But with the construction of the Aswan High Dam, completed in 1970, "newly created upstream water reservoirs, as well as altered river currents and sedimentation, markedly affected the relative distribution of snails carrying different *Schistosoma* species," said Sanaa Antonios, a professor of parasitology at Tanta University in Egypt. And where the snails go, so goes the disease, with a resulting boom in *S. mansoni* infections.

Thanks in large part to this surge in *S. mansoni* infections, liver disease emerged as a major health problem in Egypt in the second half of the 20th century. Untreated, *S. mansoni* infections can lead to liver cancer. In addition, from the 1920s until the 1980s, health-care workers often treated schistosomiasis with multiple injections of tartar emetic, unintentionally introducing another assault on the liver. Extensive needle reuse and poor sterilization associated with these injections—and treatment of other conditions—led to the spread of the hepatitis C virus and the insidious liver disease it causes. Until its very recent mass treatment campaign, Egypt reported the highest prevalence of hepatitis C of any country in the world.

Derr's next book will chronicle the history of liver disease in 20th-century Egypt. Her research finds her scouring archives across the world, interviewing physicians, and attending scientific meetings on liver disease. In addition to investigating the connections between the environment and liver disease, she plans to explore how Egyptian

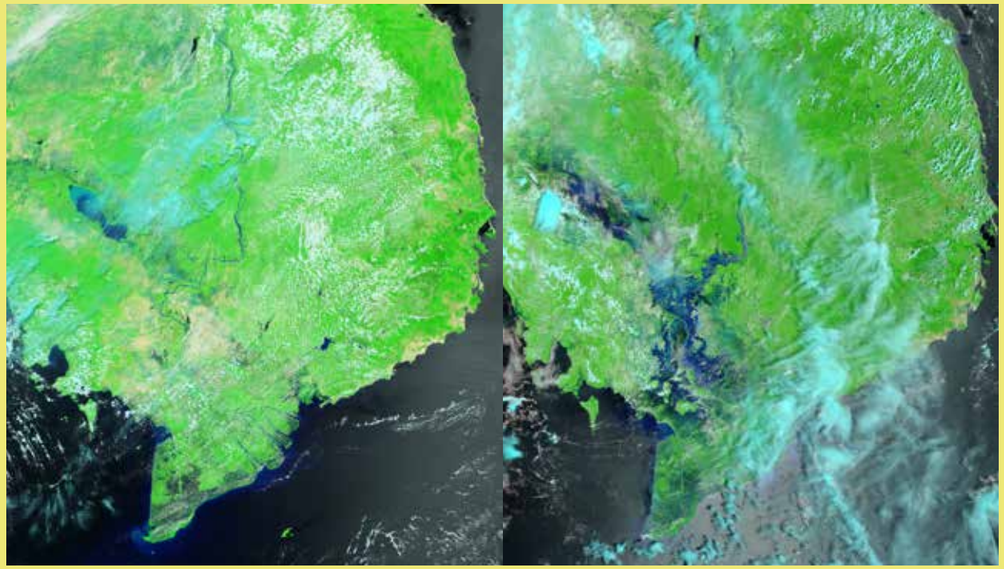
## Dam drawbacks

At the turn of the 19th century, the Khazan Aswan Dam was the largest dam ever built. Today, large dams span many of the world's rivers. Some 57,000 surpass 15 meters in height, according to International Rivers, an Oakland, CA–based global advocacy group focused on protecting rivers. Of these large dams, more than 300 are giants topping 150 meters and restraining enormous reservoirs. Now built primarily to produce hydropower, these huge dams cause vast changes to rivers, their surrounding landscapes, and the ecosystems they support. And more are coming: At least 3,700 major dams, each with a power-generating capacity of more than 1 megawatt, are either planned or under construction, mostly in countries with emerging economies.

The Mekong River, for example, has its headwaters in China and flows 4,350 km through Myanmar, Laos, Thailand, Cambodia, and Vietnam before reaching the South China Sea. One of the world's richest freshwater fisheries, the Mekong supports more migratory fish than any other river in the world, said Brian Eyler, the director of the Southeast Asia program at the Stimson Center in Washington, DC. Along with fish, the river transports organic material that forms the basis of the food web, as well as sediment that provides nutrients for agriculture. "Dams block all that," said Eyler, author the 2019 book, *The Last Days of the Mighty Mekong*.

Dozens of dams currently dot the Mekong, with many more in the works. The Xayaburi Dam, a large dam in Laos, started operating in October 2019; in Laos alone, 64 more dams are under construction on the Mekong and its tributaries. Downstream communities already experience a substantially altered river, with reports of extreme changes in water levels and clarity. Further south in Cambodia, the Mekong seasonally reversed the flow of the Tonlé Sap River into Tonlé Sap Lake, greatly swelling its size with water from the annual monsoons. The lake would then contract, a seasonal heartbeat that the dams—along with climate change—have now crippled, greatly reducing the lake's size, said Eyler. The largest source of freshwater fish in the world, Tonlé Sap once provided 70 percent of the protein for the people living nearby. Now fisherman can no longer depend on regular catches, and locals go hungry.

In Southeast Asia, Eyler said, alternatives to dams are increasingly viable. Countries there have started to develop other renewable energy resources like solar and wind; Vietnam now generates more than 5 gigawatts from solar. "Electric demand can be met in other ways," Eyler said. "These dams don't need to be built."



Intended primarily to generate hydroelectric power, dozens of dams, many already in place and others planned, are threatening fisheries and farms along the lower Mekong River in Vietnam and Cambodia. These livelihoods, and the way of life they support, depend on the flooding caused by the August-to-November monsoon rains that fill the rivers of Southeast Asia and broaden the water covering the Mekong River Delta well beyond its dry season footprint. These false-color space images from 2004 contrast the lower Mekong River immediately before the start of the monsoon rains (left, July 5) and at its flood stage (right, September 21). In false color, vegetation is bright green, water is blue and black, and clouds are light blue. The flood waters hide the river's normal channel and obscure the vast Tonlé Sap Lake seen in the pre-flood image. Credit: Jesse Allen, NASA Earth Observatory (public domain).

Left: In the 1930s, a man stands in the Nile while using a *shaduf* to lift water from the river to irrigate a field of cotton. The three pyramids of Giza are seen in the background. Credit: Library of Congress (public domain).

Above: A 1908 stereograph shows people crossing the Nile by way of the Khazan Aswan Dam, completed in 1902. This first large dam controlling the Nile would be raised two times to meet the increasing demand for irrigation. The much larger Aswan High Dam was completed in 1970. Credit: Library of Congress (public domain).

scientists—often relegated to second-class status in global medical circles—have contributed to the field of tropical medicine.

Looking at history through an environmental lens allows Derr to see the interaction of large and small, how country-wide decisions about water management can impact microscopic parasites. These interactions continue to play out on the Nile today. Although upstream users control the water on most rivers, Egypt has been the exception. "Egypt is the furthest downstream, and, yet, throughout the course of history, it has been in charge of how the Nile's resources have been used," said Mikhail. But now Ethiopia, Egypt's southern neighbor, will soon complete the Grand Ethiopian Renaissance Dam on the Blue Nile, allowing it to contain the Nile at its upper reaches. As of late March 2020, tense—and sometimes aborted—discussions over the new dam continued between the two countries. To lessen the potential impact on the Nile downstream, Egypt has asked for a slow fill of the new dam's huge reservoir.

Derr's research suggests that, even as these political discussions play out, the new dam's impact could be both more subtle and more widespread across Egypt and neighboring countries than expected, potentially affecting anything and everything connected to the Nile. "Derr's work is very timely for how we understand public health and the environment in contemporary Egypt, and provides insights that apply across North Africa," said assistant professor of history **Muriam Haleh Davis**, who studies development, decolonization, and race in North Africa. The connections between these North African nations and their neighbors have recently become part of Derr's academic remit, as she directs the newly launched (early 2020) UCSC Center for the Middle East and North Africa.

Looking outward from North Africa, Derr said, "the question of how we treat the environment is fundamentally also a question of what will happen to our own bodies." As our seasons become warmer and wilder, we may find ourselves altered as well, the channels of our personal watersheds harboring new threats from emerging viruses and other menaces not yet imagined. Where else will our changing rivers take us?



By Ramin Skibba

# Robotic etiquette

## Engineering improved human-robot interaction

Most people don't know what to do when they first encounter a robot. Some swarm around it. Some stand back. And some misinterpret its behavior. That's what happened to **Leila Takayama**, UC Santa Cruz associate professor of computational media, when she first met PR2 (Personal Robot 2), a social robot built by the robotics company Willow Garage.

When she walked through the front door of the company's Palo Alto headquarters, the PR2 rolled up to her and paused. She expected a greeting, but it spun its head around and ran away. "I felt blown off, but that doesn't make sense," Takayama said. "It was just trying to get from point A to point B and was replanning its path, but I couldn't help but feel insulted."

It's natural to misread a robot's intentions, both because of how robots are currently designed and also our usually inflated expectations of what they can do, said Takayama, who aims to improve both sides of this stilted relationship with her research on human-robot interaction. This growing field of study, driven by rapid advances in both artificial intelligence and robotics engineering, employs a broad set of disciplines to explore a wide range of challenging subjects, from how humans work with remote, tele-operated unmanned vehicles and surgical robots, to self-driving vehicles and collaborations with anthropomorphic social robots.

While personal computers have become much more user-friendly over time, that's not the case for robots. "They're still in the dark ages, in terms of being usable and useful for normal people. I felt like that's a pretty big problem that could be addressed with better human-centered design and research," Takayama said.

### Bad manners

In the next several decades, we'll likely see a wide range of robots ambling about our hospitals, homes, workplaces, and groceries, as well as on sidewalks and in the street, where autonomous cars count as robots, too. Prototypes of those future robots already wander about some cities, especially in the Bay Area. But today's robots lack the subtle common sense we humans take for granted every day as we navigate our social world. And without this common sense in robots, humans get confused. Takayama's broad background in the social sciences, cognitive science, behavioral

Associate professor of computational media Leila Takayama works in the growing field of human-robot interaction, which seeks to improve this interaction by studying robots, like the one sitting here in Takayama's hand, and their human users to better understand the dynamics on both sides of the relationship. Credit: Melissa De Witte.

science, and psychology, comes in handy here, giving her insights that engineers might not recognize as relevant and important.

For example, in order to conserve power, engineers typically build robots to be efficient with their motions. But that can be a problem, said Wendy Ju, an assistant professor of information science at Cornell University and frequent Takayama collaborator. "The unintended effect is that robots seem stiff, even kind of snotty. Robots need to move around to seem natural and make people feel more comfortable. That's something that only someone who studies people would think of," she said.

To improve robot manners, Takayama and her team are working to help them take cues from people. When a robot trundles into an elevator, it typically does the selfish thing and sits smack in the center, leaving little room for human passengers. The same happens in hospital corridors, where robots bother staff by hogging space. "Most humans know it's not polite to do that. We use interactive behavior programming to help people help robots do the right thing—it's basically teaching them social skills," Takayama said.

As might be expected, people warm up to robots that behave more like people. In one collaboration, Takayama is studying people's perceptions of robots that spend time exploring, in addition to performing a primary task. The findings of this work, presented in March 2020 at a human-robot interaction conference, showed that people often have positive views of these "curious" robots, but assessed competence drops when these robots deviate too far from their task.

Humans commonly misread a robot's intentions, as was the case when Takayama first encountered a PR2 robot, like the one shown here, and it surprised her by appearing to run away. No longer in business, Willow Garage, the robot's Palo Alto–based maker, spent years investing in robotics research that produced the PR2's sophisticated visual and tactile sensors and open-source software. Credit: Oleg Alexandrov (CC BY-SA 3.0).

In an earlier project, Takayama tapped an expert animator to help generate movements for a robot that allowed people to understand its intentions, to open a door or pick up a bottle, for instance. "Takayama showed how a robot can be incredibly expressive," said Anca Dragan, an assistant professor of electrical engineering and computer sciences at UC Berkeley. Dragan was developing algorithms that enable robots to work with, around, and in support of people, and Takayama's demonstration inspired her to work on robots to autonomously have expressive motions: "I ended up asking is there a way for the robot to come up with those motions itself?"

Ultimately, if robots behave more expressively, people can better understand what they're doing and anticipate what they're going to do. This has important consequences for self-driving cars, Dragan said, since the way robots drive needs to be consistent with human driving, and both need to anticipate the other to avoid accidents.

## Human side

Importantly, when humans and robots both learn, both benefit. Human-robot interactions improve when people have more informed and realistic expectations of a robot's abilities, said Laurel Riek, an associate professor of computer science and emergency medicine at UC San Diego.

In a recent study, which supports the findings in Takayama's work, Riek asked people to collaborate with a mobile robot to cooperatively hang a large banner. Unbeknownst to participants, the robot was intentionally programmed to make mistakes, such as dropping its end. Some participants were told the robot might malfunction, and they responded differently from others who received no warning. "The participants in the low-expectation setting recovered more quickly from the errors, regaining trust in the robot and improving their perceptions of its reliability," Riek said.

The implication is that people's unrealistic expectations can hamper their interactions with robots. The videos they see online, such as the popular YouTube clips of the robots built by Boston Dynamics, give the wrong impression, Takayama said. "I wish they'd show more of the blooper reels, the 199 takes before the demo finally worked. This stuff is hard. Robots are actually not that capable," she said.

False impressions and unrealistic expectations stemming from media and popular culture portrayals have promoted hope, hype, and fear about robots and artificial intelligence, said Takayama. Robots in science fiction, like in (top row, L to R) the *Doctor Who* TV series and the *Star Wars* and *Terminator* movies, are far more capable than currently available robot technology. Most of today's robots, like (bottom row, L to R) the Roomba vacuum cleaner, the da Vinci surgical robot, and the Robomower, are made to excel only at a single task. Credits: *Doctor Who, Terminator*, Roomba (CC BY 2.0); *Star Wars* (CC BY-NC 4.0); da Vinci (public domain); Robomower (CC BY-SA 3.0).

These outsized expectations also have important implications for the robot-enabled future, beyond their immediate impact on human-robot interactions. People have preconceived notions about robots shaped by decades of media-fueled hope, fear, and hype. Early roboticists envisioned anthropomorphic robots with broad, human-like functionality, a concept now firmly planted in the minds of most people. It's now clear, however, that robots work best when they're specialized, which translates to myriad different designs depending on the robot's main task. The faceless robot that stocks the shelves will be strikingly different from the one with the friendly face working the cash register.

The image problem is exacerbated by the media portrayals of humanoid robots that frequently give the impression of much broader capability than is actually the case, Takayama said. Such robots typically disappoint when encountered in real life, offering just a highly articulated face and not much else. These false impressions contribute to the hype that surrounds and damages the field, Takayama said. "If you're going to make it look like a human, you should make it live up to those expectations," she said. "Why not make a Roomba instead?"

Portrayals of robots in popular culture have also contributed to the misconceptions. East Asian science fiction, like the Japanese series *Astro Boy*, has promoted both hope and fear about artificial intelligence and robots. More recent Western movies like *Robot & Frank* and series like *Westworld* ask nuanced questions about potential relationships with robots, but robot portrayals in earlier ones, like Hal in *2001: A Space Odyssey*, primarily warned about the potential dangers of a robotic future, Takayama said.

Takayama and her colleagues are hard at work trying to shape a robotic future that reflects the best of humanity. "We should be thinking harder about what robots we should be building, not just what robots we *could* be building," she said. "Just because you can build it, is that the future we want? That's the real question."

By Ula Chrobak

# A dangerous element

## Tracking the elusive biogeochemistry of mercury

Along Northern California's coastline, scientists have found concerning levels of mercury in two top predators. In the Santa Cruz Mountains, **Peter Weiss-Penzias**, a UC Santa Cruz associate researcher in microbiology and environmental toxicology, discovered that coastal-dwelling pumas have three times the amount of the toxic heavy metal in their fur and whiskers compared to inland mountain lions. And in UCSC dining halls, ecotoxicologist **Myra Finkelstein**, an adjunct associate professor, documented that some students were eating more than 20 servings of tuna a week—enough to accumulate potentially harmful levels of mercury in their bodies.

Both cases are worrisome. Mercury is a neurotoxin, and high enough doses degrade the mental capacities and motor skills of those exposed. In pregnant mothers, the metal can enter the womb and harm infant brains. And the silvery element can build up in the living tissues of both plants and animals, compounding the danger.

Despite relatively recent laws and treaties that now limit its release, a lot of mercury has wound up in bodies of water—creeks, rivers, lakes, and the ocean—where it transforms into its most toxic form and enters food chains. In addition, key steps in the metal's movements through the environment—its "biogeochemistry"—remain unclear, including how it changes from its less dangerous, inert forms to an organic molecule that accumulates in living tissue. To better understand the mercury threat, UCSC scientists are working to learn how this mysterious element shifts between its different forms. "Nothing is simple when it comes to mercury," said Weiss-Penzias. "It has a way of disappearing and then reappearing somewhere else."

Above: It's been recommended that people should avoid eating too much of certain types of fish, like these yellowfin tuna (*Thunnus albacares*) swimming in the Gulf Stream—commonly served as sushi and sashimi—because these and other top ocean predators contain high levels of mercury. Credit: OAR/National Undersea Research Program (public domain).

### Gold and coal

The elevated levels of mercury in the environment today are the result of its current and historic use in gold mining, and from the continued use of coal for energy production. Gold Rush–era mining contaminated watersheds throughout California. Miners used the shiny liquid quicksilver—mercury in its pure, elemental form—to recover gold from gravel deposits adjacent to rivers. At these placer mines, miners washed gold-containing sediments through sluices lined with quicksilver. The mercury and gold formed a heavy amalgam easily sifted from other sediments. In the process, much of the metal escaped and drained into rivers and streams. An estimated 10 million pounds of mercury entered the environment from placer mining throughout California. The San Francisco Bay is tainted by this past, as are the 131 reservoirs identified by the state as "mercury-impaired."

Today, small-scale gold mining in Asia, Africa, and South America still relies on mercury—and may account for over half of ongoing global mercury pollution. The remainder comes primarily from coal-powered energy production. Millions of years ago, the metal glommed onto the ancient plant and animal remains that eventually became coal. Now, burning this fossil fuel releases mercury into the atmosphere as a gas that drifts around the globe.

Thanks to gold mining and coal burning, a lot of mercury contaminates the environment. "The general consensus is that we've increased the amount of mercury moving around the active reservoirs of the Earth—the ocean, soils, and the atmosphere—by somewhere between a factor of three and seven," said associate professor of ocean sciences **Carl Lamborg**, an expert in the biogeochemistry of mercury. "Seventy-five percent or more of all the mercury in the air around you right now is a consequence of human activity."

### Mobilized metal

All this mobilized mercury exists in three main forms. Its elemental form, Hg0, the liquid quicksilver at room temperature, easily volatilizes into a gas. That gaseous mercury becomes charged in the atmosphere to its Hg2+ form, or mercuric ions. These ions can diffuse into water. Under low-oxygen conditions, such as in lake bottom, coastal, and seafloor sediments, bacteria convert mercuric ions into methylmercury ($CH_3Hg^+$) ions. Toxicologists worry especially about methylmercury. "The mercury in our bodies is mostly methylmercury," said Lamborg. "Methylmercury by itself is not necessarily more toxic than any other form of mercury, but it sits there as a reservoir that bleeds out into the rest of your tissues."

That methylmercury comes mostly from eating fish, especially top predator fish. In the ocean, methylmercury sticks to phytoplankton, which are eaten by small fish, which are eaten by tuna, swordfish, and sharks. At every step up the food chain, the metal becomes more concentrated. Each tiny plankton accumulates mercury across its life, and fish eat these concentrated morsels. Plankton eaters have about 100 times more mercury in their bodies than what's in their food. And top

Cinnabar (left), mercury sulfide (HgS), with its distinctive red color, was extensively mined throughout California during the Gold Rush era to provide quicksilver (right), liquid elemental mercury (Hg0) that played a key role in placer mining for gold. Gold mining and coal energy production have contributed to a substantial amount of this toxic element contaminating the environment. Credit: cinnabar, H. Zell (CC BY-SA 3.0); quicksilver, Bionerd (CC BY 3.0).

## A dangerous element

Looks good, but perhaps you shouldn't eat it too often; some types of tuna contain potentially concerning levels of mercury that end up in you. Credit: public domain (CC0).

predators—like the tuna served at UCSC dining halls—have mercury concentrations another 100 times higher than plankton eaters. When we eat tuna, more than 90 percent of the methylmercury in the fish remains in our bodies, stored mostly in fat. From there, some slowly releases as mercuric ions, which is what does the damage to our tissues. To play it safe, Finkelstein recommends minimizing your exposure by being careful about what type and how much fish you eat (see table below).

But fish is apparently not the only way mercury gets into the bodies of land animals. In 2010, while working in the Elkhorn Slough, an estuary on the coast about halfway between Santa Cruz and Monterey, Weiss-Penzias wondered about the thick fog that rolled in every day. When he analyzed fog droplets for mercury, the concentration was much higher than he expected. In research that followed, Weiss-Penzias showed how this mercury entered the food chain: lichen and plants absorbed the fog, deer eat the lichen and plants, and mountain lions eat the deer. One coastal mountain lion he sampled (via its fur and whiskers) had levels of mercury known to be toxic to mink and otters, and two others showed concentrations that could cause confusion and potentially impair their ability to breed and parent kittens.

### Mercury Levels in Fish: A Guide to Healthy Seafood Consumption (1 serving = 4 oz.)

| Least— enjoy | | Moderate— ≤6 servings/ month | High— ≤3 servings/ month | Highest— avoid! |
|---|---|---|---|---|
| Anchovies | Plaice | Bass | Croaker | Bluefish |
| Butterfish | Pollock | Buffalofish | Halibut | Grouper |
| Catfish | Salmon | Carp | Mackerel (Spanish, Gulf) | Mackerel (King) |
| Crawfish | Sardine | Cod | Perch (ocean) | Marlin |
| Flounder | Sole | Mahi-mahi | Sablefish | Orange Roughy |
| Haddock (Atlantic) | Tilapia | Monkfish | Sea Bass | Shark |
| Hake | Trout | Perch (freshwater) | Tuna (Albacore, Yellowfin) | Swordfish |
| Herring | Whitefish | Sheepshead | | Tuna (Bigeye) |
| Mackerel (N. Atlantic, Chub) | | Snapper | | |
| Mullet | | Tilefish | | |
| | | Tuna (Canned chunk light, Skipjack) | | |

*Source: Natural Resources Defense Council. NRDC used the reference dose considered safe by the EPA and seafood mercury concentrations from the USDA. Servings are based on the weight of an average woman of child-bearing age (130 lbs.).*

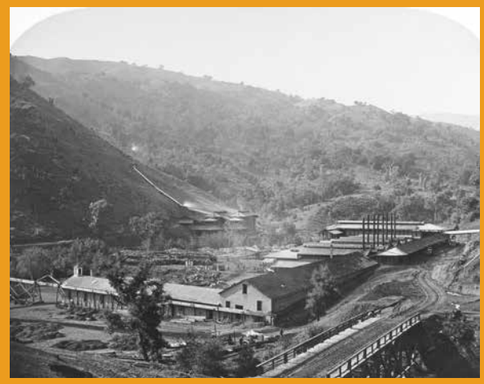
### Mercury's California legacy

California needed mercury to become the golden state. A key ingredient in placer mining, mercury was churned out during the Gold Rush era by almost 40 major mines between Santa Barbara and the Oregon border.

The New Almaden Quicksilver Mines, established in 1847, was the biggest of these mining operations, located 12 miles from downtown San Jose. Here, miners extracted 82 million pounds of mercury, most of it by 1905, from the red mercury sulfide ore, known as cinnabar, dug from the mines. Heated in a furnace, the mercury in the cinnabar became a gas. Then cooled and condensed, the vapor became quicksilver. Leftover rock was dumped around the mine, including into streams draining into the San Francisco Bay.

After a brief boom in the 1960s with mercury back in demand during the Vietnam War—it was used in explosives—cinnabar mining in California finally stopped in the 1970s, due to rising operating costs and environmental regulations. Today, after extensive clean-up of contaminated rock, the New Almaden site is now Almaden Quicksilver County Park. In the area's Guadalupe and Almaden reservoirs, fishing is strictly catch and release due to mercury levels that remain high. "I can readily pan tiny beads of mercury for miles downstream," said now retired Michael Cox, who worked as an environmental remediation consultant with New Almaden Quicksilver County Park Association.

The New Almaden mercury mining lives on in other ways. *The San Jose Mercury News* newspaper owes its moniker to the importance of mercury in the local economy (and also partly to Mercury, the Roman god of commerce whose winged feet made him extra fast). Place names in the area also reflect this history—Cinnabar Elementary School, for example.



This 1863 photograph shows the mercury smelting works at the New Almaden Quicksilver Mines, 12 miles from downtown San Jose. Here, workers heated the red cinnabar ore to extract quicksilver—mercury in its elemental form—for use in placer mining for gold. To this day, the waste from this largest mercury mining operation in North America, mostly shut down by 1905, contaminates local streams, reservoirs, and the San Francisco Bay. Credit: Carlton Watkins (public domain).

## Toxic pathways

While the mercury in tuna, humans, and pumas ultimately traces back to the methylmercury generated in the ocean by anaerobic bacteria, exactly how these microbes transform elemental mercury into methylmercury remains unknown. It's not a result of their metabolism—these anaerobes eat organic matter and breathe sulfate or oxidized iron. Another process must drive the change.

And although these microbes typically live in low-oxygen environments, mercury methylation has been shown to occur even in well-aerated ocean waters that contain few methylating bacteria. This suggests there's probably another pathway to methylmercury in addition to the one associated with the anaerobes. According to Feiyue Wang, professor of biogeochemistry at the University of Manitoba in Canada, there's a "bizarre" shallow layer of methylmercury in the Arctic Ocean, even though those waters are well-oxygenated. "In that kind of water, we normally would not anticipate a large population of anaerobic bacteria," Wang said. "This newly discovered phenomenon really forces us to consider other possibilities."

## A dangerous element

To investigate the mercury methylation process, Lamborg has directed research to selectively filter seawater to narrow down the possibilities by a process of elimination. In an experiment performed by graduate student Kathleen Munson, now a postdoctoral fellow at the University of Manitoba, methylmercury continued to form in seawater samples after all the microbes were filtered out. Lamborg has some leads on the mystery reaction. Bacteria produce vitamin B12, and that could react with mercuric ions to produce methylmercury. "There's all this circumstantial evidence suggesting that we should be looking for a B12-related mechanism," he said.

Another enigma lies at the bottom of the San Francisco Bay, where the sediments contain an estimated five-fold increase in mercury from natural levels due to gold production activity, including from mercury mining (see sidebar, p. 43). However, the fish reeled in contain low levels of mercury. One explanation is that most of the mercury remains in the inert form in which it was mined, mercury sulfide (known as cinnabar, with its characteristic red color). "It should make us all nervous," said Lamborg. "If we messed with that system in some way, that could make that mercury suddenly bioavailable to methylating bacteria."

### Living with it

A better understanding of mercury's elusive movements could help to minimize its toxic effects. It could, for instance, suggest ways for clean-up efforts at contaminated sites to keep the sedimentary mercury in its inert cinnabar form. But even with targeted clean-up efforts at some reservoirs and wetlands, we can't do anything about most of the mercury we've already unleashed. "You can't clean up the ocean, you can't clean up the atmosphere," said Weiss-Penzias. "It's just too dispersed."

Meanwhile, Weiss-Penzias continues to study how mercury makes its way into the mouths of humans and other animals. After he published his study on the element in pumas, he received many concerned inquiries, including from a farmer who worried about their goats eating lichen. Weiss-Penzias hopes an experiment he's planning can help address some of the concerns, by measuring how mercury-laden fog might be affecting strawberries, broccoli, and artichokes grown on the Central Coast.

More education about mercury exposure is probably also a good idea. In her dining hall study, Finkelstein found that nearly all the students were unaware of the risk associated with eating too much tuna. "Many students seem to have limited to no understanding," she said. "It was alarming." Finkelstein said that while a national educational effort has aimed to keep women from eating mercury-rich fish during pregnancy, the risk to the general public—including to children and young adults, whose developing brains may also be vulnerable—isn't widely acknowledged. "It has changed what I allow my children to eat," Finkelstein said. "I think about it a lot. We are exposed to such a large amount of chemicals on a daily basis."

This risk—and the element's enigmatic ways—keep the UCSC mercury scientists engaged. "I've been working in the field for almost 20 years trying to understand the fate and transport of mercury in the environment," said Weiss-Penzias. "It's still quite vexing."

Scientists on a GEOTRACES cruise retrieve ocean water samples from an instrument called the CTD Rosette. GEOTRACES expeditions have allowed researchers, including associate professor of ocean sciences and mercury biogeochemistry expert Carl Lamborg, to measure the concentration of mercury and other trace metals at various places and depths in the ocean. Credit: Alex Fox.



By Emma Hiolski

# Fungi and fuel rise to top

## Grad student research stars in Grad Slam

"This is a handshake-free event," said **Quentin Williams** during his opening remarks at the sixth annual UC Santa Cruz Grad Slam. Williams, emcee and acting vice provost and dean of graduate studies, cited growing concerns about the spread of the novel Covid-19 coronavirus. The Grad Slam, held for the second year at Kuumbwa Jazz center in downtown Santa Cruz, was one of the last university-sponsored events to occur before such gatherings were canceled in response to the global pandemic. But even though one judge and one participant were absent due to voluntary self-quarantine, coronavirus couldn't upstage the evening's enthusiastic presentations.

Eleven graduate students shared three-minute, public-oriented summaries of their research in UCSC's portion of the UC-only contest, similar to the Three Minute Thesis (3MT®) competition created at the University of Queensland in Australia. A panel of nine judges, including Santa Cruz Mayor Justin Cummings and several UCSC alumni, ranked the presentations.

The participants hailed from disciplines spanning planetary science, psychology, ecology, and beyond. **Amanda Carbajal**, a Ph.D. student in molecular, cellular, and developmental biology, talked about how prion proteins—which cause neurological diseases in humans and other mammals—might help explain the origins of life on Earth. Environmental studies Ph.D. student **Justin Luong** shared his research on restoring native grasses in coastal California—check out his native grass Instagram page (*gramho.com/profile/stipapulchra/12270282672*). **Katie Hellier**, a Ph.D. student in the Physics Department, discussed her work creating glass panels that double as solar panels for greenhouses. And Earth and planetary sciences Ph.D. student **Ricky Garza-Girón** spoke about analyzing seismic activity during volcanic eruptions to determine when these cataclysmic events have concluded.

"The presentations this year were really extraordinary—any of them could have won," said Williams. But a champion must always be crowned, and this year the honor of both first place and the people's choice award (a combined $3,750) went to **Tori Klein**, a fifth-year Ph.D. student in the Chemistry and Biochemistry Department. Klein presented her research on using compounds made by a parasitic fungus to block growth of cancerous cells ("Using zombie insects to find a cure for cancer"). "One of my favorite parts of science is communicating it to a non-scientific audience," she said. "It means a lot to me that everyone's excited about biochemistry—it's usually not the most popular subject in school."

Second place (and $1,500) was awarded to **Abel Mkulama**, a first-year M.S. student in the Coastal Science and Policy Program. Mkulama, who grew up in Malawi, presented his work developing fuel briquets for cooking from agricultural waste to reduce deforestation and indoor air pollution in his home country ("How briquets can prevent deforestation and save lives in Malawi"). "Communicating my research is how I can get people to act on it," he said. "And the Grad Slam provides an opportunity to share it in the most concise way."

Klein would have represented UCSC at the final round of the UC-systemwide Grad Slam on May 8, but the event was canceled due to the Covid-19 pandemic. To watch past presentations, head to *gradslam.universityofcalifornia.edu*.

Acting vice provost and dean of graduate studies Quentin Williams (back row, center) and finalists at the sixth annual UCSC Grad Slam competition. Credit: Kurtz Photographics.

By Lindzi Wessel

# Local goes global

## As national governments waver, cities take up the climate fight

Climate-change related decline of snowpack and glaciers in the Andes Mountains threatens the water supply of roughly six million residents in Chile's capital city, Santiago, its skyline seen here. Environmentalists and scientists had planned to highlight the environmental challenges facing Santiago, a C40 Group member city, on an international stage while hosting the United Nation's climate talks in 2019. Their plans were derailed by an explosion of civil unrest due to simmering anger over inequality and access. Credit: Güldem Üstün (CC BY 2.0).

The Earth's temperature creeps steadily upwards and its oceans lap progressively higher. Meanwhile, for many national governments, prioritizing climate change as an imminent threat has fallen off the agenda. In fact, some of the world's most powerful leaders flatly reject the existence of man-made climate change. In key countries like the United States and Brazil, their decisions have even worked to overturn critical environmental policies aimed at curbing global warming or tempering its effects.

In the face of this denial, city mayors and other local politicians across the globe are taking matters into their own hands. More than half the world's population resides in urban centers, with one in eight people living in megacities of more than 10 million inhabitants. As elected representatives of this vast congregation, city leaders have banded together, amassing their collective clout and power to confront the climate crisis.

This local-goes-global movement is the focus of research for UC Santa Cruz assistant professor of politics **David Gordon**, one of a growing number of political scientists studying how cities wield their influence. Gordon wants to know how cities as dramatically different as Ghana's Accra, Vietnam's Hanoi, and Canada's Montreal can work together to attain shared, global goals. "These cities have no power over one another and no ability to impose penalties or coerce one another," he said. "How do they agree on anything and coordinate their actions to achieve something collectively?"

To answer this question, Gordon examines organizations like the C40 Cities Climate Leadership Group, a network of cities from six continents. C40 member cities have pledged to curb emissions, work towards a carbon-neutral future, and, in accordance with the 2015 United Nations Paris Agreement, limit global warming to no more than 1.5° C by 2050. The group shares strategies and blueprints for implementing climate projects and policies and leverages their collective voice in the hopes of influencing international decisions on climate change.

### Coming together

As of February 2020, the C40 Group included 96 cities, more than double its 40 first-year members almost 15 years ago. The roster includes São Paulo, Brazil, which faces a future of increasing drought, extreme heat, and vector-borne diseases driven by climate change. It also includes Melbourne, which, already working to troubleshoot sea-level rise, recently saw itself surrounded by flames as record breaking fires raged across Australia. Both cities joined C40, in spite of federal leadership that denies man-made climate change. Miami, where residents now regularly trudge through downtown flooding and the number of dangerously hot days is expected to quadruple by 2050, stepped around their own conservative state and federal governments to become one of the most recent C40 members in January 2020.

Other city networks are similarly focused on climate change. For example, the Global Covenant of Mayors for Climate & Energy, formed when two pre-existing city initiatives merged in 2016, links more than 10,000 cities whose leaders are taking steps to prepare for the eventual impacts of climate change. And the Carbon Disclosure Project, headquartered in London, tracks carbon emissions from more than 700 cities.

Such groups are attractive not just for cities already dealing with real impacts of climate change, but also for those looking for opportunities to grow and modernize, said Gordon. Membership sometimes opens a path for access to funding from development banks, philanthropies, or investors, which, in turn, can lead to more climate-friendly development. This strategy could become more broadly followed once people see the associated benefits, like more green space and improved public transportation, Gordon said.

Displaying the beneficial outcomes of adopting such "green" models can also be a way for cities and their leaders to establish international standing. But it's a delicate balance, said Sara Hughes, assistant professor of environment and sustainability at the University of Michigan in Ann Arbor. Too much focus on international issues can exacerbate resentment of officials who neglect problems within their cities. For example, "cities have historically not done a great job of addressing inequality," said Hughes, who studies governance strategies for responding to climate change in cities. "Whether that can be centered in some of this work is still an open question."

### Blow back

In fact, overstepping local issues for global ones can backfire drastically, as illustrated by the fall of Toronto's one-time mayor, David Miller. Now the North American director for the C40 Group, Miller was slammed for spending too much of his time as mayor on building connections outside of Toronto instead of dealing with problems plaguing the city's working class. Many saw Miller as a "globe-trotting elitist," Gordon said, which contributed to a precipitous drop in his approval ratings and ouster in 2010 by Rob Ford, a politician who, in many ways, embodied the opposite of Miller's environmental ideals.

A similar tipping point was reached last October in Santiago, Chile, another C40 city, as it prepared to host the U.N.'s 25th international Climate Change Conference. While researchers and environmentalists geared up for the chance to position Santiago as a climate leader on the global stage, long-simmering anger about inequality exploded into weeks of rioting, paralyzing the city and forcing conference organizers to relocate the conference to Madrid. "If you don't connect a global


According to the C40 Cities Climate Leadership Group, a coalition of more than 90 cities from around the world, the time for cities to act on climate change is now. An estimated 80 percent of global emissions come from cities, and the C40 Group supports city leaders in their efforts to reduce these emissions and reverse climate change. Credit: Green Energy Futures (CC BY-NC-SA 2.0).

political project to the interests of people living in and around your city, there's a real problem with the viability of the whole thing," Gordon said. "That can really throw everything off the rails in a big hurry."

## Juggling needs

In fact, how cities juggle the immediate needs of their citizens with the longer-term, global challenges posed by climate change may be one major factor determining whether these city coalitions ultimately succeed, Gordon said. He plans to test this by comparing specific cities more closely, based on how they score on measures of international and local accountability.

For example, Quito, Ecuador, has already experienced substantial weather pattern changes due to an average temperature increase of 1.2° to 1.4° C. The city is deeply involved in global climate groups but has made little effort to educate its citizens about why, Gordon said. In contrast, Iskandar in Malaysia scores high on Gordon's metrics of local accountability, engaging regularly with its citizens and creating opportunities for education and input. What could make the difference, he said, "is the ability to effectively build that bridge between the interests of cities and the allure of international investment and recognition."

Because this field of research is relatively new, when it comes to what brings success, there are many more questions than answers, said Gordon, whose new book (April 2020), *Cities on the World Stage: The Politics of Global Urban Climate Governance*, explores these questions. Many cities have made bold climate commitments, but will they actually be able to deliver? What happens if their positions conflict with those of their state or national governments, as has occurred with sanctuary cities in the United States? And will developing municipalities clash with more modern metropolises which, despite having made negative environmental impacts in the past, now are asking others to curb their advancement for the sake of fighting climate change?

"We really need to better understand what makes city climate action succeed, and David's work in that regard is very important," said Sander Chan, a political science researcher studying global climate action at the German Development Institute in Bonn, Germany. "What cities do, and their action or inaction is vital."


Subject to increasing periods of extreme heat and flooding, as seen here, the city of Miami declared a climate emergency in November 2019. Soon after, Miami city leaders side-stepped its climate-denying state and national governments to become one of the newest members of the C40 Group coalition of cities from around the world working to fight climate change. Credit: Wikimedia Commons (CC BY-SA 4.0).



By Bethany Augliere

# Fish for all

## Seeking sustainable aquaculture via fish-free feeds

Aquaculture is a booming business. In 2014, for the first time in modern history, people ate more aquaculture-produced seafood—roughly 74 million tonnes—than seafood harvested from capture fisheries. Due to increasing demand for seafood products and depleted wild fish stocks, farmed seafood has become the world's fastest growing food sector. And as our global population increases, so will our dependence on aquaculture to feed a world filled with billions more hungry people.

But farmed seafood faces the same long-term sustainability problem as capture fisheries: dwindling stocks of wild fish. Fish farming operations depend on smaller wild fish, like anchovies, sardines, and mackerel, to feed the larger fish that end up on our dinner plates. These smaller species—called "forage fish"—live lower on the food chain where they provide an important base of the marine food web, critically supporting everything from larger fish to marine mammals and seabirds. According to a 2017 report published in the journal *Fish and Fisheries*, of all fish caught in the world, about 20 million tonnes (90% of which could be eaten by humans) are ground up to produce fishmeal and fish oil, primarily to feed farmed fish. At that rate, experts worry that the demand could outstrip the supply as soon as 2037, with additional severe consequences for marine ecosystems that are already threatened. "Is aquaculture really adding to world fish supplies or is it actually helping deplete

This fish-free feed created in the laboratory of UCSC professor of environmental studies Anne Kapuscinski contains two types of microalgae. Kapuscinski and co-team lead associate research professor Pallab Sarker are evaluating this and other feed formulations in experiments that involve carefully hand feeding the fish that are their test subjects. Credit: Kapuscinski-Sarker Lab.

# Fish for all

In an effort to return aquaculture to its more sustainable historical roots, UCSC professor of environmental studies Anne Kapuscinski, who also directs the UCSC Coastal Science and Policy Program, seeks to develop fish-free feeds that contain marine microalgae instead. Credit: C. Lagattuta.

wild fisheries?" asked food security expert Rosamond Naylor, a professor of Earth system science at Stanford University in Palo Alto.

Humans farm more than 580 species of aquatic animals and plants, everything from fish, oysters, and clams, to shrimp and seaweed. This flourishing enterprise provides roughly 50 percent of the seafood currently consumed by people. In the early 2000s, fishery products were the primary protein source for some 950 million people, a number that is certainly much higher today. Aquaculture is clearly necessary and important to feed populations all over the world. The good news is that, compared to producing beef, pork, and chicken, aquaculture is more efficient and emits the lowest amount of greenhouse gases. But it could and should be better, and that's the goal of UC Santa Cruz professor of environmental studies **Anne Kapuscinski**.

"Aquaculture started over 2,000 years ago in China, and also arose in some other parts of the world. It actually mimicked natural ecosystems in that there wasn't any waste," said Kapuscinski. Armed with this knowledge, Kapuscinski wants to steer aquaculture in a more sustainable direction that eliminates the need for wild-caught forage fish and reduces waste. To do that, she's been experimenting with using microscopic marine algae as the basis for healthy, environmentally-friendly fish feeds that swap out the fishmeal and fish oil.

Kapuscinski's work to create a green and nutritionally superior aquaculture sector with minimal environmental impact is "valuable and progressive," said Naylor. There are "real opportunities for improvement," she said, "and they are right there at UCSC—it's time to find replacements for wild fishmeal."

## Nutritional nuances

The key to developing a fish-free feed is understanding fish nutrition. You need to achieve the right balance of proteins and fats so the fish grows as well, if not better, than they would on a conventional diet, Kapuscinski said. At least 40 essential nutrients must be included in their diet, so it's no easy feat.

The menu for most farmed fish currently includes a mix of fishmeal and fish oil. For a carnivorous species like salmon, fishmeal accounts for about 25 percent of their food. Together, these ingredients are chock-full of proteins, amino acids, and two critical omega-3 fatty acids, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). Walk into any vitamin store or vitamin isle and you'll see myriad jars of fish oil supplements. That's because research has linked these omega-3s to a variety of human health benefits, including a decreased risk of heart disease. In the wild, the DHA and EPA required by fish come from marine microalgae. Fish and other marine organisms obtain these omega-3s by directly eating marine microalgae, or by eating other animals that have eaten the microalgae.

To develop fish-free fish diets, Kapuscinski closely collaborates with **Pallab Sarker**, a fish nutrition expert and associate research professor of environmental studies. Their goal is to replace the fish-derived products in fish feed with marine microalgae, which hasn't been done before. "Microalgae are a particularly good candidate for fish feed because they are at the base of the aquatic food chains," said Sarker. So far, the researchers' efforts have focused primarily on Nile tilapia, a freshwater species—*Oreochromis niloticus*—native to the northern half of Africa and Israel. After Chinese carps, tilapia constitute the second most important group of farmed fish, and the most widely cultivated.

Tilapia is mostly farmed in land-based ponds and tanks, less frequently in cages like these in Lake Kariba in Zimbabwe, Africa. Tilapia farming currently uses feeds that contain substantial amounts of fishmeal and fish oil derived from wild fish. Such feeds are wasteful and ultimately unsustainable, and—as research performed by Kapuscinski and her team is showing—can likely be replaced with more environmentally-friendly fish-free feeds. Credit: M. Reantaso, courtesy of FAO Aquaculture Photo Library.

The Nile tilapia, an important food for ancient Egyptians, remains a staple throughout northern Africa today. Mostly farmed on a local level in small ponds, the fish is also Kapuscinski and Sarker's primary research subject. Credit: Bjørn Christian Tørrissen (CC BY-SA 3.0).

Like that of farmed salmon and trout, the commercial diet of farmed tilapia includes fishmeal and fish oil. However, unlike wild salmon and trout, which are carnivores, wild tilapia occupy a lower level on the food chain and don't eat fish. They primarily graze on mats of algae and bacteria. Despite this, almost 20 percent of total world production of fishmeal and fish oil from capture fisheries goes to support tilapia farming, said Kapuscinski. "That's why I started our work with tilapia."

## Hand fed

Kapuscinski and Sarker's experiments involve feeding tilapia diets with different compositions of fishmeal, fish oil, and algae. The fish are first measured and weighed and then divided randomly into different tanks where they receive one of the

# Fish for all

Integrating agriculture and aquaculture can increase food yields while reducing waste and environmental impacts. Here, in Yogyakarta, Indonesia, juvenile tilapia feed in a rice field planted according to an integrated practice of rice-fish farming. Credit: A. Stankus, courtesy of FAO Aquaculture Photo Library.

test diets. The fish are weighed throughout the studies, and then again at the end, when tissue samples are also taken. The team carefully feed the fish the test feed pellets by hand, three times a day for 12 weeks. "We pay attention to make sure that feed waste is minimized," said Sarker. "We distribute the feed to the tank very slowly and ensure every pellet has been received by the fish."

In a study published in *PLOS One* (July 2018), the researchers fed the tilapia a conventional diet and ones with fishmeal replaced by the microalga *Nannochloropsis oculata* at 33 percent, 66 percent, and 100 percent levels. The results showed that the protein-rich portion of the microalgae could replace 33 percent of the fishmeal. "We were really excited to find that the microalgae could replace a significant amount of the fishmeal," Kapuscinski said.

In a more recent study, not yet published, Kapuscinski and Sarker replaced both fishmeal and fish oil with two different species of microalgae. This work showed that the replacement feed produces tilapia better and faster than a conventional diet. In addition to measuring the fish, the team also calculates the "feed conversion ratio" (FCR), an estimate of the amount of feed that actually becomes fish flesh. The lower the FCR the more efficient the feed, and the fish fed the algae diets have a lower FCR. "Farmers keep using the fishmeal and fish oil assuming the tilapia will do best with that," said Kapuscinski. "But we've found that the fishmeal and fish oil aren't needed. With the two types of marine microalgae together, we get a superior diet."

## Cost cutting

A big concern with using algae for fish feed is its potentially high cost. Companies are already using less-expensive alternatives such as soy, corn, and canola to reduce the fishmeal—which has become more expensive—in their feeds. But these substitutes are not healthy for fish or humans eating the fish, nor are they sustainable solutions. They lack the omega-3s, have lower digestibility, and contain antinutrients, compounds that actually interfere with nutrient absorption. For example, the phosphorous in land-based crops is particularly difficult for fish to digest, said Sarker. Seventy percent of the phosphorous remains undigested, meaning increased pollution from the resulting sewage.

Following the sustainability concept known as circular economy, Kapuscinski and her team plan to keep the price tag of their algae-based feed down by using what would otherwise be a waste product. Instead of making their protein ingredients from whole algae, they're using "defatted biomass"—the leftovers from whole algae first pressed for other uses in the biofuel and nutraceutical industries. Because this leftover algal meal currently serves no other purpose, the cost is low.

Kapuscinski originally wanted to use the whole algae, but realized that would not work economically, said Martin Sabarsky, CEO of San Diego–based Cellana, and a collaborator with Kapuscinski's team on one current project. At the end of the day, he said, you can have a perfect fish-free feed, but if farmers can't afford it, it won't matter. "Anne is one of the first in this space who thinks deeply about formulation with commercial scaling in mind," Sabarsky said. "She's combining what would be a perfect product with what could also work commercially." Naylor agreed: "Anne and Pallab are rock stars in developing prototype feeds. They are thoughtful both about the ingredient list and the economics. If whole algae was the only revenue stream, you would not be able to commercialize it."

Right: In an attempt to increase sustainability by reducing waste and creating a circular economy, Kapuscinski and her team used wastewater from a brewery to grow microalgae that might later be used in their experimental fish feeds. Credit: Kapuscinski-Sarker Lab.

Below: In a photograph taken at Kapuscinski's previous laboratory at Dartmouth College in New Hampshire, co-team lead and now UCSC associate research professor Pallab Sarker (right) and Dartmouth undergraduate student Alexandra Kariotis weigh fish to document their weight gain on different experimental diets. Credit: Kapuscinski-Sarker Lab.

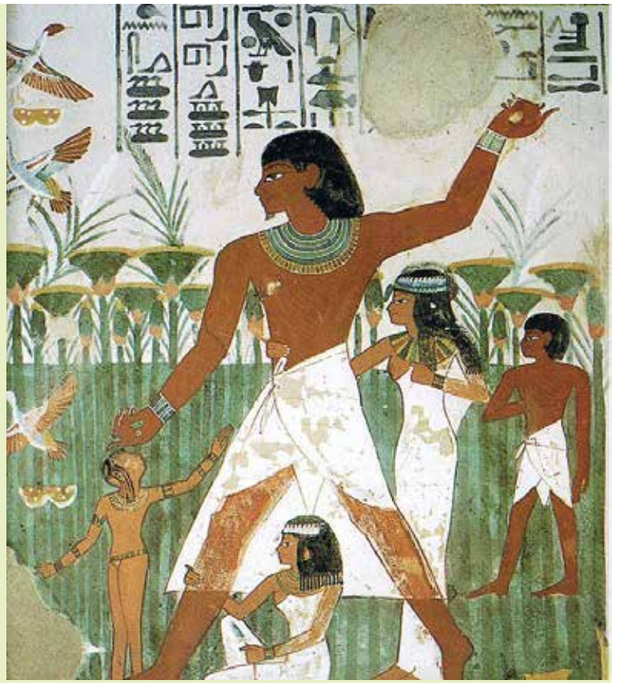
## Waste as resource

For more than 2,500 years in southeast China, farmers have grown mulberry trees. Leaves from the trees feed the silkworms they raise to produce silk. The silkworm "frass"—insect poop—feeds fish in nearby ponds, and humans eat the fish. Every winter, the farmers collect the nutrient-rich mud from the bottom of the fishponds and use it to fertilize the mulberry orchards. This circular system, called the Zhejiang Huzhou Mulberry-dyke & Fish-pond System, reduces waste and sustainably integrates agriculture and aquaculture.

Humans have farmed fish for a long time. The practice arose independently in several locations around the world, including ancient China, Egypt, and Hawaii. The ancient Egyptians farmed fish in ponds along the Nile, as documented in a bas-relief found in a 4,000 year-old Egyptian tomb. The Nile tilapia—one of the world's most widely farmed fishes—was so important that it had its own hieroglyph, also the symbol for fertility.

"In these ancient systems, you always see the recycling of what we in our modern world would consider waste," said Kapuscinski. Aquaculture was never done on its own, but rather, it was coupled in a systematic way with agriculture and capture fisheries. For example, in Hawaii, villages would raise small fish in ponds and lagoons, with fishing managed by the village chief. When wild fish were spawning, he would close fishing in open waters and only allow fish harvesting from the ponds.

The key to a sustainable future in aquaculture is modeling these systems of the past to reduce and recycle waste and adopt integrated systems, said Kapuscinski. "We need to try to understand how we might apply these principles—given modern conditions—in the present."



Top: A wall painting from the Tomb of Nakht (1500 BC), on the west side of the Nile across from Luxor in Egypt, displays a tilapia hieroglyph—also the symbol for fertility—just above the head of the central figure. An important food source then, the Nile tilapia remains so today. Credit: unknown, public domain.

Bottom: Drawn view of fishponds in 1825 at Honoruru (present-day Honolulu) on the island of Oahu in Hawaii. Native Hawaiians practiced aquaculture extensively; until the early 1900s there were more than 100 fishponds on Oahu, some covering hundreds of acres. Credit: Robert Dampier, public domain.

## Salmon in sight

While most of their work to date has focused on tilapia, Kapuscinski and Sarker have set their sights on another goal—to create a fish-free feed for farmed trout, a member of the salmon family. The trout, however, serve as a model for salmon, the ultimate prize. Touted for its health benefits, salmon is one of the highest economic value fishes produced in aquaculture, particularly for wealthy countries, like the United States, Japan, and in Europe. And it's a big player. Global aquaculture production of salmon is more than 2 million tonnes and gobbles up about 25 percent and 50 percent of the world's production of fishmeal and fish oil, respectively. China—the world's largest aquaculture producer—now has plans to farm millions of salmon in giant offshore pens in the middle of Yellow Sea, between mainland China and the Korean Peninsula.

The big difference between tilapia and salmon is that salmon sit higher on the food chain in the wild. Salmon are mid-tier predators that eat small fish and invertebrates, which makes the idea of feeding them a vegan diet somewhat illogical. This makes replacing the fishmeal and fish oil in salmon feed more of a challenge than doing so in feeds for tilapia. But it's also a challenge from Kapuscinski's green perspective. "The planet just beautifully produces salmon. If I had a magic wand and could change the world, I would steer us away from raising farmed salmon and instead put all that effort and financial resources into restoring wild salmon populations," Kapuscinski said. "But I'm also a pragmatist and realize that you can't just do that."

As carnivores, salmon pose more of challenge for removing fishmeal and fish oil from their farmed feed. Globally, salmon farms, like this one in the sea at Loch Ainort off the Isle of Skye in Scotland, consume an estimated half of all fishmeal, and a quarter of all fish oil produced today. Credit: Richard Dorrell, Loch Ainort fish farm (CC BY-SA 2.0).

Sarker and Kapuscinski's initial results in reducing the fish products in feeds for rainbow trout are promising. While trout fed a fish-free diet had slightly lower growth rates compared to those fed a conventional diet, the fillets from both contained similar levels of DHA, the important omega-3. "This is an exciting opportunity to potentially achieve fish-free trout feed with improved growth performance and palatability," said Sarker.

And while the UCSC research focuses on microalgae, it could turn out to be just one part of the optimal fish-free feed solution. It's possible that future fish-free feeds, whether for tilapia or salmon, could contain a combination of microalgae and other sustainable products like insect meal, bacteria, and yeast. "There are other innovators both in the private sector and the research community, who are trying to develop many other alternative ingredients," said Kapuscinski, whose team is developing an open-access, decision-support tool to compare alternative and conventional fish-feed ingredients for their nutritional value, environmental impacts, and cost competitiveness.

Wild may still be preferred by those who can afford it, but aquaculture promises to be an important part of our future, thanks to the enlightened efforts of Kapuscinski and others for whom sustainability provides purpose. "Aquaculture can add net value to our food systems," Kapuscinski said. "It can be regenerative in helping to improve environmental quality, but it needs to be done in a circular economy way. We need to think mindfully about how to link aquaculture with other production systems, to recycle and reuse nutrients and material."

By Dana Mackenzie

# Superior simulations

## Mathematical quest seeks to embrace uncertainty

*Does this mean that physics, a science of great exactitude, has been reduced to calculating only the probability of an event, and not predicting exactly what will happen? Yes. That's a retreat, but that's the way it is: Nature permits us to calculate only probabilities. Yet science has not collapsed.*

—Richard Feynman, *QED: The Strange Theory of Light and Matter*

"Propagating uncertainty" sounds, for a scientist, like a not very good idea. Isn't science supposed to reduce uncertainty, or eliminate it entirely? That's not what UC Santa Cruz associate professor of applied mathematics **Daniele Venturi** thinks. He agrees with Nobel Prize–winning physicist Richard Feynman: scientists often need to accept uncertainty. But, he asks, is there a good mathematical way to propagate uncertainty—or, in math terms, to "transport a probability distribution"—from one place (or time) to another? If so, such math could potentially be applied, for example, to create more robust and useful models of complex natural phenomena.

Take the weather, for instance. Small uncertainties in today's weather—say, whether the temperature in Peoria at 2 p.m. was 78 degrees or 79 degrees—can become larger uncertainties tomorrow or a week from now. But computer weather models do a poor job of reproducing this effect. That's because they use a legacy mathematical tool, called differential equations (in particular, the Navier-Stokes equations), that was designed to represent systems without including uncertainty.

Weather forecasters know this, and they have a kludgy work-around. "They sample the weather in five or ten initial conditions and push each through the equations," Venturi said. "Based on the outcome, they might say there is a 30 percent chance of rain. That just means that three simulations out of ten produced rain."

We could call this approach "sample-then-propagate." It's a necessary kludge because differential equations can only transport points to points. If you give them the fog of a probability distribution as input, they don't know what to do. Sample-then-propagate gives us pretty good weather forecasts. But it's awkward and inefficient, and it does not deliver a representation with any guarantee of accuracy.

Ever since he was an undergraduate at the University of Bologna in Italy, Venturi has dreamed of building a tool that can actually solve the problem the right way: by transporting the fog of uncertainty from place to place or from time to time. He calls his method "functional differential equations" (FDE). But we can call it "propagate-then-sample."

For math nerds, there is one difference between FDE and ordinary DE that is almost a showstopper. Ordinary DE involve finitely many variables, the dimensions of space and time that points move around in. But probability distributions live in an infinite-dimensional space, because you can vary them in infinitely many different ways. "When I tell my colleagues I work on differential equations with infinitely many variables, they say, 'Are you crazy?'" Venturi said. "That's the biggest compliment I could get. It means it's something interesting."

Venturi traces the origins of FDE to Eberhard Hopf of Indiana University, who first used them in a theory of turbulence that dates from 1952. Russian mathematicians Andrei Monin and Akiva Yaglom revived them in 1971, calling Hopf's equation "the most compact formulation of the general turbulence problem." Functional differential equations were a perfect fit for studying turbulence because turbulent fluid flow cannot be predicted with certainty. Recently, though, FDEs are beginning to appear in disciplines not related to fluids.

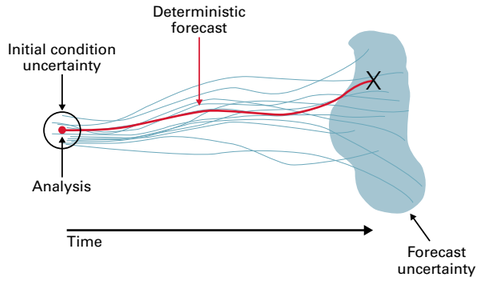
One surprising new example arises in machine learning. In recent years, deep neural networks—"deep" refers to a great number of layers—have had good success in realms like image recognition and computer chess and go. These networks loosely imitate the human brain, in which one layer of neurons might recognize individual pixels, while a deeper one pieces the pixels into curves, the next organizes them into trunk, limbs, and head, and the deepest layer finally recognizes the animal as a cat.

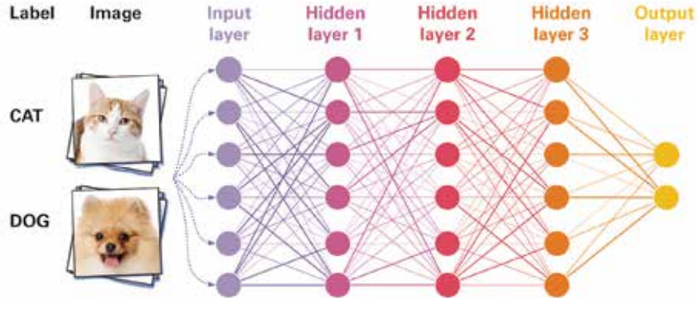
These complex constructs occupy the attention of mathematicians Weinan E and Jiequn Han at Princeton University, whose work explores the theoretical concept of a neural network with infinitely many layers. Such a network has to learn from essentially random input: a training set of images, some of which contain cats while others do not. It then needs to propagate uncertainty through all the layers of the network to obtain a classifier with (hopefully) the smallest amount of uncertainty possible. If this sounds to you like a problem made for FDE, you've passed the test.

That FDE is called a Hamilton-Jacobi-Bellman equation, and its solution is an operator that allows you to compute the weights—the strength of connections between layers—from any input. "It's the core of how you train a neural network," Venturi said.

Han said the advantage of "considering the problem in an infinite-dimensional space" is that it explains what neural networks are and why they work. They are discrete versions of a continuous, infinite-dimensional tool for propagating uncertainty. And, provided they are good approximations of such a hypothetical tool, they work well.

Venturi devotes a lot of effort to finding good discrete approximations to the solutions of FDE, in other words the second part of "propagate-then-sample." In practice, this means solving some very high-dimensional (but not infinite) ordinary DE. It's no longer "crazy," but conventional, hard mathematics. "You need to know the state of the art really well to see if it is sufficient to achieve the goal you set at the beginning," Venturi said. "The current state is insufficient. I don't claim any victory, but what I do claim is a heroic attempt. The winner will be whoever is first able to compute the solutions well."




Above: In the current "sample-then-propagate" approach to simulating natural phenomena, such as the weather, an initially uncertain measurement is taken. Several initial conditions are randomly chosen within the range of uncertainty, then propagated through a deterministic differential equation. These are assumed to provide a representative sample of the final state, up to uncertainty (blue region). Venturi's work aims to compute the blue region directly, using a non-deterministic "functional differential equation." Credit: Adapted from Met Office, United Kingdom (public domain).

Above, right: In a deep neural network for image recognition the purple input layer collects the raw pixel data. The yellow output layer gives the computer's guess on whether the image is a dog or a cat. The strength of the connections between hidden layers are indicated by the widths of the lines. These strengths, or "weights," are tuned in a way that maximizes the frequency of correct guesses. Credit: Ziv Goldfeld, with permission.

Opposite page: This image depicts the sample-then-propagate method for weather forecasting. Shown here are a subset of 50 slightly different estimates for the current weather conditions that have been propagated forward in time to create 50 considerably different forecasts a few days later. Credit: ©European Centre for Medium-Range Weather Forecasts (CC BY-SA 4.0).

By Emma Hiolski

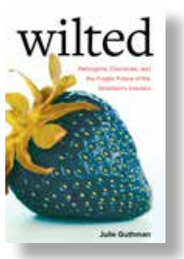



## Politics Built In

"These days talk of revolutionary change doesn't usually refer to politics," said professor of feminist studies and critical race and ethnic studies **Neda Atanasoski**. Instead, it refers to technological advances. But new technologies often embody old ideas about which jobs can be automated, Atanasoski said. Such work is devalued as boring, dirty, and repetitive—and has historically been performed by women, colonized peoples, or immigrants.

In **Surrogate Humanity: Race, Robots, and the Politics of Technological Futures**, Atanasoski and co-author Kalindi Vora, UC Davis professor of gender, sexuality, and women's studies, explore the myriad ways technology builds upon racialized and gendered ideas. Darwinian notions of race and evolution, for example, often are engineered into the artificial intelligence of social robots.

Technology cannot remedy social inequality by itself and cannot be separated from politics, said Atanasoski. "Technology is political—how it's engineered, how it's used, and how we think, or don't think, about using it."

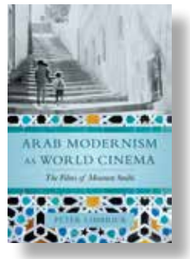



## Strawberry Woes

While studying the regulatory battle over soil fumigants used in the California strawberry industry, professor of social sciences **Julie Guthman** was struck by how deeply the use of these toxic chemicals had permeated production. "The whole system was built around the presumption of fumigation," she said.

Interviews with dozens of growers led Guthman to insights about how fumigation—which protects plants against soil-borne fungal disease—has changed from solution to problem. In her book **Wilted: Pathogens, Chemicals, and the Fragile Future of the Strawberry Industry**, Guthman explores how fumigant use created a web of reliance across numerous aspects of strawberry production.

Without fumigation, for example, growers would need to rotate crops to avoid disease, planting strawberries only once every three or four years. But no other crop could make that practice economically viable. "Land was once abundant, but now it's scarce, expensive, and diseased," said Guthman. "It's a complex story and there are no easy answers."




## Arab Cinema

American audiences are largely unfamiliar with the films of Moumen Smihi and with Arab cinema in general. **Peter Limbrick**, professor of film and digital media, hopes to change that. In **Arab Modernism as World Cinema: The Films of Moumen Smihi**, Limbrick showcases the Moroccan filmmaker's work, using it as a lens to refocus our understanding of Arab and global cinema.

"In the West, we have a pretty restricted view of film history in the Middle East and North Africa," Limbrick said. It's easy to assume most films from those regions center only on questions of politics, gender, or relationships with the West. But they also demonstrate beautiful experimentation with form, music, images, and poetry.

Such films, including Smihi's, reflect the rich history of both Arab and global cinema. "These films are multicultural, multilingual, multiethnic," said Limbrick. "I want people to recognize the diversity and possibility of Arab cinema."


## Heritage Education

When granted a rare opportunity to observe teaching practices at a brand-new, charter high school in Tucson, **Kimberly Adilia Helmer** wasn't sure what her research would focus on. But Helmer, a teaching professor in the Writing Program who studies educational and linguistic anthropology, soon recognized that the school's compulsory Spanish class was going poorly.

The students, heritage speakers of Mexican origin, responded negatively to the teaching and exercises, all designed for non-native speakers. At the same time, they thrived in their English-based humanities course, which used more authentic learning materials.

Helmer compares and contrasts these approaches in **Learning and Not Learning in the Heritage Language Classroom: Engaging Mexican-Origin Students**. A heritage Spanish speaker herself, Helmer highlights the likely benefits of designing teaching methods and practices specifically for heritage speakers and learners: "It's good for the brain, good for society, good for social justice and peace, and good for the economy."


## Cosmic Questions

"If you want to understand the established current view of fundamental physics, this is not the book for you. If you want to go on a bit of an adventure into the unknown, then it might be," said professor of physics **Anthony Aguirre**. In **Cosmological Koans: A Journey to the Heart of Physical Reality**, Aguirre adopts the Zen tradition of koan practice to explore paradoxes of physics and the cosmos.

In a series of more than 50 vignettes, Aguirre leads readers on a journey set in the early 17th century, starting in Italy and ending in Japan. Each vignette's blend of koan and physics commentary both informs readers and exposes them to deeper and more interesting questions.

Aguirre's goal is to share the experience of grappling with a variety of meaty, thorny cosmological mysteries. "This is not a book of answers," he said, "but a book of questions."


**Names are listed left to right.*

With the distinctive expertise of scientists-turned-journalists, the 16 writers shown above, all graduates of the UC Santa Cruz Science Communication Program (*scicom.ucsc.edu*), created the stories that grace these pages. Directed by editor **Dave Egerter** ('88), their reporting captures the great scope, creativity, and global reach of the research being performed across UCSC's five academic divisions.

Upgraded last year (2019) to award a master's degree, the "SciCom" program uniquely trains former scientists to use their expertise to foster the public understanding of science, health, technology, and the environment. The urgency of this mission stepped up a notch with the arrival of Covid-19. Like all UCSC instruction, the SciCom curriculum moved online. Program instructors, led by director and veteran journalist **Erika Check Hayden**, taught courses via Zoom. The nine-student class of 2020 (eight less Stanford Ph.D. immunologist **Jonathan Wosen**, hired early out of the program by the *San Diego Union-Tribune* as a biotech reporter) gained real-world experience in both their classwork and remotely-conducted internships. While working flat-out to keep up with Covid-19 developments as a reporter at *BuzzFeed*, lecturer in policy and investigative reporting **Peter Aldhous** redirected his spring-quarter class to support science reporters at the *San Jose Mercury News*. Through that collaboration, the SciCom students helped cover the pandemic's impact in the Bay Area.

The pandemic is also being professionally chronicled by many of the program's 350-plus graduates in their work for local, regional, national, and international media outlets, in newspapers, radio, television, online media, peer-reviewed journals, magazines, and university public relations. Covid-19 and near-constant attacks on the credibility of science and the news media make the accurate, engaging science journalism practiced by SciCom graduates—as exemplified by their writing herein—more important than ever.

In these abruptly trying times, we hope you stay safe and enjoy reading this year's *inquiry@UC Santa Cruz*.

Learn more: **news.ucsc.edu**