These people are ... on a mission to build a sustainable world.

chemists, biologists, geologists, ecologists, engineers ...

One day in 1903, a bout of smog darkened the skies of Los Angeles so much that many people thought a solar eclipse had occurred. For several decades to follow, smog outbreaks regularly closed schools and forced residents to don gas masks.

By mid-century, Caltech chemist Arie Haagen-Smit had discovered that ozone was the chief cause of this haze and the automobile industry a primary culprit that produced these noxious molecules. He went on to pioneer policy changes for motor vehicle pollution standards and now, while there are more cars and people in L.A. than ever, dark smog days are a thing of the past.

Water

Graduate student Andre Vyatskikh (MS '17) builds tiny light-activated devices that could be used to purify drinking water using sunlight.

Caltech researchers have long been central to sustainability research, and they are now on the cusp of new opportunity: in September 2019, philanthropists and entrepreneurs Stewart and Lynda Resnick pledged $750 million dollars to the Resnick Sustainability Institute (RSI) at Caltech to fund innovative research and education. In existence for a decade, the RSI is reenergized by this pledge.

"Addressing the challenges of climate change and the stewardship of our precious natural resources is a responsibility we all share. This historic pledge affords the Caltech community a unique opportunity to respond via bold research and educational initiatives that can have transformational societal impact," says RSI director and Bren Professor of Chemistry Jonas Peters. "As a small but remarkably impactful institution with a demonstrated capacity to solve really tough problems, we will now have resources, tools, and some of the world's brightest minds on a mission to deliver real-world solutions to society's vexing challenges in energy, climate, water, and the broader environment."

This support also has established four core research initiatives, each led by a faculty researcher: Water Resources (Mark Simons, John W. and Herberta M. Miles Professor of Geophysics and JPL Chief Scientist), Climate Science (Paul Wennberg, the R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering), Sunlight to Everything (Harry Atwater, Howard Hughes Professor of Applied Physics and Materials Science), and Ecology and Biosphere Engineering (Dianne K. Newman, Gordon M. Binder/Amgen Professor of Biology and Geobiology).

As plans take shape for these new initiatives, the RSI continues to shed light on some fundamental questions. What does it mean to create a sustainable society? Where can we improve, and where are we doing well? What questions is Caltech in particular best positioned to answer?

THE CHALLENGE:

Availability of Fresh Water

Ensuring sustainable supplies of fresh water to meet human and environmental needs, which are stressed by changes in climate, land use, and population, requires a dynamic understanding of both natural and human systems, and how they interact. Acquiring this understanding is the overarching goal of the RSI's Water Resources initiative led by Mark Simons.

"We will aim to develop new tools to accurately measure surface and underground water resources, and how these resources change over time," says Simons. "With these data we will develop a new scientific understanding of water flow as impacted by site-specific geography. This framework will inform decision-support tools and expand our knowledge of built and natural water systems. The design and engineering of new and innovative water treatment technologies is also a central element of our vision."

To that end, the RSI recently sponsored projects that have helped to create models for the interconnected surface water network, which will enable better water management in the face of climate change.

Simons also notes the importance of remote sensing as a tool for studies of water resources. Recently, using an unprecedented number of satellite radar images, Caltech geophysicists tracked how the ground in Southern California rises and falls as groundwater is pumped in and out of subsurface aquifers. The results of this research may provide water management districts with means to assess the precise shape and size of aquifers, and the impact of the region's water use on those aquifers.

Next Steps:

The group's research priorities, says Simons, are to:

- Investigate the potential of tools developed by seismologists to be used to monitor underground water
- Monitor the budget of subsurface water in aquifers with remote sensing
- Enhance understanding of groundwater interactions with surface waters to best replenish underground reservoirs and optimize their use
- Develop an integrated model of the land surface and near-surface that accounts for the role of plants, geography, climate, and hydrologic processes
- Improve treatment options for both salt and wastewater to increase fresh water supply
- Build smart nanostructured materials that can efficiently extract salt from water

THE CHALLENGE:

Climate Change

Climate

Graduate students Siraput Jongaramrungruang (MS '18) (left) and Liyin He (MS '18) (right) use satellite imaging and machine learning models to predict crop yield and measure greenhouse gas emissions, respectively.

Greenhouse gas concentrations are increasing as a result of emissions from fossil fuel extraction and use as well as those produced in nearly all aspects of society: from agriculture and air conditioning to Ziploc bags and zoning, nearly everything impacts the climate. It is hard to determine what the future holds for the levels of carbon dioxide and other greenhouse gases.

The goal of the Climate Science initiative is to answer questions about the impact of elevated temperature and carbon dioxide on the biosphere; why methane concentrations rapidly increase; and how we should respond to these changes.

"Fundamentally, we want to know what the fate of Earth is and how we can improve our predictions of that fate. Developing pathways to alter that fate is perhaps the biggest challenge we face," says Paul Wennberg. "We aim both to reduce the uncertainty around prediction and to engineer solutions to mitigate climate change."

One of the major climate science tools is remote sensing: observing and making measurements of Earth from space and on the ground. The last several decades, says Wennberg, have been revolutionary in terms of being able to observe the earth, both in situ and through remote sensing. Now, scientists can observe global changes in atmospheric composition, in the land surface, and in our oceans and polar regions. They also can monitor emissions of carbon dioxide from burned fossil fuels and leaks of methane from the natural gas infrastructure.

Next Steps:

The initiative's next priorities, says Wennberg, are to:

- Quantify the factors that drive climate change, including emissions of methane from agriculture and natural gas production, land-use changes in tropical regions, the rapidly changing arctic, and carbon dioxide emissions from growing megacities
- Develop new methods and models to improve climate change forecasts
- Develop methods to mitigate greenhouse gas emissions through the reduction of methane losses from the energy infrastructure and agriculture, and removal and burial of carbon dioxide
- Create resiliency in built and natural systems so that they can adapt to rising temperatures, floods, drought, and sea level changes

THE CHALLENGE:

Sustainable Energy

The RSI's focus on sustainable energy is based on the recognition that while coal, oil, and natural gas make up 81 percent of the United States' energy consumption, these resources are finite, and the use of fossil fuels injects massive amounts of carbon dioxide into the atmosphere, which contributes to climate change. As Harry Atwater notes, this means that the development of renewable energy from naturally replenished sources will be vital for a more sustainable future.

Perhaps the most renewable resource of all, says Atwater, is sunlight: more energy from the sun falls on the earth in one hour than is used by every person in the world over the course of a year. Photovoltaic solar energy, where photons are harnessed from the sun and converted into usable energy, offers a promising alternative to fossil fuels. While the price of oil has remained relatively steady over the decades, photovoltaic solar energy technology has become less and less expensive. "Sunlight could power everything we make and do in our world," says Atwater.

The Sunlight to Everything initiative aims to develop technological capabilities to advance zero-carbon renewable resources and reimagine industrial and manufacturing processes in an environmentally sustainable way.

Though solar power is abundant, its supply still fluctuates; when clouds block the sun, for example, no power can be created. Thus, batteries that can store excess solar-derived electricity are crucial if solar energy is to replace fossil fuels. Caltech researchers have recently

Sunlight

Graduate students Madeline Meier (left) and Jackie Dowling (right) co-taught a course on sustainability in fall 2019, where students conceived and implemented practical solutions to make the Caltech campus more sustainable.

POWERED BY PEOPLE

The RSI has supported 96 graduate students and postdoctoral scholars. These junior scientists, collectively known as the Resnick Fellows, are central to innovative research projects and creative solutions to a wide range of sustainability challenges. Already, Resnick Fellows and alumni have started a number of sustainability-focused companies.

The landmark 2019 pledge provides for an additional focus on undergraduate education. Funds from the gift will support the renovation of undergraduate chemistry laboratories and help restructure core undergraduate courses that will train generations of scientists in sustainability science.

To that end, the RSI has formed a campuswide education committee led by Professor of Chemistry Theodor Agapie (PhD '07) and Jess Adkins, Smits Family Professor of Geochemistry and Global Environmental Science. The committee will examine how best to enrich and create a focus on sustainability within all of Caltech's educational programs.

The Resnick Sustainability Resource Center, funded by the pledge, will include laboratories focused on ecology and biosphere engineering, and translational science and engineering, as well as a solar science and catalysis center, a high-performance computing center, a water and environment lab, and a remote-sensing center. The RSI center also will feature lecture and interaction spaces as well as new state-of-the-art undergraduate teaching labs. Every first-year undergraduate student will rotate through these labs in conjunction with redesigned core educational courses that incorporate sustainability science and engineering.

Biosphere Ecology

Postdoctoral scholar Kurt Dahlstrom studies the intimate relationship between bacteria and fungi in soils to demonstrate how fungi protect plants from harmful toxins. In a warming world, this work could be used to make crops more sustainable.

developed a new method to develop rechargeable batteries based on fluoride, which can last up to eight times longer than today's standard lithium-ion batteries.

Researchers at the Institute also have developed complex mathematical frameworks to map the energy grid across the nation, frameworks that will help determine when and where energy may be used most efficiently and where blackouts may occur.

Next Steps:

Atwater says the group will focus on research that will:

- Turn solar and wind energy into baseload electricity as well as fuel sources
- Use solar power to produce cheap and energy-efficient fertilizers and fuels
- Make dramatic leaps forward in battery technology and efficient electrical grids
- Utilize machine learning to find new catalysts for chemicals, energy, and materials
- Develop commercially viable solar power that can be beamed from space to Earth
- Harness microbial biomass degradation to generate biofuels

THE CHALLENGE:

A Harmonious Biosphere

Many of Earth's organisms, from microbes to plants to humans, profoundly affect important global processes, including the flux of greenhouse gases into and out of the atmosphere. Throughout Earth's history, no group of organisms has been more important in this respect than microbes; their metabolic activities have shaped the atmosphere, lithosphere, and hydrosphere over billions of years. However, in the past century, human activities have changed the earth's systems significantly.

The goal of the Ecology and Biosphere Engineering (EBE) initiative, led by Dianne Newman, is to understand how complex ecological relationships are affected by human activities and to identify means to promote more sustainable ecosystems. Specifically, the initiative will support research to advance knowledge of the distribution, abundance, and global impacts of diverse lifeforms on Earth; the physical, chemical, and biological interactions that define them; and how the control of particular organisms or communities may lead to desirable outcomes.

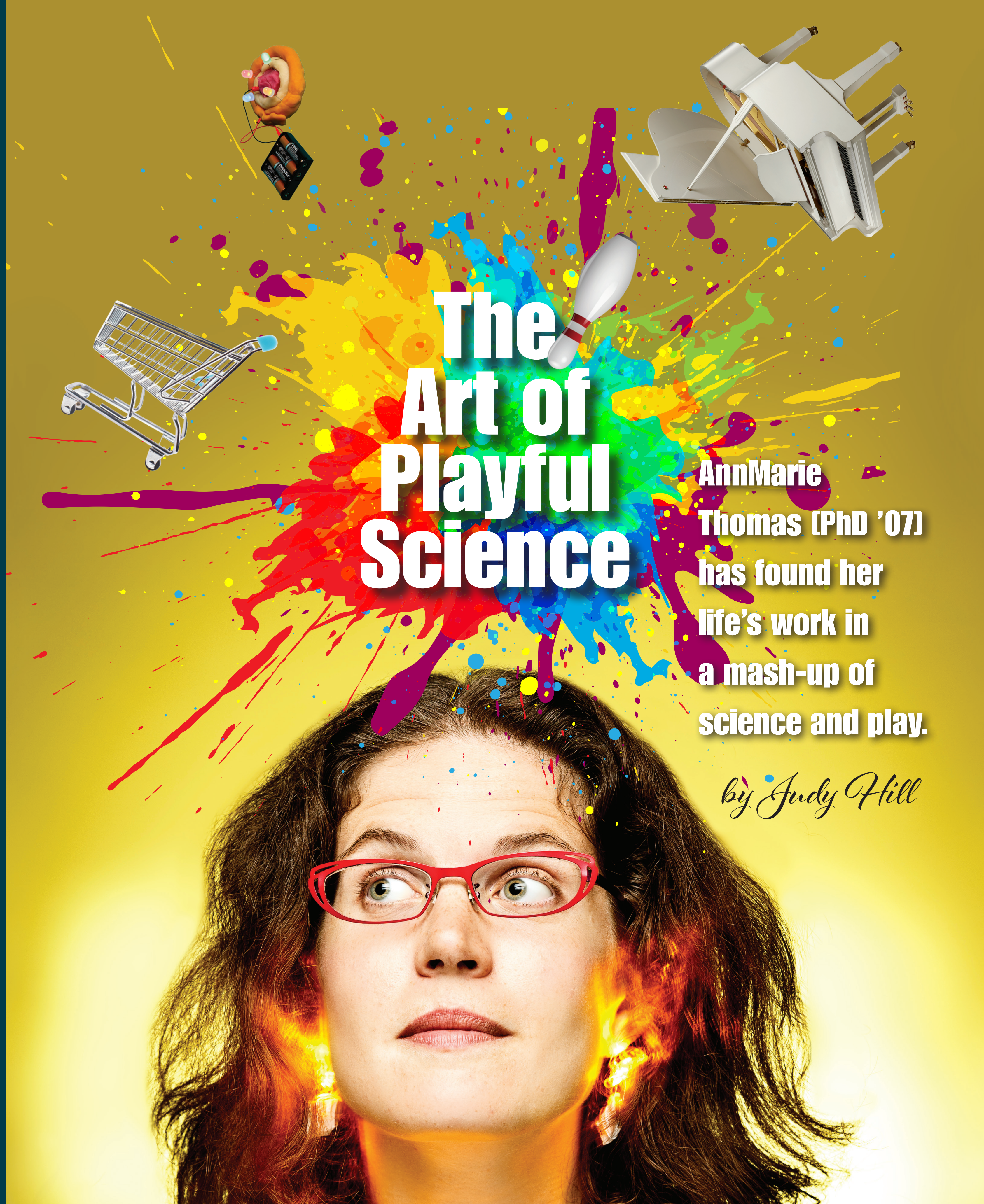
"A focus on ecology and biosphere engineering will be a new direction for Caltech," says Newman. "Though we have many interested scientists and engineers on campus, ecology is an area we have not traditionally studied."

Newman notes that Caltech's interdisciplinary Center for Environmental Microbial Interactions (CEMI) provides an example of the type of focus and collaboration that will characterize the EBE initiative. Members of CEMI, which has brought together more than 30 faculty from nearly every division since its inception in 2012, work on diverse problems that range from the control of methane by microbial communities in deep ocean sediments to the development of new tools for ultrasound imaging that harness microbial gas vesicles.

Next Steps:

Areas for initial investment, says Newman, could include research that will:

- Develop more accurate ways to monitor and/or control certain species in ecosystems
- Develop real-time sensors to monitor ecosystem changes over diverse spatial and temporal scales
- Characterize soil microbial communities that associate with particular crops or forests in order to explore ways to bolster plant resilience in the face of increased drought or floods, to maximize nutrient retention and recycling, and to protect plants from pathogens whose ranges are expanding due to climate change
- Find ways to better model the terrestrial biosphere's contribution to the global carbon cycle to minimize negative consequences associated with fertilizer production, transport, and runoff.
- Engineer novel capabilities in photosynthetic organisms to make them more efficient at energy capture
- Devise new ways to make greener plastics [C]



The Art of Playful Science

AnnMarie Thomas (PhD '07) has found her life's work in a mash-up of science and play.

by Judy Hill