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The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

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Editor’s Note

A Bridge to Public Engagement

Just over a year ago, the 50th anniversary issue of The Bridge was released.¹ Fifty years is a long time, and all that has transpired in our now technologically intense world over the past 5 decades is remarkable by any standard.

When I was a teenager, I was very impressed with Dick Tracy’s seemingly impossible two-way wrist radio! It first appeared in Chester Gould’s comic in 1946, and then as a wrist TV in 1964. I now wear a wristwatch that does everything Gould envisioned and more.

That’s but a small example of the extraordinary technical developments in our lifetimes. The 50th anniversary issue considers how engineering will evolve in the next several decades to extend its role in our social fabric. Topics span wearable technologies as well as healthy buildings, climate change, imperatives for the Web, vaccine development, quantum computing, the illusion of new technology and products that may not be envisioned today, and lessons learned to better serve society.

The issue offers a wealth of subjects for conversation and contemplation. For example, it is a trove of topics and presenters for an online science and technology forum that I host in Winchester, Massachusetts.² The forum bears the name of David Wilson (1928–2019), a retired mechanical engineering professor, colleague, and friend from MIT who founded a local S&T meeting in 2015. I gave the inaugural talk, “Unintended Consequences of Science and Technology,” at his invitation; it was videotaped and played on the town TV station. When David passed away we assigned his name, as a tribute, to the meeting as the Wilson S&T Forum. You can get a feel for what we do by looking at our website: https://jenksst.blogspot.com/. It is a completely volunteer effort.

The forum is open to anyone who is interested. You can join the meetings! We meet on the second and fourth Friday of each month. Typically 20–25 people show up—doctors, lawyers, Westinghouse and GE technologists, Apollo engineers, nuclear fusion experts, occasionally a Nobel Prize recipient (Dick Schrock), and some generalists who keep us honest! The agenda includes presentations both of local technological interest (the local water supply, for example) and on national and international issues.

We decided to make the 50th anniversary Bridge essays a guide to our discussions on a regular basis. The first such conversation, in February 2021, took up the President’s Perspective from John Anderson and the keynote essay by Sheila Jasanoff. Zoom enables us to reach out to speakers and participants from beyond our local community, so we do just that! For example, Dan Metlay addressed us from Bethesda, Maryland, Joel Myers from State College, Pennsylvania, Ali Mosleh from UCLA, and Kerry Emanuel (NAS) from MIT. We will work through the entire 50th anniversary issue. It is a timeless source of thoughtful and thought-provoking ideas for conversation and exploration.

Forum sessions and meetings are conducted with a guiding philosophy that I adopted from my late friend, Ohio State thesis advisor, and mentor, Roger Staehle. I learned a lot from Roger. Much of it has to do with corrosion, of course; but what I consider most important was his sense of humanity.

Roger was a model of the view that reasonable people can disagree but they do not have to become personally disagreeable. I recognized this in him early on, and it was reinforced when we were on opposite sides of the Westinghouse steam generator litigation in the 1990s, in which Duquesne Light and Power alleged that

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¹ It is freely accessible on the NAE website at https://www.nae.edu/244832/The-Bridge-50th-Anniversary-Issue.
² The group had been meeting in the Jenks Center in Winchester.
Westinghouse had sold them defective steam generators. As Roger and I were in court waiting for opening arguments, he approached me and said, “Ron, we have been friends for a long time; we will be friends after this ends, right?” I could not have been happier to hear this. My response was emphatically “Yes!” We had both examined the same information but come to different opinions. We disagreed, but we were not personally disagreeable. Never! This is a philosophy that I think would be useful to everyone, including our elected officials in Washington who are supposed to lead this country.

As scientists and engineers, disagreement is not an unusual part of our lives. We observe, hypothesize, debate, and disagree as a way to understand that which Nature provides and, with that understanding, to make Nature useful. But we can also put aside these debates and get together for a social evening.

I am old enough to remember when Everett Dirksen (R-IL) and Gerald Ford (R-MI) would get together (the “Ev and Jerry show”) and have civil conversations about issues that concerned the public. This was not so unusual at the time and I think the public responded in much the same way—until fairly recently, when it has become seemingly almost impossible.

Among practicing scientists and engineers, I believe there is more of a spirit of democratic values in the way we conduct our affairs. We are at a turning point in America (and maybe on this planet broadly) and reasonable people must regain the momentum to carry the day lest we fall deeper into a troubling spiral of public discord that continues to exceed public harmony. I am personally very concerned about this.

Small acts can create rippling effects. My experience over the past year with the Wilson Forum suggests that the anniversary Bridge issue could stimulate others to think about where this country is headed and begin the process of righting our course through respectful communication and learning.

I believe it is important for people and communities all over the world to have an appreciation of and willingness to understand the current context in which science, engineering, and technology serve social purposes. The anniversary issue provides a vehicle for that. And I believe it can serve that purpose for policymakers in their deliberations. I urge you to explore its contents, and hope you will find it as useful and rewarding as I have.

As always I welcome your comments at rlatanision@exponent.com.
Last October the NAE Council approved a new strategic plan for the academy, developed by a team led by our executive officer, Al Romig. It is a concise statement of the vision and mission of the NAE, building on the objectives set forth in the original charter for the NAS, signed by President Lincoln in 1863 and applied to the NAE at its founding in 1964.

The strategic plan does not directly address the question of who should be elected to the NAE, but it has important implications for the academy’s membership. In particular, notwithstanding the substantial effort expended each year in identifying, nominating, and voting on new members, the strategic plan points out that the NAE is far more than just an honorific society. The plan clearly lays out our vision:

- to be the trusted source of engineering advice for creating a healthier, more secure, and more sustainable world.

And our mission:

- to advance the welfare and prosperity of the nation by providing independent advice on matters involving engineering and technology, and by promoting a vibrant engineering profession and public appreciation of engineering.

The strategic plan further notes that our principal strength, enabling us to fulfill our mission, is our ability to call on the academy’s elected members in business, academia, and government.

It is worth noting that, not too long ago, the NAE membership overwhelmingly came from academia. This is not all that surprising given the value that individuals and institutions in academia put on recognition and awards for both promotional considerations and institutional prestige. Business has other priorities, among them protecting trade secrets, and often views the identity of its major contributors as a matter of confidentiality, in fear of poaching by competitors.

Recognizing the need to effectively reflect the US engineering profession, NAE leadership instituted incentives to achieve a better balance between new members from business and academia. These incentives have evolved over the past 2 decades as their efficacy has been examined. The net impact on our membership has been slow, but the infusion of new members from business has improved our ability to ensure that our advice reflects the many lessons learned applying engineering principles in the United States and worldwide. It should be noted that, with the increases in class size, the focus on members with a business background has not come at the expense of those in academia. This year’s class of 2022 has 42 new members elected from academic institutions, an all-time high.

The advice that the academy provides, through NRC studies and NAE programs, principally addresses areas of public policy that are influenced by engineering considerations. These are not simple matters of assessing the adequacy or correctness of engineering efforts conducted by others. They require an ability to put engineering questions in the context of public policy. In many cases, we are tasked with the need to define the problem to ensure that all relevant aspects are considered.

Questions addressing the realism, risks, likely costs, and schedule of an engineering effort must be complemented by the identification and assessment of collateral considerations, be they intended or unintended. This requires a systems engineering perspective and the ability to provide a broader, societal perspective on engineering questions. But such a perspective is difficult.

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1 The plan is available at https://www.nae.edu/File.aspx?id=261887&v=138d1d19.
to achieve if those so tasked fail to represent society at large. Furthermore, the credibility of our advice, as viewed by our clients in government and the public, is likely to be compromised if those who developed that advice come from a narrow sector of our society.

Our task is not to perform or assess engineering in a laboratory setting. It is to assess the broad implications of engineering writ large, to address public policy matters of consequence to society. Ensuring that the NAE membership can support such efforts—now and in the future—represents an important challenge.

Given the current demographics of NAE members, significant efforts are needed to identify the highly qualified engineers that will better represent all aspects of the diverse US engineering population. To that end, the council has approved incentives to motivate the NAE sections to search for and nominate membership candidates who come from underrepresented groups. It is my hope and expectation that these incentives will help the NAE maintain its objective of being a trusted advisor to the nation while motivating a diverse future generation of engineering leaders.
Guest Editor’s Note

Enhancing Engineering Approaches to Understand and Treat Women’s Health

The field of biomedical engineering has been emerging over the last few decades. While its contributions may be less visible than engineering applications in cars, trains, bridges, electrical grids, and buildings, it is no less critical. And it is rich with opportunities for development to enhance health through knowledge, diagnostics, and treatment.

Those of us involved in that field get excited every day about researching and solving problems directly related to the human body. There are many interesting areas of study and applications of engineering, whether focusing on a disease type or on specific organs.

One area that is slowly getting more attention is women’s health, particularly conditions that affect reproductive organs or female anatomy and physiology. Some of the products available to evaluate women’s health conditions were developed many years—even centuries—ago, but research and development in this area have lagged compared with other areas, and much of the attention has focused on male subjects. Fortunately, that is starting to change, although much more needs to be done.

**Government Initiatives**

Women’s health is an increasing area of focus in US government agencies, including the National Institutes of Health (NIH) and the US Food and Drug Administration (FDA).

NIH has identified health issues or conditions that are unique to women, including urinary tract health, gynecological issues and disorders, pregnancy, fertility, contraception, menopause, and osteoarthritis.1 Recently, in response to a congressional request, the NIH Office of Research on Women’s Health sponsored a Women’s Health Conference on maternal morbidity and mortality, chronic debilitating conditions, and cervical cancer.2

The FDA Center for Devices and Radiological Health (CDRH) created the Health for Women Program in 2016. It focuses on issues related to the performance of medical devices in women, improved analysis and communication of sex- and gender-specific data to ensure the safety and effectiveness of medical devices, and development and implementation of CDRH programs focusing on women’s health issues.

The CDRH Health of Women Strategic Plan (January 2022) lays out the goals of a “modern program to explore the unique issues related to the performance of medical devices in women, not only in the reproductive health space, but across a woman’s lifetime” and highlights the importance of medical devices to “optimally align with the considerations of usability and performance in women.”3 The plan outlines three priorities:

1. sex- and gender-specific analysis and reporting to improve and better understand performance of medical devices in women,
2. an integrated approach to analyze current and emerging issues related to the health of women, and
3. a research roadmap that not only considers the gaps and unmet needs of women’s health but also promotes the advancement of regulatory science in this space.

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1 See, for example, the NIH pages “What health issues or conditions affect women differently than men?” (https://www.nichd.nih.gov/health/topics/womenshealth/conditioninfo/howconditionsaffect) and “What health issues or conditions are specific to women only?” (https://www.nichd.nih.gov/health/topics/womenshealth/conditioninfo/whatconditions).
2 https://orwh.od.nih.gov/research/2021-womens-health-research-conference
Such government initiatives can inform funding and policies to advance science and engineering developments in support of women’s health.

**Industry**

Products involving the application of engineering and scientific principles to address women’s health include those for breast reconstruction, diagnostic imaging (e.g., for breast and cervical cancer), prenatal monitoring, urogynecological applications, breast pumps, and wearables, among others.

“A new term has evolved for this growing industry: “femtech,” which comprises the technologies, services, and products that address health concerns that solely, disproportionally, or differently affect women and girls.

**Organizations**

The Society for Women’s Health Research (SWHR; https://swhr.org/) was founded in 1990 to inform science, policy, and education as part of its vision to “Make women’s health mainstream.” In addition to influencing the inclusion of women in clinical trials at both NIH and FDA, SWHR creates interdisciplinary science networks for researchers, clinicians, and patients with diverse perspectives and publishes peer-reviewed articles.

The nonprofit FemTech Focus (https://femtechfocus.org/) brings together healthcare professionals, entrepreneurs, and investors, and maintains a database of companies categorized by product type and subsection.

**In This Issue**

The articles represent a small sample of engineering approaches to better understand women’s health, ways to monitor or treat conditions, and the use of data to improve the effectiveness of existing tools.

In the opening article, Alexa Baumer, Alexis Gimovsky, Michael Gallagher, and Megan Leftwich discuss an engineering framework based on synthetic analog models to study the biomechanics of pregnancy and childbirth, with an emphasis on the role of a prematurely softened cervix in preterm birth. By combining synthetic modeling with clinician input, they created material silicone synthetic models to mimic clinically relevant material properties for cervical tissue analogs and then tested these to identify failure loads of cerclage. The authors see this as a first step toward providing material information on cervical tissue that may be useful in other physical and computational models.

Jessica Walter, Shuai Xu, John A. Rogers, and Jeffrey Stringer describe the role of wearables in remote monitoring for pregnancy and the growth of digital health care due to the pandemic. They identify factors that should be considered for effective wearables in pregnancy: the suite and interpretation of measurements required to improve clinical outcomes, the spectrum of environments in which the sensors are to be used, the intended users (lay consumers, experts, or both), and an adaptable device form factor. The authors briefly survey existing and emerging remote pregnancy monitoring systems, and present their own wireless sensor system for pregnant women. There is a lot of room for development and growth in this area that incorporates the challenges of integrating data analytics, data security, real-world data, engineering design, and machine learning to ensure optimal effects on women’s pregnancy health across various settings.

Ridhi Tariyal and Stephen Gire present a novel concept using real-world data to improve female reproductive care with an accessible, objective, and precise diagnostic tool. The “menstrualome” is a discrete dataset of molecular profiles of cells from the reproductive tract acquired via tampons and informed by deep phenotypic annotation. Using sequencing technologies to determine the composition of menstrual effluence from tampon samples collected longitudinally, the authors' NextGen Jane system extracts information from gene expression of samples (along with peripheral blood samples) to determine patterns in the cell types analyzed. Their approach improves signal-to-noise to facilitate
identification of signatures of disease. The application includes a self-administered, home-based device for privacy and ease of use, and diagnosis that incorporates the patient’s medical history. The ability to collect and analyze so much real-world data could greatly benefit women’s health.

In the next article Srinivasan Vedantham and Andrew Karellas explain the role of mammography screening for early detection of breast cancer and review the evolution of breast imaging technologies to include modalities such as digital breast tomosynthesis (DBT) and dedicated breast computed tomography (BCT). One advantage of BCT is that it does not require physical compression of the breast, a demonstrated factor in women’s lack of regular screening, with implications for early detection, treatment, and mortality. The authors note that technical challenges, clinical adoption, and data analysis will play a crucial role as teams collaborate to move this technology forward.

Finally, Nicole Danos reflects on the social and ethical responsibilities of the engineering profession in supporting women’s health. In considering what hampers engineering engagement and development in this area, she observes that, among other things, basic questions are not asked or studied in a systematic way and women’s individual experiences are not acknowledged or recorded. She provides examples of engineering innovation and entrepreneurship in women’s health and well-being, and reminds us that it is important for everyone to focus on this area given the role of women in society.

**Conclusion**

I thank the authors for their insightful and valuable contributions, which provide a glimpse of the vast opportunities to apply innovative engineering and scientific approaches to increase understanding and treatment of women’s health. I hope the articles spur both new thinking and greater engagement in the possibilities for engineering application in this important area.

As was noted at the NIH Women’s Health Conference in October 2021: “Women’s health matters... not because it would be nice or good or equitable, but because we are getting it wrong and it is costing lives and health and the economy.”

A multidisciplinary approach can help identify key issues and advance understanding and treatment of women’s health.

**Acknowledgments**

The following experts helped improve the articles by offering thoughtful critiques: Nicole Danos, Mitchell Goodsit, Michele Grimm, Michael House, Kathleen O’Neill, Michelle Oyen, Ronna Popkin, Jennifer Runkle, Xiangyang Tang, and Julie Yip. I also thank my colleague Anastasia Pokutta-Paskaleva, with whom I brainstormed candidate topics and authors for this issue; Ron Latanision for inviting me to edit this issue, as he recognized this as an important subject for readers of The Bridge; and Cameron Fletcher, who was instrumental in overcoming hurdles and providing guidance to ensure the quality of the issue.

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Investigating Reproductive Biomechanics Using Physical Models

Alexa Baumer, Alexis Gimovsky, Michael Gallagher, and Megan C. Leftwich

Most research into pregnancy and childbirth has historically been done through a clinical framework, relying on large-scale statistical studies. This process makes developments in standard practices and new technologies slow to implement. To find better solutions to current challenges, an engineering framework grounded in understanding fundamental biomechanics can serve as a complementary approach.

The reproductive biomechanics field is broad, involving every aspect from implantation through delivery. The focus of the work in our laboratory is
mid- to late-stage pregnancy and birth. It is difficult and invasive to research reproductive mechanics in vivo with usual methods. Therefore, we approach the biomechanics questions with an engineering modeling perspective to add to the base of knowledge and, hopefully, the scientific foundation for women’s health.

Introduction

The cervix, at the base of the uterus, is a region of dense connective tissue between the uterus and vagina (figure 1). It has a generally cylindrical shape, with a diameter around 2.5 cm and a length between 2 and 4 cm. At each end of the cervix is an opening, referred to as the internal and external orifice (or os). Between these two openings is the endocervical canal, a narrow passageway between the uterus and vagina.

The cervix is dynamic—its mechanical properties change throughout pregnancy. In the initial part of pregnancy, the cervix remains long and closed while the fetus develops. Toward the end of pregnancy, the cervix shortens and dilates to allow for a successful delivery. In addition, the cervical tissue softens throughout this remodeling process. The exact timing and rate at which the cervical tissue softens has been difficult to quantify. However, it is generally thought that if the tissue softens too quickly, it can lead to preterm birth.

Preterm Births

Complications can arise at any point during a pregnancy and may result in preterm birth (before 37 weeks gestation). Worldwide, it is estimated that 9 to 12 percent of births are classified as preterm (Beck et al. 2010; Blencowe et al. 2013). Preterm deliveries can result in neonatal complications as well as prolonged hospital stays (Ward and Beacy 2003). To minimize the rate of incidence, understanding the causes of preterm birth is vital.

In cases of preterm birth due to premature cervical remodeling, the cervix is unable to retain the pregnancy, absent the signs and symptoms of clinical contractions, or labor, or both during the second trimester (ACOG 2014). The diagnosis is typically made between 18 and 22 weeks gestation through a combination of transvaginal ultrasound, clinical examination, and patient history (Ciavattini et al. 2016).

Lack of treatment often leads to a miscarriage, but there is no cure for the condition. In managing it, the priority is to prolong the pregnancy as much as possible. A typical treatment plan is to give a progesterone supple-
Tissue Properties and Material Selection

There are limited methods to measure properties such as stiffness under physiological loading. Excising tissues and testing them is an approach to generate information, but it is limited because of mechanical behavior changes in tissues once they are outside the body. The cervix is no exception to this multifaceted challenge. To further complicate things, the nonpregnant cervix is significantly different from the pregnant cervix and, because of the cervix’s dynamic nature, measurements taken throughout pregnancy will yield distinct values. So researchers have to be thoughtful and innovative with their methods.

Studies to quantify cervical tissue have used animal models, taken samples from hysterectomies for testing, and made measurements in vivo. Investigations of remodeling in mice cervices have revealed that collagen fiber stiffness and ground substance elastic modulus decrease throughout gestation (Yoshida et al. 2016). Human cervical tissue samples (obtained during hysterectomies) from nonpregnant patients are significantly stiffer than those from pregnant patients (Myers et al. 2008).

Another approach to quantifying the stiffness of the cervical tissue has been done in vivo by aspirating the ectocervix and measuring the closure pressure (Badir et al. 2013). In this work, measurements of cervical tissue were done before, during the pregnancy, and postpartum. The results revealed an initial period of cervical softening (approximately a 50 percent decrease from the first to second trimester) earlier in pregnancy than previously thought, followed by a stabilization and gradual decrease in softening between the second and third trimesters. All these methods have expanded knowledge of this complex tissue and provided valuable insight into ways to create a synthetic tissue to mimic the softening cervix.

Cervical softness throughout pregnancy is typically determined by physical exam. This qualitative assessment involves the physician palpating the patient’s cervix and assigning it a value of “soft, medium, or hard.” Because there are minimal data on the material properties that correspond to those terms, we decided to apply this physician method in creating our synthetic tissue.

We created ten different samples of silicone to find three matching the physicians’ assessment (figure 2). Silicone is a widespread choice for mimicking properties of biological tissue; it is highly versatile and cost effective, it can produce a range of elastic moduli, and it preserves well in laboratory settings. Once we had our ten specimens of silicone fabricated, our three physician collaborators felt each sample and determined, to the best of their ability, which sample most effectively represented each clinical group. Based on their assessments, we determined material properties for the synthetic tissues (figure 2, center and right panels).

Geometry and Physical Models

To determine cervical shape and design, we acquired transvaginal ultrasound images from routine 20-week pregnancy scans at the George Washington University Hospital. These image sets were used to extract relevant geometry, such as cervical length, tissue thickness, and whether the cervix exhibited any funneling or dilation.
Patient-specific features of each cervix were generalized into a cylinder (figure 3), at the top of which the model fans out to represent the lower portion of the uterus. For experiments, the model was 3D printed in three components: the base plate, and the exterior and interior of the model. The interior represents the cervical canal. The synthetic cervices were cast with the silicone mixtures mimicking the cervical tissue as determined by the physicians.

**Cerclage Testing**

The synthetic cervices created in our lab were stitched using materials and methods similar to those in the clinic (with a McDonald cerclage using 5 mm Mersilene tape on a tapered needle). The suture was placed at the highest point possible along the cervix, close to the section of the model that fans out. The needle moved in and out of the cervix circumferentially beginning and ending at the 12 o’clock position. The two ends of the tape were pulled tight and knotted 7 or 8 times.

In the material testing facility, an aluminum insert with a conical head was designed to fit on an MTS machine and apply force to the cerclage (the cervices were constrained in a 3D-printed capsule to minimize motion). The failure criterion was determined to be when the suture began to rip through the synthetic tissue, resulting in a drop in recorded force values from the load cell. Data are illustrated in figure 4.
Selection of Parameters

The parameter space of this problem is wide, with the geometry considerations and changing material properties. In the initial experiments, we focused solely on cervical softness (Baumer et al. 2019). We found that stiffer tissues were able to maintain the cerclage at higher forces before rupturing. In experiments since then we have tested different cervical lengths (patients experiencing premature cervical remodeling often have a shorter cervix length), cervical canal shapes (figure 5), and cerclage suture materials.

In focusing on the parameters separately, we can investigate the importance of each independent of the others. But there are still more parameters to examine. For example, there are other types of cerclage technique (e.g., the Shirodkar), which could be compared in further experiments. And parameters can be combined for a deeper understanding of the cervical physiology.

While our model cervix has been used primarily to test cerclage, it could also be used in testing protocols for future experiments with emerging technology. Another application with the simple, low-cost model could be as a training tool for medical students and residents. As the knowledge base surrounding the cervix grows, new devices and methods will be developed to treat premature cervical remodeling.

Lessons Learned and Limitations

The protocol described here to develop synthetic cervical tissue is a viable first step toward providing material information useful in other physical and computational models. For our study, we recognize that creating synthetic tissues with limited physiological data and a reliance on physician training has limitations. The qualitative, “by feel” assessment can yield different results among doctors (Badir et al. 2020), and this may affect clinical decisions. We attempted to mitigate discrepancies by using multiple physicians.

The synthetic cervix developed for our experimental testing nonetheless has several limitations. The first, and possibly most important, is that in simplifying a complex, heterogeneous tissue to a homogeneous silicone, we fail to capture certain material behavior under physiological loading.

Another limitation is the boundary conditions placed on the model. In the body, the cervix is surrounded by ligaments and tissues that transfer internal forces. By eliminating these elements and instead using solid walls, the stress distribution in the model is not analogous to the physiological reality.

Finally, soft tissues, such as the cervix, display non-linear responses, becoming more compliant through subsequent loading cycles (Myers et al. 2015). In the synthetic cervix model, the loading on the cerclage was a single cycle with a direct force increasing in magnitude within a relatively short amount of time.

Future models can be modified to capture these mechanics more fully.

Conclusion

The method described above provides a framework to study reproductive biomechanics. While, like all models, it requires some simplification of a very complex problem, it can be used when in situ experiments are not possible.

We have presented one example where a model of a cervix was designed and built to study a specific condition, the relationship between cervical soften-
ing and potential cerclage success. We also discuss modifications—lengthening the mold, changing the geometry of the cervical canal and suture material—to increase the usefulness of this model.

This type of engineering model can, and should, be used to gain fundamental insight into other aspects of reproductive biomechanics. Similar models can be constructed to explore labor and delivery: the role of maternal pelvic shape, fetal presentation, or geometry. Such models are inexpensive to produce and easily modifiable. They can be an extremely useful complement to animal models, computational work, and clinical studies to enhance understanding of reproductive biomechanics and improve the care provided to pregnant women.

References


A wearable sensor ecosystem is essential to reduce health disparities and maternal mortality.

The Future of Remote Monitoring for Pregnancy

Jessica R. Walter, Shuai Xu, Jeffrey S. Stringer, and John A. Rogers

To maintain access to health care while mitigating the risk of in-person exposure during the covid-19 pandemic, digital and mobile health care expanded as did rapid acceptance by patients, physicians, insurers, and hospital systems (Whitelaw et al. 2020). The pandemic also increased interest in the adjunct role of wearable technologies.
Wearables—devices integrated in clothing or placed directly on the body—noninvasively capture, wirelessly record, and transmit biomarkers such as heart rate, temperature, and activity. This information may complement virtual medical care by providing comprehensive patient and population-level physiological surveillance (Jeong et al. 2020). The repurposing of wrist-mounted wearables like the Apple Watch or FitBit to detect early markers of covid-19 infection exemplifies how the pandemic expanded the potential value of wearable sensors with machine learning algorithms of longitudinally collected physiological data (Hirten et al. 2021; Jeong et al. 2020; Mishra et al. 2020).

There have also been significant technological advances to more sophisticated, bio-integrated devices strategically positioned directly on the body to provide continuous, clinical-grade monitoring. The US Food and Drug Administration (FDA) has expedited the approval of numerous wearable devices under the Emergency Use Act, signaling a broadly perceived urgency and utility of these and other, emerging diagnostic tools (Whitelaw et al. 2020).

Pandemic-Related Disruptions to Maternal Care
Like many aspects of medicine, prenatal care continued but was significantly disrupted during the pandemic. Pregnant patients delayed care because of stay-at-home orders, clinic closures, and fear of presenting to hospitals. Many of the recommended 14 appointments of routine prenatal care were converted to virtual visits or eliminated entirely, and essential components of postpartum care, including depression screening and uptake of long-acting reversible contraception, declined by 50 percent and 70 percent respectively (Fryer et al. 2020; Miller et al. 2021; Sakowicz et al. 2021). At the height of the pandemic, a large New York City obstetrical practice increased video visits by 3200 percent in a single week (Zork et al. 2020).

These rapid changes occurred in the context of an already failing, overburdened maternal-fetal healthcare delivery system. In the United States maternal mortality, defined as maternal death either during pregnancy or in the 42 days following delivery, has been stubbornly and soberly persistent (Rossen et al. 2020). Around the world, more than 800 women are estimated to die each day as a result of pregnancy or childbirth.\(^2\)

Furthermore, in the United States for every woman who dies as a result of pregnancy, an additional 50 to 100 women experience severe maternal morbidity (SMM), an unexpected short- or long-term complication, injury, infection, or disability due to pregnancy or delivery (Chen et al. 2021; Grobman et al. 2014). SMM occurs disproportionately in rural, low-income areas of the United States and complicates more than 8 percent of deliveries in low- and middle-income countries (Kozhimannil et al. 2019; Say et al. 2004; Zanardi et al. 2019). Equally concerning is that these life-threatening maternal conditions double rates of adverse perinatal outcomes, such as low Apgar scores and fetal or neonatal death (Zanardi et al. 2019).

\[ \text{At the height of the pandemic, a large New York City obstetrical practice increased video visits by 3200 percent in a single week.} \]

A robust understanding of covid-19’s impact on global maternal mortality rates remains incomplete, but studies from Brazil and Peru demonstrated increases of 60 percent and 102 percent, respectively, in the maternal mortality ratio (MMR) in 2020, with only a quarter of these deaths attributed to covid-19 infections (de Carvalho-Sauer et al. 2021; Gianella et al. 2021). The authors of these papers posit that higher MMR likely reflects delayed care, inadequately managed pregnancy-related disorders, and saturated healthcare systems, rather than simply an increased susceptibility to covid-19 among pregnant patients.

Needs and Opportunities for Remote Perinatal Care
Covid-19 exposed both an opportunity and a necessity to accelerate digital medicine, of which the use of


\[ \text{\textsuperscript{2} United Nations Population Fund: Maternal health (2021), } \text{https://www.unfpa.org/maternal-health} \]
wearables is likely to be an enduring cornerstone after this pandemic subsides. Wearables may also enable cost-effective, accessible remote monitoring, particularly in resource-constrained settings or healthcare deserts both in the United States and abroad.

Pregnant patients are at a higher risk for more severe disease, hospitalization, and death compared to age-matched, noninfected counterparts (Villar et al. 2021). However, of the six wearable devices that received FDA emergency approval in the first 3 months of the pandemic, none monitored physiology during pregnancy. Furthermore, the numerous longitudinal studies leveraging preexisting consumer wearable devices like the Apple Watch or Fitbit did not explicitly address inclusion or presumptive exclusion of pregnant participants.

A one-size-fits-most approach with wearables agnostic to their underlying population of interest—such as pregnant patients—may lead to inadequate, uninformative, or, worse, inaccurate surveillance. Even more concerning, many wearables fail to capture the most relevant physiological parameters of pregnancy disorders and diseases such as covid-19.

Pregnancy is a commonplace yet complex and dynamic health state. If wearable devices are to add value in maternal and fetal medicine, the following minimum considerations should drive both function and design:

- the suite and interpretation of measurements required to improve clinical outcomes,
- the spectrum of environments where sensors are used,
- the intended users (lay consumers, experts, or both), and
- an adaptable device form factor (hardware specifications including device material, size, shape, and weight).

In this article we examine the challenges of and minimal necessary criteria for designing wearable devices to monitor pregnant patients, the state of available technologies, and innovations needed to improve care in this vulnerable population.

### Monitoring Digital Biomarkers of Pregnancy

Sensors used in pregnancy must accurately capture core biomarkers such as heart rate (maternal and fetal), blood pressure, pulse oxygenation, and core body temperature. The majority of maternal deaths are caused by hemorrhage, infection, or hypertensive disorders—and most are considered preventable (Berg et al. 2005). Abnormalities in routine vital signs often precede catastrophic complications such as massive hemorrhage (hypotension, tachycardia), eclampsia (hypertension), and sepsis (temperature, hypotension, tachycardia) (table 1). Monitoring of vital signs may identify subtle clinical deterioration earlier, providing time to escalate care and improve the likelihood of preventing morbidity or death.

<table>
<thead>
<tr>
<th>Source</th>
<th>Vital sign</th>
<th>Clinical implications or disorders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maternal</td>
<td>Blood pressure</td>
<td>Gestational hypertension, Preeclampsia, Hemorrhage, Infection</td>
</tr>
<tr>
<td></td>
<td>Heart rate</td>
<td>Infection, Hemorrhage, Amniotic fluid embolism</td>
</tr>
<tr>
<td></td>
<td>Heart rate variability</td>
<td>Stress, Autonomic nervous system dysfunction, Mood disorders</td>
</tr>
<tr>
<td>Respiratory</td>
<td>SpO2 (blood oxygen level)</td>
<td>Infection, Preeclampsia, Postpartum cardiomyopathy, Amniotic fluid embolism</td>
</tr>
<tr>
<td>Sleep quality</td>
<td>Temperature</td>
<td>Infection</td>
</tr>
<tr>
<td></td>
<td>Uterine contraction</td>
<td>Preterm birth, Infection, Labor dysfunction</td>
</tr>
<tr>
<td>Weight gain</td>
<td>Fetal ECG</td>
<td>Fetal distress, Congenital cardiac defects</td>
</tr>
<tr>
<td></td>
<td>Fetal heart rate</td>
<td>Fetal distress</td>
</tr>
</tbody>
</table>
Interpretation of biomarkers in pregnancy is not as straightforward as for nonpregnant individuals. Data should incorporate not only a patient’s baseline but also the corresponding gestational age to correctly identify abnormalities. There is normal expansion of maternal blood volume, changes in cardiac activity, and pulmonary function. Some changes are progressive over 9 months, while others are more acute; for example, cardiac output increases by nearly 80 percent immediately after delivery, but returns to baseline within 1 hour postpartum (Thornburg et al. 2000).

Vital signs during pregnancy (particularly heart rate, blood pressure, and cardiac output) are also uniquely sensitive to body position. When supine, the gravid uterus compresses the inferior vena cava, limiting venous return. Hemodynamic changes are therefore most accurately interpreted if linked to posture. A sufficiently sensitive system able to incorporate posture over a wide range of vitals with high fidelity is essential (Thornburg et al. 2000).

The nascency of rigorous, evidence-based vital sign monitoring throughout pregnancy is exemplified by a recent study providing the first modern, prospective, and gestation-specific vital sign reference ranges for pregnancy based on data rather than expert opinion alone (Green et al. 2020). Previous reference ranges were derived from small cohorts and by equipment not ratified for use in pregnancy (Green et al. 2020; MacGillivray et al. 1969; Morganti et al. 1980). Longitudinal data collection from large cohorts using wearables designed for and validated among pregnant individuals will contribute to a more thorough and scientific establishment of pregnancy-specific reference ranges.

Finally, the ideal remote monitoring system in pregnancy should capture fetal, uterine, and maternal vital signs. Only through the detection of uterine contractions, baseline fetal heart rate, and variability can fetal well-being be established and characterized. Clinical decision making in pregnancy requires balancing the well-being of both the pregnant patient and the fetus.

### Monitoring Environments

Prenatal and postpartum care occur in a wide range of high- and low-resource settings both in the United States and abroad, from homes to community clinics, tertiary care facilities, and operating rooms. The potential additive value of wearable devices does not end with delivery of the fetus. On the contrary, the pregnant patient’s health in the immediate postpartum period is too often neglected.

Half of maternal deaths occur after delivery. A pilot study of outpatient postpartum blood pressure monitoring demonstrated that patients requiring readmission had symptoms earlier and outside of the traditionally recommended window for postpartum evaluation of hypertensive disorders (Hoppe et al. 2019, 2020).

The ideal remote monitoring system in pregnancy should capture fetal, uterine, and maternal vital signs.

In addition, with the universally rising rate of cesarean deliveries, many postpartum patients are also postoperative. Vital sign monitoring must address the unique needs and higher acuity inherent to postoperative care.

Developing a wearable sensor ecosystem that seamlessly spans the physiology of and physical spaces where care occurs before, during, and after delivery, appropriate for both low- and high-acuity patient recovery, is essential to reduce health disparities and maternal mortality.

### Form Factor

Designing low-profile wearable sensors for pregnancy has particular technical challenges. Sensors are ideally small and unobtrusive, and they seamlessly stretch and flex with movement while still accurately capturing physiological data and accommodating the macrobiological changes of pregnancy. Pregnant women often remain fully active until labor begins, so wearables must accommodate daily activities while accounting for anatomical changes including edema and abdominal growth.

The dramatic physiological changes of the uterus shed light on the inherent complexity of maternal and fetal monitoring. A nonpregnant uterus is roughly the size of an adult fist. By the end of the third trimester, the uterine cavity grows more than 500 times its original size—an estimated volumetric change of 10 mL to 5 L—via reversible structural changes (Thornburg et al. 2000). Immediately after delivery of the infant and
placenta, the uterus remodels to prevent bleeding from the placental site and catastrophic maternal hemorrhage; it returns to its nonpregnant size within 4 weeks.

Though the abdomen is the locus of uterine contractions and fetal heart rate, it is not necessarily the ideal location to derive other maternal biomarkers, such as heart rate or pulse oxygenation. If wearables are to meaningfully transform prenatal care, they will require an integrated form capturing physiological data for the pregnant person, fetus, and neonate.

**Current State of Wearable Technology in Pregnancy**

Surveys of pregnant patients and their healthcare providers demonstrate high acceptance rates of non-invasive monitoring. In one study, nearly half the participants reported amenability to wearing a sensor or having one embedded in maternity clothing and 22 percent reported willingness to wear a theoretical mobile, GPS-enabled sensor to monitor fetal well-being and track environmental exposures for the duration of the pregnancy (Runkle et al. 2019). When participants were asked in what scenarios they would consider using wearables, 76 percent reported pregnancy, compared to 67 percent for personal fitness or dieting. Data security and privacy are consistently identified as potential patient concerns, but more than 90 percent felt comfortable sharing results with physicians (Runkle et al. 2019).

The real-world experience of Babyscripts™, a mobile phone application with curated educational content and linked to a Bluetooth-enabled weight scale and blood pressure cuff, demonstrated high patient use of the application and ancillary devices (sphygmomanometer and scale). Among a cohort of 1058 women with low-risk pregnancies, there were more than 45,000 at-home weight measurements (roughly, a measurement every 3½ days) collected during pregnancy and postpartum (DeNicola et al. 2018).

Patient use of wearables is only the first step toward actionable improvements in maternal and fetal health outcomes. The Pregnancy Remote Monitoring Study II (PREMOM II) is an on-going, multicenter randomized controlled trial of Belgian pregnant patients at high risk for hypertensive disorders who will be randomized to (i) conventional care, (ii) remote self-monitoring, and (iii) midwife-assisted remote monitoring. This is one of the first prospective studies to assess the clinical value of remote patient monitoring for pregnancy, with primary endpoints including maternal and neonatal outcomes, compliance, cost effectiveness, and patient-reported outcome measures (Lanssens et al. 2020).

Most applications of wearable remote technologies have adopted a piecemeal approach by targeting a specific timepoint or problem during the pregnancy—such as preterm labor, gestational weight gain, or hypertensive disorders. Piecemeal approaches, though an important stepping stone to fully integrated wearable solutions, have inherent limitations in their ability to address the full scope of maternal-fetal well-being. An integrated solution must advance the hardware of devices specifically designed for pregnancy monitoring.

**Existing and Emerging Pregnancy Monitoring Systems**

**For Remote Use**

The only 510(k) FDA-cleared device specifically indicated for remote pregnancy monitoring was developed in 2020. The INVU device created by NuvoTM consists of a semirigid belt system that wraps around the abdomen. Noninvasive sensors in the belt detect both maternal and fetal heart rate via biopotential signals and acoustic sensors. The FDA approval was awarded based on a feasibility study of 76 pregnant women who demonstrated lay user functionality. The belt detected fetal heart rate (FHR) in more than 70 percent at gestational age 20–40 weeks and 90 percent among those at 32 weeks or more. In the subsequent pivotal multicenter trial of 149 individuals, accuracy of maternal heart rate (MHR) and FHR measurements was comparable to conventional methods (Mhajna et al. 2020).

In 2021 the FDA approved a supplemental Nuvo application for uterine contraction detection based on...
extrapolated data from abdominally detected maternal ECG. The INVU belt correctly identified 90 of 96 contractions in the reference dataset from tocometry, yielding a sensitivity of 94 percent, although the false detection rate was 18 percent (Schwartz et al. 2021).

INVU’s intended use is home-based monitoring of maternal and fetal heart rate for a maximum of 5 minutes in singleton pregnancies of at least 32 weeks gestational age; it is not indicated for intrapartum use or critical care. The device’s rigidity compromises its capacity to monitor maternal vital signs in the absence of a gravid abdomen, precluding seamless extension of its use early in pregnancy or postpartum. Furthermore, neither the pilot nor pivotal study demonstrated a health benefit based on device use.

Clinical utility of devices remains unclear when studies demonstrate only safety, feasibility, or comparability with gold standard measurement techniques. Devices should not simply monitor but demonstrate a measurable patient or population health benefit.

**For Clinic-based Use**

The Novii Patch of GE Healthcare (previously Monica Health), developed in 2009, is a wireless puck placed on the gravid abdomen, using wireless ECG electrodes to detect MHR, FHR, and uterine contraction frequency. In contrast to INVU, it is marketed for hospital-based use by a healthcare provider in singleton gestations after 36 weeks. Notably, use of the device is discouraged with any maternal or fetal vital sign abnormalities, including maternal tachycardia, hypertension, fever, or abnormal FHR. Six published studies of the device in 487 women present moderate-quality evidence of monitoring equivalence in a narrow population (low-risk hospitalized patients) (e.g., Cohen et al. 2012).

The MERIDIAN M110, developed by MindChild Medical, is similar in form to the Novii Patch. It is a series of connected electrodes adherent to the abdomen that capture maternal and fetal ECG and uterine contractions. The product’s intended use is even narrower, designed for inpatient use by healthcare providers among patients in labor at 37 weeks or more.

Bloomlife repurposed an FDA-cleared ECG monitor designed for cardiac arrhythmias and marketed it directly to consumers to assess uterine contractions. But the device essentially provides only a metronome of uterine frequency without quantification of contraction strength. And without concurrent measurement of FHR, the device cannot be used to inform clinical decision making. The device is not FDA approved for uterine monitoring, but Bloomlife has collected data from over 10,000 pregnant individuals in the United States (totaling more than 500,000 hours). Bloomlife intends to use this large dataset to better understand digital biomarkers of normal labor and preterm labor. The company’s efforts also include expansion in fetal ECG monitoring.

**Flexible, Bio-Integrated Sensor Networks for Comprehensive Monitoring**

Before the covid-19 pandemic, our work in developing advanced sensor systems for pregnancy was driven by a profound unmet clinical need in maternal mortality in low- and middle-income countries, where 99 percent of maternal-related deaths occur (Geller et al. 2018). Our design decisions were based on the need to provide comprehensive, clinical-grade measurements for both maternal and fetal health while also enabling wearability, compatibility with low-cost mobile devices, and ruggedization for low-resource care settings. We recently published our first validation of a bio-integrated, low-profile wireless sensor system in more than 500 pregnant women in an urban US tertiary care hospital and a Zambian hospital (Ryu et al. 2021).

The ANNE (Advanced Neonatal Epidermal Sensor) One system consists of three time-synchronized patches (placed at the suprasternal notch, on the index finger or thumb, and on the abdomen) that capture a comprehensive set of maternal and fetal vital signs (figure 1). The wireless sensors are compatible with Android and iOS mobile devices, enabling rapid scalability without expensive capital equipment. Key components of the ANNE system for pregnancy monitoring are now FDA-cleared as a wireless patient monitor.

The ability to measure core maternal vital signs (HR, respiratory rate [RR], blood oxygenation, and temperature), fetal measurements (FHR via Doppler and fetal ECG sensors), and pregnancy-specific parameters...
(uterine contractions) enables comprehensive pregnancy monitoring. Beyond these measurements, the ANNE system detects advanced parameters such as maternal body position—integrated accelerometers provide data on hemodynamic changes linked to posture—and pulse arrival time, a surrogate for continuous blood pressure (Ryu et al. 2021). As noted above, body position is particularly relevant for monitoring maternal vital signs in pregnancy, and the capacity to continuously link it with vital signs increases accurate interpretation (Thornburg et al. 2000). The ANNE system also allows for sleep-related metrics and detection of dysfunctional breathing.

Validation in low-resource settings where maternal mortality and morbidity are highest demonstrates the system’s operability even in austere environments. The ANNE One system has been deployed in three low-income countries, at four hospital sites, with an embedded data management infrastructure monitoring more than 6500 pregnant patients, totaling more than 40,000 monitoring hours. Data output streams from the ANNE system are shown in figure 1.

**Conclusion**

Despite medical progress, the maternal mortality rate in the United States has not improved. This persistence underscores the need for new monitoring technologies for pregnancy that do more than recapitulate physiological parameters captured in the hospital setting or the home.

The complex physiology of pregnancy requires a monitoring system that captures the full spectrum of both maternal and fetal health. What’s needed is a turnkey technological ecosystem that is wireless, continuous when possible, reusable, and appropriate for all levels of care and resource settings, and that incorporates core maternal and fetal biomarkers correctly interpreted based on gestational age or postpartum status and patient posture.

At a minimum, wearables for pregnancy should accurately and continuously measure maternal health parameters (HR, RR, pulse oxygenation, blood pressure, weight gain, uterine contractility, and core body temperature) as well as FHR in a variety of environments—home, clinic, hospital, and operating room, from conception through the acute postpartum period (the 6–12 hours immediately after birth). Data management must be secure and link to existing electronic health records.

New technologies incorporating biomarkers beyond typical clinical convention may help to identify high-
risk patients, yielding opportunities to intervene and potentially improve outcomes. This may be accomplished with future machine learning algorithms that identify signals of impending deterioration earlier than clinical suspicion alone. Additional opportunities include pairing biophysical data with biochemical measurements in blood, urine, and other biofluids to better assess development of major pregnancy-related complications such as preeclampsia and preterm labor.

Finally, to substantially reduce maternal morbidity and mortality, a consortium of stakeholders—physicians, engineers, patients, and policymakers—must work collaboratively to recognize and invest in technology development for pregnancy.

References


The availability of accessible, objective, and precise diagnostics is critical for delivery of adequate female reproductive care.

The Menstrualome: Bringing Precision Medicine to Reproductive Care

Ridhi Tariyal and Stephen K. Gire

A lack of accessible, precise diagnostic tools in women’s health significantly impacts the lives of female-born individuals and hampers the delivery of care by practitioners. Available ob-gyn tools are anchored in a clinical setting, costly, and not always clearly understood by the patient. We describe an effective, simple, inexpensive, in-home tool for individual monitoring and diagnosis of reproductive health.

Challenges in Healthcare Access for Women

Diagnosis of uterine diseases such as cancer, fibroids, and endometriosis requires tools available only in clinical settings, such as magnetic resonance imaging (MRI), ultrasound, and endometrial tissue biopsy. For example, the gold standard diagnosis of endometriosis depends on laparoscopic surgery and pathological assessment of excised tissue by a skilled technician. The debilitating condition, in which uterine-like tissue attaches to other organs, affects 10–15 percent of all women, causing pain and sometimes infertility (Parasar et al. 2017).

The invasiveness and cost of a confirmatory laparoscopy lead to delays in diagnosis for individuals who are hesitant to undergo surgery or who are

Ridhi Tariyal is cofounder and CEO of NextGen Jane; Stephen Gire is cofounder and chief scientific officer.
un- or underinsured. Even the mundane bedrock of gynecological preventive care, the pap smear, involves an office visit with stirrups, a speculum, and a cervical scraping.

The compounding effect of in-office procedures, high claims burden, and required specialist skills is that access to reproductive care is cumbersome for many patients.

**Diagnostic Challenges**

**Non-Disease-Specific Symptoms**

Similarities in presentation of reproductive disorders make differential diagnosis challenging. Pelvic pain, heavy menstrual bleeding, and reduced fecundity are ubiquitous features of most uterine disorders, such as endometriosis, adenomyosis, fibroids, and endometrial cancer.

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**In-office procedures, high claims burden, and specialist skills needed mean that access to reproductive care is cumbersome for many patients.**

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Abnormal uterine bleeding (AUB), a condition where cyclic bleeding is longer than average or unpredictable, is a hallmark of endometrial hyperplasia and raises concerns of endometrial cancer. However, polycystic ovarian syndrome, fibroids, benign polyps, and even early pregnancy can present with AUB, making a patient’s decision to seek care confusing and a doctor’s approach to diagnosis challenging.

With so many possible alternatives to a shared set of symptoms, the availability of accessible, objective, and precise diagnostics becomes critical for delivery of adequate female reproductive care.

**Variability in Interpretation of Test Results**

Myriad testing modalities in gynecological practice are operator dependent and subject to variability by skill-set and interpretation by a specialist (Buchweit et al. 2005). Tests that require interpretation of imaging, such as confirmation of adenomyosis by MRI or ultrasound, are inherently subjective.

As an example, a high-risk strain of HPV (human papillomavirus) infection or an abnormal pap smear requires a colposcopy to assess cervical epithelium for precancerous or cancerous cells. But the effectiveness of the procedure is highly dependent on the experience of the operator examining the patient (Xue et al. 2020). Endometrial biopsies to assess hyperplastic lesions (rapid growth of organ tissues) for endometrial cancer often provide inadequate specimens that lead to decreased confidence in negative results (Clark et al. 2002).

Moreover, the classification of female reproductive disorders is still based on interpretation of gross anatomical features, rather than more objective, molecular-based diagnostics. While the morphology of lesions, plaques, scars, endometriomas, and deep infiltrating nodules in patients with endometriosis are used to classify different types and stages of the disease, the accuracy of these findings depends on a skilled pathologist.

Similarly, an imaging-based assessment of the uterus requires interpretation to determine the presence of pathology in the muscle wall of the uterus (myometrium) and a diagnosis of adenomyosis (Chapron et al. 2020). Substantial reliance on the identification of anatomical features of a disease leads to subjectivity and associated variability in diagnoses.

**Lack of Effective Biomarkers**

A biomarker’s sensitivity and specificity are crucial standards in assessing the effectiveness of a test.\(^1\) But circulating biomarkers (those in blood or saliva) have shown inadequate sensitivity and specificity for endometriosis to warrant clinical adoption (Nisenblat et al. 2016).

Furthermore, attempts at developing global molecular biomarkers that are not dependent on identifying known features of a disease have exhibited low specificity. CA125, a protein biomarker initially developed for the detection of ovarian cancer, shows high variability for other cancers as well (Zhang et al. 2019) and also correlates with chronic conditions such as osteoporosis (Akinwunmi et al. 2018). Thus, although elevated levels of CA125 in serum are a useful factor to augment clinical decision making, they are not a standalone solution for accurate diagnosis of cancer (Muyldermans et al. 1995).

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\(^1\) Sensitivity and specificity refer mathematically to the accuracy of a test to reveal the presence or absence of a disease.
A New Noninvasive, Self-Administered Diagnostic Tool

NextGen Jane seeks to address many of these challenges in female reproductive health by developing tools that improve access to care, minimize operator subjectivity, and provide precise, molecular profiling of disease states. We do this by creating a unique catalogue of data that we call the “menstrualome,” a discrete dataset of expansive molecular profiles of cells from the reproductive tract acquired via a tampon and informed by deep phenotypic annotation.

Noninvasive Biopsy

A critical feature of the menstrualome, and a necessary component for many precision diagnoses, is access to tissue. A tampon-based sampling system provides access to cells from the reproductive tract that would otherwise be accessed only through an invasive acquisition method. Menstrual effluence is analogous to a rich natural biopsy of diverse cell types that can be interrogated for markers of disease.

This natural biopsy is not simply a redundant source of whole blood but a unique milieu of blood, cells from the uterine lining, and local microbial organisms of the endometrium. Menstrual effluence provides a novel alternative to assay the health of the endometrium and other reproductive organs and holds promise over traditional, circulating systemic biomarkers in peripheral blood.

Database for Molecular Analysis

In our lab at NextGen Jane, we have undertaken the task of charting the menstrualome and cataloguing the rich matrix of cells that can be leveraged for molecular diagnosis. By applying next-generation sequencing technologies to better understand the composition of menstrual effluence, we can begin to understand the potential such a biospecimen offers.

With longitudinal samples collected across multiple menstrual cycles (cervicovaginal and menstrual samples collected via a tampon, and peripheral blood specimens through traditional blood draw) from the same patients, a pattern of cell composition begins to emerge. The abundance of gene expression from each sample type enables identification of cell-specific expression profiles using vast repositories of cell-specific gene signatures to identify prominent cell types in the data.

Analysis of Differences in Cell Composition

By looking at each individual cell type in the endometrium, researchers can begin to understand the unique molecular signature of both abundant and rare cells that make up this highly regenerative tissue. Study of these tissues at the single-cell level throughout the menstrual cycle can yield an accurate picture of how tissue remodels in the uterus during the four phases of the cycle (menstrual, follicular, ovulatory, and luteal), influencing reproductive outcomes from fertility to longevity.

One of the most important contributions to understanding of the uterine lining across the cyclic transformation of the endometrium is a recent single cell analysis (Wang et al. 2020). Tellingly, this mapping exercise did not generate transcriptomic data to characterize the endometrium during menstruation as it has historically been difficult to collect samples during menstruation.

Cell-specific expression profiles can be identified using vast repositories of cell-specific gene signatures to identify prominent cell types in the data.

The changing composition of cells from three sample types drives most of the differences between the samples collected during a menstrual cycle (figure 1). Cervicovaginal and menstrual samples were collected in NextGen Jane’s tampon system, and venous (peripheral) blood was collected during menstruation by traditional phlebotomy. RNA was extracted from each sample and sequenced on an Illumina shotgun sequencer. After sequence read filtering and alignment to the human genome, expression of each gene was counted based on the number of reads aligned to each transcript. Read counts were then parsed through a database of cell-specific gene signatures using the University of California, San Francisco, webtool Xcell, which has 64 unique cell types from 1822 human cell type transcriptomes.

2 https://xcell.ucsf.edu/
Each cell type was given an abundance rank based on its unique signature in the heterogeneous tissue collected, and the abundances across tissue types were compared to each other using differential expression analysis and unsupervised clustering. The results show that cervicovaginal, menstrual, and venous blood each have a unique milieu of cell types.

Both peripheral blood and cervicovaginal samples include cells integral to specific immune responses (macrophages, plasma cells, and neutrophils), suggesting a highly attuned local immune environment in the vaginal cavity. While menstrual fluid and peripheral blood share some common immune cell types (e.g., T cells, macrophages, and dendritic cells), they differ dramatically in cell composition, from uterine-specific immune cells to cells lining blood vessels and specific reproductive organs.

The rich composition of cells in menstrual and cervicovaginal samples represents tissues from various organs in the reproductive tract. During ovulation we see tissue-specific transcripts for ovarian and fallopian tube cells, while menstrual samples are enriched for tissue-specific transcripts of the endometrium. The unique composition of cells in menstrual effluence explains the potential utility of the menstrualome for diagnostic development.

By targeting specific cell types in our samples, and by timing collections to coincide with a natural enrichment of cells of interest, we can improve signal-to-noise and begin to identify signatures of disease.

**Demonstrated Diagnostic Uses of Tampons**

The utility of this sample collection method motivates the question of why a tampon-based test was not previously developed for clinical use, although both standard clinical assays and research-driven inquiry have used tampons to aid in diagnosis of specific conditions. They have served as a binary indicator of rupture of placental...
membranes during pregnancy (amnio-dye test), and an early study demonstrated the superiority of tampons as a self-administered sample collection method for testing of sexually transmitted infections in remote settings (figure 2).

In the clinic, the indigo carmine test is used to detect premature rupture of the placental membrane (Medina and Hill 2006). A blue dye is injected into the amniotic sac, and then a tampon placed in the vaginal cavity is checked every 30 minutes for the presence of the dye, which would indicate a placental rupture and the leak of amniotic fluid into the vaginal cavity.

In research, tampons were used as a novel sample collection method for the detection of gonorrhea and chlamydia in remote regions of Australia (Knox et al. 2002). Through both polymerase chain reaction analysis and culture analysis, tampons showed greater sensitivity (97.2%) in detecting the presence of these diseases compared to other methods. Reported in Knox et al. (2002).

More recently, two pivotal studies in noninvasive cancer diagnostic development showed tampons as effective methods for the collection of cervicovaginal cells (exfoliated from the cervix and uterine cavity) for the detection of ovarian and endometrial cancers (figure 3).

One study used tampons to collect samples from women preparing for surgical removal of a pelvic mass (Erickson et al. 2014). Cells from these tampons were assayed for the presence of P53 gene mutations indicative of cancer. These mutations were detected at 0.01–0.07 percent, meaning that ovarian/fallopian tube cells were present in the collection in about 1 in every 1500–10,000 cells collected. In contrast, cancer cells circulating in blood are much rarer, counting for 1–10 cells for every 10 million cells collected (Müller Bark et al. 2021).

Another study used cells collected from tampons to assess genomic changes of endometrial cancer (Sangtani et al. 2020). Epigenetic analysis of methylation sites identified the presence of cancerous cells in the tampon. A panel of three genes with differential methylation in patients with endometrial cancer showed a 92 percent sensitivity and 86 percent specificity to identify endometrial cancer.

Advantages for Reproductive Health Care

NextGen Jane’s tampon-based system aims to address the gap in sample collection and motivate a deeper
interrogation of a medically relevant but underexplored biological substrate. The system has been designed to overcome some of the natural impediments to menstrual sample collection:

- The self-administered device can be used in the privacy of an individual’s home, obviating the need for an in-clinic visit for sample collection.

- The preservation medium eliminates the cold chain, allows for long-term storage and transport of the sample in ambient temperatures, and facilitates the experience of users trying to get samples to a lab for analysis.

- In the lab, NextGen Jane has optimized processing of each unique, heterogeneous sample for various molecular pipelines, yielding terabytes of data per sample for multiple downstream analyses.

NextGen Jane also catalogues deep phenotypic data (about how DNA, environment, and behavior affect an individual’s life) to contextualize the molecular data. The power of any big data analysis in medicine is only as good as the self-reported and clinical characterization of the patient’s health state.

In addition to cataloguing clinical parameters through engagement with physicians, NextGen Jane collects in-depth self-reported health context to remedy the persistent problem of missing data in women’s health. The problem is exaggerated in scientific inquiry about female reproductive health as important questions often go unasked because of stigma, shame, or embarrassment surrounding topics such as menstruation, fertility, and pregnancy loss. Understanding and treatment of female reproductive health are thus hampered by missing data due to both a lack of answers and a lack of critical questions.

NextGen Jane attempts to improve phenotypic capture by asking these critical questions. We do this by gathering information about a patient’s experience,
their observations of their menstrual cycle, their history of disease and health care, their environment, and assessment of mental health, pain, abuse, and other factors on standardized, clinically validated metrics.

A reference range for useful parameters—length of cycle, perceived pain, amount of blood loss—will enable a standard by which anomalies of menstruation can be identified early. And patients can be empowered by understanding how their menstrual cycles compare with the typical features of the cycles of their peers matched by age, ethnicity, and birth control method.

Conclusion

An inability to effectively capture and collect menstrual samples has created a critical lacuna in the reproductive lexicon. A tampon-based test, paired with next-generation sequencing, can add resolution to the diagnosis of disease categories currently defined by similar anatomical features. With the menstrualome,

- Women can engage more accessibly and less expensively with their reproductive health.
- Practitioners will have access to both the patient context and the technology to make sophisticated diagnoses without sophisticated, invasive, or subjective tools.
- Physicians will be better able to disambiguate the symptoms of reproductive disorders without specialized procedures, leading to earlier diagnoses in more generalist settings.
- Reproductive disorders can be identified more easily and with a more useful molecular classification that may enable better, more precise therapeutic options.

The scope of impact of the menstrualome will be as expansive and deep as the scale and diversity of patients recruited and samples collected. The utility of the device is not limited to one disease or a single chapter in an individual's life. From the onset of menstruation to postmenopause, many diseases and conditions can diminish quality of life, obstruct reproductive goals, and worsen mortality rates.

For effective adoption of molecular technologies in female reproductive health, the genomic revolution that transformed oncological care over the last decade needs to be applied to precision reproductive medicine. Access to tissue local to the reproductive tract, ambitious multibiomarker class sequencing (transcriptomics, small RNA, methylation, microbiome), and integration of self-reported and clinical health data are essential to this endeavor. The ability to collect and collate this information at scale will usher in the future for women’s health.

References


Breast Cancer Screening: Opportunities and Challenges with Fully 3D Tomographic X-Ray Imaging

Mammography screening aims at early detection of breast cancer in asymptomatic women. If a patient is symptomatic, or recalled following an indeterminate or a positive screening exam for additional imaging, then this imaging exam is referred to as diagnostic workup. Mammography and ultrasound are commonly used for diagnostic workup. A group of experts convened by the International Agency for Research on Cancer concluded in 2015 that there is a net benefit for mammography screening (Lauby-Secretan et al. 2015), and randomized clinical trials have shown that mammography reduces breast cancer mortality. But challenges persist.

Background
Mammography screening has been the subject of many studies over the past 50 years, both to assess its efficacy and to understand its limitations.

One important concern is a false-positive exam. Among women aged 40–50 years who undergo annual screening, it is estimated that at least 50 percent will receive a false-positive screen and approximately 7 percent will

Dedicated breast computed tomography presents an opportunity to realize fully 3D tomographic x-ray imaging.

Srinivasan Vedantham is a professor in the Departments of Medical Imaging and Biomedical Engineering, and Andrew Karellas is a professor in the Department of Medical Imaging, both at the University of Arizona.
receive a false-positive biopsy recommendation (Hubbard et al. 2011). Another concern is that the performance of mammography is dependent on breast density. The radiation dose to the breast is reported using mean glandular dose (MGD), which apportions the dose to the “at-risk” fibroglandular breast tissue. In the United States, the Mammography Quality Standards Act (MQSA) of 1992 limits the MGD to 3 mGy (milligray) for a standard breast imaged in the craniocaudal view (from the head toward the feet). For larger compressed breast thickness, the MGD can exceed 3 mGy.

Technical advances are being explored and developed to enhance the effectiveness of breast imaging methods and reduce the incidence of false-positive results.

**Digital Mammography (DM)**

Full-field digital mammography (DM) was approved by the United States Food and Drug Administration (FDA) in 2000. This marked both the start of higher-quality digital image capture without using film and wet chemical processing, and the transition to a fully digital environment in breast imaging. It enabled ease of transmitting, storing, and retrieving mammograms. It also allowed for easy image manipulation, image processing, and computer-aided detection and diagnosis.

A key component of the DM system is the x-ray detector. There are two major types of DM detectors: indirect conversion and direct conversion (figure 1). In indirect conversion, the incident x-ray photons are converted to optical photons by a scintillator (typically thallium-doped cesium iodide as it is grown in columnar structure to reduce light spread) and these photons are detected by a photodetector, which may be an amorphous silicon flat-panel detector coupled to an active matrix, thin-film transistor array or a complementary metal oxide semiconductor (CMOS) detector. In direct conversion, the incident x-ray photons are converted to electrons by a photoconductor (typically amorphous selenium) and the electrons are read out by an active matrix, thin-film transistor array.

The results from the Digital Mammography Imaging Screening Trial (2001–05) showed that the overall diagnostic accuracy of screen-film mammography and DM were similar but that DM was more accurate in younger women, women with heterogeneously dense or extremely dense breasts, and pre- or perimenopausal women (Pisano et al. 2005).

But DM suffers from a major limitation: it represents the x-ray projection of the three-dimensional (3D) breast on a two-dimensional (2D) detector, yielding a 2D image. This causes tissue superposition in the images, which may mask lesions, resulting in missed cancers (false-negative exams), or mimic the presence of abnormalities, resulting in false-positive exams. Tissue superposition also contributes to increase in the background structure or “clutter” that makes it more challenging to detect lesions. In addition, it is well established that the sensitivity (ability to detect cancer) of mammography screening decreases with increasing breast density. The need to develop an imaging technique that reduces tissue superposition was soon recognized.

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1 In the United States, the standard breast has been modeled (since at least the 1970s) as a 4.3 cm thick compressed breast consisting of 50 percent fibroglandular and 50 percent adipose tissue. Subsequent studies have shown that the average compressed breast thickness is approximately 5.9 cm and the average composition, excluding the skin, is 14.3–17.2 percent fibroglandular tissue (Yaffe et al. 2009; Vedantham et al. 2012).
Digital Breast Tomosynthesis (DBT)

In 1997 a seminal article described digital breast tomosynthesis (DBT) using a DM system (Niklason et al. 1997). In this limited-angle tomographic approach, a series of low-dose projections of the compressed breast are acquired with the x-ray tube moving along an arc and with a stationary detector.

Technology

The initial DBT method used step-and-shoot to acquire the series of projections: the x-ray tube moved to a predetermined position, acquired the projection, and then moved to each subsequent position to acquire the projection data. Early approaches then used a shift-and-add method for image reconstruction to provide pseudo-3D representation of the breast through the generation of a series of focal plane images (slices), typically with a spacing of 1 mm, from the bottom to the top of the compressed breast. While the shift-and-add algorithm is simple to implement, it suffers from substantial artifacts, so other image reconstruction algorithms for improving the image quality were investigated (e.g., Suryanarayanan et al. 2000, 2001).

Since the FDA approved DBT for breast cancer screening in 2011, there are now at least five commercial DBT systems. Most are modifications of DM systems to incorporate x-ray tube movement, reduce vibration during movement, and collimate the x-ray beam so that it is limited to the detector. The technological implementation differs among these DBT systems in terms of the angular scan range of x-ray source movement, step-and-shoot or continuous acquisition (i.e., the x-ray tube is in continuous motion while the x-ray source is briefly pulsed for each projection), detector technology, whether the detector is stationary or angulated to partially track the motion of the x-ray tube, image acquisition geometry, image acquisition technique factors, target-filter combination, and image reconstruction methods (Sechopoulos 2013; Vedantham et al. 2015).

Figure 2 shows an illustration of two DBT systems. In figure 2A, the angular range of x-ray tube movement is small and the detector tilts to partially track the x-ray source. In figure 2B, the system has a wide angular range for x-ray tube movement and the detector is stationary.

In some systems, adjacent detector pixels are grouped (binned) during acquisition, enabling faster readout and shorter scan times. DBT’s quasi-3D imaging approach partially addresses the tissue superposition problem of single projection DM, but there is still blur in the depth direction (top to bottom of the compressed breast). Increasing the angular scan range of x-ray source movement usually reduces this blur.

In the United States, DBT is interpreted either in combination with DM, which entails an additional acquisition, or with a synthesized mammogram, which is a computer-generated mammogram using the DBT data. The DBT combined with an acquired DM is often referred to as “combo” mode.

The MGD from DBT is approximately 0.5 mGy higher than DM. When the combo mode is used, for a standard breast imaged in the craniocaudal view the MGD (2.5 mGy) roughly doubles compared to DM (1.2 mGy), although it remains less than the 3 mGy limit. For larger compressed breast thickness, the MGD can exceed 3 mGy.
Clinical Trials and Studies

Prospective clinical trials and observational studies using DBT have shown a reduction in false-positive exams. In the Oslo Tomosynthesis Screening Trial (2010–12), the false-positive recall rate declined from 10.3 percent with DM to 8.5 percent with the combo mode (Skaane et al. 2013). And a large multicenter observational study (2010–12) showed that the recall rate was reduced from 10.7 percent with DM to 9.1 percent with the combo mode (Friedewald et al. 2014).

In terms of cancer detection, both the Oslo trial and the observational study reported improvement using the combo mode compared to DM: 9.4 vs. 7.1 and 5.4 vs. 4.2, respectively, per 1000 screens. Importantly, most of the additional cancers detected by DBT were invasive cancers, which are precisely the cancers that need to be detected early to improve outcomes. The Malmö Breast Tomosynthesis Screening Trial (2010–17) also reported a reduction in interval cancers with DBT (Johnson et al. 2021).

Limitations

DBT has shown several benefits and is being rapidly adopted in clinical practice. As of January 1, 2022, 81 percent of MQSA-certified facilities have at least one DBT system and 44 percent of accredited units are DBT systems.2

However, there is a need to further understand the benefits and limitations of DBT. While it has shown improved cancer detection rate, the mortality reduction benefit of DBT over DM is yet to be demonstrated, although a simulation study (Lowry et al. 2020) using DBT instead of DM screening indicated a modest reduction in breast cancer deaths (0 to 0.21 per 1000 women). The ongoing Tomosynthesis Mammographic Imaging Screening Trial3 aims to determine whether DBT leads to earlier detection of hard-to-treat or aggressive cancers. Results from this study could enable better estimation of the mortality reduction with DBT screening.

The performance of DBT is dependent on breast density, which relates to the amount of fibroglandular tissue. Radiologists during interpretation assign breast density in four categories: almost entirely fat, scattered fibroglandular densities, heterogeneously dense, and extremely dense.4

It is well established (Boyd et al. 2007) that breast density is an independent risk factor for breast cancer: likelihood increases from the lowest to the highest density category. But while DBT showed an increase in cancer detection rate for breasts in the first three categories (4.2 to 6.1 per 1000 screens), for extremely dense breasts the cancer detection rate was essentially the same with DM and DBT (3.8 vs. 3.9 per 1000, P = 0.88). This suggests that DBT may not confer cancer detection benefit for extremely dense breasts, which are reported in approximately 10 percent of women.

Additional studies are needed to better understand the limitations of DBT in extremely dense breasts. Contrast-enhanced DM (Lewin et al. 2003) and contrast-enhanced DBT (Chen et al. 2007), wherein iodinated contrast media is intravenously administered, could be of benefit for imaging lesions in extremely dense breasts (due to neoangiogenesis-associated contrast uptake), but this is challenging to implement in routine screening.

Dedicated Breast Computed Tomography (BCT)

Dedicated breast computed tomography, commonly referred to as breast CT (BCT), is an emerging modality. It is conceptually similar to whole-body CT, but the x-ray beam from the source is limited to the breast, preventing direct irradiation of other organs.

In current implementations, the patient lies prone on a table and the breast is pendant through an aperture in the table; the center of the aperture aligns with the axis of rotation. The gantry with the x-ray source and detectors revolves around the axis of rotation and

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3 https://www.cancer.gov/about-cancer/treatment/clinical-trials/nci-supported/tmist#goals
acquires several hundred low-dose x-ray projections. The projection dataset is reconstructed to provide fully 3D tomographic images. The cross-sectional images from BCT correspond to the coronal plane.

**Early Breast CT**

The idea of dedicated BCT was envisioned in the 1970s and called CT/mammography. The first-generation systems were single-slice scanners and used 127 detector elements containing xenon gas. The pixel size of the reconstructed images was $1.56 \text{ mm} \times 1.56 \text{ mm}$ and the slice thickness was 10 mm. The images had only 256 gray levels (dynamic range of $-127$ to $128$ Hounsfield Units).

Between 1976 and 1979, 1,625 patients underwent BCT with intravenous administration of iodinated contrast media at the University of Kansas Medical Center (Chang et al. 1980). The contrast-enhanced BCT exam detected 94 percent of the 78 cancers in the cohort compared to 77 percent by mammography. But clinical adoption was stymied by the limitations of the early-stage technology, including the need for contrast administration due to the limited dynamic range, inability to visualize microcalcifications because of the limited spatial resolution, and concerns about the radiation dose (about 6 times that of mammography).

In 1996 a noncontrast study with surgical breast specimens using a conventional whole-body CT scanner showed that, compared to specimen radiography, CT performed equally or better for imaging soft tissue lesions, but visualization of microcalcifications was worse (Raptopoulos et al. 1996). In 2001 a landmark article provided estimates of MGD and used a conventional whole-body CT scanner to show that it was possible to get good-quality images at an MGD comparable to that of mammography (Boone et al. 2001).

**Motivations for Breast CT**

A recent article (Duffy et al. 2021) highlighted the importance of continuous and periodic screening: women who participated in two rounds of screening before a breast cancer diagnosis had the largest reduction in breast cancer death, and missing either of these two screens increased risk (Duffy et al. 2021). But in 2019, among women 50–74 years of age, 76.4 percent had a mammogram within the last 2 years.5

An earlier systematic review and meta-analysis showed compression-induced pain or discomfort as a major reason for women to discontinue screening (Whelihan et al. 2013). If the elimination of breast compression increases participation rate, this could improve earlier detection. A compression-free technique that increases participation rate is of societal importance.

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**There is no computed tomography technique for breast cancer screening. Dedicated BCT could address this need.**

Unlike DM and DBT, BCT does not require physical compression of the breast (and the associated discomfort). BCT also alleviates tissue superposition much better than DBT. Considering that the partial reduction in tissue superposition enabled by DBT has shown clinical benefits in terms of reduced false-positive exams and increased cancer detection rate, it is imperative to understand whether nearly complete elimination of tissue superposition further improves clinical performance.

The benefit of fully 3D tomographic imaging can be inferred from the routine use of conventional whole-body CT for imaging almost all organs and anatomical regions, as exemplified in low-dose CT for lung cancer screening (NLST Research Team 2011). However, there is no CT technique for breast cancer screening. Dedicated BCT could address this need.

**BCT Technology**

Early-generation systems used off-the-shelf technology for detectors and x-ray sources, until components better suited for BCT became available (technological aspects and engineering approaches used in several clinical prototype BCT systems and in bench-top systems emulating BCT are reviewed in Sarno et al. 2015). The early-generation systems helped in identifying challenges and solutions to them.

At the time of this writing, only one BCT system has received FDA approval. In 2015 the agency approved a cone-beam dedicated BCT system (CBCT 1000, Koning 5 National Cancer Institute Cancer Trends Progress Report, Jul 2021, https://progressreport.cancer.gov/detection/breast_cancer
Prototype systems have been or are being developed by ZumaTek Inc., Malcova LLC, and Izotropic Corporation. In the European Union two systems have received CE mark approvals: Koning’s CBCT 1000 and nu:view, a product of Advanced Breast-CT GmbH (figure 3).

Broadly, the method used for BCT data acquisition can be classified as cone-beam or multidetector (figure 4). Multidetector BCT, also called helical BCT, is similar to conventional whole-body CT.

Table 1 summarizes the technical specifications of these two commercial systems. Cone-beam BCT systems (including prototypes) use amorphous silicon indirect conversion flat-panel detectors or CMOS detectors coupled to a thallium-doped cesium iodide scintillator and are capable of scan times of 10 seconds or less. Helical BCT uses a photon-counting cadmium telluride detector, which suppresses electronic noise during image acquisition. The scan time of 7–12 seconds depends on the chest wall–to-nipple dimension of the breast. Currently both cone-beam and helical BCT systems use filtered back-projection algorithms for image reconstruction. For further information on the technical aspects of cone-beam and helical BCT, readers are referred to a topical review (Zhu et al. 2022).

Clinical Studies with BCT

BCT is used primarily for diagnostic evaluation of suspicious lesions. A multireader, multicase study (Cole et al. 2015) of noncontrast BCT for diagnostic evaluation used 18 readers interpreting 235 cases (52 negatives, 104
benign, and 79 cancers), all of which had either biopsy verification or a 1-year negative follow-up. Each reader interpreted both modalities: diagnostic mammography workup along with screening mammograms and non-contrast BCT with screening mammograms. The study found that the sensitivity of BCT was higher than that of diagnostic mammography (88 percent vs. 84 percent, \( P = 0.008 \)). Similar to whole-body CT, BCT is readily amenable to contrast-enhanced imaging with intravenously administered iodinated contrast media.

Other studies have shown that contrast-enhanced BCT improves discrimination between benign and malignant lesions (Prionas et al. 2010), detects lesions that are not visible in a standard diagnostic workup (Seifert et al. 2014), improves sensitivity (He et al. 2016), and correlates with immunohistochemical subtypes and proliferative potential (Uhlig et al. 2017). And a BCT-guided biopsy system allows biopsy of a lesion that is seen only on BCT (Wienbeck et al. 2017a).

Monitoring response to neoadjuvant therapy and predicting its treatment outcome are potential opportunities for BCT. A pilot study showed that noncontrast BCT could monitor changes in primary tumor volume (Vedantham et al. 2014). There is a need for large-scale studies using noncontrast and contrast-enhanced BCT to better understand its value.

**Needed BCT Improvements**

The most important opportunity for BCT is to translate it as a primary screening tool, potentially replacing DBT. This would require the capability to perform noncontrast breast imaging at MGD acceptable for screening, ensure sufficient posterior coverage, and be an indicator of early-stage cancer (particularly ductal carcinoma in situ).

A standard mammography screening exam comprises two views: craniocaudal and mediolateral oblique (approximately 45 degrees from the craniocaudal view). Since BCT replaces both by a single scan, 6 mGy is generally considered an acceptable limit. For an early prototype of diagnostic cone-beam BCT the median MGD was 12.6 mGy, similar to and within the range for diagnostic mammography (Vedantham et al. 2013b). Technical improvements, particularly with automatic exposure control, have reduced the radiation dose. More recent studies have reported MGD of 7.2 mGy with cone-beam BCT (Wienbeck et al. 2017b) and approximately 6.5 mGy with helical BCT for an average breast (Germann et al. 2021).

An approach called sparse-view acquisition may reduce the radiation dose by reducing the number of projections. Technical evaluations of image reconstruction algorithms based on compressed sensing (Tseng et al. 2020) and deep learning (Fu et al. 2020; Xie et al. 2020) have been reported, but clinical studies are lacking and further investigation is needed.

In addition, achieving adequate posterior coverage with BCT is important for clinical acceptance. Pectoralis muscle was included in 78 percent (107/137) of exams with an early cone-beam BCT prototype (Vedantham et al. 2012). After redesign of the cone-beam BCT, pectoralis muscle was included in 94 percent (84/89) of exams (Vedantham et al. 2013a). With helical BCT, it was included in 58 percent (341/591) of exams (Berger et al. 2020). Further improvement in

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**TABLE 1 Technical specifications of two commercial breast computed tomography (CT) systems**

<table>
<thead>
<tr>
<th>Model</th>
<th>CBCT 1000</th>
<th>nu:view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Koning Corp., USA</td>
<td>AB-CT GmbH, Germany</td>
</tr>
<tr>
<td>Approvals</td>
<td>FDA, CE mark, CFDA, &amp; several countries</td>
<td>CE mark</td>
</tr>
<tr>
<td>Acquisition method</td>
<td>Cone-beam CT</td>
<td>Helical multidetector CT</td>
</tr>
<tr>
<td>Tube voltage</td>
<td>45–60 kV</td>
<td>60 kV</td>
</tr>
<tr>
<td>Focal spot size</td>
<td>0.3 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Detector</td>
<td>CMOS detector</td>
<td>Photon-counting CdTe</td>
</tr>
<tr>
<td>Detector pixel</td>
<td>0.15 mm × 0.15 mm</td>
<td>0.1 mm × 0.1 mm</td>
</tr>
<tr>
<td>Field of view diameter</td>
<td>25 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Chest wall to nipple coverage</td>
<td>19 cm</td>
<td>16 cm</td>
</tr>
<tr>
<td>Scan time</td>
<td>≤7 seconds</td>
<td>7–12 seconds</td>
</tr>
<tr>
<td>Image reconstruction</td>
<td>Filtered back-projection</td>
<td>Filtered back-projection</td>
</tr>
<tr>
<td>Reconstructed voxel size</td>
<td>(0.2 mm)(^3) or (0.1 mm)(^3)</td>
<td>(0.15 mm)(^3)</td>
</tr>
</tbody>
</table>
posterior coverage is possible with the use of detectors with a small bezel along the chest wall.

Regarding microcalcifications, cone-beam and helical (Shim et al. 2020) BCTs resolve 0.22 mm and 0.196 mm, respectively. This exceeds the MQSA requirement of visualizing 0.32 mm calcification cluster.

**Summary**

Digital breast tomosynthesis has demonstrated benefits over digital mammography in terms of reducing false-positive results and improving lesion detection by reducing tissue superposition. However, it is a quasi-3D imaging technique.

Dedicated breast computed tomography presents an opportunity to realize fully 3D tomographic x-ray imaging. It can be a platform technology addressing needs such as risk estimation using breast density, breast cancer screening using a noncontrast exam, diagnostic evaluation, postdiagnosis extent-of-disease evaluation, monitoring and prediction of response to neoadjuvant therapy, and surgical planning.

Realizing this opportunity requires addressing challenges in a collaborative manner among radiologists, oncologists, engineers, physicists, applied mathematicians, and computational scientists, in particular for translating BCT to screening. Importantly, clinical trials are needed to evaluate the benefits and limitations of BCT for the applications discussed.

**Acknowledgments**

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**References**


It may seem puzzling that engineers have a social and ethical responsibility to improve women’s health. But although there is talk about Industry 4.0, efforts to address women’s health are not even at 1.0 yet. There is an urgent need for engineering approaches to improve women’s well-being and health. The fact that this issue of The Bridge is dedicated to this topic suggests that engineers are ready to work in this area.

**Why Is Engineering for Women’s Health Important?**

Women are half of the global population, and often the primary caregivers of the young and the elderly. Improved health outcomes for women are associated with improved life outcomes for all.¹

I offer my perspective on obstacles, what needs to be done to promote a focus on women’s health, and examples of pioneering engineers and innovators in this area. Many of the points I raise are not unique to engineering. But as a discipline devoted to using science and technology to improve lives, engineering has a unique potential to increase its impact by expanding both its knowledge of women’s health and the angles from which solutions can be pursued and developed.

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Obstacles to Engineering Contributions to Women’s Health

Questions Not Being Asked

I am a biomechanics researcher by training. For my research as a muscle physiologist interested in female athletes who become mothers, it was impossible to convince agencies to fund my work. This is because, although there is a huge gap in knowledge of muscle physiology (summarized in Bø et al. 2017), there isn’t a recognized problem to which I can point as needing solving. This lack is not because data were sought and not found but because nobody asked.

There are myriad aspects of women’s health for which there are no published studies or data.

This is true of myriad aspects of women’s health, as illustrated by the following questions—for which there are no published studies or data. For example, in the medical establishment it is common knowledge that ligaments and tendons become softer with pregnancy, but how many women experience musculoskeletal problems or injuries during pregnancy and lactation? How long does it take for these tissues to return to prepregnancy material properties? Is there a cost to the mother when performing normal activities with connective tissues that have different material properties than before? Do the changes in tissue property result in more injuries for pregnant and postpartum women? The answers to these questions are not known because they haven’t been asked in a systematic way.

Not Listening to Women

Prominent figures such as tennis player Serena Williams and five-time Olympic track and field athlete Allyson Felix have said publicly that their pregnancy and birthing experiences nearly cost them their lives because medical professionals ignored their reports of feeling unwell. If women’s reports of their health experiences are not heeded at such critical times, when their lives and those of their babies are at risk, what else is ignored and unrecorded?

Felix’s experience is particularly telling. Her sponsor (Nike) wanted to cut her pay by 70 percent when she became pregnant and included provisions for reduced compensation if her athletic performance suffered as a result of her pregnancy. Beyond the social justice aspect of this move, it was not based on any scientific data that pregnancy impairs athletic performance.

Inadequate Research and Data

A few recent studies have considered how the menstrual cycle affects athletic performance. They show that effects vary considerably among individuals such that it is not possible to establish a single rule that would apply to the majority of women (Barba-Moreno et al. 2022; Bø et al. 2017; Sims et al. 2021; Taipale-Mikkonen et al. 2021).

Personalized medicine will be key in promoting women’s health. Therefore, the commitment by engineers to engineer better medicines and advance health informatics—two of the NAE’s 14 Grand Challenges for Engineering2—will be a critical contributor to this effort. In addition, much more research is needed, taking into account a variety of demographic and other factors.

Culturally Biased Research

The Centers for Disease Control and Prevention reports that in 2019 non-Hispanic Black women died at rates 250 percent higher than White women from pregnancy-related causes (Hoyert 2021), and that the life expectancy for Black females born in 2008–18 is less than that of birth year–matched White females.3 Interestingly, Hispanic women survive motherhood at better rates and live longer than both Black and White women. What can be learned from these differences? What questions are not asked because of the absence of Black, Brown, Indigenous, and Hispanic women in studies and in decision-making positions (Gupta 2021)?

What Can Engineers Do?

Lack of attention to women’s health is a global concern. In 2020, 324,000 women died of cervical cancer, 90 percent of them in low- and middle-income coun-

2 www.engineeringchallenges.org/challenges.aspx

3 Figure 1: Life expectancy at birth, by sex and race and Hispanic origin: United States, 2008–2018 (https://www.cdc.gov/nchs/data/hus/2019/fig01-508.pdf), National Center for Health Statistics, Centers for Disease Control and Prevention
tries (Sung et al. 2021). And all over the world, women aged 24–35 are 25 percent more likely to live in poverty than men of the same age (Azcona et al. 2021). What low-cost, accessible healthcare options can be engineered for these women?

The following measures can help improve women’s health through engineering. A transdisciplinary approach will be key to the effectiveness of these efforts.

Collect Data on Women’s Health
Organizations that seek to fund the improvement of women’s health should also support the collection and dissemination of such data. They can extend their reach and effectiveness by partnering with social scientists, epidemiologists, and international organizations to apply engineering methods to track, analyze, and identify the health challenges faced by women around the world.

Academic engineering research has a particularly catalytic role to play. It can generate the background data needed for industrial innovation, identify social constraints on current engineered solutions, and train the next generation of transdisciplinary engineers. A collaborative effort between academic and clinical research will be essential in assessing the efficacy of advanced health informatics tools.

Believe the Data and Believe Women
The data on female biology and health show that the state of knowledge about women’s health is inadequate, underinformed, and biased. A conscious effort is needed to expand data collection, study it with an open mind, and allow the data to change perceptions of longstanding “knowledge”—including the idea that there is a single, homogeneous female experience.

Encourage Transdisciplinary Collaboration and Training
Transdisciplinary collaborations can blend training in engineering with training in nursing, public health, and public policy (among others). Such programs can both train the next generation of broadly aware engineers and, more importantly, help identify and describe the multiple facets of unresolved health and wellness issues faced by women.

Actively Include More Women at All Levels
Simply the presence of women is not enough. Women on engineering teams need to feel safe and supported in their experience—during pregnancy, postpartum, menstruation, menopause, or any other health condition specific to women, whether they are cisgender or transgender. One way to achieve this is to support women’s access to and success in positions of authority, to introduce new perspectives and ask questions that have been too long neglected.

Lobby for a National Institute of Women’s Health
Collection of the data required for a complete picture of the state of women’s health, ways to improve it, and differences in female and male biology needs to be a national priority and approached with the same scientific rigor as other national priorities.

Data and information about women’s health are lacking because questions haven’t been asked in a systematic way.

The National Institutes of Health is already making advances by requiring that gender be included as a biological variable in studies it funds to address the gap in understanding of female biology (since historically only male subjects have been used). A National Institute of Women’s Health would take this a step further, include trans women in its scope, and create a concerted effort to fill the historical gap with a clear goal of improving women’s health—which extends well beyond menstruation and motherhood. Women differ from men in their immunological response to infections, including covid-19 (Takahashi et al. 2020; Wehbe et al. 2021); pharmacological responses (Farkouh et al. 2020); brain neuroanatomy, function, and susceptibility to neurodegenerative diseases (Liu et al. 2020); and more (e.g., van Kessel et al. 2021).
Engineering Pioneers in Women’s Health and Wellness

In my search for studies of maternal biomechanics I have come across researchers and innovators in many areas of academia and industry who are working to reimagine a more equitable and healthier world for women. Following are selected examples (in addition to those described in this issue’s articles). Some are clearly dedicated to women’s health; others illustrate entrepreneurial innovations dedicated to women’s well-being and quality of life.

Ananya Health (https://www.ananya.health/) is building a portable medical device to treat cervical precancer in remote regions of the developing world, where over 90 percent of the women who die annually from this preventable cancer occur (Sung et al. 2021).

The laboratory of Dr. Mariana Alperin (https://alperinmlab.org/) is developing evidence-based bioengineering approaches for pelvic floor reconstruction. She is asking questions and collecting data on the biology of pelvic floor muscles throughout a woman’s life, then designing bioengineered solutions based on these data, which are currently completely lacking.

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The laboratory of Dr. Mariana Alperin (https://alperinmlab.org/) is developing evidence-based bioengineering approaches for pelvic floor reconstruction. She is asking questions and collecting data on the biology of pelvic floor muscles throughout a woman’s life, then designing bioengineered solutions based on these data, which are currently completely lacking.

Women of Wearables is a UK-based organization that supports women in wearable technology, health technology, and femtech, a term applied to technology products for women’s health (e.g., fertility solutions, period tracking apps, and sexual wellness). The involvement of more women in wearable technology is leading to the collection of data and identification of women’s health challenges that need attention. Big data approaches may lead to more solutions.

A collective of innovators, Make the Breast Pump Not Suck, applies sociological insights to the design of breastfeeding and other postpartum solutions for parents. They are especially attentive to those who traditionally face extra barriers such as women of color, women of lower socioeconomic backgrounds, and queer and trans parents. Elevating the visibility of the struggles these women face in maternity has led to crowdsourcing design solutions as well as the involvement of well-established and well-funded academic research labs.

Hologic has designed a technology to treat abnormally heavy menstrual bleeding in women who are not looking to get pregnant, and several companies offer period swimwear. Both of these technologies allow women to realistically imagine not having to sit out one quarter of their life because of menstruation.

Saysh (https://saysh.com/) is a shoe and lifestyle company founded by Allyson Felix. It designs athletic shoes for women while also empowering a collective of women “to undermine inequality with female creativity and athleticism.”

Sheertex, founded by Katherine Homuth, is a company that invented indestructible tights. Its website puts the company motivation plainly: “Humans have walked on the moon—so why did tights still break at the first sign of bad luck?”

Conclusion

Multiple factors contribute to the disparities in health care for women. But at a time when engineering has enabled self-driving cars, image recognition software, and space travel to the sun, I have faith that it can also play a role in reducing these disparities.

Resources are available for information and inspiration. These include, for example, interdisciplinary engineering programs such as the master of science in engineering for sustainability and health at my home institution; it brings together natural scientists with social scientists, clinicians, and engineers to educate the next generation of engineers. Other resources are available at Femtech Focus, Femtech Insider, and the Femtech Collective.

We all can work to improve women’s health outcomes, even those of us who already make this our life’s work.

Researchers and innovators in many areas of academia and industry are working to reimagine a more equitable and healthier world for women.

8 https://www.goodhousekeeping.com/clothing/g36801184/period-swimwear-bathing-suits/
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An Interview with . . .

Paul Drumheller,
Chemical Engineer and
Whisky Connoisseur

RON LATANISION (RML): Good afternoon, Paul. When we read of your experiences as a whisky educator and connoisseur, we decided we had to talk to you.

CAMERON FLETCHER (CHF): We got your name from Janet Hunziker—you attended one of the early Frontiers of Engineering symposia.

PAUL DRUMHELLER: Yes, I was a participant in 1997. I spent time chatting with Phil Condit, who at the time was CEO of Boeing Corporation; we talked about the corporate culture of Boeing compared to W.L. Gore & Associates. That was a nice conversation.

RML: We’re delighted to talk with you today and also to learn something about whisky. As you know from our exchange of messages, Cameron and I both have an interest in and fondness for beer, although I do have an occasional Manhattan. We’re looking forward to being educated today.

DR. DRUMHELLER: Fantastic. Since you both enjoy beer: folks who are deeply appreciative of beer are called Cicerones, just as people who are deeply appreciative of wine are called oenophiles.

Whisky actually starts life as beer. It goes through additional steps to be turned into whisky. Your beer knowledge will get us through about 50 percent of the whisky manufacturing process.

RML: That’s great. First let’s get a bit of information on your background and your activities with W.L. Gore & Associates.

DR. DRUMHELLER: My bachelor’s is from Washington State University, and my PhD is from the University of Texas at Austin.

RML: Where was home when you were growing up?

DR. DRUMHELLER: Albuquerque. With the exception of undergraduate and graduate school, I’ve lived all my life in the American Southwest—New Mexico, Arizona, Utah. But I matriculated to Washington State University, the young bird leaving the nest; I majored in chemical engineering, but also took significant classes in English composition and mathematics. Then I got my PhD in chemical engineering at the University of Texas at Austin, with an emphasis in biomaterials and how they apply to tissue engineering, biocompatibility, and molecular cell biology.

CHF: Paul, I want to back up for a moment. You said you took a significant number of classes in English composition and mathematics. How did you decide to major in engineering?

DR. DRUMHELLER: In high school I had two passions, chemistry and mathematics. I remember geometry and calculus very fondly, probably because of the instructor, who has been very influential in my life. In fact, I dedicated my PhD dissertation to him, and later forwarded it to him, wondering if he remem-
bered me. He said, ‘Absolutely, I remember you. What a wonderful gift. Thank you very much for remembering me all these years.’ It made sense to combine those two interests into a single discipline called engineering. But I felt like I needed improvement on my composition skills so I enrolled in those classes.

CHF: Do you enjoy writing?

DR. DRUMHELLER: I do. And I host a blog on whisky—whisky engineering, art, culture, and history—although I’ve been lax about updating it during Covid. It’s difficult for me to remain motivated if I’m not able to interact directly with folks, but our conversation today is going to motivate me to renew that. I have my own style; I like to be somewhat personal and use analogies and “country” stories I picked up from my mother, who grew up in rural Missouri.

RML: Your comment about a teacher who really made a difference in your life is one that we hear often, and it’s a great testimonial to teaching skills and the things that teachers instill in young people. I had the same experience, so I know what you’re talking about. I think that’s wonderful. That in itself makes for a successful beginning to an interview, in my judgment.

DR. DRUMHELLER: I can offer some additional information on that. My wife, who is an electrical engineer, is a coach for a local high school robotics team and has taken some of the girls on the team under her wing. One of the girls she mentored, over 10 years ago, was the first person in her family to attend college. She obtained a full-ride scholarship to Worcester Polytechnic, and now she’s an engineer for NASA, and she credits my wife for being that teacher and that inspiration for her. This is something that has deeply resonated with both of us.

We have funded a scholarship at Washington State University for female engineering students and female faculty in engineering and other STEM fields, to support their education and research. We try to be mentors for the next generation. That’s another passion that I hold besides whisky.

RML: I wish more people had that attitude, Paul, because I think it’s so important. You and your wife are role models, and the fact that you’ve had such impact on young people is a wonderful thing to be able to say.

DR. DRUMHELLER: Thank you. When my wife and I signed the paperwork to complete the scholarship, we both had tears in our eyes. It’s very deeply meaningful that this is our legacy.

CHF: What a rewarding way for you to contribute.

Can you tell us what followed after you finished your PhD—did you go directly to W.L. Gore?

DR. DRUMHELLER: In my work on biomaterials and molecular cell biology, in the laboratory at UT Austin under Jeff Hubbell, we were the first laboratory in the world to look at how can you modify a biomaterial surface with something bioactive—or conversely, something bioinert—to engineer a particular reaction or host response in a patient. That led to about a half-dozen patents and the foundation of a startup company called Focal, in Boston, in the early 1990s. The company exploited the bioinert formulations and materials developed at the University of Texas to try to minimize any inflammatory reaction during a surgical procedure or during implantation of a device. Focal was a darling of the biotech scene in Boston. A big chunk of its technology was developed at Hubbell’s laboratory, a small part of it by me. But Focal wasn’t able to reach its human clinical milestone, so it no longer exists.

My work on biomaterials and molecular cell biology looked at how to modify a biomaterial surface with something bioactive—or bioinert—to engineer a particular reaction in a patient.

When I got my PhD, I wasn’t certain if I wanted to enter academia or a government lab or industry. I considered the University of Michigan and Sandia National Labs, but I settled on a subsidiary of W.L. Gore called Gore Hybrid Technologies. They were developing a cell encapsulation device for treatment of type 1 diabetes. We had a partnership with a company that was a spinout from University of Texas Southwestern Medical Center, based on Chris Newgard’s work (he’s
now at Duke University Medical School). Chris and his spinout, called BetaGene, were humanizing rat cells for the Gore Hybrid Technologies cell encapsulation device, for implantation in patients to treat their type 1 diabetes.

Some of my graduate school work, modifying biomaterials to engineer specific responses, included cell encapsulation, and that experience pointed to my hiring at W.L. Gore & Associates. Also, I found their location in Flagstaff very compelling—to move from Texas to Arizona and be so near the Grand Canyon and Sedona, that was a big plus. I was familiar with this part of the country, having grown up in Albuquerque; and living next to the Grand Canyon was a wonderful personality fit for me and my wife.

RML: So you’ve been at Gore ever since?

DR. DRUMHELLER: I have not. I was with Gore Hybrid Technologies for about 7 years, then for 5 years I was a freelance consultant and an entrepreneur. Then I rejoined Gore.

RML: And what is your responsibility at Gore today?

DR. DRUMHELLER: Oh, gracious, there are so many things that I do at Gore. Gore has an interesting culture that is fairly supportive of individuals finding their sweet spot. Over the years I’ve worked as a principal investigator on drug delivery, biomaterials, tissue engineering, photochemistry, and nanotechnology, as well as new product development, project management, and intellectual property prosecution. Recently I’ve also started a role with Gore’s government and public relations team.

RML: I have to admit my understanding of Gore is from my Gore-Tex jacket, which I bought when I was a runner. I had no idea that Gore had such a broad outreach as the product lines you’ve identified. Has that always been the case?

DR. DRUMHELLER: Yes. Gore is diversified into four major divisions: Fabrics, of course, which most people know as Gore-Tex; Medical, with facilities in Flagstaff and in the Delaware-Maryland area, where the corporate headquarters are; Industrial Products—polymers and chemicals; and Electronics, whose major components are cabling and circuit boards. The company is actually a major supplier to NASA—Gore has gone to the moon, is currently on Mars, and products from our Electronics Division are floating somewhere through the solar system right now.

The company has about 10,000 employees and about $4 billion in sales; the Medical Division is about 3000 employees, with $1.5–1.8 billion in revenue.

RML: I understand that you publish in the open literature rarely, but have 300-plus patents. Is that correct?

DR. DRUMHELLER: I have 300-plus patents globally, both issued and pending; in the United States, I have 70 patents issued and pending.

Gore is a quiet company, they don’t publish very often in the scientific literature; they publish much more often in the clinical literature. Any scientific discoveries that Gore makes are held as trade secrets, or we want to patent them so that we can turn them into products. As a result, my patents read very much like a scientific peer-reviewed paper, not like a typical patent, because that’s really the only place that I can publish at Gore. So I have only a handful of peer-reviewed papers, and publish instead in the patent literature, which accounts for the number of patents I have both in the United States and globally.

RML: What’s the scope of your patents? What areas are typical?

DR. DRUMHELLER: They include new Gore-Tex types of resins—how they’re polymerized in the reactor and how you can convert them into usable medical products; they’ve also been used in applications for filter membranes in the Industrial Products Division, for example. I’ve been involved with drug delivery and drug
formulations. I’ve worked on nanotechnology, developing nanoparticles for various applications. I’ve developed coatings to decrease or increase friction. There’s a breadth of technologies on which I’ve been principal investigator.

Another role of mine is intellectual property. I’ve helped drive a lot of my own technologies through the US Patent Office alongside Gore’s IP attorneys, and those of my colleagues as well. I believe that’s probably unique at Gore, where the inventor is also a person talking to the Patent Office.

CHF: This is an extraordinary breadth of areas. Are you personally directly involved in the research and development of applications for every one of these products and areas? It’s hard to imagine how you would do that, although you clearly have a zillion of energy.

DR. DRUMHELLER: That’s a good point. I’m well upstream of the product development process. I’m an idea generator, not an optimizer or a manufacturer. I go into the lab, mix test tubes together, and come up with proofs of concept, which then are handed off to businesses that have established and competent product development individuals, who can take these discoveries and turn them into products that we sell to our physicians and patients. So I’m engaged upstream. I have in the past done some work on the manufacturing floor, but that’s not my sweet spot.

When I was at Gore Hybrid Technologies, one of the coatings that I developed was how to attach drugs onto, essentially, Gore-Tex, which we use not only in our fabrics but also in our medical products.

The chemical name of Gore-Tex is expanded polytetrafluoroethylene (ePTFE). It’s renowned for its chemical inertness. How can you attach a delicate drug onto ePTFE? I developed a coating that allows you to do exactly that. The technology was developed as part of the cell encapsulation effort, but it was also used to immobilize the blood thinner heparin on an ePTFE vascular graft. Heparin is an anticoagulant, so when it’s immobilized onto a vascular graft, which is essentially an artificial blood vessel, it prevents blood clots from forming on it as well.

RML: Is this an implantable device?

DR. DRUMHELLER: Yes; it’s under the trade name PROPATEN. I was involved in the initial proof of concepts, but not in taking the product to the manufacturing floor nor commercializing it nor getting the salespeople involved.

PROPATEN became a blockbuster in the vascular graft market. It’s been implanted in over 600,000 people. I consider that one of my biggest professional achievements—it’s saved the lives of 600,000 people.

RML: The satisfaction that comes with seeing something that was a brainchild find its way into the marketplace and successfully into human bodies must be enormous.

DR. DRUMHELLER: It is. When I joined Gore Hybrid Technologies, our mission was to develop a cell encapsulation device using engineered cells that could be implanted in diabetics. But 25 or 30 years ago, the tools necessary to engineer the cell weren’t available. Now they are, so Gore has a joint venture with a company in San Diego called ViaCyte, which has engineered cells using modern technology, and Gore has the encapsulation device, which has a large foundation from work that we did in the mid-/late 1990s. Gore and ViaCyte are currently in clinical trials, and I find that deeply gratifying, that the work we did in the mid-/late 1990s is being utilized today as a possible cure for diabetes.

I find it deeply gratifying that the work we did in the mid-/late 1990s is being utilized today as a possible cure for diabetes.

RML: That’s what engineering is all about, isn’t it? Service to society. That’s as good a demonstration as I can imagine.

CHF: Paul, how do you get involved in these very different areas?

DR. DRUMHELLER: Sometimes I see an unmet need and I’m qualified to address it. I do have a reputation of doing it and then asking for permission—and then doing it anyway no matter what the answer is. [Laughter.] Which has been positive and negative for my reputation at Gore.

If we have people already looking at something, I think, ‘What are they not looking at?’ I identify where the white space is, where I can help fill in the blanks.
And I think Gore, because of its culture, allows me to do that.

I know some individuals from Genentech, for example, and when I’ve given them the answer I just gave you, there were looks of absolute disbelief, maybe even horror, on their faces—this is something you would never be able to do at Genentech.

CHF: It sounds like you’re pretty well recognized and appreciated at Gore.

DR. DRUMHELLER: I think so. I’ve been at Gore cumulatively now coming up on 25 years. A lot of my research has led to products that are implanted in people. I have patents, and I also have breadth of experience across fields.

RML: All of what you’ve described to us is fascinating, Paul, but how does it lead you to become a whisky educator? What is it about whisky that attracted you? I understand brewing to a certain extent, having brewed beers, but my appreciation of whisky is limited to Manhattan—it’s usually mixed in something. I want to understand how you made the transition from this wonderful career as a chemical engineer and a bioengineer to this fascinating history with whisky.

DR. DRUMHELLER: Well, I was on a business trip to Europe about 10 years ago, with a couple of colleagues, and one night we went out to dinner at a small Italian restaurant with an incredibly impressive wine menu. My two colleagues, very much lovers of wine—they dedicated parts of their homes to wine cellars—were reviewing the menu and trying to out-snob each other.

I could appreciate their love of wine and that they were students of wine, and I knew that I didn’t understand wine. I knew if I liked a red wine. But these two were talking about different vintages and different grape varieties.

CHF: Don’t forget terroir.

DR. DRUMHELLER: And terroir, absolutely. Cameron, when you bring up that term terroir, that applies to whisky as well, which we’ll get to later in our tasting here. The language of beer, of wine, of whisky—they’re all dialects of the same mother tongue.

As I said, I could appreciate their love of wine. They knew wine, they studied wine, they took these deep dives. Could I love wine? I was looking for something maybe I could be a snob about as well.

When I returned to Flagstaff, I dropped by the local bookstore and went to the wine section and started looking at books—*Wine for Dummies, The Joy of Wine*—but it just wasn’t making a connection to me. One reason is that when you open a bottle of wine, you have to drink it then and there. Wine doesn’t keep once you’ve opened it. I couldn’t see myself having 50 bottles of wine, where once I open one I have to drink the entire thing.

Well, on that same bookshelf at the end was a book on whisky. I thought, ‘What about whisky? You open a bottle of whisky, it’ll still stay pretty good for several years if you store it properly. I think maybe I could do it.’

CHF: Paul, that is so random.

[Laughter.]

DR. DRUMHELLER: Not completely random, actually. My mother was a fan of Tennessee sour mash whisky. When I was growing up, I have memories of
her pouring it into a glass from a white ceramic bottle, and on special family occasions I could have some.

I had sampled some high-end whiskies at local restaurants, but my main introduction to whisky was Crown Royal or Jack Daniels. When I picked up this book that was a good 300 pages thick, it told me there’s a lot more to whisky than meets the eye. This book describes probably 250-plus individual whiskies. It discusses the terroir of whisky, and the body, the structure, the glintiness of whisky—the same terms I saw in the wine books were applying to whisky.

As is my personality, I don’t just take on a hobby or research project; I do a deep dive. With the work I’ve done at Gore, I’ve been taking a deep dive for 25 years. And with whisky, I’ve been taking a deep dive for 10 years.

I became a student of whisky. I started enlarging my library, taking classes online or in person at a whisky festival or conference, and building my own whisky collection based on advice from these books on the more obscure or more high-end or more complex whiskies. Now my collection is over 300 bottles.

I have certifications that are recognized or endorsed by the Scotch Whisky Association, the Kentucky Distillers Institute, and the Institute of Hospitality. So I have not only the passion but also some formal education.

I’m not the only one with an engineering or science degree who has found a passion in whisky. At one festival, for example, a luminary in the field with a degree in analytical chemistry is one of the most famous whisky blenders alive today, a very dapper English gentleman who always wears a tuxedo, even at work. That’s his personality. I met him at that whisky festival. He and I, again, spent about a half-hour talking about engineering applied to whisky.

At another festival, I met a distiller, also a luminary in his field, who has a PhD in chemical engineering. His focus was on distillation column design. One of my undergraduate projects was on distillation column design, so he and I, again, spent about a half-hour talking about engineering applied to whisky.

CHF: You mentioned that you have several certifications. In what?

DR. DRUMHELLER: I have certifications in Scotch, bourbon, and world whisky.

CHF: What does it mean to be certified in those three things?

DR. DRUMHELLER: I’ve taken classes where we cover the history of Scotch or the history of bourbon, some of the legalities. For example, the legal definitions of bourbon, Scotch, and Irish whisky—the three that we’ll be tasting today—are all different. I’ve also learned how to appreciate, critique, and host tastings and help organize whisky festivals.

A whisky steward, or perhaps a wine sommelier, is someone who not only has a deep knowledge and love of a particular spirit or wine but also is engaged in the hospitality industry. I’ve worked with restaurants, festivals, with liquor stores to build their whisky inventory. So I do have that engagement, although I haven’t been paid. Actually, I should correct that: I’ve been paid in kind. I have several whisky bottles that I’ve received as gifts from a restaurant or liquor store that I’ve worked with.

RML: Given that history, I know you can answer a question that has been on my mind for a long time. I grew up in rural northeast Pennsylvania. When I was a kid, we had a chicken coop. In half of it my dad raised chickens for Sunday dinners; in the other half, he had this gleaming copper still and he brewed moonshine. Until one day a carload of guys arrived at our house and walked to our chicken coop with axes and chopped it up for reasons I didn’t understand—I was only 5 or 6 years old at the time.

But I remember seeing some of the fellows that were my dad’s pals, they would go off and drink some of this
moonshine. So one day my friends and I decided to try it. We got royally sick. But I’ve always wondered what moonshine was, chemically. Is it close to wine? beer? whisky? What is moonshine?

**DR. DRUMHELLER:** Do you recall what your father used to create the wort? If he used fruit, he was making brandy. If he used corn, he was making whisky. Do you recall?

**RML:** I don’t know. But there were a lot of corn fields near us.

**DR. DRUMHELLER:** And there are a lot of rye fields as well in Pennsylvania, so he could have been using that. He was distilling moonshine, which is also called white dog, red eye, or new-make. That was whisky he was making, whisky straight off the still.

Just like with beer, you start with the grain and you allow it to germinate. Then you have to stop the germination, which you do by heating things up, or you can use smoke; the Scots like to use smoke pretty often. Then you grind the grain and soak it in a mash tun to suck out all the sugars. You then introduce those sugars to yeast and let it ferment for 2, 4, or 8 days. If you put it in a bottle now, you have beer; if you put it in a distillation column, you’ll get whisky.

**RML:** My father used to store the product that came out of the copper—it was beautiful, this stuff in ceramic jugs.

**DR. DRUMHELLER:** I’m guessing that what your father was doing was, after he made a “beer,” he put it into his still. Beer is about 8 percent alcohol, but Ron, that’s not what you drank, was it?

**RML:** No!

**DR. DRUMHELLER:** When beer is first distilled, it raises the alcohol content from 8 percent to 25 percent; additional distillation gives 75 percent, up to 85 percent. Your father was distilling probably up to 75–85 percent.

What’s being distilled is not only the alcohol but also a lot of the flavor compounds, which are called congeners or feints. Coming off your dad’s still it was probably 70, maybe even 80 percent alcohol. It had not yet been exposed to a wooden cask, which calms down the spirit through additive and subtractive chemical reactions. What you had going into that ceramic jug didn’t have any sort of aging. So you were drinking some really hot stuff.

**RML:** I wish I’d been a little older when I drank it. I think this is a good introduction to our tasting, Paul.

**CHF:** I’m going to go get two more glasses so I don’t have to do any field mixes—impromptu blends in an unrinsed glass. I’ll pick glasses that keep the bouquet. Incidentally, Paul, you mentioned beers at about 8 percent. For most people, that’s the upper ABV level; for me, it’s the baseline. Last week I was treated to a beer with 19 percent alcohol. It was so tasty—and it did wonders for my back spasm.

**DR. DRUMHELLER:** We’re looking forward then to whisky, which is 40 percent alcohol. This is a difference between whisky and beer. The yeast kill themselves once the alcohol content gets too high, and your typical brewer’s yeast can tolerate only about 8 percent alcohol before they start dying off. Some proprietary

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2 ABV is “alcohol by volume,” a term to enumerate the alcohol content (another term is “proof,” for example, which is ABV × 2).
yeasts can handle 15, 18, 19 percent before they start to die off. The 19 percent beer you had, Cameron, which was not distilled—you can’t call it beer if it’s distilled—used a proprietary yeast that can tolerate those high concentrations.

**RML:** I was looking at the tasting chart you sent us.³ What’s the origin of this? Is it used for wine and beer and whisky tasting?

**DR. DRUMHELLER:** Absolutely. It might have a slightly different structure or adjectives, but yes, this tasting chart is used for wine and beer as well as whisky. It’s also used for tea, coffee, rum, and tequila. All those different beverages have the same type of chart (or it could be in the form of a wheel, for example, rather than a two-by-four matrix). It’s to help you dissect and define what you’re experiencing.

For example, we can say that a particular whisky is sweet. What does “sweet” mean? It’s not really a term that has a firm definition. Honeysuckle is sweet, and so are saccharine, fructose, and glucose, but they all taste vastly different. So when I say something is sweet, how can I be more precise? That’s where a tasting chart helps you to organize your thoughts, impressions, and emotions.

A “woody” flavor comes from a very particular origin in the whisky process; “winey” comes from a different part of the whisky-making process, as does “floral.” “Woody” comes from the maturation process, “cereal” comes from the germination and kilning process. “Fruity” comes from how it was fermented—was it fermented in the yeast for a long time or a short time? “Sulfur” comes from how it was distilled.

Ron, you mentioned your father had copper. Well, what if you’re using a different-shaped column made of copper? How it’s distilled can affect how much sulfur is in there. This is where you can use the tasting chart and what you experience with engineering principles to reverse engineer a whisky to understand how it was made, from malting the grain to distilling the spirit all the way to aging in oak.

That’s something I also enjoy quite a bit with whisky: I can let my engineering brain come forth to not only determine what adjective I want to use for a particular note, but then I can also ask, why is that note there? What could have happened during whisky manufacturing that led to that specific note?

³ The chart is available at https://www.pinterest.com/pin/678354762594252516/.

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**CHF:** That’s good because I did want to ask, how does your engineering background inform your approach to whisky—its preparation, degustation, any of the aspects?

**DR. DRUMHELLER:** As I describe doing this reverse engineering, I’ve visited distilleries; again, I can see the unit operations that they’re using. There’s as much art as there is science in all of this.

Historically, a lot of these unit operations were given very quaint terms. For example, for the catalysis that occurs between the vapor of distillation and the copper in the copper still, back in the 1700s and early 1800s, they didn’t know about catalysis, so they called it “conversation”: The vapor was “conversing” with the copper.

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**For the catalysis between the distillation vapor and the copper still, in the 1700s they didn’t know about catalysis, so they said the vapor was “conversing” with the copper.**

Something that is very quaint is the maturation process terminology. If the white dog that your father made were put into a cask, the whisky and the cask would “speak” to each other, then after a couple of years the two “embrace” each other. Keep going for more years, they “marry” each other. Then you keep going, and that’s when the “magic happens.”

Let’s sample some whisky, shall we? We’ll begin our around-the-world tour with the Irish whisky Jameson, then come to the United States with Maker’s Mark Kentucky bourbon, and then go to Scotland with a blended Scotch, Johnnie Walker Black Label. The reason to go in that order is that Johnnie Walker Black is made with a smoky whisky, and if we started with that we wouldn’t taste anything other than smoke for the rest of the night.

Let’s each open our bottles. Jameson is whisky at 40 percent alcohol, so we’ll just take a couple of sips.

There is an art and a science to tasting whisky. There are five main elements: there’s the “color” in the glass; the aroma, which is also called the “nose”; the “palate”—
what does it taste like?; the “body”—what does it feel like on the tongue?; and finally, the “finish.”

Let’s look at the color of Jameson. To me, it’s a nice light gold. The color tells you a lot about how long it was aged. This is probably a younger whisky. In fact, this particular Jameson is 3 years old, so it hasn’t had much opportunity to absorb a lot of colorants from the barrel or to have oxidation reactions to give it a darker color.

Let’s give the glass a nice swirl, like you were swirling wine, and look at the legs that form. Wine would call those legs, but whisky calls them “cathedral windows.” So let’s look at those cathedral windows. This is the Marangoni effect that we’re seeing.

In my glass, the legs are taking a pretty long time to form. That means there’s a lot of oil compounds, as congeners. Jameson uses not only barley whisky but also grain whisky, which often has a lot of oil in it.

Now let’s move to the nose. We’re going to pretend that we’re smelling a beautiful flower but we don’t know if there’s a bee in it: approach it carefully. The reason to do that is, at 40 percent alcohol, it might numb your nose so you can’t smell anything. So we’re going to approach it carefully and take a nice deep inhalation. Also, open your mouth a little. That allows more turbulence inside the nose (here’s the engineering coming out). The turbulence inside the nose activates more of your scent receptors.

RML: This reminds me of a flower shop!

DR. DRUMHELLER: I’m picking up those floral notes as well.

Now let’s move on to the palate. Again, we’re talking 40 percent alcohol, we don’t want to numb our tongue, so take a small sip and let it warm on your tongue and coat it, get all the taste buds involved. Also, try to open up your throat because we only have five senses of taste, but we have thousands of receptors for smell, and so the palate is still largely the nose, not the tongue.

I’m tasting those floral notes, but I’m also getting some zestiness, a little tingliness. And what kind of sweet am I picking up? Maybe some nectarines or perhaps marmalade. In the “fruity” section on the chart, there’s something called barley sugar, and I think that’s a great descriptor of what I’m picking up.

Then there’s the tongue feel, which is also the body. For me, this is a fairly light tongue feel. I’m not getting a lot of coating on my tongue. Recall I mentioned that the cathedral windows indicate the oiliness. Here, those oils must be a low molecular weight oil because of how this whisky is distilled—going back to reverse engineering.

RML: I can really feel it on my tongue, unlike beer. When I drink a beer, whether I brew it or buy it, I’m initially very thirsty so I take a big gulp and I love it.

DR. DRUMHELLER: You can’t do that with straight whisky!

CHF: When you suggested taking a small sip and letting it warm a bit in the mouth, it was a little bite-y and sting-y on my tongue.

DR. DRUMHELLER: That’s called “heat.” If it has a lot of alcohol and it prickles your tongue, that’s called a “hot whisky.” That’s what you’re picking up. It has nothing to do with the temperature or spices or anything; it has to do with the reaction of your tongue to the alcohol.

CHF: You’re saying that’s called a hot whisky, which implies that there are whiskies that are not hot?

DR. DRUMHELLER: That’s correct. But it’s just perception: to me this Jameson is not a hot whisky, but to you, it is. Many of the whiskies that I drink are closer to 50 or 60 percent alcohol, so 40 percent is a much lower ABV than many of the whiskies I drink.

Let’s conclude this Irish tasting with the finish. It’s been a couple of minutes, so what are we now sensing...
on our tongue? I’m getting more of the same—the barley sugar, the florist shop.

What I notice with this Jameson is that the nose and the palate and the finish are all very similar to each other. That would be called a “balanced” whisky. That’s a reason why Jameson is as popular as it is and why it’s often used in cocktails; it’s a great mixer because you know what you’re going to get in all of those phases—the nose, the palate, and the finish.

Why don’t we move on to the next whisky?

You’ll notice with Maker’s Mark that there’s a wax seal on the bottle. Maker’s Mark has a trademark on that and has sued in the past for infringement. It kind of tickles my fancy that they’ve trademarked the drippy wax on the bottle.

Maker’s Mark is a bourbon and is made in the United States from at least 51 percent corn. Bourbon can have other grains in it as well, such as wheat, and it also has barley because barley contains the enzymes necessary to turn the germinated grain into sugars from the starch in the grain seed.

Maker’s Mark has an interesting history. The founder is the Samuels family, and Grandma Samuels had a wonderful baked bread recipe, which is what’s used in this whisky. So this is whisky that didn’t originally come from a beer recipe, it came from Grandma Samuels’ bread recipe using corn, barley, yeast, and wheat, and it was modified by the founders of Maker’s Mark into a bourbon.

Let’s go through the tasting exercise again. First let’s look at the color. Maker’s Mark is a little darker than the Jameson. I might call this tawny, maybe auburn. That color comes exclusively from the cask. Bourbon, by law, must be placed in a brand new oak container or barrel.

Maker’s Mark is aged about 6 years. Actually, they could age this for a tenth of a second and still call it bourbon. But with the additional aging, you get more complexity—you lose a lot of the really harsh notes in what your father was distilling, Ron.

I can really smell the oiliness on the nose here. I’m also getting candy corn.

RML: When I first poured this, it smelled really musty. As I’m swirling it, it seems less so. Is that possible, or am I imagining it?

DR. DRUMHELLER: Absolutely. Just like with wine, whisky breathes. It could also be that a lot of those notes were the first ones to volatilize, and now they’ve escaped the glass over time, so you’re not sensing them as much.

Going back to reverse engineering, it seems to me that the oils I detect in this whisky must be a low molecular weight because of how this whisky is distilled.

This bourbon is going to taste very different from the Jameson because it has corn. I’m getting candy corn, but I’m also picking up molasses and maybe prunes as well. For the body, this is very coating on my tongue. It has a butteriness to it. Cameron, this is 45 percent alcohol, 5 percent more than the Irish, so it’s going to be even more heat.

RML: I was going to say, I sense more of a buttery feel. This doesn’t bite or tingle as much as the Jameson.

CHF: That’s true for me too.

DR. DRUMHELLER: The Jameson that we had has a lot of grain alcohol, which is known to have that fizzy sensation on the tongue.

CHF: On the flavor, I get a hint of nail polish remover.

DR. DRUMHELLER: That actually is one of my favorite notes. I love whiskies that have that note.

CHF: There’s something kind of chemical in there; I haven’t put my finger on it. I’ve been scanning the chart….

DR. DRUMHELLER: There are 239 adjectives on our tasting chart, which is pretty impressive. I crafted my own tasting wheel with close to 400 adjectives, and the structure of the wheel allows me to identify other aspects of a whisky. But 239 is already overwhelming.
Now we can contemplate the finish. I'm starting to pick up some cracked black pepper, maybe some red wine, certainly some astringency. Just like with some red wines, that astringency, to me, kind of dries out the tongue.

**RML:** I imagine if you’re doing this with a group of people, you get all kinds of reactions, don’t you?

**DR. DRUMHELLER:** The largest group of people that I’ve hosted for a tasting is probably about 70. I was the tutor for a whisky class at a state fair a few years ago. Over the course of that weekend, we served about 600 drams of whisky.

Let’s clear our palate with a little drink of water, swish it in your mouth to try to clear out as much of the Maker’s Mark as possible, and we’ll move on to the Johnnie Walker Black.

Johnnie Walker is a blended Scotch whisky, in contrast to the Maker’s Mark. Everything that Maker’s Mark puts into its bottle came from themselves; in contrast, Johnnie Walker buys Scotch from all over Scotland and blends them together to produce a particular taste profile. There are 70 possible different whiskies in this bottle. The reason there are so many is that, as I mentioned, whisky is as much art as it is science, and, even coming from the same distillery, what comes out of one barrel could taste totally different from what comes out of a different barrel.

How do you ensure that the Johnnie Walker Black you’re tasting now tastes like it did 5 years ago, and will taste like this 5 years from now? The blender chooses from a menagerie of different Scotches and blends them such that the final product has the same general nose and the same general palate, the same general finish from batch to batch, year after year.

You also notice on this label that it’s got an age statement: “aged 12 years.” That’s the age of the youngest whisky in here. That means there’s probably some 15-year-old whisky, some 20-year-old whisky, there might even be some 30-year-old whisky—not very much, just enough to give the flavor profile that Johnnie Walker wants to maintain in the Black label.

The history here is that Johnnie Walker was a grocer in Scotland, and also a tea blender. He used his tea blending knowledge in the 1800s to start blending whisky for his customers. His son invented the square bottle so they could pack more whisky bottles on the shelf.

**CHF:** Very clever. What distinguishes the Johnnie Walker Red, Black, Blue, Green?

**DR. DRUMHELLER:** There used to be a Johnnie Walker White and a Johnnie Walker Platinum too. They’re just different expressions. Johnnie Walker Red is the budget expression, focusing more of the ground cinnamon, kind of a woody note. Johnnie Walker Black and Double Black get more of the smoky peatiness—black smoke, hence black label. The different colors go up in perceived quality and in price, all the way up to Johnnie Walker Blue, their top of the line. It’s a very soft creamy whisky, with very little peatiness but an amazing mouth feel.

**RML:** Why are Scotch whiskies blended?

**DR. DRUMHELLER:** Not all Scotch whiskies are. You’ve heard the term “single malt.” “Single” is not actually a descriptor of the malt, it means that it comes from a single distillery. “Malt” means that the whisky was made with 100 percent malted barley: there’s nothing else in it—no corn, no wheat.

A blended Scotch whisky doesn’t have the word “single” or “malt” on the label. That means it uses single malt whiskies as well as other whiskies that may have been made from corn or wheat, which are called grain whisky. Corn grain whisky is made totally differently than corn bourbon.

**RML:** One of my friends is very fond of Glenlivet. Is that a single malt?

**DR. DRUMHELLER:** Yes. You can even have bottles that come from a single cask. Glenlivet has its own single malts that they marry and put in a bottle, but they also have single casks. I have several Glenlivets in my collection.

**RML:** This one seems to me very sulfurous, like sulfur dioxide or hydrogen sulfur.

**DR. DRUMHELLER:** That’s intentional. They want to capture that smokiness, that sulfur note, and so it’s purposely placed in there. I like Johnnie Walker Black quite a bit; it’s one of my go-to whiskies, so I’m glad you recommended it.

**CHF:** Just what I happened to have on hand. I find this very sweet on the nose—like candy, it smells that sweet to me.

**DR. DRUMHELLER:** Absolutely, Cameron, I’m getting something I might even say is cotton candy—maybe cotton candy that got too close to the campfire. That sweetness is from the barley used during the mashing and fermentation.
RML: I think it’s the smoothest of what we’ve tried. Maybe because it’s the third.

DR. DRUMHELLER: It could also be because it’s a blended Scotch whisky. With the blended Scotch, you have so many different single malts that you’re mixing together, you can try to get that mouth feel, and the grain whisky used in Johnnie Walker Black helps to tie all the notes together for this nice smooth characteristic. Johnnie Walker Black has a kind of creaminess to it as well. It’s around $35–$40 for a bottle, and I think is very pleasant for what it is.

CHF: On the finish, I’m getting a lot of peaty smokiness lingering.

DR. DRUMHELLER: Can you tell what kind of smoke you might be experiencing here?

CHF: Really, I’m thinking along the lines of the peat. I see Lapsang Souchong on the list and that might fit.

RML: This does remind me of tea, I agree. I don’t know what kind, but it does feel like I’m drinking a strong tea.

DR. DRUMHELLER: Peat is used in the kilning process. You germinate the grain, then you have to dry it out. This is done with beer as well.

You have to dry out the grain before you do the extraction to create the mash. Peat is sometimes used for this, especially in the part of Scotland called Islay, because there aren’t any trees there, but there are a lot of peat bogs. Peat burns with a really heavy cold smoke. It has all kinds of guaiacols and tannins and phenols. When you dry out the grain, those phenols and guaiacols survive all the way through the manufacturing process to wind up in the bottle sitting before you. I like to think about the journey of these particular flavors—from 5000 years ago in a peat bog somewhere in Scotland to what I’m now sensing on my tongue thousands of years later.

In a guided tasting we all have our own reactions, but I find that I can really go deep into a whisky and pull out all these notes and have an amazing appreciation that I wasn’t able to have simply sampling my mother’s Tennessee whisky—or, Ron, certainly with the white dog that your father was making.

My appreciation for going deep also extends to beer, for example. Cameron, I have to admit, I’m not an IPA aficionado. I’ve had some imperial IPAs or some black IPAs that I’m okay with. But what I really can appreciate is the structure of a beer. Even if I don’t like it, is it a good beer on its own merits? I can do that even with whiskies that I don’t particularly like: is it still a good whisky, or is it just a terrible whisky?

Having the certifications, doing guided tastings, taking classes in dessert/whisky pairings, in food/whisky pairings—all this has allowed me to dive deeply into whisky and also to bring in my engineering and apply that to whisky.

RML: Well, Paul, I have to tell you, this has been a real treat for me.

CHF: And for me.

DR. DRUMHELLER: I’ve enjoyed it as well.

RML: If you get back to offering tastings, send me a note.

DR. DRUMHELLER: Absolutely. I can talk whisky all day, and I have before! I’d be delighted to have some additional tastings.

There’s something else I want to share with you. I mentioned at the beginning of our conversation that it was important that I live in northern Arizona, and having a meaningful career has been very important to me.

There’s a personal hero of sorts, a fellow by the name of Everett Ruess. Back in the 1930s he was a vagabond, he wandered the mountains and deserts and slot canyons of the American southwest. He kept a diary, and he wrote poetry. Well, he suddenly disappeared without a trace, and about 3 months later his mules were found wandering, starving, in the Utah desert. It’s still a mystery to this day: what happened to Everett Ruess?

In the last letter he wrote is a quote that I find very inspirational. He wrote: “I have not tired of the wilderness. It is enough that I am surrounded by beauty. I have left no strange or delightful thing undone I’ve wanted to do.”

If I were to give a message to your readers, it’s don’t leave those strange or delightful things undone.

CHF: That is the loveliest message.

RML: It really is.

DR. DRUMHELLER: Thanks. And slàinte mhath. That’s “to good health” in Gaelic.
The NAE has elected 111 new members and 22 international members, bringing the total US membership to 2388 and the number of international members to 310.

Election to the NAE is among the highest professional distinctions accorded to an engineer. Academy membership honors those who have made outstanding contributions to “engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature” or to “the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education.”

Individuals in the newly elected class will be formally inducted during the annual meeting October 2, 2022. The list of new members and international members follows, with their primary affiliation at the time of election and their citation.

New Members

Ahmad Abdelrazaq, former senior executive vice president, Samsung C&T Corp., Seongnam, South Korea. For innovation in design, construction, and health monitoring of the world’s tallest and most complex building structures.

Noubar B. Afeyan, cofounder and chair, Moderna Inc., Cambridge, MA. For leadership in developing and commercializing engineered enzyme products with industrial, consumer, and sustainability benefits.

Brian M. Argrow, professor and chair, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado Boulder. For contributions to unmanned aerial systems capable of penetrating severe storms and leadership in their application to scientific observation.

MiMi A. Aung, senior manager, Project Kuiper, Kuiper Systems LLC, Bellevue, WA. For development of the NASA Mars Helicopter and the first flight on another planet.

Anna Christina Balazs, John A. Swanson Chair, Swanson School of Engineering, University of Pittsburgh. For creative and imaginative work in predicting the behavior of soft materials that are composed of multiple cooperatively interacting components.

Richard G. Baraniuk, C. Sidney Burrus Professor, Department of Electrical and Computer Engineering, Rice University, Houston. For the development and broad dissemination of open educational resources and for foundational contributions to compressive sensing.

Kathleen Bergeron, vice president, Hardware Engineering, Apple Inc., Los Gatos, CA. For contributions to and leadership in the invention and engineering product realization of innovative designs.

Rena Bizios, Lutcher Brown Endowed Chair Professor, Department of Biomedical Engineering, University of Texas, San Antonio. For contributions to the theory and applications of cellular tissue engineering, cell/biomaterial interactions, and surface modification biomaterials.

Alan C. Bovik, Cockrell Family Regents Endowed Chair in Engineering and professor, electrical and computer engineering, University of Texas, Austin. For contributions to the development of tools for image and video quality assessment.

Charles R. Bridges Jr., executive vice president and chief scientific officer, CorVista Health Inc., Washington, DC. For leading the industrial development of new engineered device treatments in the cardiopulmonary space and for pharmaceutical innovation.

Jian Cao, Cardiss Collins Professor, McCormick School of Engineering, Northwestern University, Evanston, IL. For pioneering a flexible sheet forming system and for leadership in manufacturing.

Paul J. Carter, Genentech Fellow, Antibody Engineering, Genentech Inc., San Francisco. For creating novel approaches to discovering and developing life-saving antibody therapeutics, including bispecific antibodies.

Robert L. Clark Jr., professor, Department of Mechanical Engineering, University of Rochester, NY. For development of automated tools for rapidly identifying and indexing desirable genetic traits for next-generation seed and biotechnology product development.
Norma B. Clayton, vice president (retired), Learning, Training, and Development, Boeing Co., St. Charles, MO. For leadership in transforming manufacturing processes and supply chain management, and for innovative training programs for commercial aerospace industries.

John Maxwell Cohn, IBM Fellow, MIT-IBM Watson AI Lab, Cambridge, MA. For improving design productivity of high-performance analog and mixed-signal circuits and for evangelizing STEM education.

Marian R. Croak, vice president, Engineering, Google LLC, Fair Haven, NJ. For technical and managerial leadership in the implementation of packet voice networking and for promotion of minority inclusion in engineering.

Mary Czerwinski, partner researcher and research manager, Microsoft Research, Redmond, WA. For the application of psychological principles to the design and understanding of human computer interaction.

John Davies, vice president (retired), World Ahead, Intel Corp., Sonoma, CA. For contributions in computer technology to improve education and health care, stimulate economies, and enrich lives throughout underdeveloped countries.

James J. De Yoreo, chief scientist, Physical Sciences Division, Pacific Northwest National Laboratory, Richland, WA. For advances in materials synthesis from nucleation to large-scale crystal growth.

Michael Dettinger, visiting researcher, Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, Carson City, NV. For hydroclimate research that significantly enhanced the understanding and management of water resources in the western United States.

Nancy J. Dudney, corporate fellow and group leader (retired), Materials Science and Technology Division, Oak Ridge National Laboratory, TN. For contributions to the development of high-performance solid-state rechargeable batteries.

Louis Durlofsky, Otto N. Miller Professor, Department of Energy Resources, Stanford University, CA. For the development of innovative modeling and optimization techniques to enable the recovery of hydrocarbon and water resources.

Taher Elgamal, chief technology officer, Security, Salesforce, San Francisco. For contributions to cryptography, e-commerce, and protocols for secure internet transactions.

Stephen D. Fantone, president and CEO, Optikos Corp., Wakefield, MA. For contributions to optical engineering and the development of optically based products and metrology systems.

Nuria I. Fernandez, administrator, Federal Transit Administration, San Jose, CA. For forging innovative strategic partnerships and public policies, and guiding complex transportation planning and operations.

Craig I. Fields, chair, Defense Science Board, US Department of Defense, Washington, DC. For contributions to the development of systems and technology for national security and their transfer to commercial applications.

Barbara A. Filas, partner, Filas Engineering and Environmental Services LLC, Grand Junction, CO. For business leadership, mining engineering achievements, and being a role model especially for young women mining engineers.

Denise Gray, president, LG Energy Solution Michigan Inc., Farmington Hills, MI. For leadership in the development and production of electronic controls and battery systems for electrified passenger car propulsion system applications.

Farshid Guilak, Mildred B. Simon Research Professor, Department of Orthopaedics, Washington University School of Medicine, St. Louis, MO. For contributions to regenerative medicine and mechanobiology and their application to the development of clinical therapies.

Jerome F. Hajjar, CDM Smith Professor and chair, Civil and Environmental Engineering, Northeastern University, Boston. For development of design criteria and models for stability and seismic design of innovative steel and composite structures.

William S. Hammack, William H. and Janet G. Lycan Professor, Chemical and Biomolecular Engineering, University of Illinois, Urbana-Champaign. For innovations in multidisciplinary engineering education, outreach, and service to the profession through development and communication of internet-delivered content.

Leonard Harris, president (retired), B&H Mine Services, Nashville, TN. For contributions to the development of mineral resources in Peru and advancing humanitarian programs in associated communities.

Daniel M. Hart, president and CEO, Virgin Orbit, Long Beach, CA. For engineering leadership in the development and operations of satellites, launch vehicles, missile defense, and national systems.

Youssef M.A. Hashash, William J. and Elaine F. Hall Endowed Professor and John Burkitt Webb
Endowed Faculty Scholar, Civil and Environmental Engineering, University of Illinois, Urbana-Champaign. For contributions to geotechnical engineering, seismic safety, and the evaluation, design, and construction of underground infrastructure.

**John D. Hooper**, director, Earthquake Engineering, Magnuson Klemencic Associates, Seattle. For advancement of building code seismic design provisions and earthquake-resistant structural design of major buildings around the world.

**Bahman Hoveida**, president, Accurant International LLC, Bainbridge Island, WA. For entrepreneurial leadership in the development of advanced energy management system software for electric utility operations.

**Freeman A. Hrabowski III**, president, University of Maryland, Baltimore County. For development of a national educational model for students from diverse backgrounds to excel in engineering and science.


**Nola M. Hylton**, professor, Radiology and Biomedical Imaging, University of California, San Francisco. For engineering development and leadership in breast cancer MRI and multicenter national trials, improving the health of millions of women.

**Petros Ioannou**, A.V. “Bal” Balakrishnan Chair and professor, Viterbi School of Engineering, University of Southern California, Los Angeles. For contributions to robust adaptive control and intelligent transportation systems for improved traffic flow and driver safety.

**Waguil S. Ishak**, division vice president and chief technologist, Research and Development, Corning Inc., Sunnyvale, CA. For contributions to the design and manufacturing of VCSELs and leadership in establishing their applications.

**Bahram Jalali**, Fang Lu Chair, Samueli School of Engineering, University of California, Los Angeles. For contributions to silicon photonics, high time-resolution scientific instruments, and biomedical imaging.

**Samson A. Jenekhe**, Boeing-Martin Professor, Chemical Engineering, University of Washington, Seattle. For discovery and understanding of conjugated materials for organic light-emitting diodes (OLEDs) widely used in the commercial sector.

**Christopher W. Jones**, professor and John F. Brock III School Chair, School of Chemical and Bio-molecular Engineering, Georgia Institute of Technology, Atlanta. For contributions to the design and synthesis of catalytic materials and for advancing technologies related to carbon capture and sequestration.

**Anna Karlin**, Bill and Melinda Gates Chair, Allen School of Computer Science & Engineering, University of Washington, Seattle. For contributions to the design and analysis of randomized algorithms and their impact on computer systems and the internet.

**George Em Karniadakis**, Charles Pitts Robinson and John Palmer Barstow Professor, Division of Applied Mathematics and School of Engineering, Brown University, Providence, RI. For computational tools, from high-accuracy algorithms to machine learning, and applications to complex flows, stochastic processes, and microfluidics.

**Thomas W. Kenny**, Richard W. Weiland Professor, School of Engineering, Stanford University, CA. For the performance enhancement and commercialization of silicon MEMS resonators for timing applications.

**Mladen Kezunovic**, Regents Professor and Eugene E. Webb Professor, Department of Electrical and Computer Engineering, Texas A&M University, College Station. For contributions to automated analysis of power system faults, and leadership in education in protective relaying.

**Theresa Kotanchek**, chief executive officer, Evolved Analytics LLC, Rancho Santa Fe, CA. For contributions to the development of commercial material products and for facilitating advanced manufacturing technologies.

**Nicholas D. Lappos**, senior technical fellow (emeritus), Sikorsky Aircraft Corp., Lockheed Martin Corp., Beryl, UT. For improving rotary wing flight performance and serving as test pilot, engineer, inventor, technologist, and business leader.

**Marc Levoy**, VMware Founders Professor (emeritus), Computer Science, Stanford University, CA. For contributions to computer graphics and digital photography.

**Norman P. Lieberman**, engineering consultant, Process Chemicals Inc., Metairie, LA. For being the world’s leading developer and teacher of the practical art of troubleshooting chemical and refinery process operations.

**Rebecca Liebert**, executive vice president, Global Industrial and Automotive OEM Coatings Businesses, PPG Industries Inc., Pittsburgh. For leadership in devel-
developing and executing innovative initiatives to strengthen the US manufacturing industry.

Chao-Hsin Lin, technical fellow, Boeing Commercial Airplanes, Boeing Co., Seattle. For the development of aerospace environmental control systems to ensure the safety and well-being of passengers and crew.

Kathryn Lueders, associate administrator, Space Operations Mission Directorate, National Aeronautics and Space Administration, Merritt Island, FL. For achieving NASA’s vision to establish a globally competitive US commercial space sector, yielding new, fully operational space transportation systems.

Robert J. Madix, senior research fellow, John A. Paulson School of Engineering and Applied Science, Harvard University, Cambridge, MA. For development of quantitative models for predicting catalytic selectivity through fundamental understanding of reaction mechanism and kinetics.

Sandra Magnus, principal, AstroPlanetview LLC, Arlington, VA. For national accomplishments in the US civil space program and in Department of Defense engineering and technology integration.

Ravindranath Vithal Mahajan, Intel Fellow, Assembly and Test Technology Pathfinding, Intel Corp., Chandler, AZ. For contributions to advanced microelectronics packaging architectures and their thermal management.

Michele Viola Manuel, department chair and Rolf E. Hummel Professor, Department of Materials Science and Engineering, University of Florida, Gainesville. For contributions to research, implementation, and teaching of computational materials design of biomimetic self-healing metals and high-performance lightweight alloys.

John C. Mauro, professor, Department of Materials Science and Engineering, Pennsylvania State University, University Park. For developing and applying data-driven models and machine learning that enable high-strength, damage-resistant glasses.

John D. McDonald, smart grid business development leader, GE Grid Solutions, Atlanta. For leadership in smart grid development and for advancing the professional growth of power system engineers.

Donald Nathan Meehan, president, CMG Petroleum Consulting Ltd., Houston. For technical and business innovation in the application of horizontal well technology for oil and gas production.

Sanjay Mehrotra, president and chief executive officer, Micron Technology Inc., San Jose, CA. For contributions to nonvolatile memory design and architecture enabling multilevel cell NAND flash products.

Roland J. Menassa, vice president, Manufacturing Technology, Champion Home Builders, Macomb, MI. For contributions to robotics and automation in aerospace, automotive, and e-commerce.

Paul Mensah, vice president, BioTherapeutics Pharmaceutical Sciences, Pfizer Inc., University City, MO. For leadership in accelerating process development of biotherapeutics including the key components for the first approved COVID-19 vaccine.

Daniel N. Miller, senior fellow, Skunk Works, Lockheed Martin Corp., Bainbridge Island, WA. For theoretical contributions and practical innovations in flow control that improve the performance of aircraft propulsion systems.

Stephen Gene Monismith, Obayashi Professor, School of Engineering, Stanford University, CA. For development of physically based understanding of freshwater and coastal fluid environments for ecosystem health and sustainable management.

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Herbert Allen Myers, president and founder, Ag Leader Technology, Ames, IA. For inventing and bringing to market technology that is the foundation of precision agriculture.

Roger M. Myers, consultant, R Myers Consulting LLC, Woodinville, WA. For technical leadership in the development of advanced electrical and chemical space propulsion systems.

Satya Nadella, chair and chief executive officer, Microsoft Corp., Redmond, WA. For advancing corporate computing infrastructure as a cloud service, and for international leadership on sociotechnical systems and practice.

Farzad Naeim, founder and president, Farzad Naeim Inc., Irvine, CA. For advancing performance-based seismic design of tall buildings and other structures with instru-
mentation, isolation, and energy dissipation devices.

Klara Nahrstedt, Grainger Distinguished Chair, Grainger College of Engineering, University of Illinois, Urbana-Champaign. For contributions to managing quality of service in distributed multimedia systems and networks.

Guy Jérôme Pierre Nordenson, professor of architecture and structural engineering, Princeton University. For structural engineering and leadership in promoting structures as art and culture.

Richard P. O’Neill, distinguished senior fellow, Advanced Research Projects Agency–Energy, Silver Spring, MD. For leadership and contributions to the liberalization and design of efficient natural gas and electric power markets.

Dani Or, affiliate research professor, Hydrologic Sciences, Desert Research Institute, Reno, NV. For contributions coupling soil physics, hydromechanics, and microbiology through novel measurements, theory, and models of key near-surface hydrologic processes.

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Colin James Parris, senior vice president and chief technology officer, GE Digital, Foxborough, MA. For leadership and advancement of industrial operational technologies and innovation based on digital data analytics and the Internet of Things.

Nelson Pedreiro, vice president, Advanced Technology Center, Lockheed Martin Corp., Palo Alto, CA. For technical innovation and engineering leadership on programs of national importance in space exploration, strategic systems, and missile defense.

Kenneth Peters, adjunct professor, Stanford University, CA. For development and application of geochemistry for basin analysis, hydrocarbon production, and biodeterioration metrics.

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Maryann T. Phipps, president, Estructure, Oakland, CA. For leadership in structural engineering and contributions to assessment, mitigation, and design of building components for seismic effects.

Zoya Popović, distinguished professor and Lockheed Martin Endowed Chair, Electrical, Computer, and Energy Engineering, University of Colorado Boulder. For developing high-efficiency microwave transmitters and active antenna arrays for wireless communication systems and for engineering education.

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Guillermo Sapiro, James B. Duke Distinguished Professor, Electrical and Computer Engineering, Duke University, Durham, NC. For contributions to the theory and practice of imaging.

Julie Mae Schoenung, department chair and professor, Materials Science and Engineering, University of California, Irvine. For innovative and interdisciplinary applications of materials engineering in trimodal composites, coatings, additive manufacturing, and green engineering.

Kate M. Scow, professor, Department of Land, Air, and Water Resources, University of California, Davis. For elucidating the role of soil microbial communities in polluted ecosystems and their responses to agricultural management practices.

Manoj R. Shah, professor of practice, Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY. For contributions to design, analysis, and electric machine performance enhancements.

Pradeep Sharma, M.D. Anderson Chair Professor and department chair, Department of Mechanical Engineering, University of Houston, TX. For establishing the field of flexoelectricity, leading to the
creation of novel materials and devices and insights in biophysical phenomena.

Leslie L. Shoemaker, president, Tetra Tech Inc., Pasadena, CA. For developing and applying innovative technology to complex large-scale watershed management systems and sustainable water programs.

Deepika B. Singh, founder and chief executive officer, R&D Investment Holdings LLC, Newberry, FL. For manufacturing innovation and entrepreneurship of chemical-mechanical planarization (CMP) for wide band-gap semiconductors and superhard materials-related products.

Vijay P. Singh, Distinguished Professor, Regents Professor, and Caroline & William N. Lehrer Distinguished Chair, Department of Biological and Agricultural Engineering, Texas A&M University, College Station. For contributions to wave modeling and development of entropy-based theories of hydrologic processes and hydroclimatic extremes.

Daniel Sperling, Distinguished Blue Planet Prize Professor of Civil and Environmental Engineering and founding director, Institute of Transportation Studies, University of California, Davis. For leadership and outstanding entrepreneurial contributions in transportation energy, advancing alternative energy policies and promoting government-industry-university collaborations.

Leon Thomsen, chief scientist, Delta Geophysics Inc., Houston. For contributions to seismic anisotropy concepts that produced major advances in subsurface analysis.

Masayoshi Tomizuka, Cheryl and John Neerhout Jr. Distinguished Professor, Mechanical Engineering, University of California, Berkeley. For leadership in control of mechanical systems through innovations applied globally in industry, and education of coming generations of leaders.

Franz-Josef Ulm, professor, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge. For contributions to nanoscale improvement of concrete and other materials and structures important for sustainable development of infrastructure and energy resources.

Manuela M. Veloso, head, Artificial Intelligence Research, JPMorgan Chase & Co., New York City. For contributions to machine learning and its applications in robotics and the financial services industry.

Solveig Maria Ward, executive advisor, Quanta Technology LLC, Cooperstown, PA. For contributions to electric power system protective relaying, and new data communication technologies.

Michael M. Watkins, director and vice president, NASA Jet Propulsion Laboratory and California Institute of Technology, Pasadena. For leadership in the development of space geodesy and leading robotic missions for exploration of the Earth and planetary bodies.

David West, corporate fellow, Corporate Research and Innovation, Saudi Basic Industries Corp., Sugar Land, TX. For solutions to problems with technological, commercial, and societal impacts while advancing chemical sciences by applying reaction engineering fundamentals.

Telle Whitney, CEO, Telle Whitney Consulting LLC, Scotts Valley, CA. For contributions to structured silicon design and for increasing the participation of women in computing careers.

Karen E. Willcox, director, Oden Institute for Computational Engineering and Sciences, University of Texas, Austin. For contributions to computational engineering methods for the design and optimal control of high-dimensional systems with uncertainties.

Charles E. Wyman, Ford Motor Company Chair and Distinguished Professor, Marlan and Rosemary Bourns College of Engineering, University of California, Riverside. For advances in transforming lignocellulosic feedstocks to low-carbon-footprint fuels and chemicals.

Yushan Yan, Henry B. Dupont Chair, Chemical and Biomolecular Engineering, University of Delaware, Newark. For creativity, innovation, and entrepreneurship in separation membranes and electrochemical reaction engineering, catalysis, and materials.

Taiyin Yang, executive vice president, Pharmaceutical Development and Manufacturing, Gilead Sciences Inc., Foster City, CA. For the invention, production, and global distribution of single tablet regimens for treating HIV.


New International Members

Yusuf Altintas, NSERC–P&W–Sandvik Coromant Industrial Research Chair, Department of Mechanical Engineering, University of British Columbia, Vancouver, Canada. For contributions to metal-cutting mechanics and machine tool systems research and industry applications.

Juan Andres, chief technical operations and quality officer, Moderna Inc., Chestnut Hill, MA.
For technical leadership in the scale-up and manufacturing of important pharmaceutical products, including the COVID mRNA-1273 vaccine.

Gurumooorthy Bhuvaneswari, professor, Department of Electrical and Electronics Engineering, Indian Institute of Technology, New Delhi. For contributions to advancement of power converters to improve power quality, and leadership in using advanced technologies for education.

Nigel Peter Brandon, dean, Faculty of Engineering, Imperial College London, United Kingdom. For contributions to the science and engineering of solid oxide fuel cells, and to their technological development and commercialization.

Edwin Thomas Brown, professor (emeritus), University of Queensland, Milton, Australia. For advancing understanding of the mechanical behavior of rock masses and application to the design of engineered structures in rock.

Natarajan Chandrasekaran, chair, Tata Sons Private Limited, Mumbai. For changing the nature and advancing the capabilities of the software industry in India.

Jérôme Faist, professor, Institute for Quantum Electronics, ETH Zürich (Swiss Federal Institute of Technology), Switzerland. For contributions to the development of mid-infrared and terahertz quantum cascade lasers.

Daining Fang, chair professor, Institute of Advanced Structure Technology, Beijing Institute of Technology, China. For contributions to the mechanisms of ferroelectric/ferromagnetic materials and lightweight multifunctional structures under extreme conditions.

Klaus G. Hoehn, vice president, Advanced Technology and Engineering, John Deere, Naples, FL. For leadership and contributions in product technology and engineering that have advanced precision agriculture and digital farming.

Peter A. Irwin, senior executive consultant and founding partner, Rowan Williams Davies & Irwin Inc., Guelph, Ontario, Canada. For contributions to wind engineering for the design of tall buildings and long span roofs and bridges.


Ravindra D. Kulkarni, founder, Elkay Chemicals Private Limited, Pune, India. For innovation-centric business and technology development and leadership across disciplines.

Wook Hyun Kwon, professor (retired), Department of Electrical and Computer Engineering, Seoul National University, South Korea. For contributions to model-predictive and robust controls and their commercialization.

Bin Liu, Provost’s Chair and professor, Department of Chemical and Biomolecular Engineering, National University of Singapore. For bringing organic electronic materials into aqueous media, opening new directions in biomedicine, environmental monitoring, sensors, and electronic devices.

James Rufus McDonald, principal and vice chancellor, University of Strathclyde, Glasgow, United Kingdom. For contributions to engineering leadership and inter-disciplinary education, expert power systems, and low-carbon technologies and renewable energy.

Heike Riel, IBM Fellow and head, IBM Research Zürich, Switzerland. For global leadership and technical innovations in the semiconductor industry, covering OLED, fundamental device processes, materials, and nanowire devices.

Byrana Nagappa Suresh, honorary distinguished professor, Indian Space Research Organization, Bengaluru. For contributions to advances in technologies for space exploration and for leadership to promote peaceful uses of outer space.

Keh-Chyuan Tsai, distinguished professor, Department of Civil Engineering, National Taiwan University, Taipei. For international leadership and contributions to earthquake engineering research and design of steel structures.

Rodney S. Tucker, honorary laureate professor (emeritus), Department of Electrical and Electronic Engineering, University of Melbourne, Victoria, Australia. For contributions to semiconductor lasers, high-speed optoelectronics, and energy-efficient optical networking.

Ganapati Dadasaheb Yadav, emeritus professor of eminence, Chemical Engineering, Institute of Chemical Technology, Mumbai, India. For research, innovation, and education in green chemistry, catalysis, nanotechnology, and chemical engineering leading to clean and green technologies.

Oz Yilmaz, founder, Anatolian Geophysical, Istanbul, Turkey. For leadership in developing innovative methods for processing seismic reflection data and educating a generation of geophysicists.

Hongjiang Zhang, senior advisor, The Carlyle Group, Beijing, China. For technical contributions and leadership in the area of multimedia computing.
NAE Newsmakers

M. Katherine Banks, president, Texas A&M University–College Station, has been honored by the university’s Engineering Advisory Council with the establishment of the Dr. M. Katherine Banks Endowed Chair in Engineering. An endowed chair is the highest academic award the college can bestow on a faculty member. The council members honored Dr. Banks for all she did for the College of Engineering during her time as vice chancellor and dean.

Cynthia Barnhart, chancellor and Ford Professor of Engineering, Massachusetts Institute of Technology, was awarded the 2021 George E. Kimball Medal by INFORMS. She received the award for “her distinguished service to INFORMS and her wide-ranging contributions to the profession of operations research through research, practice, education, leadership, and service.”

Rudolph Bonaparte, chair and senior principal, and Michael C. Kavanaugh, senior principal, Geosyntec Consultants, received the 2021 Berkeley Spirit of 1868 Volunteer Award from the University of California, Berkeley on October 1, 2021. The award acknowledges alumni and friends who have demonstrated outstanding volunteer leadership and accomplishments supporting UC Berkeley’s philanthropic and outreach efforts.

Nicholas M. Donofrio, CEO, NMD Consulting LLC, and Lisa T. Su, president and CEO, Advanced Micro Devices, have been chosen as International Peace Honorees. Mr. Donofrio is recognized for “his commitment to the promise of peace and technology to build just and thriving communities.” Dr. Su is honored for “her achievements in revolutionizing high-performance computing, the donation of supercomputing power for infectious disease research, and inspiring people from all backgrounds to pursue careers in STEM.” They were honored at the 2022 International Peace Honors (IPH) February 27. The IPH celebrates outstanding global leaders and change agents who make philanthropy and humanitarian service a hallmark of their lives, to advance humanity and our planet.

On November 4, 2021, Christine A. Ehlig-Economides, professor and Hugh Roy and Lillie Cranz Cullen Distinguished University Chair, Cullen College of Engineering, University of Houston, received the Distinguished Engineering Service Award from the University of Kansas. The school’s highest award is presented to individuals who have maintained close association with the school and have made outstanding contributions to the engineering profession and to society. Professor Ehlig-Economides was recognized for her seminal contributions to the development and application of technology in the field of petroleum engineering and a distinguished track record of leadership in academic and professional settings, including advocating for women and underrepresented minorities in the field and organizing and helping to establish new petroleum engineering departments at two universities.

Andrés J. García, executive director of the Parker H. Petit Institute for Bioengineering and Bioscience and Regents Professor in the Georgia Tech George W. Woodruff School of Mechanical Engineering, has received the Class of 1934 Distinguished Professor Award, the highest honor given to a Georgia Tech professor. The award is presented to an active professor who has made significant, long-term contributions that have brought widespread recognition to the professor, their school, and the institute. Previous NAE winners of the award are Jeff Wu (2020), George L. Nemhauser (2015), Richard J. Lipton (2012), Robert M. Nerem (2009), James D. Foley (2008), and C.-P. Wong (2004).

Chennupati Jagadish, distinguished professor, Research School of Physics, Australian National University, will become the 20th president of the Australian Academy of Science in May. His responsibilities will include championing scientific excellence and leading the organization in providing advice to the Australian Parliament.

Ahsan Kareem, Robert M. Moran Professor of Engineering and director of the NatHaz Modeling Laboratory at the University of Notre Dame, has been selected for the 2021 Nathan M. Newmark Medal from the American Society of Civil Engineers. Dr. Kareem was cited for “his innovative contributions to advancements in a wide range of areas in structural engineering and engineering mechanics from theory and practice to leadership and education.”

Marcia McNutt, president, National Academy of Sciences, was elected to a second term as NAS
The president and chair of the National Research Council. Dr. McNutt took office in 2016, and her new, 4-year term begins July 1, 2022.

The Engineering Academy of Japan announced the 2022 election of international fellows, who include the following NAE members: Zdeněk P. Bažant, McCormick Institute Professor and W.P. Murphy Professor of Civil and Mechanical Engineering and Materials Science, Northwestern University; Lewis M. Branscomb, professor emeritus of public policy & corporate management, Harvard University; Bacharuddin J. Habibie (posthumously), former president of Indonesia and board chair, Habibie Center; Ahsan Kareem, Robert M. Moran Professor of Engineering, University of Notre Dame; Enrique A. Marcatili (posthumously), retired head, Photonics Research Laboratories, AT&T Bell Laboratories; Sanjit Mitra, distinguished professor emeritus of electrical and computer engineering, University of California, Santa Barbara; and Wm. A. Wulf, AT&T Professor of Computer Science and University Professor Emeritus, University of Virginia.

Shuji Nakamura, CREE Professor, materials, and professor of electrical and computer engineering at the University of California, Santa Barbara, has been honored with the 3rd annual Richard J. Goldstein Energy Lecture Award from the American Society of Mechanical Engineers. The award recognizes “pioneering contributions to the frontiers of energy, leading to breakthroughs in existing technology, leading to new applications or new areas of engineering endeavor, or leading to policy initiatives.” Professor Nakamura was selected for “transformational innovation in energy-conserving electronic and photonic materials, particularly pioneering work in light emitters based on wide-bandgap semiconductors and the invention of efficient blue-light emitting diodes that have rendered substantive bright and energy-saving white light sources.” He gave a lecture on the invention of the blue LED and the future of lighting at the virtual ASME International Mechanical Engineering Congress & Exposition that took place November 1–4, 2021.

Kimberly A. Prather, distinguished professor and distinguished chair in atmospheric chemistry, Scripps Institution of Oceanography, University of California, San Diego, received the Pittsburgh Analytical Chemistry Award at the virtual PITTCON Conference March 5–9. The award was established to recognize a scientist’s significant contributions to the field of analytical chemistry, whether by introducing a significant technique, theory, or instrument or providing exceptional training or a fertile environment for progress in analytical chemistry.

John A. Rogers, Louis Simpson and Kimberly Querrey Professor of Materials Science and Engineering, Biomedical Engineering and Neurological Surgery, Northwestern University, and chair of the Scientific Advisory Committee at X Display Company, has been selected to receive the Washington Award for “his pioneering work in technology development which focuses the concern for humanity, through platforms that address key medical challenges, in designs that facilitate use across all global communities.” The award is conferred annually on an engineer whose professional attainments have promoted the happiness, comfort, and well-being of humanity.

A $5 million gift from IBM will endow two computer science professorships in Northwestern University’s McCormick School of Engineering in honor of Virginia M. Rometty, former chair, president, and CEO of IBM Corporation. The two Gini Rometty Professorships of Computer Science will support research and teaching related to artificial intelligence and machine learning.

Ponisseril Somasundaran, director, NSF/IUCR Center for Surfactants and La Von Duddleson Krumb Professor, Columbia University, has been elected a foreign fellow of the National Academy of Sciences, India.

David M. Van Wie, sector head, Air and Missile Defense, Johns Hopkins University Applied Physics Laboratory, was awarded the 2021 von Karman Lectureship in Astronautics from the American Institute of Aeronautics and Astronautics. The lectureship honors an individual who has performed notably and distinguished themselves technically in the field of astronautics. Dr. Van Wie accepted his award and delivered a talk on the multidomain convergence of space and near-space on November 16, 2021, at the AIAA ASCEND Forum in Las Vegas.

David R. Walt, Hansjorg Wyss Professor of Biologically Inspired Engineering, Harvard Medical School, has been selected to receive the $250,000 Kabiller Prize in Nanoscience and Nanomedicine, the world’s largest monetary award for a career of outstanding achievement in the field of nanotechnology and its application to medicine and biology. Professor Walt is recognized for his pioneering work aimed at the
development of ultrasensitive single-molecule array detection technology, which is affecting the way cancer, infectious disease, and neurological disorders are diagnosed and treated.

Marvin H. White, professor of electrical and computer engineering, Ohio State University, will receive a Technology & Engineering Emmy Award. According to the Engineering Achievement Committee of the National Academy of Television Arts and Sciences, “the award helps honor the ‘tool makers’ of the industry who crafted the modern television viewing experience.” Professor White and Northrop Grumman Mission Systems Group are recognized for their work on correlated double sampling for image sensors, a critical component of high-definition video capture and image noise reduction. The award ceremony is tentatively scheduled April 25.

Blake S. Wilson, director of the Duke Hearing Center and adjunct professor, Duke University and Duke University Medical Center, received the North Carolina Award, the state’s highest civilian honor, in recognition of his significant scientific contributions to the state. Governor Roy Cooper presented Dr. Wilson and eight other distinguished North Carolinians with their awards on November 18, 2021, at the North Carolina Museum of Art.

The National Academy of Sciences announced its 2022 award recipients. The awards will be presented May 1 during the NAS annual meeting. John P. Holdren, Teresa & John Heinz Professor of Environmental Policy, Harvard University, will receive the most prestigious NAS award, the Public Welfare Medal. John A. Rogers will receive the 2022 NAS James Prize in Science and Technology Integration for “his development of unique, biocompatible forms of electronic, optoelectronic, and microfluidic technologies; pioneering their use in areas ranging from neuroscience to clinical care; and converting them into widely available forms, through interdisciplinary approaches in materials science, technology integration, and translational research in health and medicine.” Esther S. Takeuchi, SUNY Distinguished Professor, Stony Brook University, will receive the Award in Chemical Sciences “for breakthrough contributions to our understanding of electrochemical energy.”

The AAAS announced the election of its 2021 fellows, who include Ruzena K. Bajcsy, NEC Chair Professor of EECS and director emerita of CITRIS, University of California, Berkeley; Georges Belfort, institute professor, Rensselaer Polytechnic Institute; Pratim Biswas, dean, College of Engineering, University of Miami; John E. Bowers, director, Institute for Energy Efficiency, University of California, Santa Barbara; Dorota A. Grejner-Brzezinska, Lowber B. Strange Endowed Chair and University Distinguished Professor, Ohio State University; Mark S. Humayun, Cornelius J. Pings Chair in Biomedical Sciences and Integrative Anatomical Sciences, University of Southern California; Mae C. Jemison, president, The Jemison Group Inc.; Yann A. LeCun, chief AI scientist, Facebook, and professor, New York University; and Yannis C. Yortsos, dean, Viterbi School of Engineering, University of Southern California.

The IEEE announced its 2022 award recipients, men and women whose exceptional achievements and outstanding contributions have made a lasting impact on technology, society, and the engineering profession. Of the 18 medals awarded, 12 were given to NAE members:

The institute’s highest award, the IEEE Medal of Honor, went to Asad M. Madni, independent consultant, distinguished adjunct professor of electrical and computer engineering at UCLA Samueli School of Engineering, and retired president, COO, and CTO of BEI Technologies Inc., “for pioneering contributions to the development and commercialization of innovative sensing and systems technologies, and for distinguished research leadership.”

Anantha P. Chandrakasan, dean, MIT School of Engineering, received the Mildred Dresselhaus Medal for “contributions to ultralow-power circuits and systems, and for leadership in academia and advancing diversity in the profession.”

Jingsheng J. Cong, Volgenau Chair for Engineering Excellence and director of VAST Lab, UCLA, is the recipient of the Robert N. Noyce Medal for “fundamental contributions to electronic design automation and FPGA design methods.”

The John von Neumann Medal went to Deborah S. Estrin, Tishman Professor of Computer Science and associate dean for impact, Cornell Tech, for “leadership in mobile and wireless sensing systems technologies and applications, including personal health management.”

The Medal for Innovations in Healthcare Technology was presented to James G. Fujimoto, Elihu Thomson Professor of Electrical Engineering and Computer Science at MIT, “For pioneering the development and commercialization of
optical coherence tomography for medical imaging and diagnostics.”

The Medal in Power Engineering was awarded to Thomas M. Jahns, Grainger Professor of Power Electronics and Electrical Machines, University of Wisconsin–Madison, for “contributions to the development of high-efficiency permanent magnet machines and drives.”

P.R. Kumar, University Distinguished Professor, Computer Engineering and Systems Group, Texas A&M University–College Station, was selected for the Alexander Graham Bell Medal “For seminal contributions to the modeling, analysis, and design of wireless networks.”

Azad M. Madni, chief executive officer and chief technology officer, Intelligent Systems Technology Inc., received the IEEE-USA George F. McClure Citation of Honor for sustained excellence, dedicated commitment, and contributions to the socioeconomic and diversity aspects of IEEE professional activities in the United States.

Umesh Mishra, professor, Electrical and Computer Engineering Department, University of California, Santa Barbara, was honored with the Jun-ichi Nishizawa Medal for “contributions to the development of gallium nitride-based electronics.”

Ned Mohan, Regents Professor and Oscar A. Schott Professor of Power Electronics and Systems, University of Minnesota, Minneapolis, received the James H. Mulligan Jr. Education Medal for “leadership in power engineering education by developing courses, textbooks, labs, and a faculty network.”

The Frances E. Allen Medal was shared by Eugene W. Myers, director, Max-Planck Institute for Molecular Cell Biology and Genetics, and Webb Miller of Pennsylvania State University for “pioneering contributions to sequence analysis algorithms and their applications to biosequence search, genome sequencing, and comparative genome analyses.”

John Brooks Slaughter, professor of education and engineering, USC Rossier School of Education and Viterbi School of Engineering, was honored with the IEEE Founders Medal “For leadership and administration significantly advancing inclusion and racial diversity in the engineering profession across government, academic, and nonprofit organizations.”

Pravin P. Varaiya, professor, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, was selected for the IEEE Simon Ramo Medal for “seminal contributions to the engineering, analysis, and design of complex energy, transportation, and communication systems.”

The National Academy of Inventors announced the election of 164 new fellows, the highest professional distinction accorded solely to academic inventors. Among the new fellows are NAE members Santokh S. Badesha, corporate fellow and manager of open innovation, Xerox Corporation, and adjunct professor for innovation, Purdue University; Joan F. Brennecke, Keating-Crawford Professor, McKetta Department of Chemical Engineering, University of Texas, Austin; S. Edward Law, D.W. Brooks Distinguished Professor Emeritus, University of Georgia; Ajay P. Malshe, Goodson Distinguished Professor of Mechanical Engineering, Purdue University; and Ganesh C. Thakur, director of energy industrial partnerships and distinguished professor of petroleum engineering, University of Houston. They will be inducted at the 11th annual meeting of the National Academy of Inventors in June in Phoenix.

Five NAE members will be inducted into the National Inventors Hall of Fame on May 5 at a ceremony in Washington, DC. Dana C. Bookbinder, retired corporate fellow, Corning Incorporated, for bend-insensitive optical fiber; Raffaello D’Andrea, professor, Department of Mechanical and Process Engineering, ETH Zürich, for mobile robotic material handling for order fulfillment; Ming-Jun Li, corporate fellow, Corporate Research, Corning R&D Corporation, for bend-insensitive optical fiber; Mick C. Mountz, retired founder and CEO, Kiva System (now Amazon Robotics), for mobile robotic material handling for order fulfillment; and Margaret M. Wu, retired senior scientific advisor, ExxonMobil Research and Engineering Company, for synthetic lubricants.
Message from NAE Vice President Corale L. Brierley

What a year! As we have continued to grapple with the covid-19 pandemic over the past 2 years, your ongoing support is more imperative than ever to ensure that the vital work of the National Academy of Engineering remains robust and timely.

In 2021 our members, friends, and partner organizations contributed almost $16.3 million in new cash, pledges, and planned gifts, including nearly $2.3M in unrestricted funds that provide flexibility in these challenging times. Thanks to your support, 2021 was the NAE’s most successful fundraising year ever! I am so proud and grateful for the generosity and care shown by the NAE community.

Among the highlights of 2021 is The Grainger Foundation’s $10 million commitment to endow the FOE program, building on their philanthropic support and championship of this signature NAE program over more than a decade and providing over 50 percent of the program’s annual budget. This contribution is the largest single gift to the NAE’s Frontiers of Engineering Program, and makes The Grainger Foundation the NAE’s largest philanthropic contributor in its history. In recognition of this extraordinary gift, the FOE program will be renamed The Grainger Foundation Frontiers of Engineering.

I am also very pleased to report that NAE member Ming Hsieh and his company Fulgent provided a $1M gift to sponsor the Global Health Summit and the Tri-Academies Covid Seminar Series with speakers and participants on at least three continents and time zones to share ways that engineering is helping to address the pandemic across borders.

The NAE also secured 18 six-figure commitments and planned gifts, including two $500,000 donations and nine new endowed funds, that, when fully funded, will generate approximately $540,000 to the NAE’s annual budget. These new funds are critical to the NAE’s future and financial health.

In addition, over $820,000 was raised for the NAE’s diversity initiatives: the President’s Committee on Racial Justice and Equity (RJ&E Committee), led by the Honorable Percy Pierre, and the program on Inclusive, Diverse, and Equitable Engineering for All (IDEEA). This funding enables us to work toward diversity and equity in the engineering profession and to inspire and engage youth, families, and educators with engineering.

Philanthropy remains crucial in providing sustainable funding for established NAE programs. In 2021 we launched the $200,000 Ligler-Wagoner Challenge for FOE to encourage and incentivize FOE alumni, friends, and the companies/institutions that employ them to match contributions 1:1 to the program. Funded by NAE members and FOE champions Frances and George Ligler and Robyn and Rob Wagoner, the Challenge’s goal is to leverage FOE alumni support and raise the profile of this signature NAE program to ensure its longevity for future generations through a solid foundation of unrestricted support.

Last, I am pleased to announce the establishment of the National Academies' Great Hall Society, recognizing donors who make annual leadership gifts at two levels: silver, for donors who give $5,000–$9,999, and gold, for donors who give $10,000 or more in a calendar year. We are delighted to introduce this giving society—in addition to our existing lifetime giving societies, Lincoln, Franklin, Curie, Einstein, Heritage, and Loyalty (see pages 72–81 for details)—as a way to engage more members and new donors with the NAE, National Academies, and each other, fostering a more cohesive community of supporters.

Onward

As we look ahead to a new year and a new NAE vice president beginning in July, the NAE is prepared to pursue its mission with refreshed vision, vigor, and drive thanks to the generosity of our members, friends, and partners. I thank the NAE councillors for their leadership and generosity—100 percent of them made gifts to the NAE, totaling over half a million dollars. We also saw increases in the number of NAE donors and dollars to the Academy, for which I’m deeply grateful. I hope this trend continues during the silent phase of the NAE campaign.
The campaign and resulting funds will be critical in the successful implementation of the NAE’s new strategic plan, and underscores our Academy’s effectiveness, efficiency, and potential for growth. Our donors understand the importance of an authoritative voice to provide evidence-based advice and guidance on significant challenges facing the nation and world. You play a vital role in ensuring a dynamic and proactive NAE. Thank you for your continued support.

Corale L. Brierley

2021 Honor Roll of Donors

We greatly appreciate the generosity of our donors. Your contributions enhance the impact of the National Academy of Engineering’s work and support its vital role as advisor to the nation. The NAE acknowledges contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. The gifts reflected on this list are as of December 31, 2021.

Lifetime Giving Societies
We gratefully acknowledge the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of the academies as advisor to the nation on matters of science, engineering, and medicine.

The Abraham Lincoln Society
In recognition of members and friends who have made lifetime contributions of $1 million or more to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

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Anthony J. Yun and Kimberly A. Bazar

*Deceased
The Benjamin Franklin Society

In recognition of members and friends who have made lifetime contributions of $500,000 to $999,999 to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

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The Marie Curie Society

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Wm. A. Wulf
Anonymous (3)

The Einstein Society

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Paul and Julie Kaminski
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Samuel L. Katz and Catherine* M. Wilfert
K.I. Kellermann
Charles F. Kennel
Ivan R. King*
Judson and Jeanne King
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Joanne Knopoff
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Jaya and Venky Narayananurthi
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F. Stan Settles
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Gail L. Warden
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Great Hall Society (Annual Giving Society)

The Great Hall Society, the Academies’ new annual giving society, recognizes donors who make leadership-level gifts at two levels: the silver level, for annual gifts totaling $5,000–$9,999, and the gold level, for annual gifts totaling $10,000 or more. Annual funding provides resources that support ongoing activities and outreach efforts while also enabling the NAE to respond to emerging issues facing our nation and world in a timely manner every year. The NAE gratefully acknowledges the following members and friends who have joined this new society.

**Gold Level ($10,000+)**

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Foundations, Corporations, and Other Organizations

In recognition of foundations, corporations, or other organizations that made gifts or grants of $5,000+ to support the National Academy of Engineering in 2021.

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<th>Amazon.com, Inc.</th>
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We have made every effort to list donors accurately and according to their wishes. If we have made an error, please accept our apologies and contact the Office of Development at 202.334.2431 or giving@nae.edu so we can correct our records.

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NAE Announces $10 Million Endowment from The Grainger Foundation for Frontiers of Engineering

The National Academy of Engineering is pleased to announce a $10 million endowment from The Grainger Foundation to support the Frontiers of Engineering (FOE) program. This generous commitment from The Grainger Foundation builds on more than a decade of philanthropic support to FOE, totaling more than $9 million since 2008.

“Our nation’s emerging engineering leaders benefit greatly through participation in Frontiers of Engineering,” said NAE president John L. Anderson. “We are grateful to The Grainger Foundation for this remarkable endowment, which ensures that future generations will have continued access to this outstanding program.”

The Grainger Foundation is an independent private foundation based in Lake Forest, Illinois. Established in 1967, the foundation provides substantive support to a broad range of organizations including educational, medical, cultural, and human services institutions.

Established in 1995, Frontiers of Engineering is a 2½-day symposium that brings together a select group of emerging engineering leaders from industry, academia, and government labs to discuss pioneering technical work and leading-edge research in various engineering fields and industry sectors. There are five Frontiers of Engineering programs: the US symposium held annually, and a rotating schedule of FOE symposia with Germany, Japan, China, and the European Union.

2021 EU-US Frontiers of Engineering Held Virtually

The EU-US Frontiers of Engineering symposium was held as a virtual event November 15–17, 2021, after being postponed from 2020 because of the Covid pandemic. The NAE partnered with the European Council of Applied Sciences, Technologies and Engineering (Euro-CASE) to carry out the event, with organizational support for the EU side provided by the Royal Swedish Academy of Engineering Sciences. Vahid Tarokh, Rhodes Family Professor of Electrical and Computer Engineering at Duke University, and Pontus Johnson, professor of network and systems engineering at the Royal Institute of Technology in Stockholm, cochaired the organizing committee and the symposium.

The participants met virtually for 4 hours over each of 3 days to discuss leading-edge developments in these areas: Improving the Reliability and Resiliency of Electric Power Grids, Applications and Uses of Graphene, Technologies for the Detection and Treatment of Dementia, and Machine Learning for Emerging Networks. In addition, virtual poster sessions and other networking events allowed the attendees to interact outside of the technical sessions. Participants attended from the United States and 11 EU countries: Belgium, Denmark, France, Germany, Italy, Poland, Romania, Spain, Sweden, Turkey, and the United Kingdom.

Improving the reliability and resiliency of power systems in the face of increasingly common disturbances—such as fluctuating renewable generation and extreme natural disasters—requires the development of advanced computational tools to help engineers better design and operate future electric power grids. Speakers in this session described the forefront of research on such tools with talks on multi-infrastructure modeling for next-generation energy systems; state-of-the-art techniques used by RTE, the French transmission operator, to adapt system operations to the rapid growth of renewable generation; applications of machine learning to problems with power system reliability and resiliency; and modeling of the risk of wildfire ignitions and power outages in the electric grid.

The next session surveyed some of the most promising current applications of graphene, which was discovered in 2004. The first talk provided a historical overview and described the synthesis of graphene for applications with stringent cost requirements. The next speaker talked about the synthesis of graphene and 2D materials in biosensing, exploring how field-effect transistors based on graphene can be used for ultrasensitive detection of
biomarkers. The session closed with a discussion of the potential impact of graphene biosensors across markets from agriculture to pharmaceuticals and the prospect of using biosensors to tap into humans’ internal biological network, enabling a new era—the Internet of Biology.

Dementia is a major brain disorder that is accelerated by aging, and Alzheimer’s disease (AD) is the leading cause, accounting for 60–70 percent of all dementia cases. Worldwide about 50 million people live with dementia, and this number is projected to triple by 2050. The devastating scale of the disease and lack of effective pharmacological treatment demonstrate the need for new approaches. This session explored how cutting-edge engineering is reshaping the landscape of dementia research and the therapeutic pipeline. Presentations described how sound and light can be engineered to slow the pathology and boost cognitive function in animal models of AD, the coupling of sophisticated AI computation with affordable sensors to provide effective management solutions for people with dementia, and CMOS neural probes and brain-on-chip devices for studying and detecting neurodegenerative diseases.

The final session of the meeting was on machine learning (ML) for emerging networks. The next generation of communication networks will enable applications (e.g., self-driving cars and cyberphysical systems) that process multiple streams of rich data autonomously without human intervention. Building such high-throughput, low-latency networks will require overcoming various challenges faced by different elements of communication networks. This session explored the role of ML in addressing these challenges. The first speaker explained how deep learning can facilitate more efficient multiple antenna transceivers and help harvest more capacity from the scarce spectrum. This was followed by a presentation on ML-enabled innovation in emerging wireless networks and challenges that hamper the immediate practical impact of ML on wireless networks. The next speaker described federated learning, a promising framework for enabling privacy-preserving ML across many decentralized users. The last speaker talked about AI-based machine-to-machine communication in 6G.

Videos and/or slides of the presentations can be accessed in the List of Sessions on the 2021 EU-US FOE website at www.naefrontiers.org.

Financial support for the symposium was provided by The Grainger Foundation and the National Science Foundation.

The next EU-US FOE will be held October 20–22, 2022, in Bled, Slovenia. Vahid Tarokh will continue as US cochair.

The NAE has been holding Frontiers of Engineering symposia since 1995, and the EU-US FOE since 2010. For more information about the symposium series or to nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at the NAE Program Office at JHunziker@nae.edu. The FOE website is www.naefrontiers.org.

Q&A from Graphene session.
Guru Madhavan Receives IEEE Award

GURU MADHAVAN, the NAE’s Norman R. Augustine Senior Scholar and Senior Director of Programs, was selected to receive the IEEE-USA George F. McClure Citation of Honor, “For outstanding leadership in advancing engineering professionalism through public policy, programs, and engagement.” Please join us in extending hearty congratulations to Guru.

New Membership Office Staff

GREG VICKERS joined the Membership Office January 3 as a membership associate. He will manage member and committee records, the directory, and section meetings. With over 30 years of regional, national, and international experience in trade association management and heavy construction–related industries, Greg has demonstrated success in database management, member communications, event management, and training development and delivery. Greg graduated summa cum laude with a bachelor’s in English language learner studies from Ashford University in Clinton, IA. In his spare time he enjoys running marathons—he has completed 26! He can be reached at 202.334.2261 or GVickers@nae.edu.

Mirzayan Fellow Joins Program Office Staff

DAYOUNG KIM is a PhD candidate in engineering education and a Bilsland Fellow of the College of Engineering at Purdue University. She received her BS at Yonsei University (Seoul, South Korea) in 2017 and MS at Purdue in 2021, both in chemical engineering. As a scholar interested in the role of engineering professionals in society, she has harmonized her engineering background with social science approaches in Purdue’s interdisciplinary research environment, examining ethics in engineering practice by working with engineers from various industries. She is interested in enhancing understanding of the ethical and innovative practice of engineers in business settings, taking into account complex social, economic, and political contexts and identifying how best to support practice through both education and science and technology policy. She received the 2020 Best Formal Paper by a Graduate Student Award from the Association for Practical and Professional Ethics (APPE) and was an officer of the American Society of Engineering Education’s Engineering Ethics Division. As a Mirzayan Fellow (March 7–May 27), she is excited to gain experience in science and technology policy and to contribute to the NAE’s Cultural, Ethical, Social, and Environmental Responsibility (CESER) program. If her schedule permits she will also be involved in the NAE studies on Extraordinary Engineering Impacts on Society and on Health Risks of Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches. Dayoung is in Keck W1023. You can reach her at DKim@nae.edu or 202.334.1577.
### Calendar of Meetings and Events

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<th>Date</th>
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<tr>
<td>January 1–</td>
<td>NAE Awards call for nominations</td>
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<td>April 1</td>
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<td>February 1–2</td>
<td>Committee meeting on Laying the Foundation for New and Advanced Nuclear Reactors in the United States</td>
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<td>February 15–March 14</td>
<td>Call for nominations for 2022 US Frontiers of Engineering Symposium</td>
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<td>February 24–25</td>
<td>Workshop on Infusing Advanced Manufacturing in Engineering Education</td>
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<td>Late February–Late April</td>
<td>Call for new nominations for 2023 election cycle (from current members/international members only)</td>
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<td>March 1–31</td>
<td>Election of NAE officers and councillors</td>
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<td>March 17</td>
<td>NAE-GRP Colloquium: Opportunities and Challenges – Carbon Capture, Utilization, and Sequestration</td>
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<td>March 18, 30, April 20</td>
<td>Workshop on Connecting Efforts to Support Minorsities in Engineering Education [virtual workshop, 3 hours per day]</td>
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<td>March 30</td>
<td>NAE regional meeting University of Arizona, Tucson</td>
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<td>April 18–19, 21</td>
<td>Public Understanding of Engineering: Planning Workshop to Explore Ways to Move the Needle [virtual workshop, 3–4 hours per day]</td>
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<td>April 28</td>
<td>NAE regional meeting Rensselaer Polytechnic Institute, Troy, NY</td>
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<td>May 4</td>
<td>NAE Council meeting Beckman Center, Irvine, CA</td>
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<td>May 4</td>
<td>EG Steering Committee meeting Beckman Center, Irvine, CA</td>
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<td>May 4–5</td>
<td>EngineerGirl Women in Engineering Celebration Beckman Center, Irvine, CA</td>
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<td>May 5</td>
<td>NAE national meeting Beckman Center, Irvine, CA</td>
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<td>May 6</td>
<td>2022 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education presentation University of Southern California, Los Angeles (by invitation only)</td>
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<td>May 19</td>
<td>NAE regional meeting Amazon, Seattle (University of Washington cohost)</td>
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<td>June 13</td>
<td>2022 Charles Stark Draper Prize for Engineering presentation Washington, DC (by invitation only)</td>
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Meetings are held virtually unless otherwise noted.

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### In Memoriam

**Sir Eric Ash**, 93, retired rector, Imperial College London, 93, died August 22, 2021. Sir Eric was elected a foreign member in 2001 for innovations in optics and acoustics and for leadership in education.

**James B. Bassingthwaighte**, 92, emeritus professor of bioengineering, University of Washington, died February 2, 2022. Professor Bassingthwaighte was elected a foreign member in 2000 for contributions to integrative physiology and bioengineering using transport theory and computational methods.

**Wallace B. Behnke**, 95, retired vice chair, Commonwealth Edison Company, died January 11, 2022. Mr. Behnke was elected in 1980 for leadership in the US Breeder Reactor Program and in developing economical nuclear power for the generation of electricity.

**Morton Collins**, 85, managing partner, MCollins Ventures, died December 13, 2021. Dr. Collins was elected in 2016 for accomplishments as a builder and manager of technology-based companies and as an advisor to government and universities.

**Stephen H. Davis**, 82, McCormick Institute Professor and Walter P. Murphy Professor of Applied Mathematics, Northwestern University, died November 12, 2021. Professor Davis was elected in 1994 for contributions to the mathe-
matics of hydrodynamic stability theory and interfacial phenomena.

**Robert H. Grubbs**, 79, Victor and Elizabeth Atkins Professor of Chemistry, California Institute of Technology, died December 19, 2021. Professor Grubbs was elected in 2015 for developments in catalysts that have enabled commercial products.

**Kenneth A. Jackson**, 91, professor emeritus of materials science and engineering and of optics, University of Arizona, died January 7, 2022. Professor Jackson was elected in 2005 for advancing the science and technology of single crystal growth and materials made by casting.

**Bernard L. Koff**, 94, engineering consultant and retired executive vice president of engineering at Pratt & Whitney, died November 2, 2021. Mr. Koff was elected in 1988 for pioneering leadership in the design and development of gas turbine engines for aircraft.

**Ronald K. Leonard**, 87, associate professor of agricultural and biosystems engineering, Iowa State University, died November 8, 2021. Mr. Leonard was elected in 1999 for contributions to the design and manufacturing of cotton harvesters, lawn and garden machines, and agricultural tractors.

**Hans Mark**, 92, chancellor emeritus, University of Texas System, died December 18, 2021. Dr. Mark was elected in 1976 for leadership in exploring the solar system, nuclear engineering, and application of advanced computers to fluid dynamics.

**James A. Miller**, 75, retired distinguished member of the technical staff, Sandia National Laboratory, died October 3, 2021. Dr. Miller was elected in 2008 for research on the theory and modeling of combustion chemistry that has led to universally applied codes for combustion modeling.

**Linn F. Mollenauer**, 84, retired Bell Labs Fellow, Bell Laboratories, Lucent Technologies, died July 8, 2021. Dr. Mollenauer was elected in 1993 for contributions to the realization of soliton-based, ultra-high-capacity lightwave communication.

**Babatunde A. Ogunnaike**, 65, William L. Friend Chaired Professor, Chemical Engineering Department, University of Delaware, died February 20, 2022. Professor Ogunnaike was elected in 2012 for advances in process systems, process engineering practice, and systems engineering education.

**Robert J. Patton**, 99, retired senior vice president, LTV Aerospace Products Group, died December 26, 2021. Mr. Patton was elected in 1998 for aerodynamics, propulsion, and systems engineering on military aircraft.

**James F. Roth**, 96, consultant and emeritus corporate chief scientist, Air Products and Chemicals Inc., died December 7, 2021. Dr. Roth was elected in 1982 for outstanding contributions to the development of industrial chemical process technology in the manufacture of acetic acid and linear olefins.

**Merrill I. Skolnik**, 94, superintendent emeritus, Radar Division, Naval Research Laboratory, died January 27, 2022. Dr. Skolnik was elected in 1986 for contributions to the advancement of radar, and for leadership in radar engineering research and development.

**John D. Warner**, 81, retired senior vice president and chief administrative officer, Boeing Company, died September 8, 2021. Dr. Warner was elected in 1995 for contributions to commercial aircraft cockpit and avionic systems.

**Eric F. Wood**, 74, Susan Dod Brown Professor Emeritus, Civil and Environmental Engineering, Princeton University, died November 2, 2021. Professor Wood was elected in 2015 for development of land surface models and use of remote sensing for hydrologic modeling and prediction.
As the NAE’s EngineerGirl celebrates its 20th year, I am thinking about how far we have come and how much there is still to do. In 2000 only 9 percent of the US engineering workforce identified as women despite gains in female involvement in other professions.\(^1\) Women now account for 16 percent of engineers.\(^2\) While that is evidence of progress, it is nowhere near enough. If the United States is to remain a technological powerhouse, all youth must be invited and encouraged to see themselves as engineers, and they must have access to equitable training and opportunities to get there.

**Background**

In 1997 NAE members and staff recognized the need to create a more diverse engineering workforce, and getting more women engaged was seen as an important first step. A committee was formed with the dual goal of organizing a national summit to consider what should be done and developing a public-facing website celebrating the contributions of female engineers. That website and the summit were dubbed the Celebration of Women in Engineering. At the time the internet was still relatively new and the website represented a novel way for the NAE to communicate with the public.

After the summit a second committee was assembled to advise the NAE on next steps. That group identified the importance of focusing on a younger audience—middle school girls—and the website was redesigned with them in mind. A Girls Advisory Board of 15 middle school girls throughout North America met via chat rooms to talk about what they would like to see in a site about engineering, and in 2001 EngineerGirl was launched with many redesigned resources from the Celebration site. It went live during Engineers Week, in combination with activities around the country to establish the very first Introduce a Girl to Engineering Day,\(^3\) which continues today.

**EngineerGirl’s Unique Focus**

The unique focus on middle school girls has defined and sustained EngineerGirl ever since. Other visitors—high school and elementary school girls, educators, caregivers, and families—are certainly part of the site’s intended audience, but every resource or program added is specifically evaluated to see if it would be understandable and helpful to children in grades 6–8.

The goal is still to support and inspire girls to explore engineering careers, by

1. giving girls and their caregivers nonthreatening ways to learn about engineering fields through programs like the annual writing contest, the Ask an Engineer feature, and EngineerGirl Ambassadors;
2. helping students understand what engineers do, with articles and features that spotlight engineers and put faces behind the products;
3. providing approachable role models from a wide range of fields and backgrounds to help youth imagine what a career in engineering could look like for them;
4. pointing out how engineering relates to girls’ lives (and those of their family and community) and how engineers make a positive difference in the world;

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5. and, perhaps most importantly, highlighting girls' voices by giving them recognition, sharing their stories, and bringing attention to the issues that matter to them.

**Extending the Engineering Community**

With all the focus on women and girls over the last 20 years, it is worth asking if there is more the NAE ought to be doing, and if we are reaching the girls with the least access to engineering.

While the percentage of women working in engineering careers has nearly doubled, they still receive only 22.4 percent of US engineering bachelor's degrees. What's more, despite representing 31.7 percent of the US population, only 16.8 percent of US engineering bachelor's degrees go to Native American, Hispanic, and Black students, and only one quarter of those to women. This means that an even larger part of the population is being excluded—even as the economy increasingly depends on skilled technical and engineering jobs.

**The Importance of Listening**

A new campaign to build a more diverse engineering workforce is needed, but now the starting place is different, thanks to an additional 20 years of research on technological learning. Numerous initiatives support early introduction of engineering into K-12 classrooms, and programs highlight diverse role models, but one thing that remains mostly quiet is the voice of the youth themselves.

It is all too easy to believe that the engineering community can by itself fix the issues that deter people from engineering careers, but effective solutions will not be found without listening carefully to other relevant stakeholders. These include not only social scientists and educators who work with youth but also the families and children who will make decisions in the next few years about where they would like to spend their lives and careers.

As EngineerGirl completes its 20th year, I propose a new campaign: a national listening campaign, to collect and share stories and amplify the many voices that are often unheard. This will involve talking with youth, finding out why they may or may not consider a career in engineering, and thoughtfully considering their perspectives. Asking questions and defining the issues are, after all, a major component of the engineering design process, and only when the nature of the problem and the expectations of stakeholders are fully understood can effective solutions be imagined.

There are likely many reasons why youth opt not to study engineering, so simply telling them that engineering offers great opportunities may not change minds—and in some cases it may not be true. Before we can honestly tell children that engineering will offer them a better future, we must be sure that that is true for those whom we aim to reach. We can know that only when we understand their perspectives and know what they imagine a better future to be.